Jet Measurements in Forward Kinematics: from LHCb to the EIC

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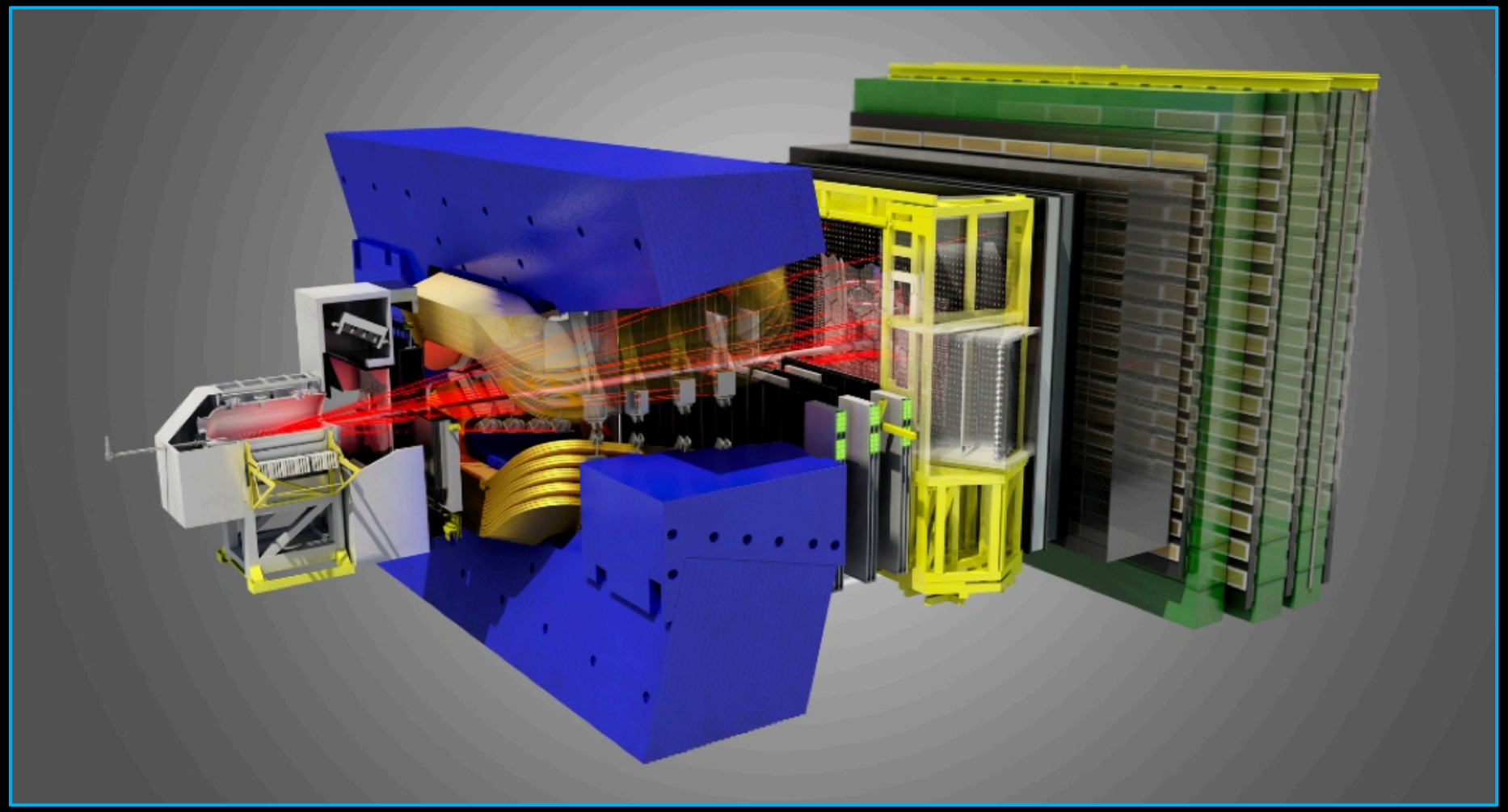
Why is LHCb relevant for the Electron-Ion Collider?

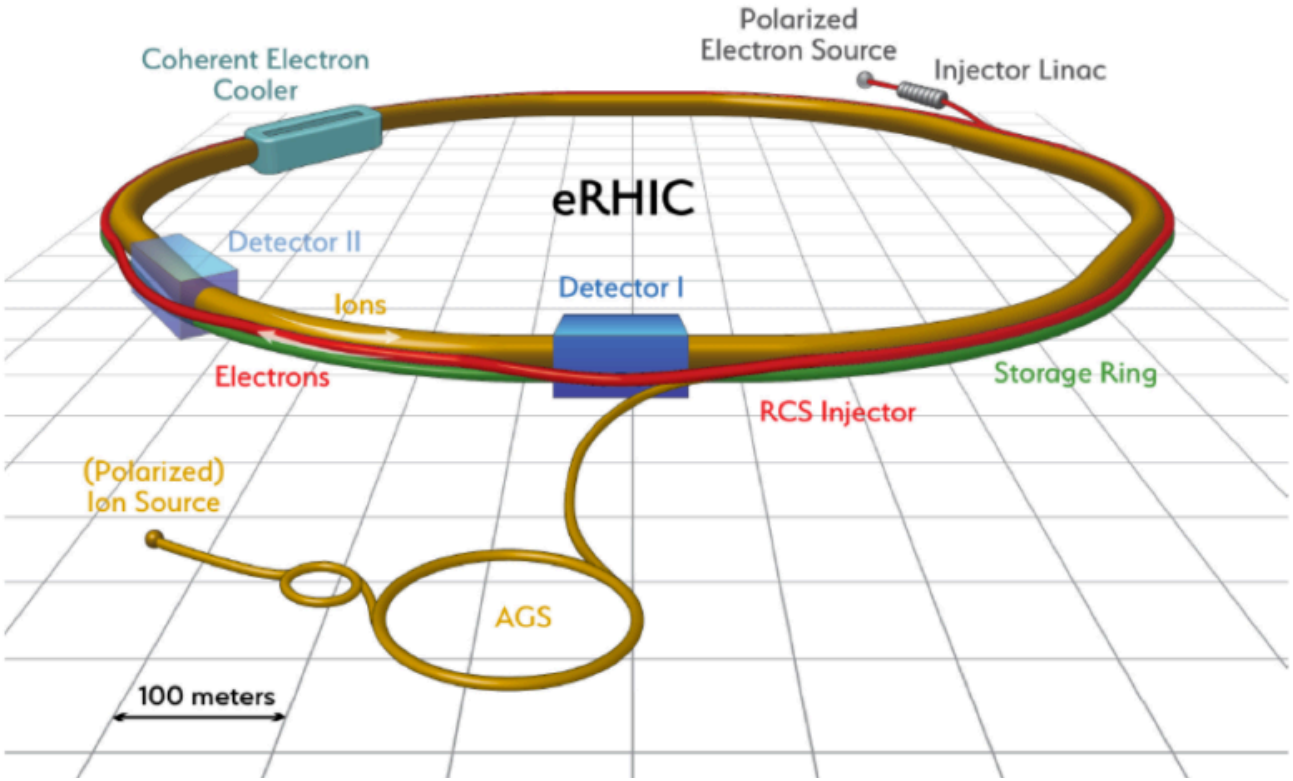
Why is LHCb relevant for the Electron-Ion Collider?

LHCb: The Large Hadron Collider beauty Experiment



Forward spectrometer at the Large Hadron Collider designed to study the production and decay of heavy-flavor hadrons

Why is LHCb relevant for the Electron-Ion Collider?



eRHIC design parameters:

- Up to 18 GeV electron beam
- Up to 275 GeV proton beam
- Up to 100 GeV/nucleon ion beam energy for nuclei up to uranium
- Polarized electron, proton, and light nuclei beams

What can a flavor physics experiment at the LHC contribute to jet physics at an EIC?

BNL eRHIC pre-CDR

This talk: Connecting the dots between LHCb and the EIC

Part 1 — Detector Instrumentation in the Forward Region, from LHCb to the EIC

Part 2 — Jet Measurements, from LHCb to the EIC

- Constraining PDFs with Jets
- Hadronization and Jet Substructure
- Jets from p+A to e+A

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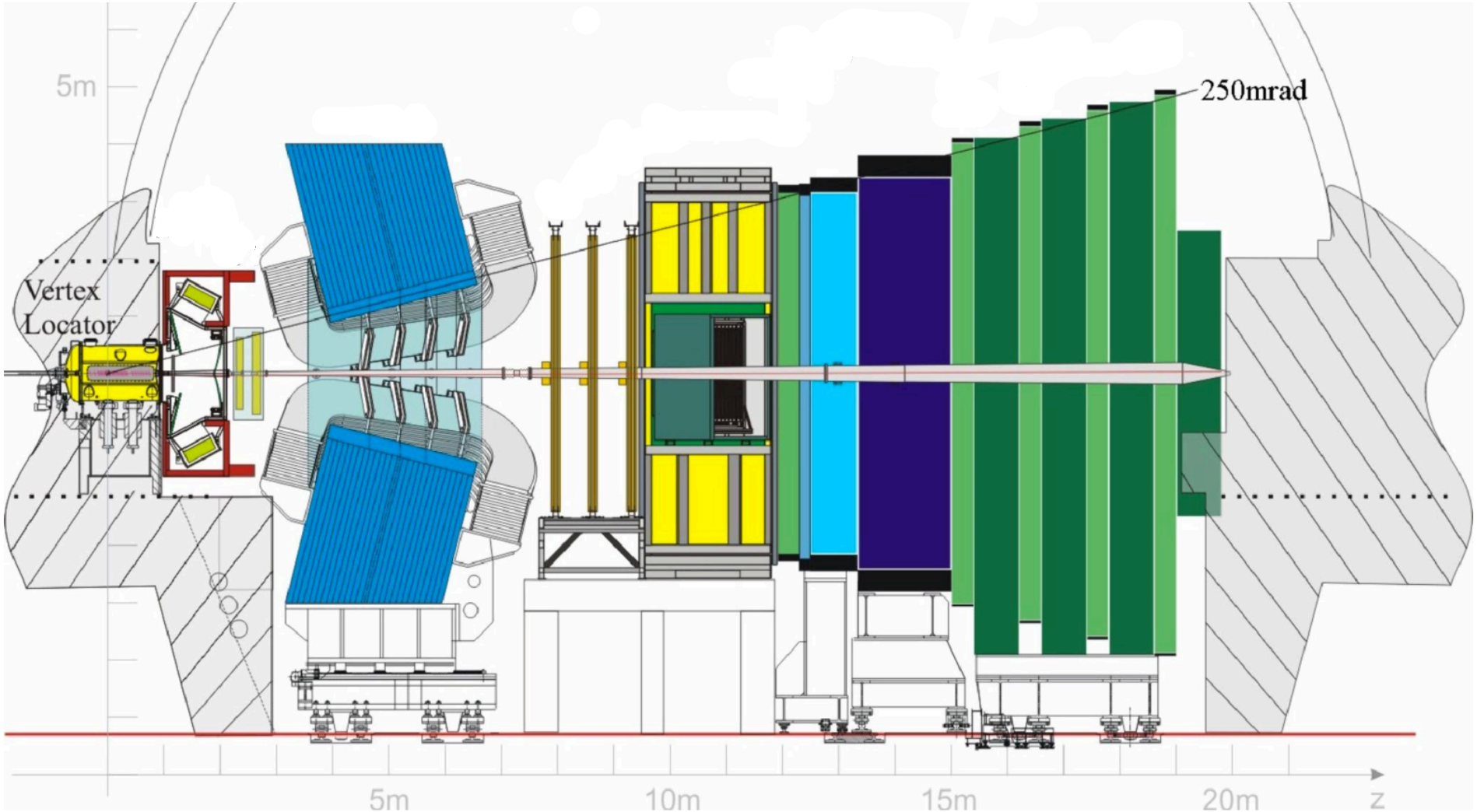
The LHCb Detector

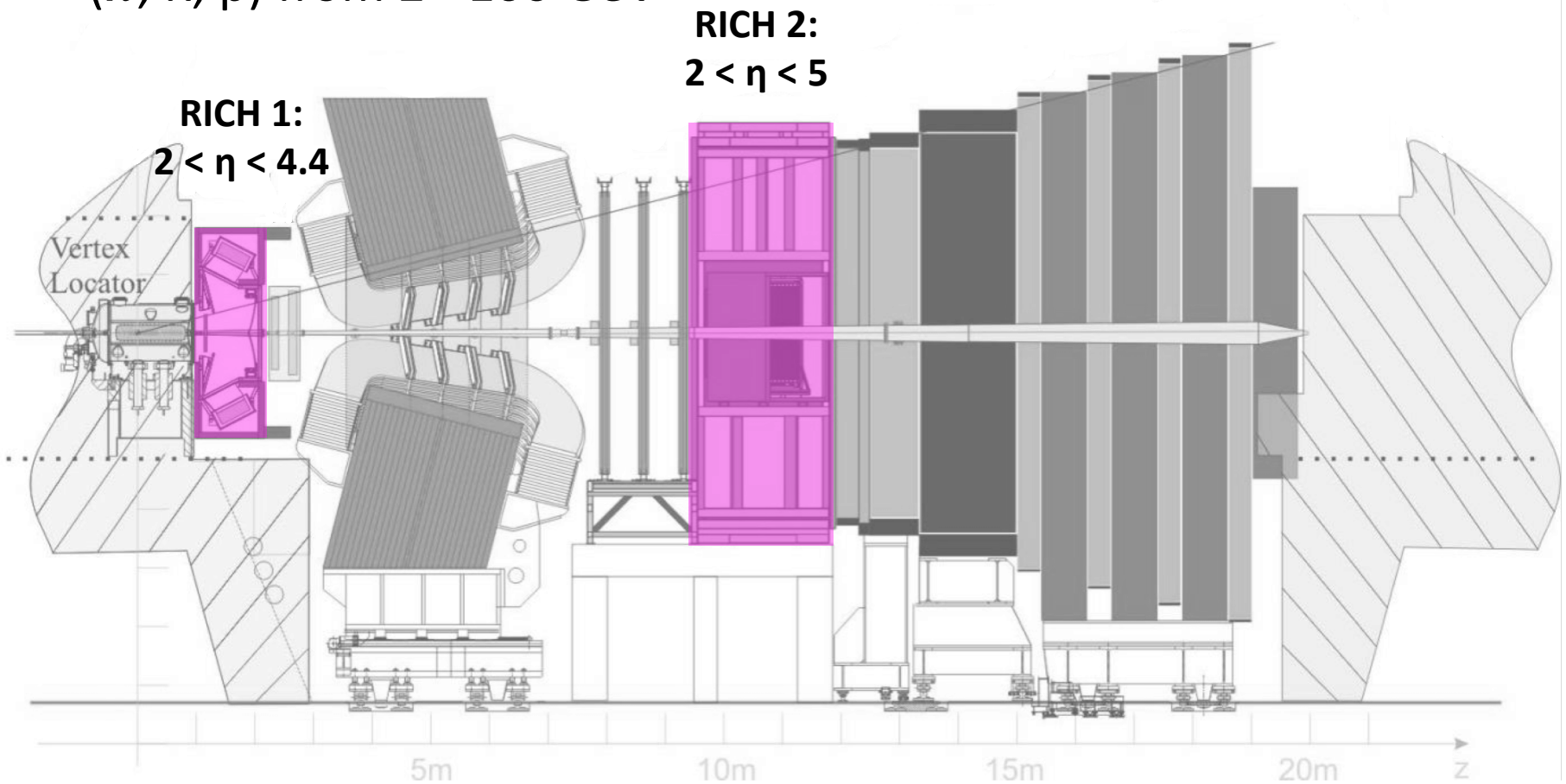


- Covers $2 < \eta < 5$
- Full Hadronic and Electromagnetic Calorimetry, Tracking, Particle Identification, and Muon ID

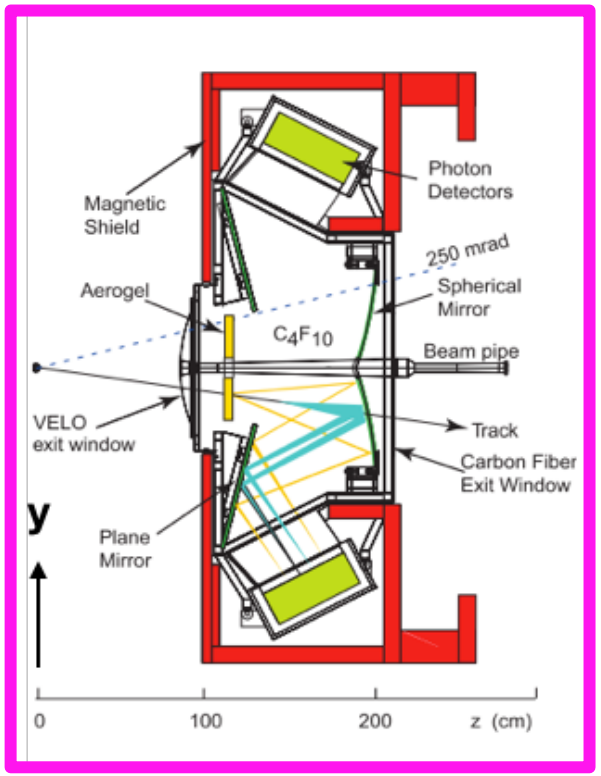
Int. J. Mod. Phys. A **30**, 1530022 (2015)

The LHCb detector – Particle ID

- Two Ring Imaging Cherenkov (RICH) Detectors provide particle ID for charged hadrons (π, K, p) from 2 - 100 GeV



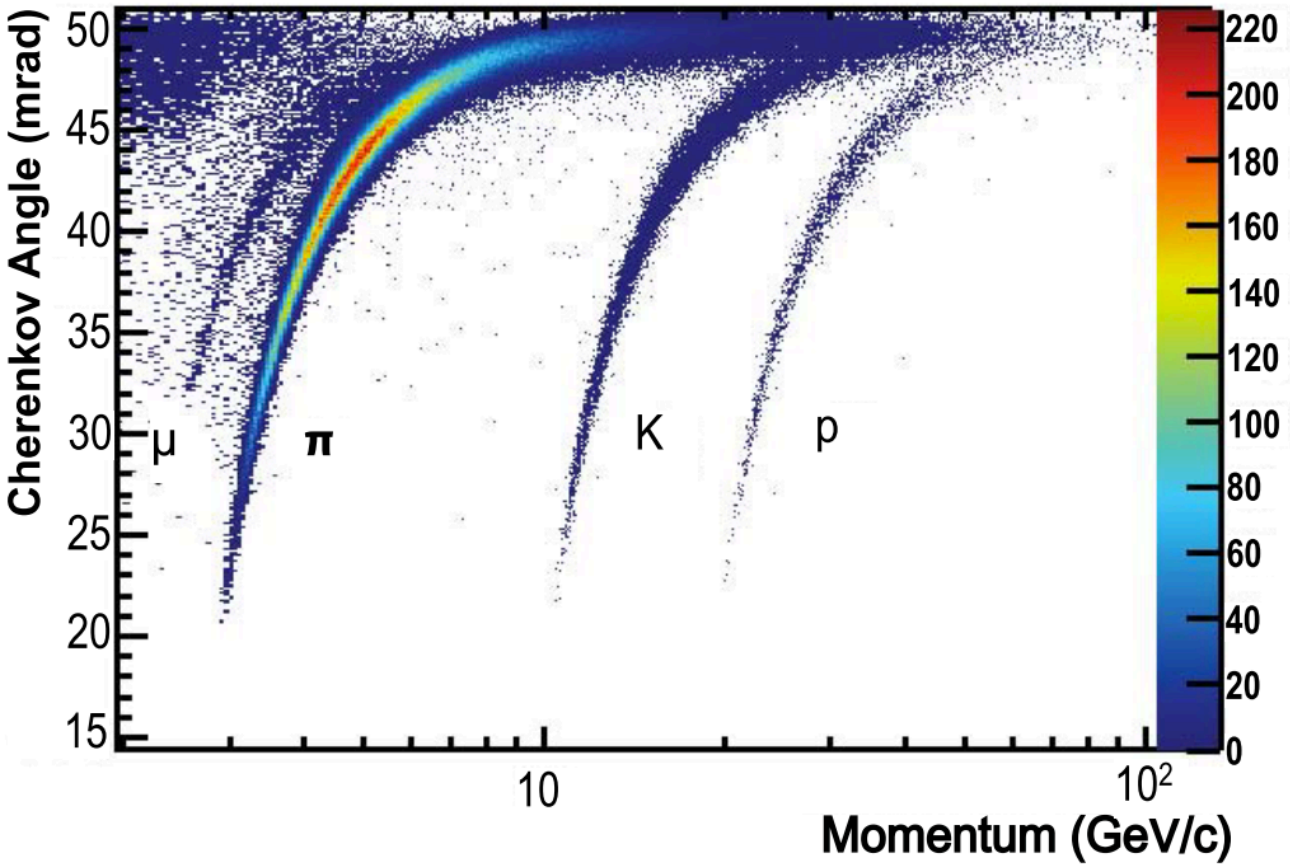
RICH 1



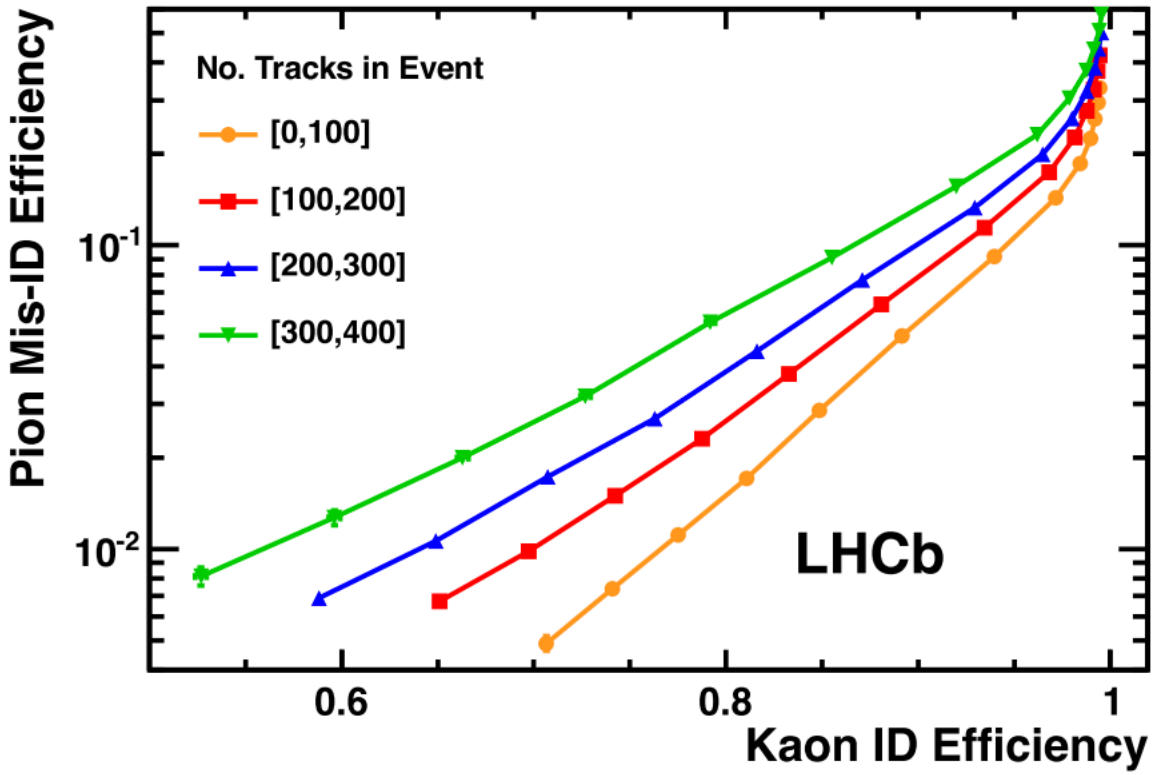
JINST **3**, S08005 (2008)
Int. J. Mod. Phys. A **30**, 1530022 (2015)

The LHCb detector – Particle ID

Reconstructed Cherenkov angle for Isolated Tracks

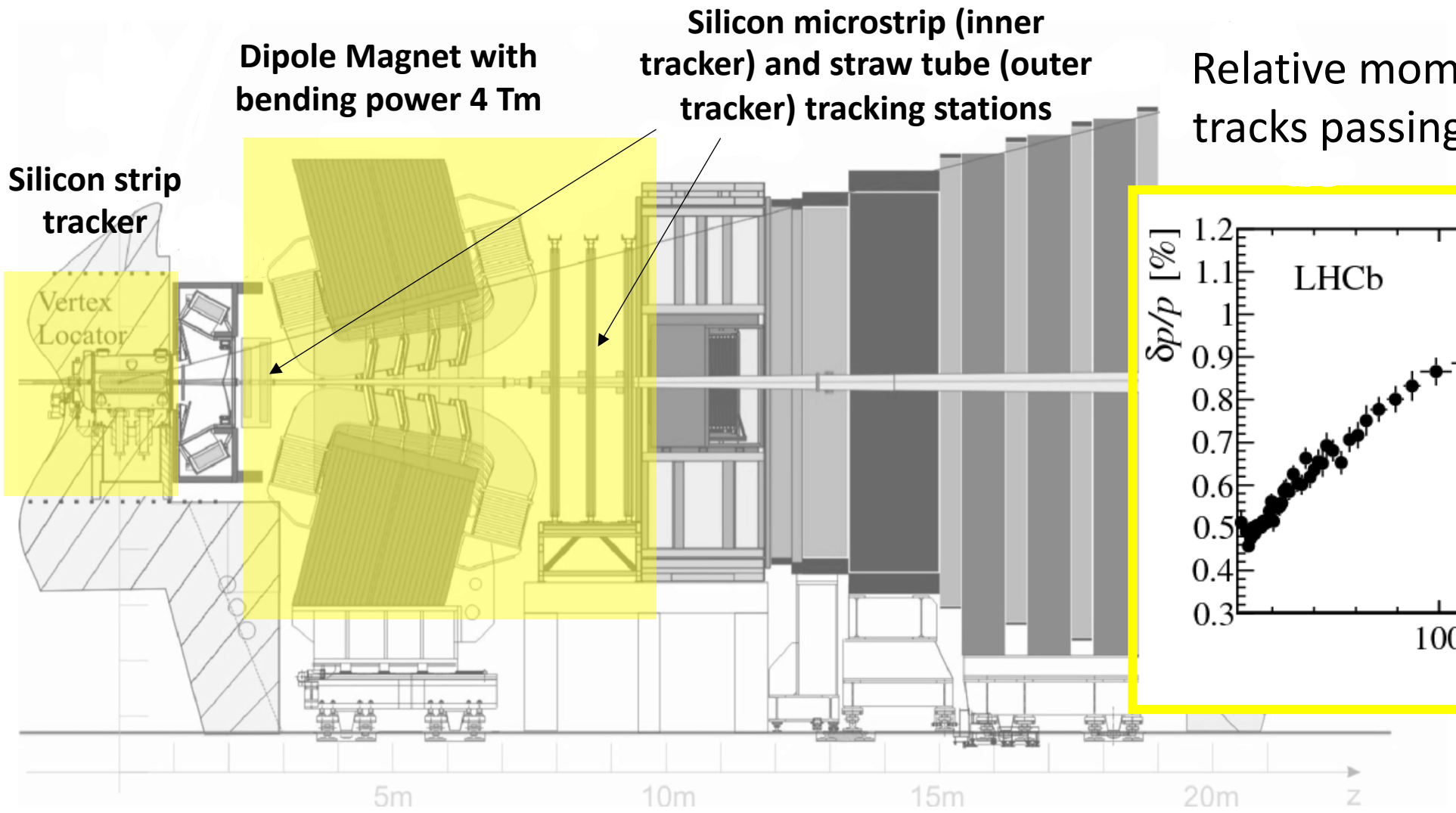


Pion Mis-ID vs Kaon ID efficiencies for events with many tracks

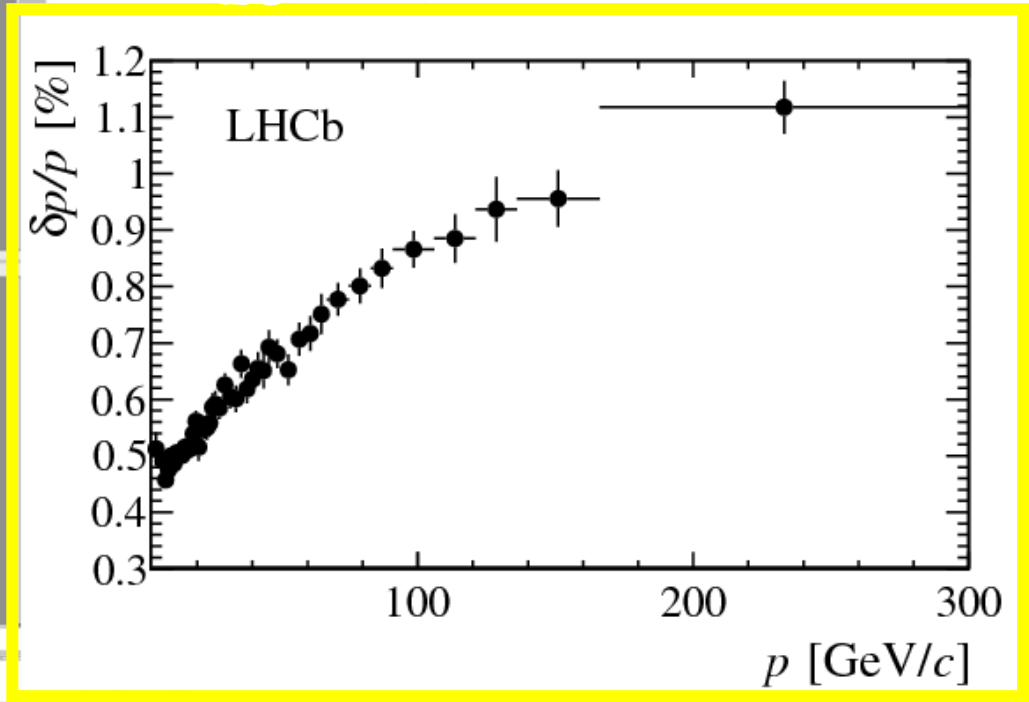


Int. J. Mod. Phys. A **30**, 1530022 (2015)

The LHCb Detector - Tracking



Relative momentum resolution for tracks passing through all stations:



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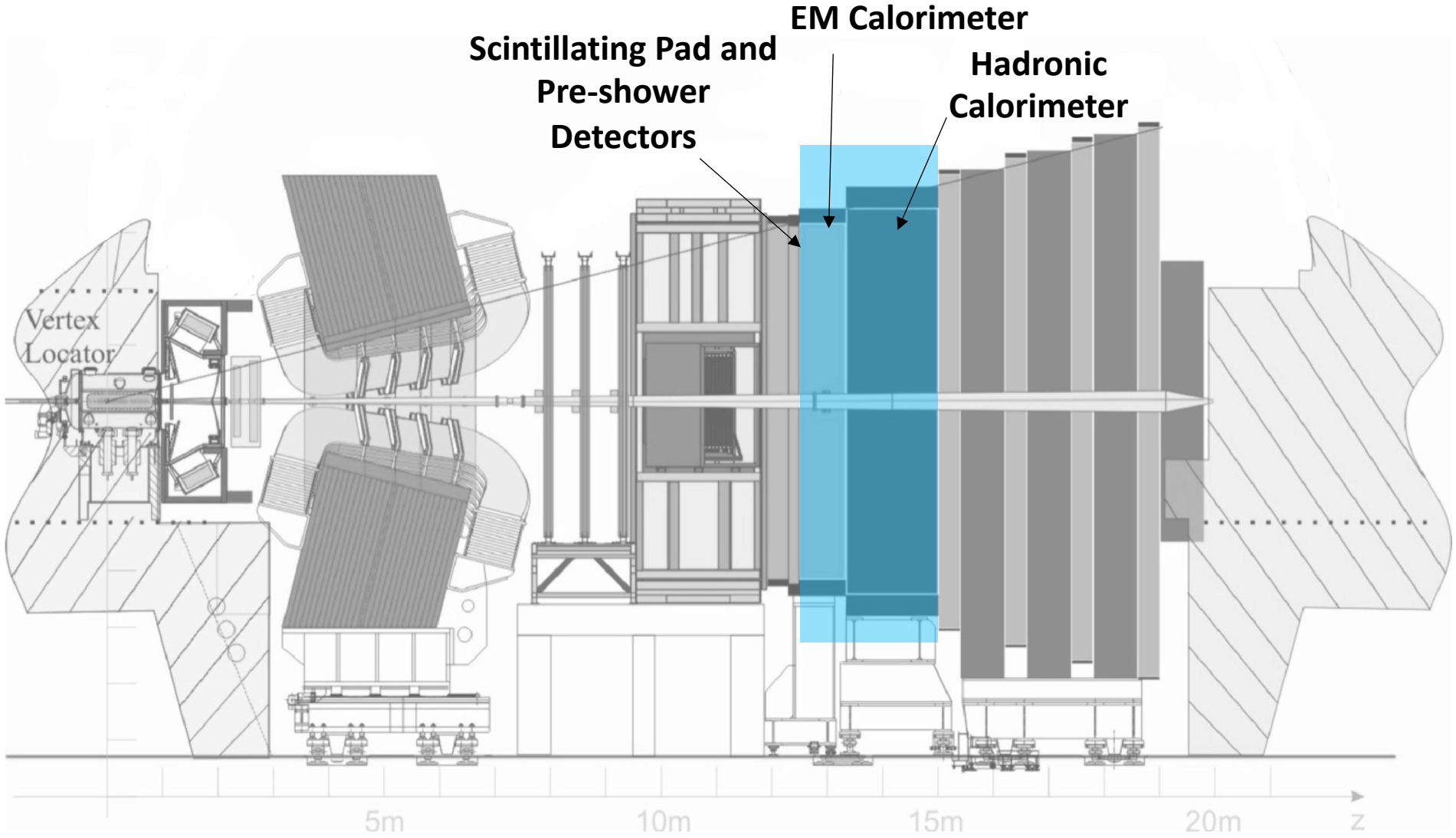
The LHCb Detector - Calorimetry



- Shashlik scintillator/lead EM calorimeter
- Sampling scintillator/iron hadronic calorimeter

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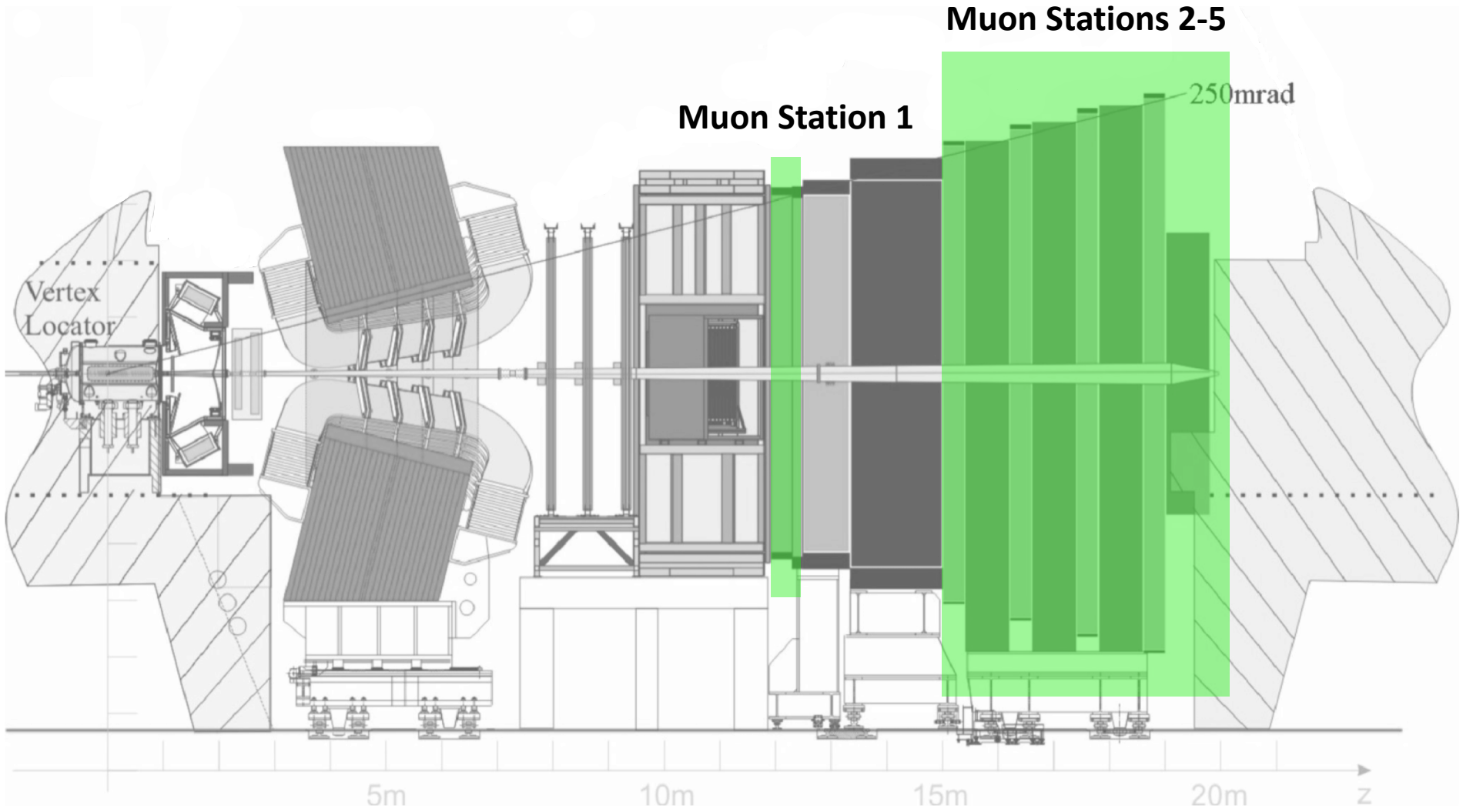
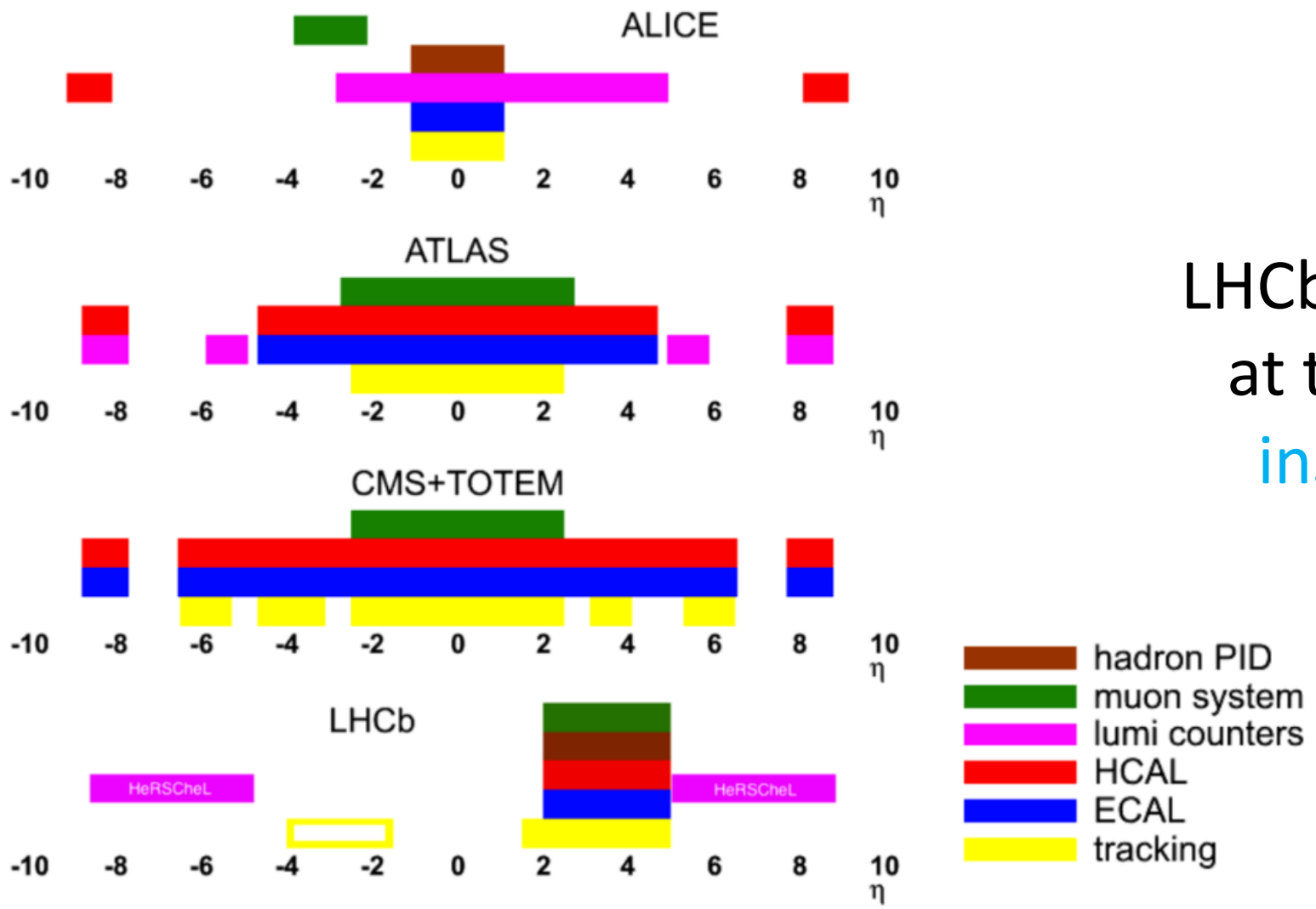
The LHCb Detector – Muon System



- Muon Station 1: Gas Electron Multipliers (GEMs) and Multi-wire Proportional Chambers (MWPCs)
- Muon Stations 2-5: MWPCs interleaved with iron absorbers

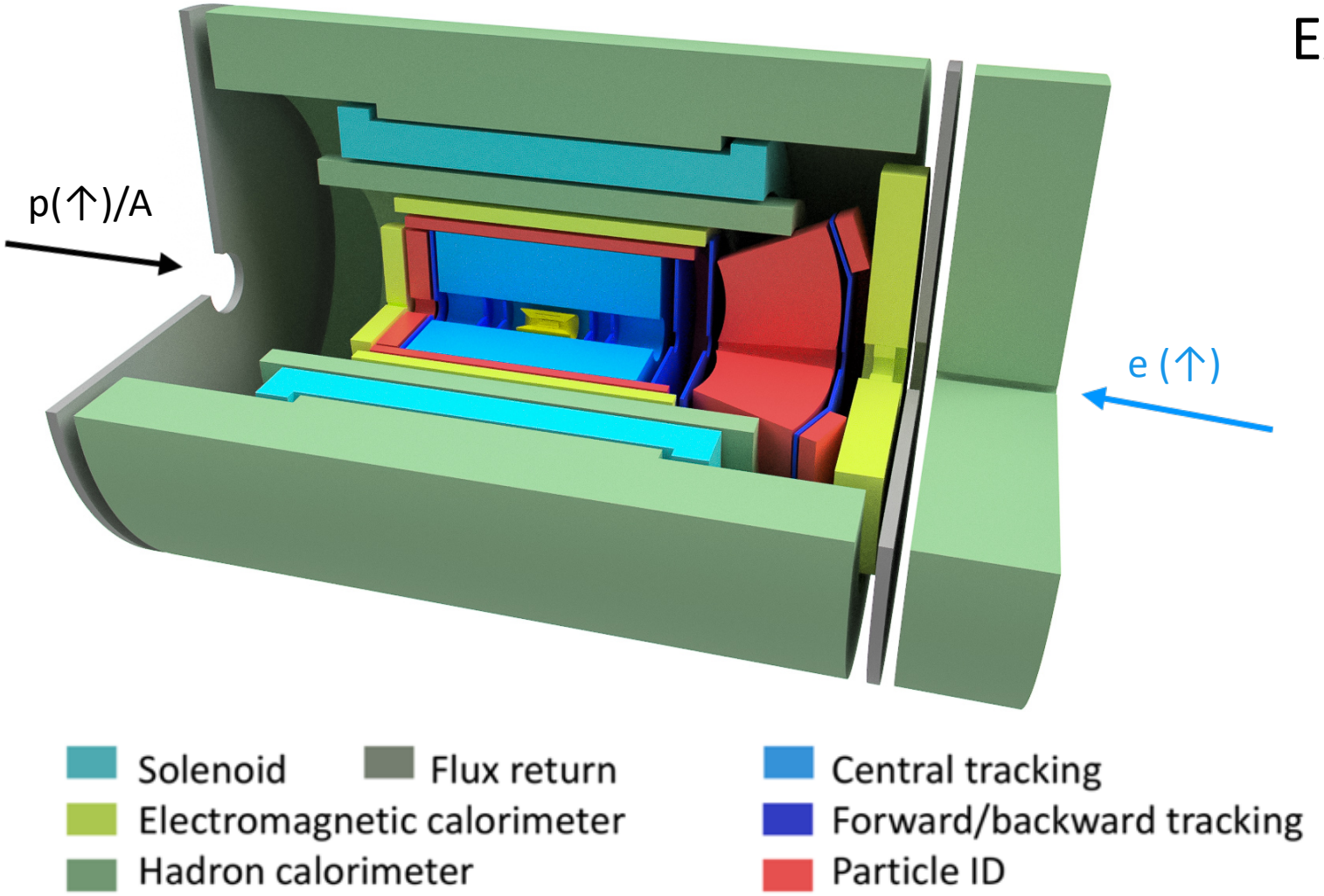
Int. J. Mod. Phys. A **30**, 1530022 (2015)

Full Instrumentation in the Forward Region



LHCb is the only detector at the LHC that is fully instrumented in the forward region

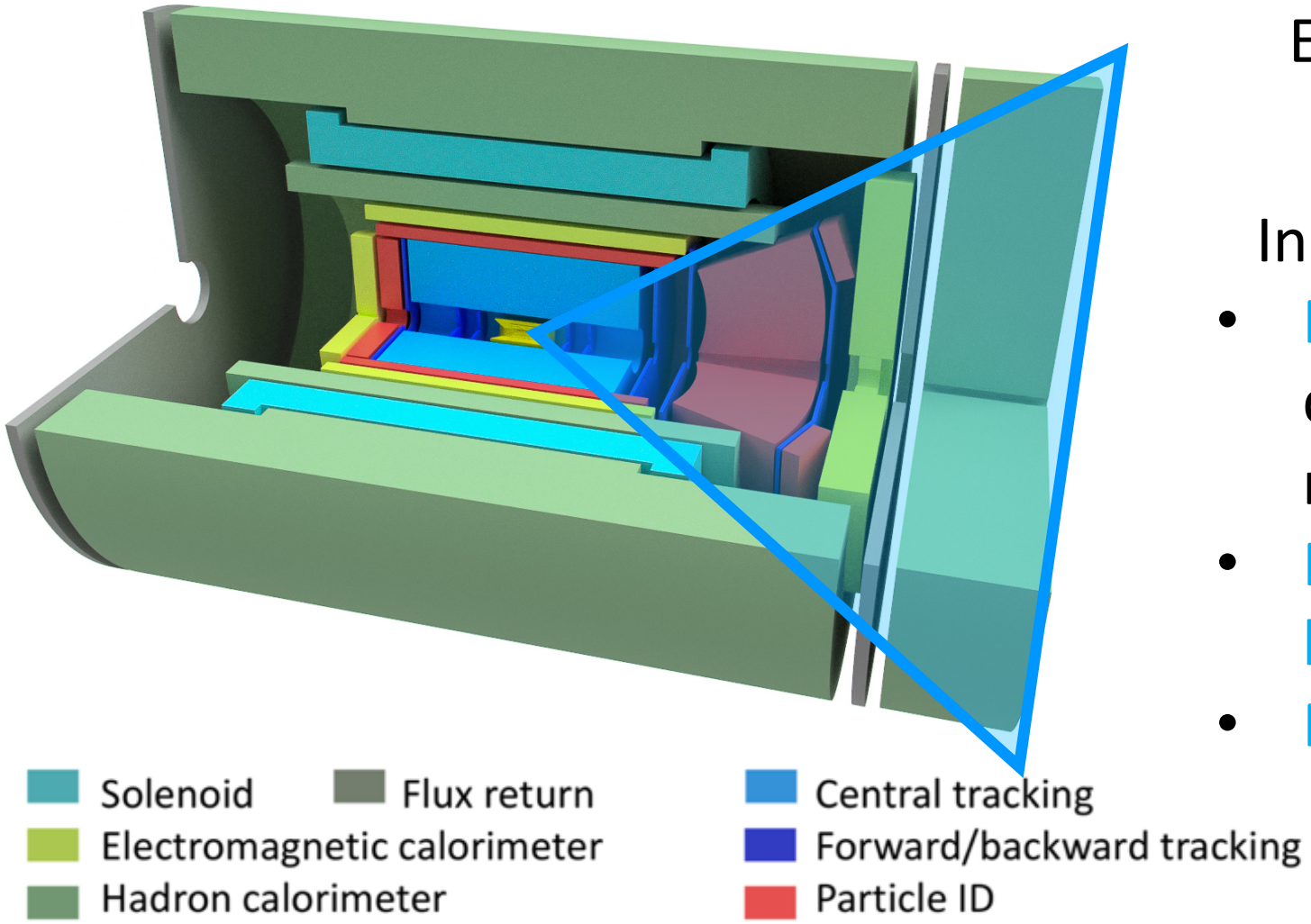
An Example EIC Detector



Example detector based on the sPHENIX solenoid

sPHENIX-note sPH-cQCD-2018-001

An Example EIC Detector



Example detector based on the sPHENIX solenoid

In the forward region ($2 < \eta < 4$):

- Full particle ID with a RICH detector for charged hadron momenta ~2-50 GeV
- Full electromagnetic and hadronic calorimetry
- Full tracking

… just like LHCb!

sPHENIX-note sPH-cQCD-2018-001

What can we gain from LHCb that is relevant for the EIC?

- Experience with using RICH detectors for particle ID in forward jets
  - Overlap in momentum range for RICH particle ID at LHCb and EIC
- Experience with jet reconstruction and flavor tagging in the forward region, where jets typically have much lower p_T
- Experience with what jet measurements can be done with full hadronic calorimetry, EM calorimetry, tracking and particle ID in the forward region and what detector requirements might be desired at an EIC

This talk: Connecting the dots between LHCb and the EIC

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- Hadronization and Jet Substructure
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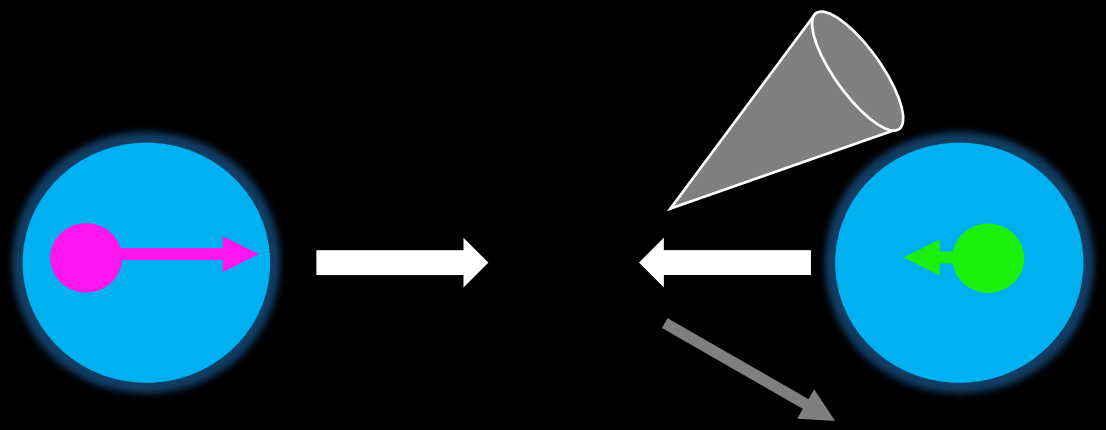
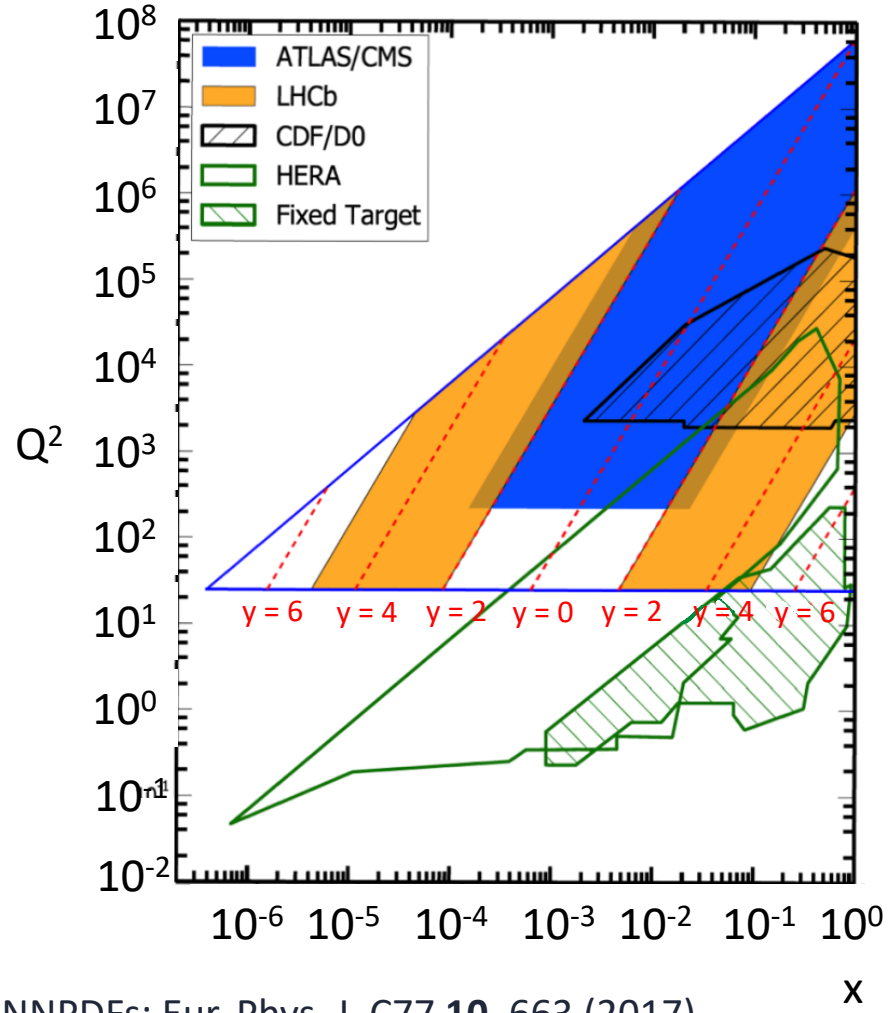
Constraining PDFs with jets



Unique Access in the Forward Region to PDFs

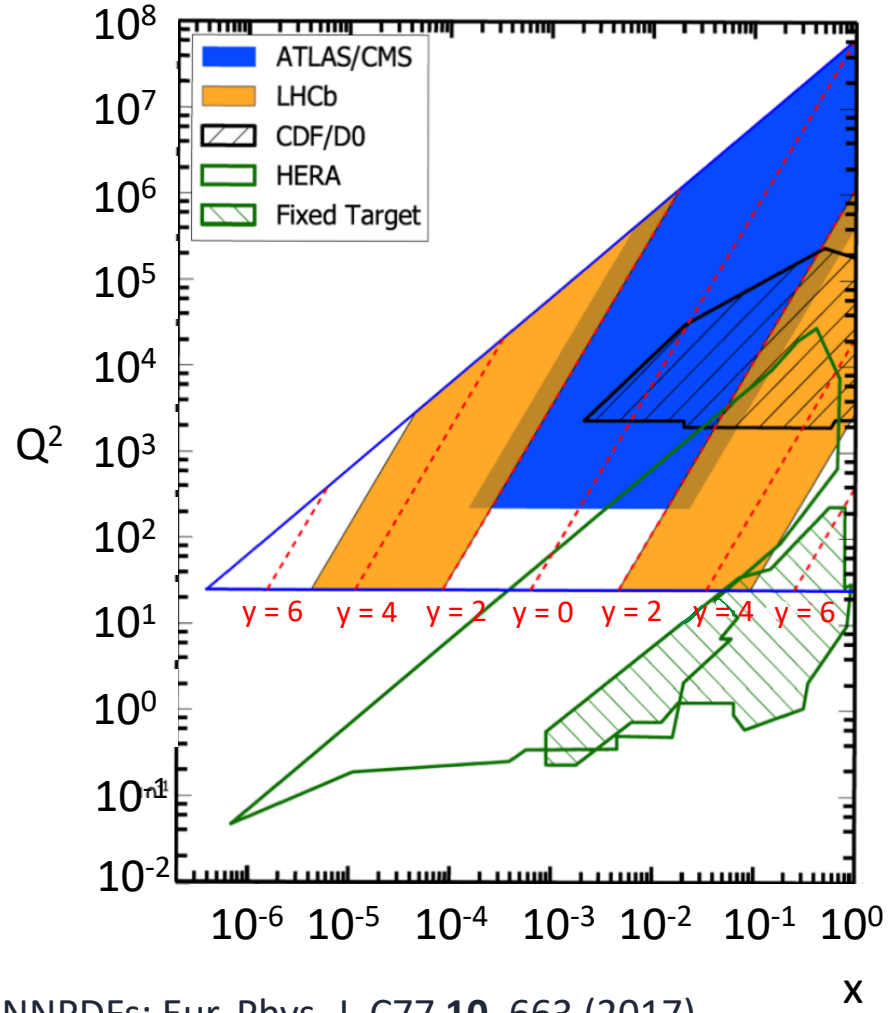
LHC 8 TeV Kinematics



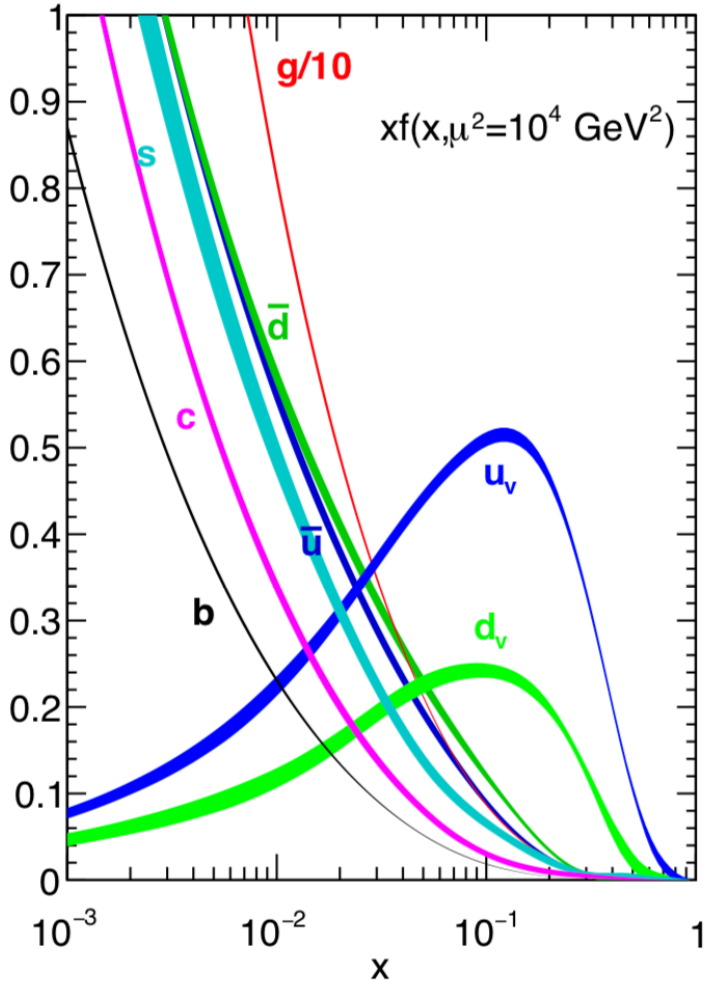
NNPDFs: Eur. Phys. J. C77 **10**, 663 (2017)
LHC 8 TeV Kinematics: arXiv: 0808.1847

Unique Access in the Forward Region to PDFs

LHC 8 TeV Kinematics



NNPDF3.1 NNLO PDFs



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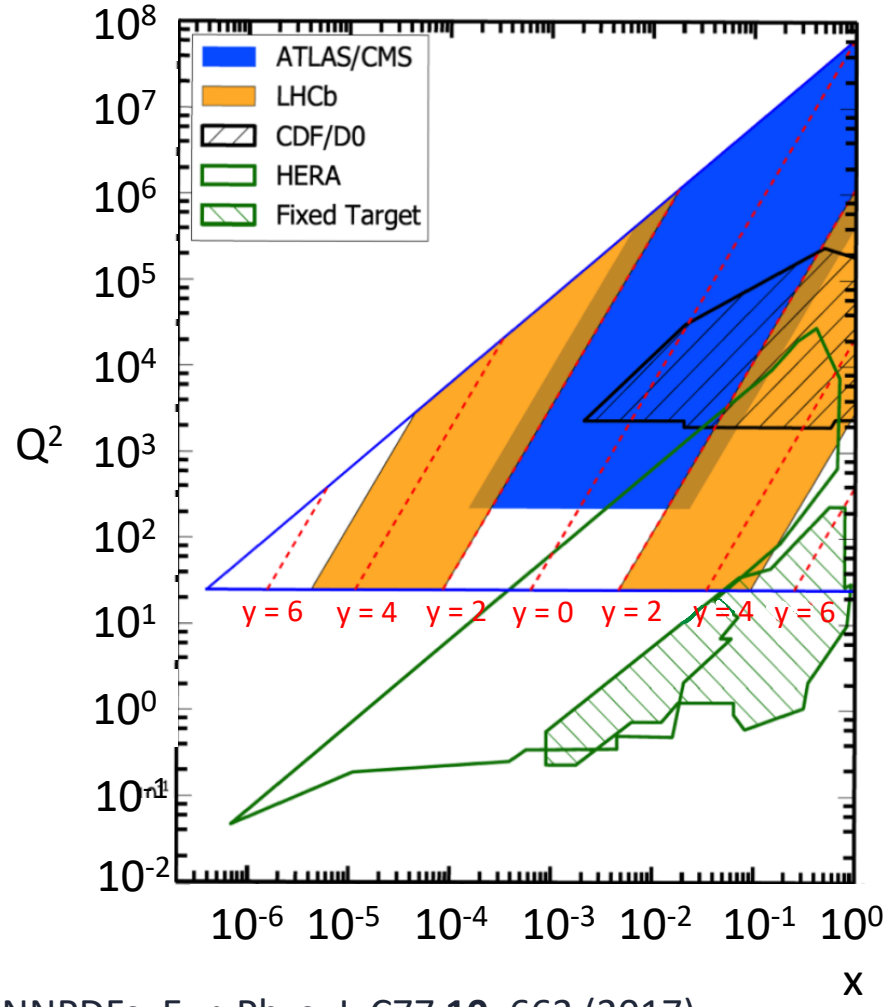

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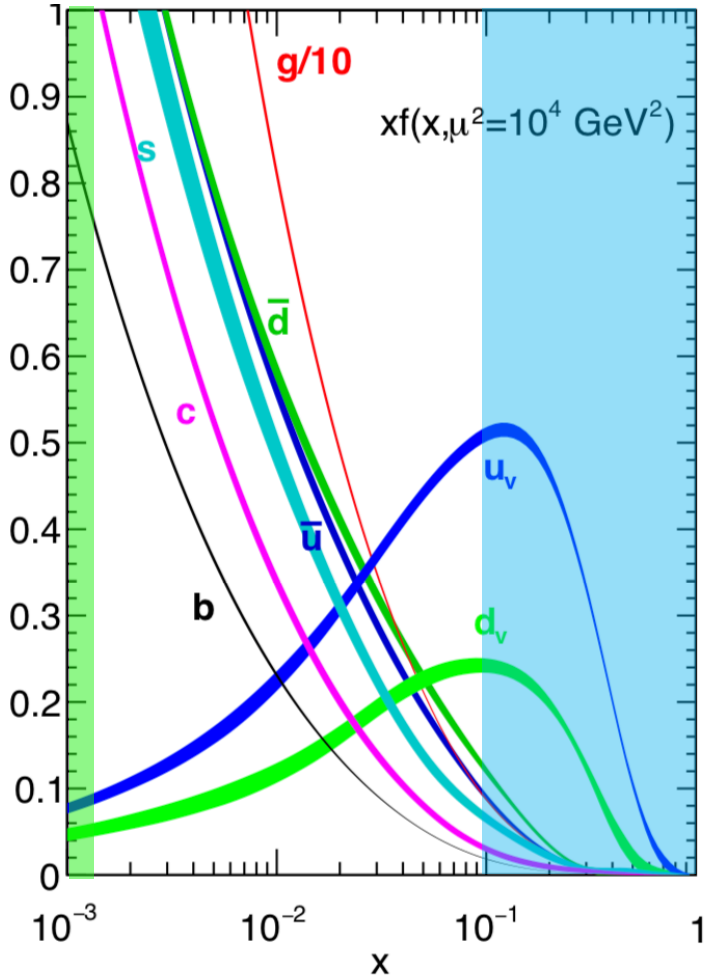

- LHCb is sensitive to both high-x and low-x PDFs, where the PDF uncertainties are largest

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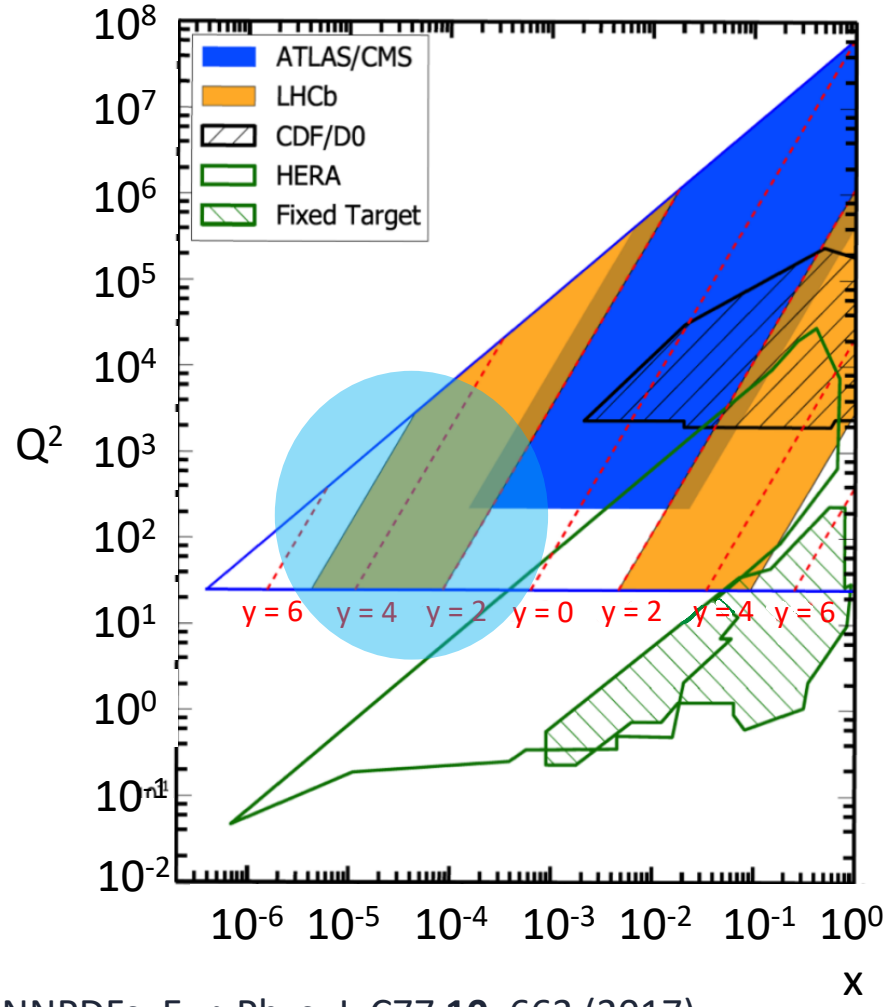
Unique Access in the Forward Region to PDFs

LHC 8 TeV Kinematics



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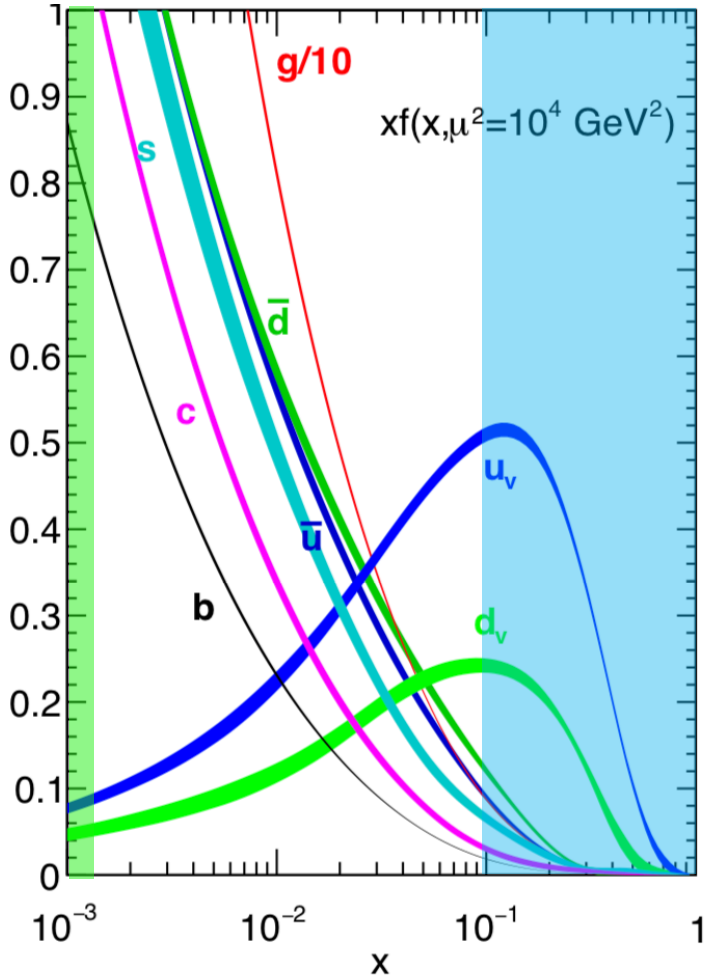


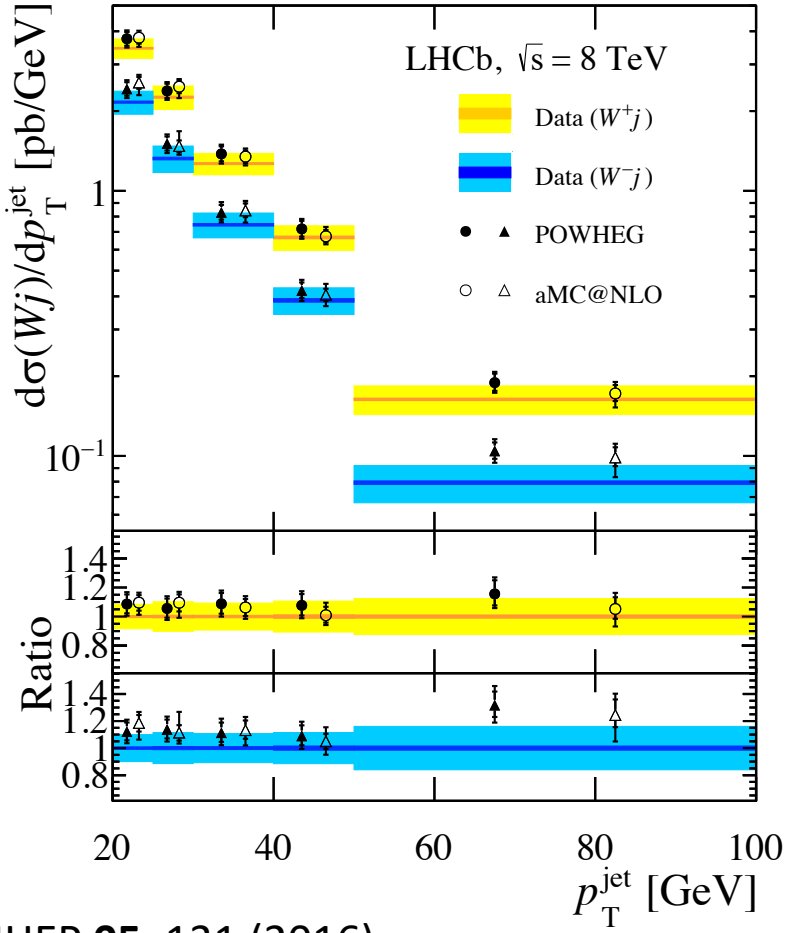
- LHCb is sensitive to both high-x and low-x PDFs, where the PDF uncertainties are largest
- The low-x region accessible by LHCb has not previously been studied

NNPDFs: Eur. Phys. J. C77 **10**, 663 (2017)
LHC 8 TeV Kinematics: arXiv: 0808.1847

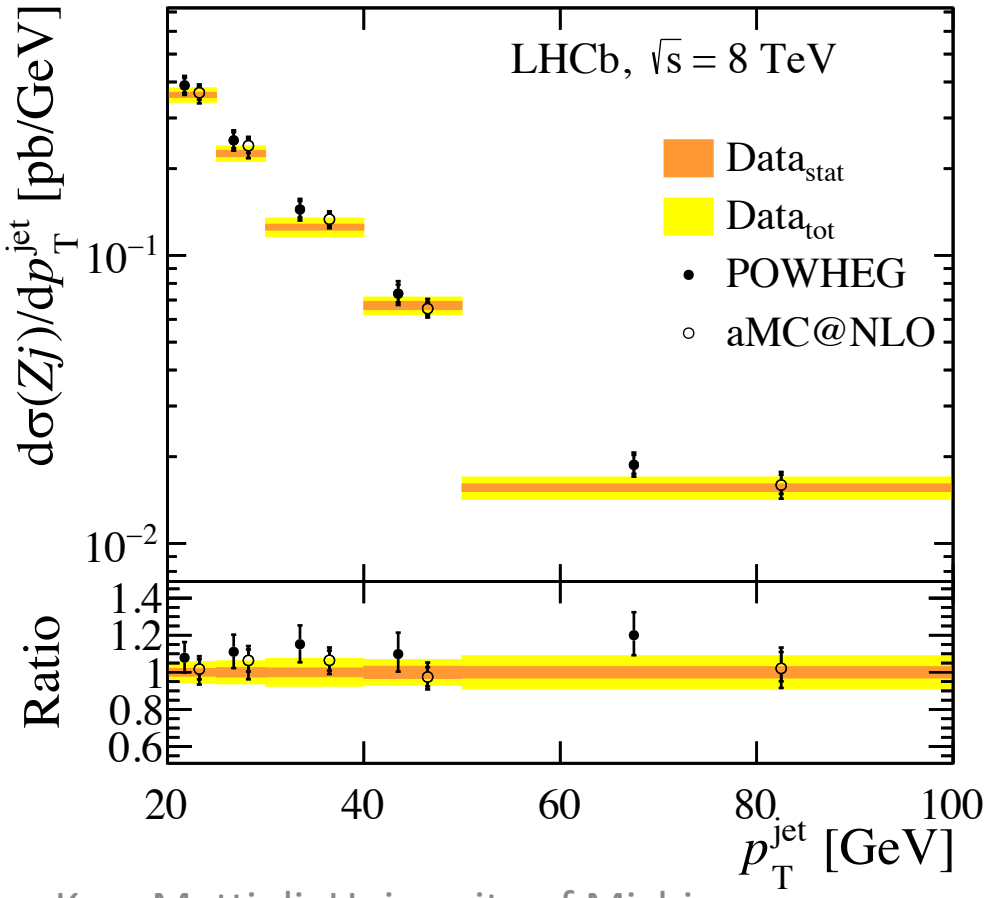
LHCb Jet Measurements to constrain PDFs

Jets produced in association with a vector boson

W + jet production



Z + jet production



JHEP **05**, 131 (2016)

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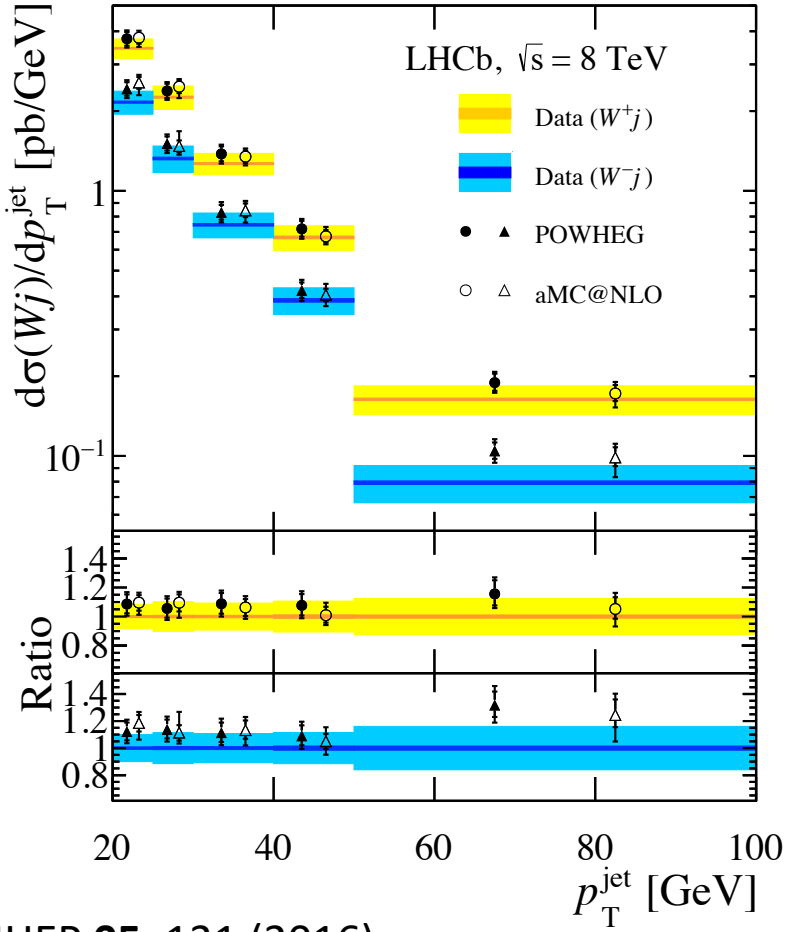
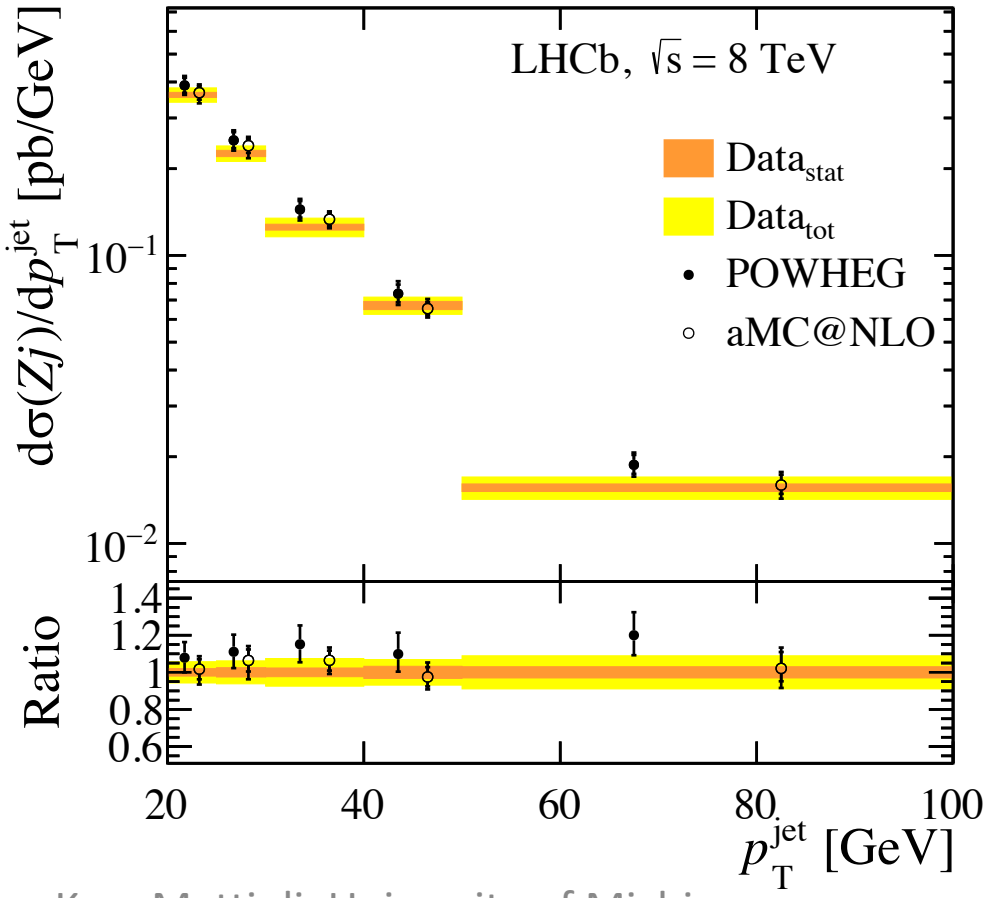


Z + jet production

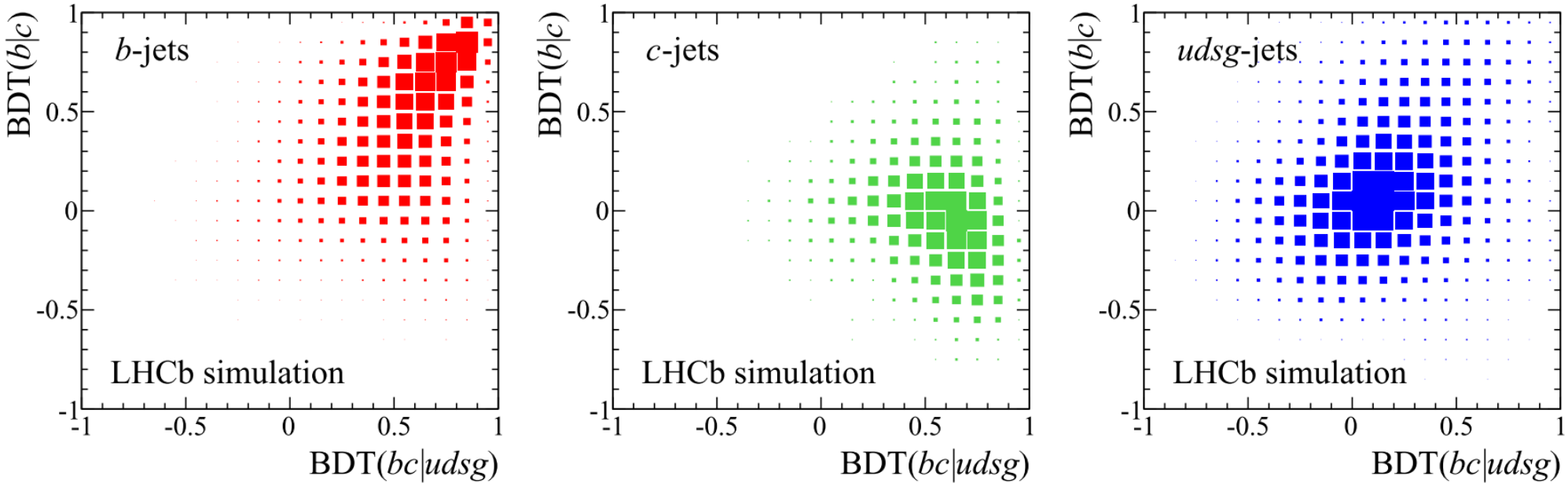


- Z + jet and W + jet measurements in the forward region predominantly probe light-quark PDFs
- Also sensitive to sea quark and gluon PDFs

JHEP **05**, 131 (2016)

Jet Flavor Tagging Improves PDF Constraints

- Heavy flavor jets are tagged by the presence of a secondary vertex within the jet cone
- Two Boosted Decision Trees (BDTs) are used for further discrimination between b-, c- and light-parton jets: BDT(bc|udsg) discriminates between heavy- and light-flavor jets while BDT(b|c) discriminates between beauty and charm jets

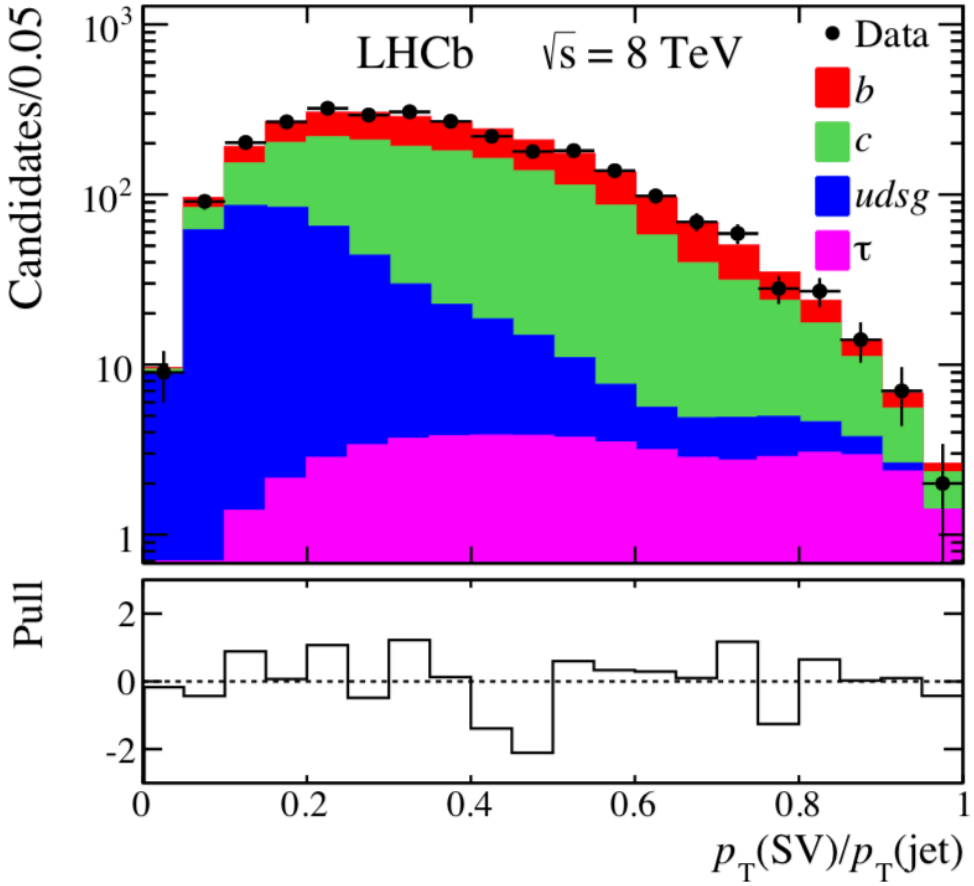


JINST **10**, P06013 (2015)

LHCb Jet Measurements to constrain PDFs

Flavor-tagged Jets produced in association with a vector boson

W + jet production



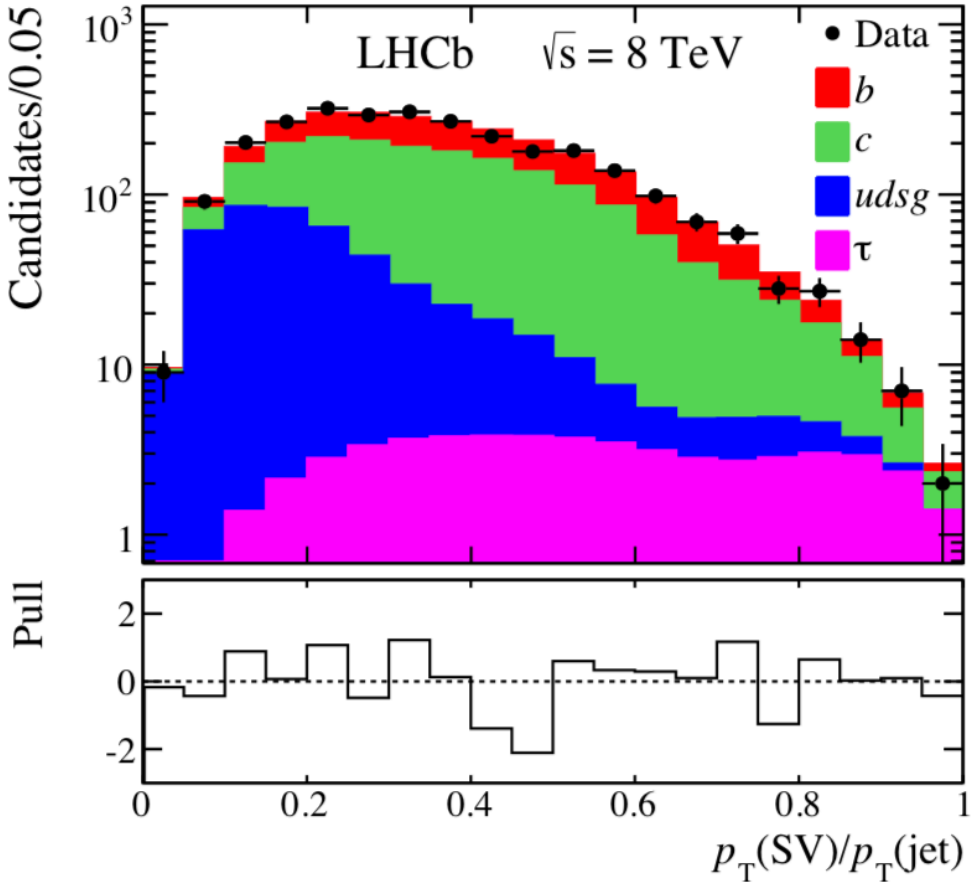
- With jet flavor tagging, can separate contribution of different quark flavors to W + jet production

PRD **92**, 052001 (2015)

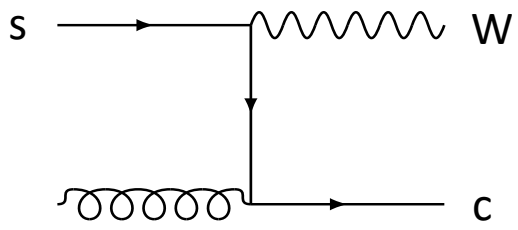
LHCb Jet Measurements to constrain PDFs

Flavor-tagged Jets produced in association with a vector boson

W + jet production



- With jet flavor tagging, can separate contribution of different quark flavors to W + jet production
- W + charm jet probes strange quark PDF

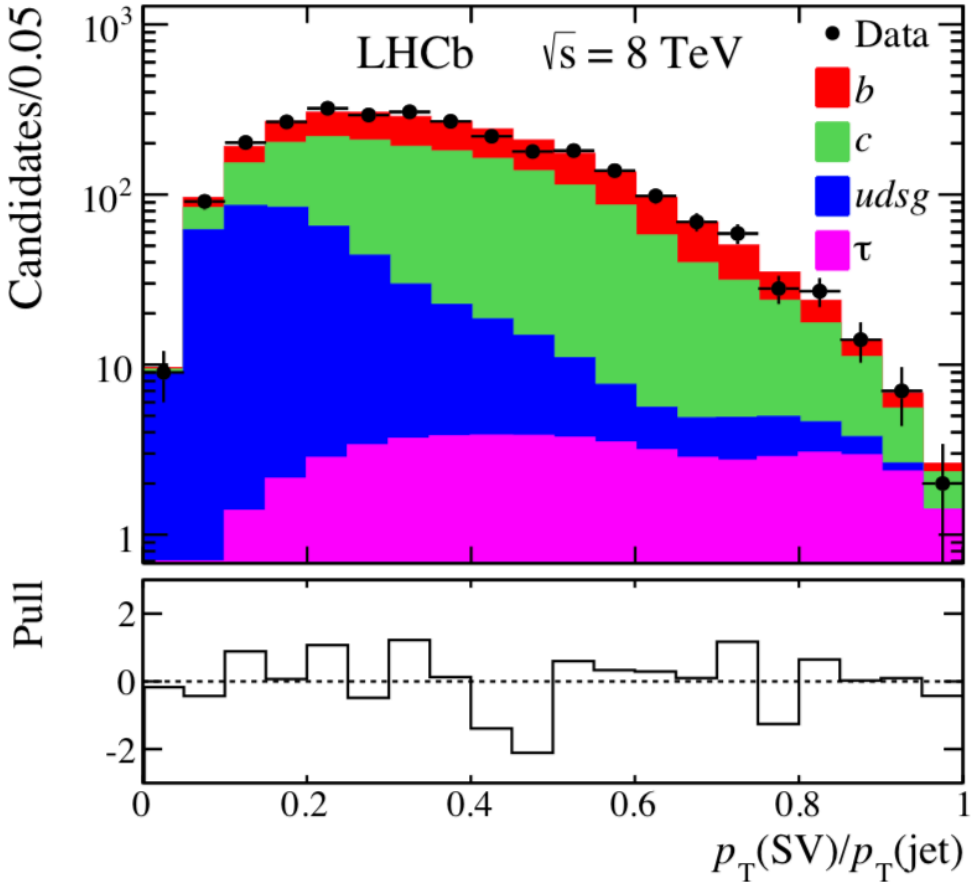


PRD **92**, 052001 (2015)

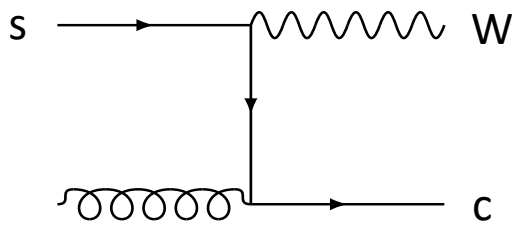
LHCb Jet Measurements to constrain PDFs

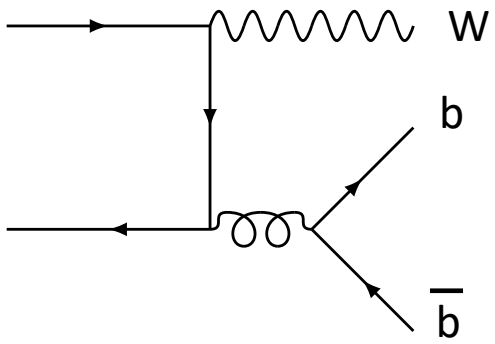
Flavor-tagged Jets produced in association with a vector boson

W + jet production



- With jet flavor tagging, can separate contribution of different quark flavors to W + jet production
- W + charm jet probes strange quark PDF
- W + beauty jet probes light (sea) quark PDFs



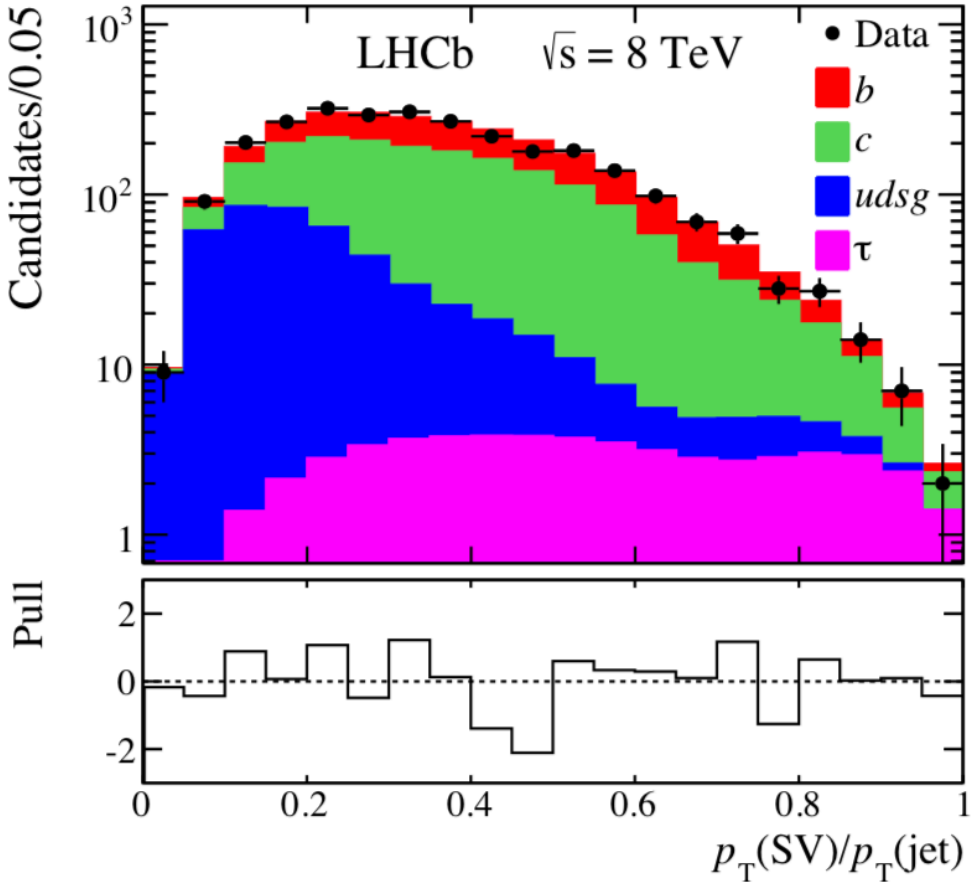


PRD **92**, 052001 (2015)

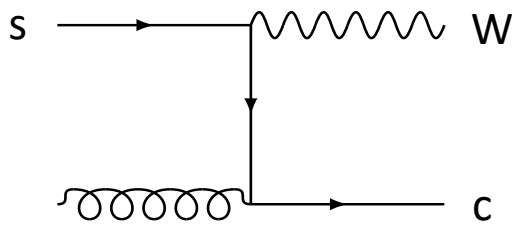
LHCb Jet Measurements to constrain PDFs

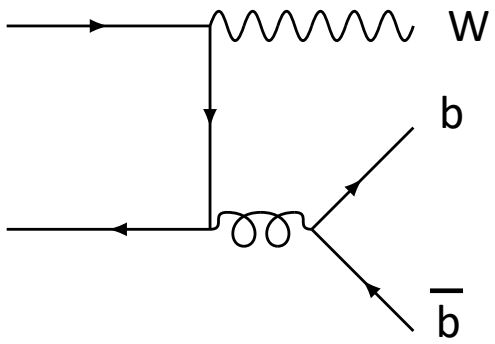
Flavor-tagged Jets produced in association with a vector boson

W + jet production



- With jet flavor tagging, can separate contribution of different quark flavors to W + jet production
- W + charm jet probes strange quark PDF
- W + beauty jet probes light (sea) quark PDFs
- See also LHCb Z+b-jet measurement: JHEP **01**, 064 (2015)



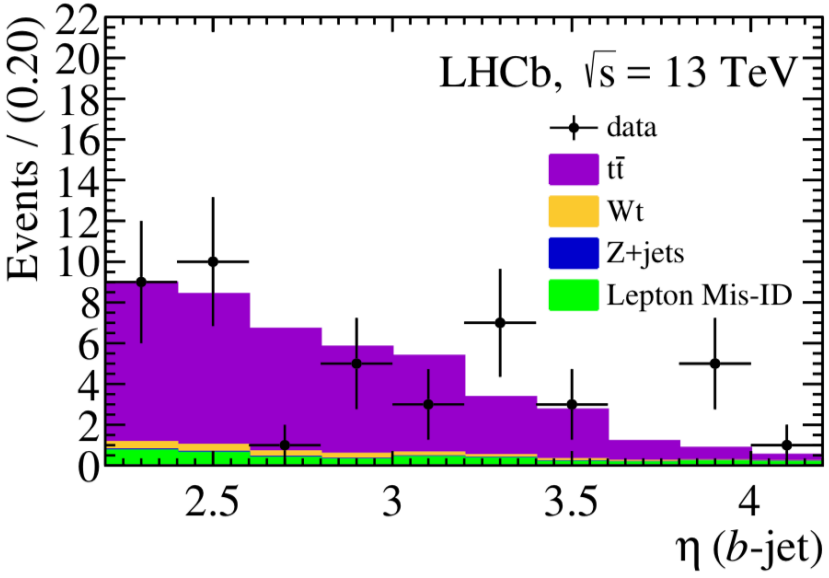


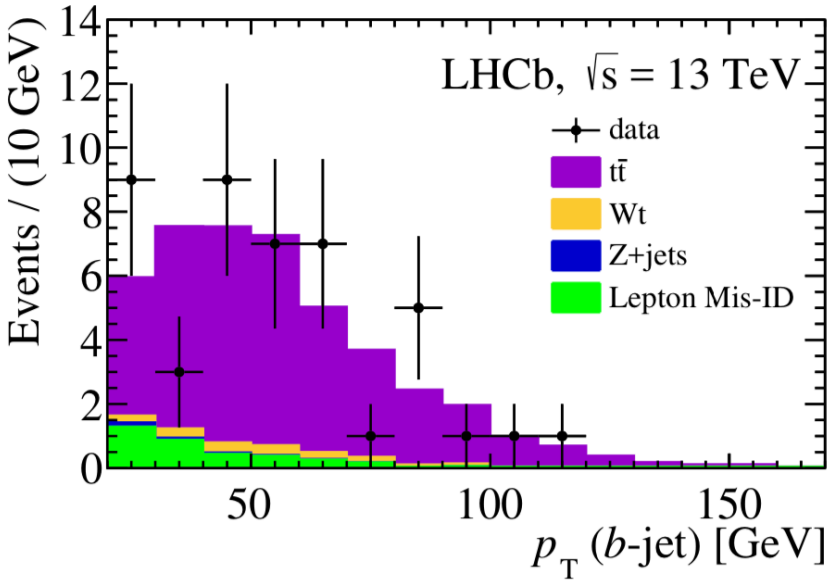
PRD **92**, 052001 (2015)

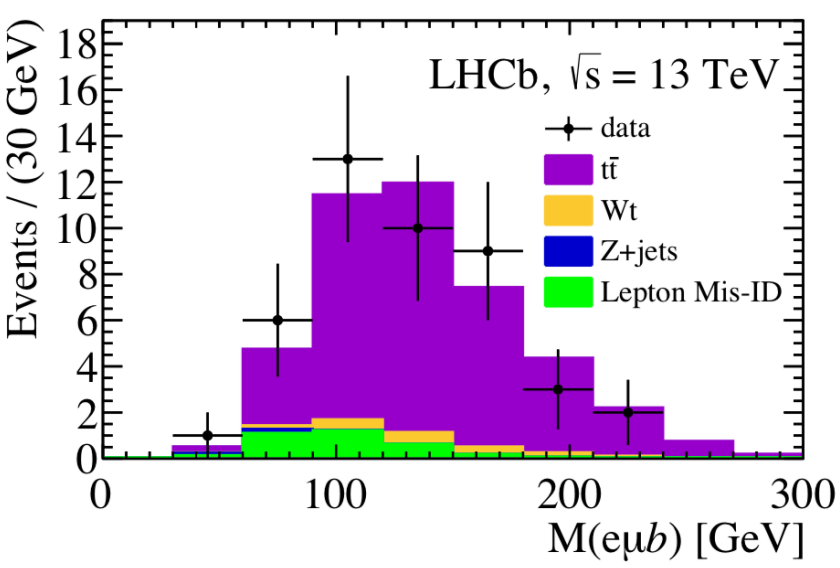
LHCb Jet Measurements to constrain PDFs

Top quark pair production in the forward region

- Larger contribution to top production from quark-antiquark annihilation in the forward region
- Measured in dilepton final state with one b-jet







JHEP **08**, 174 (2018)

Access to PDFs at the Electron-Ion Collider

Why are LHCb measurements to constrain PDFs relevant for an EIC?

- Very different partonic processes at an EIC compared to the LHC – but we will still be probing proton PDFs!

- The specific process (Z + jet, W + c-jet, W + b-jet, top production) might not be relevant, but the unique access that the forward region grants to high-x PDFs is

Questions to consider:

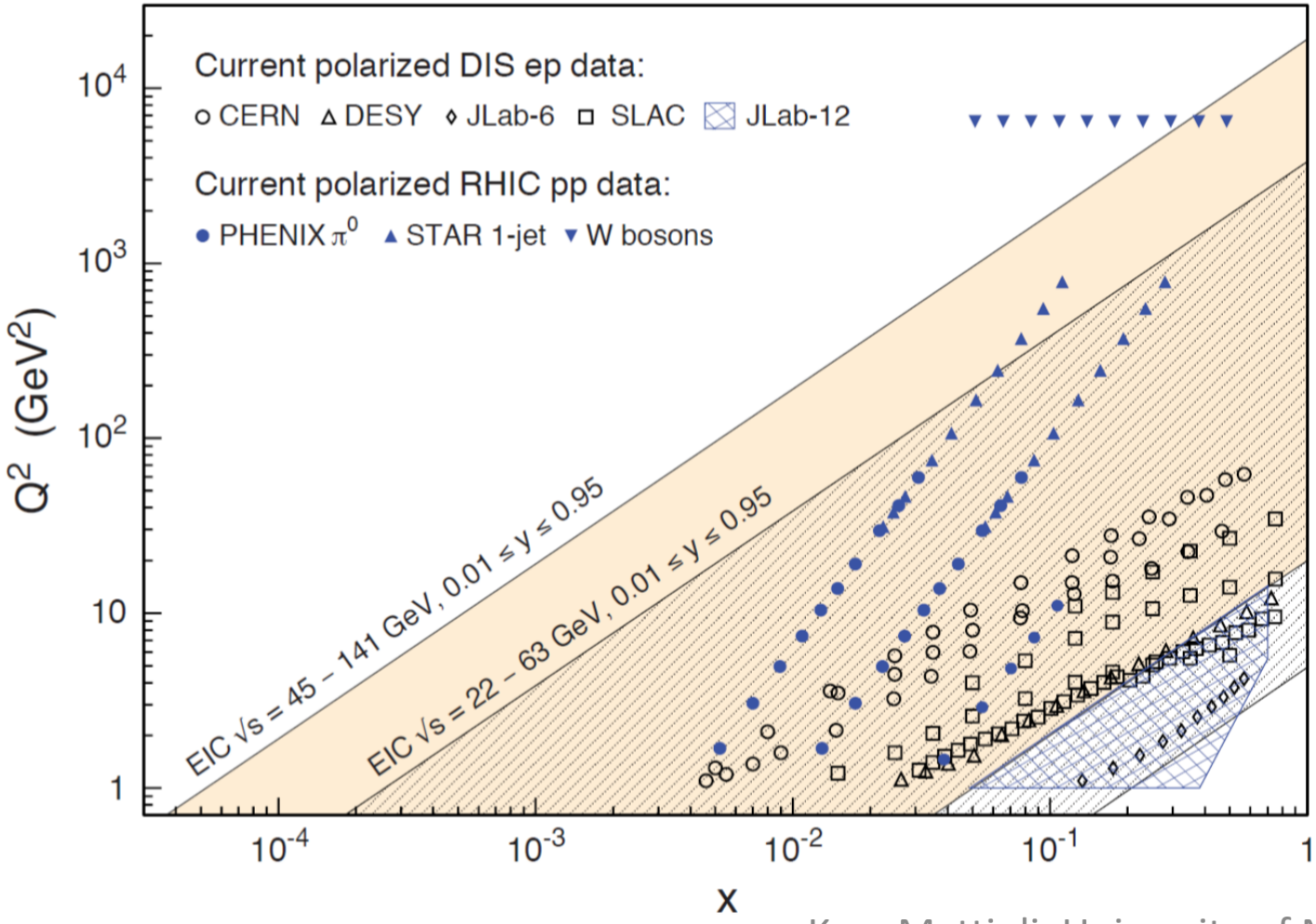
→ How does the LHCb phase space complement that of the EIC?

→ What partonic processes are accessible in the forward region at an EIC that we can use to constrain PDFs?

JHEP **08**, 174 (2018)

Access to PDFs at the Electron-Ion Collider

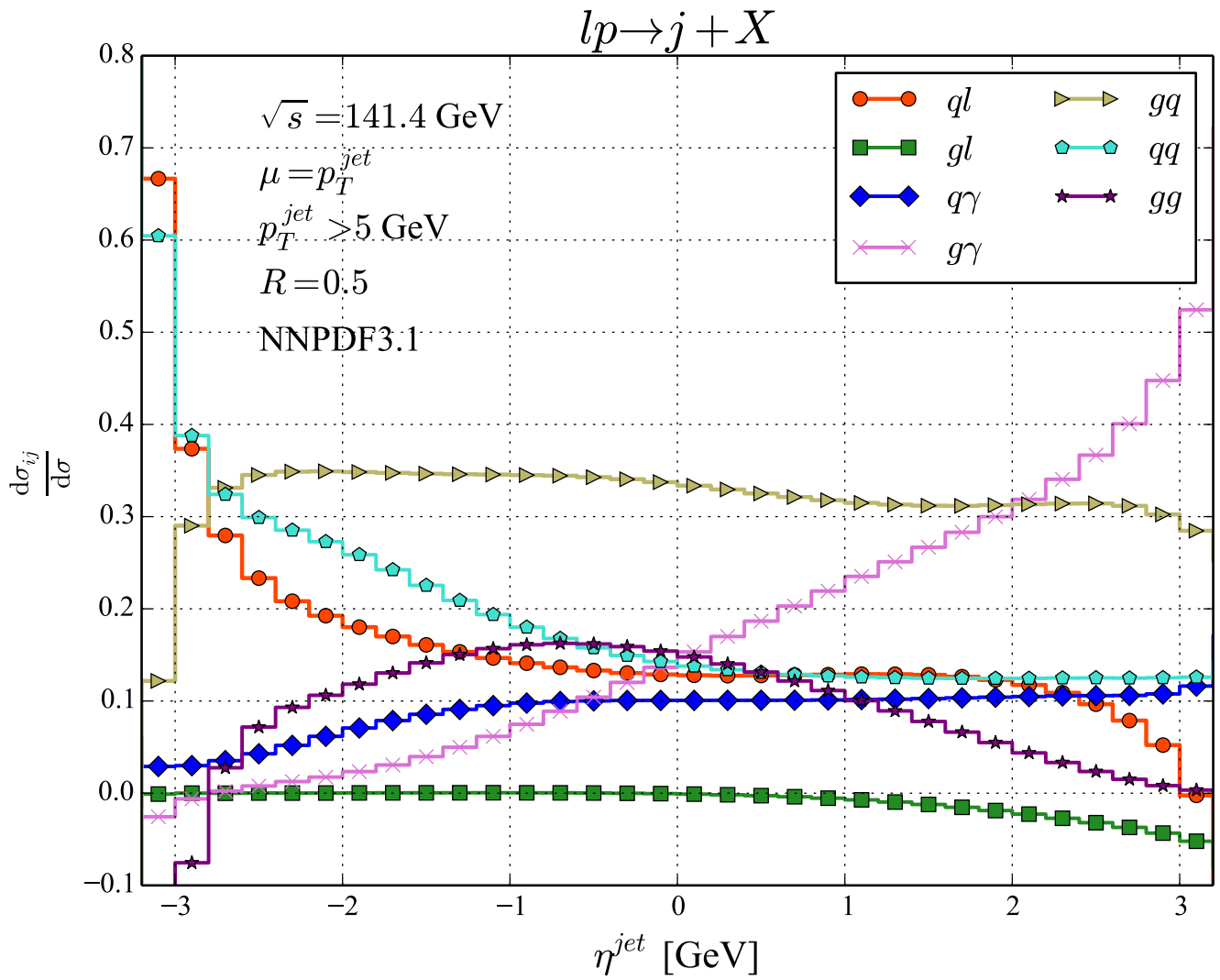
x-Q^2 coverage in e+p collisions at an EIC



Eur. Phys. J. A **52**, 268 (2016)

- The EIC will be able to probe polarized PDFs in regions of phase space that have never been explored
- In the forward (proton-going) region, jets at an EIC can be used to constrain high-x PDFs, just like at LHCb
- At low x, LHCb probes a complementary high-Q^2 region of phase space for unpolarized PDFs that will not be accessible at an EIC

Access to PDFs at the Electron-Ion Collider

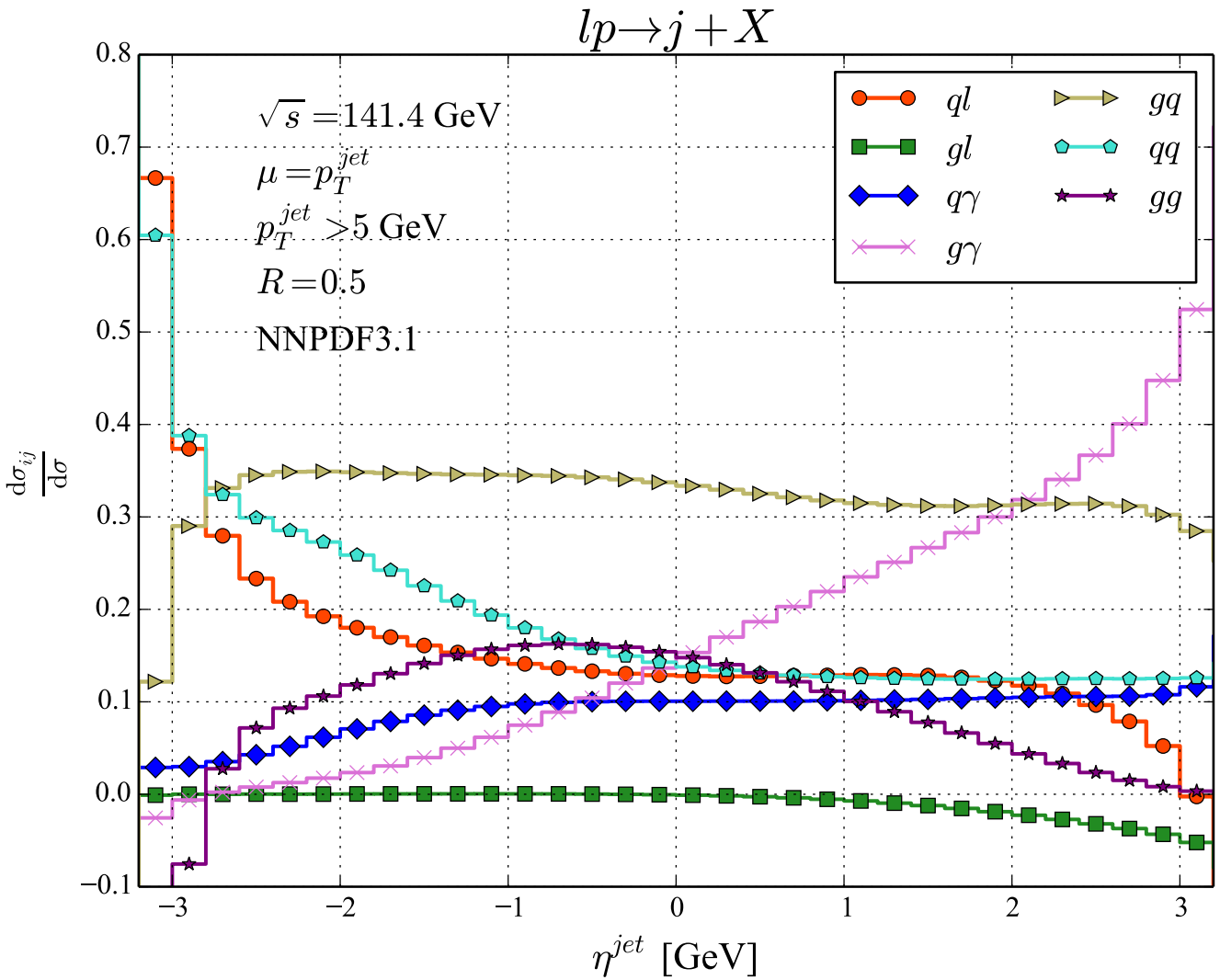


- Jet measurements at the EIC probe a variety of partonic channels

Plot courtesy of Frank Petriello

See also PLB **763**, 52 (2016)

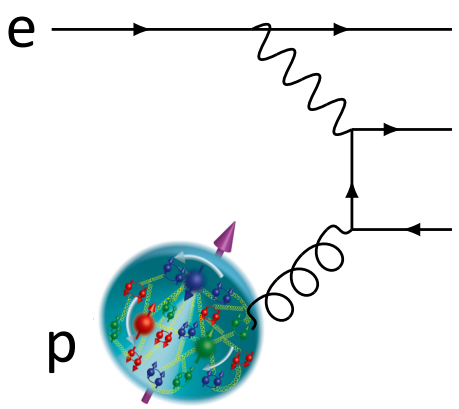
Access to PDFs at the Electron-Ion Collider



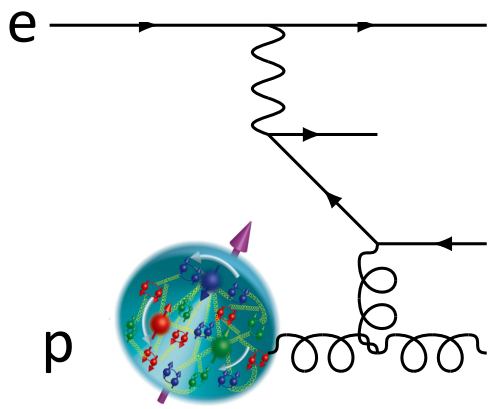
Plot courtesy of Frank Petriello

See also PLB **763**, 52 (2016)

- The inclusive jet cross section in the forward region is dominated by photon-gluon and quark-gluon scattering:

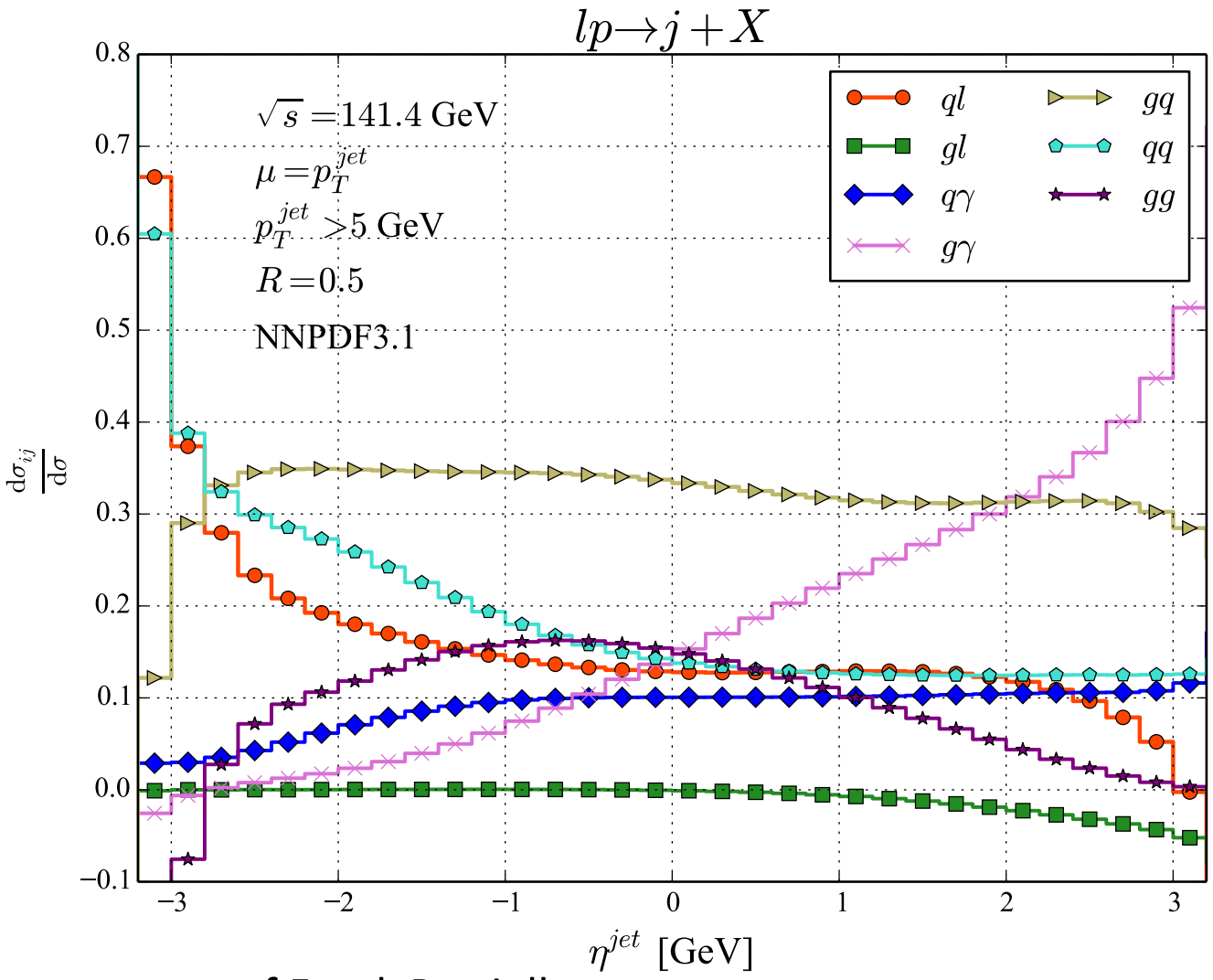


Nearly on-shell photon, scattered e^- not detected



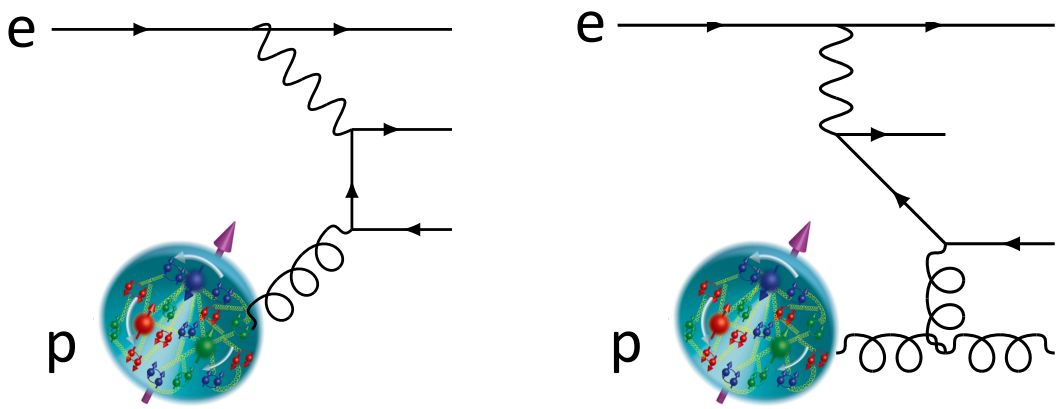
Resolved photon splits into $q\bar{q}$ pair that participates in hard scattering

Access to PDFs at the Electron-Ion Collider



Plot courtesy of Frank Petriello
See also PLB **763**, 52 (2016)

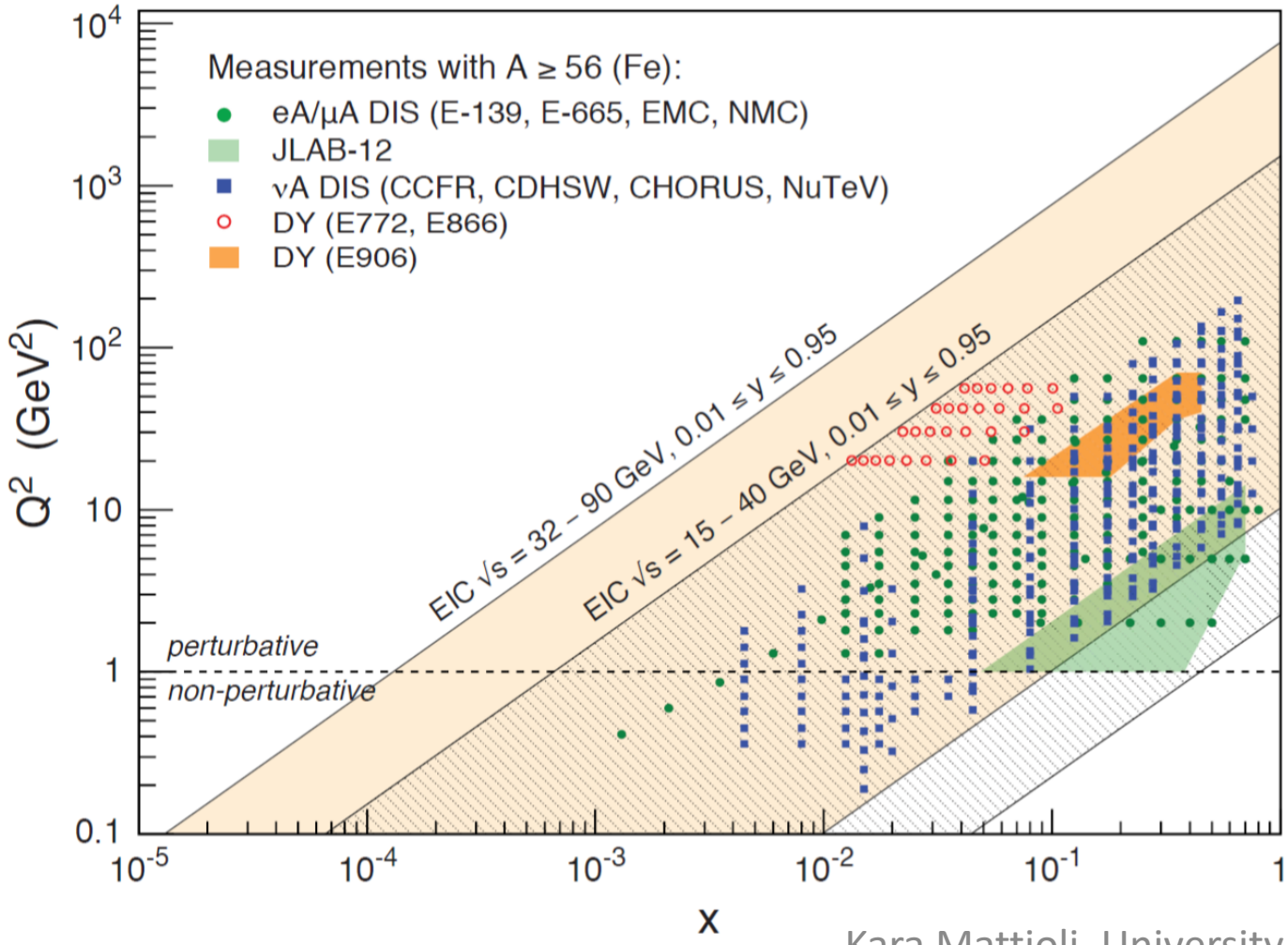
- The inclusive jet cross section in the forward region is dominated by photon-gluon and quark-gluon scattering:



- In the forward region, sensitive to polarized and unpolarized gluon and photon PDFs

Nuclear PDFs from LHCb to the EIC

x-Q^2 coverage in e+A collisions at an EIC

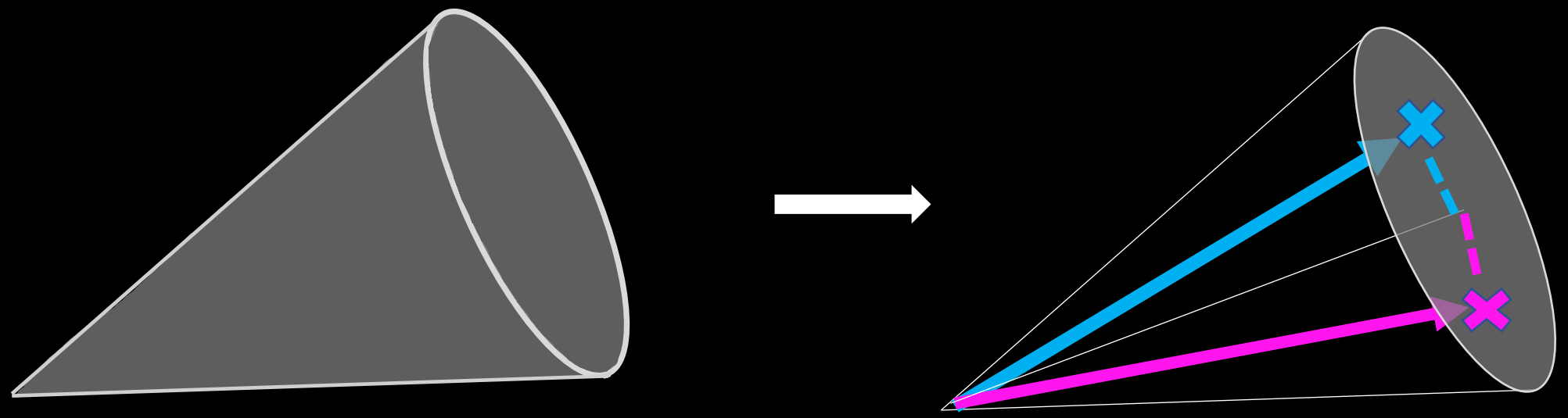


Eur. Phys. J. A **52**, 268 (2016)

- At LHCb, low-p_T jets in p+A collisions can be used to study nuclear PDFs at low x (~10^{-4} - 10^{-5}) and ~10 $GeV^2 < Q^2 < 10^4$ GeV^2
- Low-x reach of LHCb allows searches for gluon saturation which will be continued at an EIC

LHCb phase space will nicely complement, but not overlap, that of the EIC at low x

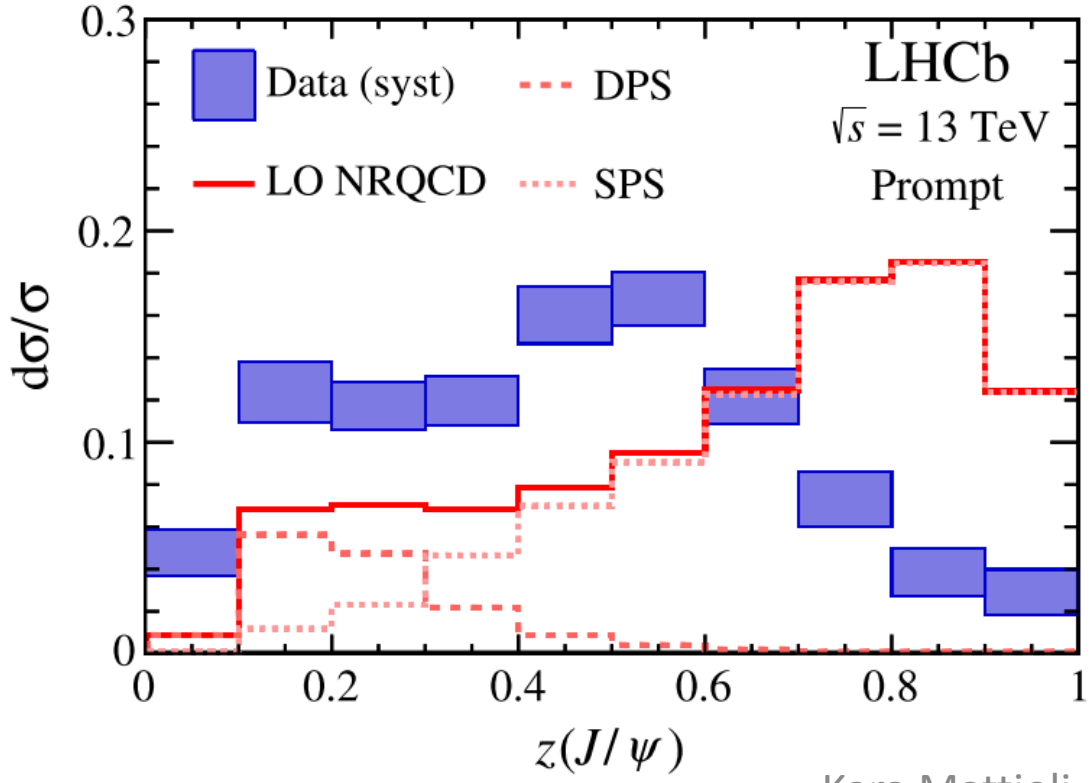
Hadronization and Jet substructure



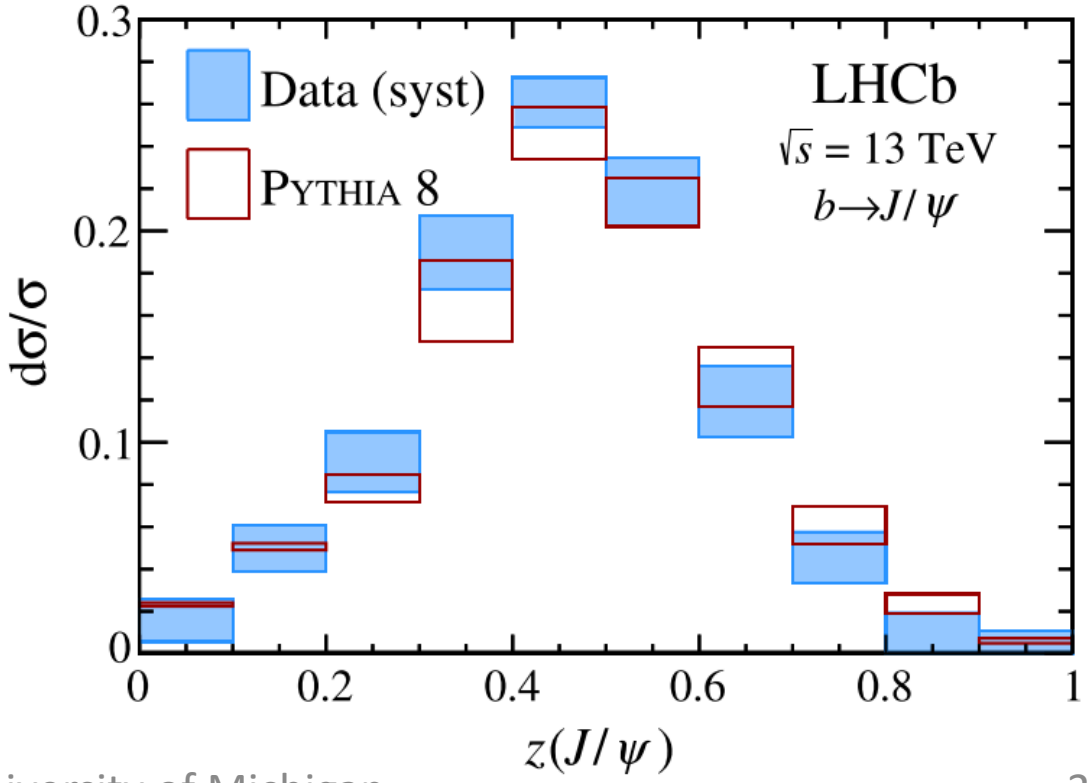
J/ψ Production in Jets at LHCb

- Measuring quarkonia in jets allows access to the radiation they are produced with
- Can compare prompt J/ψ production to theoretical predictions

Prompt J/ψ



J/ψ from b-hadron decays

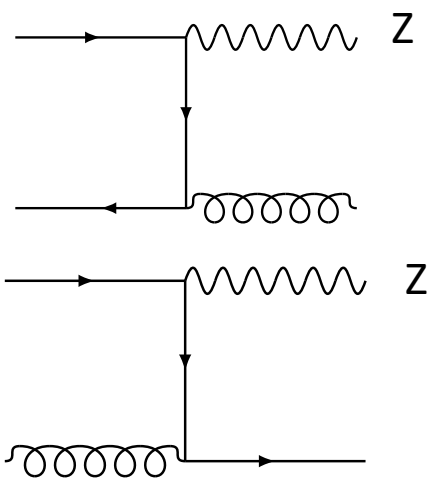


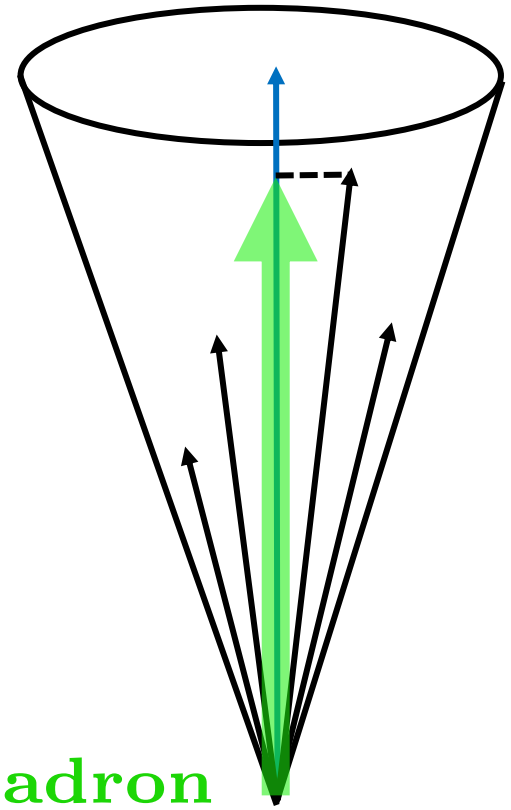
PRL **118**, 192001 (2017)

Hadronization Studies in Jets at LHCb

Charged Hadron Distributions in Z-tagged Jets

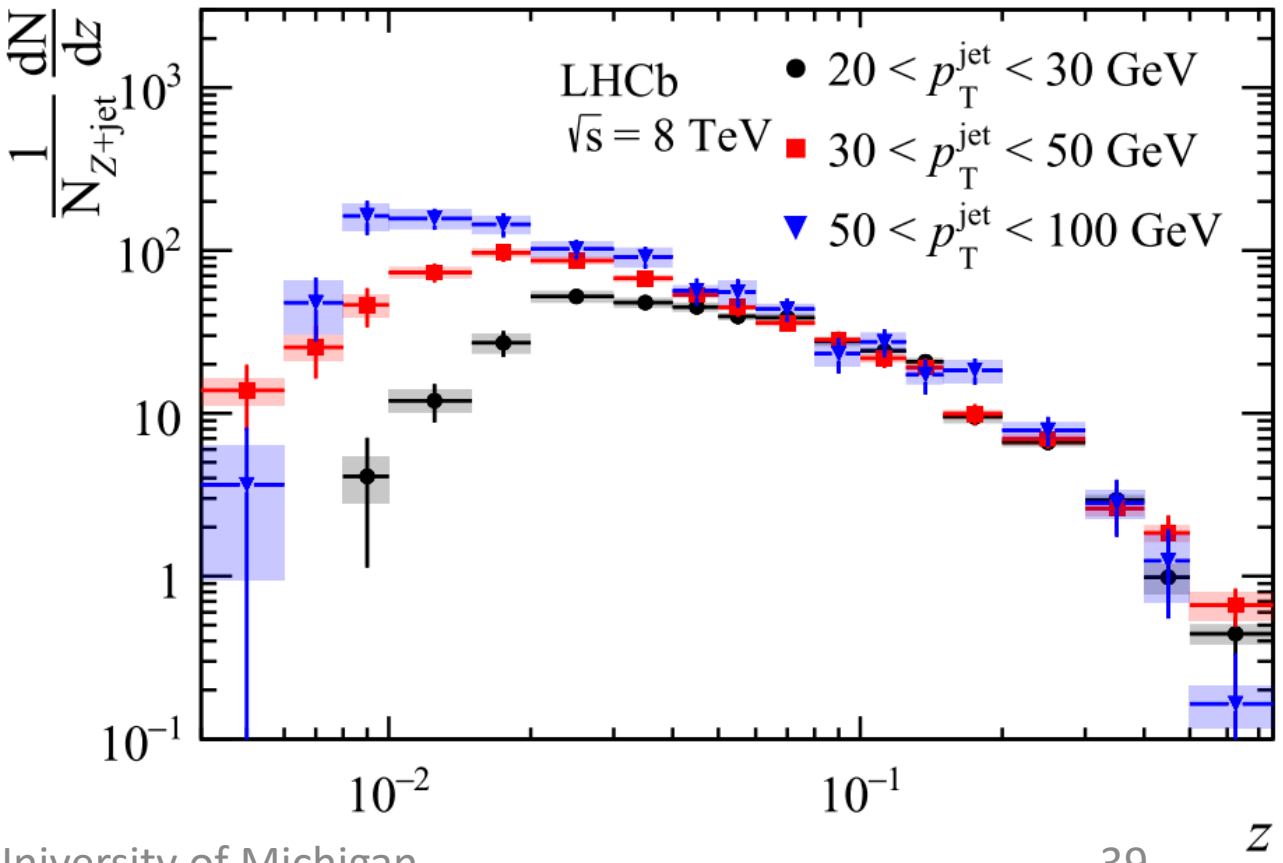
- Sensitive mainly to light-quark fragmentation functions:





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

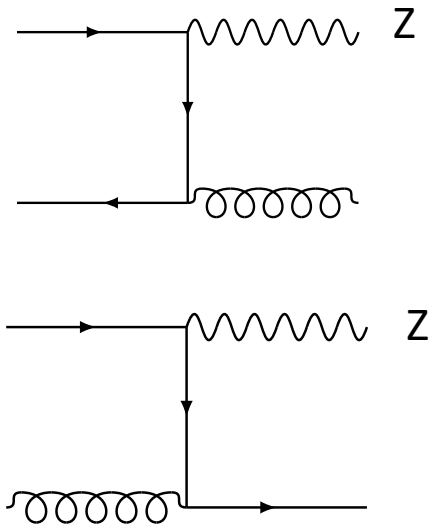
Longitudinal Momentum distribution

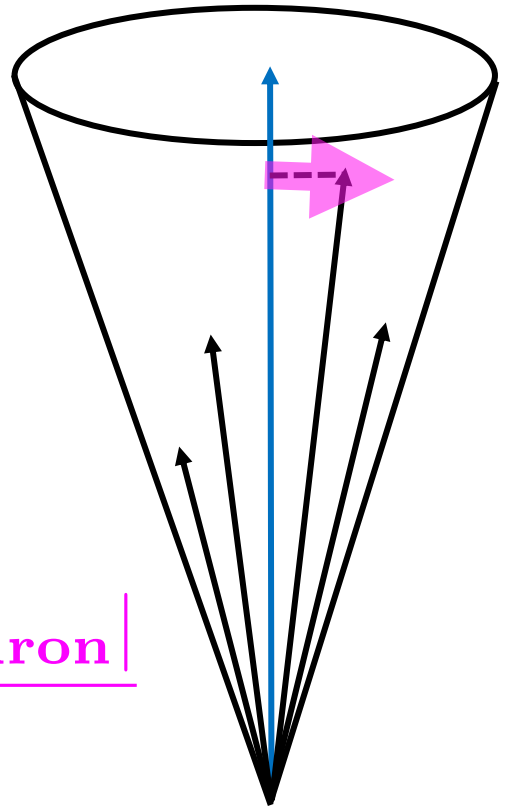


arXiv: 1904.08878

Hadronization Studies in Jets at LHCb

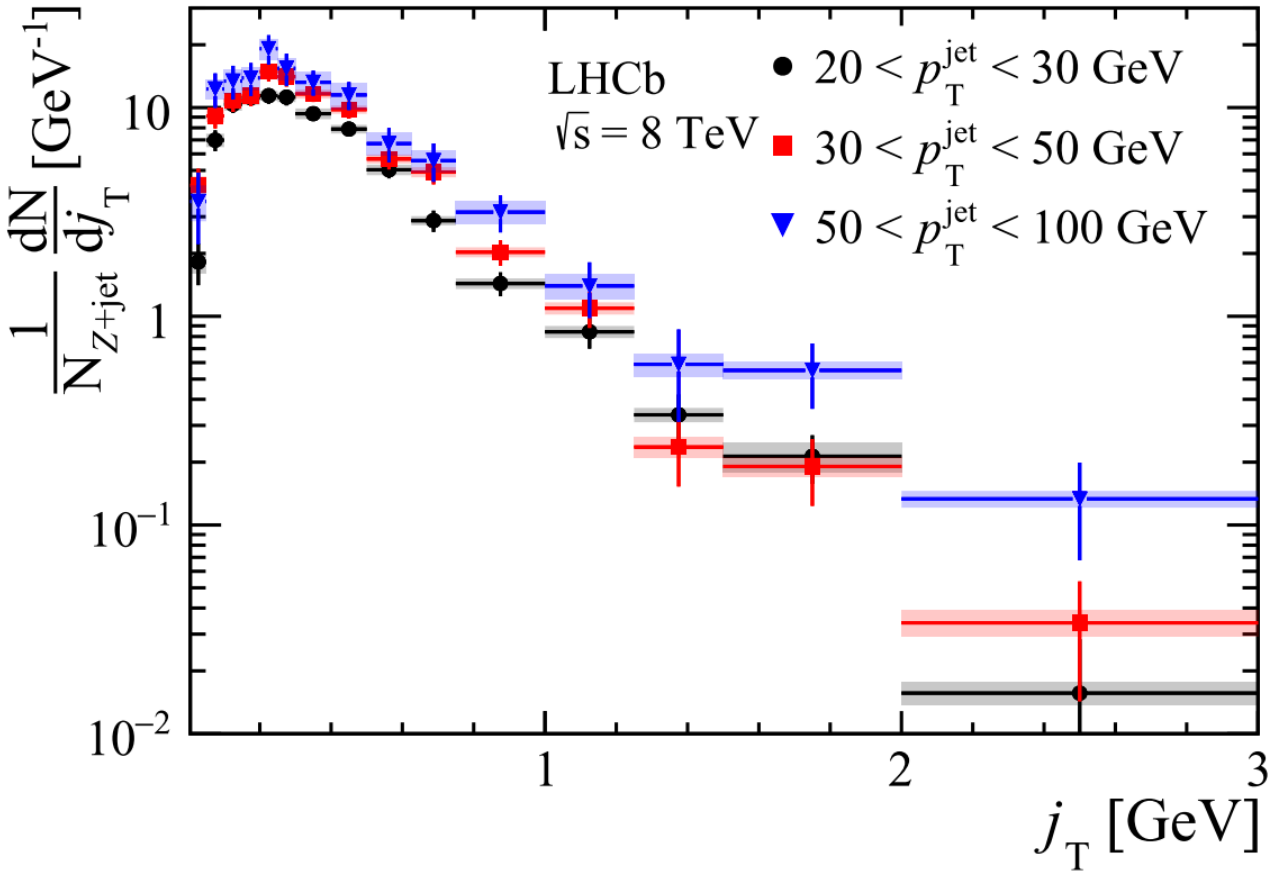
Charged Hadron Distributions in Z-tagged Jets





$$j_T = \frac{|\mathbf{p_{jet}} \times \mathbf{p_{hadron}}|}{|\mathbf{p_{jet}}|}$$

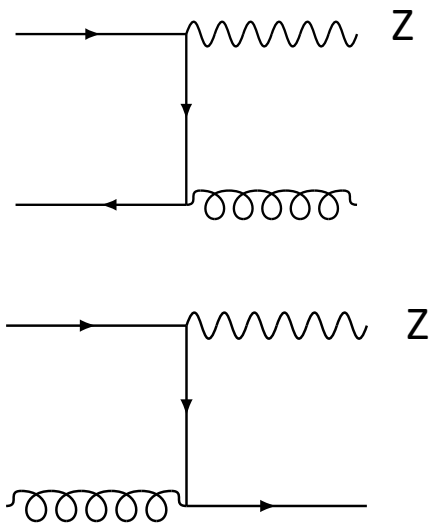
Transverse Momentum distribution

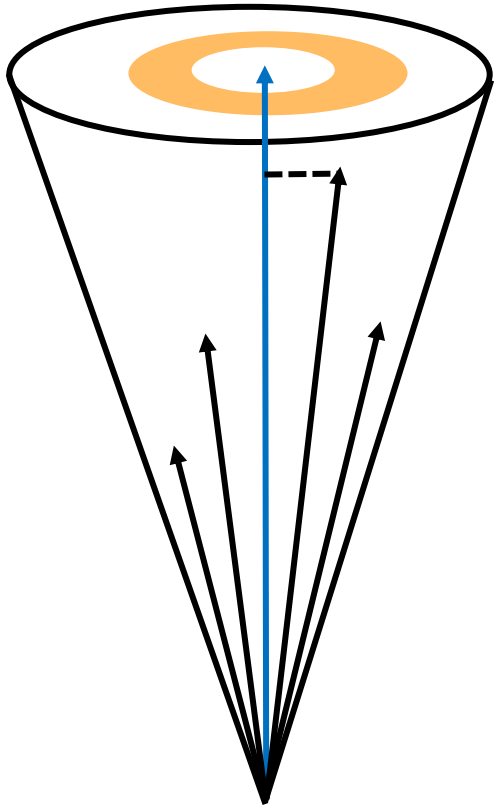


arXiv: 1904.08878

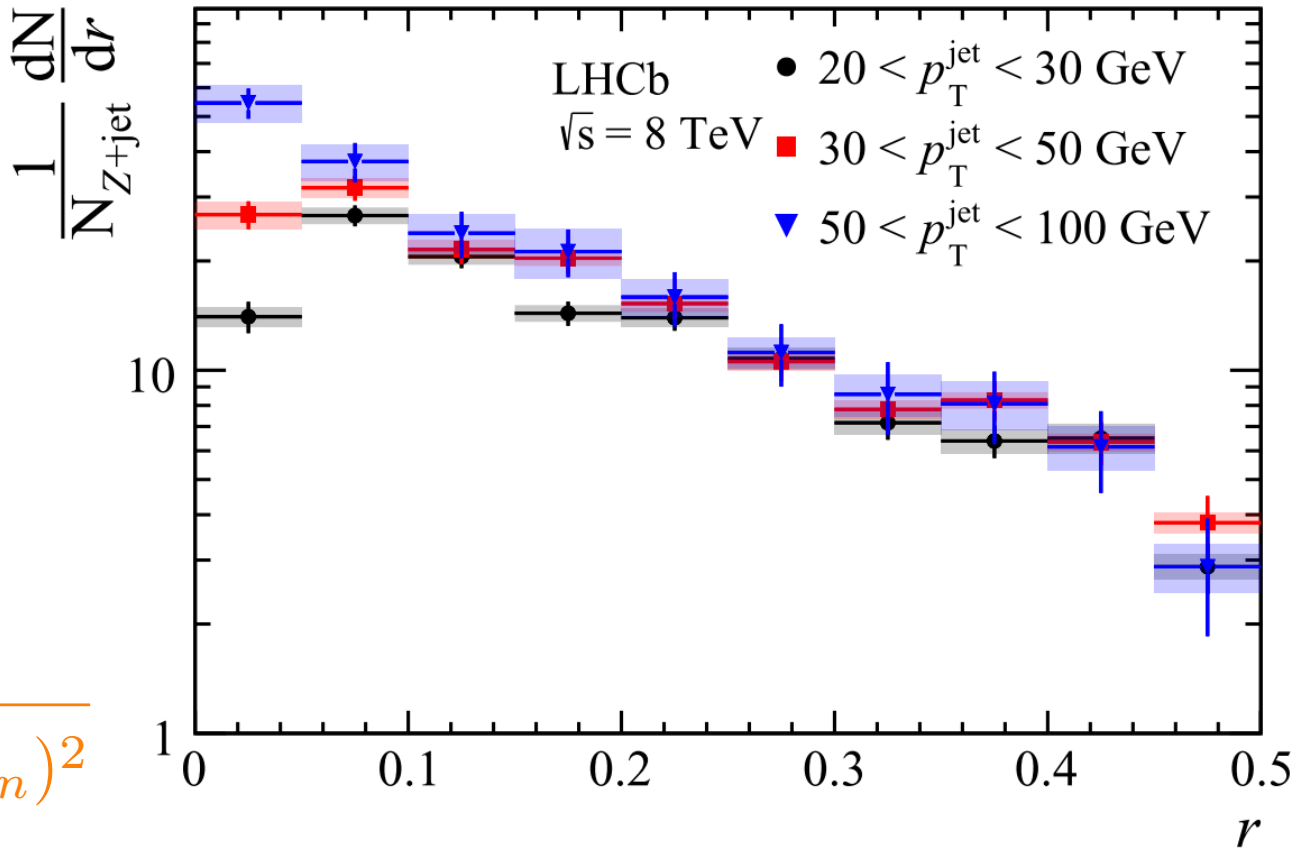
Hadronization Studies in Jets at LHCb

Charged Hadron Distributions in Z-tagged Jets





Radial distribution



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

arXiv: 1904.08878

Hadronization Studies in Jets at LHCb – more coming!

- Charged Hadron Distributions in b- and c-tagged jets
- Identified Hadron ($\pi^{+/-}$, $K^{+/-}$) Distributions in light-quark, b- and c-tagged jets using LHCb Particle ID
- Beauty and Charm Hadron Distributions in b- and c-tagged jets
- Baryon and Meson distributions in jets

More quarkonia in jets coming too – Υ, ϕ, J/ψ polarization in jets

Jet Substructure in the forward region at an EIC

Excellent opportunities to continue and expand on the hadronization program at LHCb:

→ Less background from underlying event in e+p

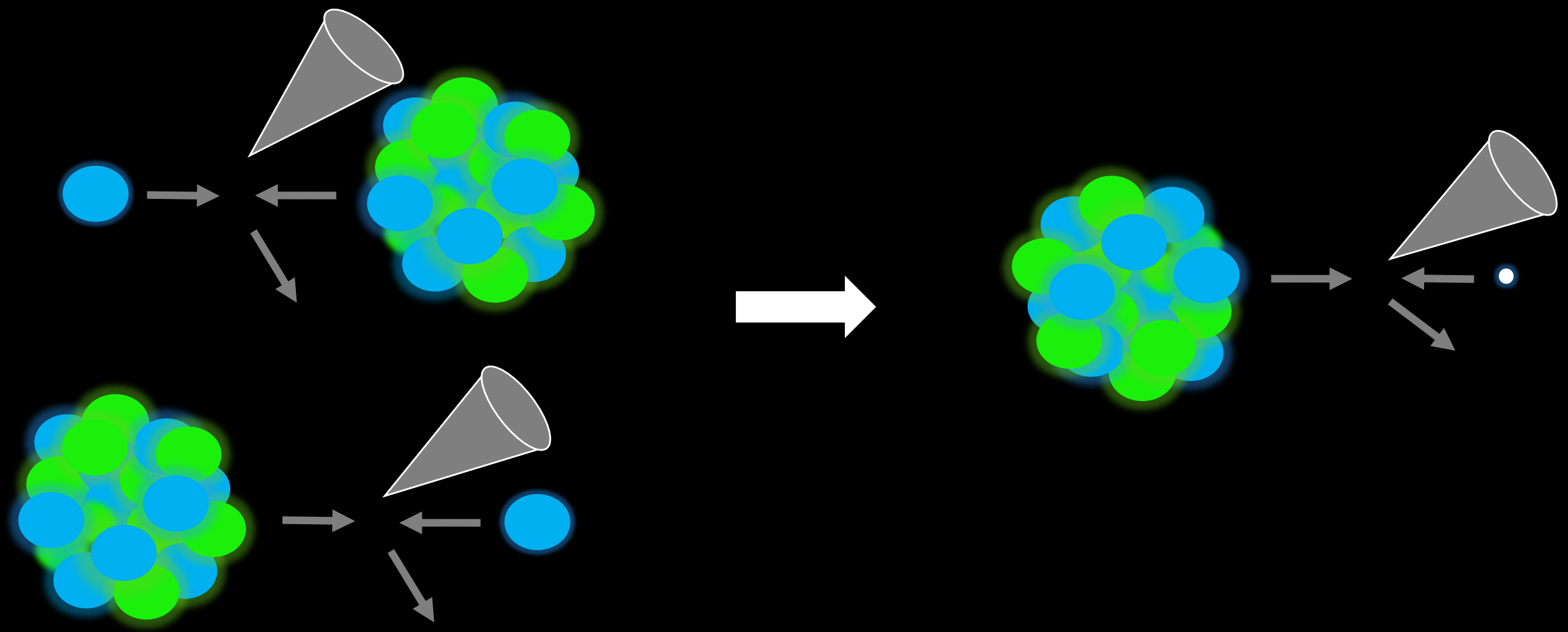
→ Potential to tag u, d, s jets at EIC (see X. Chu et al., PRD **96**, 074035 (2017))

- Can compare charged hadron distributions in jets at LHCb to distributions in u,d,s jets at EIC

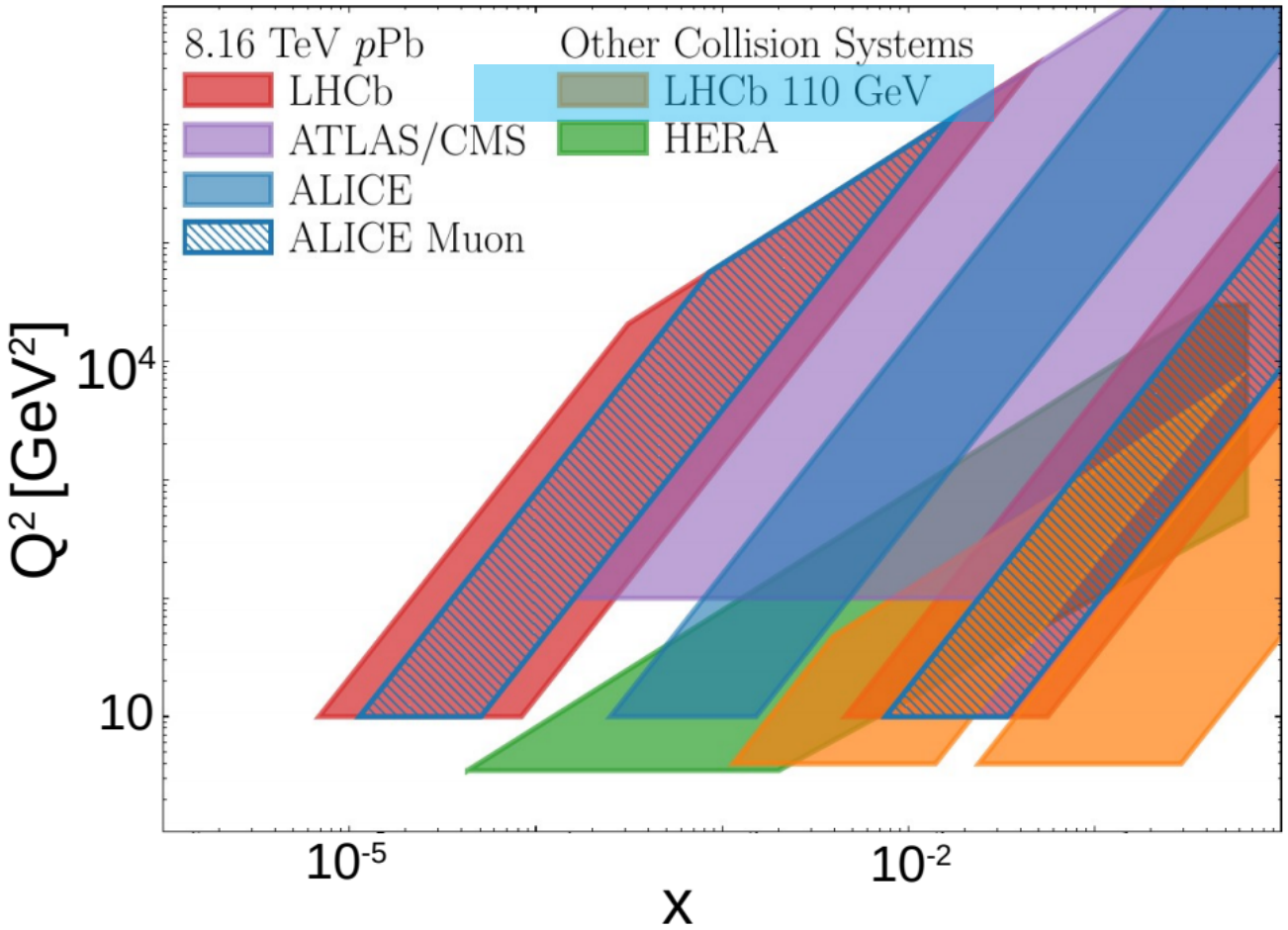
→ With a vertex detector in the forward region, could tag heavy flavor jets at EIC and compare to LHCb measurements

See Kolja Kauder's talk later today for more on jet substructure at an EIC!

Jets from p+A to e+A



LHCb as a Fixed Target Experiment



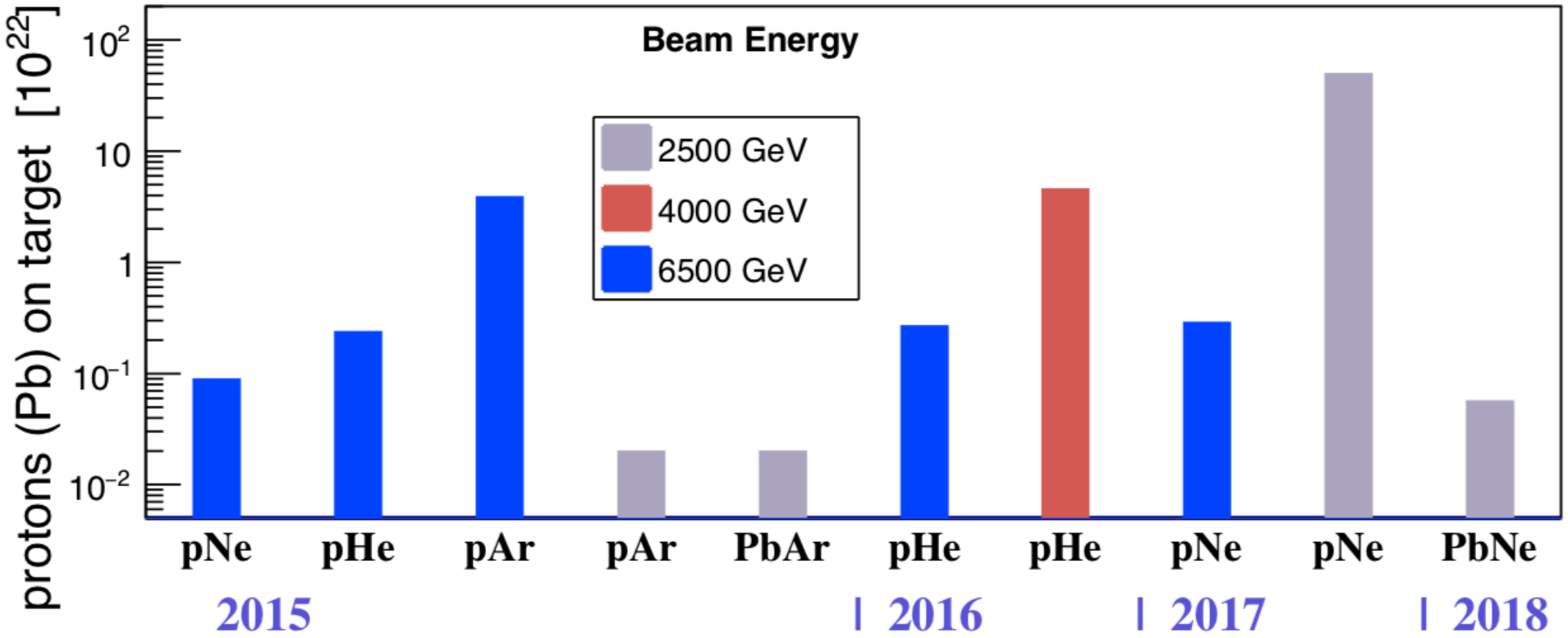
SMOG (System for Measuring Overlap with Gas):

- Injects noble gases into the LHC beam pipe around the LHCb interaction point
- Makes LHCb a fixed target experiment!
- Luminosity ~6 x 10^{29} cm^{-2} s^{-1}
- $\sqrt{s_{NN}}$ = 41-115 GeV

Can study jets in p+A at EIC energies at LHCb!

LHCb as a Fixed Target Experiment

LHCb Fixed Target Data by Beam Species and Year



Can directly compare jets in p+A and e+A in the forward region for A = Ne, He, Ar!

LHCb Public Note: LHCb-PUB-2018-015

Upgrades to the LHCb Fixed Target Program

- Upgrade in progress to add a gas storage cell and capability to inject Kr, Xe, H^2, D^2, N^2, and O^2 gases with 2 orders of magnitude higher luminosity to the SMOG system

  -> Even more opportunities to directly compare jet measurements in p+A and e+A

- Proposal to add a polarized gas target in front of the LHCb interaction region

  -> Ability to measure polarized fragmentation functions

  -> Study flavor dependence of polarized fragmentation functions in b-, c- and light-parton jets at LHCb, then continue at EIC with improved jet flavor tagging

SMOG 2: LHCB-TDR-020

LHCSpin: arXiv:1901.08002

Summary: What can a flavor physics experiment at the LHC contribute to jet physics at an EIC?

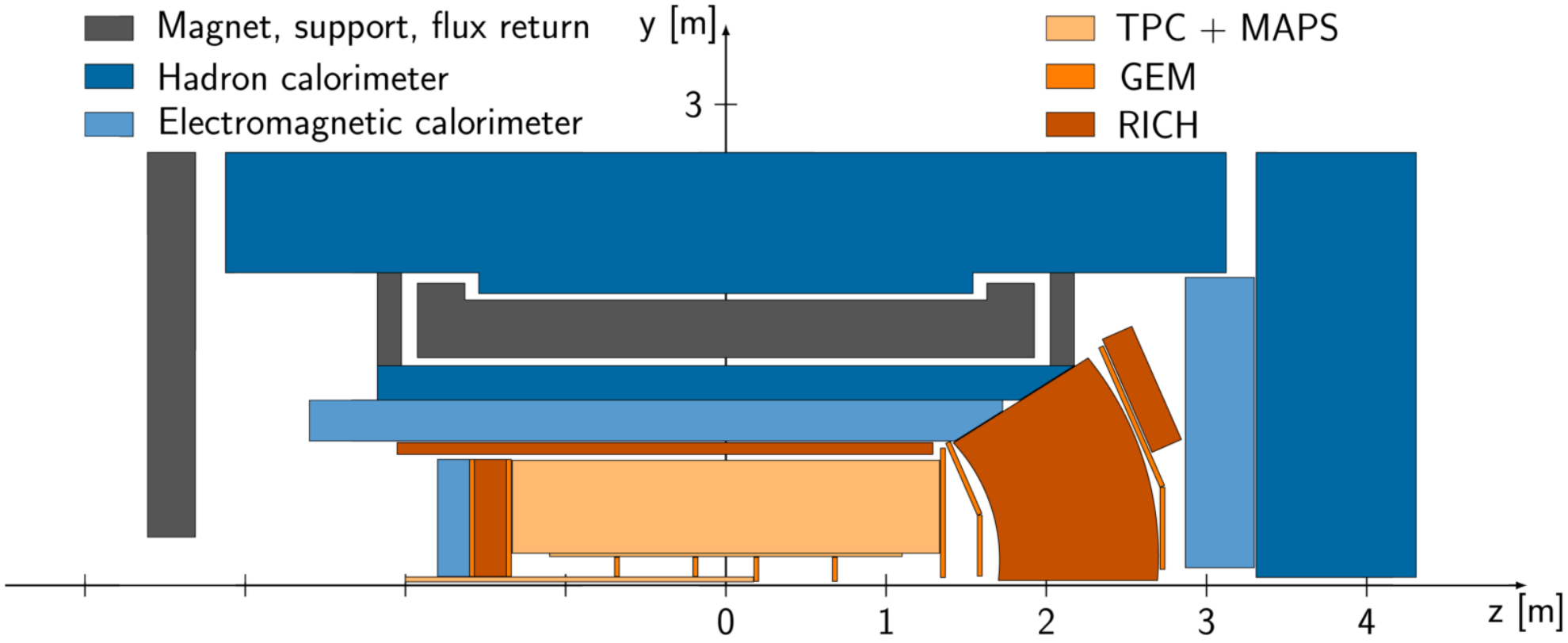
- Experience with similar detector instrumentation in the forward region
- PDF constraints in a complementary yet distinct region from what the EIC will cover
- Constraints on searches for gluon saturation
- Hadronization measurements that can be refined and expanded on at an EIC
- Direct comparisons between jet measurements in p+A and e+A for a variety of nuclear species
- Spin-dependent measurements with jets
- …

Interested? Join LHCb!

- Experience with similar detector instrumentation in the forward region
- PDF constraints in a complementary yet distinct region from what the EIC will cover
- Constraints on searches for gluon saturation
- Hadronization measurements that can be refined and expanded on at an EIC
- Direct comparisons between jet measurements in p+A and e+A for a variety of nuclear species
- Spin-dependent measurements with jets
- …

Backup

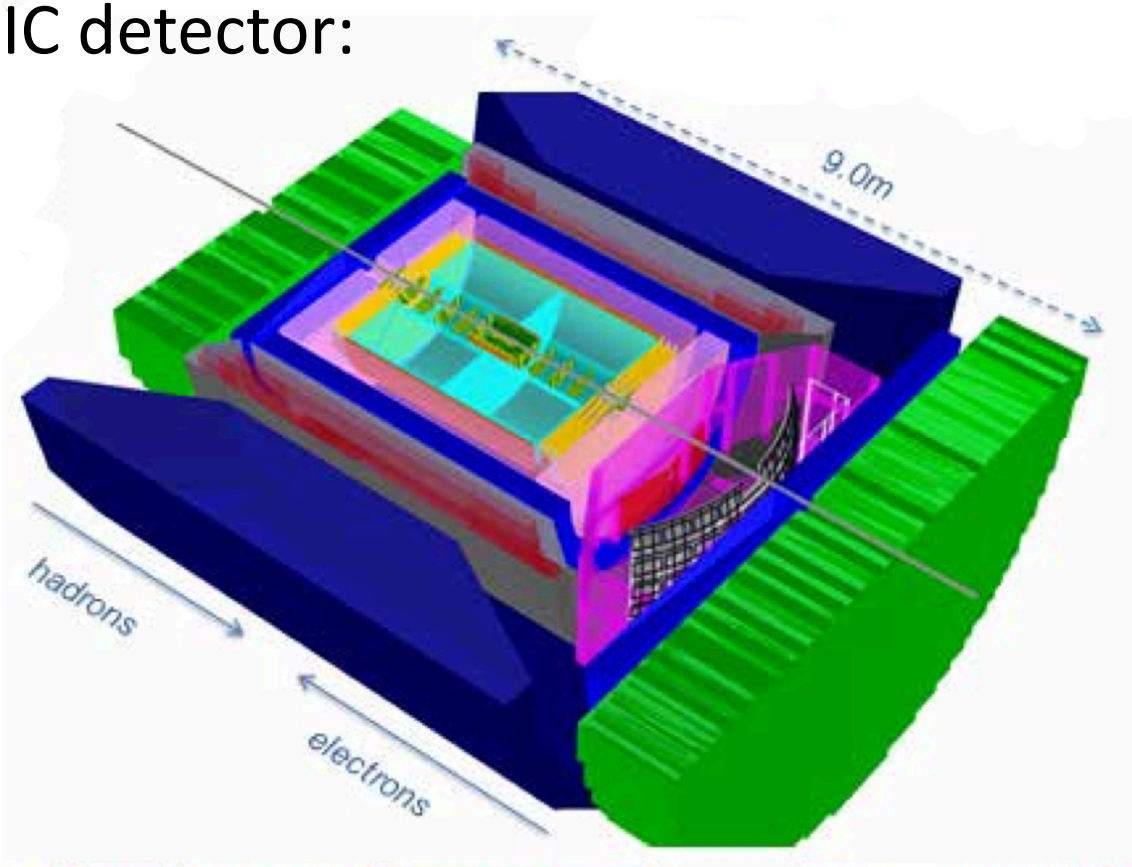
EIC Detector based on the sPHENIX Solenoid



sPHENIX-note sPH-cQCD-2018-001

BeAST (Brookhaven eA Solenoidal Tracker) Detector

Another proposed design for an EIC detector:



hadronic calorimeters

e/m calorimeters

RICH detectors

silicon trackers

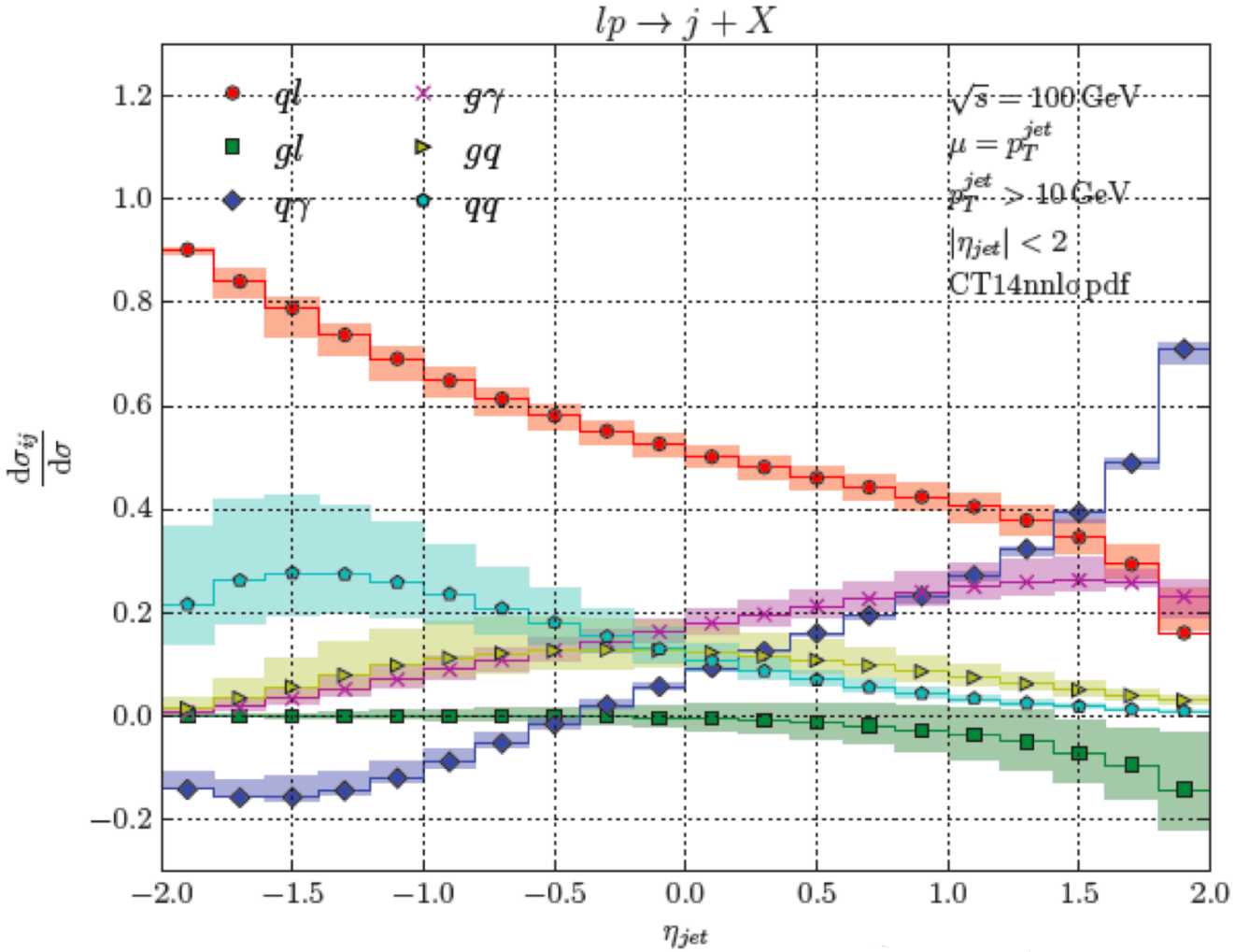
TPC

GEM trackers

3T solenoid coils

Figure taken from J. Repond's talk at Electromagnetic Interactions with Nucleons and Nuclei 2017

Inclusive Jet Production at an EIC, $\sqrt{s}$ = 100 GeV



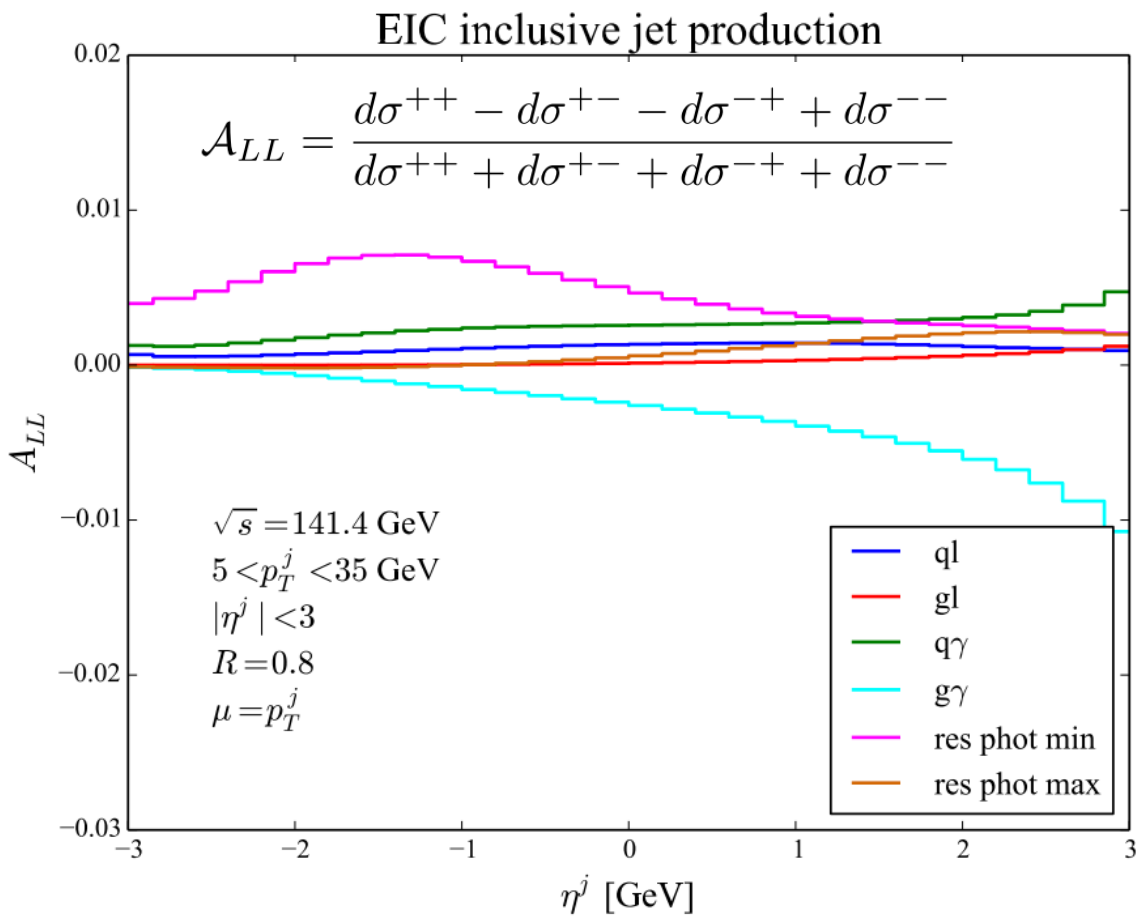
- Different jet p_T cutoff, center of mass energy shift contributions of partonic channels to inclusive jet cross section

  → Access different partonic channels at an EIC by measuring the inclusive jet cross section as a function of $\sqrt{s}$, jet p_T, and jet eta

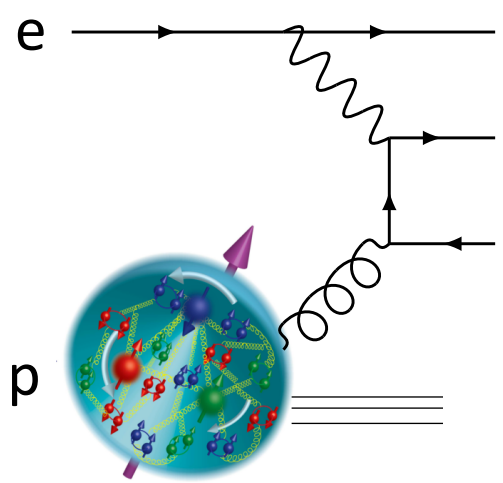
See slide 30 for inclusive jet production at $\sqrt{s}$ = 141.4 GeV, jet pT > 5 GeV

G. Abelof, R. Boughezel, X. Liu, F. Petriello
PLB **763**, 52 (2016)

Access to polarized PDFs at the EIC



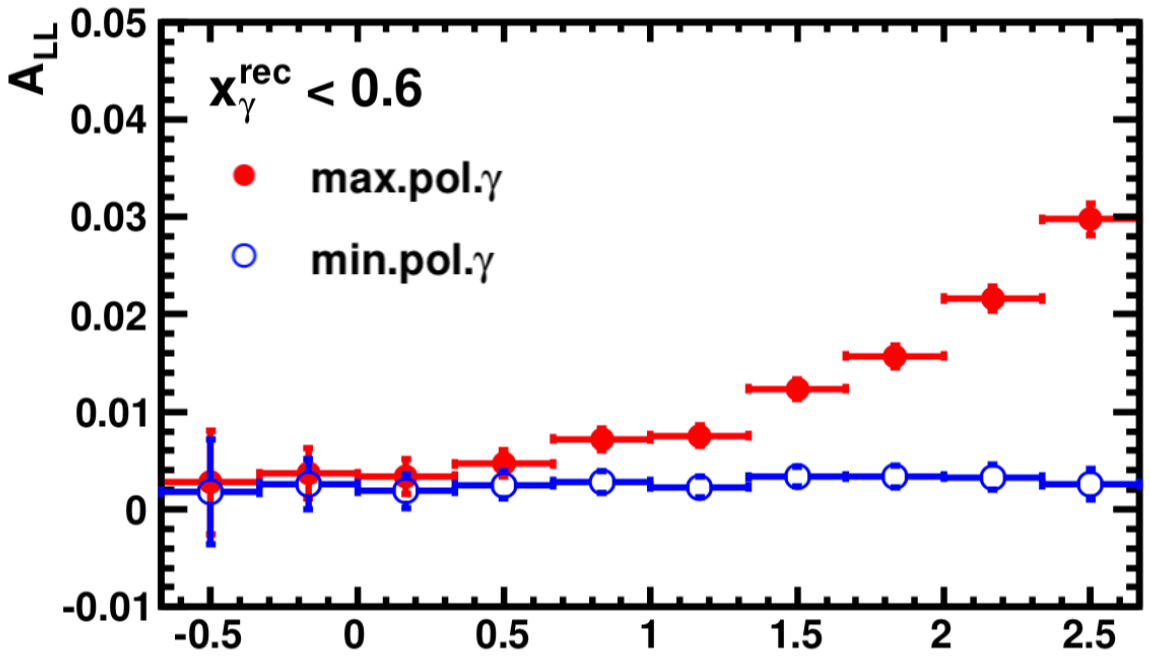
- In the forward region, inclusive jet production from photon-gluon scattering is predicted to give a ~-1% double-longitudinal spin asymmetry (A_{LL})
- Photon-gluon scattering is sensitive to polarized and unpolarized gluon PDFs



Nearly on-shell photon, scattered e^- not detected – only sensitive to this channel with inclusive jet measurements!

R. Boughezel, F. Petriello, H. Xing
PRD **98**, 054031 (2018)

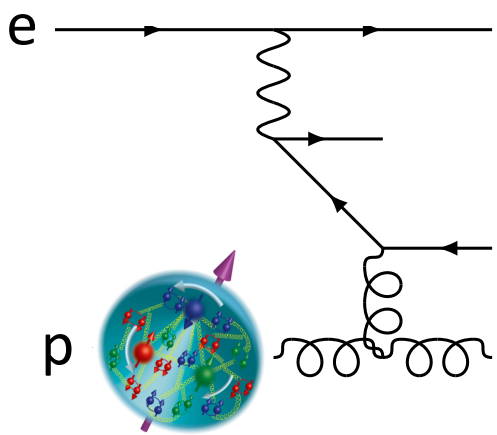
Access to polarized PDFs at the EIC



$\eta^{\text{di-jet}} = \frac{\eta^{\text{jet}1} + \eta^{\text{jet}2}}{2}$

- In the forward region, the A_{LL} from dijet production in resolved photon processes is predicted to differentiate between the minimal and maximal photon polarization models

Example of resolved process:
qg -> qg channel

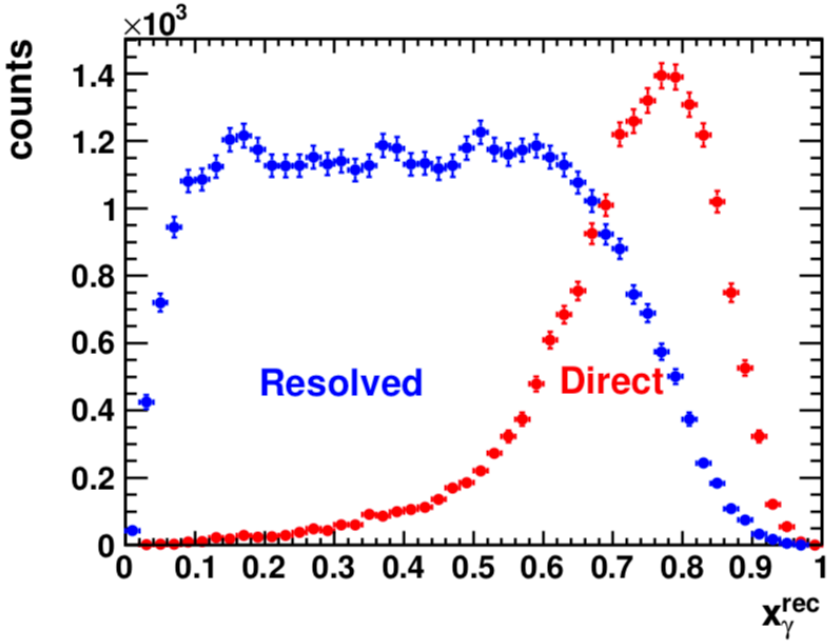


Reconstructed momentum fraction x_γ of parton in photon:

$$x_\gamma^{\text{rec}} = \frac{1}{2E_e y}(p_{T,1}e^{-\eta_1} + p_{T,2}e^{-\eta_2})$$

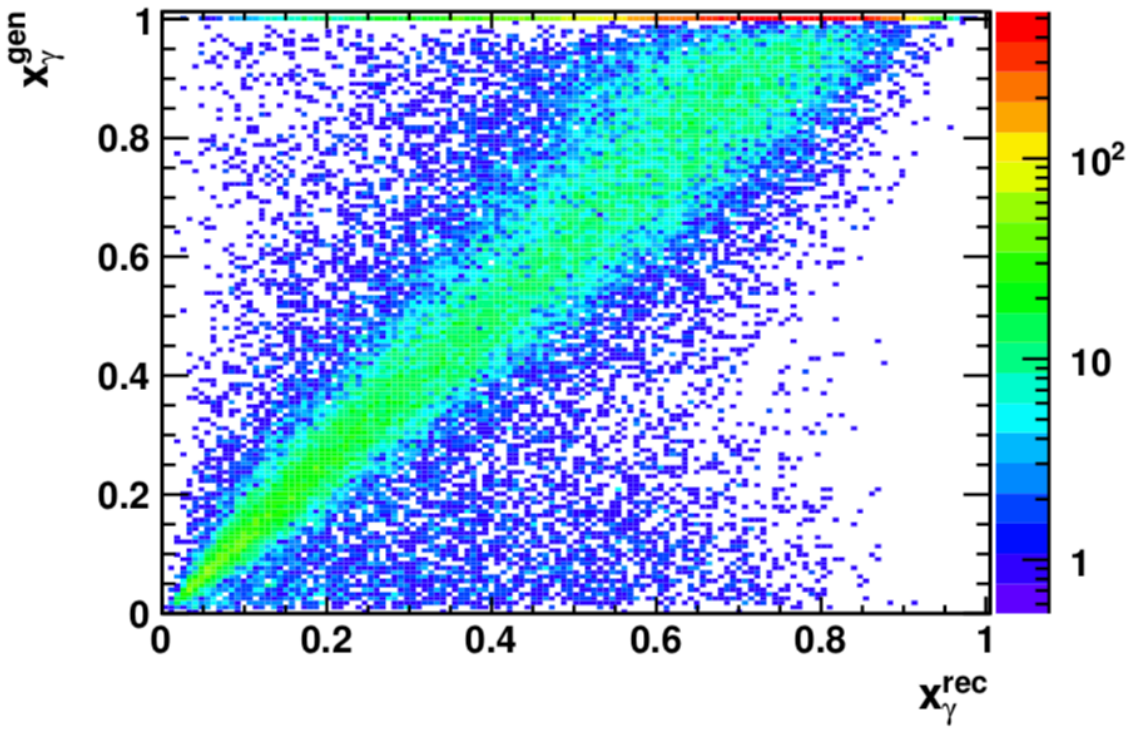
X. Chu, E. Aschenauer, J. H. Lee, L. Zheng
PRD **96**, 074035 (2017)

Photon Structure at an EIC with Dijets



$$x_\gamma^{rec} = \frac{1}{2E_e y}(p_{T,1}e^{-\eta_1} + p_{T,2}e^{-\eta_2})$$

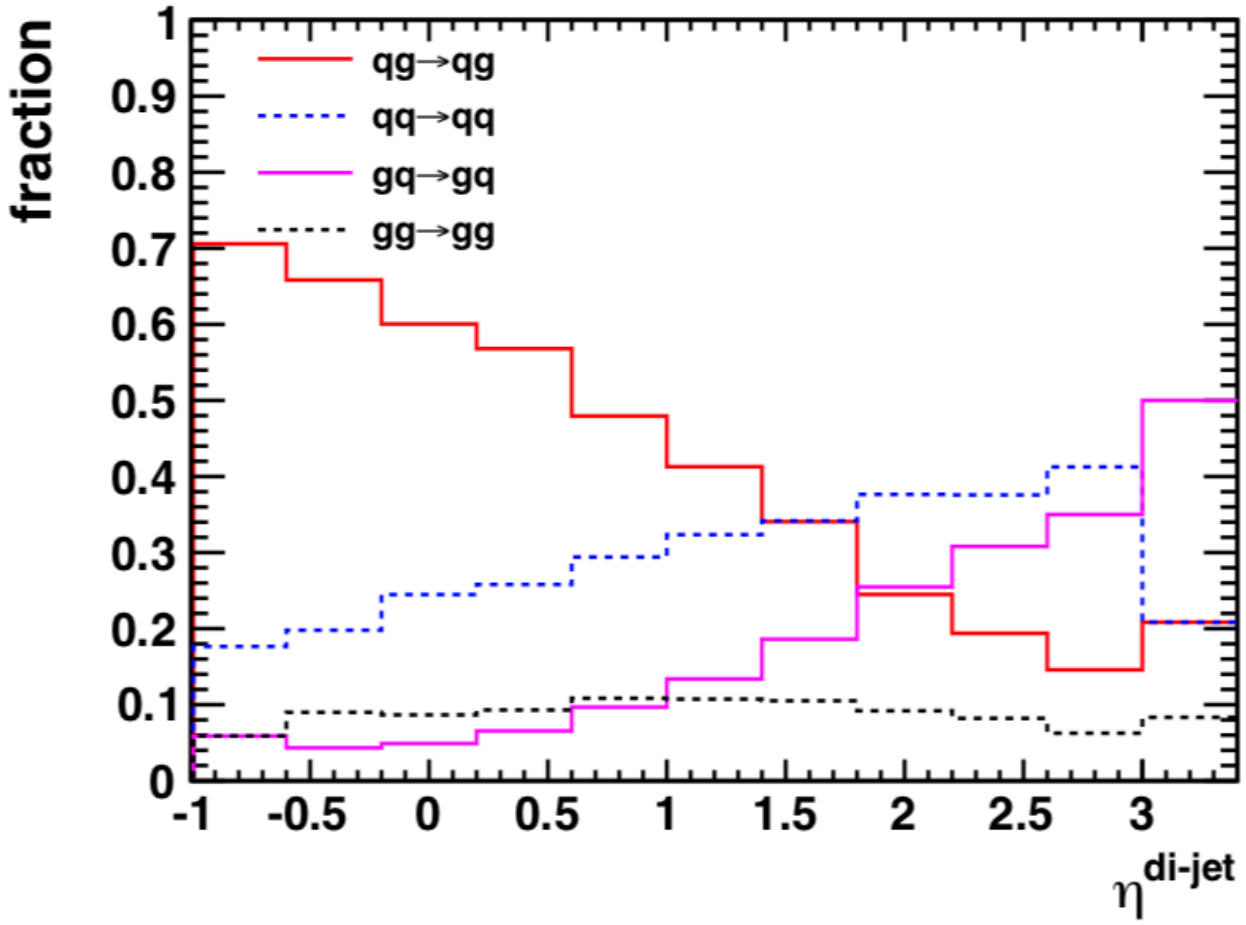
- Cut on x_γ separates resolved from direct processes



- Excellent reconstruction of true x_γ with dijets

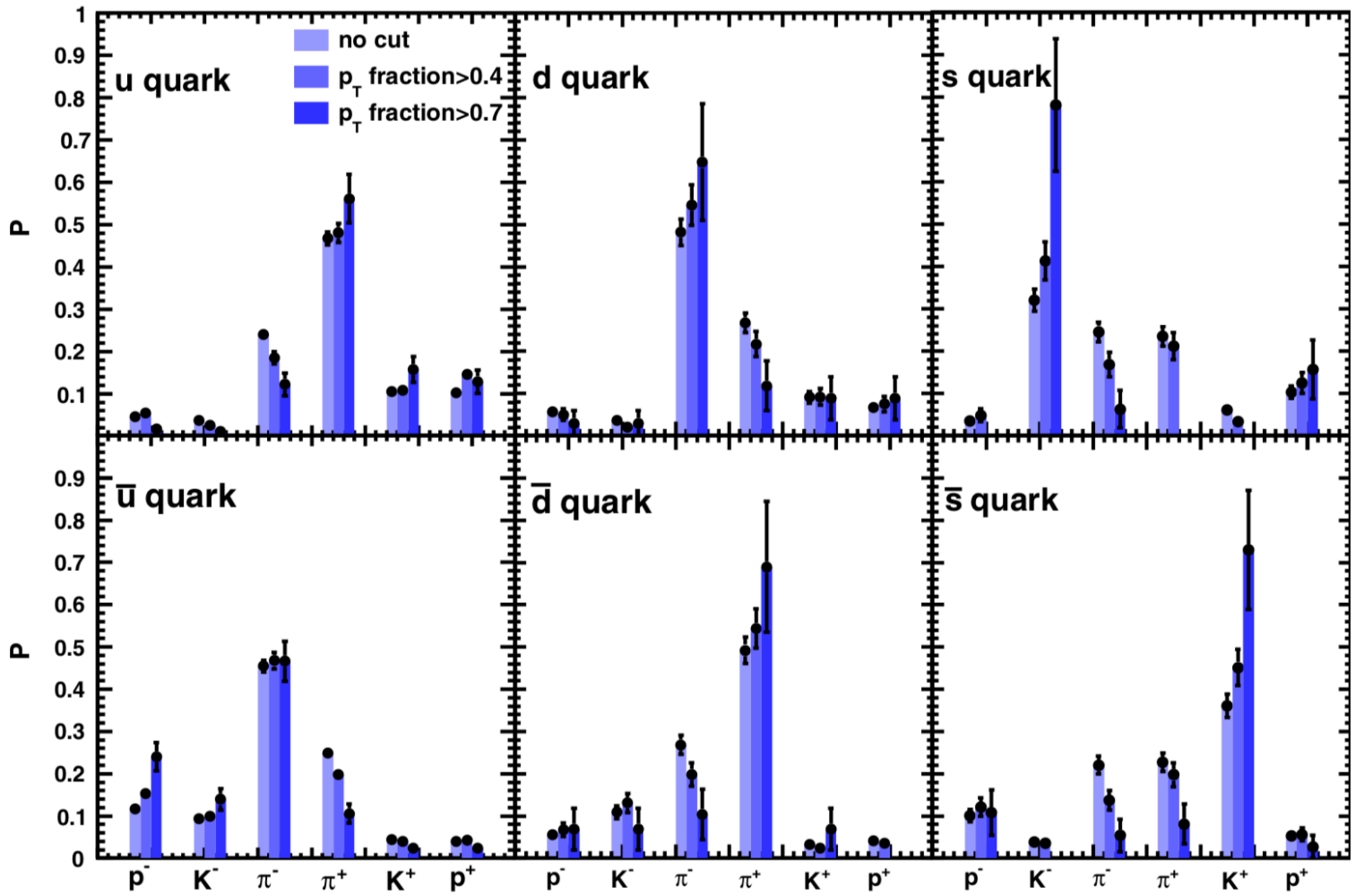
X. Chu, E. Aschenauer, J. H. Lee, L. Zheng
PRD **96**, 074035 (2017)

Fraction of Resolved Subprocesses from PYTHIA



X. Chu, E. Aschenauer, J. H. Lee, L. Zheng
PRD **96**, 074035 (2017)

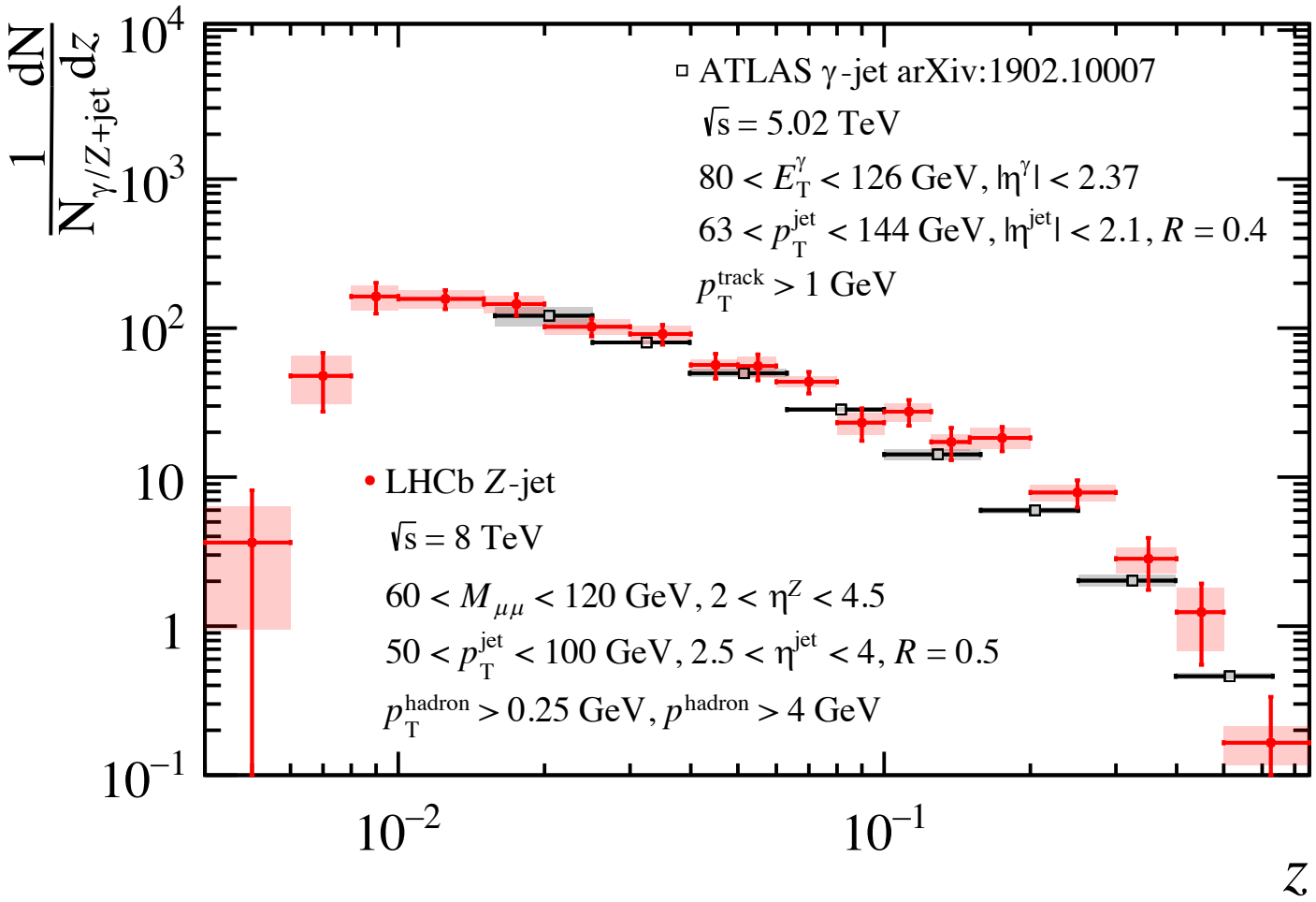
Flavor Tagging of u,d,s Jets at an EIC



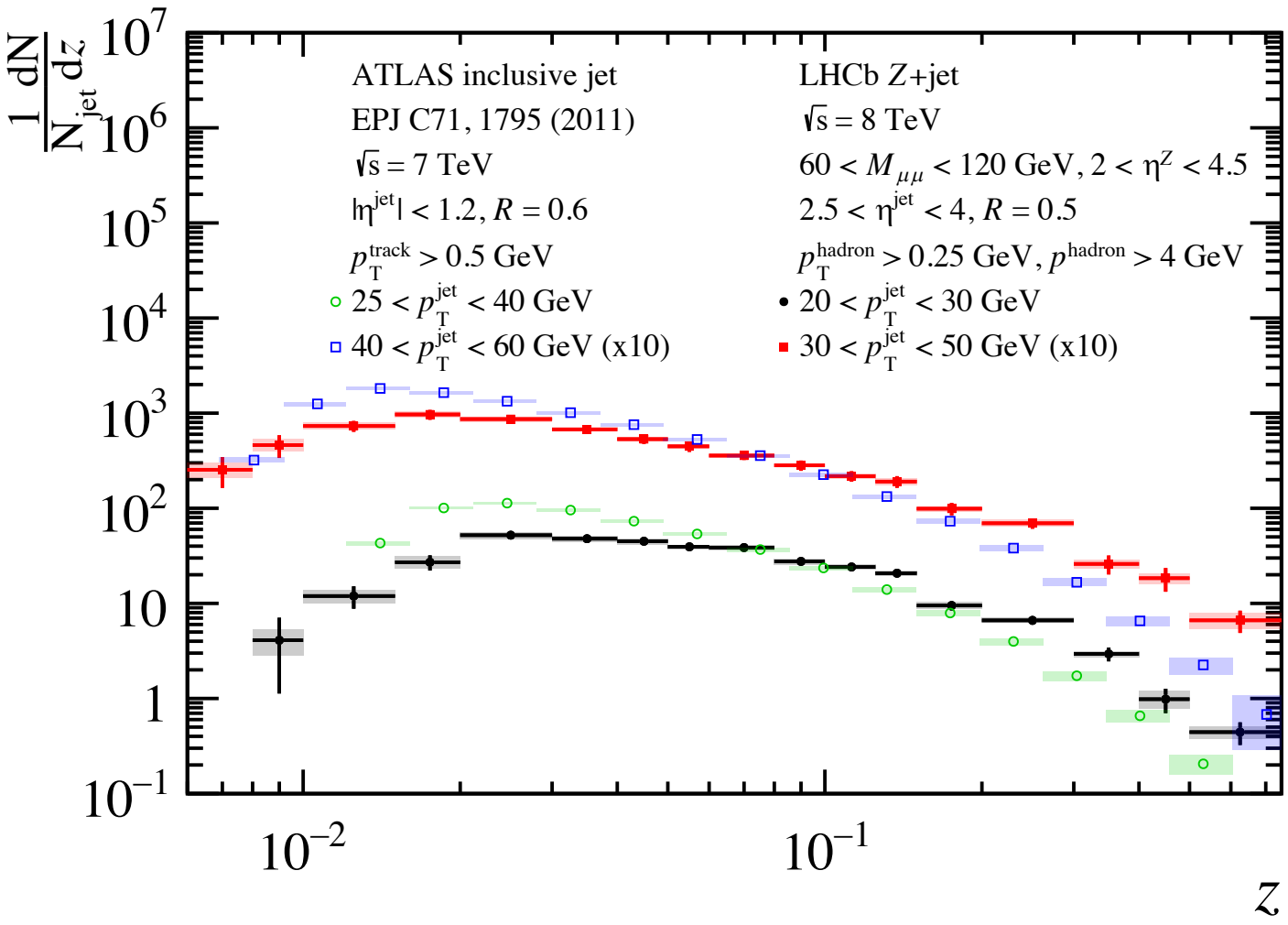
- The probability of finding a leading charged hadron for different parton flavors of the photon

X. Chu, E. Aschenauer, J. H. Lee, L. Zheng
PRD **96**, 074035 (2017)

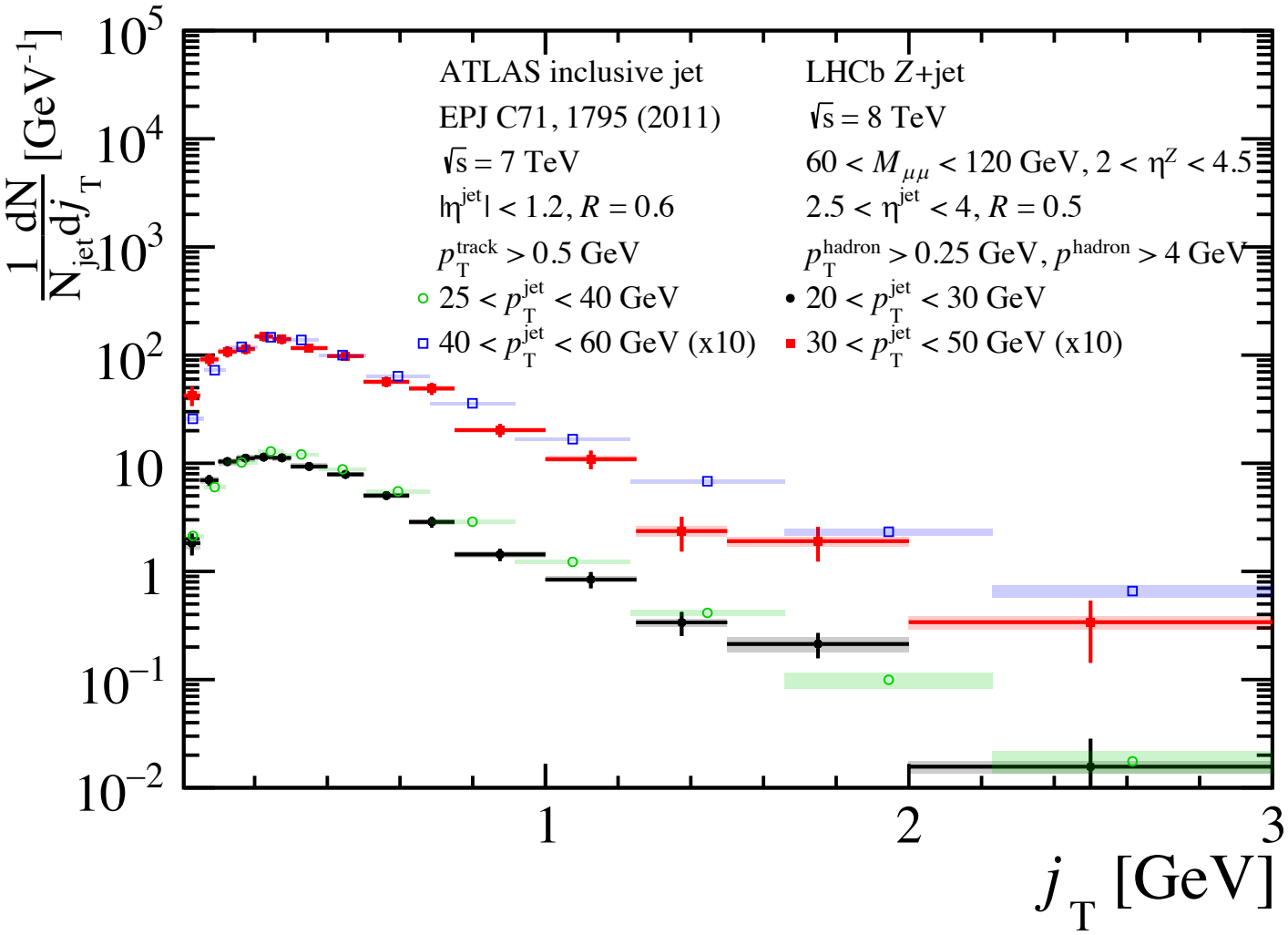
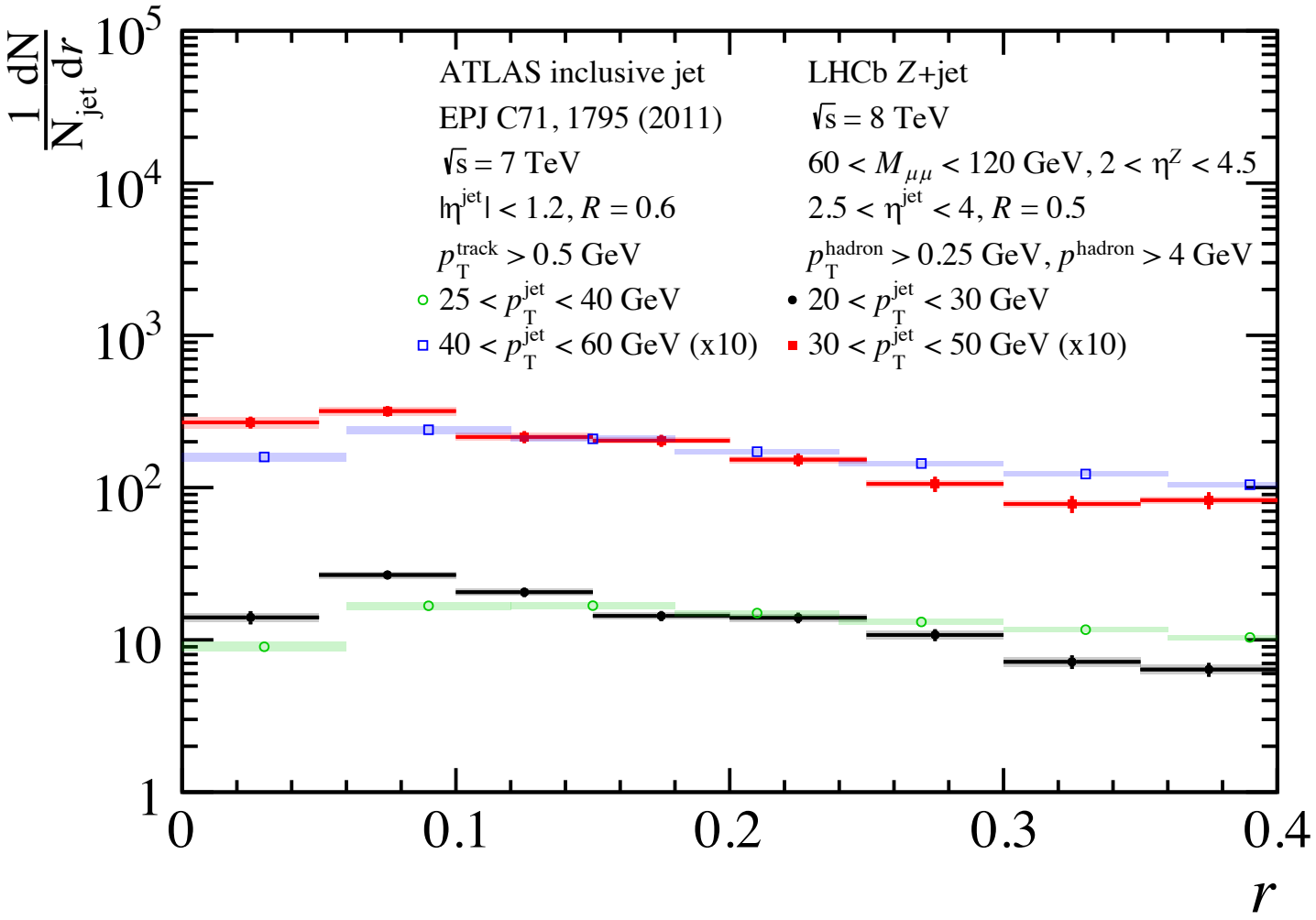
ATLAS γ-jet compared to LHCb Z-jet



ATLAS inclusive jets compared to LHCb Z-jet



ATLAS inclusive jets compared to LHCb Z-jet



ATLAS inclusive jets compared to LHCb Z-jet