Studying hadronization at LHCb

Transverse-momentum-dependent fragmentation functions

Cynthia Nuñez

On behalf of the LHCb Collaboration

DIS 2024, WG5 Spin and 3D Structure

April 11, 2024

Hadronization

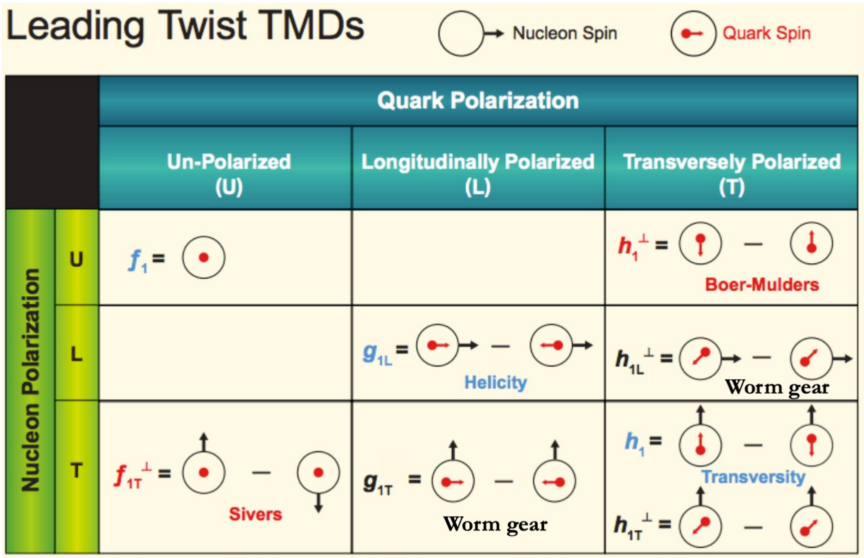
- **Parton Distribution Functions (PDFs):** probability of finding a parton inside a hadron
- **Fragmentation Functions (FFs):** probability of an outgoing parton transforming into a hadron
- **Transverse-momentum-dependent:** spin-momentum correlations
- Important processes in studying hadron formation:

$$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes FF$$

$$\sigma^{lN\to lhX} = PDF \otimes \hat{\sigma} \otimes FF$$

$$\sigma^{pp\to hX} = PDF \otimes PDF \otimes \hat{\sigma} \otimes FF$$

TMD PDF:



TMD FF:

Quark / Hadron	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	$H_1, H_{1T}^\perp$

Unpolarized: D_1

Spin-spin correlations: G_{1L}, H_1

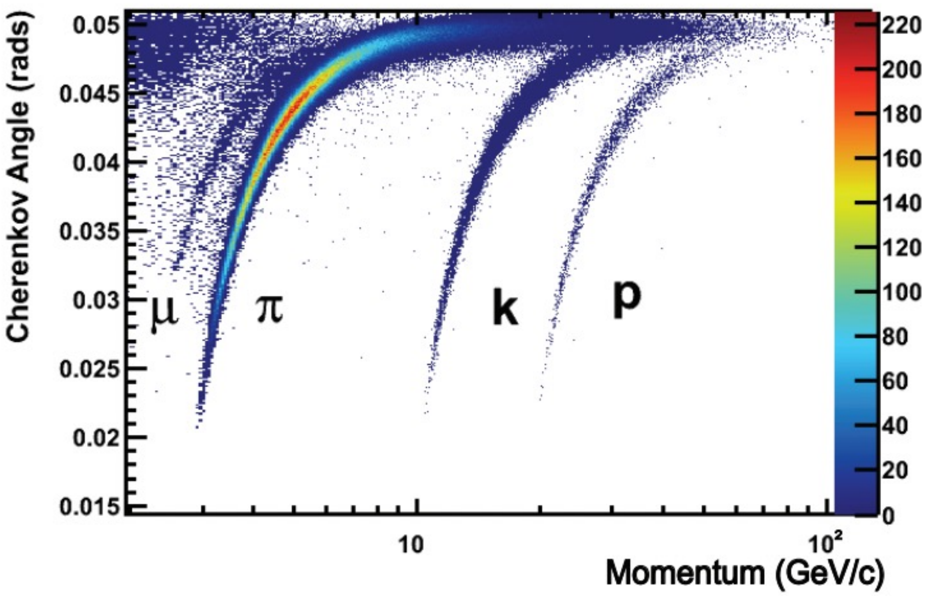
Spin-momentum correlations: $D_{1T}^\perp, G_{1T}, H_{1L}^\perp, H_1^\perp, H_{1T}^\perp$

Outline

- **Large hadron collider beauty (LHCb) detector**
- **Hadronization in jets (TMD jet FF)**
  - Charged hadron in jets (results)
  - Identified charged hadrons in jets (results)
  - Heavy quark jet hadronization (prospective)
- **Hyperon polarization**
  - Λ and $\overline{\Lambda}$ heavy-ion *p*Pb (prospective) and fixed-target *p*Ne (results)
  - Λ_c^+ polarization (results and prospective)
- **Polarized target program at LHC (LHCSpin)**

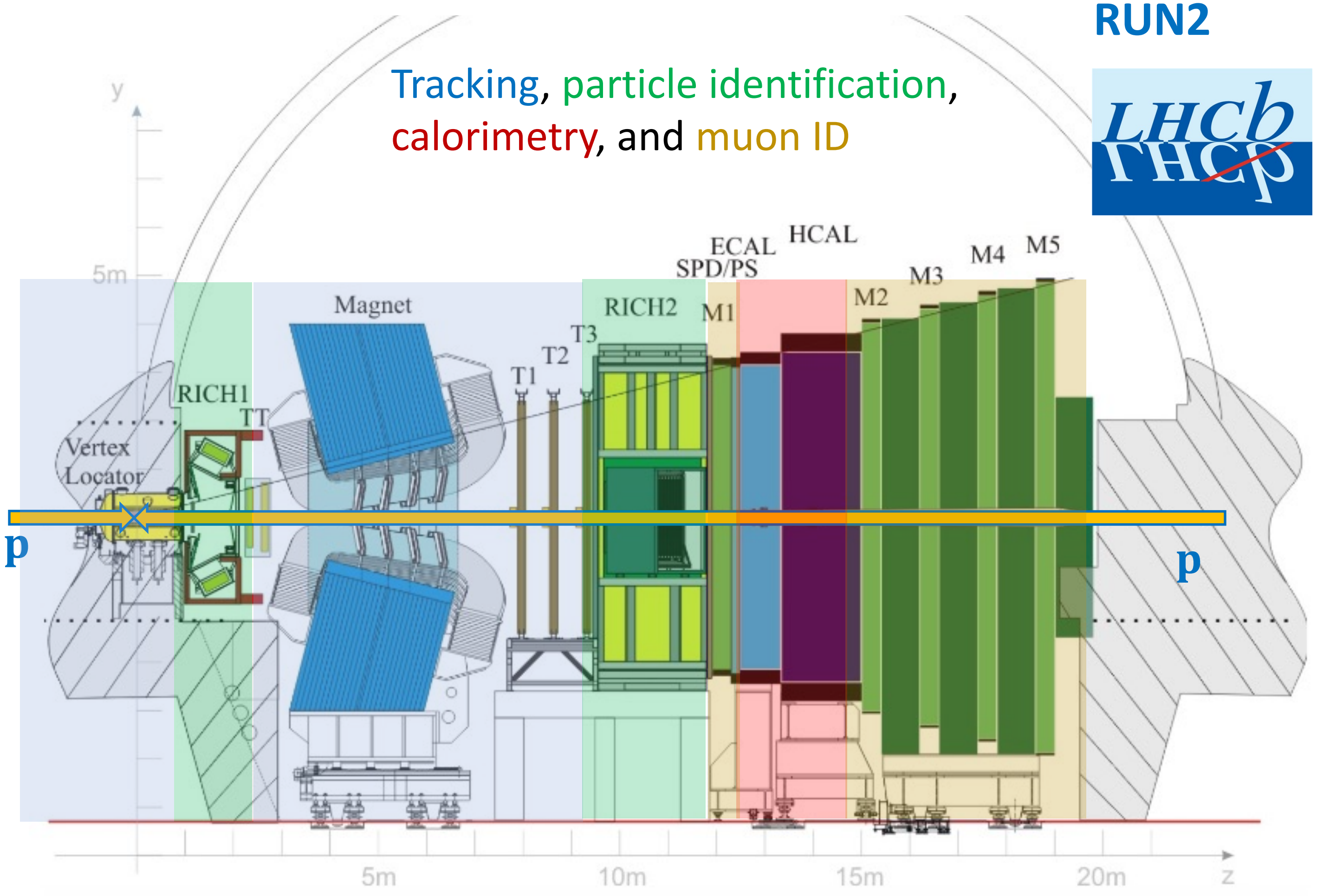
- Forward spectrometer designed to search for CP violation and rare decays of b and c hadrons
- Fully instrumented $2 < \eta < 5$

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



RUN2

Tracking, particle identification, calorimetry, and muon ID



Hadronization in jets

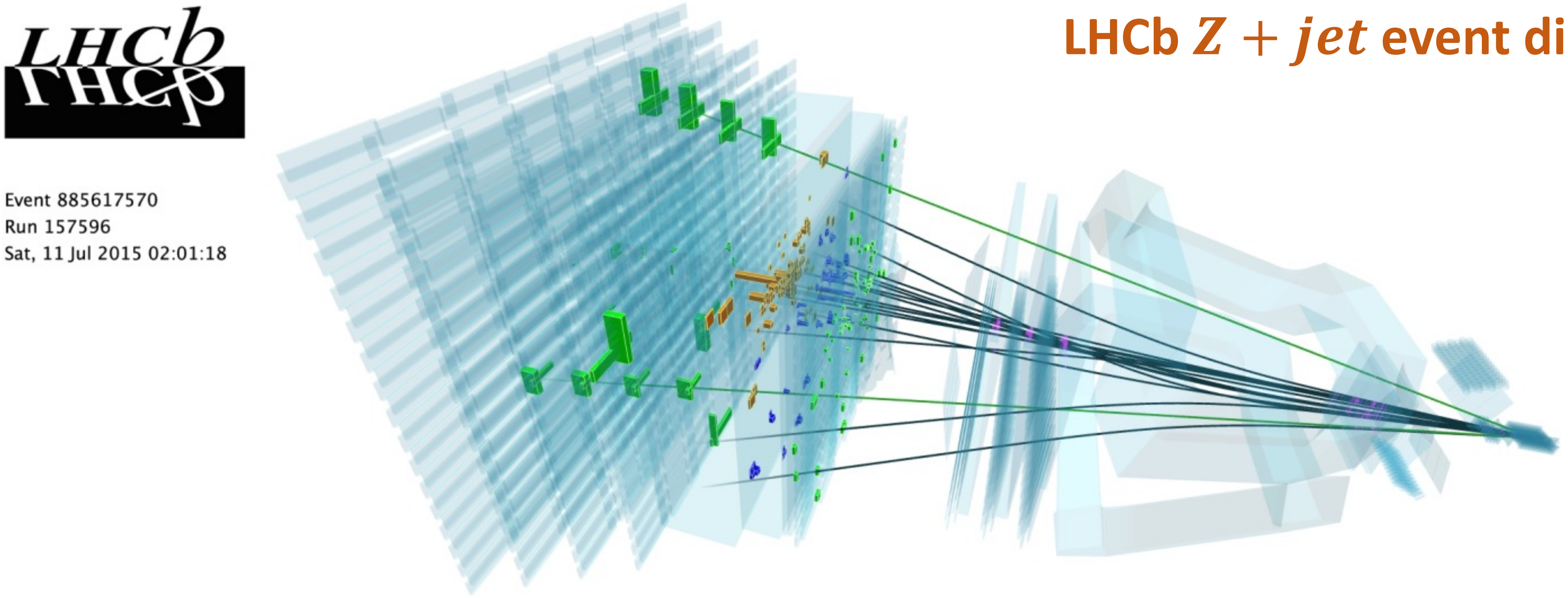
PRL 123, 232001 (2019)

PRD 108, L031103 (2023)

Jet substructure

- **Jet**: collimated spray of particles
- Contains information about partons scattered out of proton during collision
  - Probe hadronization dynamics, flavor dependence, etc.

LHCb $Z + jet$ event display



Jet substructure at LHCb

PRL 123, 232001 (2019)

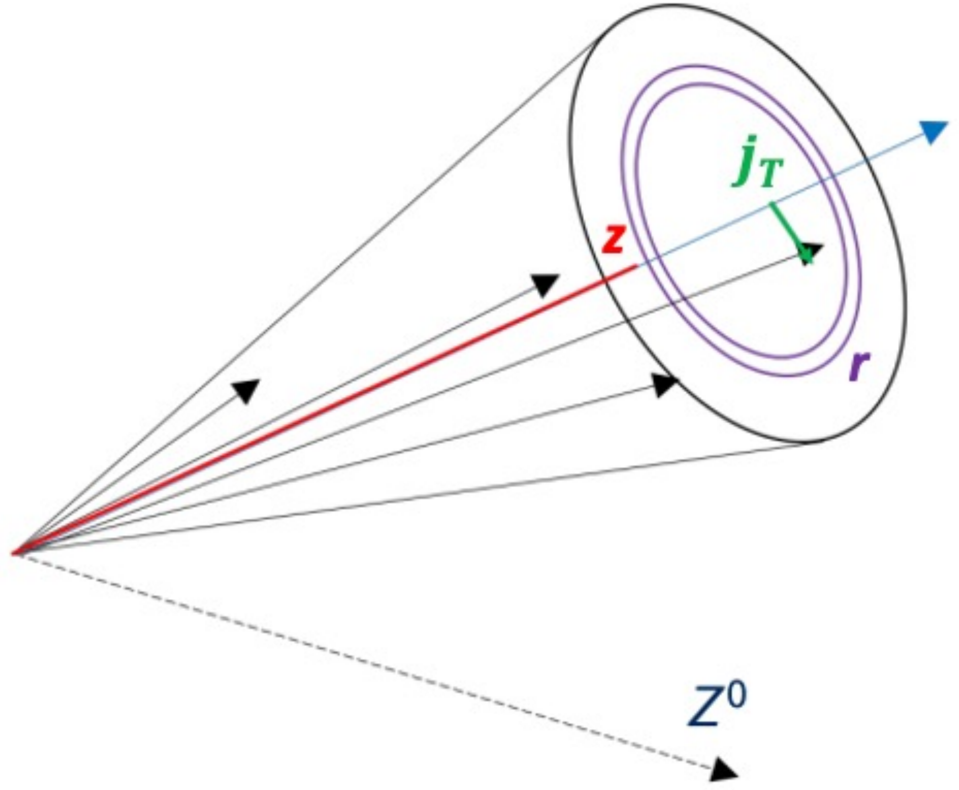
- TMD Jet Fragmentation Functions: (z, r, j_T)
- Measurement of Z-tagged jets
  - sensitive to light quark jets

$$qg \rightarrow Zq \rightarrow Z + jet$$

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

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

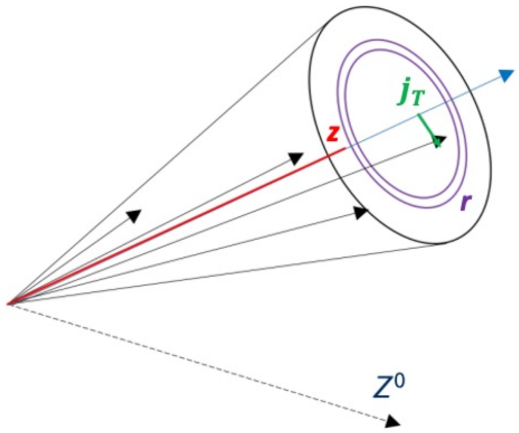
$$r = \sqrt{(\phi_h - \phi_{jet})^2 + (y_h - y_{jet})^2}$$



Jet substructure at LHCb

PRL 123, 232001 (2019)

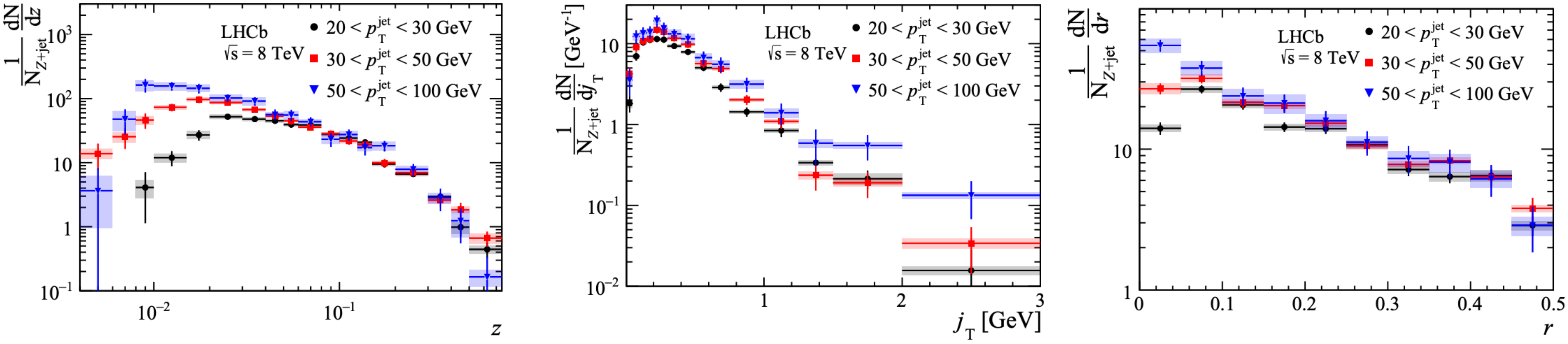
- **1D measurement of charged hadrons in Z+jet**
  - *pp* data, $\sim 2\ \mathrm{fb}^{-1}, \sqrt{s} = 8$ TeV
  - Jets produced in association with a Z→ $\mu\mu$ boson
  - Jets are clustered with the anti-k_T algorithm



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

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

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

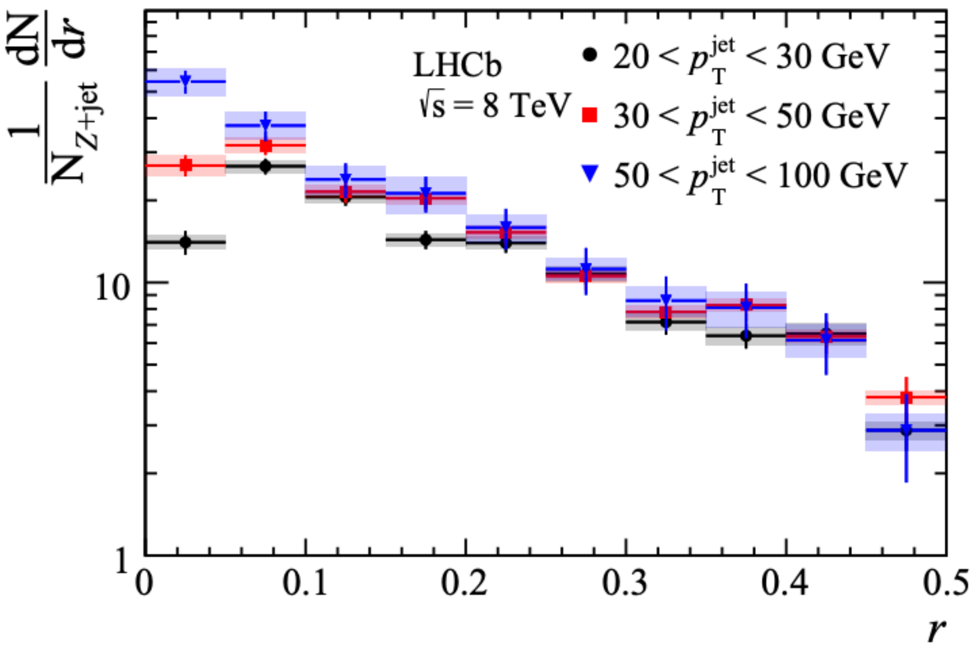


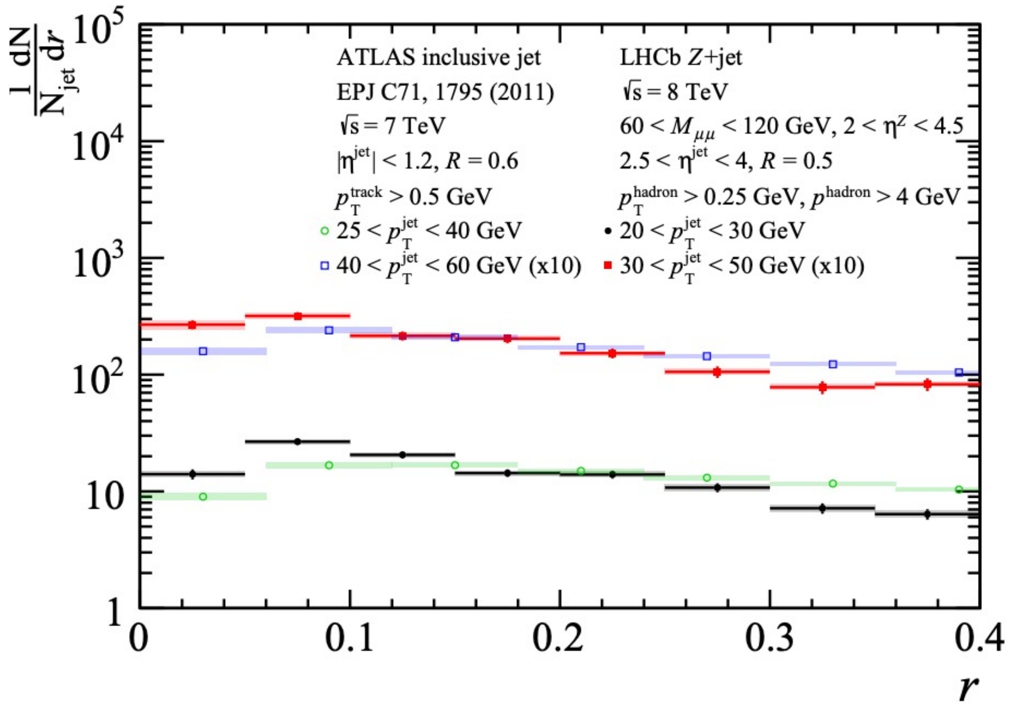
Light quark fragmentation in jets

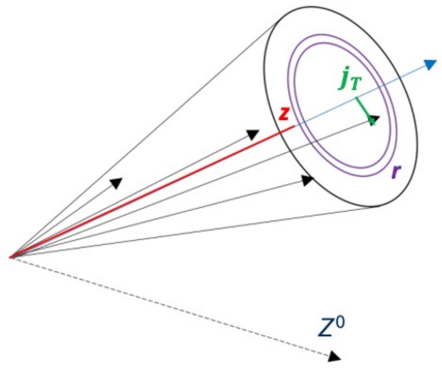
PRL 123, 232001 (2019)

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

$pp \rightarrow Z + jet$







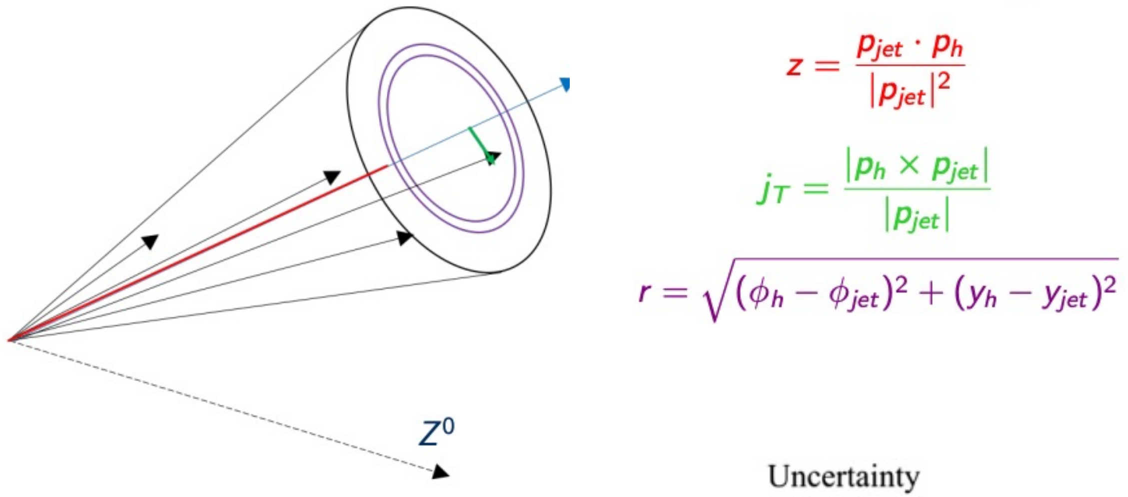
- Have more hadrons in jets with higher jet p_T along jet axis

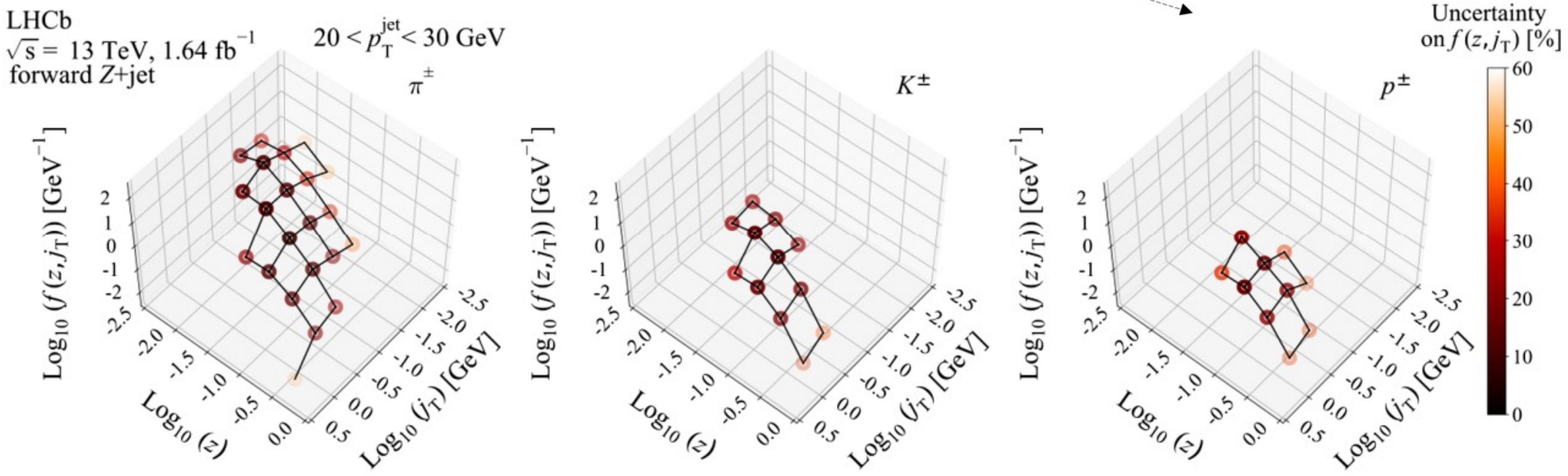
- Compared to ATLAS-inclusive jets at midrapidity sensitive to gluon jets
- Light quark-initiated jets are more collimated than gluon jets

TMD jet fragmentation functions for identified hadrons: $\pi^{\pm}, K^{\pm}, p^{\pm}$

PRD 108, L031103 (2023)

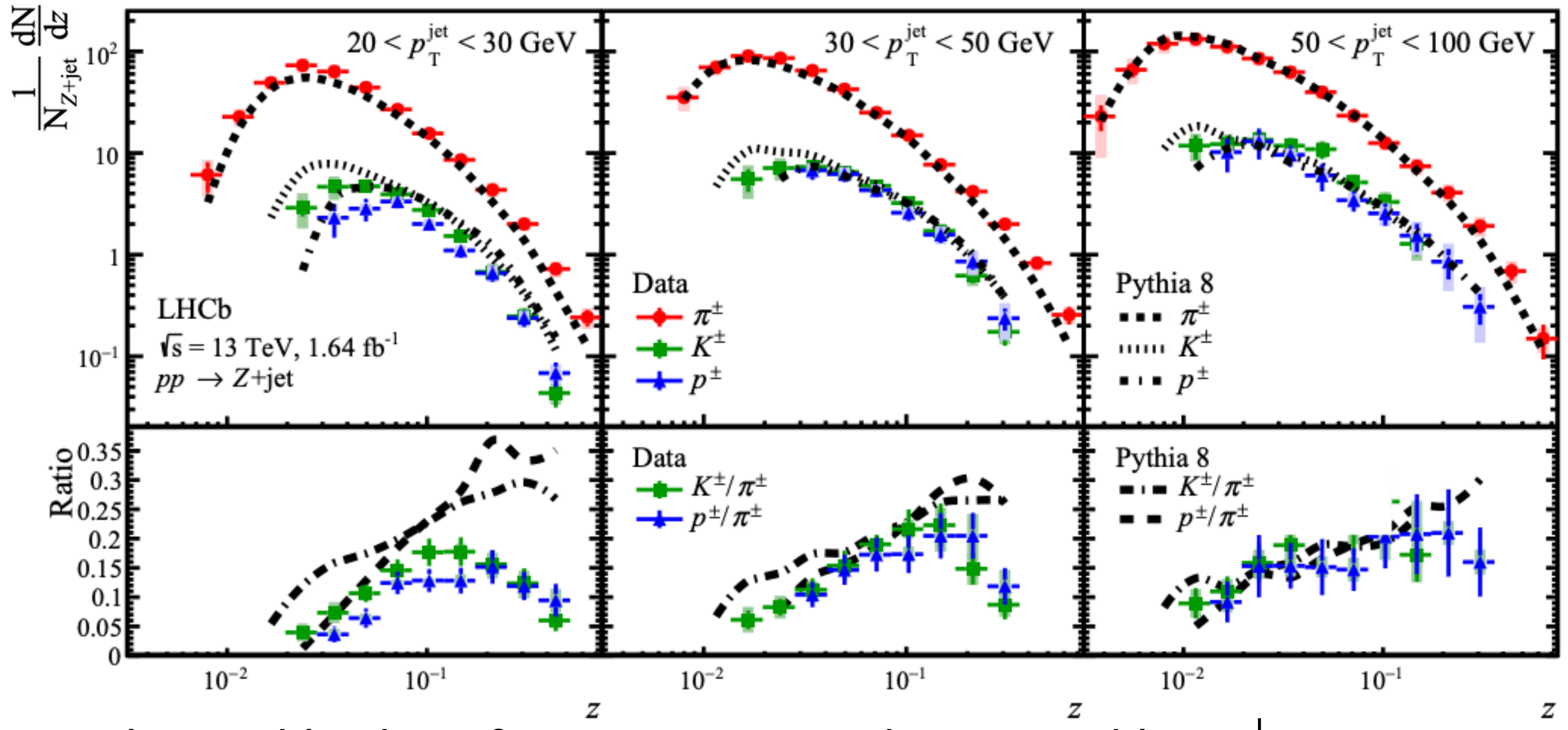
- Multi-differential jet substructure measurement
- Heavier hadrons are produced from harder partons → larger j_T and z

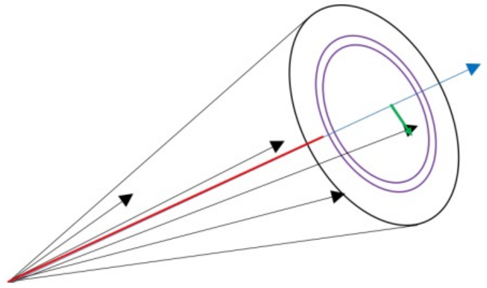




TMD jet fragmentation functions for identified hadrons: $\pi^{\pm}, K^{\pm}, p^{\pm}$

PRD 108, L031103 (2023)





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

- Charged hadron formation in jet dominated by $\pi^{\pm}$
- Heavier hadrons require larger momentum fraction, z, for formation
- Simulation (Pythia8) overestimates $K^{\pm}$ and $p^{\pm}$ production at low jet p_T

Heavy flavor in jets

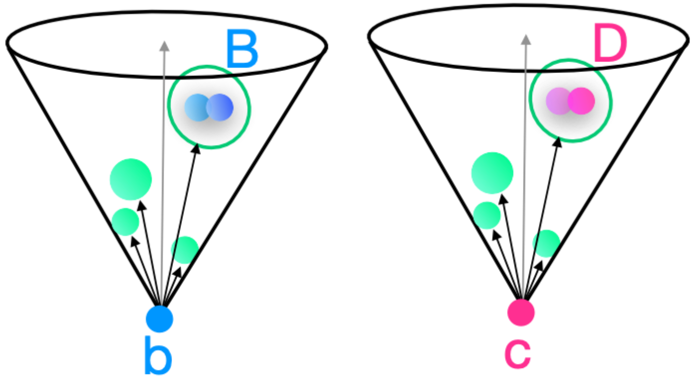
JINST 10 (2015) P06013

- Complementary to the LHCb Z + jet hadronization
- Expand on LHCb study of J/ψ production in jets

PRL 118, 192001 (2017)

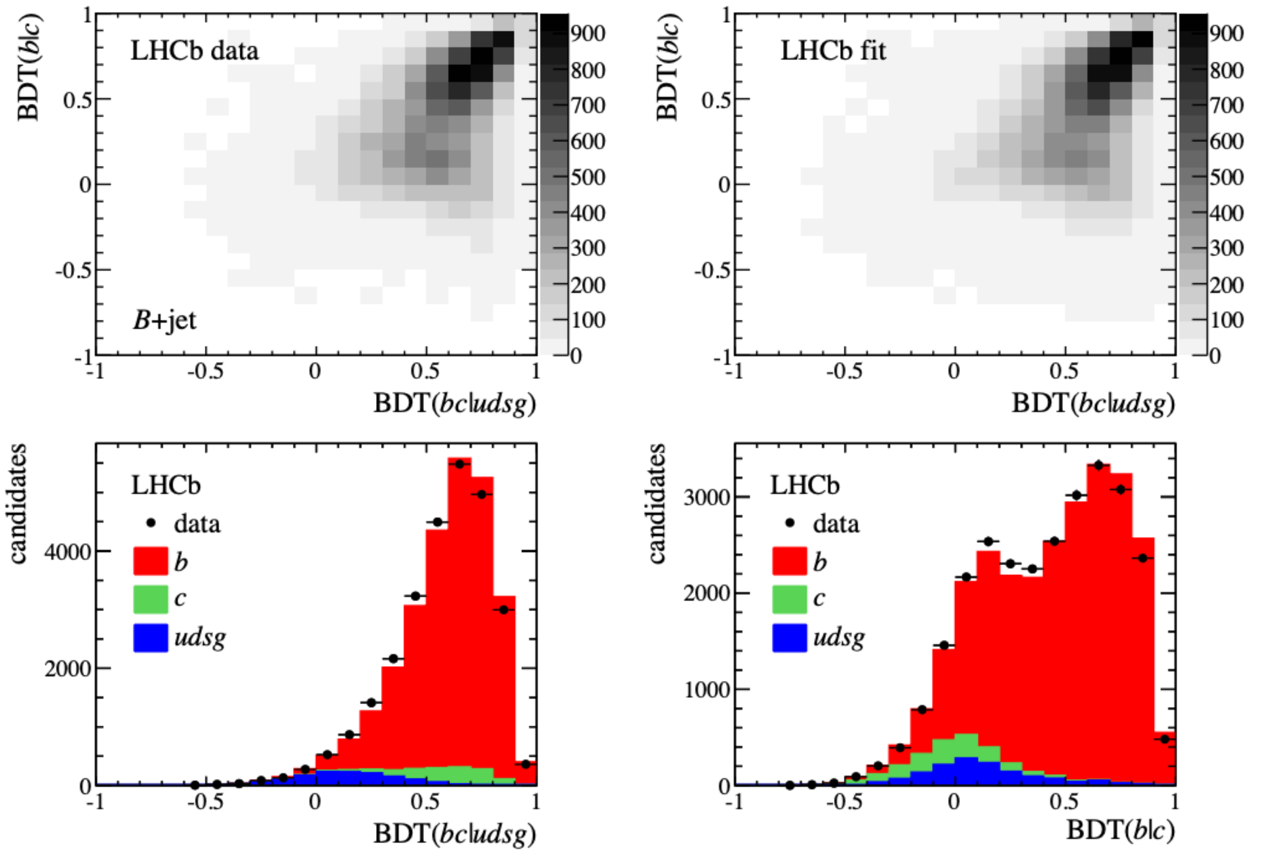
- Access to heavy-quark TMD FF
  - *b*- and *c*- jets using Secondary Vertex tagging
  - Identified heavy flavor hadrons in jets

Final states: **produced hadrons**



Initial state: fragmenting **beauty** or **charm** quark

SV-tagger Boosted Decision Tree fit results for B + jet



Hyperon polarization

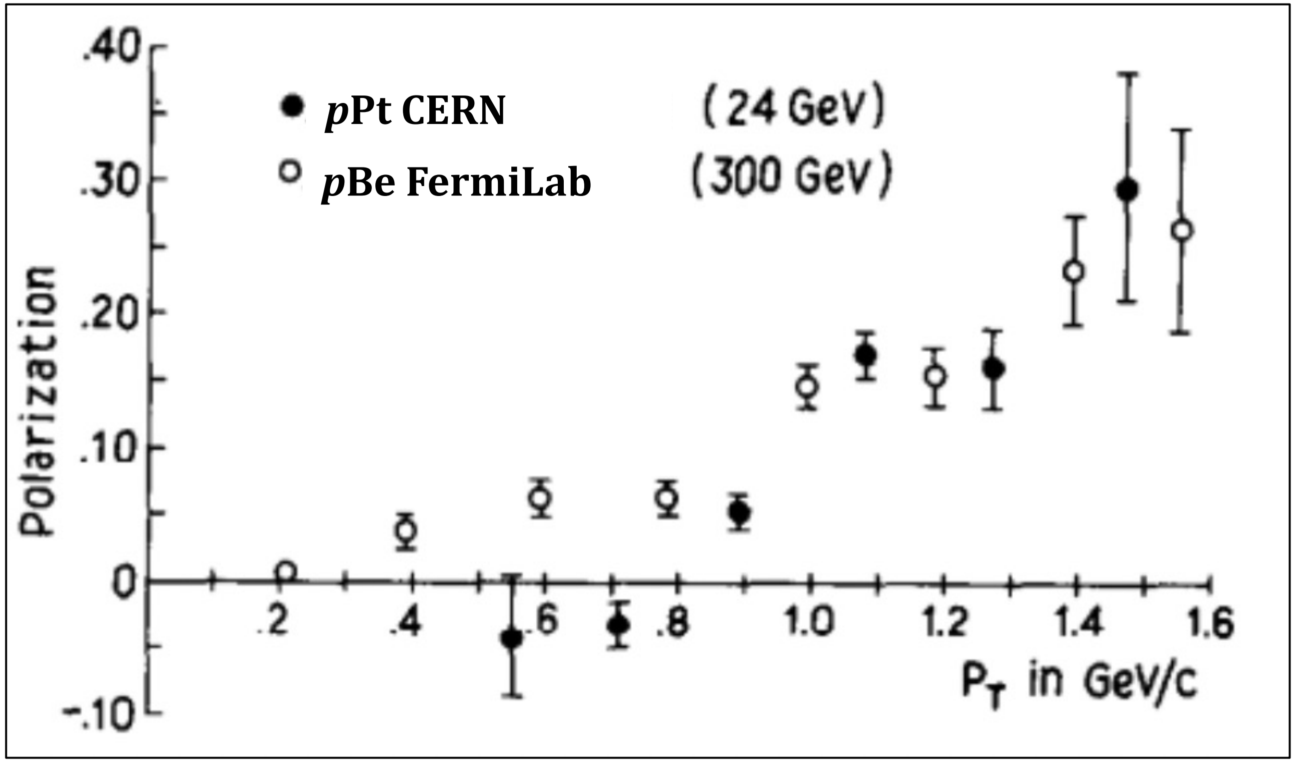
arXiv:2307.07878

LHCb-PAPER-2024-009, in preparation

Λ (uds) polarization

- First observed in 1976 in unpolarized *p*Be
- **Spontaneous transverse polarization values up to 30%**
- Contradictory to understanding at the time that transverse-spin asymmetries suppressed in pQCD
- Observed non-zero polarization in e^+e^- for Λ and $\bar{\Lambda}$

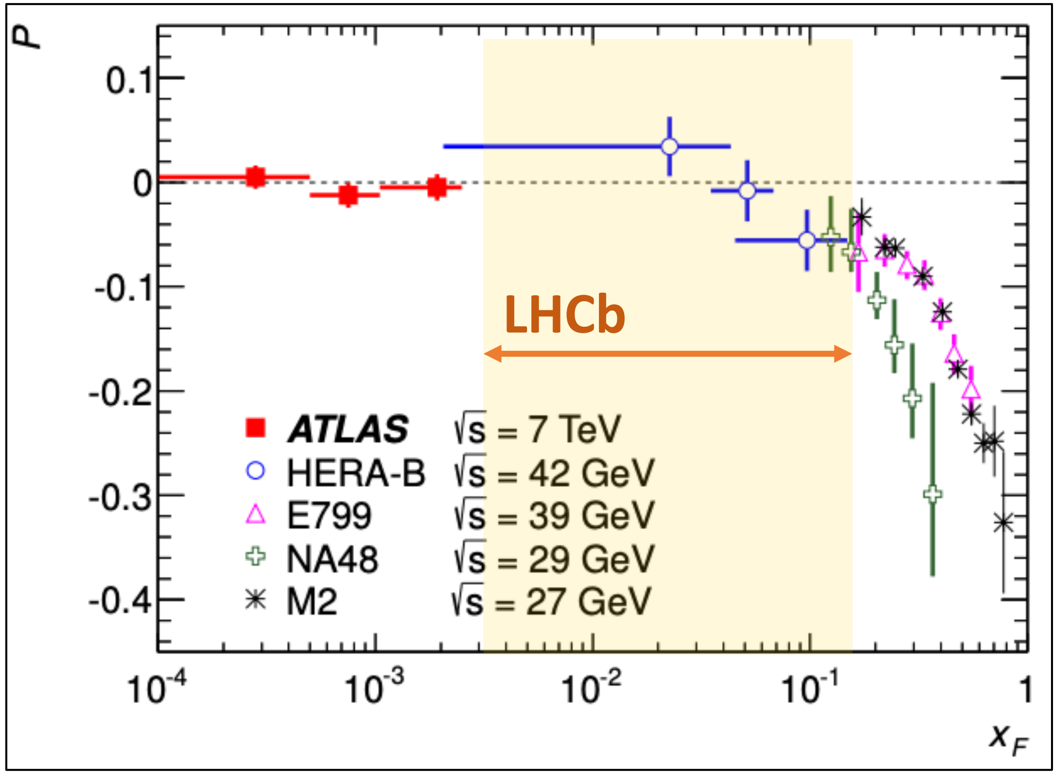
  → **hadronization effect**



PRL36, 1113 (1976)
PLB68, 480 (1977)
PRL 41, 1689 (1978)
PRL 122, 042001 (2019)

*sign convention different when compared to later measurements

Λ (uds) polarization



PRD91, 032004 (2015)

$$x_F = 2p_z^*/\sqrt{s}$$

K. Heller, Proceedings, 12th International Symposium on Spin Physics, Amsterdam, 1996

Common features observed

- Negative* and ~independent of the beam energy
- Increases with $|x_F|$ and p_T
- Polarization has been observed for beams other than proton including $e^{\pm}$ on target nuclei, $\pi^{\pm}$, $K^{\pm}, \Sigma^-, \nu N, n, \gamma$

In unpolarized hadronic collisions, **polarization of other hyperons also observed**:

- **Negative polarization** for Λ, Ξ^0, Ξ^-, and $\bar{\Xi}^-$
- **Positive polarization** for $\Sigma^+, \Sigma^-, \Sigma^0$, and $\bar{\Sigma}^+$
- **Zero polarization** $\Omega, \bar{\Lambda}$

*sign convention different when compared to earlier measurements

Frameworks to explain Λ polarization

Approaches in explaining transverse Λ polarization in unpolarized collisions have focused on:

- Polarizing transverse-momentum dependent (TMD) fragmentation functions (FF) $D_{1T}^{\perp\Lambda/q}(z, k_{\perp}^{2})$
- Higher twist multiparton correlators

. . .

TMD FF:

Hadron \ Quark	U	L	T
U	D_1		$H_1^{\perp}$
L		G_{1L}	$H_{1L}^{\perp}$
T	$D_{1T}^{\perp}$	G_{1T}	$H_1, H_{1T}^{\perp}$

Unpolarized: D_1

Spin-spin correlations: G_{1L}, H_1

Spin-momentum correlations: $D_{1T}^{\perp}, G_{1T}, H_{1L}^{\perp}, H_1^{\perp}, H_{1T}^{\perp}$

PRD 63, 054029 (2001)

PLB 809, 135756 (2020)

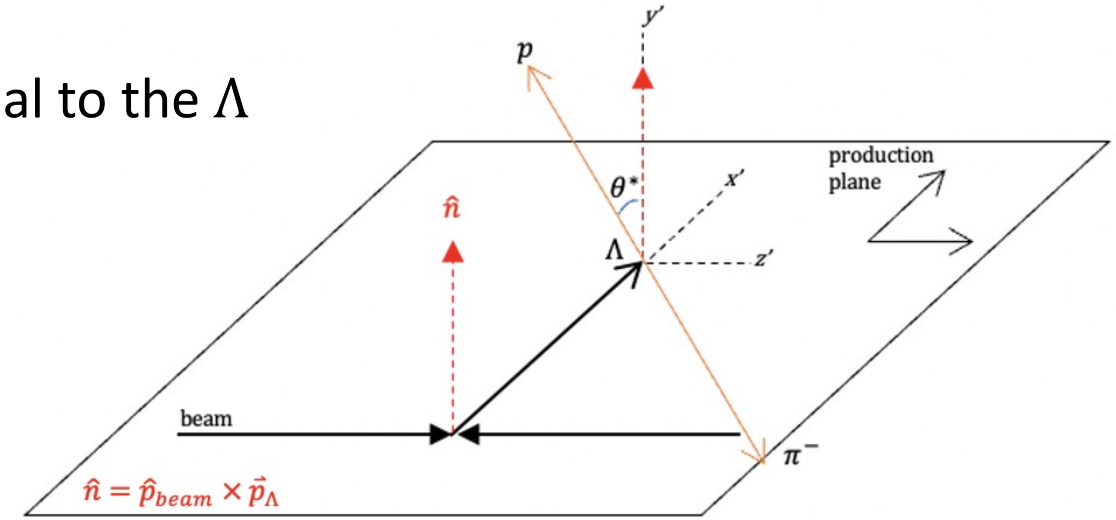
PRD 95, 114013 (2017)

Transverse Λ polarization

- Λ hyperon: $m_\Lambda = 1115.683 \pm 0.006\ \mathrm{MeV}/c^2$ and $c\tau = 7.89$ cm
- $\Lambda \rightarrow p\pi^-$ **self analyzing decay**
- Transverse polarization measured in the direction normal to the Λ hyperon and beam momentum: $\vec{n} = \vec{p}_{beam} \times \vec{p}_\Lambda$
- The distribution of θ^* for polarized Λ:

$$\frac{dN}{d\cos\theta^*} = \frac{N}{2}(1 + \alpha_\Lambda P\cos\theta^*)\varepsilon_{tot}(\cos\theta^*)$$

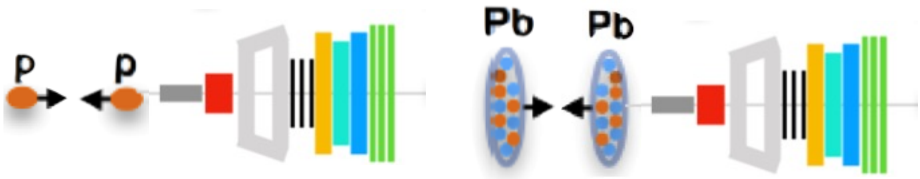
$\alpha_\Lambda = 0.748 \pm 0.007$ PDG 2023



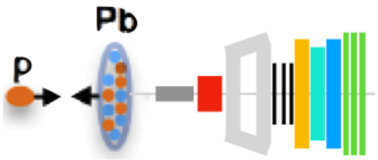
LHCb measured value of $0.74^{+0.04}_{-0.03}$
JHEP 2006 (2020) 110

LHCb Experimental Data

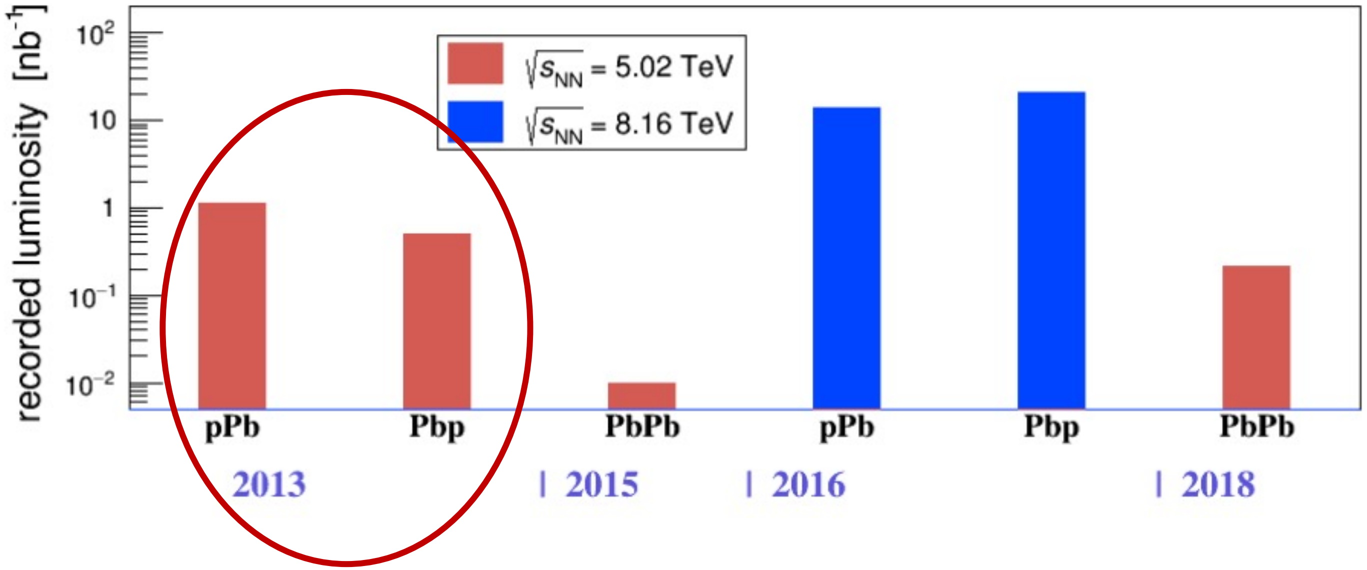
Colliding beam mode:



Forward pPb $1.5 < y^{*} < 4.5$



Backward Pbp $-5.0 < y^{*} < -2.5$



$$x_F = \frac{p_L^{*}}{|\max(p_L^{*})|} \sim \frac{2}{\sqrt{s_{NN}}} \sqrt{M^2 + p_T^2} \sinh(y^{*})$$

Forward pPb: $x_F > 0$

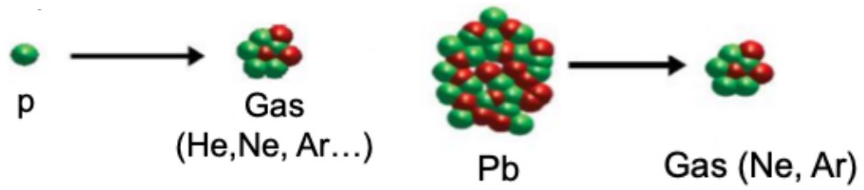
Forward Pbp: $x_F < 0$

LHCb Experimental Data

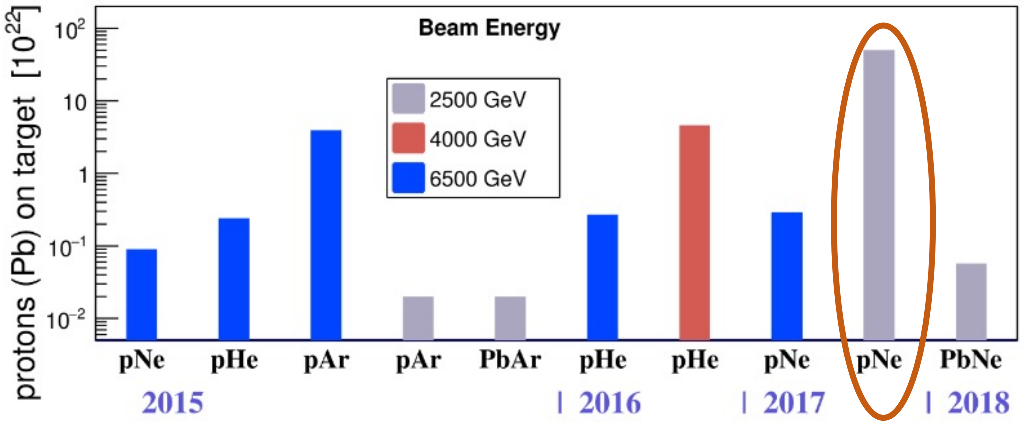
Fixed-target mode

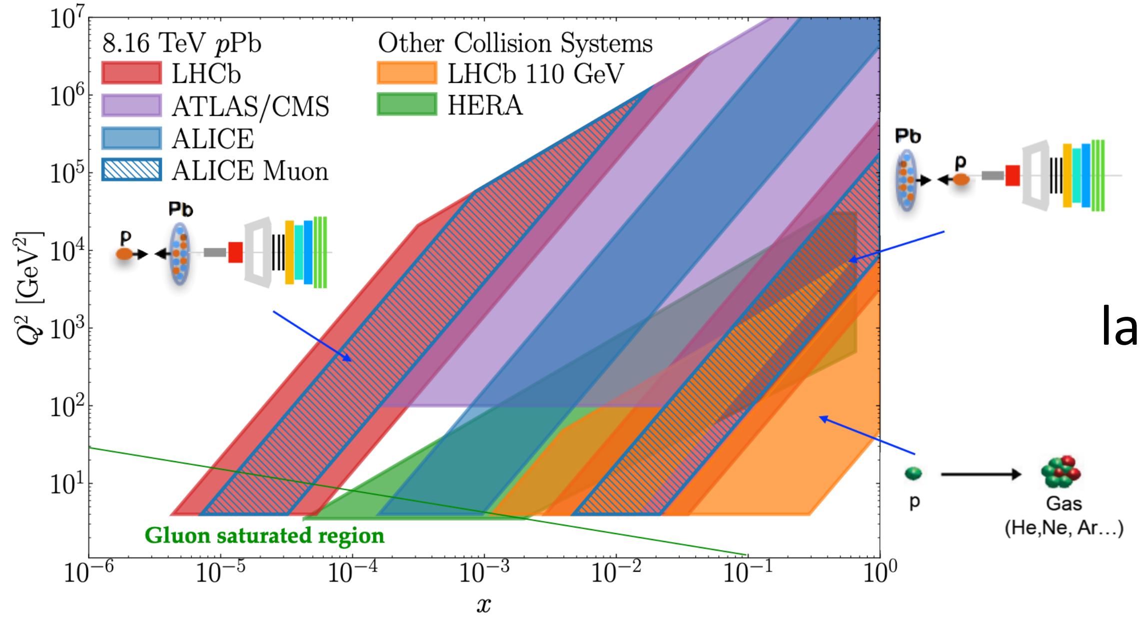
System for Measuring the Overlap with Gas (SMOG)

injection of noble gases into interaction region



LHCb-PUB-2018-015





$\sqrt{s_{NN}} \sim 41 - 110$ GeV

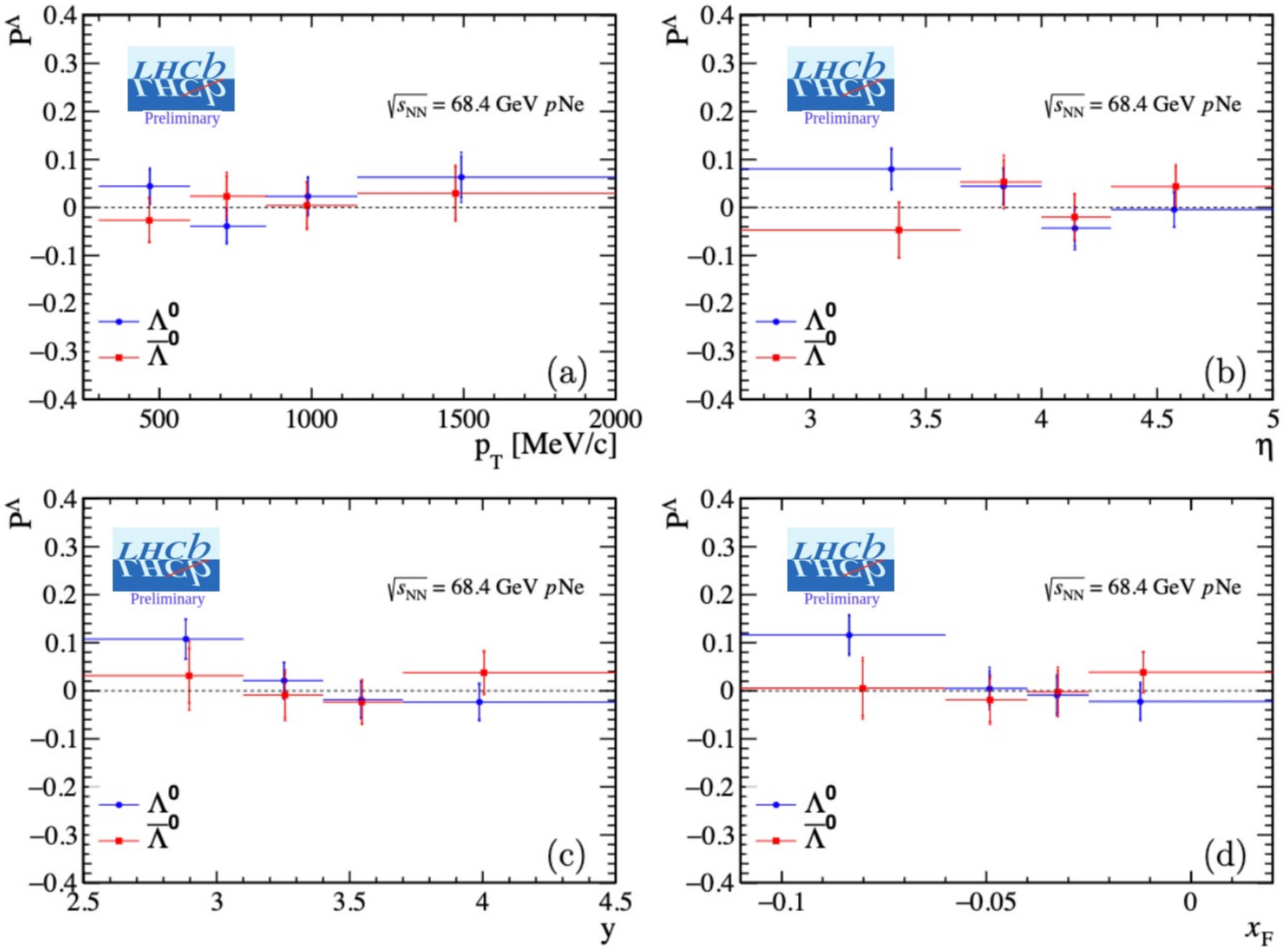
Central and backward rapidity $y^* \sim 3.8 - 4.8$

large negative x_F corresponds to large x in target nucleon

- **Allow observation of particles with larger $|x_F|$**

Transverse Λ and $\bar{\Lambda}$ polarization measurement

LHCb-PAPER-2024-009
in preparation



Polarization in bins of $\mathrm{p_T}, \eta, y$, and x_F

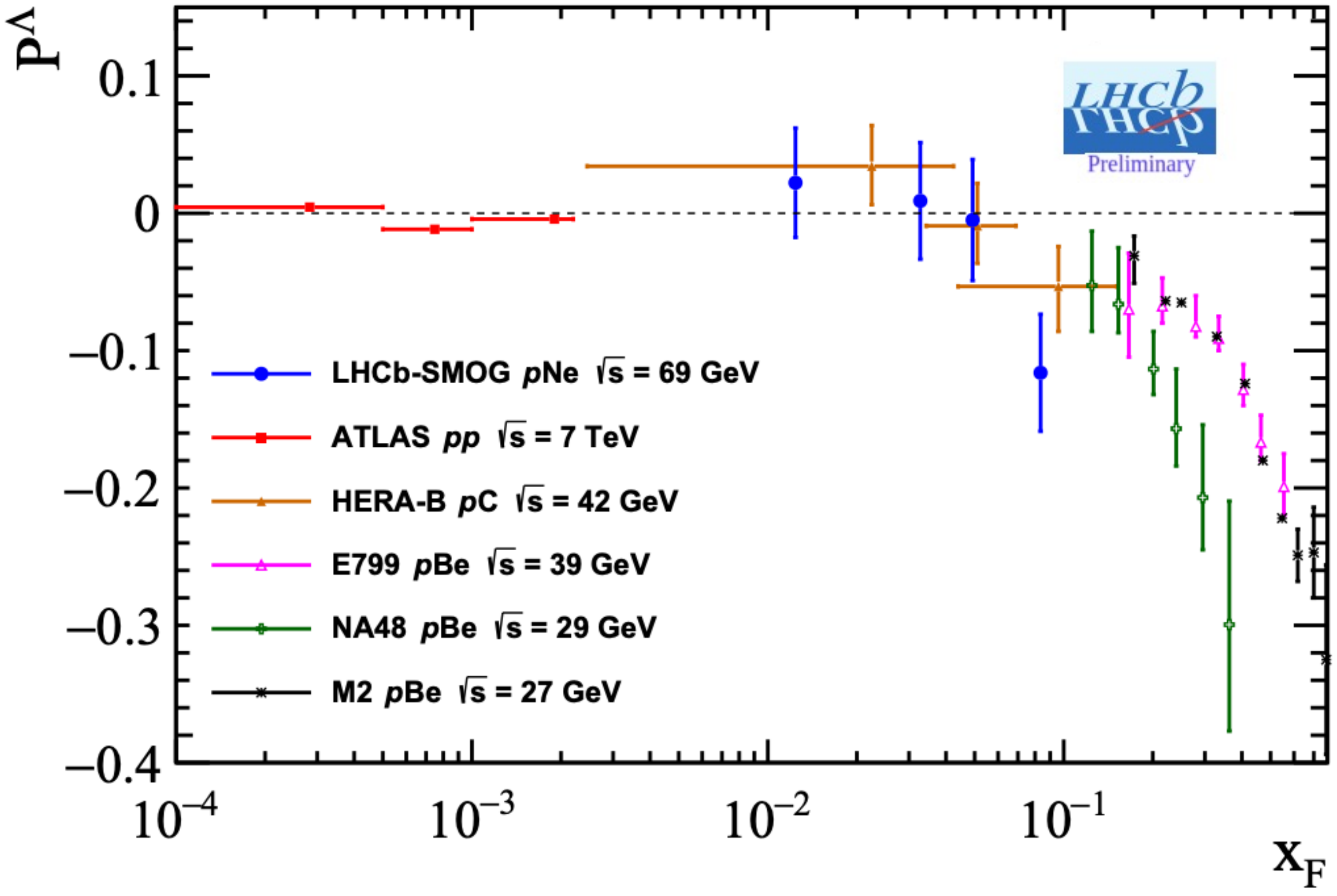
- $300 < p_T < 3000$ MeV/c
- $2 < \eta < 5$

$$P(\Lambda) = 0.029 \pm 0.019 \pm 0.012$$
$$P(\bar{\Lambda}) = 0.003 \pm 0.023 \pm 0.014$$

See talk by C. De Angelis
April 9, 2024, 2:10 PM in WG4

Transverse Λ and $\bar{\Lambda}$ polarization measurement

LHCb-PAPER-2024-009
in preparation



Comparison with previous results

$$P(-x_F) = -P(x_F)$$

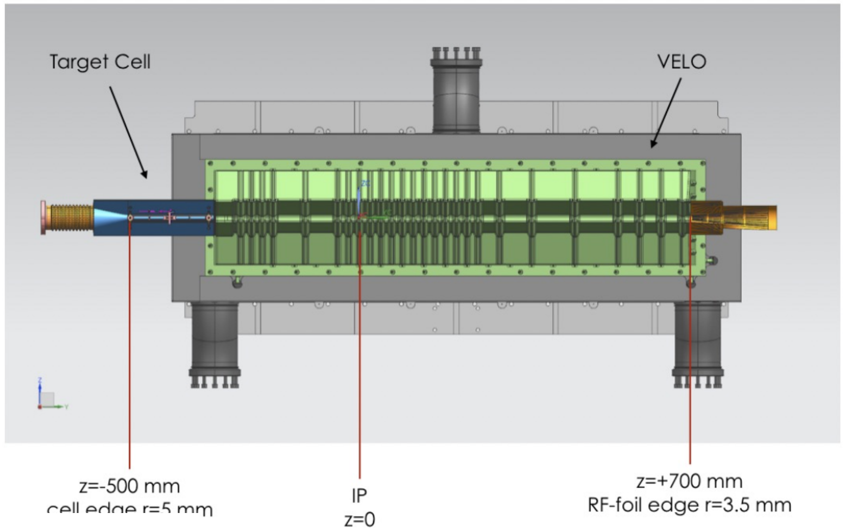
Very good agreement with previous measurements

See talk by C. De Angelis
April 9, 2024, 2:10 PM in WG4

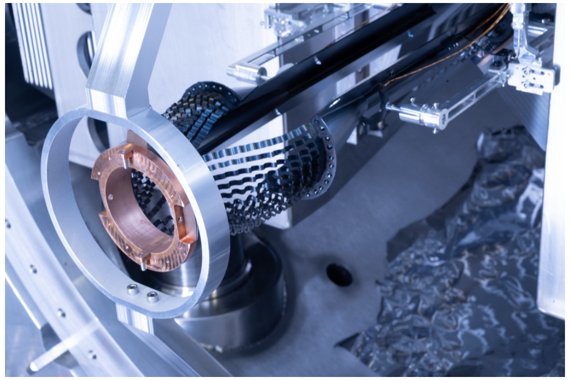
Run 3 upgrade: SMOG2

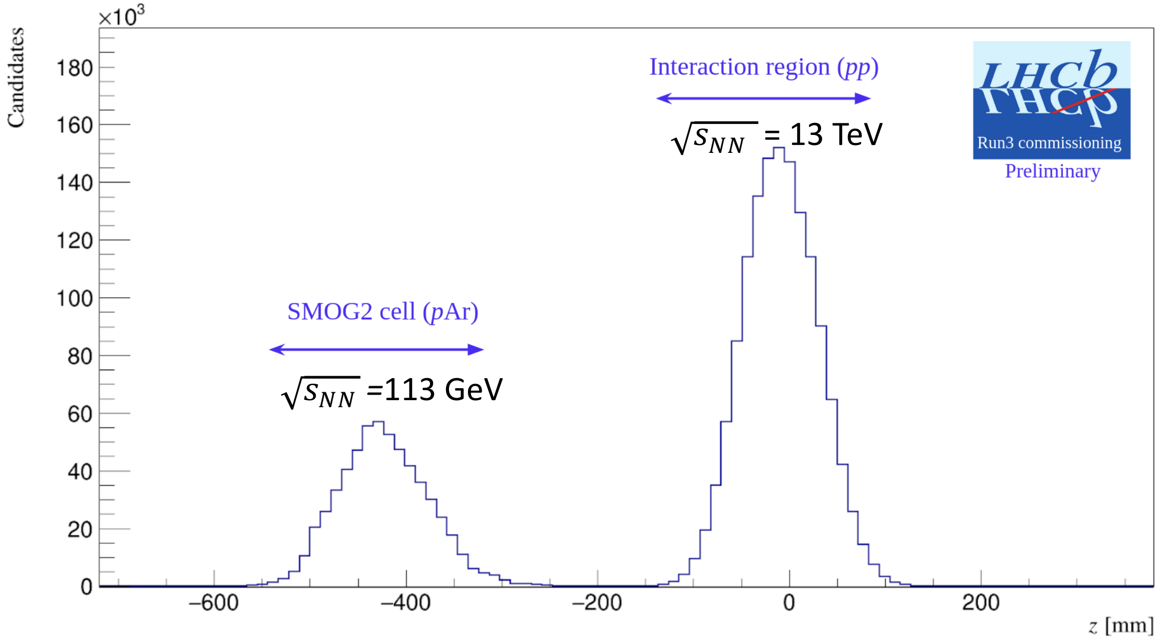
Target storage cell installed for Run 3

- Increased gas pressure
- Higher luminosity
- Well-defined separation from *pp*
- Wider target species variety



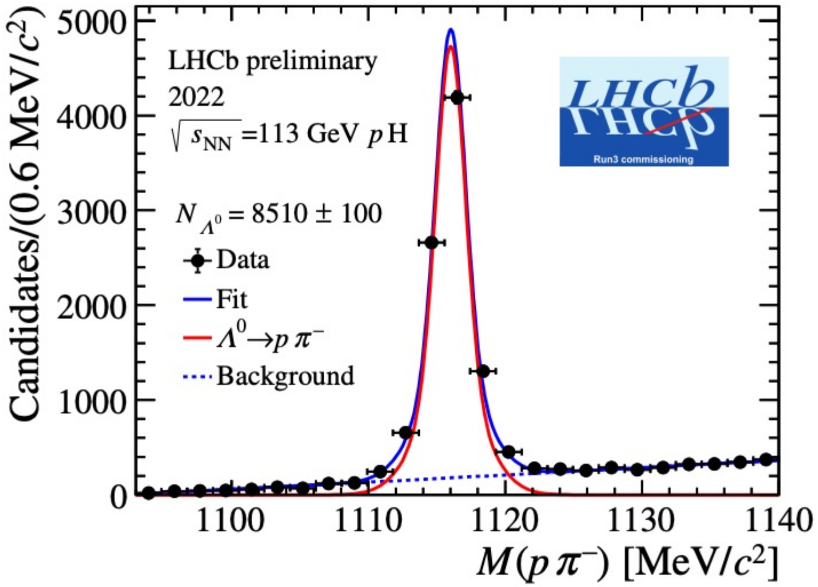
LHCB-TDR-020





LHCb-FIGURE-2023-001

18-minute *p*H run

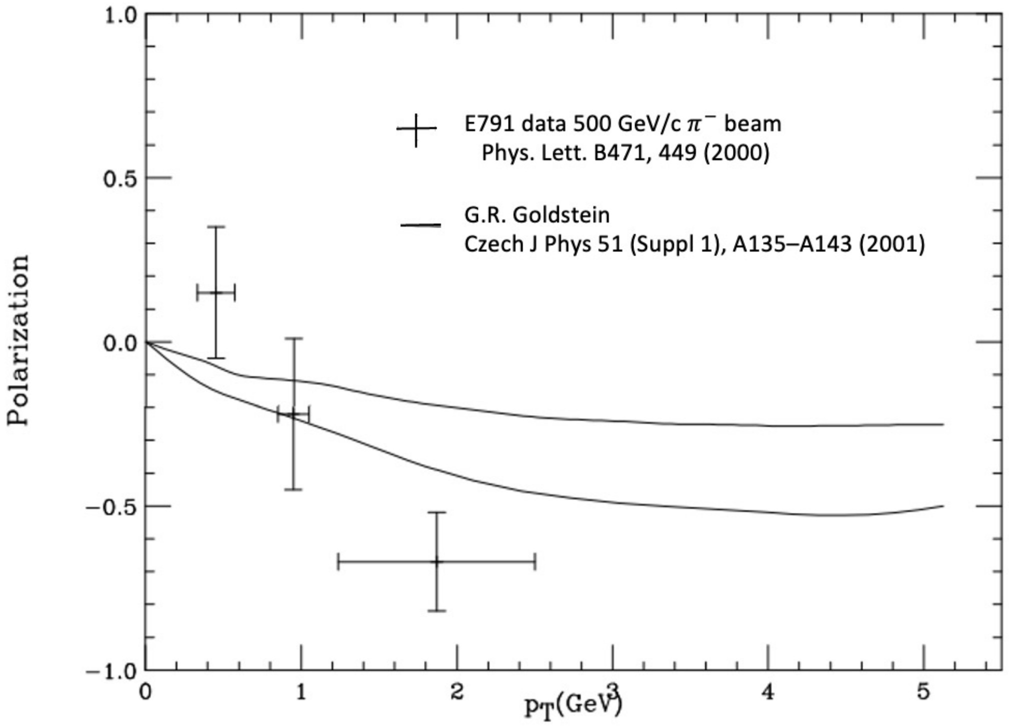


LHCb-FIGURE-2023-008

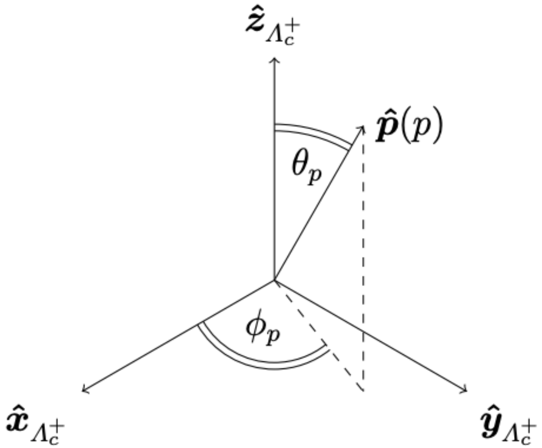
Λ_c^+ polarization at LHCb

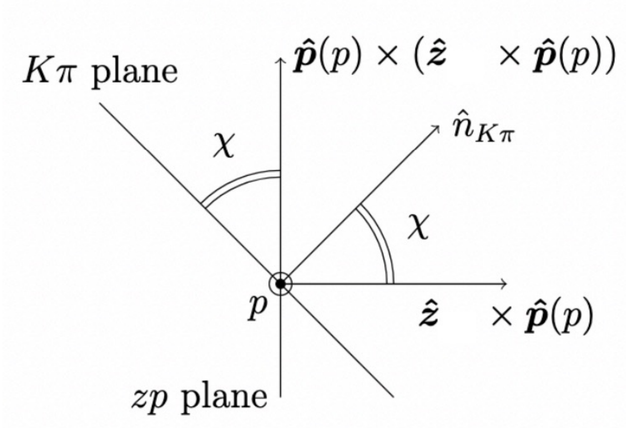
- Polarization measurement of Λ_c^+ to understand hadronization of heavy charm quarks

- Test models for Λ polarization in the production of heavy- flavor hadrons
    - Test x_F and p_T dependence comparable to Λ data



$\Lambda_c^+ \to pK^-\pi^+$





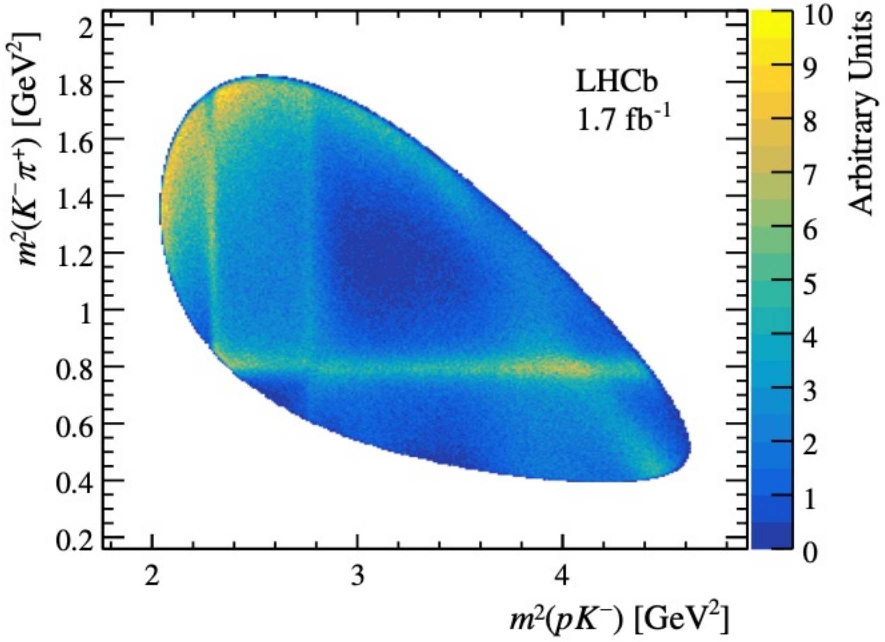
θ_p, ϕ_p polar (azimuthal) angle of the proton in the Λ_c^+ rest frame
χ angle between $K\pi$ and $(\hat{z}, \overrightarrow{p_p})$ decay plane

Λ_c^+ polarization at LHCb

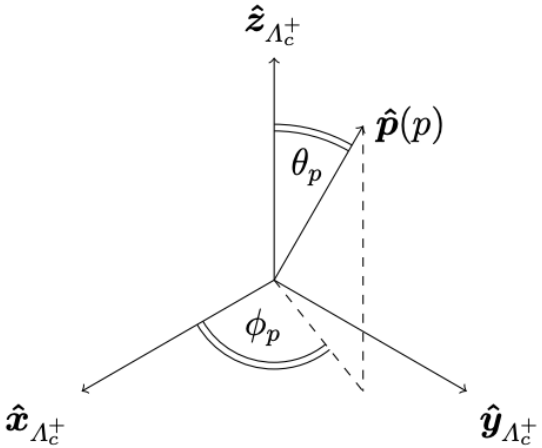
PRD 108 (2023) 1, 012023, JHEP2307 (2023) 228

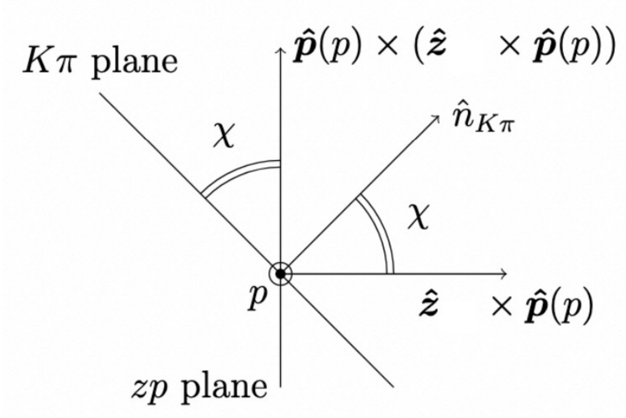
- LHCb unpolarized pp $\sqrt{s} = 13$ TeV
  - Transverse polarization in lab frame (%):
    $\boldsymbol{P_x(\Lambda_c^+) = 60.32 \pm 0.68 \pm 0.98 \pm 0.21}$
  - Longitudinal polarization in lab frame (%):
    $\boldsymbol{P_z(\Lambda_c^+) = -24.7 \pm 0.6 \pm 0.3 \pm 1.1}$

Dalitz plot for $\Lambda_c^+ \to pK^-\pi^+$ candidates



$\Lambda_c^+ \to pK^-\pi^+$





θ_p, ϕ_p polar (azimuthal) angle of the proton in the Λ_c^+ rest frame
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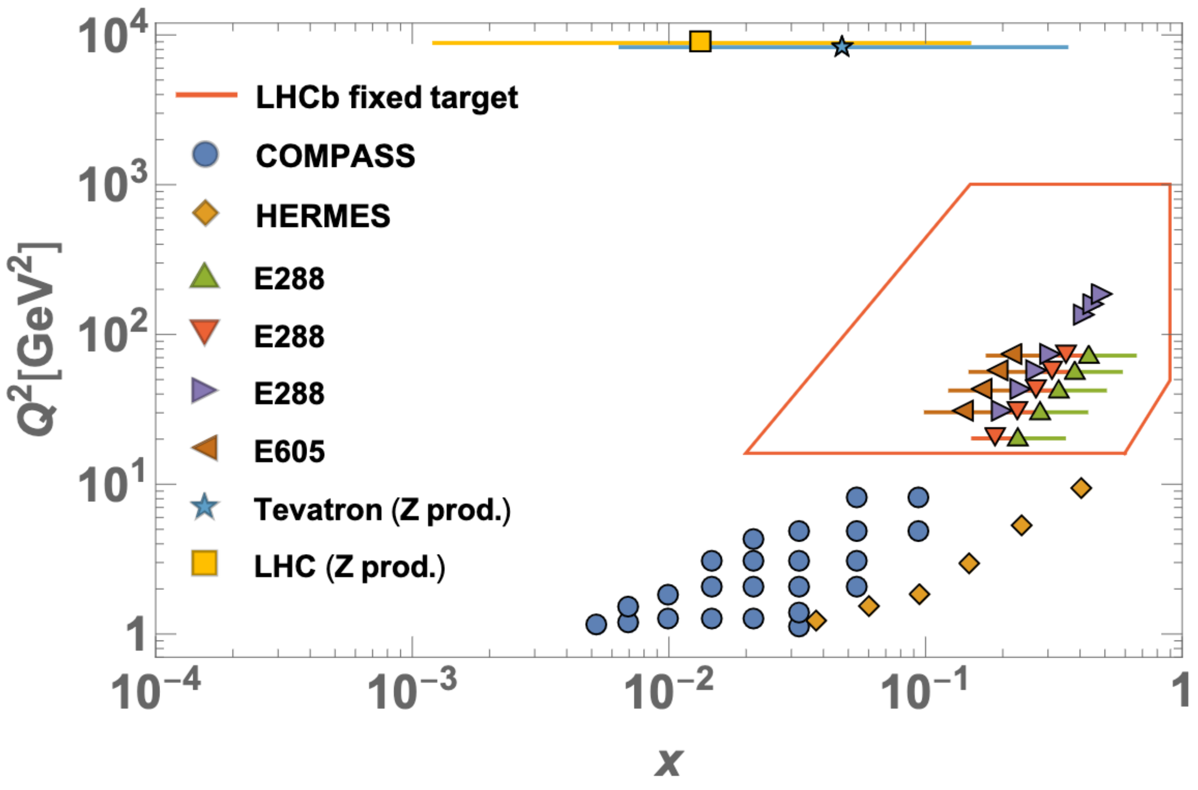
Polarized target program at LHC

arXiv:1901.08002

LHCSpin Project

- Supported R&D to add a transversely polarized target by 2029

- <u>Polarized physics at the LHC:</u>
  - Polarized quark and gluon distribution at high x and intermediate Q^2
  - Test process dependence of quark and gluon TMDs
  - Complementary measurements to existing and future SIDIS



<u>LHCb Collaboration, arXiv:1901.08002</u>

- **TMD Jet Fragmentation Functions**
  - Measured charged hadrons in jets at $\sqrt{s} = 13$ and 8 TeV
  - Multi-differential TMD JFF measured for charged pions, kaons, and protons

- **Heavy flavor jets**
  - Measurement of charged hadrons and heavy flavor hadrons in *b*- and *c*-jets

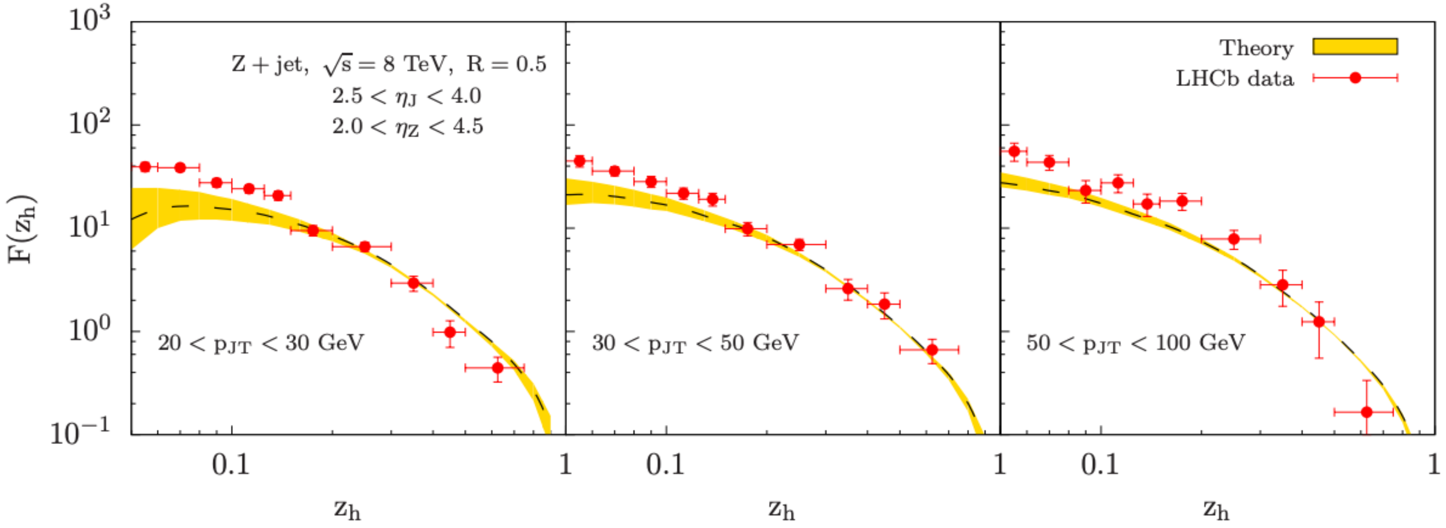
See talk by C. De Angelis
April 9, 2024, 2:10 PM in WG4

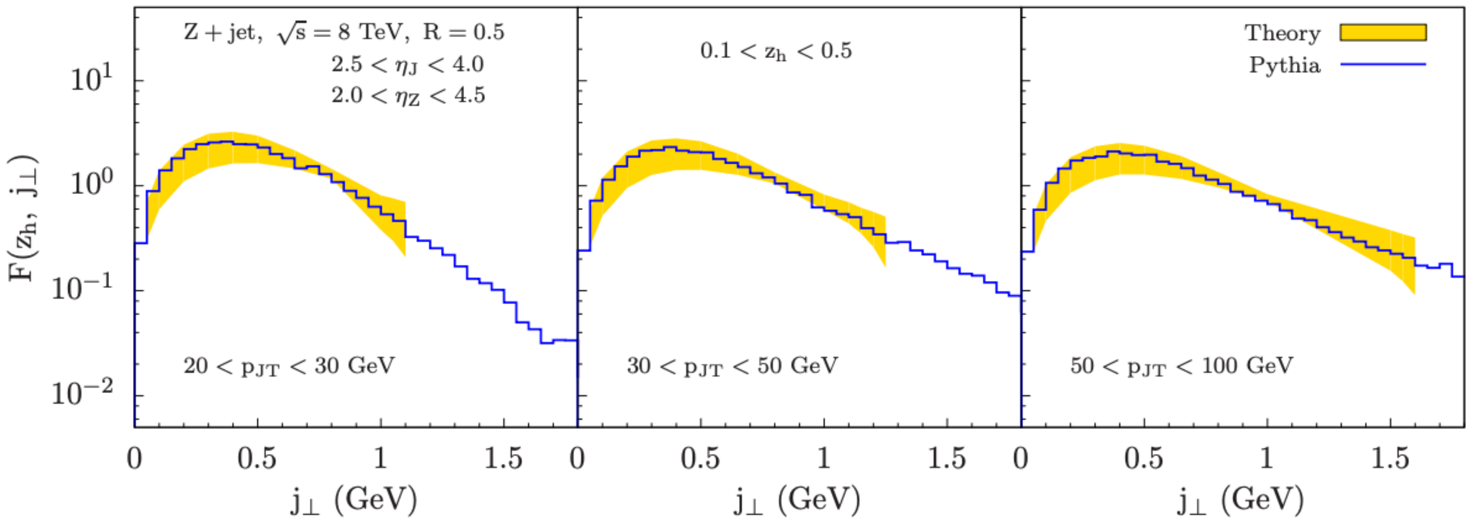
- **Hyperon polarization**
  - Measurement of Λ and $\overline{\Lambda}$ in *p*Pb, Pb*p*, and fixed-target *p*Ne data
  - Λ_c^+ polarization

- **LHCSpin:** polarized physics at LHC by adding a transversely polarized target

Back up

Kang, Lee, Terry, Xing PLB 798, 134978 (2019)

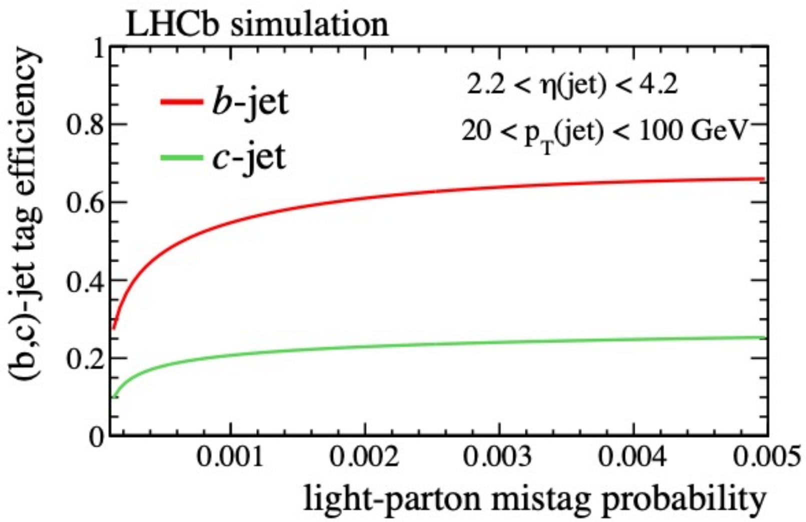




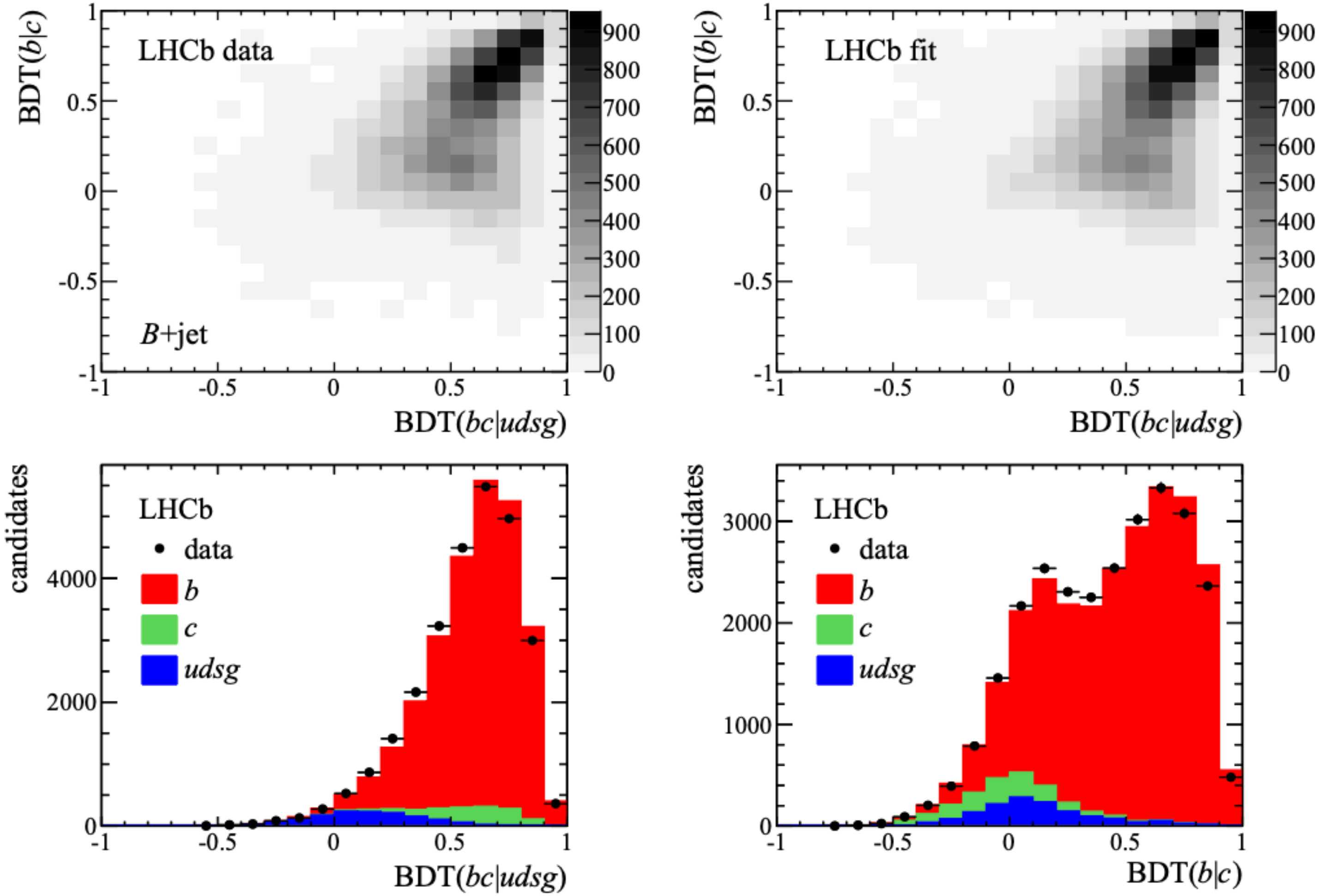
Heavy flavor jets

- Secondary Vertex tagging (SV-tagger) identifies SV within a jet, and uses boosted decision trees (BDTs) for flavor discrimination

Efficienty-mistagging performance



SV-tagger BDT results for the B+jet data



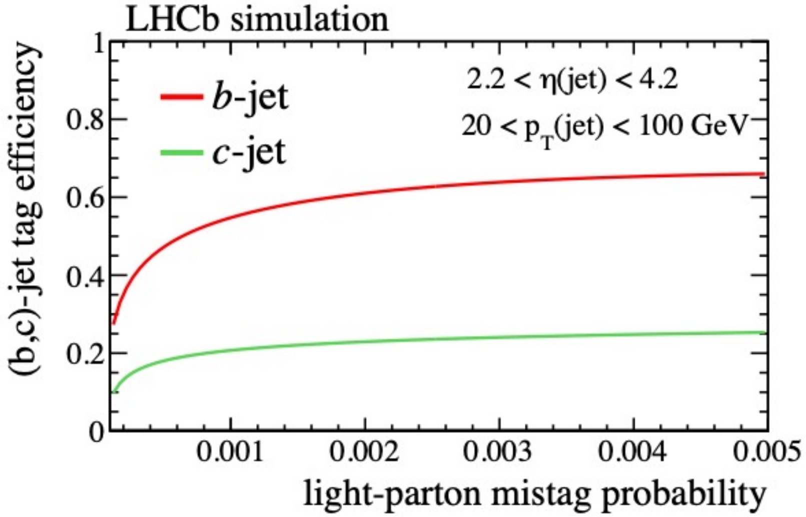
2015 JINST 10 P06013

Heavy flavor jets

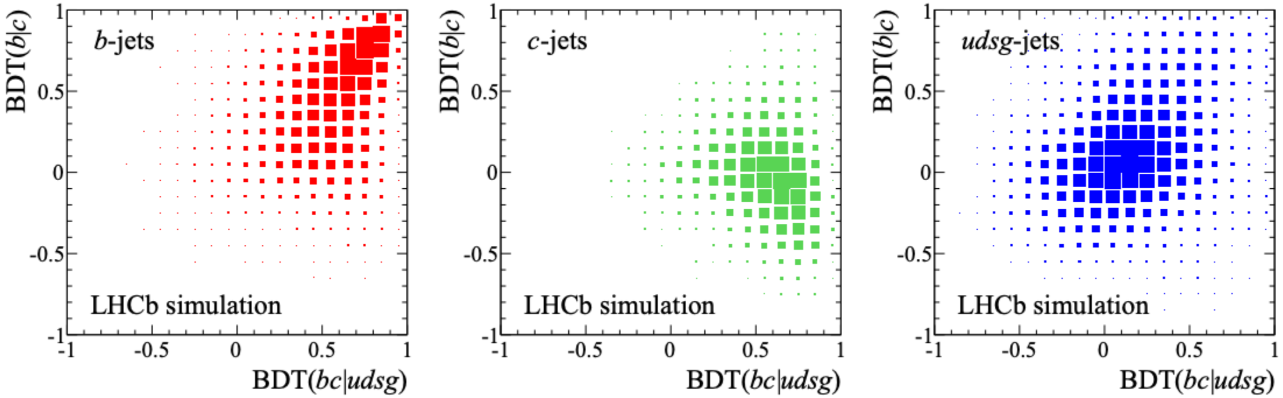
2015 JINST 10 P06013

- Secondary Vertex tagging (SV-tagger) identifies SV within a jet, and uses boosted decision trees (BDTs) for flavor discrimination

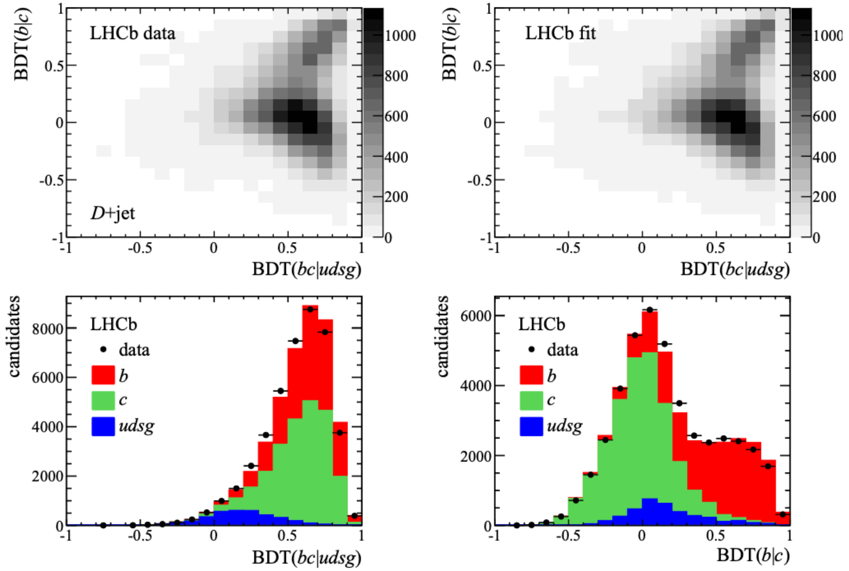
Efficienty-mistagging performance



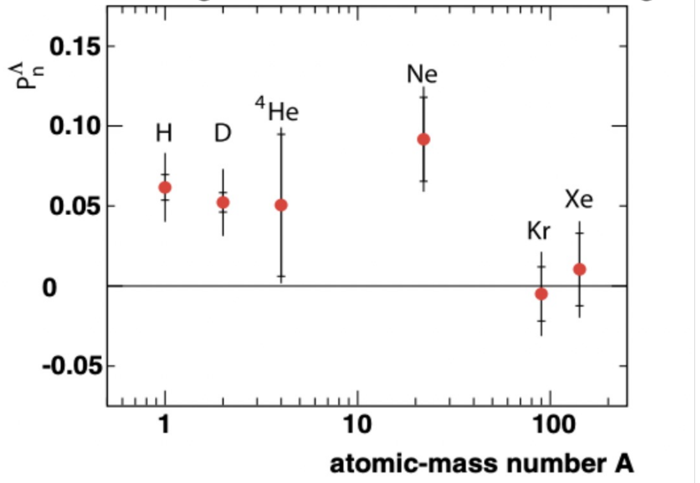
SV-tagger BDT simulation



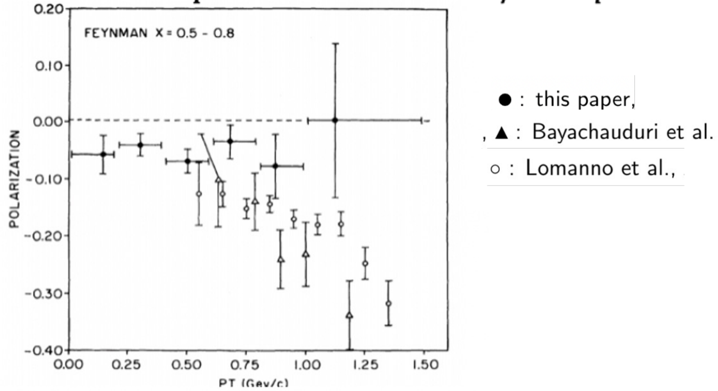
SV-tagger BDT results for $D + jet$



SIDIS using 27 GeV e^- beam on various target nuclei

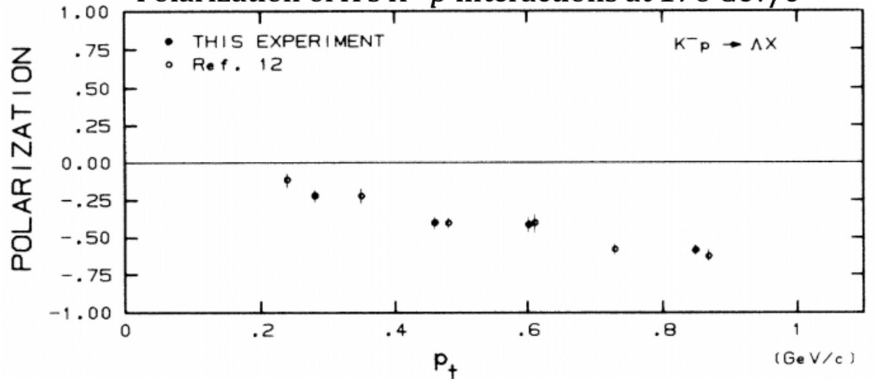


Inclusive Λ production and polarization in 16-GeV/c $\pi - p$ interactions



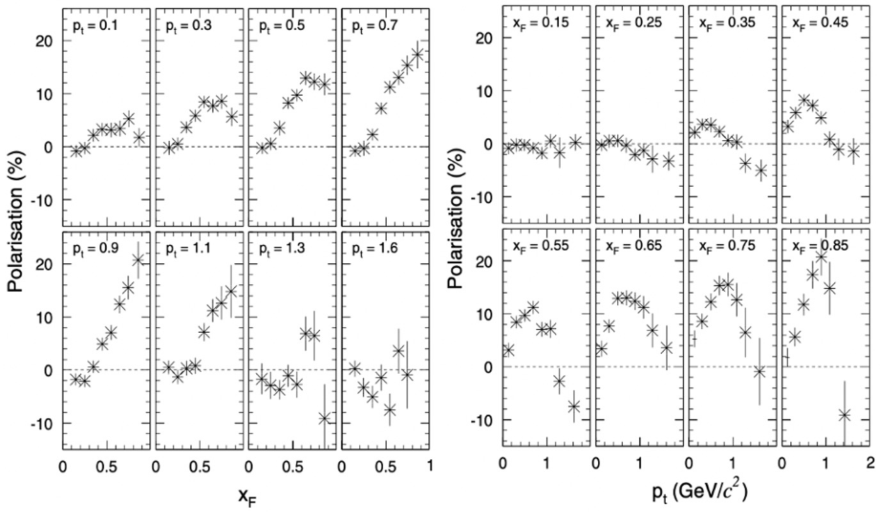
PRL50, 313 (1983)

Polarization of Λ's K^-p interactions at 176 Gev/c



PRL 56, 2244 (1986)

A measurement of Λ polarization in inclusive production by Σ^- of 340 GeV/c in C and Cu targets



EPJC 32, 221(2004)

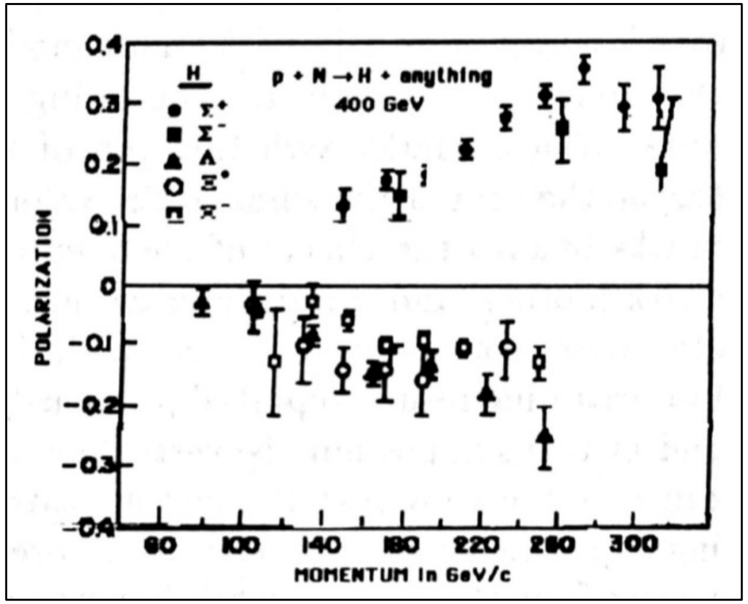
- SIDIS: Polarization positive in both forward and backward direction.
- For K^- and Σ^- beams the polarization was positive at positive x_F
- π^- beams the polarization was positive at negative x_F

Other not shown:

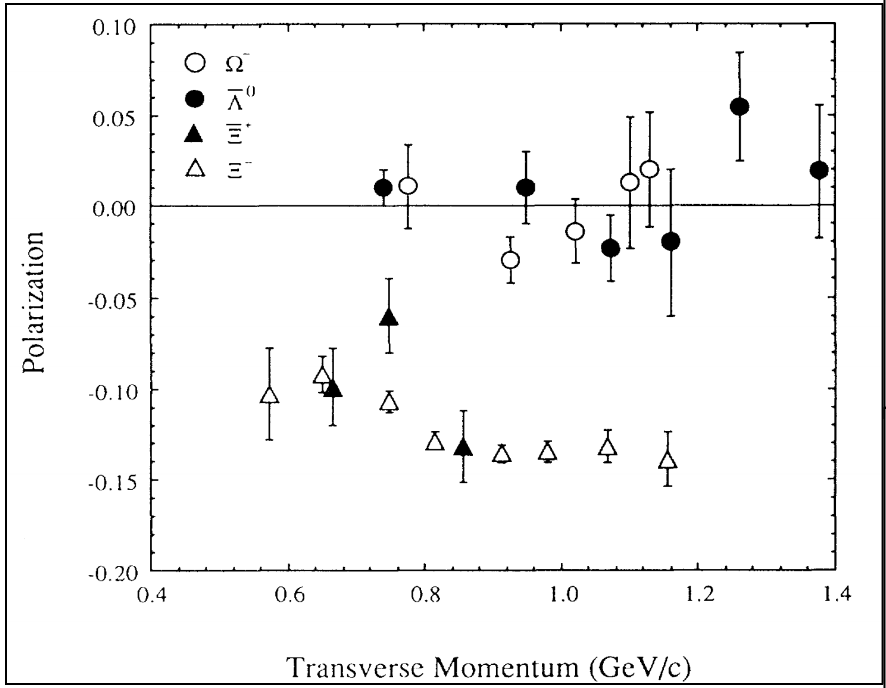
- The same polarization sign and general x_F dependence has been observed for neutron beams
- The polarization was measured to be consistent with zero for π^+ and K^+beams
- Polarization measured in $\nu_\mu N$ consistent with unpolarized pp experiments for both Λ and $\overline{\Lambda}$

Other hyperons

- **In unpolarized hadronic collisions:**
  - Negative polarization for Λ, Ξ^0, Ξ^-, and $\bar{\Xi}^-$
  - Positive polarization for $\Sigma^+, \Sigma^-, \Sigma^0$, and $\bar{\Sigma}^+$
  - Zero polarization $\Omega, \bar{\Lambda}$

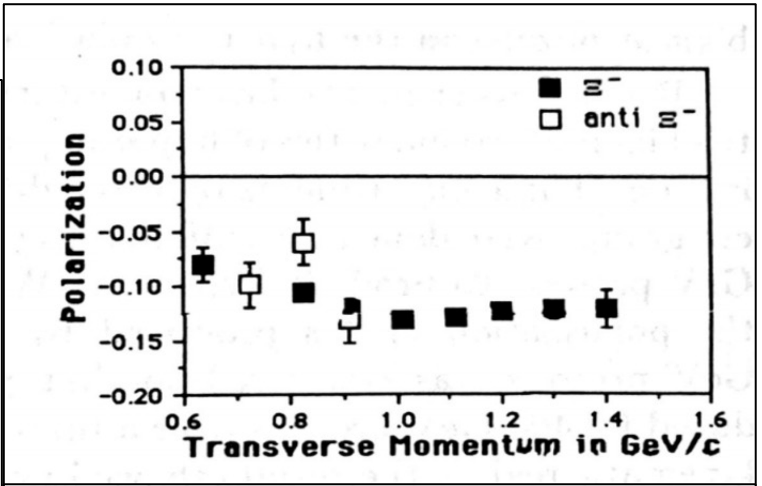


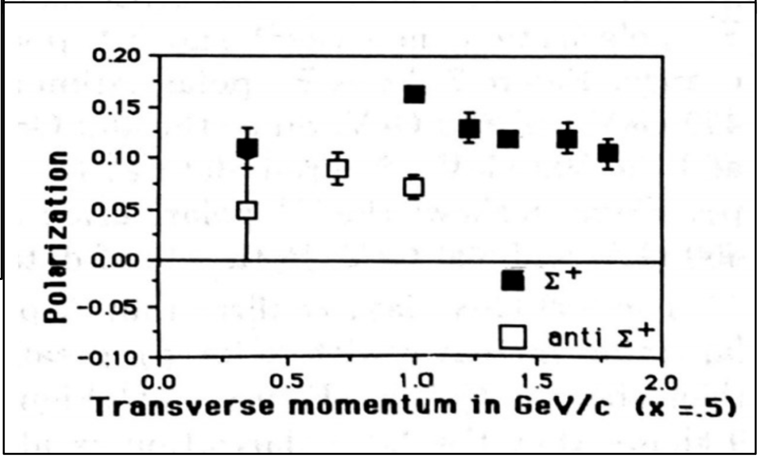
K. Heller, Proceedings, 12th International Symposium on Spin Physics, Amsterdam, 1996



K.B Luk, et al. PRL 70, 900 (1993)

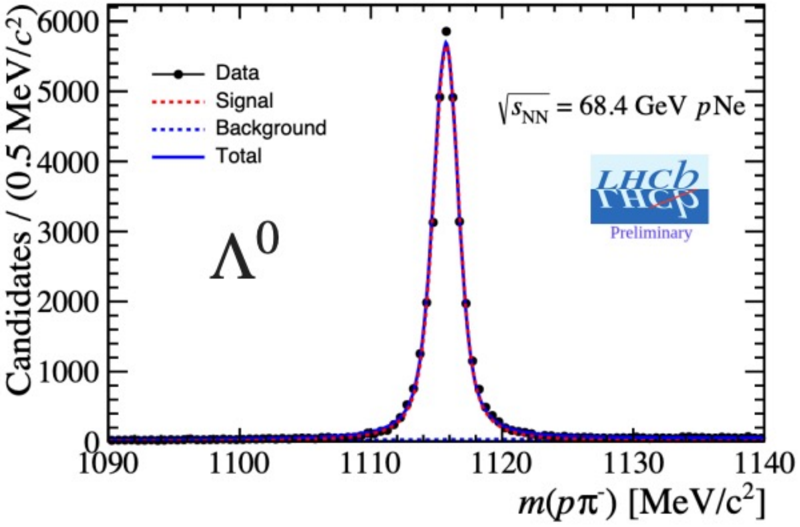
K. Heller, Proceedings, 12th International Symposium on Spin Physics, Amsterdam, 1996

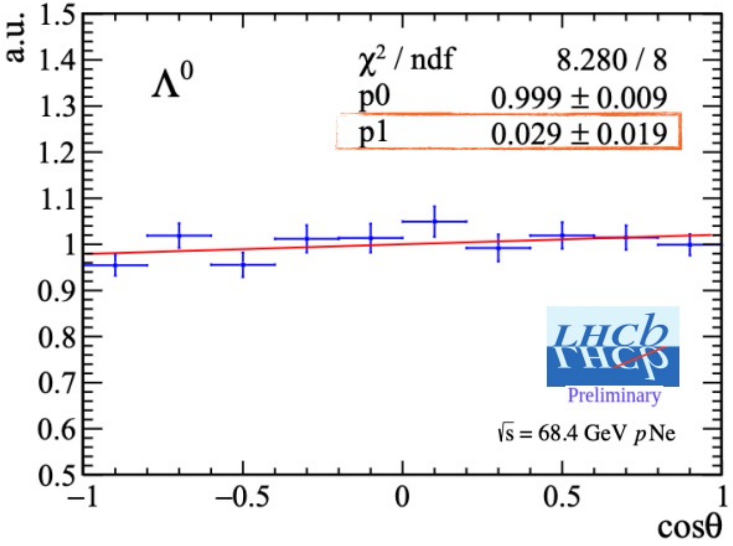


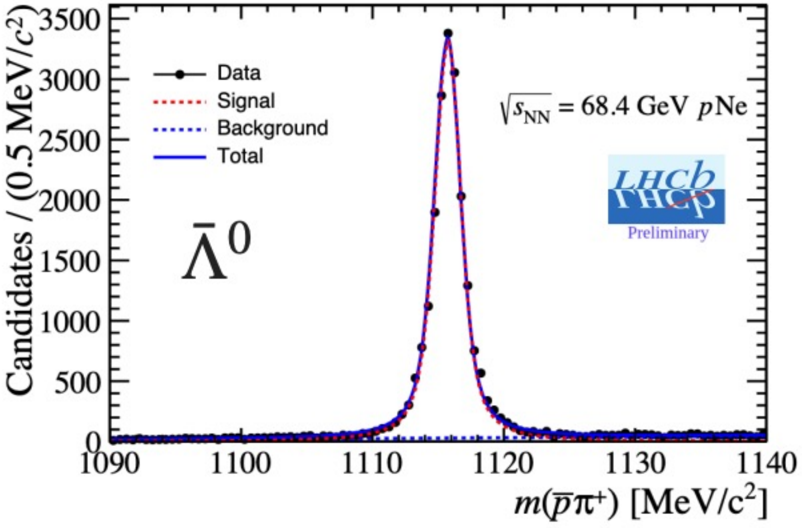


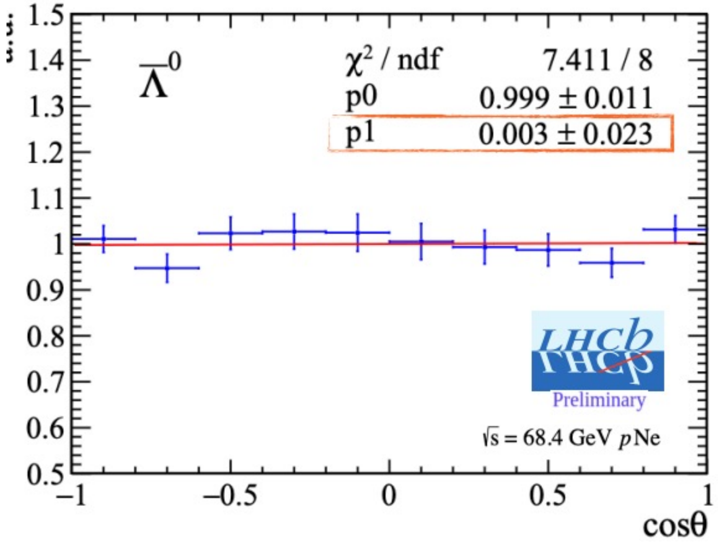
Why are some hyperons polarized while others are not?

pNe Λ and $\bar{\Lambda}$ transverse polarization









Systematic uncertainties

contribution	Λ	$\bar{\Lambda}$
signal estimation	0.007	0.001
background estimation	0.001	0.010
kinematical weights uncertainties	0.001	0.001
multiplicity dependence	0.001	0.004
binning of the $\cos\theta$ distributions	0.007	0.006
PID efficiencies	0.002	0.005
nonprompt contamination	0.005	0.002