Prospects of transverse hyperon polarization measurements at LHCb

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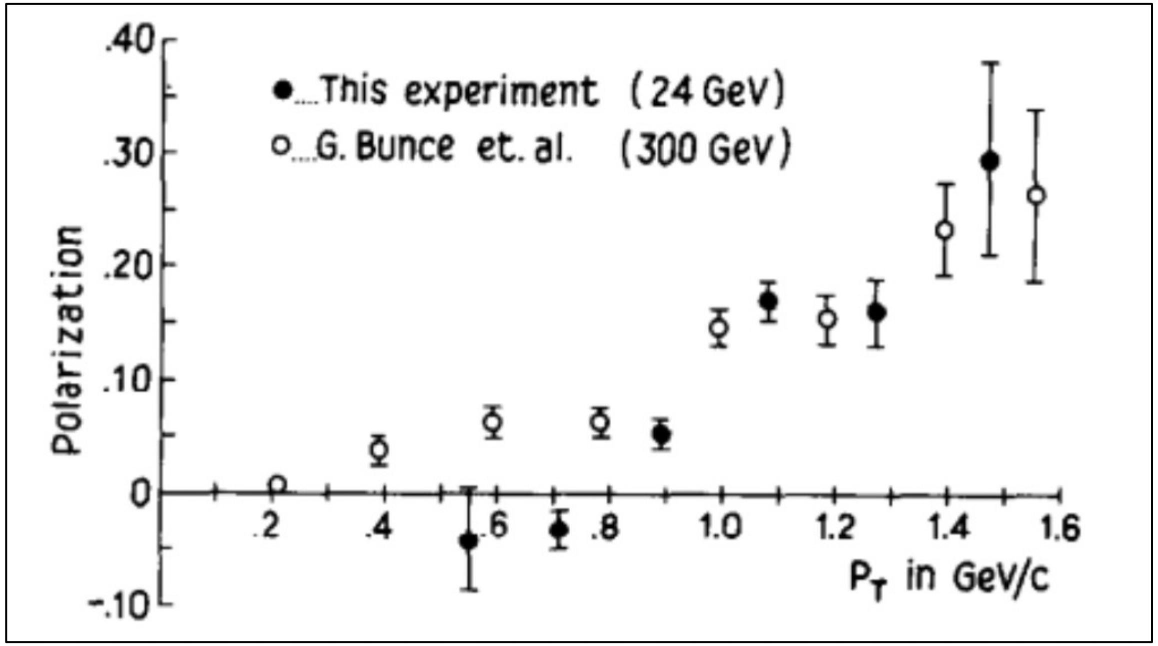
On behalf of the LHCb Collaboration

SPIN 2023

September 26, 2023

Λ (uds) polarization

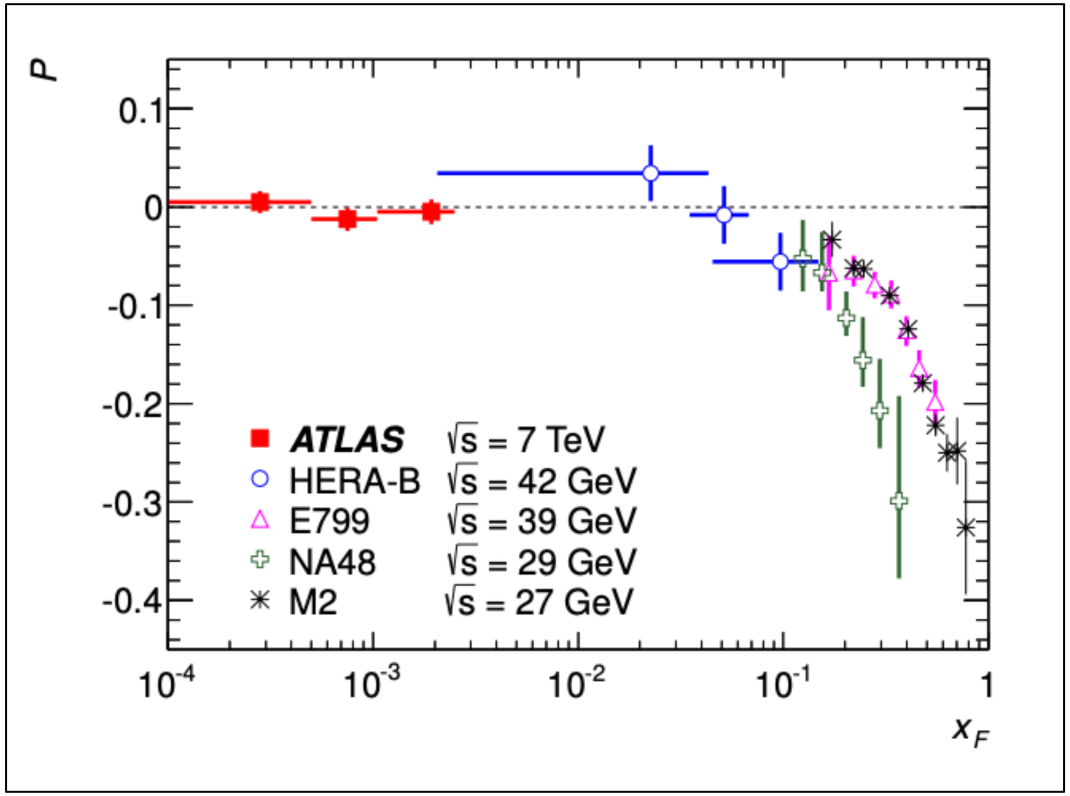
- Transverse Λ polarization was confirmed in 1976 at Fermilab in $p\mathrm{Be}$ using a 300 GeV beam and followed by various $p\mathrm{A}$ and pp experiments with polarization values to be up to 30%
- Leading order perturbative QCD calculations predicted very small polarization for light quarks and go to zero for increasing momentum transfer
- Must account for polarization due to non-perturbative QCD effects



G. Bunce, et al. PRL36, 1113 (1976)
K. Heller, et al. PLB68, 480 (1977)
G. L. Kane, J. Pumplin, and W. Repko PRL 41, 1689 (1978)

*sign convention different when compared to later measurements

Λ (uds) polarization



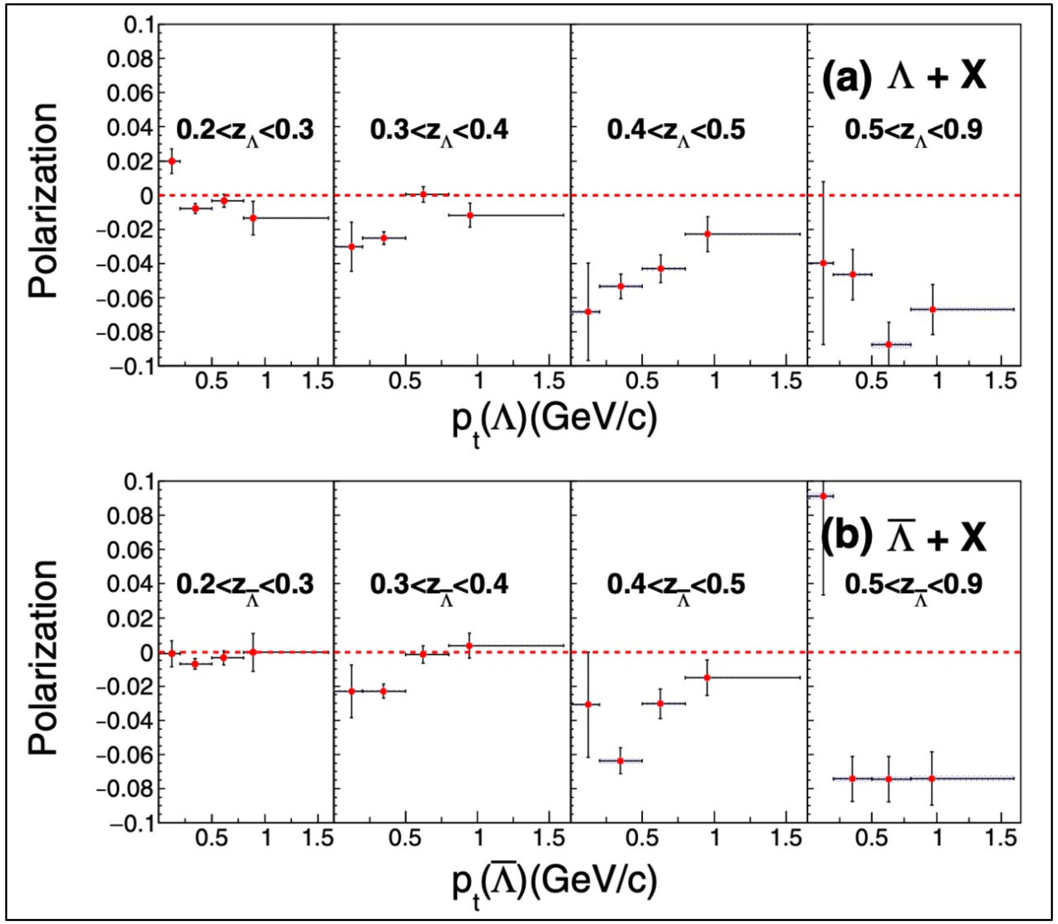
ATLAS Collaboration, PRD91, 032004 (2015)

- In 2015, ATLAS measured Λ and $\bar{\Lambda}$ polarization at low x_F

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

- Common features observed for Λ polarization
  - Transverse polarization of prompt Λ is found to be negative
  - Approximately independent of the beam energy
  - Increases with increasing $|x_F|$ and increasing p_T up to a few GeV range
- Polarization has been observed for beams other than proton including: $e^{\pm}$ on various target nuclei, $\pi^{\pm}, K^{\pm}, \Sigma^{-}, \nu N, n$

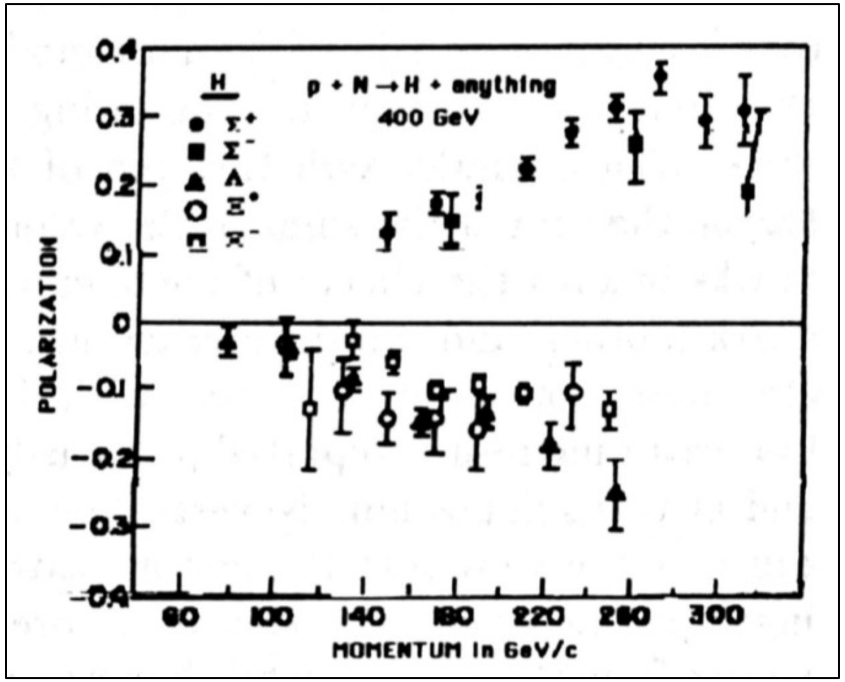
Λ and $\bar{\Lambda}$ polarization in e^+e^-



Belle Collaboration, PRL 122, 042001 (2019)

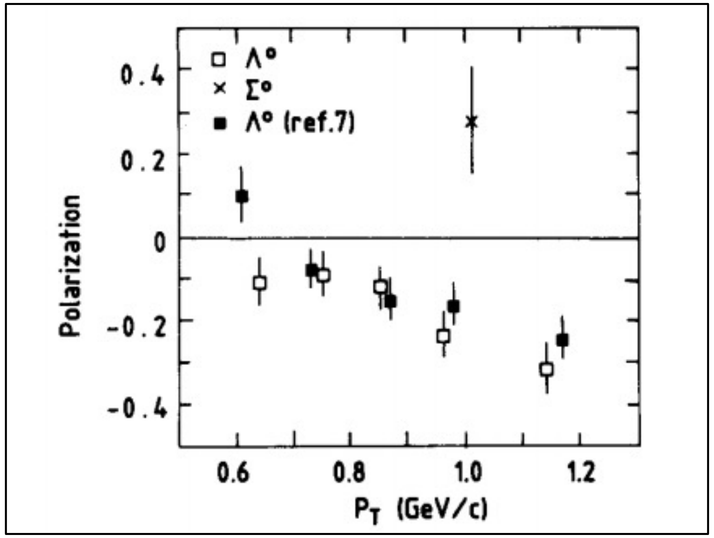
- In 2019, Λ and $\bar{\Lambda}$ polarization was observed in e^+e^- annihilation from Belle
- The polarization was observed to increase with the momentum fraction of the outgoing quark (anti-quark) carried by the hyperon, z
- Since there is no initial state hadron in e^+e^-, there must be a hadronization effect

Ξ^0 (uss), Ξ^-(dss), Σ^-(dds), and Σ^+(uus), Σ^0(uds) polarization

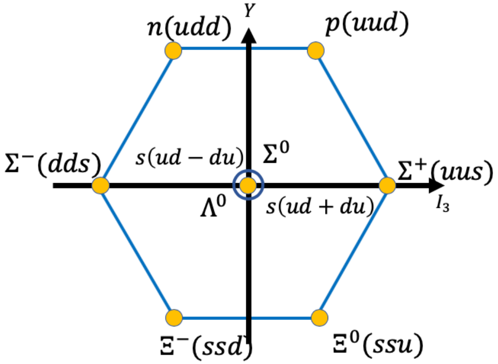


K. Heller, Proceedings, 12th International Symposium on Spin Physics, Amsterdam, 1996

- Negative polarization for Λ, Ξ^0, and Ξ^-
- Positive polarization for Σ^+ and Σ^-
- Σ^0 seems to have the same polarization as Σ^+ and Σ^- , and opposite polarization than Λ even though they have the same valence quarks (uds)

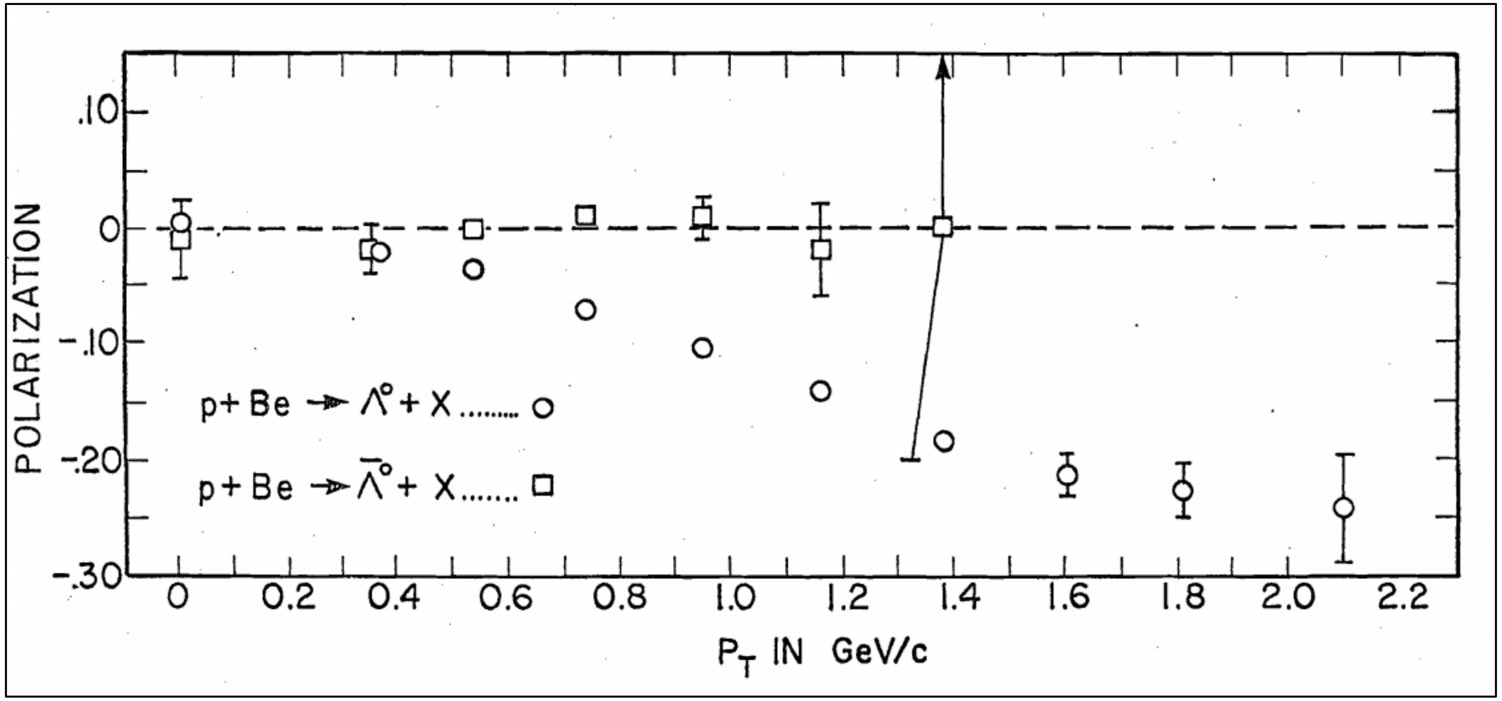


E. C. Dukes, et al. PLB193, 135 (1987)

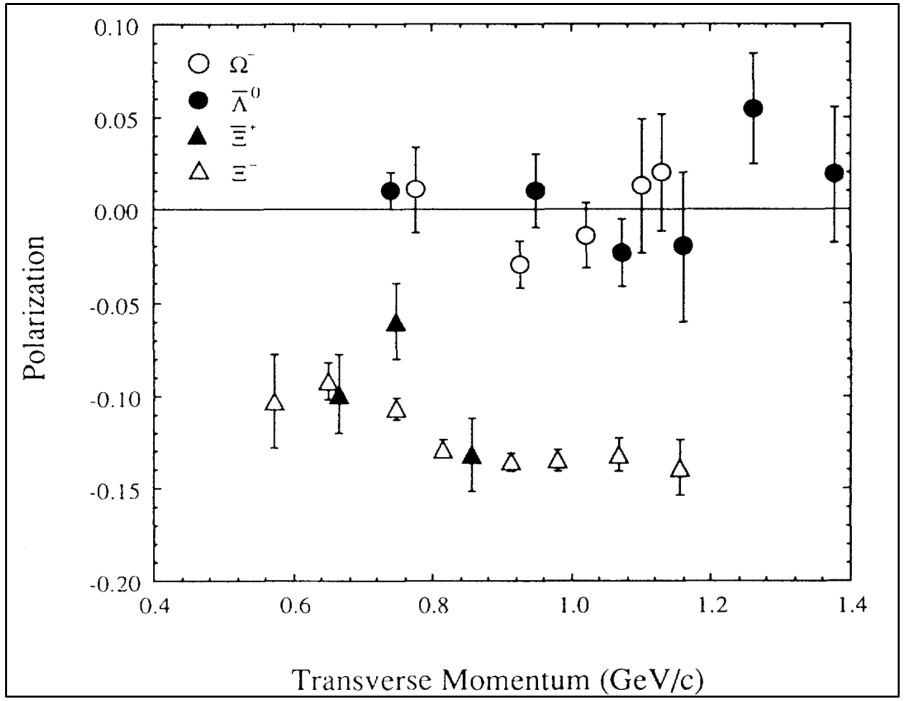


$\bar{\Lambda}$ ($\bar{u}\bar{d}\bar{s}$), Ω (sss) polarization

- No observed $\bar{\Lambda}$ or Ω polarization



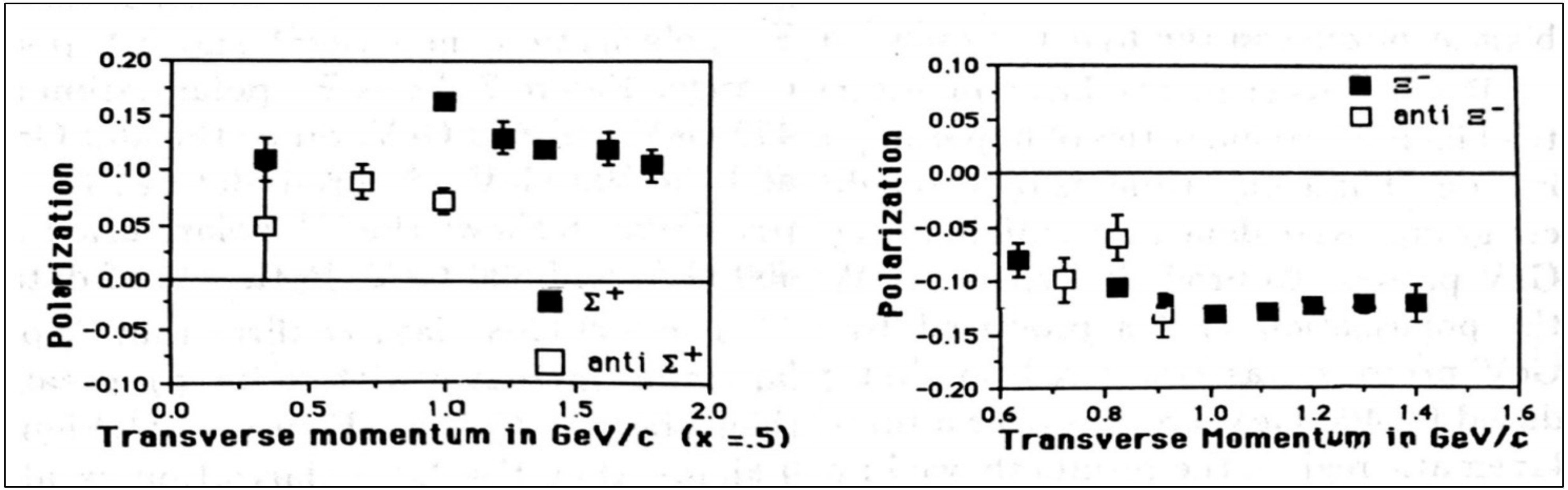
K. Heller, et al. PRL41, 607 (1978)



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

$\bar{\Sigma}^+$ $(\bar{d}\bar{s}\bar{s})$ and $\bar{\Xi}^-$ $(\bar{u}\bar{s}\bar{s})$ polarization

- $\bar{\Sigma}^+$ and Σ^+ both have positive non-zero polarization
- $\bar{\Xi}^-$ and Ξ^- both have negative non-zero polarization



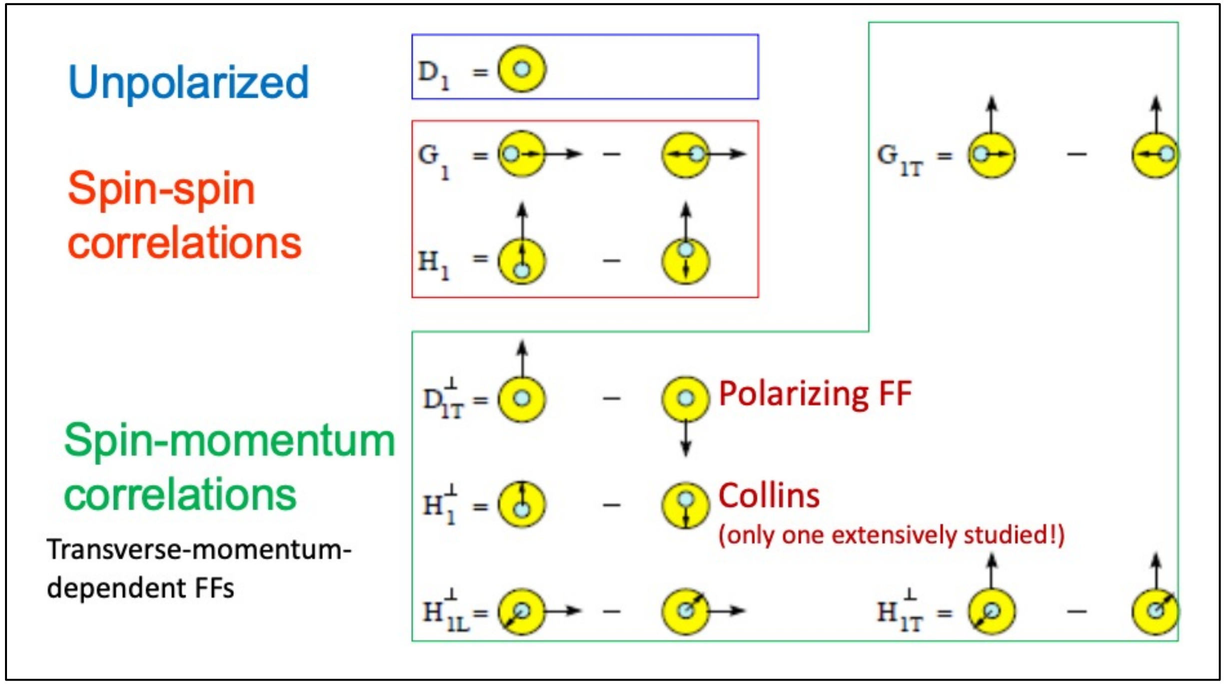
K. Heller, Proceedings, 12th International Symposium on Spin Physics, Amsterdam, 1996

Why are some hyperons polarized while others are not?

Frameworks to explain Λ polarization

Phenomenological approach in explaining transverse Λ polarization in unpolarized collisions has focused on:

- **Polarizing transverse-momentum dependent (TMD) fragmentation functions (FF): $D_{1T}^{\perp\Lambda/q}(z, k_\perp^2)$**
    - Fragmentation counterpart of the Sivers TMD PDF
    - Polarization from convolution of a twist-2 TMD PDF with a twist-2 TMD FF
- **Higher twist multiparton correlators**
    - Higher twist effects alternatively provide sensitivity to spin-momentum correlations in hadron structure and formation



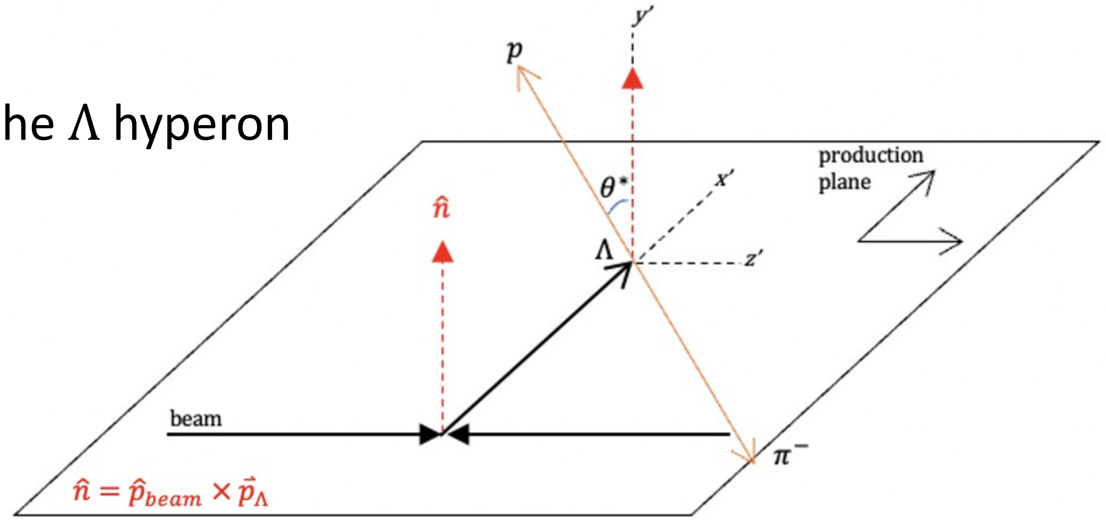
M. Anselmino, D. Boer, U. D'Alesio, and F. Murgia PRD 63, 054029 (2001)
Yuji Koike, et al. PRD 95, 114013 (2017)

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:

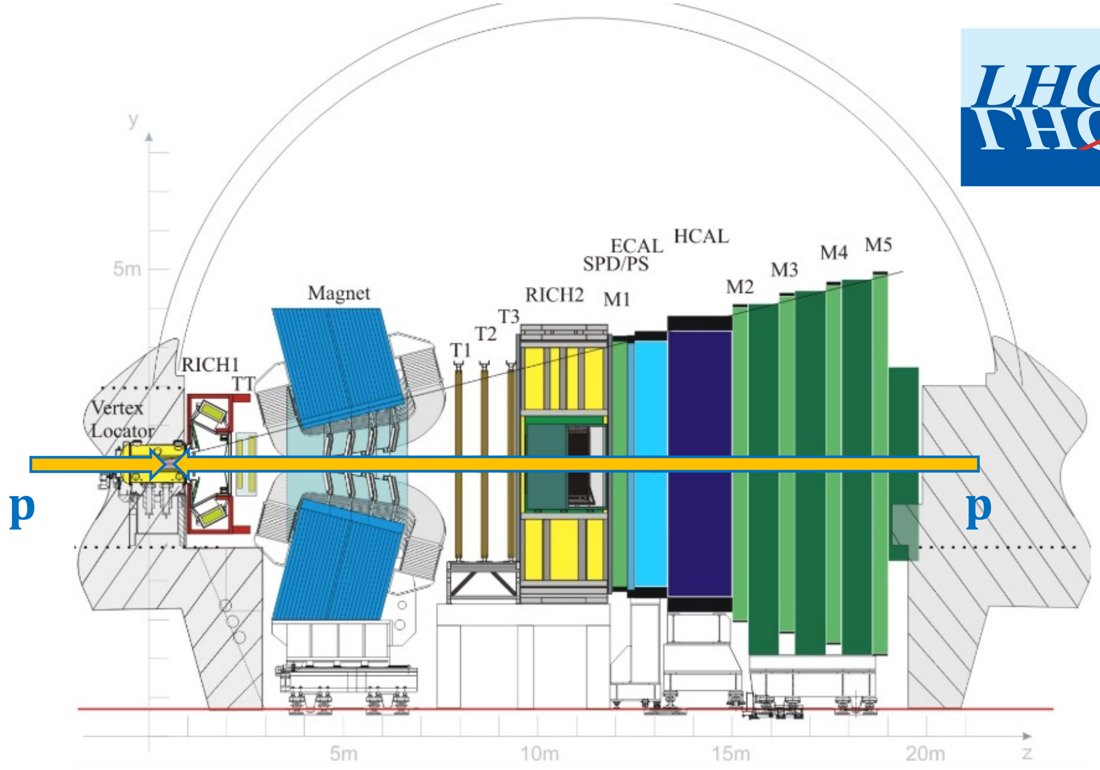
$$\frac{dN}{d\cos\theta^*} = \frac{N}{2}(1 + \alpha_\Lambda P\cos\theta^*)\varepsilon_{tot}(\cos\theta^*)$$

$\alpha_\Lambda = 0.732 \pm 0.014$ [PDG 2022]



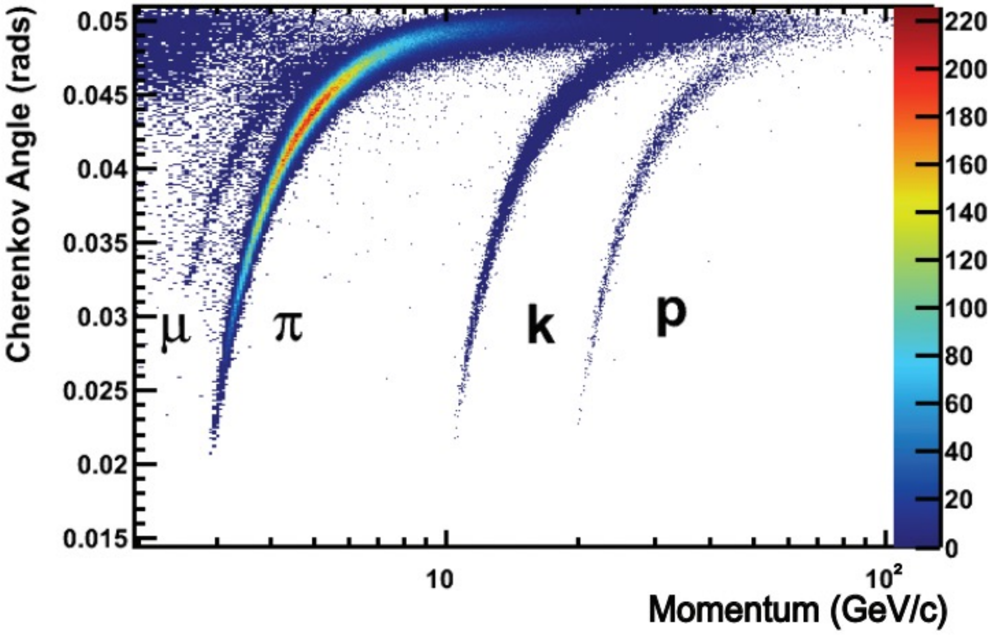
- Forward spectrometer with precision tracking and particle identification
- Designed to search for CP violation and rare decays of b and c hadrons
- Pseudorapidity coverage $2 < \eta < 5$

OPEN-PHO-ACCEL-2017-005-1

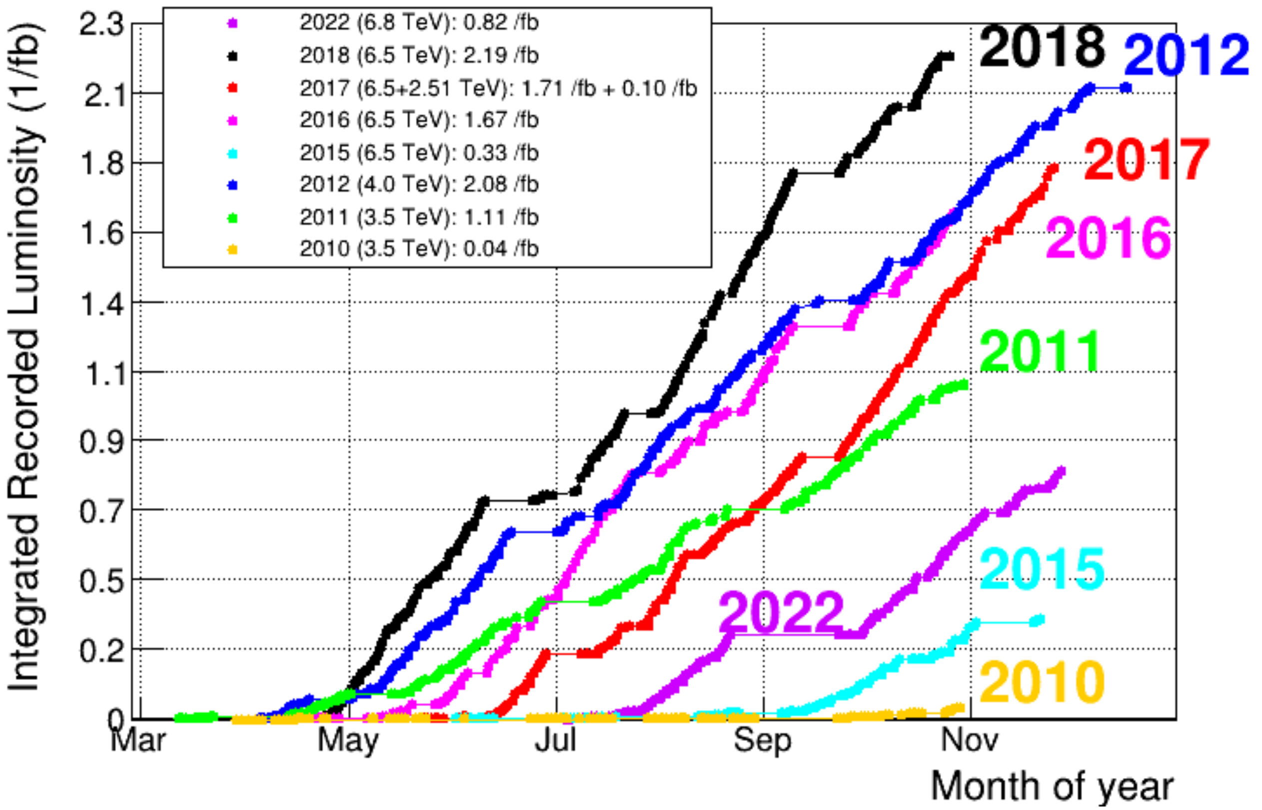


2008 JINST 3 S08005

- Particle identification optimal for μ, π, K, and p
- Various data sets available at different energies for pp

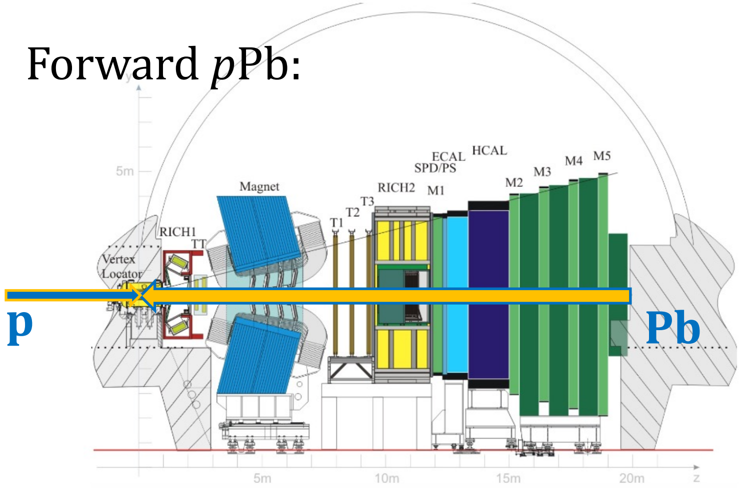


Int. J. Mod. Phys. A 30, 1530022 (2015)

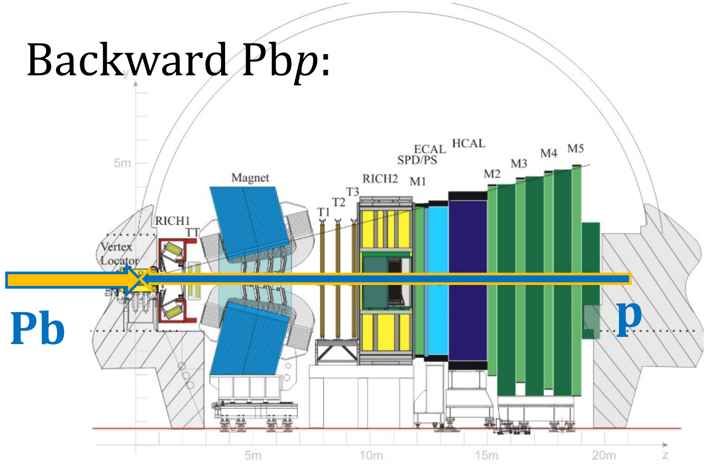


Collider data: *p*Pb and Pb*p*

Forward *p*Pb:



Backward Pb*p*:



- Access to higher $|\mathrm{x_F}|$ Λ and $\overline{\Lambda}$
- Proton-lead data taken in two different collision configurations with different rapidity coverages

Forward:	$1.5 < y^* < 4.0$
Backward:	$-5.0 < y^* < -2.5$
2013 Data:	$\sqrt{s_{NN}} = 5.02$ TeV
2016 Data:	$\sqrt{s_{NN}} = 8.2$ TeV

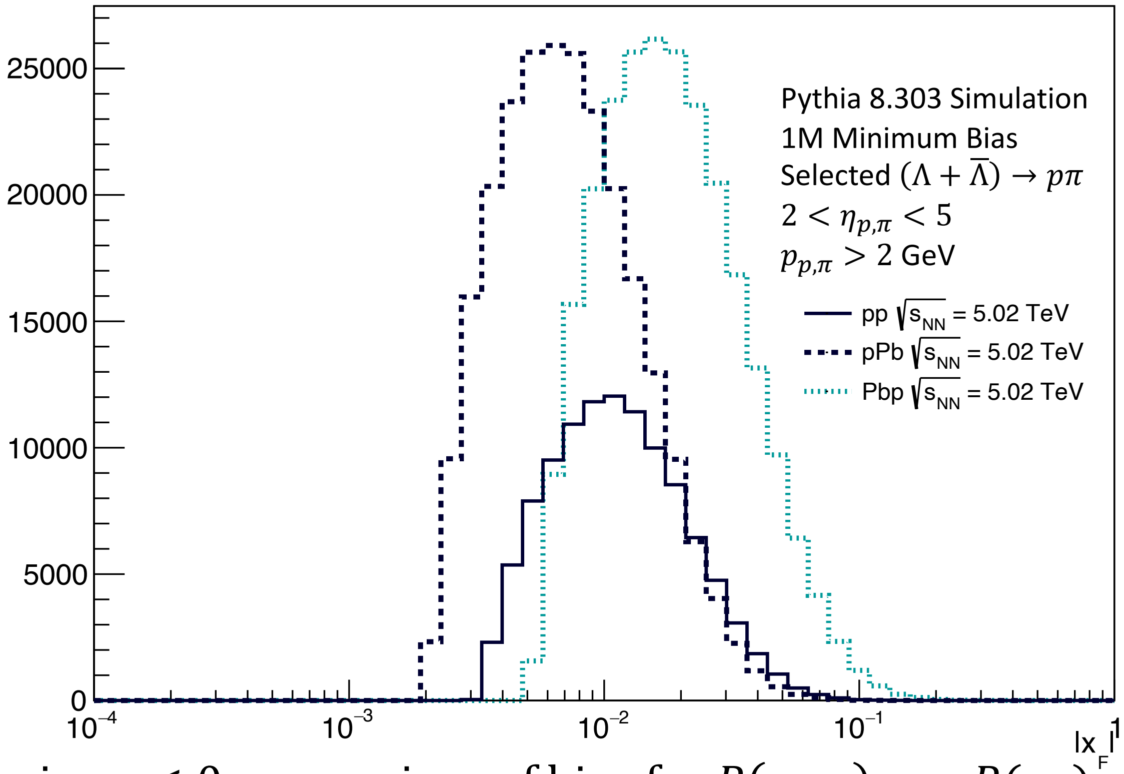
$$x_F = \frac{p_L^*}{|\max(p_L^*)|} \sim \frac{2}{\sqrt{s_{NN}}} \sqrt{M^2 + p_T^2} \sinh(y^*)$$

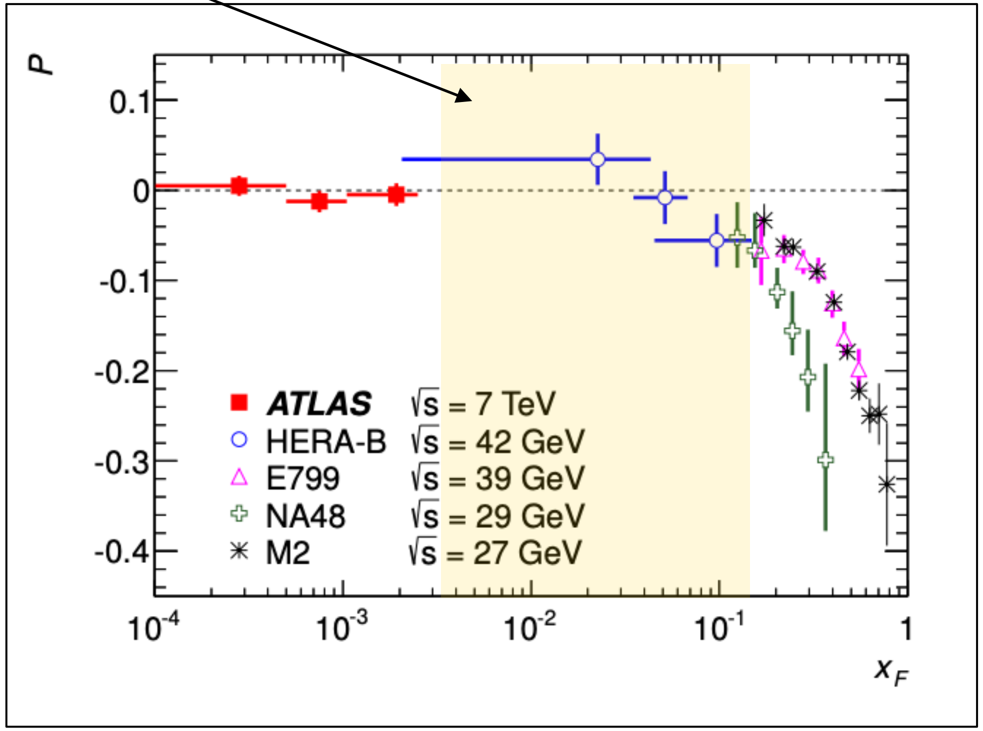
Kinematic Reach: *pp*, *p*Pb data

LHCb x_F kinematic reach overlap with HERA-B pC and pW collisions

0.6 GeV/c $< p_T <$ 1.2 GeV/c, $-0.15 < x_F < 0.01$

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



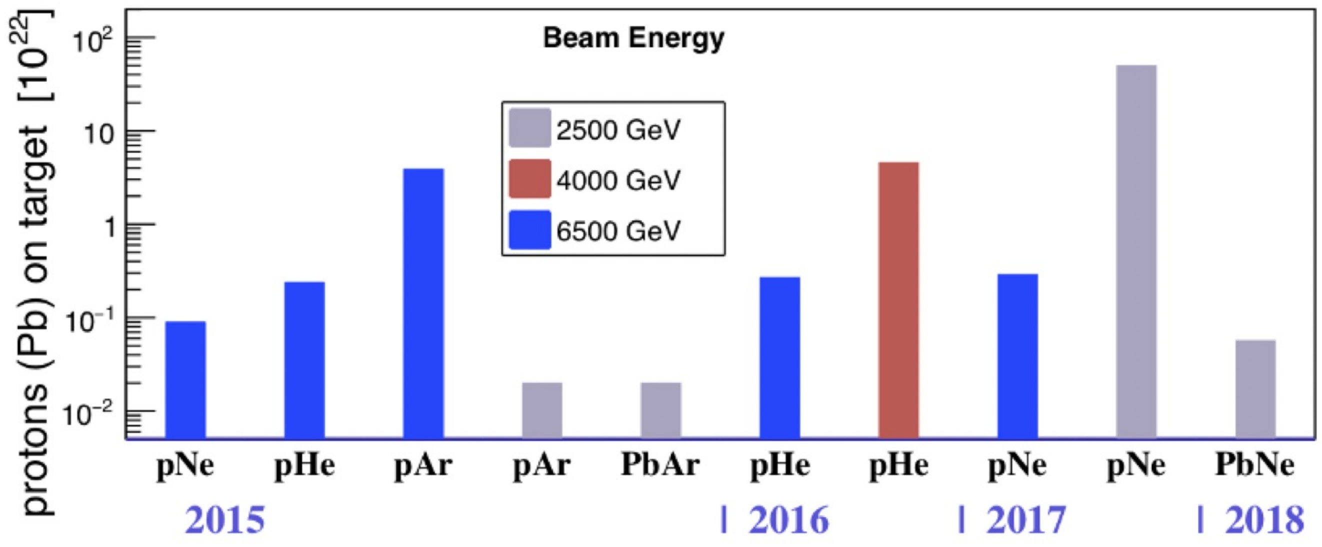


Pbp data is $x_F < 0$, comparison of bins for $P(-x_F) = -P(x_F)$

ATLAS Collaboration, PRD91, 032004 (2015)

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

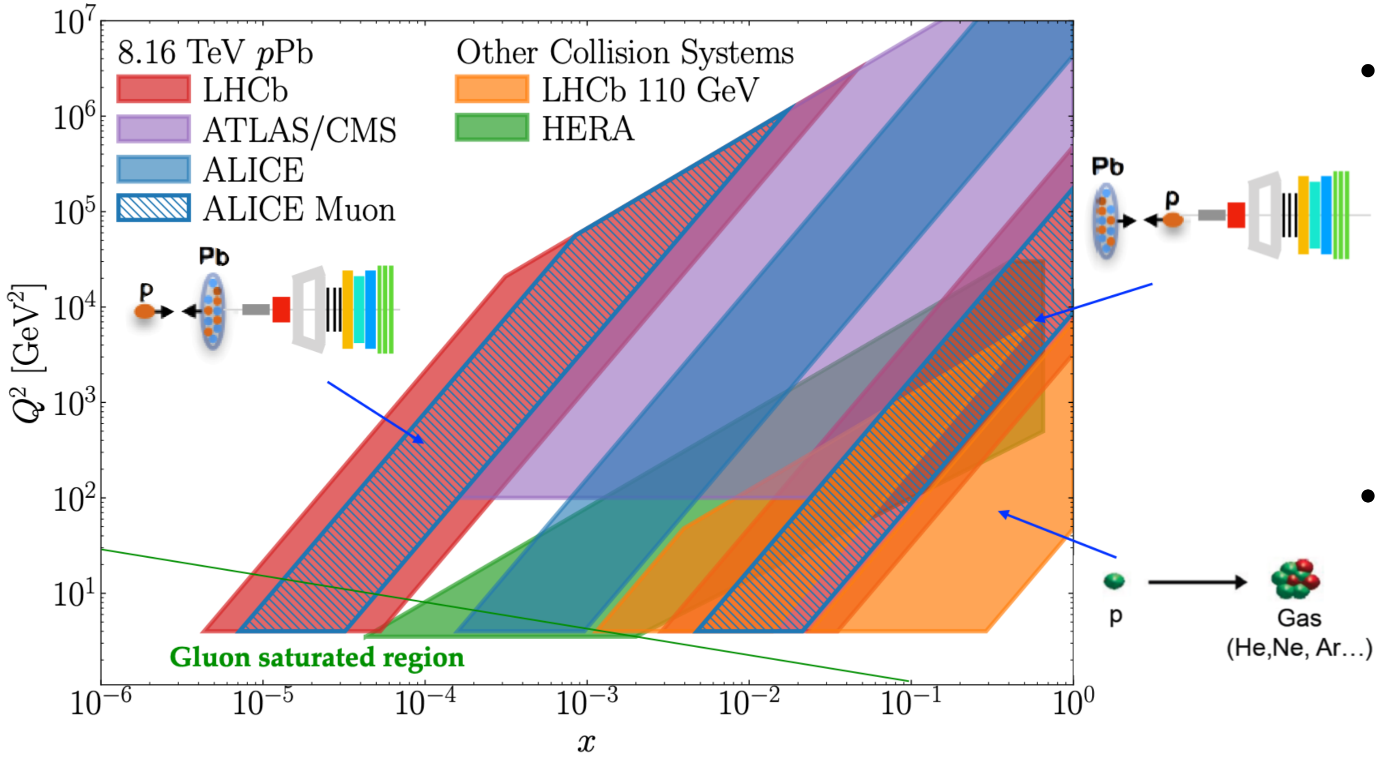
- Unique to LHCb is the ability to collect fixed-target data
- Originally for luminosity calibration of colliding proton beams
- Injection of noble gas (He, Ne, Ar) into the Vertex Locator while one of the circulating beams produces beam-gas collisions



LHCb-PUB-2018-015

SMOG Kinematic Coverage

- For $E_{beam} = 0.9 - 6.5$ TeV
  - Center of mass energy per nucleon-nucleon collision: $\sqrt{s_{NN}} \sim \sqrt{2E_N M_N} \sim 41 - 110$ GeV
  - Central and backward rapidity : $y^* \sim \text{arcsinh}\sqrt{E_N/2(M_N)} \sim 3.8 - 4.8$



- Allow observation of particles with large $|x_F|$:

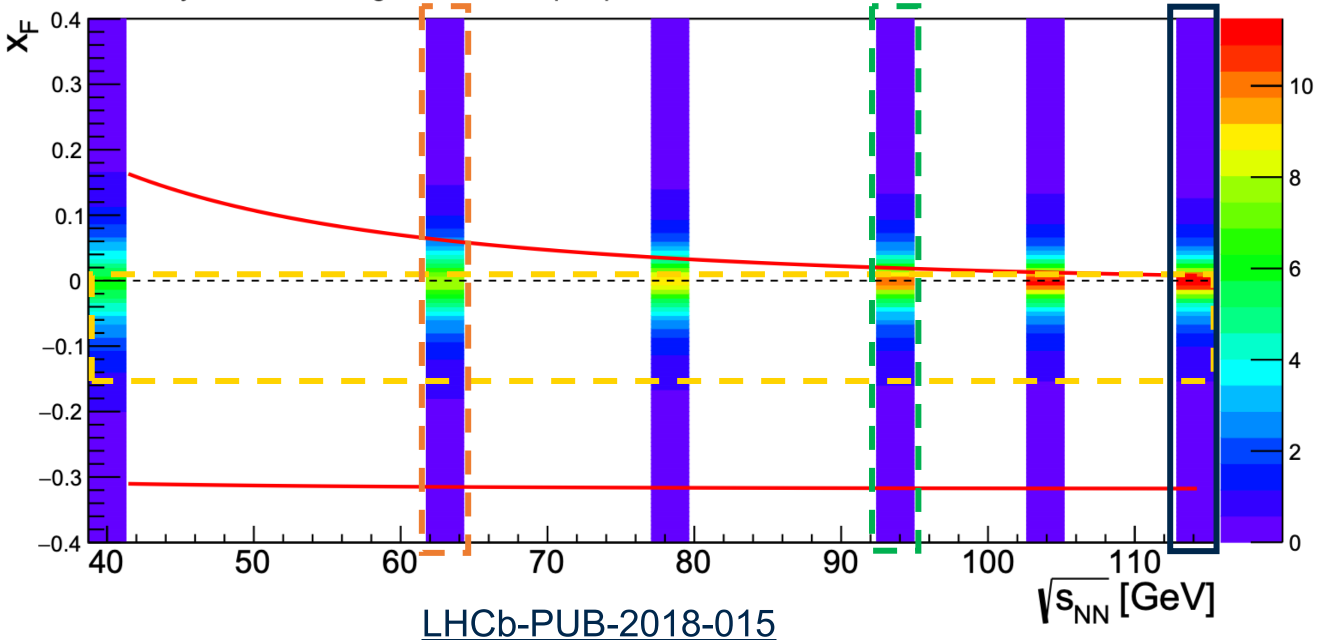
$$x_F = \frac{p_L^*}{|\max(p_L^*)|} \sim \frac{2}{\sqrt{s_{NN}}}\sqrt{M^2 + p_T^2}\sinh(y^*)$$

$$\rightarrow x_F < 0$$

- Relating x_F to x for two colliding partons as $x_F \sim x_1 - x_2$ then large negative x_F corresponds to large x in target nucleon

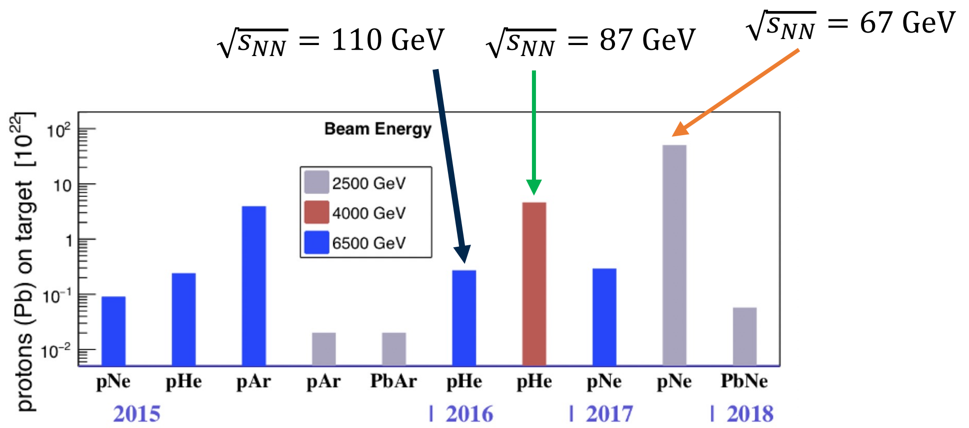
SMOG Kinematic Coverage

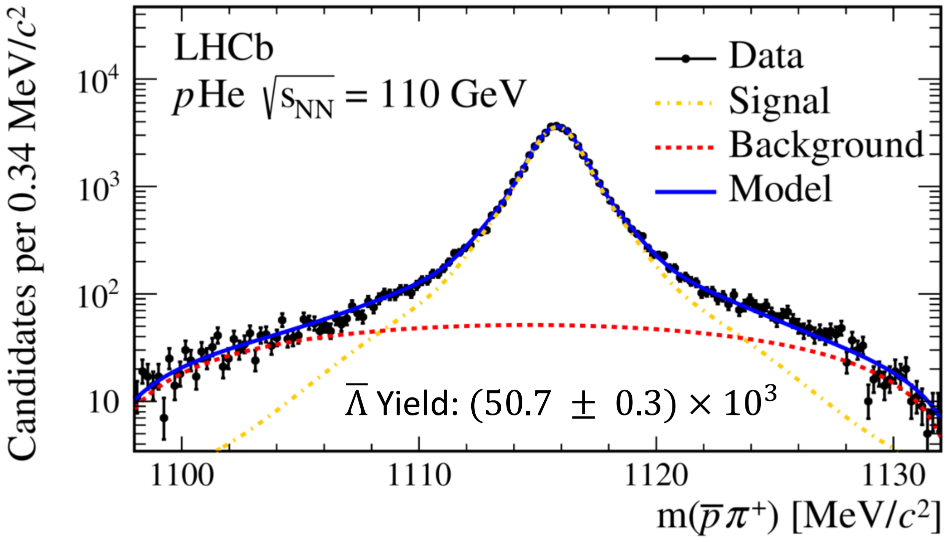
- Expected x_F reach for $\bar{p}$ with $12 < p < 110$ GeV



LHCb-PUB-2018-015

Compare with HERA-B : $-0.15 < x_F < 0.01$

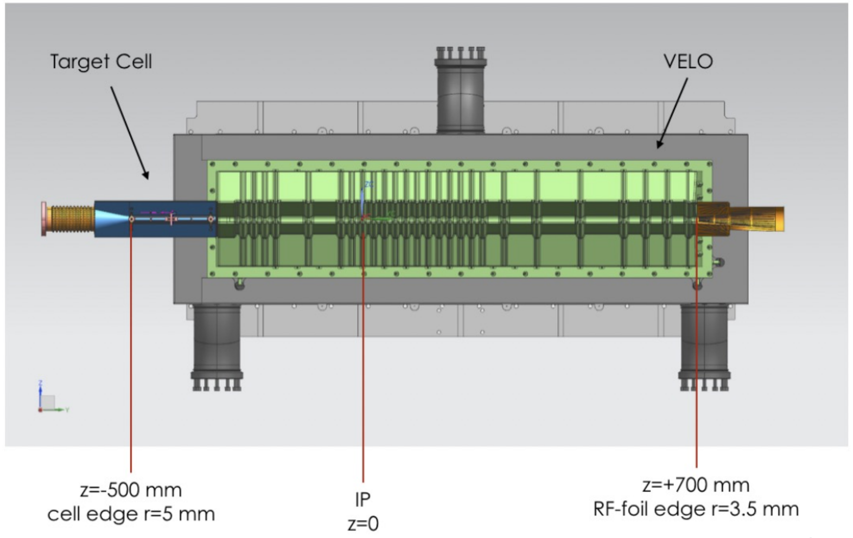


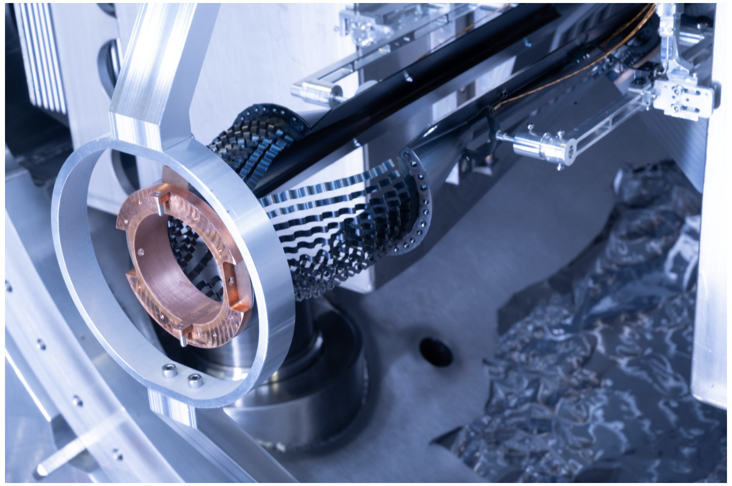


LHCb Collaboration, arXiV: 2205.09009

Run 3 upgrade: SMOG2

- Addition of target storage cell installed for Run 3, which allows for an increased gas pressure
- Higher luminosity measurements than SMOG
- Located before the Vertex Locator with well-defined separation from the *pp* interaction point
- Wider variety of target species: He, Ne, Ar, + New: $\mathrm{Kr}, \mathrm{Xe}, \mathrm{H}_2\ \mathrm{D}_2, \mathrm{N}_2, \mathrm{O}_2$



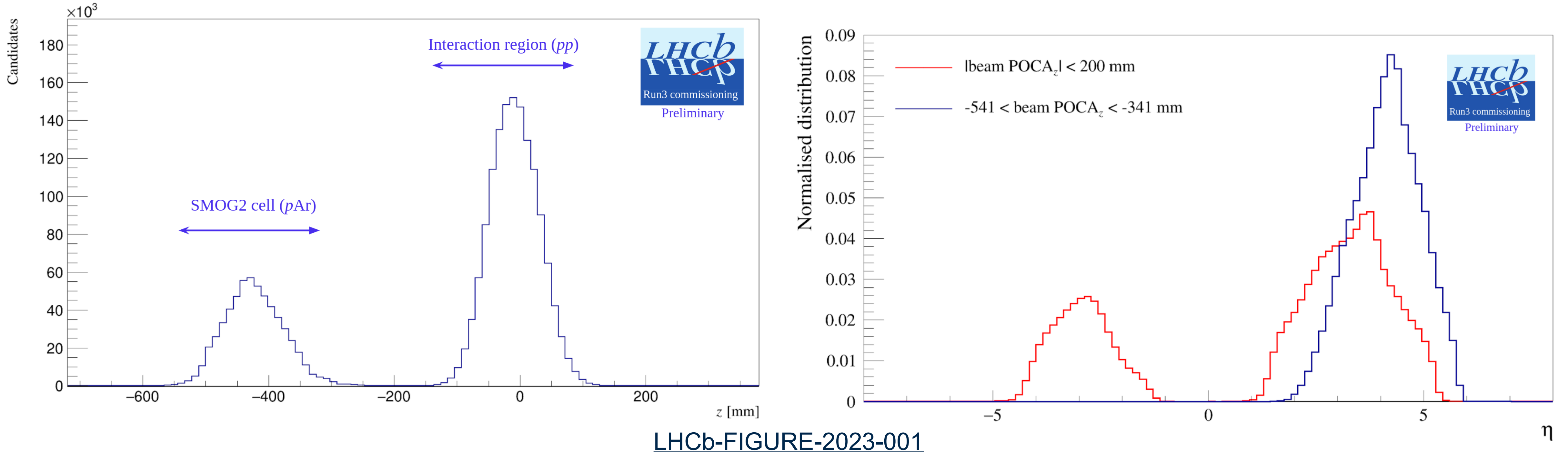


LHCB-TDR-020

Run 3 upgrade: SMOG2

- Run 3 preliminary data shows a good separation between SMOG2 (*p*Ar) and *pp* vertices
- The pseudorapidity distribution shows reconstructed tracks in the Vertex Locator being more symmetric for *pp* collisions and more forward for *p*Ar collisions

Run 3 data

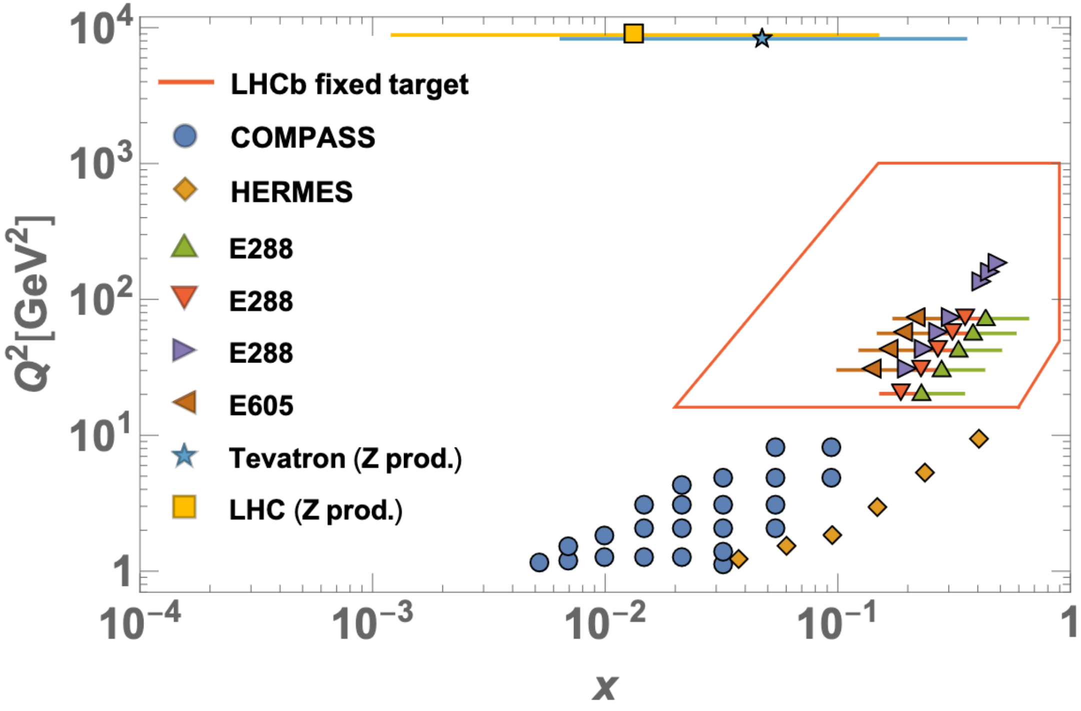


LHCb-FIGURE-2023-001

LHCSpin Project

Pasquale Di Nezza
Friday, Sep 29 3PM

- Supported R&D to add a transversely polarized target by 2029
- Polarized physics at the LHC by installing a polarized target in the target storage cell
  - 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



LHCb Collaboration, arXiv:1901.08002

Measurement of other hyperons

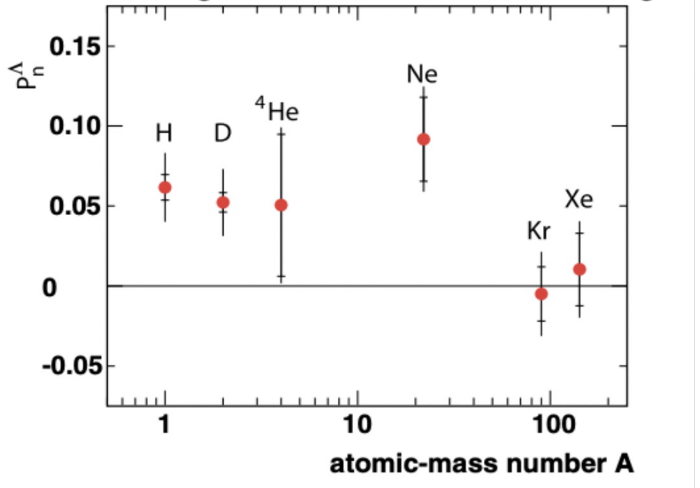
Particle	Makeup	Common Decay Mode	Branching Ratio
$\boldsymbol{\Lambda^0}$	**uds**	$\boldsymbol{p + \pi^-}$	$\mathbf{63.9 \pm 0.5\%}$
		$n + \pi^0$	$35.8 \pm 0.5\%$
Σ^+	uus	$p + \pi^0$	$51.57 \pm 0.3\%$
		$n + \pi^+$	$48.31 \pm 0.3\%$
Σ^0	uds	$\Lambda^0 + \gamma$	100%
Σ^-	dds	$n + \pi^-$	$99.848 \pm 0.005\%$
Ξ^0	uss	$\Lambda^0 + \pi^0$	$99.522 \pm 0.032\%$
$\boldsymbol{\Xi^-}$	**dss**	$\boldsymbol{\Lambda^0 + \pi^-}$	$\mathbf{99.887 \pm 0.035\%}$
$\boldsymbol{\Omega^-}$	**sss**	$\boldsymbol{\Lambda^0 + K^-}$	$\mathbf{67.8 \pm 0.7\%}$
		$\Xi^0 + \pi^-$	$23.6 \pm 0.7\%$
		$\Xi^- + \pi^0$	$8.6 \pm 0.7\%$

PDG 2022

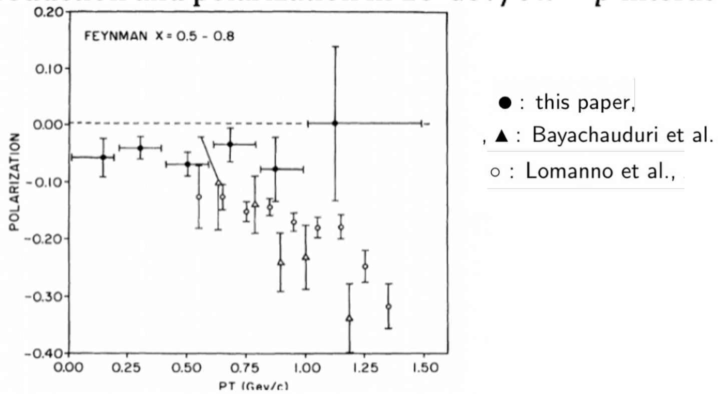
Summary

- Transverse Λ polarization was first observed over 40 years ago with values up to 30% and has been linked to the process of hadronization
- The high energy from the LHC and coverage from LHCb's forward geometry will be interesting to study transverse hyperon polarization at different energies and collision configurations
- Ability to perform comprehensive measurements of the polarization of Λ and $\overline{\Lambda}$ as a function of p_T and x_F using the LHCb detector in a kinematic area that has been poorly explored
- LHCb measurements, along with e^+e^- and SIDIS measurements, can put us in a better position to understand transverse hyperon polarization

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

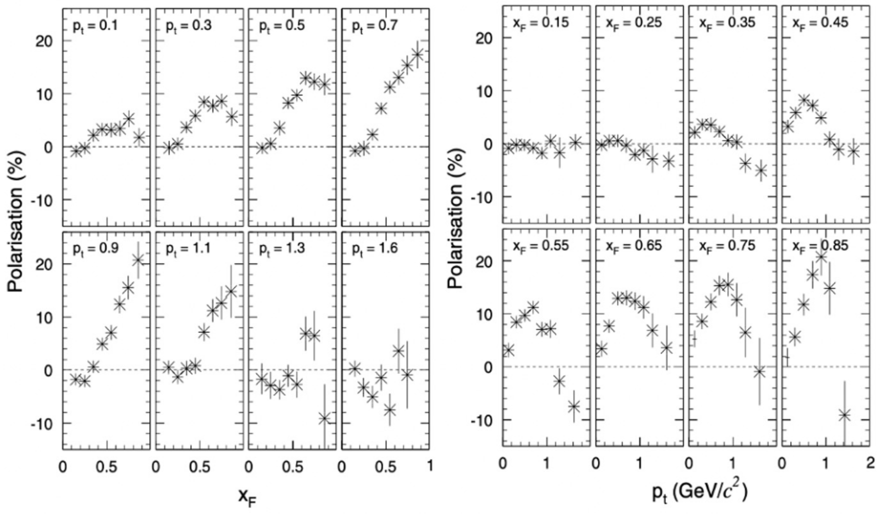


Inclusive Λ production and polarization in 16-GeV/c $\pi - p$ interactions



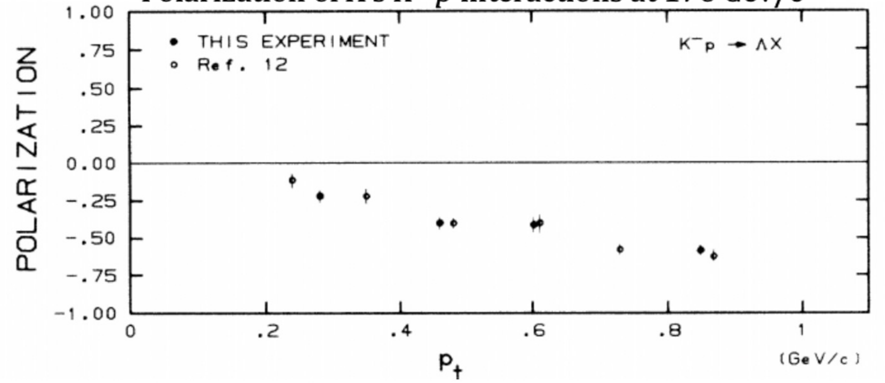
PRL50, 313 (1983)

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



EPJC 32, 221(2004)

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



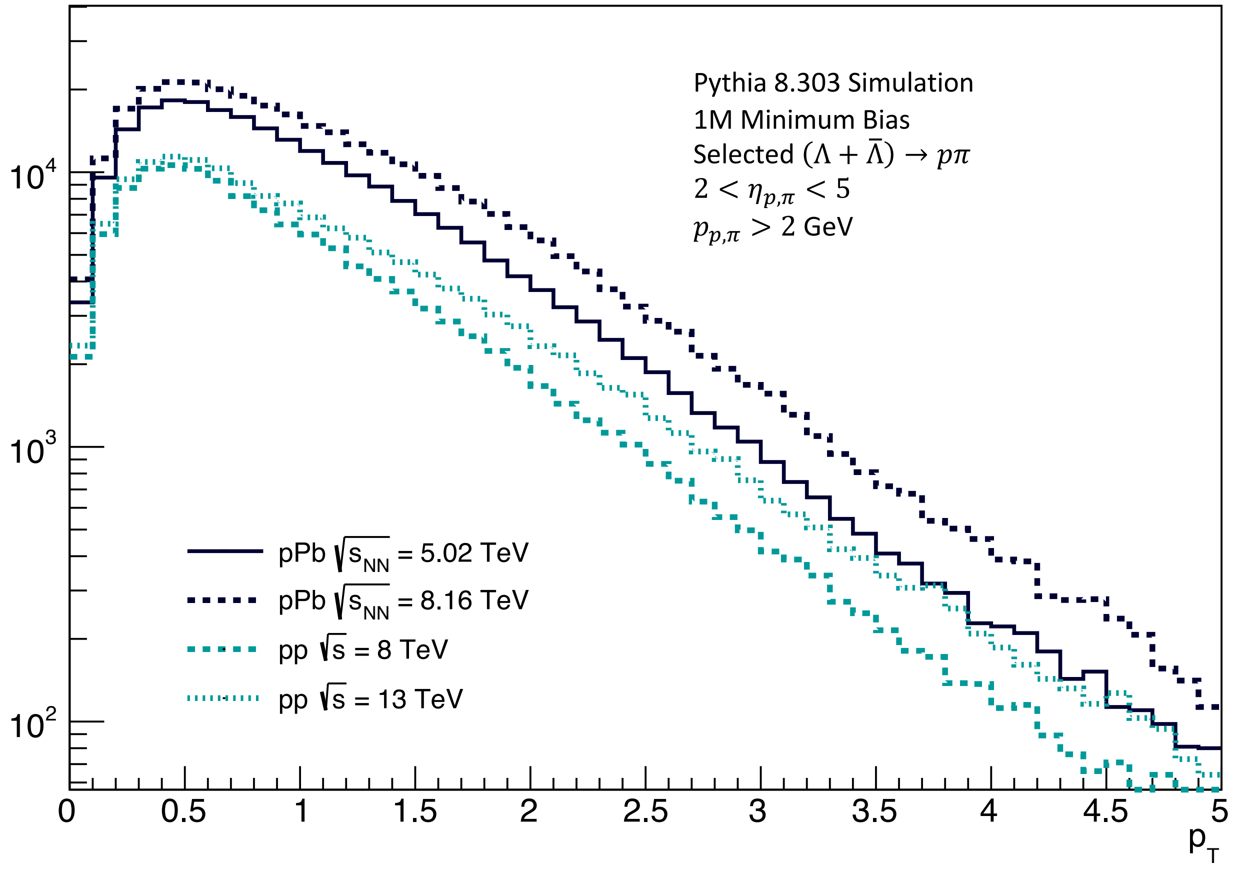
PRL 56, 2244 (1986)

- 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

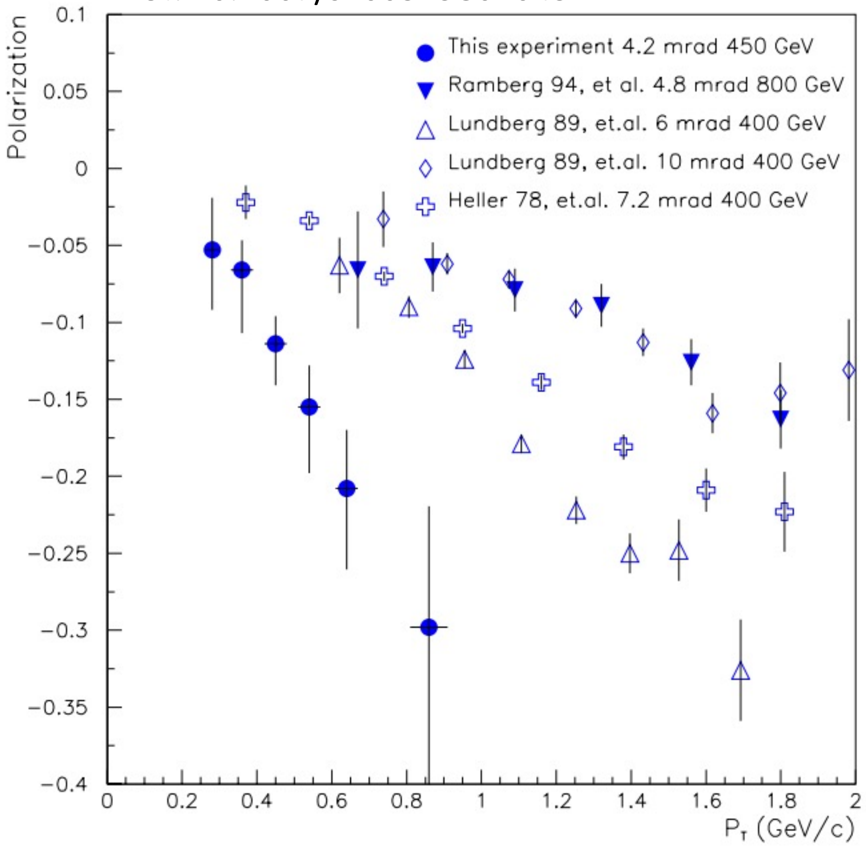
Other not shown:

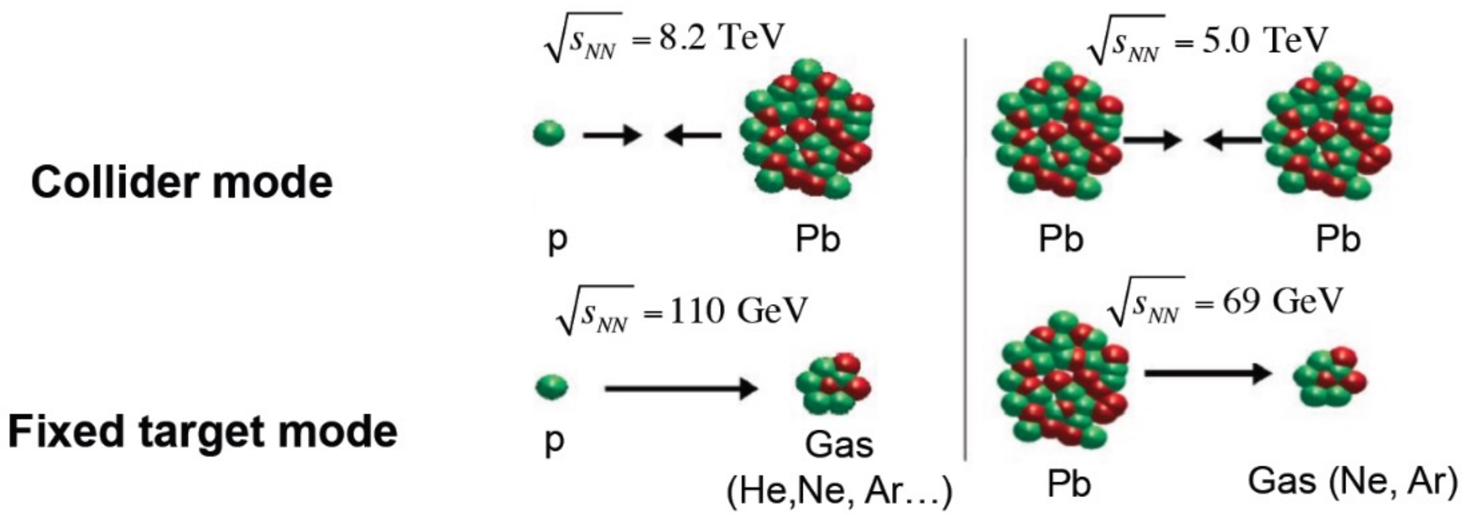
- The same polarization sign and general x_F dependence has been observed for neutron beams
- The polarization was measured to be consistent with zero for π^+ and K^+beams
- Polarization measured in $\nu_\mu N$ consistent with unpolarized pp experiments for both Λ and $\bar{\Lambda}$

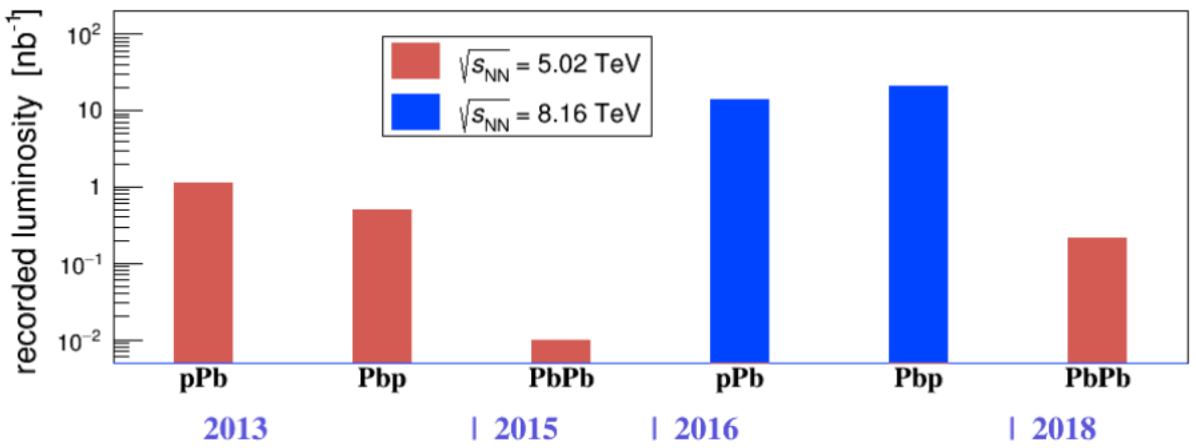
Kinematic Reach: pp, pPb data

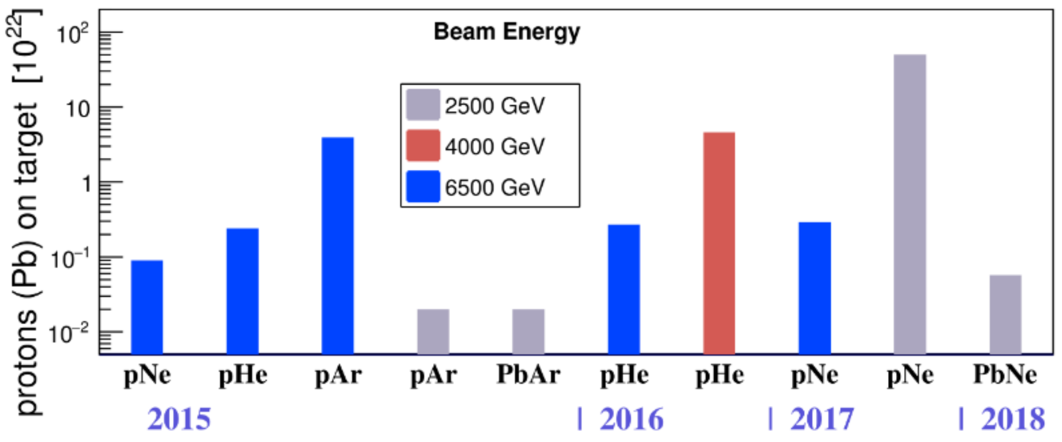


DOI: 10.1007/s100529801045

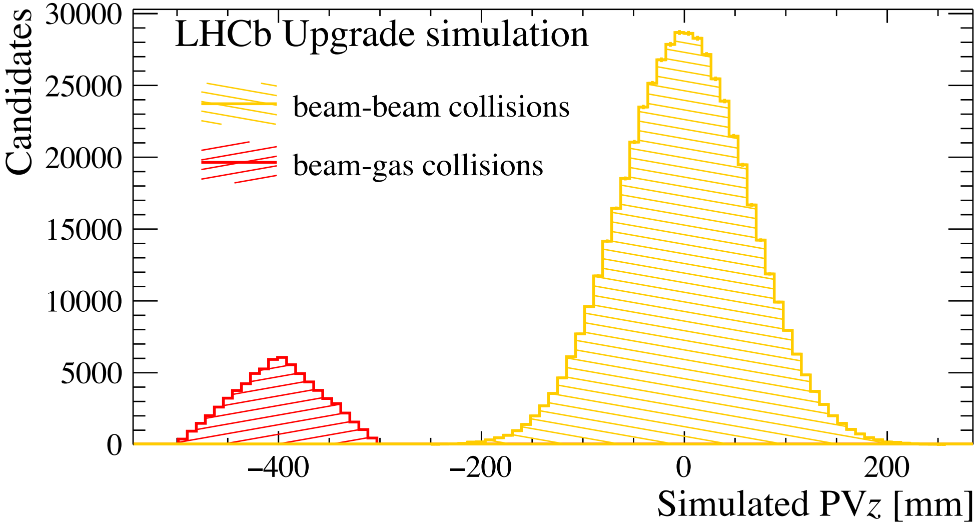


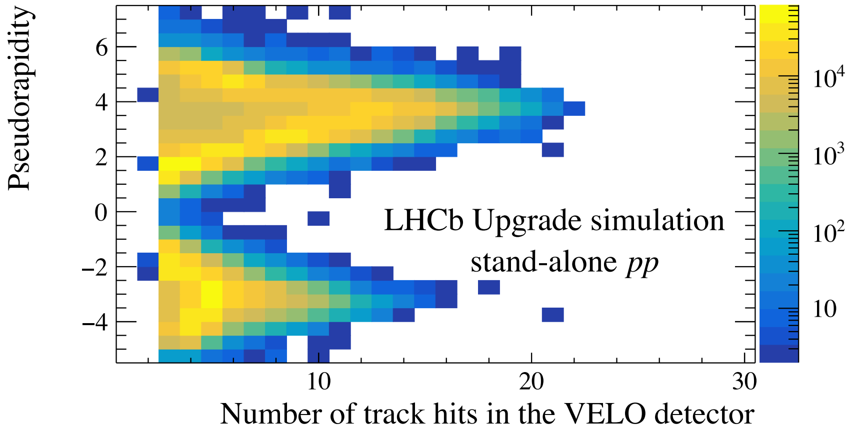

Collider mode
Fixed target mode
$\sqrt{s_{NN}} = 8.2$ TeV
p
Pb
$\sqrt{s_{NN}} = 5.0$ TeV
Pb
Pb
$\sqrt{s_{NN}} = 110$ GeV
p
Gas
(He,Ne, Ar…)
$\sqrt{s_{NN}} = 69$ GeV
Pb
Gas (Ne, Ar)

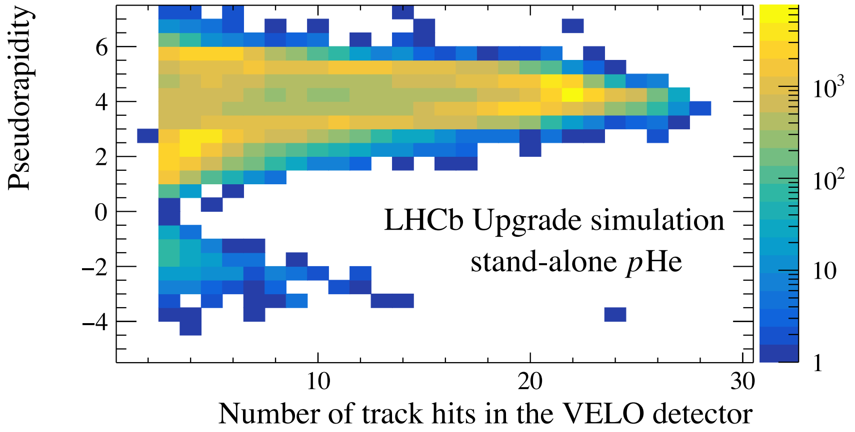

recorded luminosity [nb^{-1}]
10^2
10
1
10^{-1}
10^{-2}
$\sqrt{s_{NN}} = 5.02$ TeV
$\sqrt{s_{NN}} = 8.16$ TeV
pPb
Pbp
PbPb
pPb
Pbp
PbPb
2013
2015
2016
2018


protons (Pb) on target [10^{22}]
10^2
10
1
10^{-1}
10^{-2}
Beam Energy
2500 GeV
4000 GeV
6500 GeV
pNe
pHe
pAr
pAr
PbAr
pHe
pHe
pNe
pNe
PbNe
2015
2016
2017
2018

- LHCb upgrade simulation shows a good separation between p-gas and pp vertices
- The pseudorapidity distribution shows events being more symmetric for pp collisions and more forward for pHe collisions







LHCb-FIGURE-2022-002

- To measure non-zero polarization, one needs to have both nonzero α and P
- For $\bar{\Lambda}$ use $\alpha_{\bar{\Lambda}} = -\alpha_{\Lambda}$ considering CP conservation
- For the decay $\Sigma^{+} \rightarrow p\pi^{0}$ has $\alpha = -0.98 \pm 0.017$, which makes it easy to measure the Σ^{+} polarization through its decay mode
- $\Sigma^{-} \rightarrow n\pi^{-}$ has small $\alpha = -0.068 \pm 0.008$ making it necessary to have a large data sample and good control of systematic errors to get its polarization
- $\Xi^{-} \rightarrow \Lambda\pi^{-}$ and $\Omega^{-} \rightarrow \Lambda K^{-}$ information about the spin direction of hyperon is contained in the Λ decay, so to extract the polarization one needs the information from the Λ decay to determine the parent polarization