Polarization measurement and prospects at LHCb

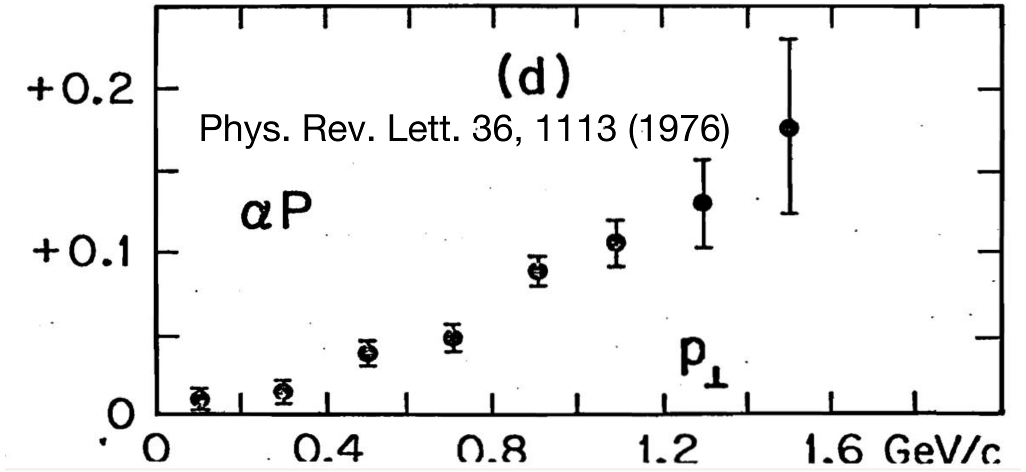
Speaker: Youen Kang
On behalf of LHCb collaboration

Overview

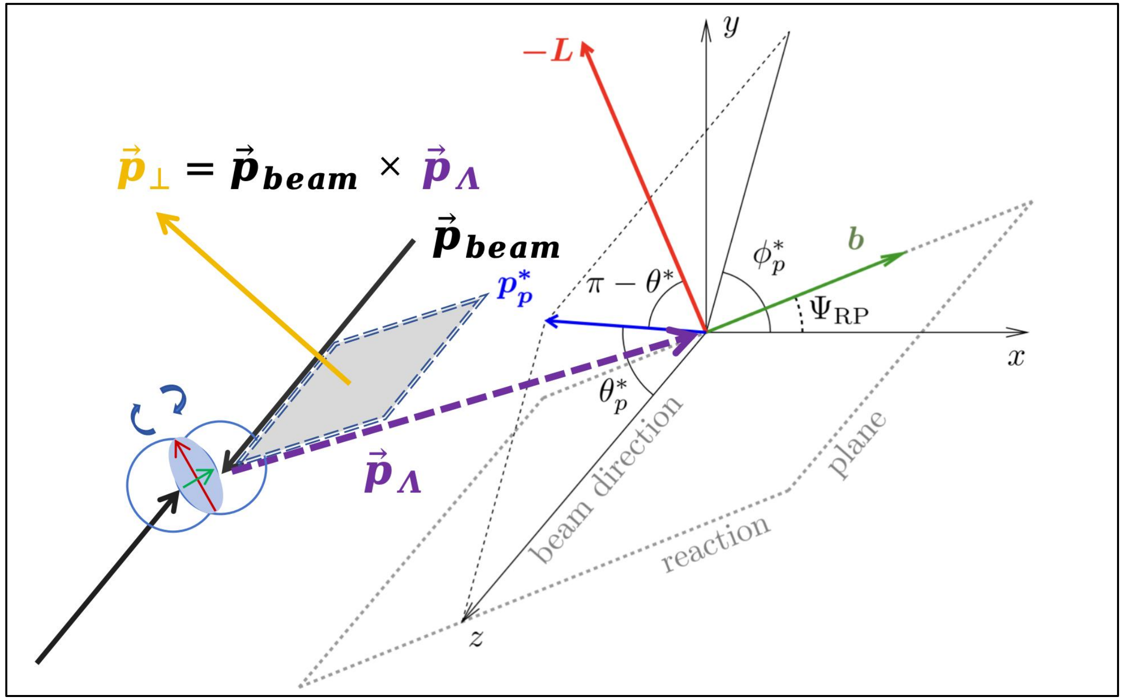
- Physics background
- SMOG in LHCb
- Λ transverse polarization
- Prospect

Hyperon polarization discovery

- **Λ polarization observed in pBe collisions in 1976 by FermiLab:**
  - **Not expect** in high-energy unpolarized-beams collisions
  - Comes from the **non-perturbative** hadronization process
  - Spin effect plays an important role in high-energy collisions
  - Lots of models proposed, achieve **partial explanation**

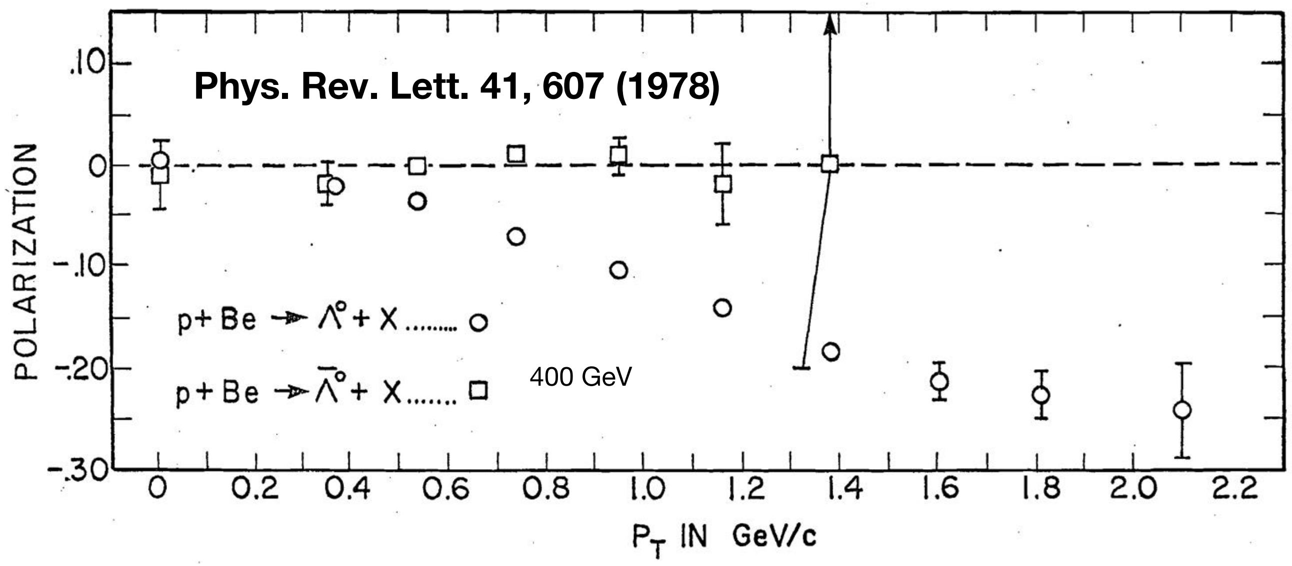


- Types of observables for polarization along:
  - Global polarization (along $\vec{L}$): originate from spin-orbit interaction
  - **Longitudinal (local) polarization** (along $\vec{p}_{beam}$): originate from inhomogeneous expansion of fireball
  - Transverse polarization (along $\vec{p}_\perp$): obtained in the fragmentation



Λ Transverse polarization

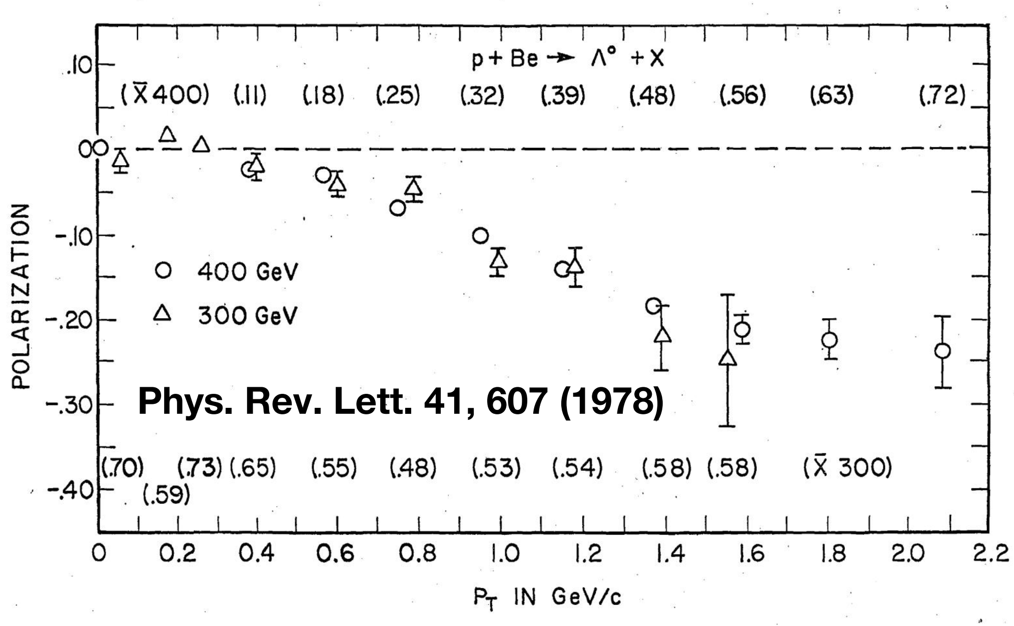
- All the measurements before show a transverse polarization for Λ **but not for** $\bar{\Lambda}$
  - Transverse polarization is **definitely not** a universality for all high energy baryon poduction
  - Suggest that s quark in Λ is produced polarized while $\bar{s}$ quark in $\bar{\Lambda}$ **is not**
  - Suggest a **different production mechanism** for Λ and $\bar{\Lambda}$ (e.g. gluon bremsstrahlung [Phys. Rev. Lett. 41, 607 (1978)])

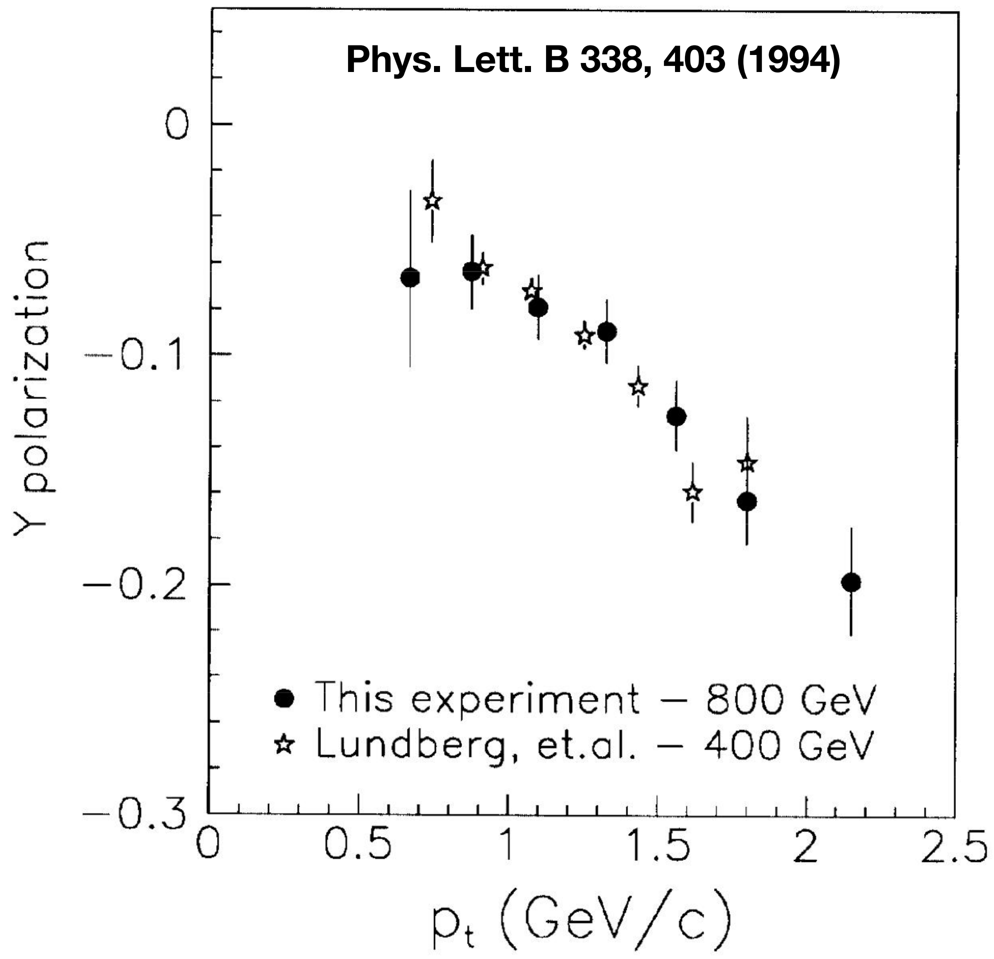


- Phys. Rev. Lett. 36, 1113 (1976)
- Phys. Rev. Lett. 41, 607 (1978)
- Phys. Rev. Lett. 41, 1348 (1978)
- Phys. Rev. Lett. 51, 2025 (1983)
- Phys. Rev. D 43, 2792 (1991)
- Phys. Rev. D 40, 3557 (1989)
- Phys. Lett. B 338, 403 (1994)
- Eur. Phys. J. C 6, 265 (1999)
- Phys. Lett. B 638, 415 (2006)

Λ Transverse polarization dependence

- Λ transverse polarization found to be:
  - **not obviously dependent** on collision energy (collision energy do have effects on the proportion of Λ from decays)
  - **increase** with transverse momentum to several GeV



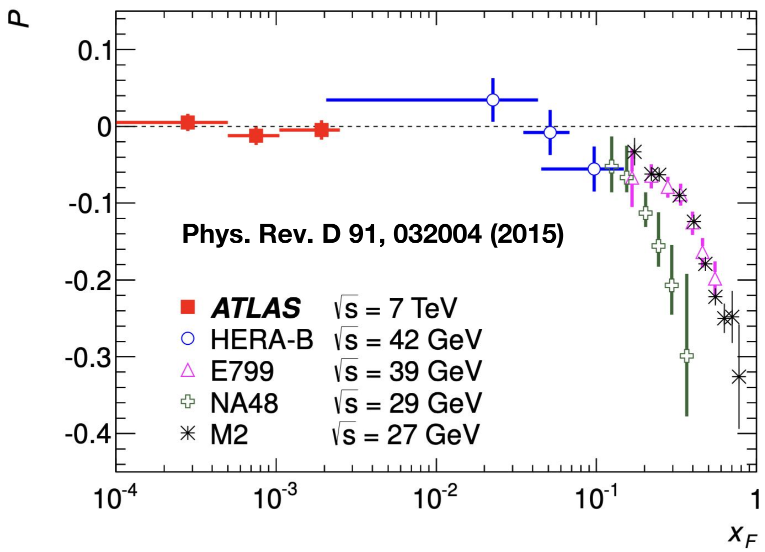


Λ Transverse polarization dependence

- Λ transverse polarization is found to
  - **increase** with increasing x_F in hadronic collisions

$$x_F = \frac{p_L}{p_{L,\,max}} = \frac{2p_L}{\sqrt{s_{NN}}}$$

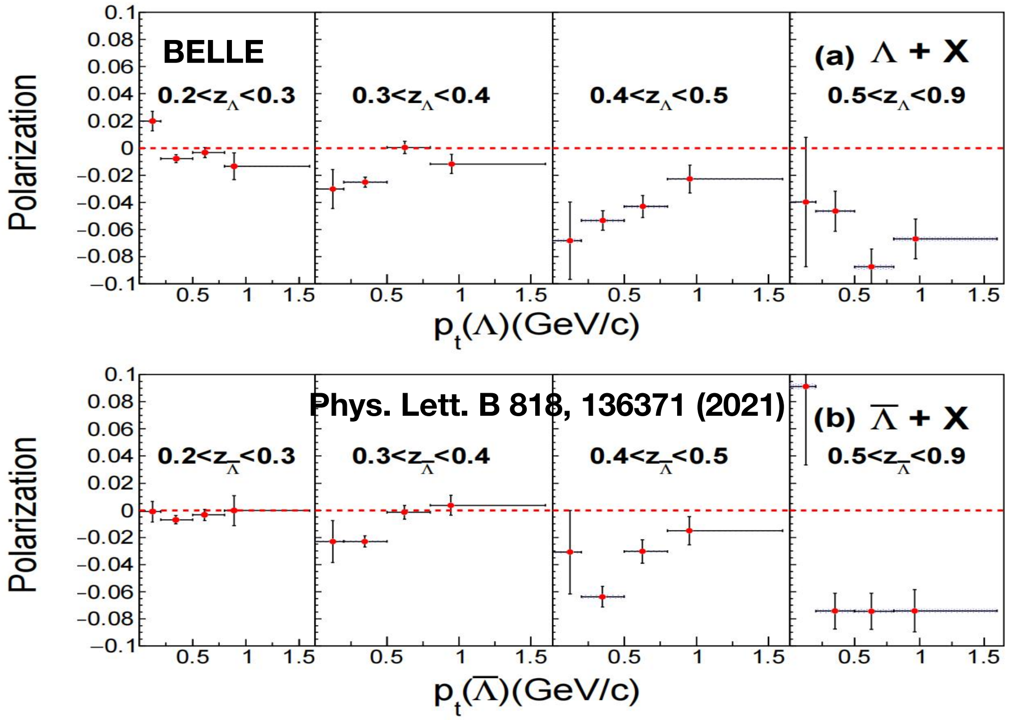
where p_L is the longitudinal momentum, and $p_{L,\,max}$ is the maximum of p_L can reach, which is half the center-of-mass energy



- **increase** with increasing z_Λ in e^+e^- collisions (**first observed**)

$$z_\Lambda = \frac{2E_\Lambda}{\sqrt{s}}$$

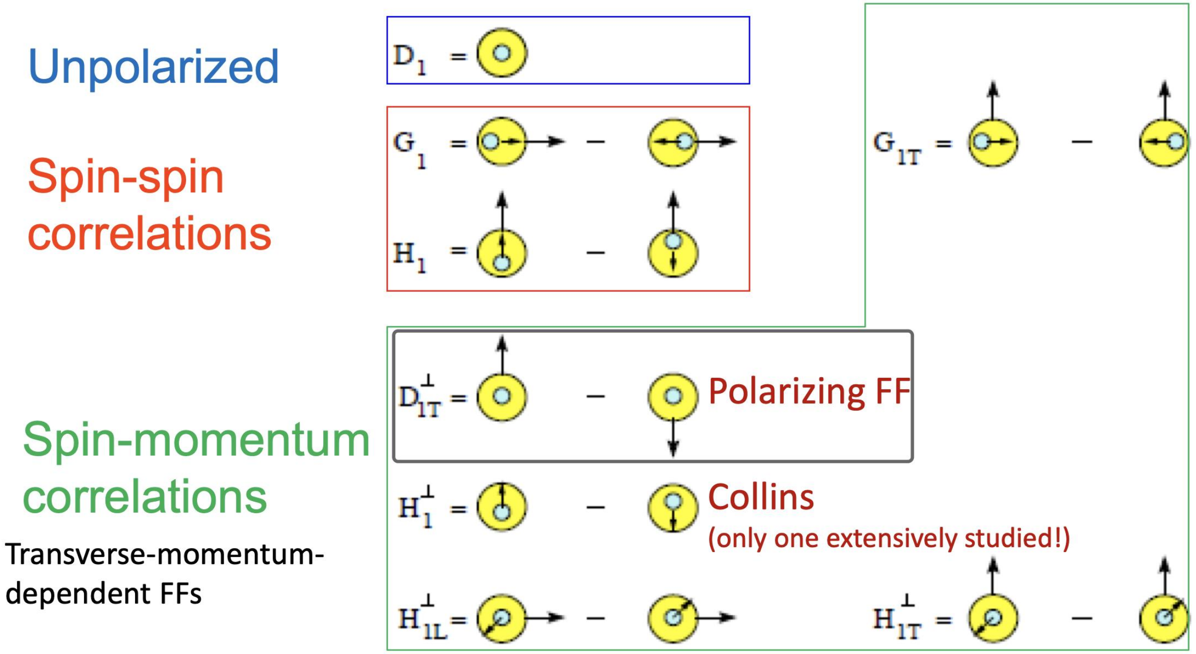
Transverse polarization found for both Λ and its anti-particle in high fractional energy region



Phenomenological approach

- Theoretical models describe relatively better in global polarization, but **poorly** in local and transverse polarization

- A phenomenological approach is Transverse Momentum Dependent (TMD) Fragmentation Function (FF), which:
  - Describes the fragmentation of **unpolarized quark into transversly polarized hadron** [Phys.Rev. D63 (2001) 054029]
  - TMD FF can be studied through experimental data

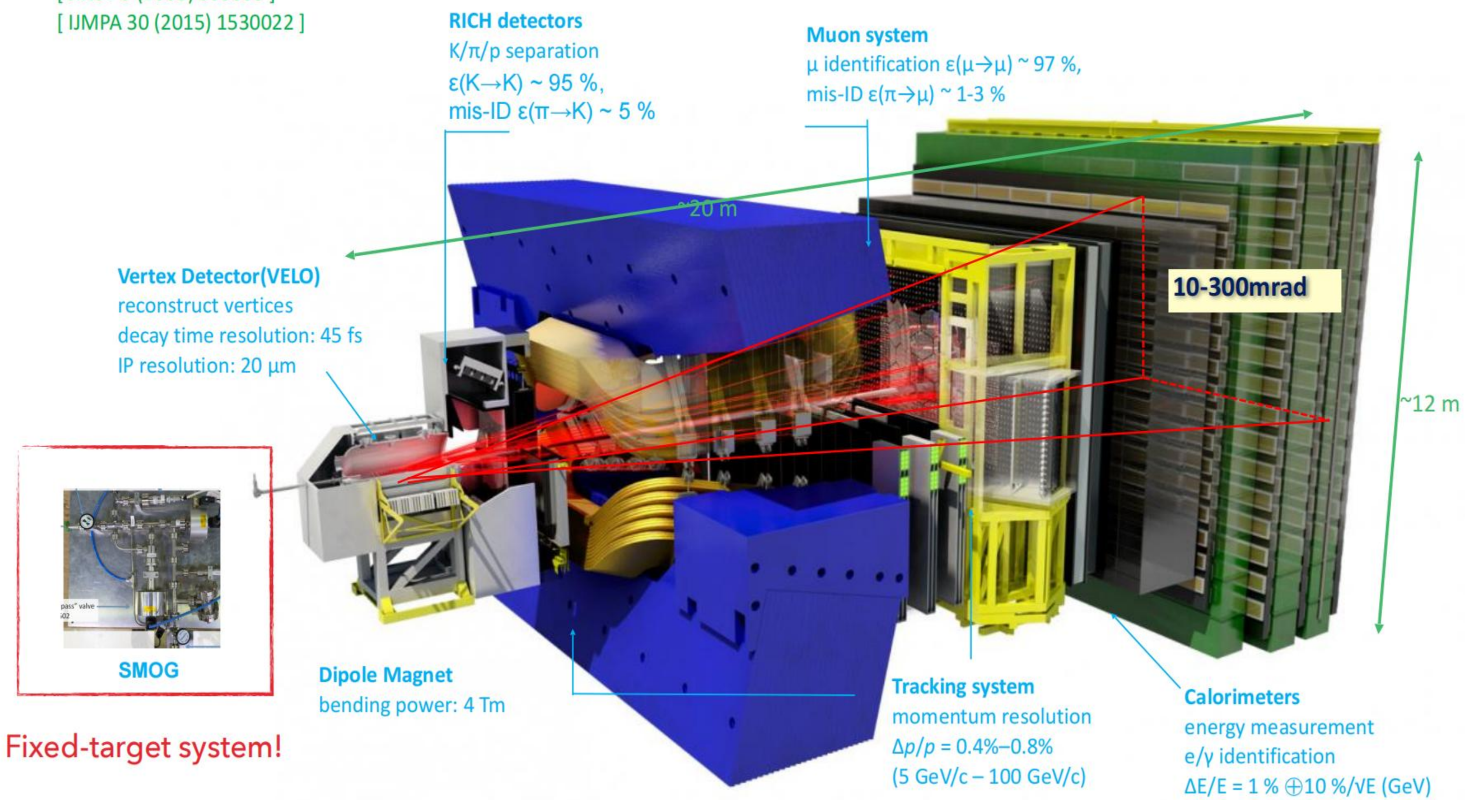


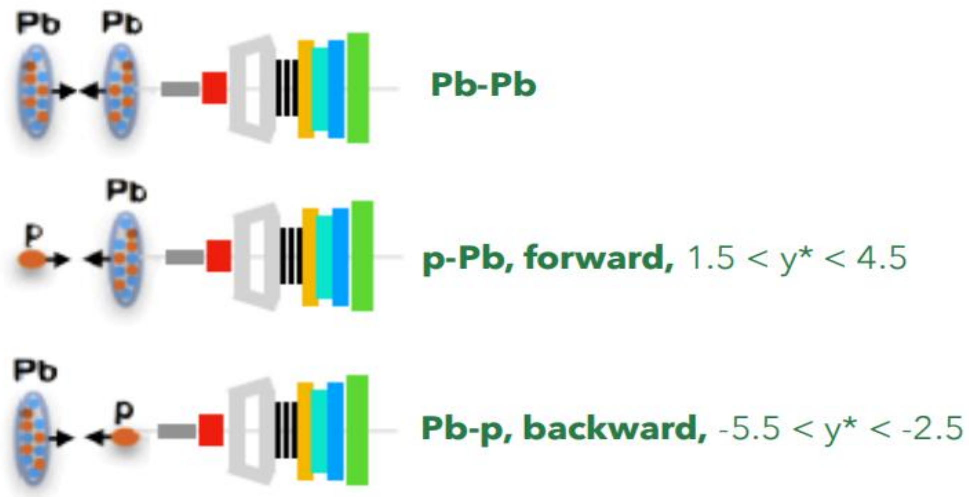
https://www.phenix.bnl.gov/WWW/publish/caidala/UniMiQCDLectures2020/AidalaQCDAndBaryonPolUniMi2020Lect3.pdf

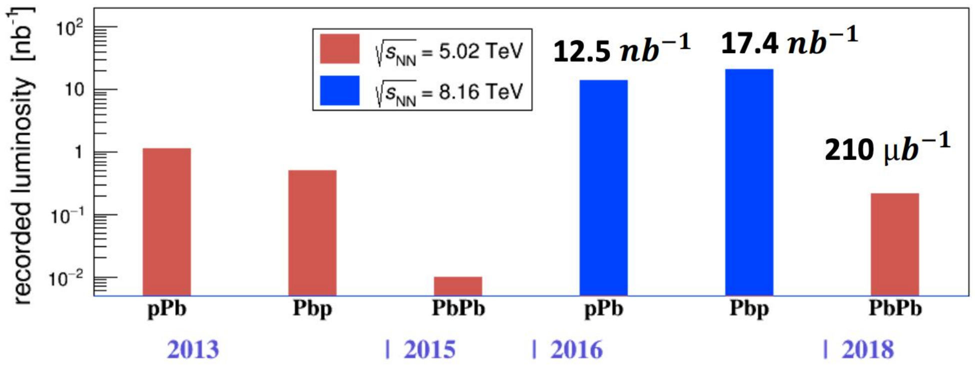
The LHCb detector

- Single-arm forward spectrometer with unique coverage $2 < \eta < 5$
  - Designed for heavy-flavour physics, now a general purpose experiment
  - Forward and backward coverage for asymmetric beams

[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

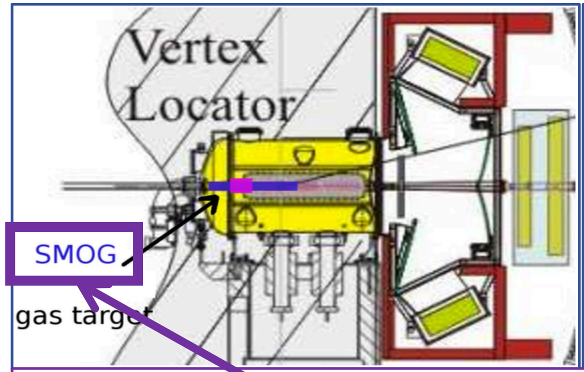


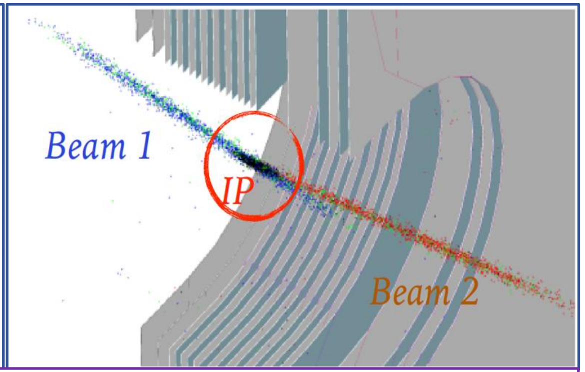


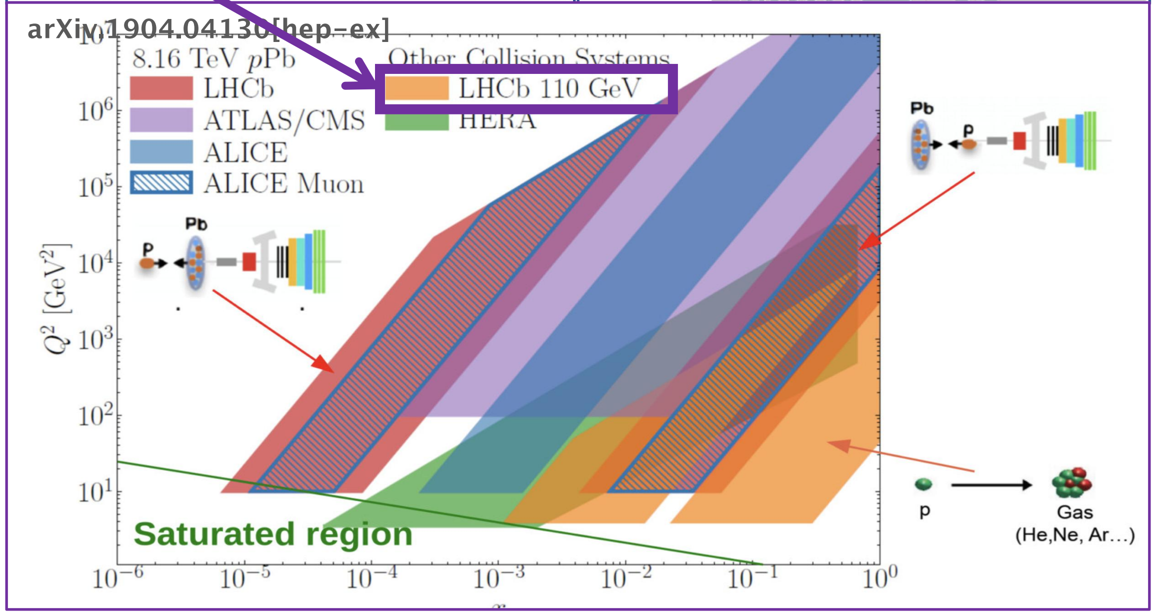


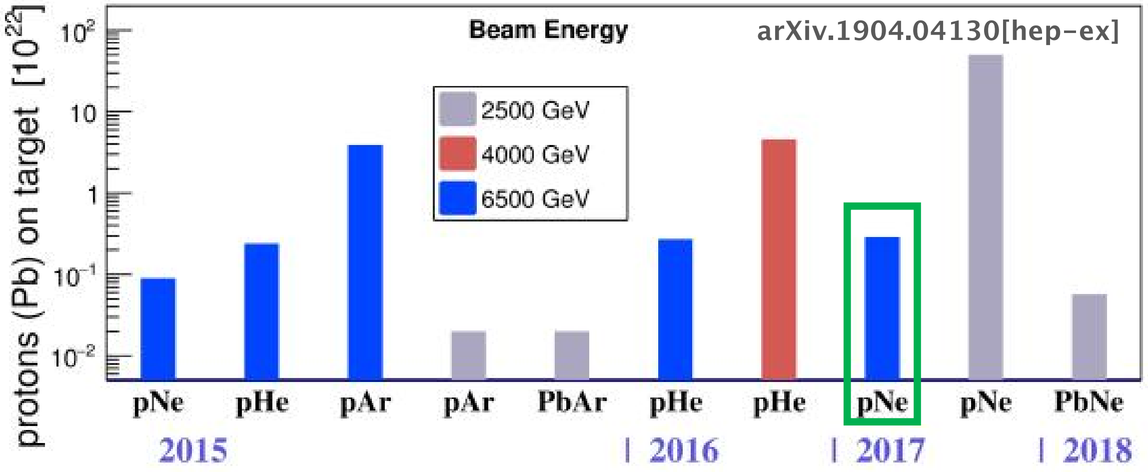
Fixed-Target experiment: SMOG

- SMOG: System for Measuring Overlap with Gas
  - Highest-energy fixed-target experiment ever built, a bridge between SPS and LHC energies
  - Noble gases (He, Ar, Ne) injected around Interaction Point (IP) with pressure 10e-7 mbar
  - Unique kinematic region accessible, helps to investigate high-x and intermediate Q^2



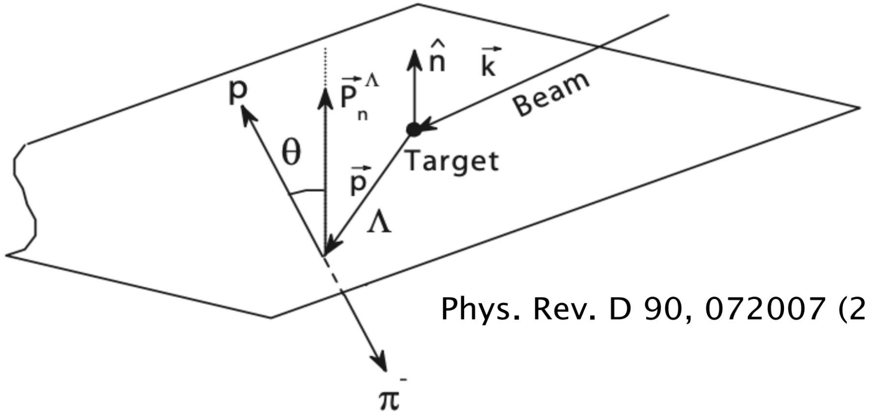




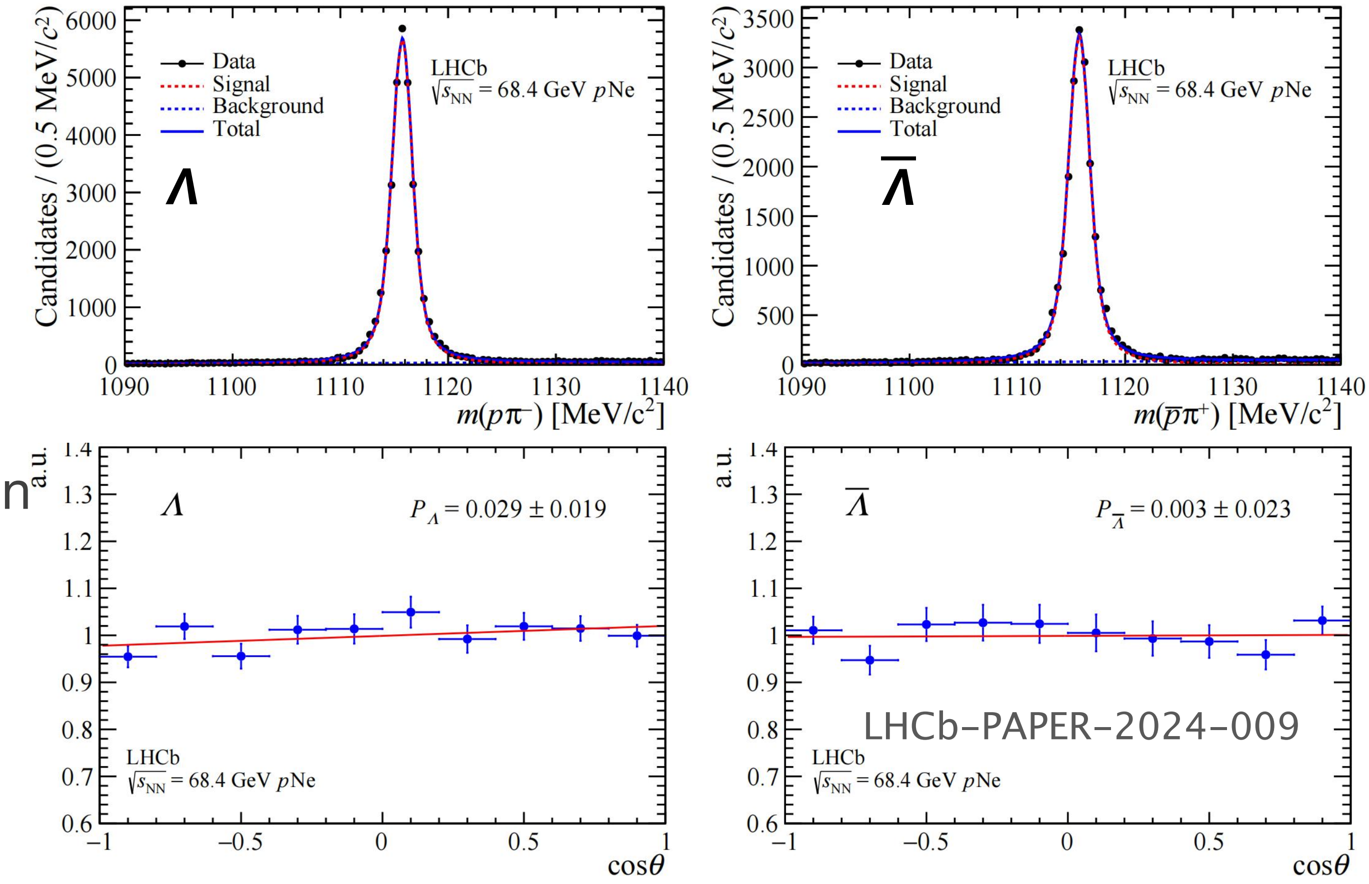


Λ transverse polarization

- Decay channel: $\Lambda \rightarrow \pi^- + p$ and $\bar{\Lambda} \rightarrow \pi^+ + \bar{p}$
- $P(\Lambda) = 0.029 \pm 0.019 \pm 0.012$
- $P(\bar{\Lambda}) = 0.003 \pm 0.023 \pm 0.014$



Phys. Rev. D 90, 072007 (2014)



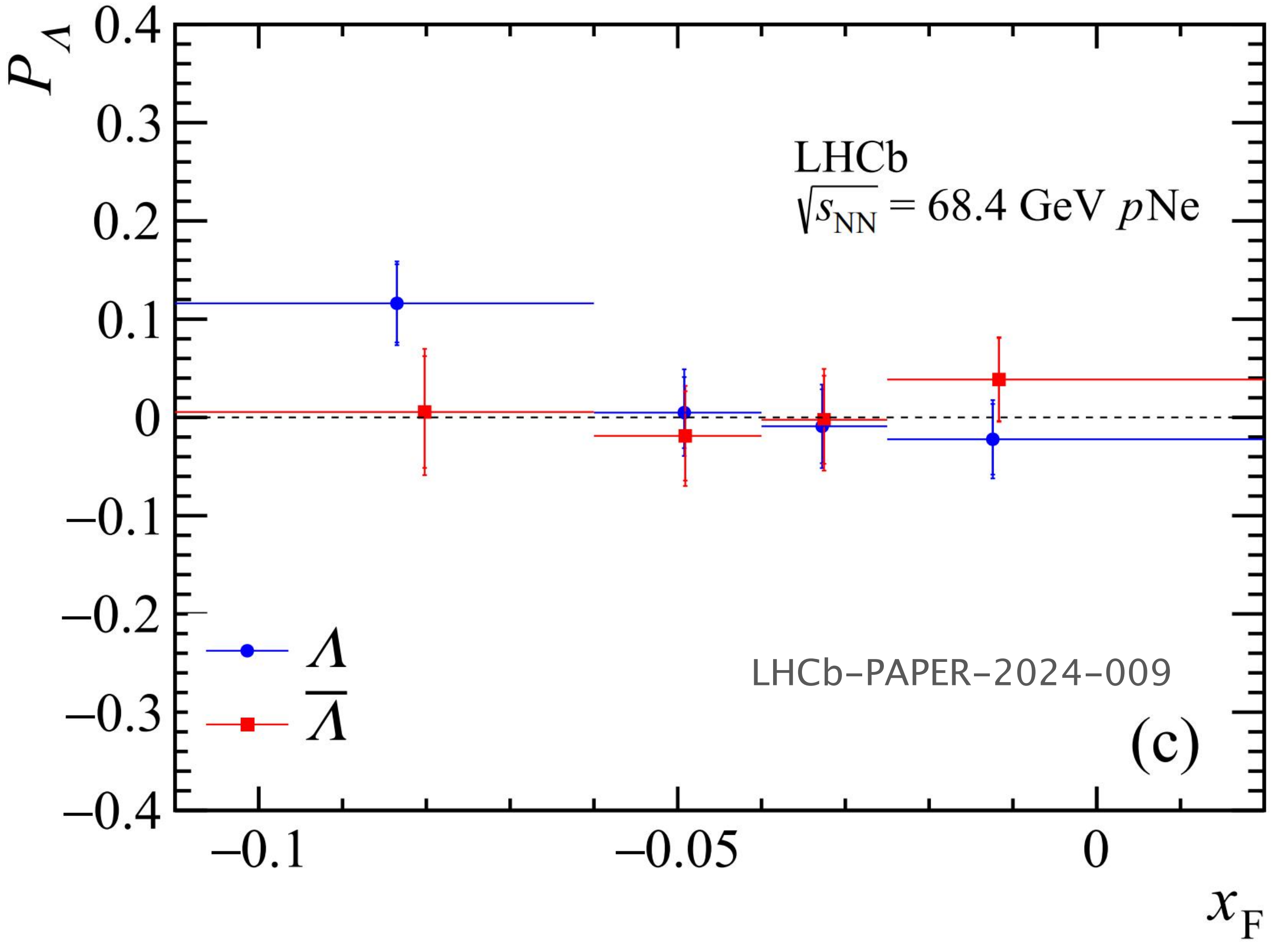
- Protons preferentially emitted in Λ spin direction in its rest frame, the polarization extracted by

$$\frac{dN}{d\Omega} = \frac{dN_0}{d\Omega}\left(1 + \alpha P_n^{\Lambda} cos(\theta)\right)$$

α: parity-violating decay asymmetry for Λ(0.746 ± 0.007) and $\bar{\Lambda}$(-0.757 ± 0.004)

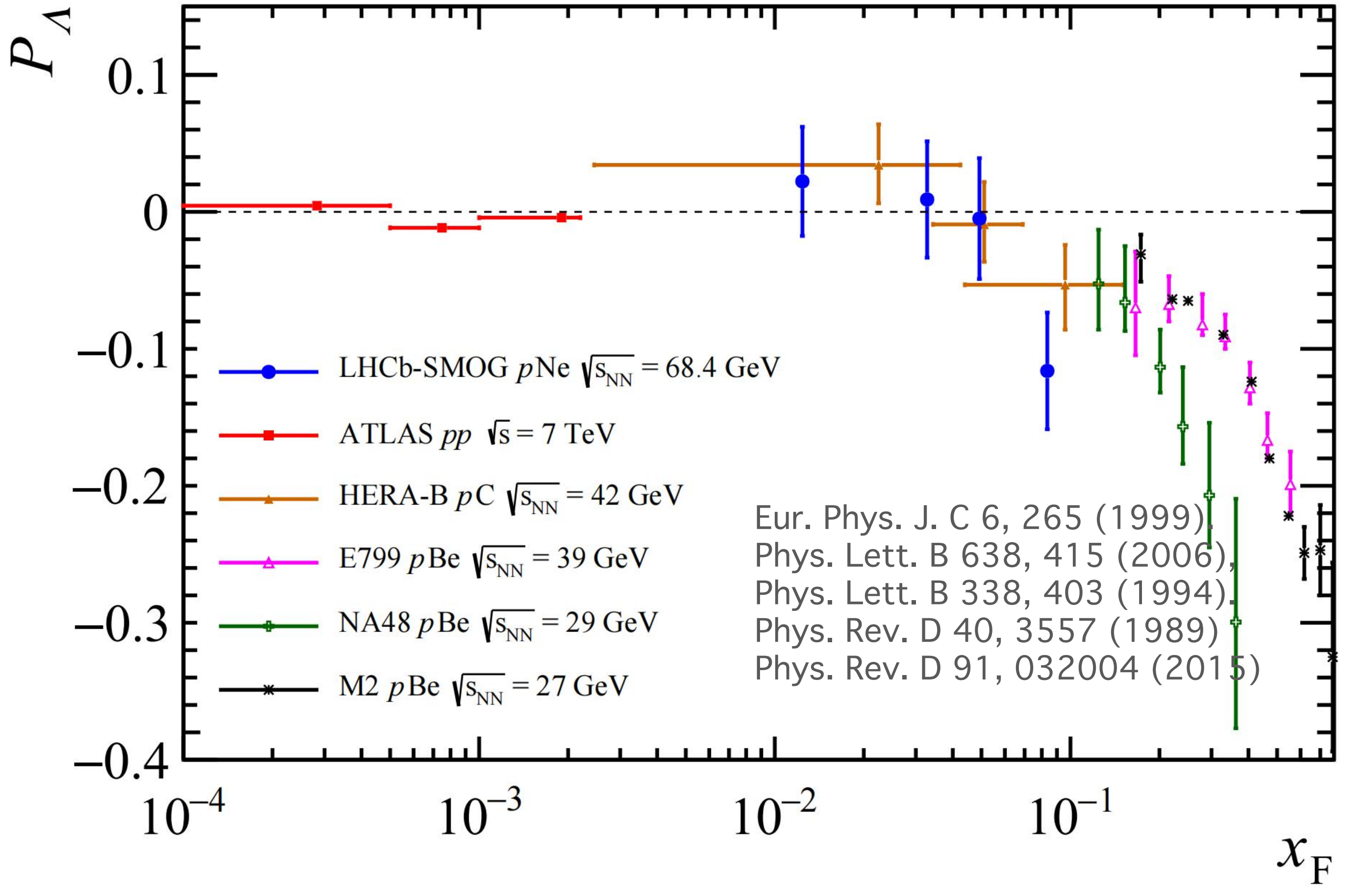
Λ transverse polarization v.s. x_F

- Λ transverse polarization **increase slightly** with increasing $|x_F|$, an obvious non-zero transverse polarization is observed for $|x_F|$~0.1
- $\overline{\Lambda}$ is **not transversely polarized**, even in highest $|x_F|$ bin, which consistent with the other fixed-target experiments
- For lower $|x_F|$ region, transverse polarization for both Λ and $\overline{\Lambda}$ are **consistent with zero**



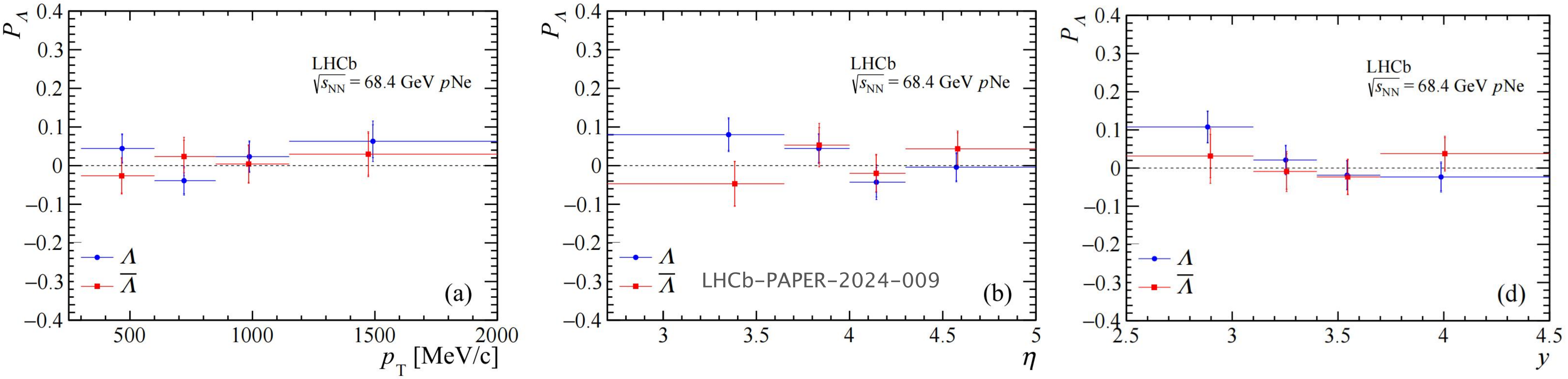
Λ transverse polarization v.s. x_F

- Λ transverse polarization v.s. x_F
  - Good agreements with other measurement can be extrapolated from measurement in high x_F
  - As a comparison, HERA-B results are measured:
    - in a different collision system
    - in different kinematic regions
    - at different center-of-mass energy



Λ transverse polarization v.s. p_T, y, η

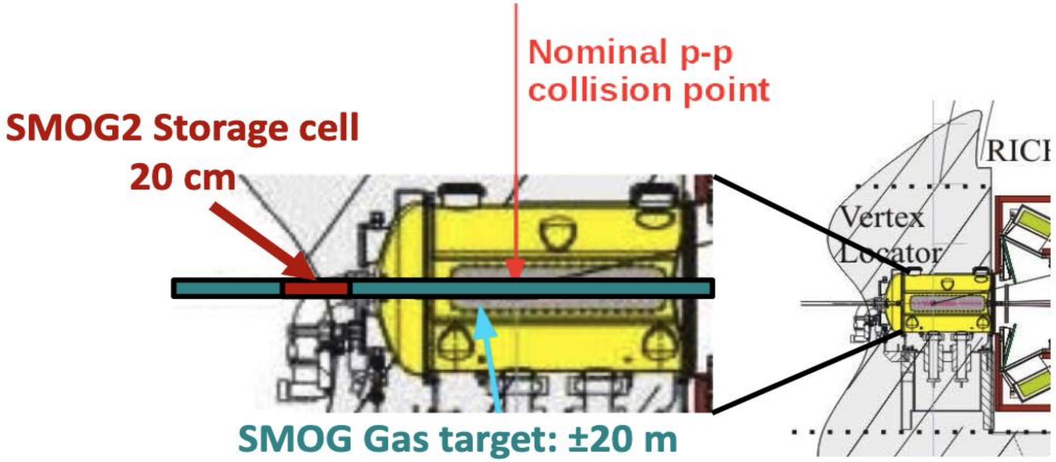
- **No significant dependence on p_T** is found, could result from the overall low x_F for the measurement
- A **slight decreasing trend** is observed for transverse polarizarion on y and η



Prospects

SMOG2

- Gas confined in a 20 cm long storage cell
- Higher areal density than SMOG → Luminosity × ~100
- Wider choices of gas: He, Ne, Ar, H_2, D_2, O_2, Kr, Xe
- Data taken simultaneously in *pp* and *p*A mode

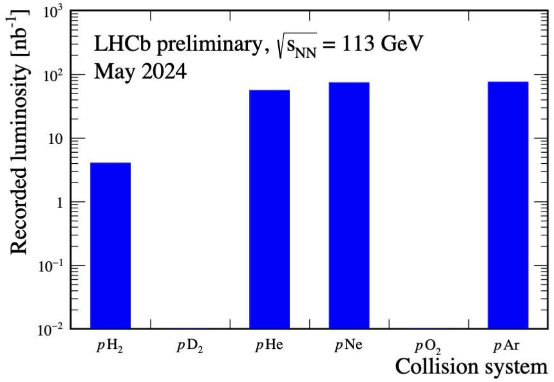


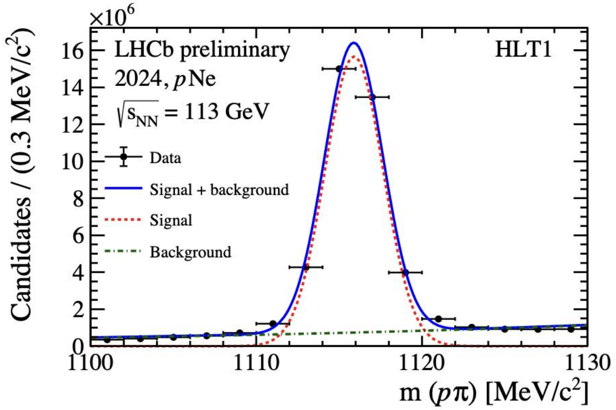
POSTER: SMOG2: a high-density gas target at the LHCb experiment, Federica Fabiano

(For more details)

Improve on transverse polarization measurement

- Better statistical resolution
- Measurement repeated with different mass targets and beam energies
- Possibility to increase $|x_F|$ ~ 0.3
- Possibility to look into other hyperon polarization





LHCb-Figure-2023-005

Back Up

Reaction Plane and Event Plane

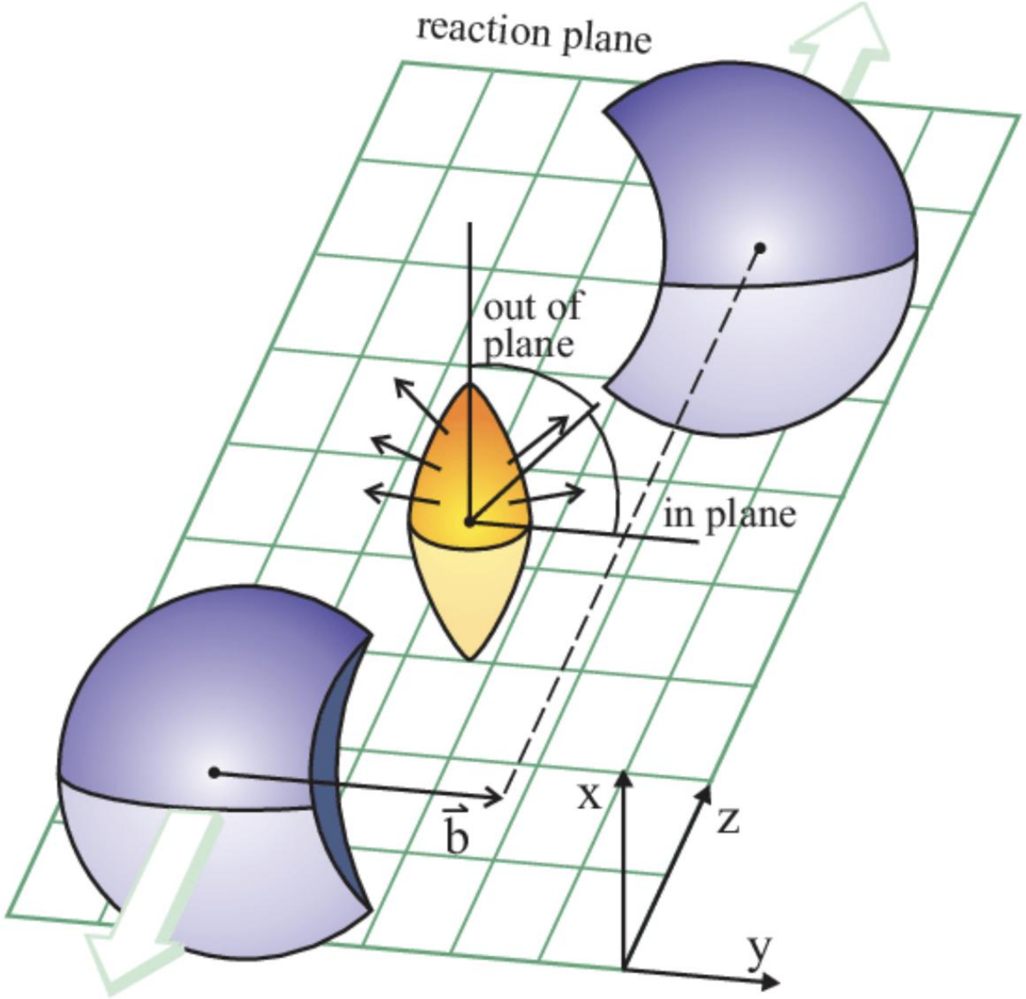
- **Reaction plane**
  - Reaction plane angle denoted by Ψ_R
  - Spanned by vector set $\{\vec{b}, \vec{p}_{beam}\}$, $\vec{b}$ is impact parameter
  - RaCan't be defined for central collisions
- Can't be obtained, can be approximated by **Event Plane**
  - The n-th harmonic Event Plane angle is defined as:

$$\Psi_n = \frac{1}{n} arctan(\frac{\sum_i w_i sin(n\phi_i)}{\sum_i w_i cos(n\phi_i)})$$

w_i is weight and ϕ_i azimuthal angle of i-th particle in an event

  - This approximation has a resolution of:

$$R_n = \langle cos(n(\Psi_n - \Psi_R)) \rangle$$



Global polarization

- The **spin polarization $\vec{P}$** reveals the parity-violating nature of hyperon decay, the projection of $\vec{P}$ on system angular momentum $\vec{L}$ is called **global polarization**:

$$P_{global} = \langle \vec{P}, \vec{L} \rangle = \frac{8}{\pi \alpha_H} \frac{1}{R_1} \langle sin(\Psi_1 - \phi_p^*) \rangle$$

details for measurement of this quantity: **Phys. Rev. C 104 (2021) L061901 (invariant mass method)**

  - α_H: parity-violating decay asymmetry for hyperon
  - R_1: resolution for 1st order event plane
  - Ψ_1: 1st order event plane angle
  - ϕ_p^*: azimuthal angle for decayed proton in hyperon rest frame

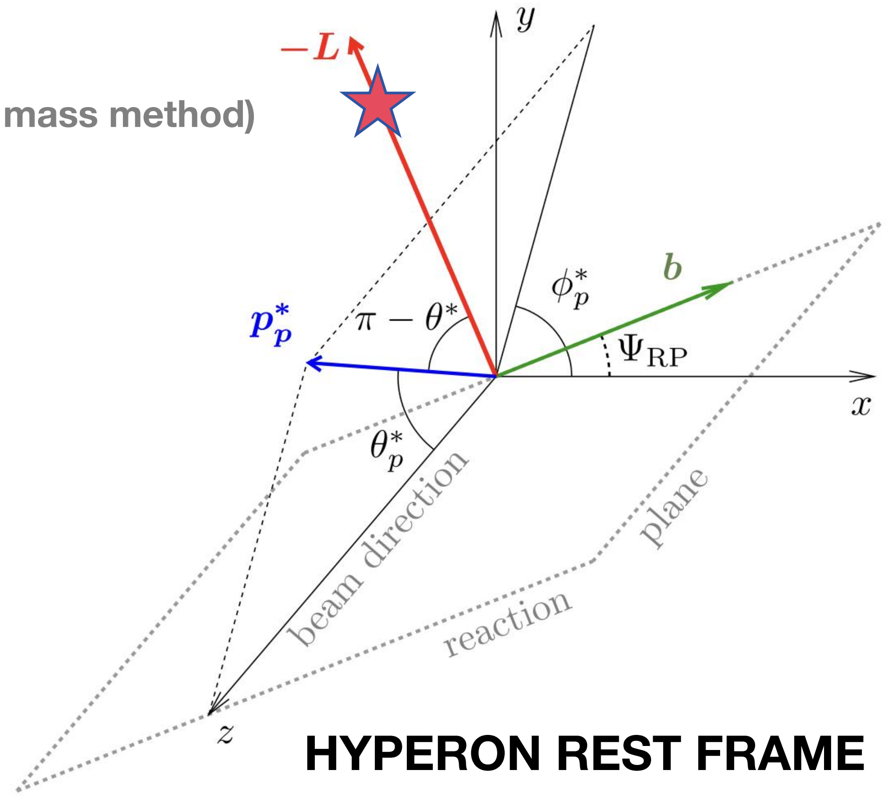
- **Revelant measurement:**

Λ global polarization in AuAu at RHIC:

- Phys. Rev. C 104 (2021) L061901
- Phys. Rev. C 98, 014910 (2018)
- PRC76.024915(2007)
- arXiv:2305.08705v4 [nucl-ex]

Others:

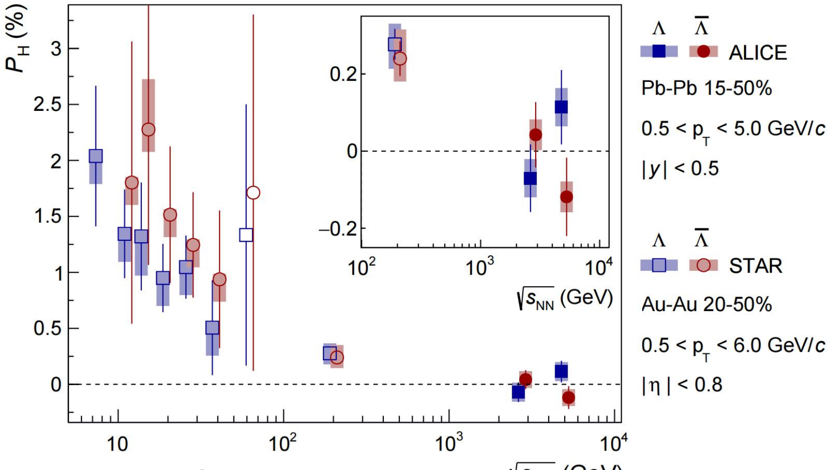
- Phys. Rev. C 101, 044611 (ALICE PbPb 2.76, 5.02 TeV)
- Phys. Lett. B 835 (2022) 137506 (HADES, AuAu 2.4TeV and AgAg 2.5TeV)



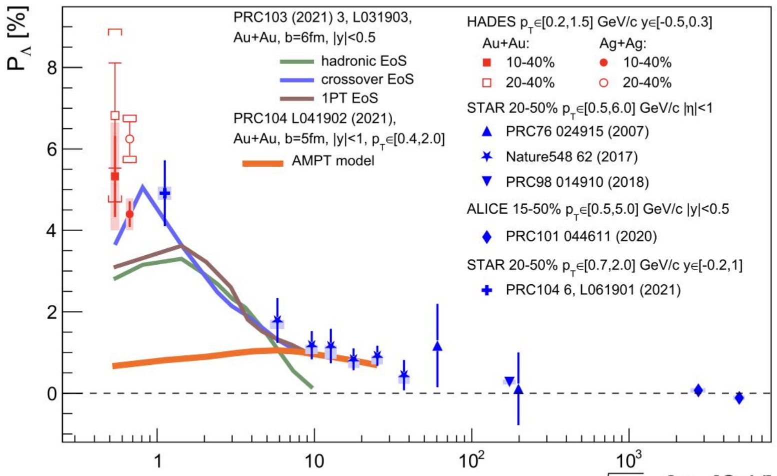
HYPERON REST FRAME

Global polarization v.s. $\sqrt{s_{NN}}$

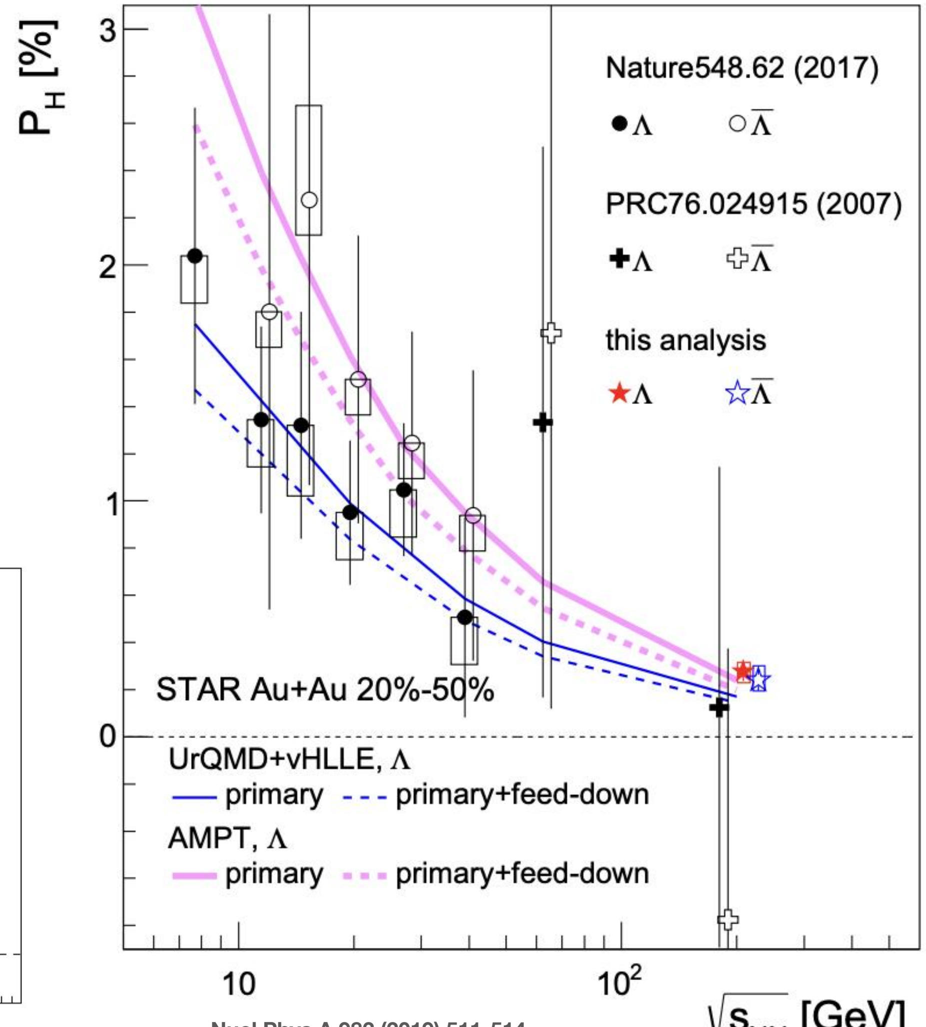
- **Decreases** with center-of-mass energy $\sqrt{s_{NN}}$
  - **Several models** like hydrodynamic model [Eur.Phys.J.C77(2017)213] and AMPT model [Phys.Rev.C96(2017)054908] are proposed
  - This may be partly due to **longer evolution times** at higher energies, increasing the viscosity-driven decay of vorticity before polarized hyperon emission [Nucl. Phys. A 967, 764 (2017)]



Phys. Rev. C 101, 044611



Phys. Lett. B 835 (2022) 137506



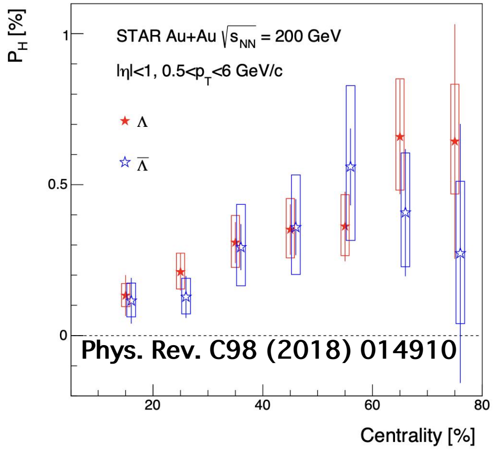
Nucl.Phys.A 982 (2019) 511-514

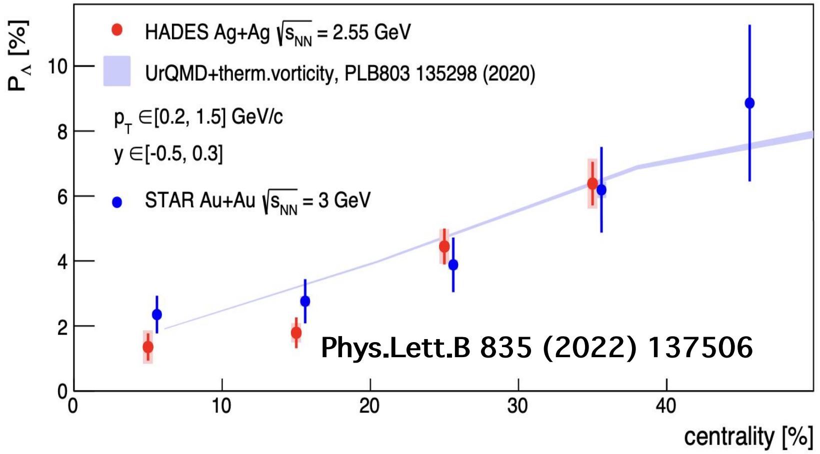
Global polarization v.s. Centrality

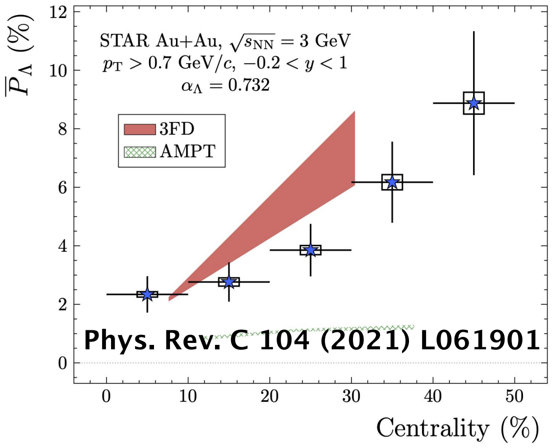
- Global polarization **increase** monotonically with increasing centrality. This behavior is qualitatively consistent with the system angular momentum increasing with collision centrality as well as numerous model calculations with varying underlying assumptions

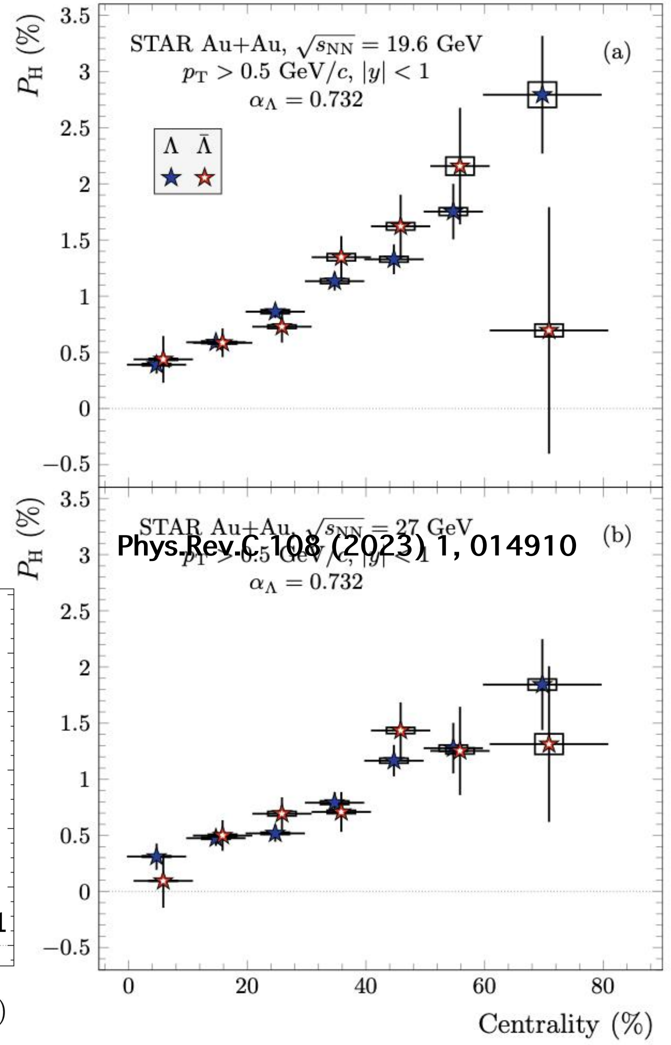
AMPT (Multiphase Transport) model [Phys. Rev. C 94, 044910 (2016)]

3FD (Three-fluid dynamics) [Phys. Rev. C 103, L031903 (2021)]







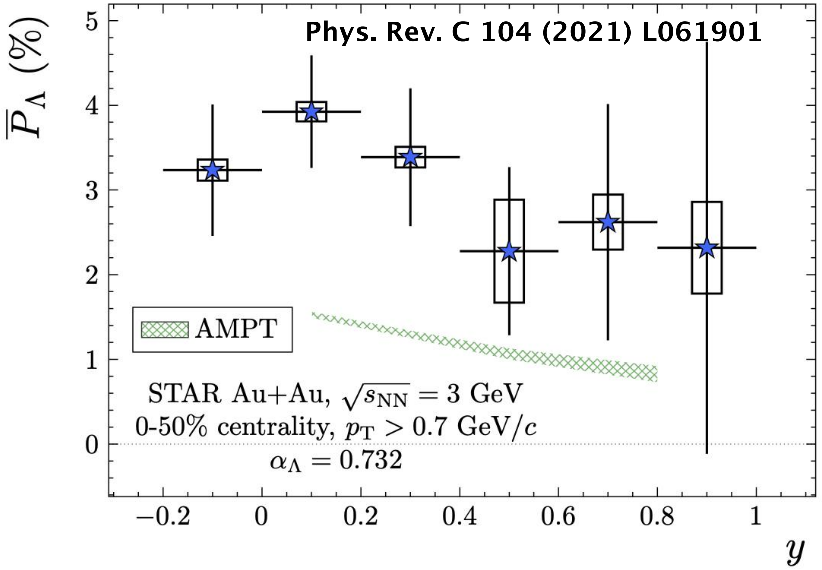


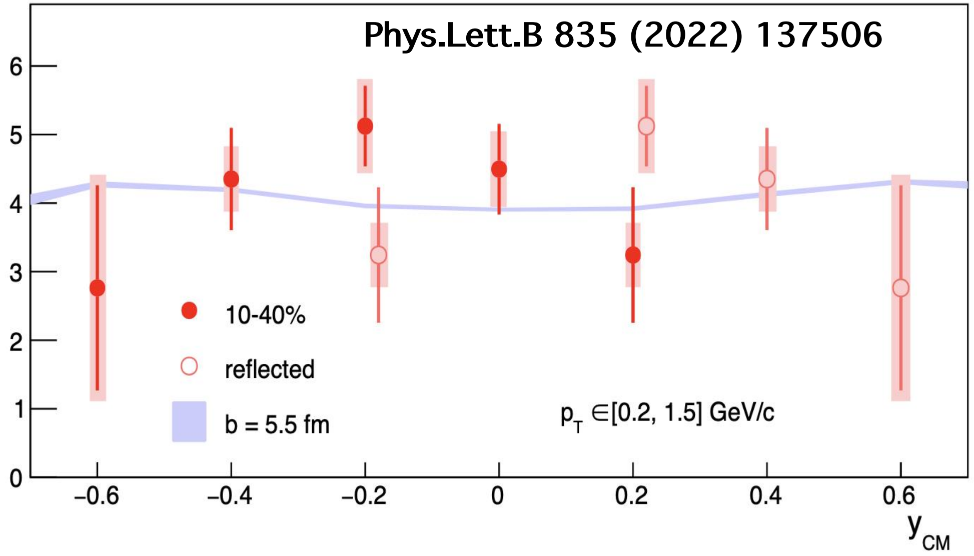
Global polarization v.s. y

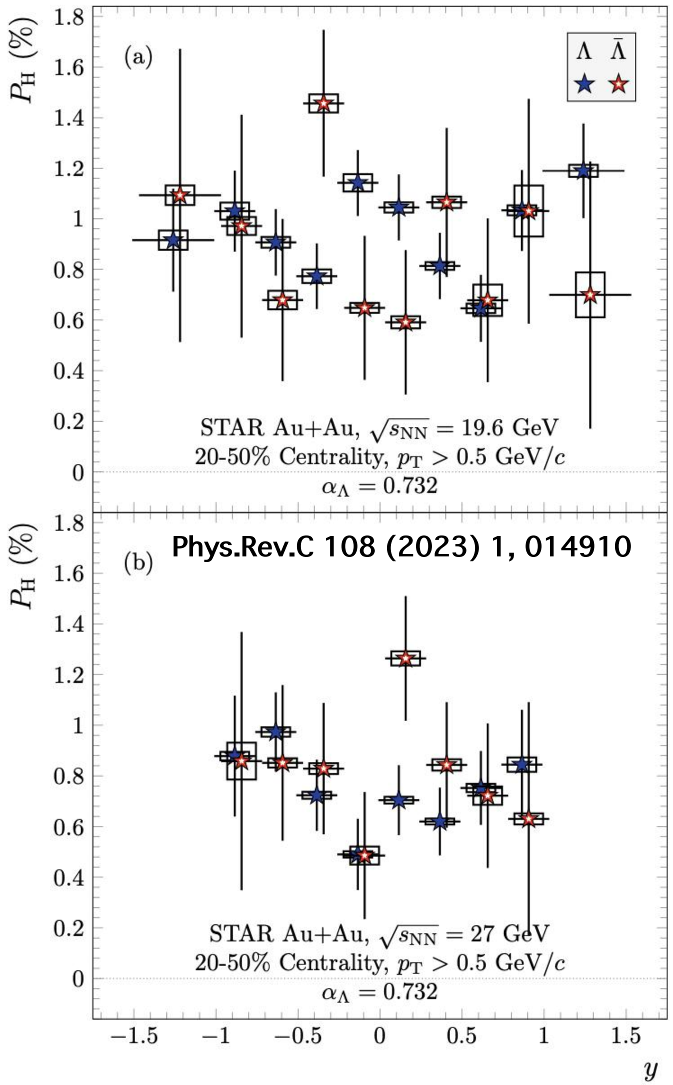
- ➢ In many experiments, **no dependence** on rapidity is found. Different models or different parameters in a model give very different predictions on the rapidity dependence of global polarization:

AMPT [Phys. Rev.C 99, 014905 (2019)]   UrQMD model [Phys.Lett.B803,135298 (2020)] ↓

AMPT [Phys. Rev. C 104, 041902 (2021)]   (Ultrarelativistic Quantum Molecular Dynamics)

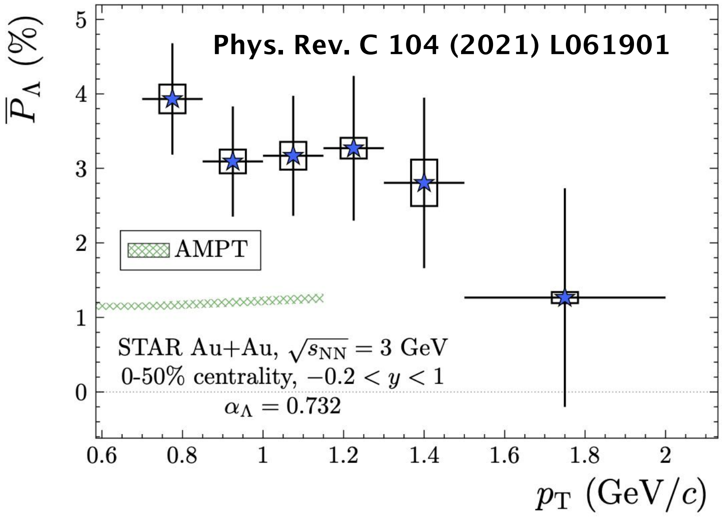


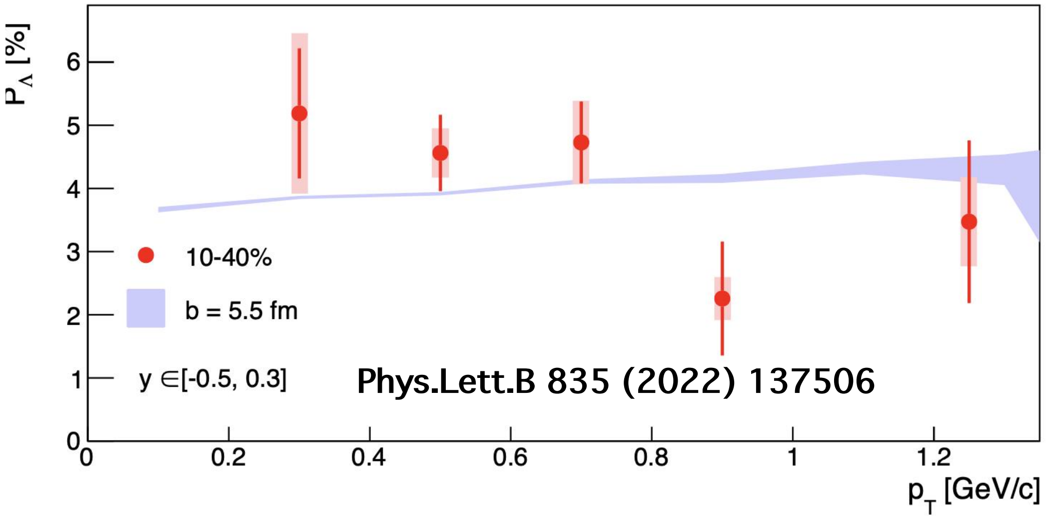


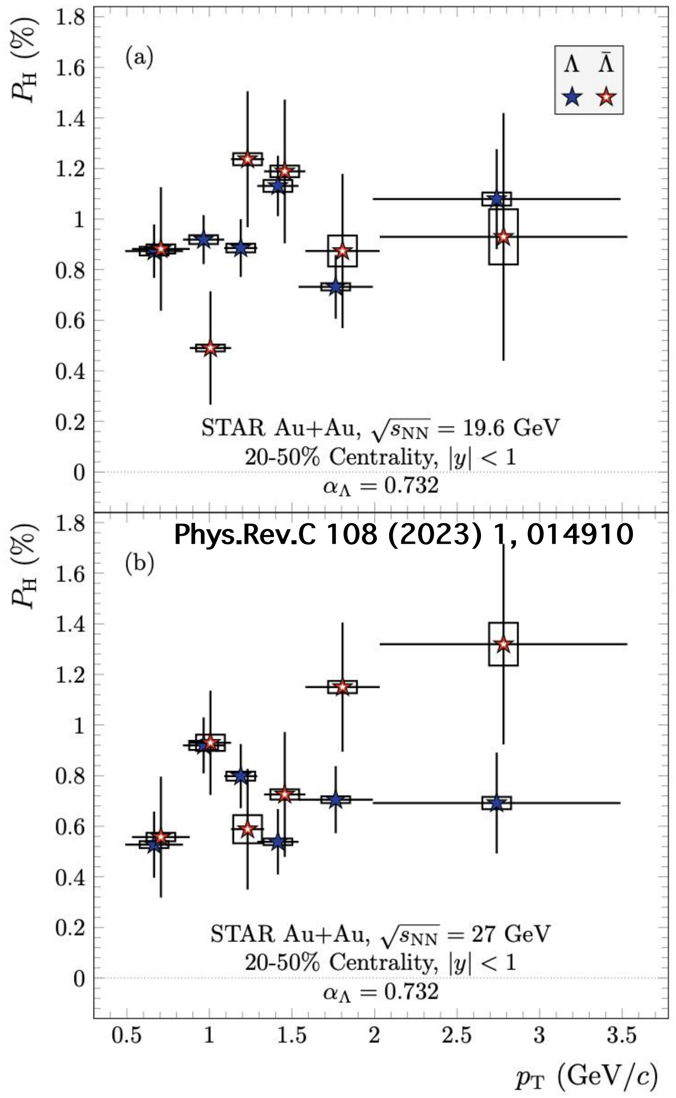


Global polarization v.s. p_T

➢ No obvious p_T dependence of global polarization found. Some models like AMPT and UrQMD can describe this behavior.







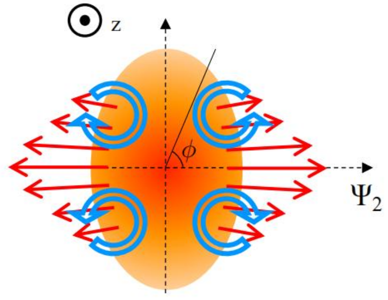
Longitudinal (Local) polarization

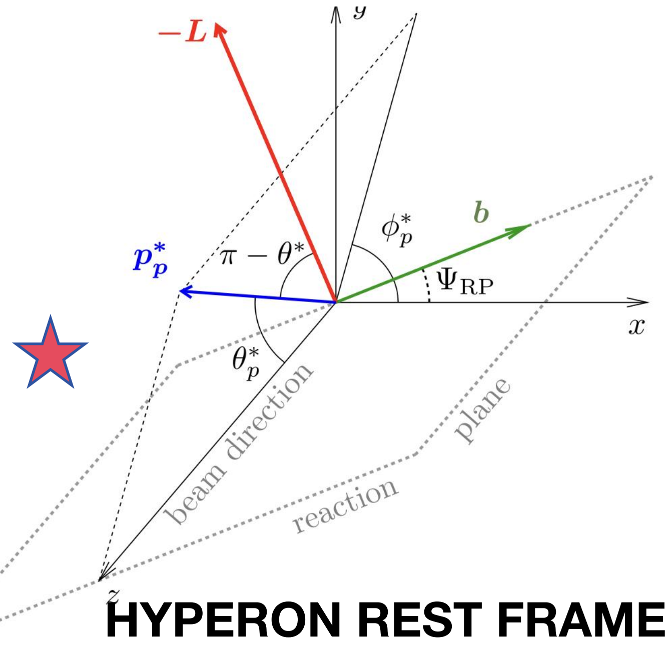
- The longitudinal component of the polarization can be measured by projecting the polarization onto the beam direction, denoted as P_z and called **local polarization**, **arises from inhomogeneous expansion of the fireball (ϕ-dependent velocity difference -> vorticity along beam)**:

$$P_z = \frac{\langle cos(\theta_p^*) \rangle}{\alpha_H \langle cos^2(\theta_p^*) \rangle}$$

  - $\langle cos^2(\theta_p^*) \rangle$ account for **pseudorapidity dependent detector acceptance effects**, should be **1/3** if detector has perfect acceptance and efficiency
  - To get $\langle cos(\theta_p^*) \rangle$, two methods are proposed [Phys. Rev. C 98, 014910 (2018)]
    - The event plane method
    - Invariant mass method. By this method the measurable is changed to the Fourier sine coefficient of Pz (usually second-order) (resolution corrected)

$$P_{z,s_n} = \langle P_z sin(n\phi_p^* - n\Psi_n) \rangle = \frac{\langle cos(\theta_p^*) sin(n\phi_p^* - n\Psi_2) \rangle}{\alpha_H R_n \langle cos^2(\theta_p^*) \rangle}$$



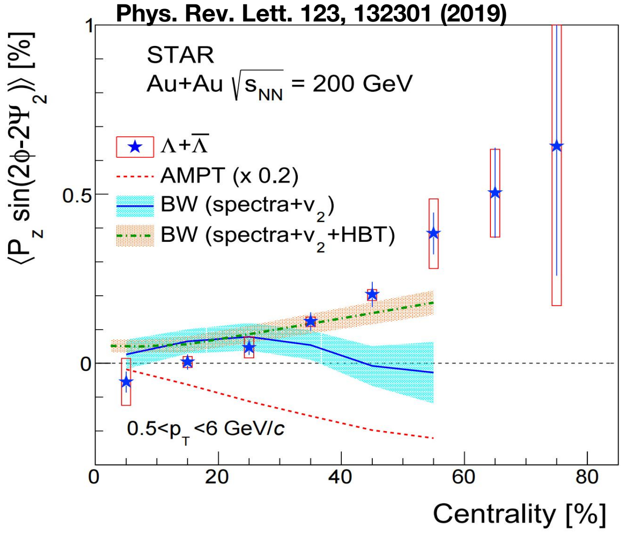


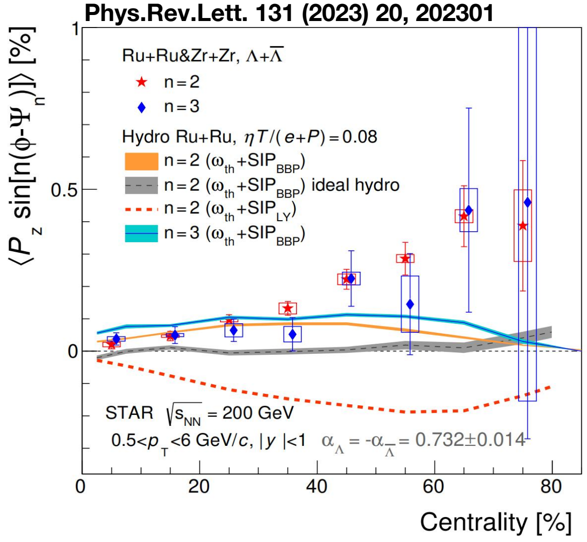
HYPERON REST FRAME

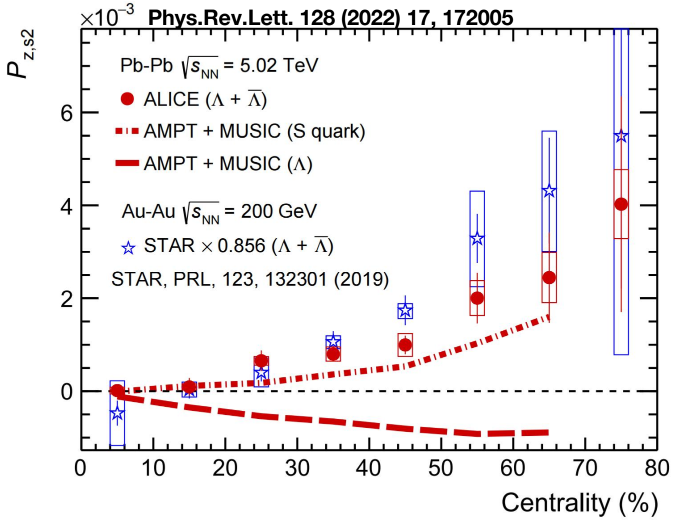
main contribution from elliptic flow induced vorticity

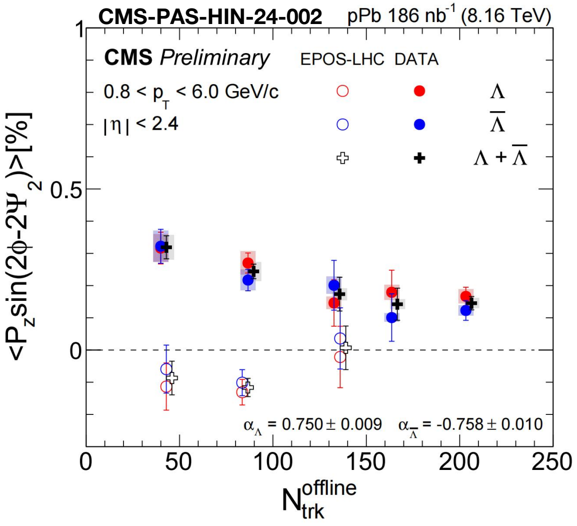
Local polarization v.s. Centrality

- The increase of the signal with increasing centrality is **likely due to increasing elliptic flow contributions** in peripheral collisions.
  - They are found to be consistent in:
    - 5.02 TeV PbPb collisions (ALICE, Phys.Rev.Lett. 128 (2022) 17, 172005)
    - 200 GeV AuAu collisions (STAR, Phys. Rev. Lett. 123, 132301 (2019))
    - 200 GeV RuRu and ZrZr collisions (STAR, Phys.Rev.Lett. 131 (2023) 20, 202301)
  - But the result in CMS does not follow the trend of elliptic flow in 8.16 TeV pPb collisions (CMS-PAS-HIN-24-002)









Local polarization v.s. p_T

- The increase of the signal with increasing p_T is **likely due to increasing elliptic flow contributions**
  - They are found to be consistent in:
    - 5.02 TeV PbPb collisions (ALICE, Phys.Rev.Lett. 128 (2022) 17, 172005)
    - 200 GeV AuAu collisions (STAR, Phys. Rev. Lett. 123, 132301 (2019))
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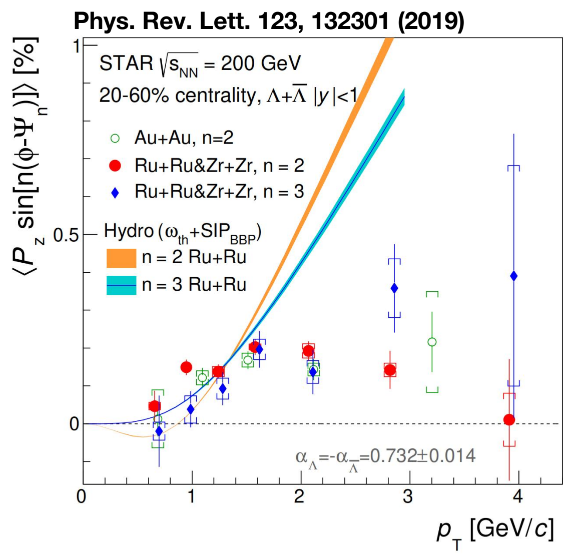
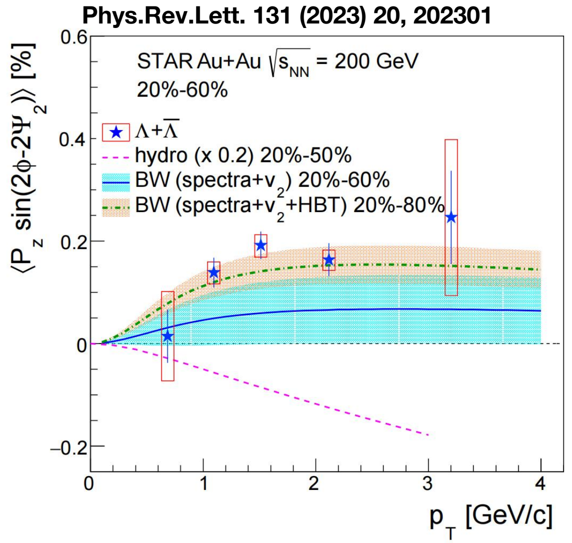
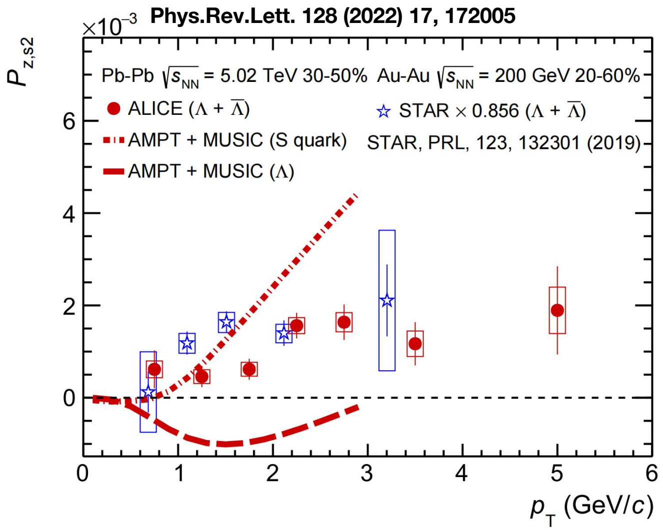
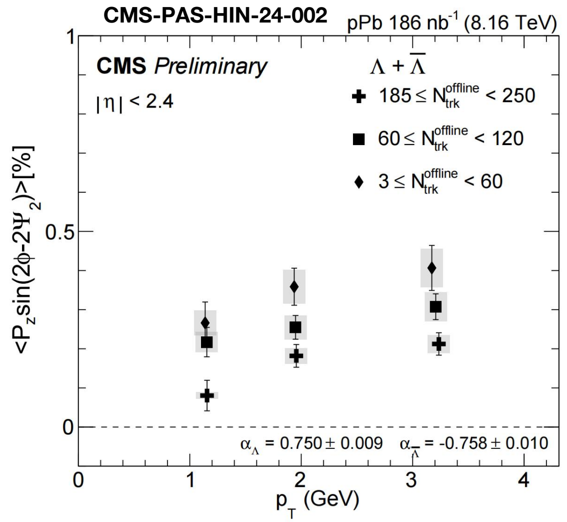
    - 8.16 TeV pPb collisions (CMS-PAS-HIN-24-002)



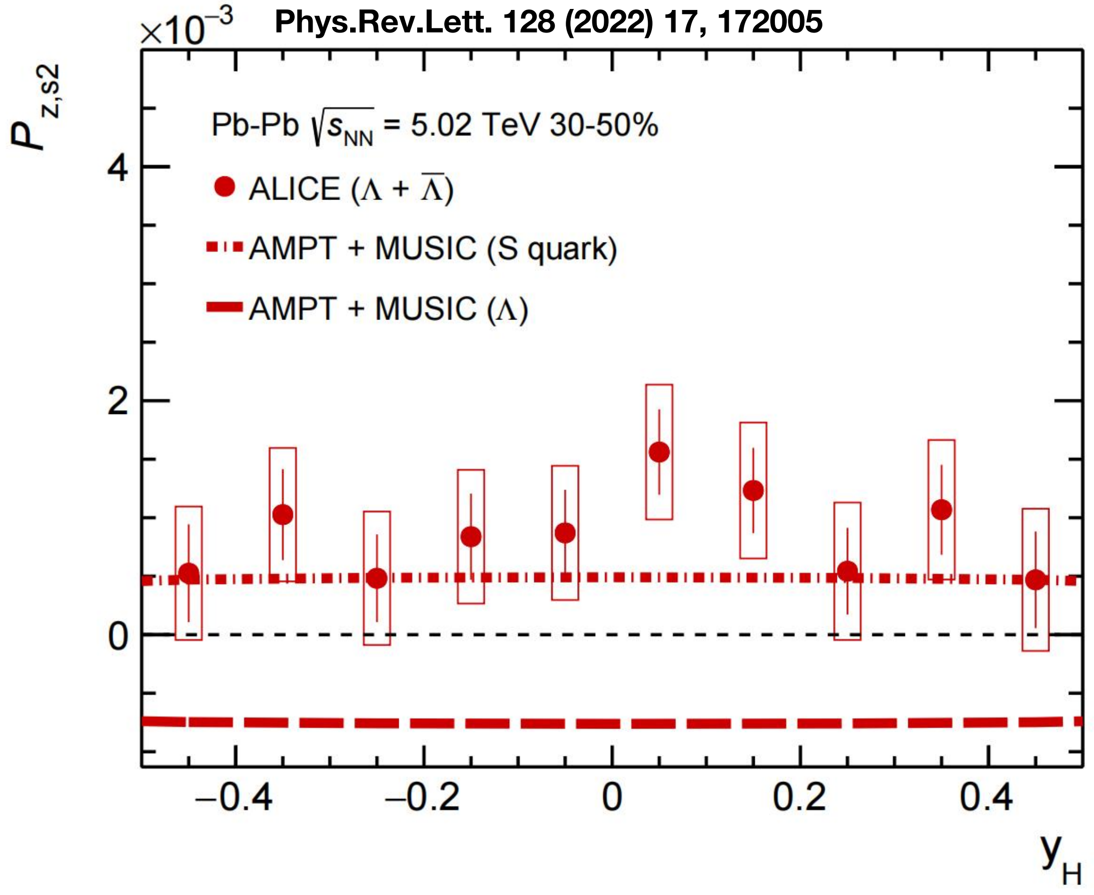






Local polarization v.s. y

- No rapidity dependence has been found for local polarization in 5.02 TeV PbPb collisions
- Can be described by AMPT model

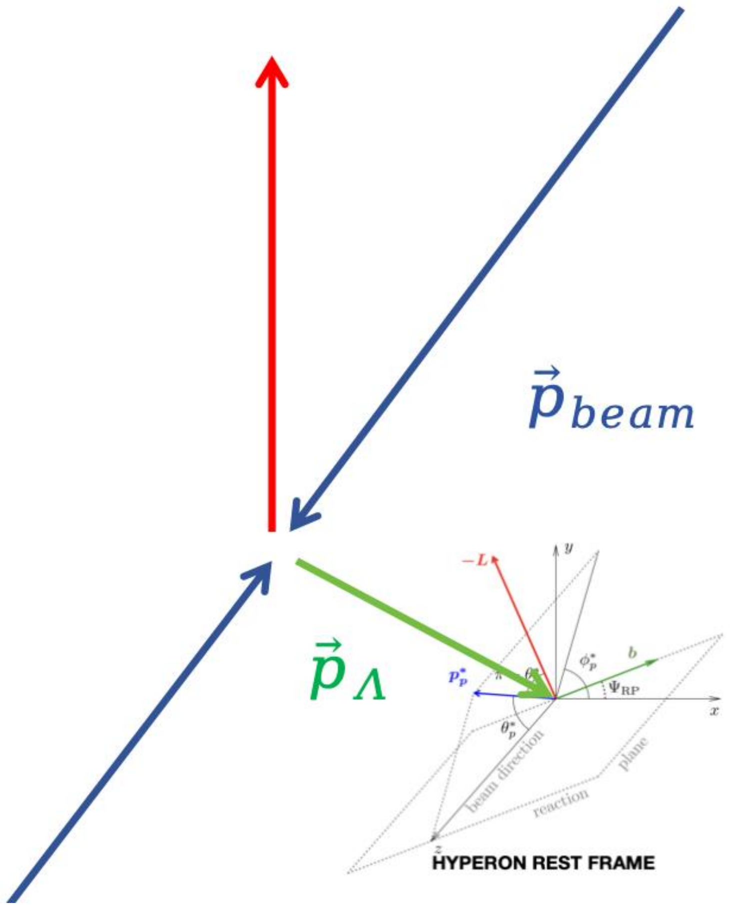


Transverse Polarization

- Transverse polarization is the polarization in direction $\vec{n}$, which is **normal to the production plane**, spanned by $\{\vec{p}_{beam}, \vec{p}_{\Lambda}\}$
- **Revelant measurement**
  - 68.4 GeV pNe collisions (LHCb, arXiv:2405.11324v1)
  - 7TeV pp collisions (ATLAS, Phys.Rev.D 91 (2015) 3, 032004)
  - 10.58 GeV ee collisions (Belle, Phys.Rev.Lett. 122 (2019) 4, 042001)
  - 800 GeV proton+A (FermiLab, Phys.Lett.B 338 (1994) 403-408)
  - ...

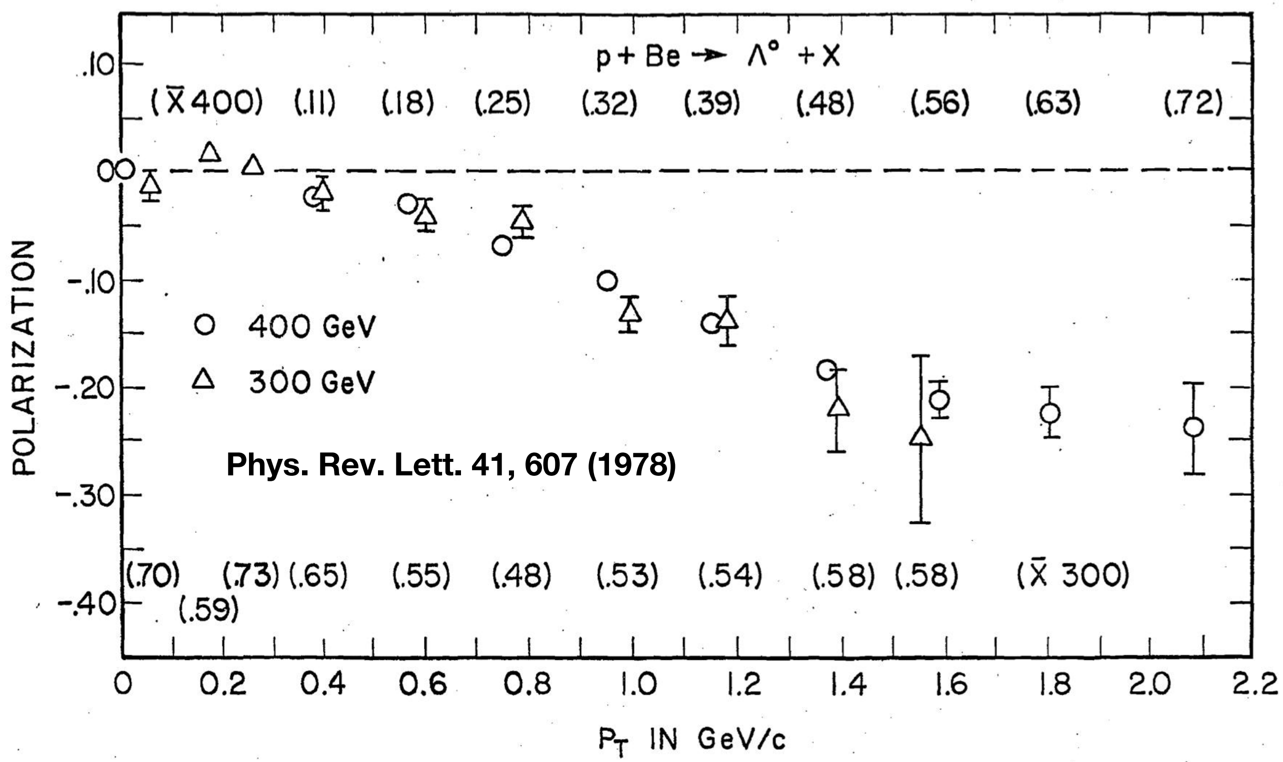
Most of them did not find polarization for $\bar{\Lambda}$

$$\vec{n} = \vec{p}_{beam} \times \vec{p}_{\Lambda}$$



Transverse Polarization v.s. $\sqrt{s_{NN}}$

- The following fixed-target experiments:
  - Phys. Rev. Lett. 36, 1113 (1976);
  - Phys. Rev. Lett. 41, 607 (1978);
  - Phys. Rev. Lett. 41, 1348 (1978);
  - Phys. Rev. Lett. 51, 2025 (1983);
  - Phys. Rev. D 43, 2792 (1991).
  - Phys. Rev. D 40, 3557 (1989).
  - Phys. Lett. B 338, 403 (1994).
  - Eur. Phys. J. C 6, 265 (1999).
  - Phys. Lett. B 638, 415 (2006),



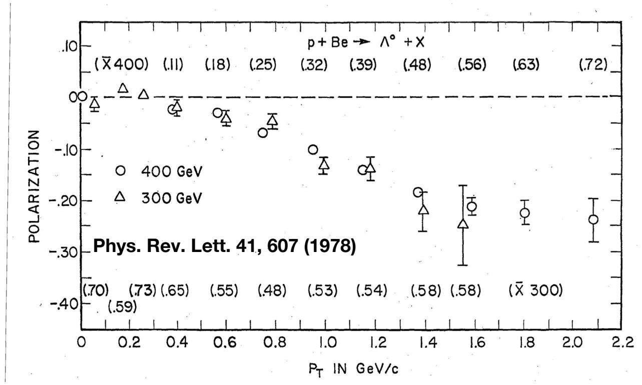
- Did **not observe strong dependence** of the Λ polarization on the collision energy.
- It is not totally independent from energy. High collision energy may **change the proportion of Λ from decays**, about only 40% of data is comparable to that in NA48.

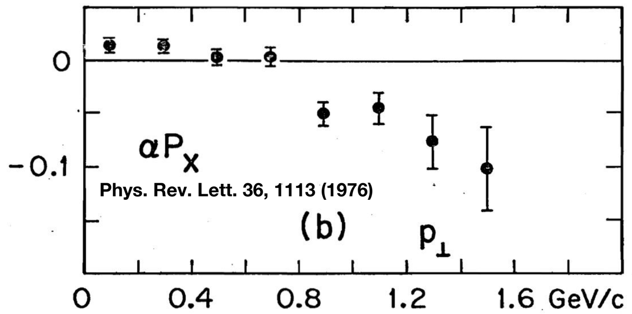
Local polarization v.s. p_T

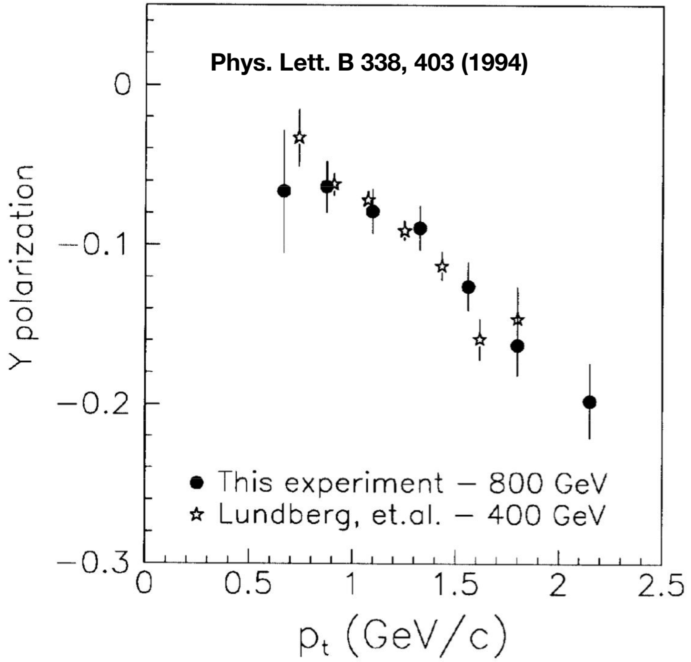
- **Increase** (absolute value) with transverse momentum. But still, $\bar{\Lambda}$ is not transverse polarized (phenomenon, not fully understand)

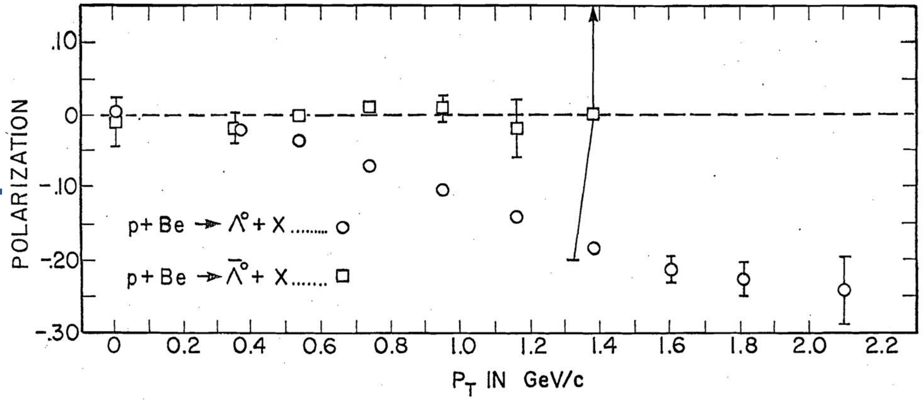
different.

The above comparison makes it clear that polarization is not a universal property of all high energy baryon production. Lambdas, which in this experiment are leading particles, are polarized while the antilambdas, which are unrelated to the incident particle, are not. From the quark picture outlined previously, it might appear that the s quark of the Λ° is produced polarized while the $\bar{s}$ quark of the antilambda is not. Figure 4 illustrates a mechanism, gluon bremsstrahlung, which could give rise to a Λ° polarization without a $\bar{\Lambda}^\circ$ polarization. In the interaction two of the proton quarks, u and d, are spectators in a singlet spin state. The other u quark is scattered by the target and radiates a gluon which produces an $s\bar{s}$ pair. It is the s from the pair which gives the Λ° both its transverse momentum and its spin. The scattered u quark, the $\bar{s}$ and the fragments of the target form the unobserved products. If the gluon is polarized, so is the $s\bar{s}$ pair and this polarization is correlated with the transverse momentum direction of the









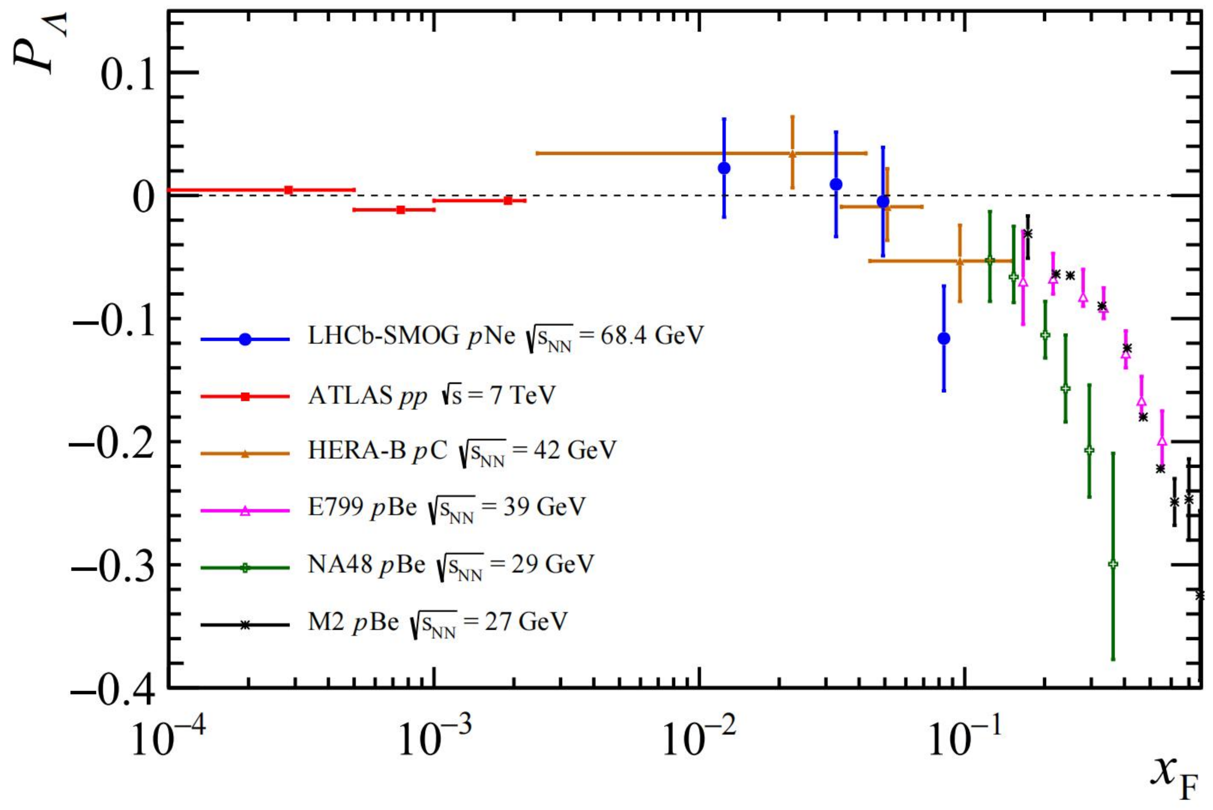
Transverse Polarization v.s. x_F

- **Increase significantly** with increasing absolute Feymann-x, which is defined as,

$$x_F = \frac{p_L}{p_{L,\,max}}$$

where p_L is the longitudinal momentum, and $p_{L,\,max}$ is the maximum of p_L can reach, which is half the center-of-mass energy. So it becomes,

$$x_F = \frac{2p_L}{\sqrt{s_{NN}}}$$



Comparison

➢ Global polarization

- Along $\vec{L}$
- **Originate** from spin-orbit interaction
- Provide information of:
  - **initial condition** and **dynamics of QGP** (*e.g. split on particle and anti-particle global polarization give information about magnetic field in heavy-ion collisions and electric-conductivity in QGP*)
  - both the **nature of the spin-orbit interaction** and the **profile of velocity fields** of the expanding system
- Its observation characterizes the system created in heavy-ion collision as the **most vortical** fluid known
- Can be **(relatively) well described** by models, see ref 1~6 in the next page

➢ Local polarization

- Along $\vec{z}$
- **Originate** from vorticity induced by gradient pressure from the in-homogeneous expansion of fireball
- Provide information of:
  - vorticity induced by elliptic flow
  - fluid nature during expansion of fireball
- **Poorly described**, most of them give opposite sign or over-estimated magnitude, see ref 7~10 next page. On the other hand, the calculations based on a simple blast-wave model [11,12] utilizing only kinematic vorticity and without the temperature gradient and acceleration contributions **can describe** experimental data well. Known as **spin puzzle**.

➢ Transverse polarization

- Along $\vec{z} \times \vec{p}_{\Lambda}$
- Origination remain unknown
- Provide information for the fragmentation process in Λ production
- **No successful model reach full description**, compare with other measurement through extrapolation

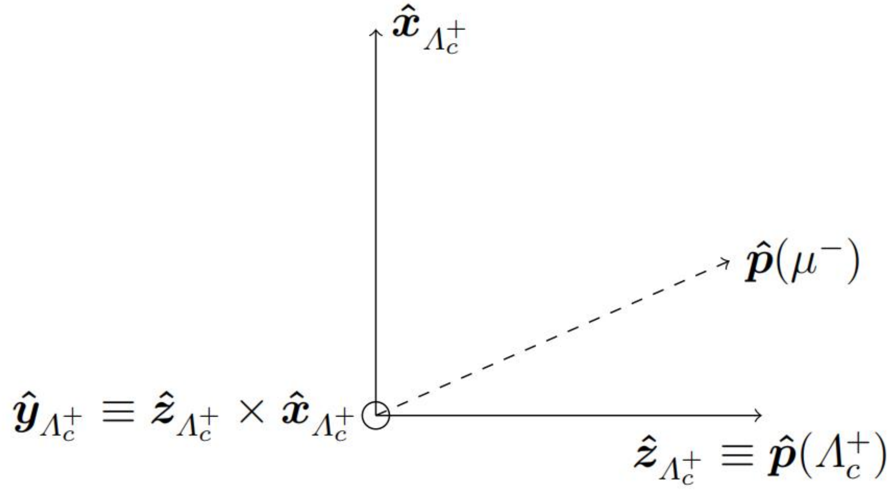
Reference for last page

1. Eur. Phys. J. C 77, 213 (2017)
2. Phys. Rev. C 96, 054908 (2017)
3. Phys. Rev. C 96, 024906 (2017)
4. Phys. Rev. C 95, 031901(2017)
5. Phys. Rev. C 100,014908 (2019)
6. Phys. Lett. B 803, 135298(2020)
7. Phys. Rev. Lett. 120, 012302 (2018)
8. Phys. Rev. C 98, 024905 (2018)
9. Phys. Rev. C 103, 024903 (2021)
10. Phys. Rev. C 100, 054907 (2019)
11. Phys. Rev. C 48, 2462 (1993)
12. Phys. Rev. C 70, 044907 (2004)

Lambda_c polarization

Component	Value (%)
P_x (*lab*)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (*lab*)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (*lab*)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x ($\tilde{B}$)	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y ($\tilde{B}$)	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z ($\tilde{B}$)	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

$$\begin{aligned}
\hat{\boldsymbol{z}}_{\Lambda_c^+} &= \hat{\boldsymbol{p}}(\Lambda_c^+) \\
\hat{\boldsymbol{x}}_{\Lambda_c^+} &= \frac{\boldsymbol{p}(\mu^-) - [\boldsymbol{p}(\mu^-)\cdot\hat{\boldsymbol{p}}(\Lambda_c^+)]\,\hat{\boldsymbol{p}}(\Lambda_c^+)}{|\boldsymbol{p}(\mu^-) - [\boldsymbol{p}(\mu^-)\cdot\hat{\boldsymbol{p}}(\Lambda_c^+)]\,\hat{\boldsymbol{p}}(\Lambda_c^+)|} \\
&= \frac{\boldsymbol{p}(\Lambda_c^+)\times\boldsymbol{p}(\mu^-)}{|\boldsymbol{p}(\Lambda_c^+)\times\boldsymbol{p}(\mu^-)|}\times\hat{\boldsymbol{p}}(\Lambda_c^+) \\
\hat{\boldsymbol{y}}_{\Lambda_c^+} &= \hat{\boldsymbol{z}}_{\Lambda_c^+}\times\hat{\boldsymbol{x}}_{\Lambda_c^+} \\
&= \frac{\boldsymbol{p}(\Lambda_c^+)\times\boldsymbol{p}(\mu^-)}{|\boldsymbol{p}(\Lambda_c^+)\times\boldsymbol{p}(\mu^-)|},
\end{aligned}$$



lab frame and approximate rest frame of lambda_B
(non-detectable neutrino)