Global Λ Polarization Without Vorticity: Insights from a 50–Year Spin Puzzle

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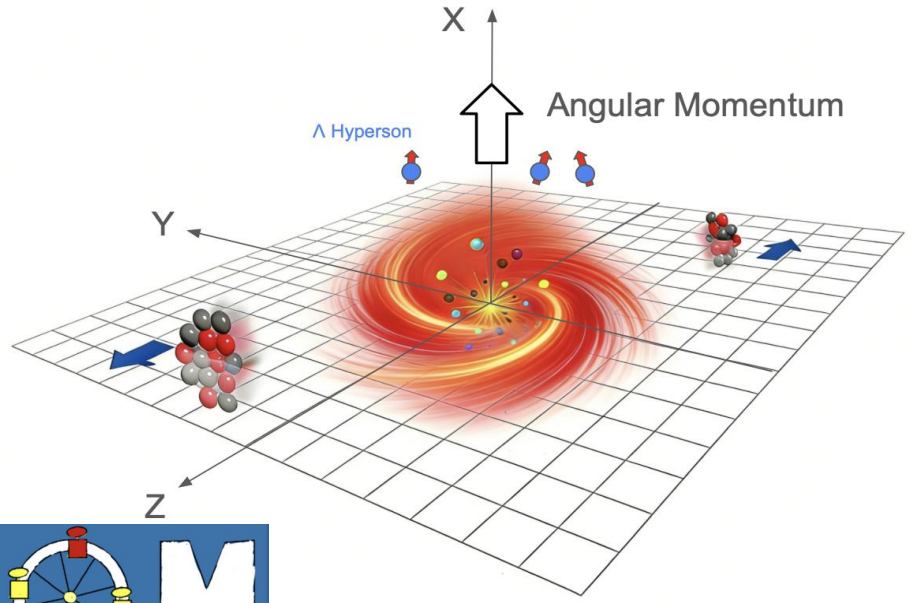
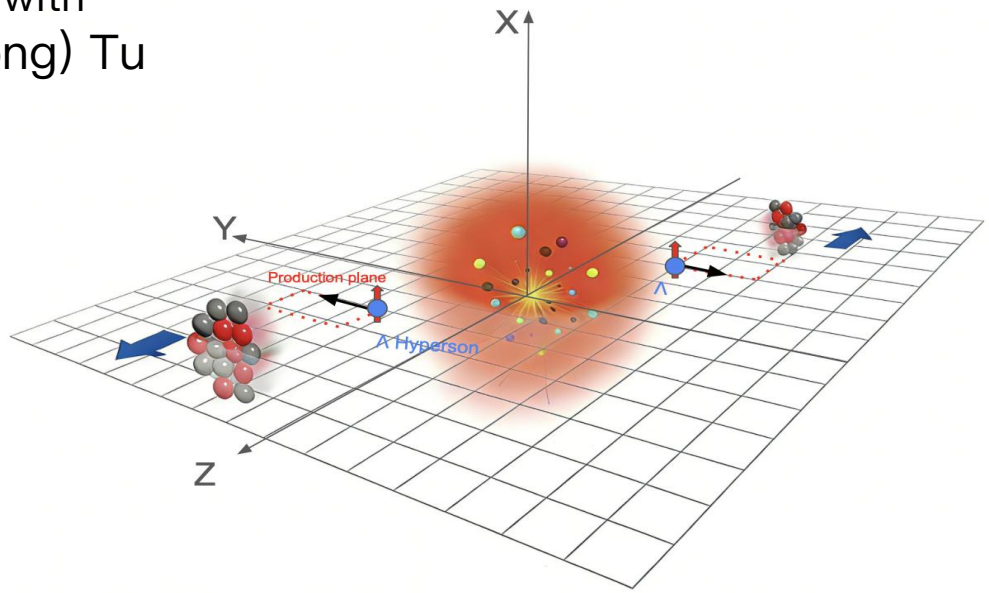
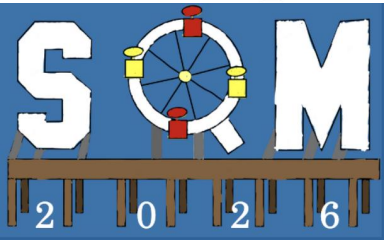






Based on arXiv 2603.19581

Global Polarization in Heavy Ion Collisions

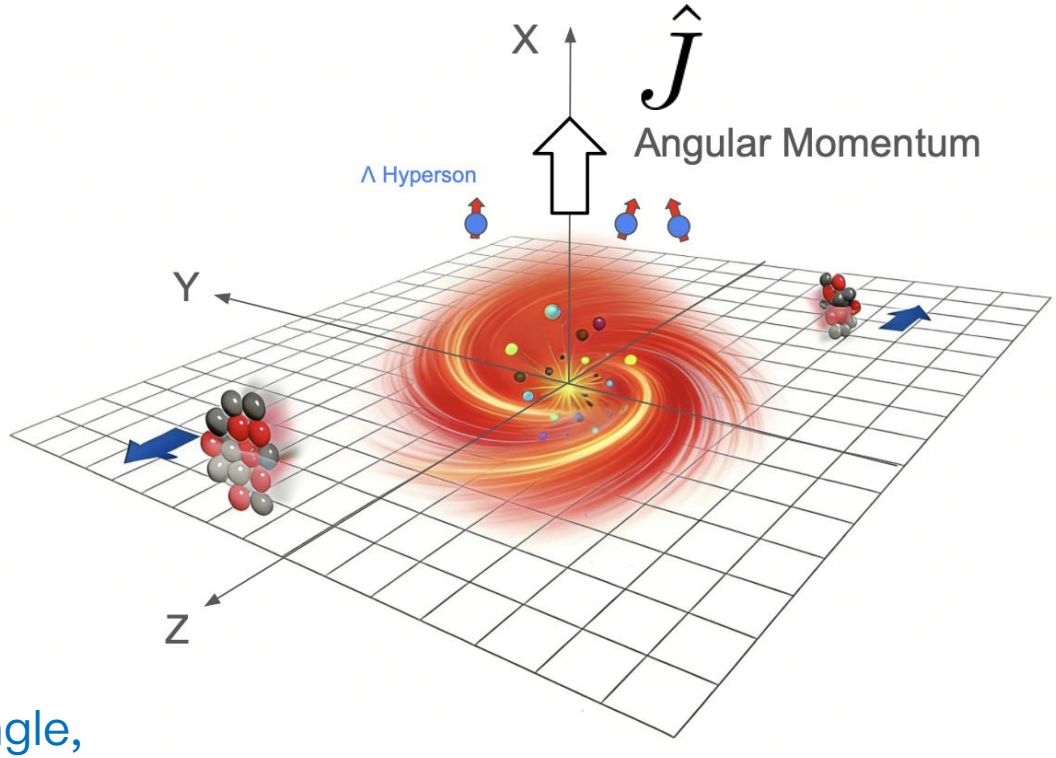
- **The produced QGP behaves like rotating liquid with large orbital angular momentum(OAM).**
- Spin–Orbit interaction transfers OAM into particle spin.
- **Particle spin preferentially aligns with OAM.**

Self–analyzing weak decay: $\Lambda \rightarrow p + \pi^-$

$$\overline{P}_\Lambda \equiv \left\langle \vec{P}_\Lambda \cdot \hat{J} \right\rangle = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{\mathrm{EP}}^{(1)}} \left\langle \sin\left(\Psi_1 - \phi_p^*\right) \right\rangle$$

Event Plane, define the OAM

Proton azimuthal angle, a proxy of Λ spin



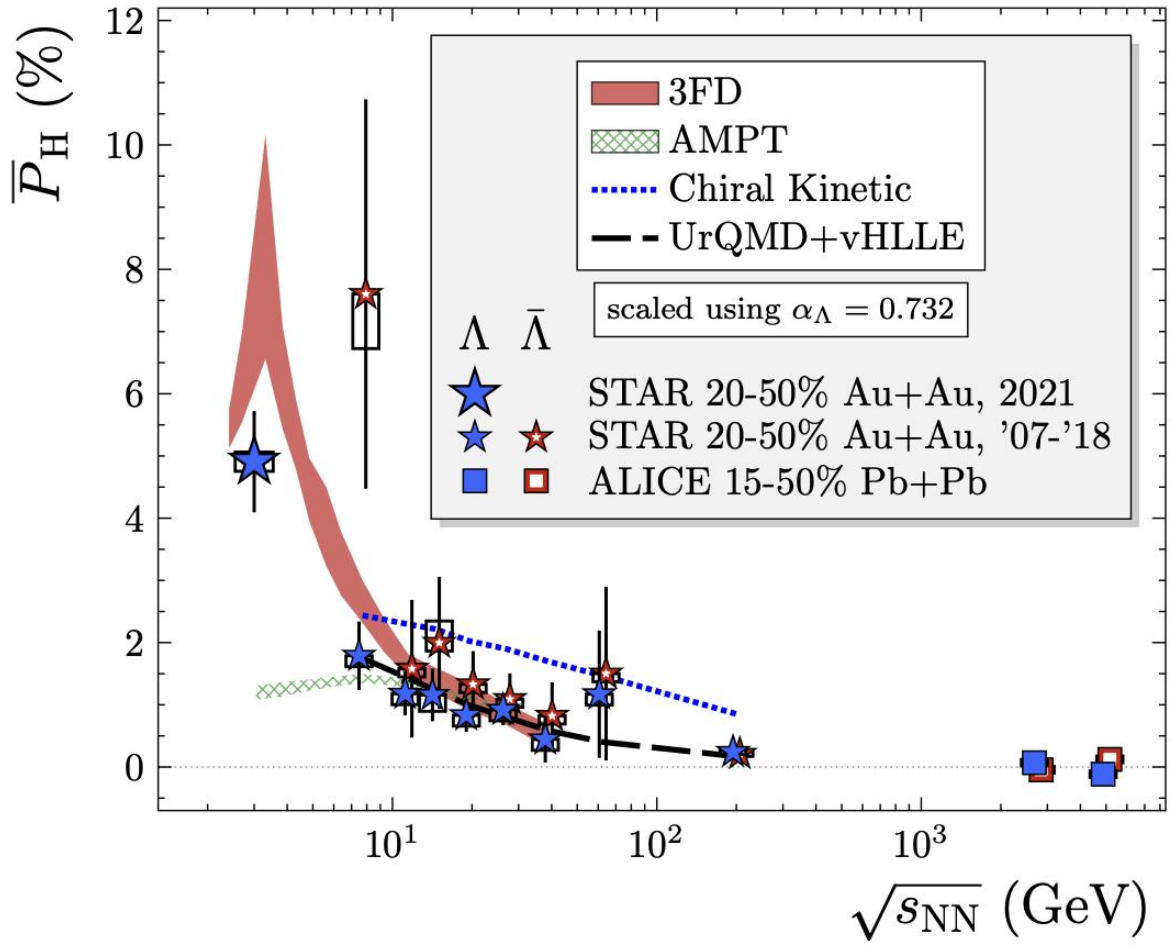
Adapted from figure of Nature 614, 244–248 (2023)

Global Polari sions

- The produced Q
with large orbital
- Spin–Orbit intera
particle spin.
- Particle spin pre

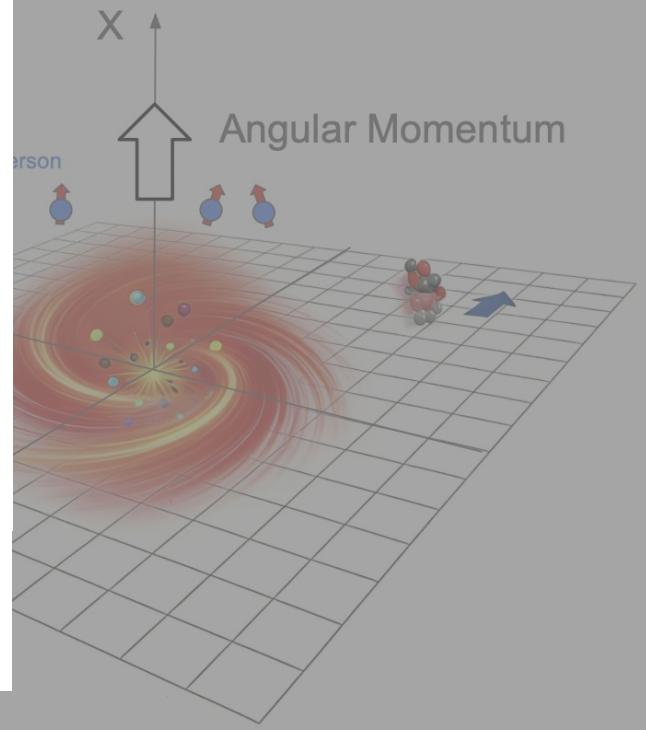
$$\overline{P}_\Lambda \equiv \left\langle \vec{P}_\Lambda \cdot \hat{J} \right\rangle = \frac{8}{\pi c}$$

Phys. Rev. C 104, L061901



A few % of magnitude

but most vorticity ever observed



Event Plane, define the OAM

Proton azimuthal angle, difine Λ spin

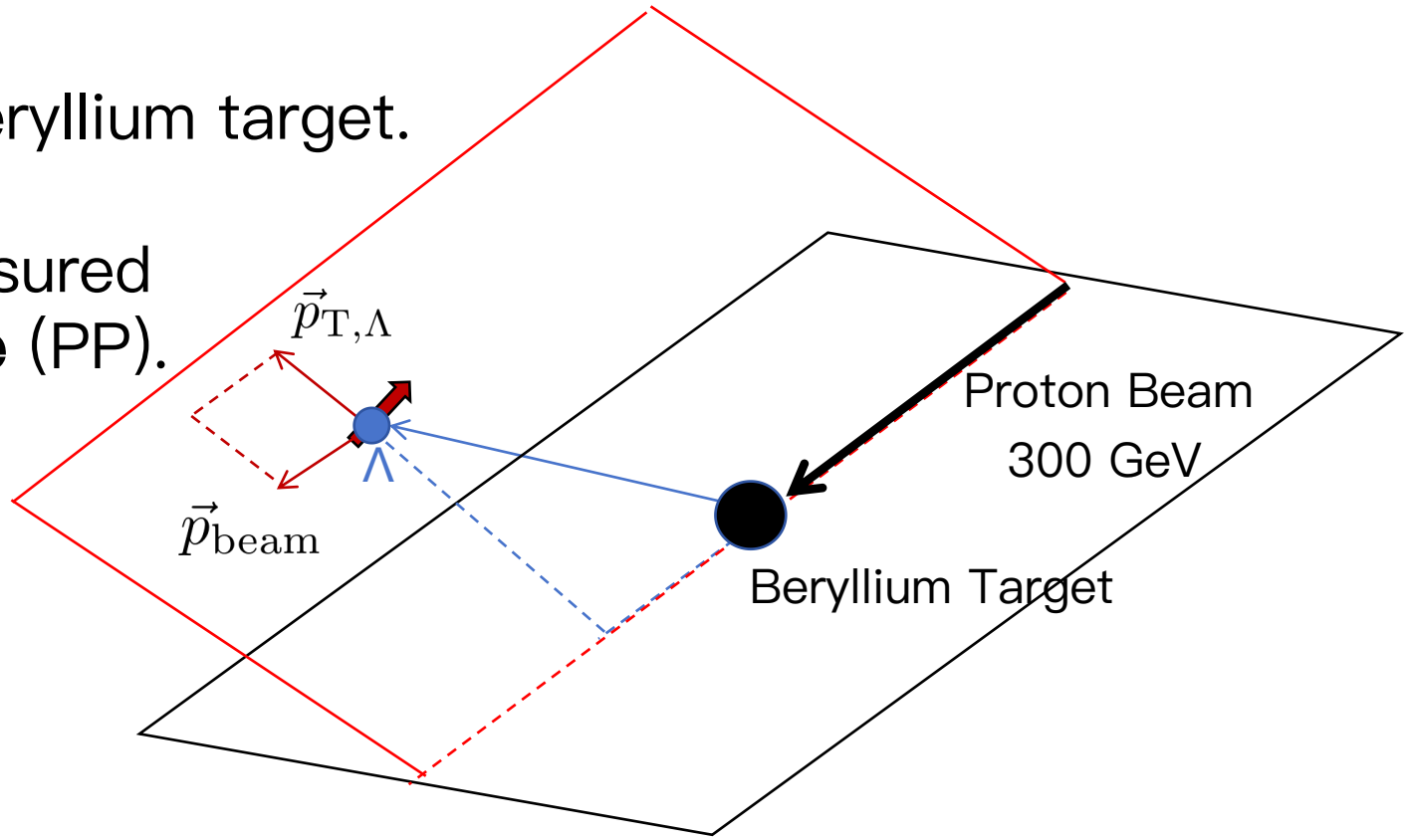
Adapted from figure of Nature 614, 244–248 (2023)

Λ Polarization Puzzle: Transverse Polarization

- First measured at Fermilab in 1976.
- **Unpolarized** proton beam and Beryllium target.
- Transverse polarization was measured with respect to **Production Plane** (PP).

$$\hat{n}_{\mathrm{PP}} = \hat{p}_{\mathrm{beam}} \times \hat{p}_{\mathrm{T},\Lambda}$$

$$\frac{dN}{d\cos\theta_p^*} = \frac{1}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta_p^*)$$



Production Plane

Λ

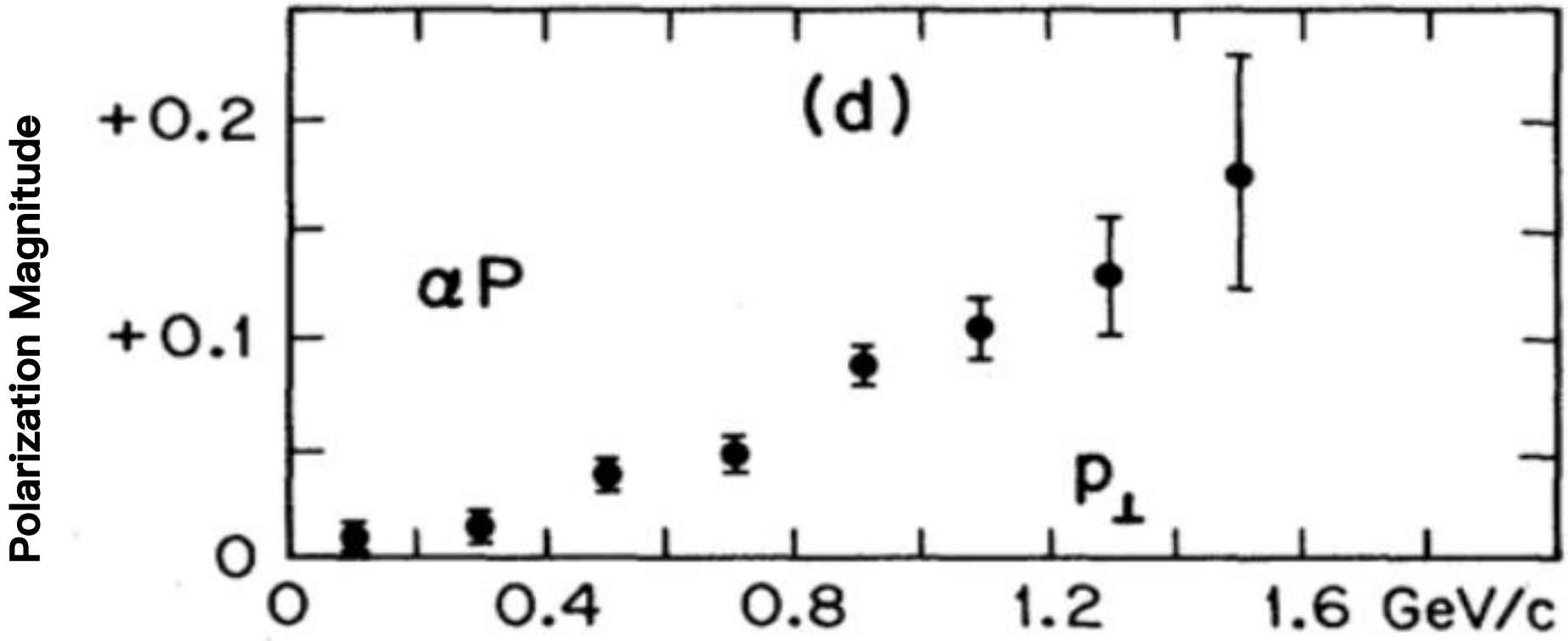
- Fi
- ur
- M

$$\frac{d\sigma}{d\Omega}$$

$$P_\Lambda$$

Λ^0 Hyperon Polarization in Inclusive Production by 300-GeV Protons on Beryllium

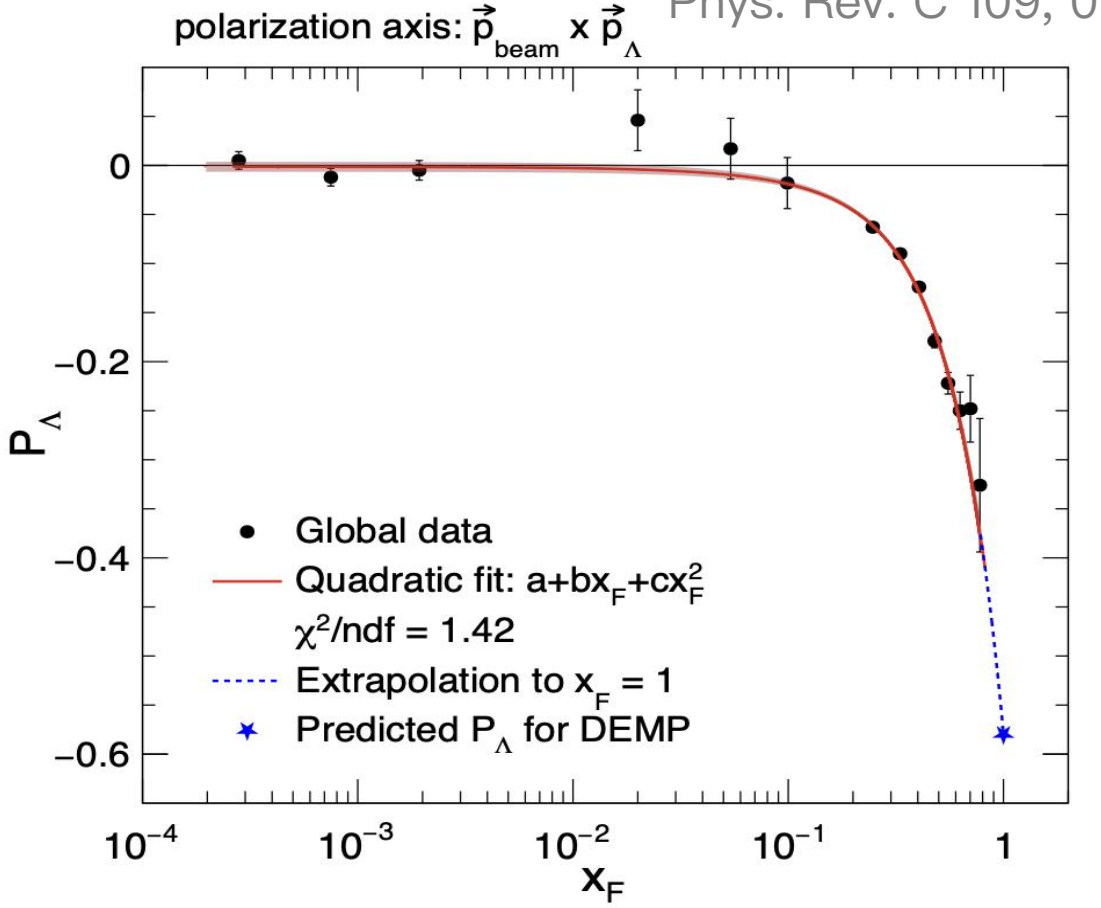
Phys. Rev. Lett. 36, 1113 (1976)



$$\hat{n}_{pp} = \hat{p}_{beam} \times \hat{p}_\Lambda$$

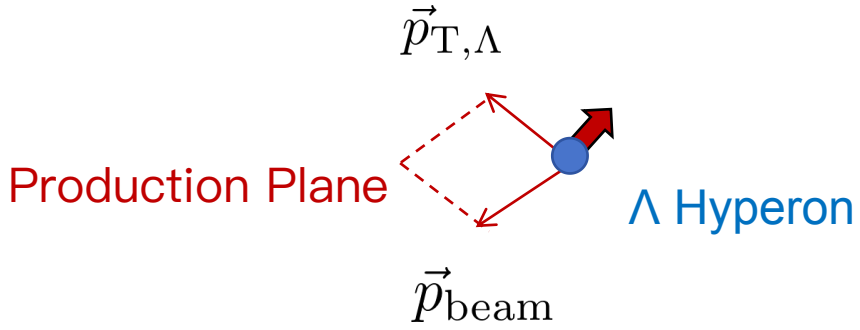
A 50-Year Puzzle: Λ Transverse Polarization

Phys. Rev. C 109, 055205



$$\frac{dN}{d\cos\theta_p^*} = \frac{1}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta_p^*)$$

$^*x_{\mathrm{F}} = p_{\Lambda,\mathrm{z}}/p_{\mathrm{beam}}$



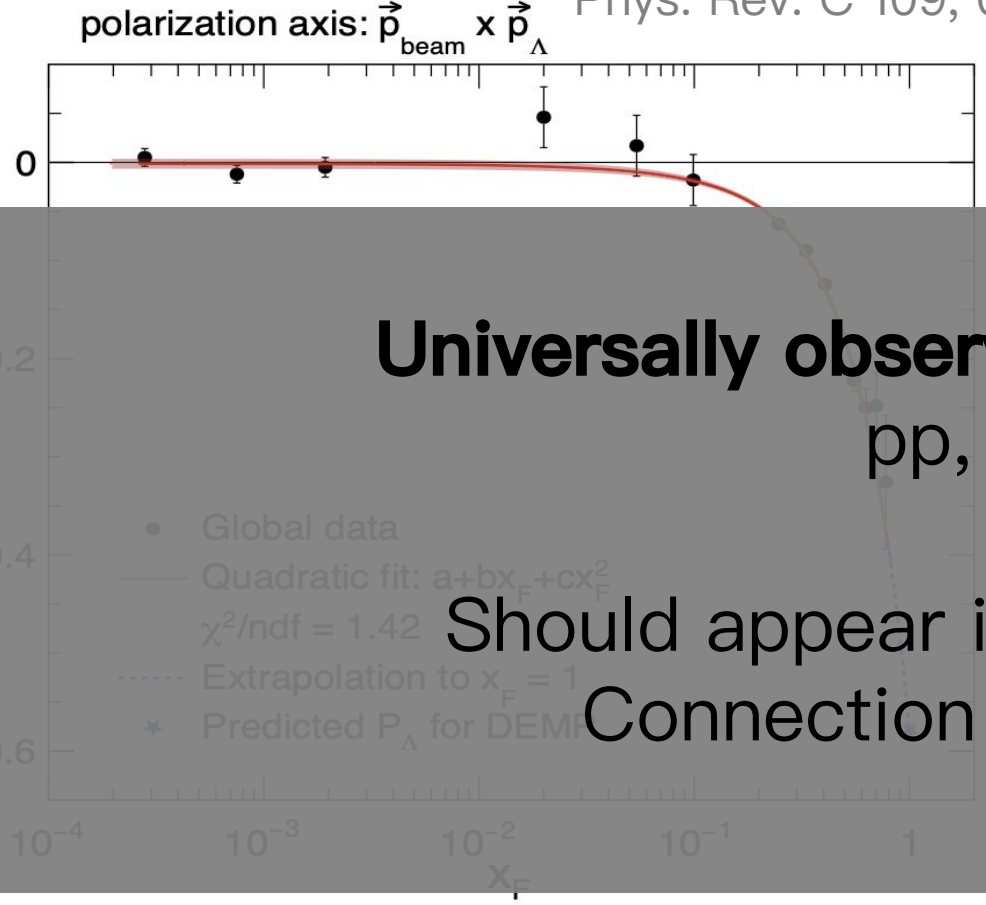
$$\hat{n}_{\mathrm{PP}} = \hat{p}_{\mathrm{beam}} \times \hat{p}_{\mathrm{T},\Lambda}$$

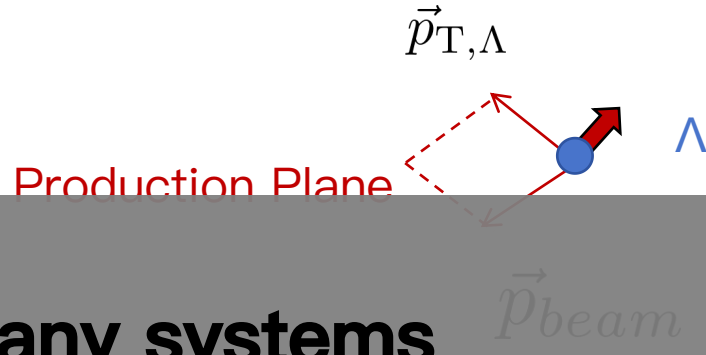
- Λ hyperon is found to be **negatively polarized** with respect to production plane.
- P_Λ strongly depends on Feynman-x ($\mathrm{x_F}$)
- Explanations are many, seem to point to a common direction: *hadronization/final-state effects*.

PRD 24, 2419,
PRL. 68, 907,
PLB Vol. 818, 10 July 2021, 136371
Phys. Rev. D 23, 1227(R) .....

A 50-Year Puzzle: Λ Transverse Polarization

Phys. Rev. C 109, 055205





Universally observed in many systems

pp, pA, ee, DIS ...

- Λ is found to be negatively polarized with respect to production plane.
- P_Λ strongly depends on x_F
- Explanations are too many, all point to non-perturbative hadronization effects.

Should appear in the Heavy Ion Collisions?

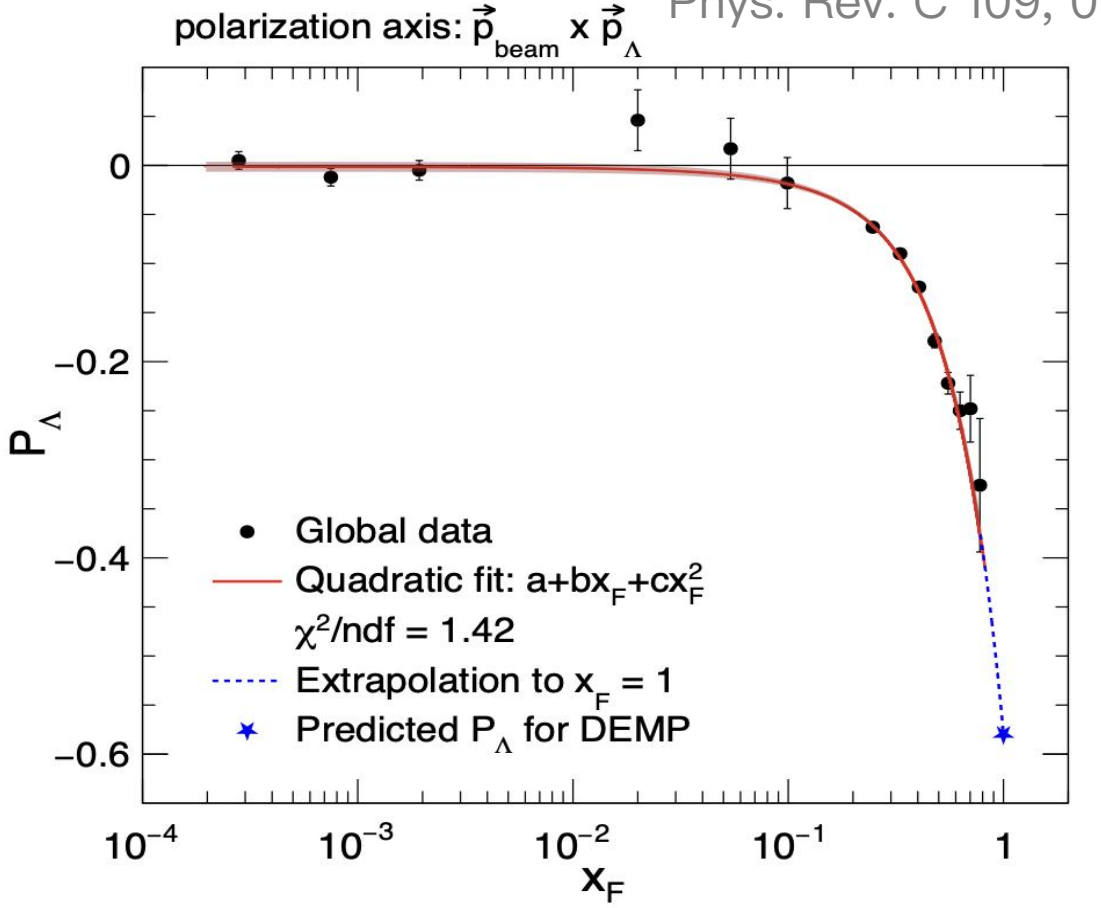
Connection to Global Polarization ?

$$\frac{dN}{d\cos\theta_p^*} = \frac{1}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta_p^*)$$

$$x_F = p_{\Lambda,z}/p_{beam}$$

Λ Transverse Polarization & Global Polarization

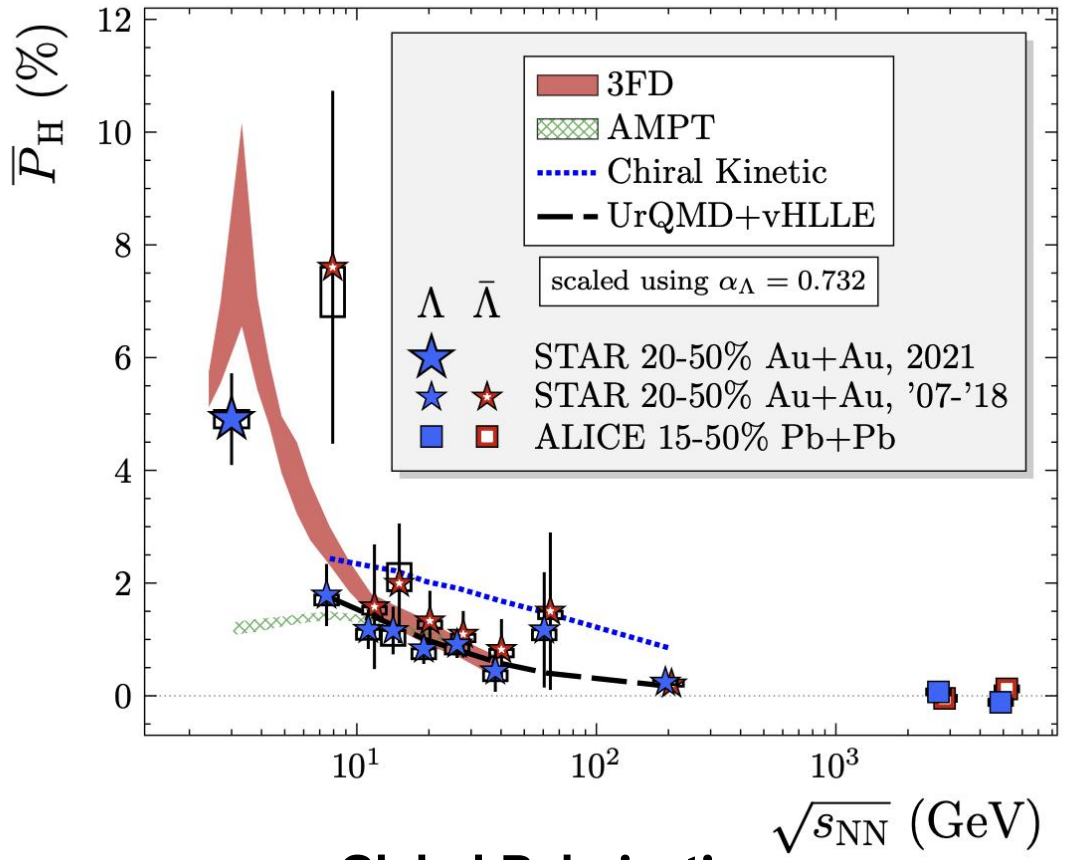
Phys. Rev. C 109, 055205



Transverse Polarization

Hadronization/Final-states effects

Phys. Rev. C 104, L061901



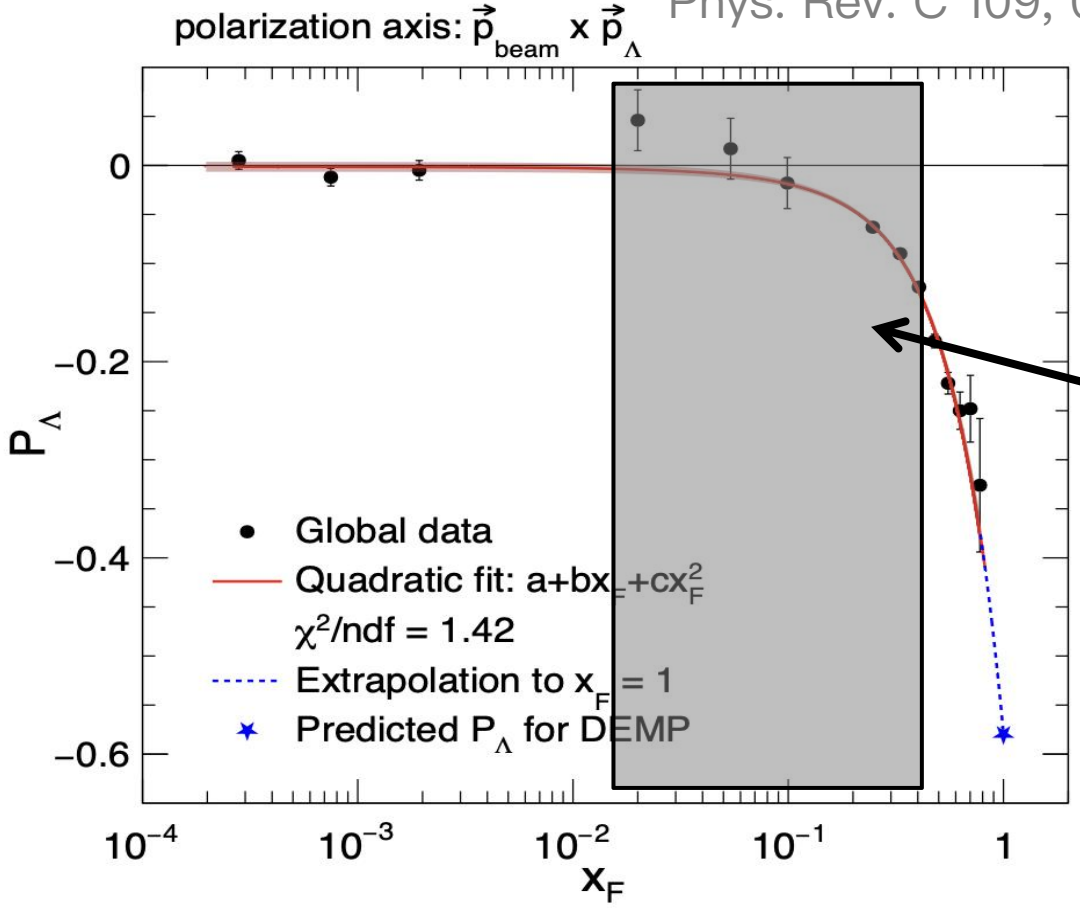
Global Polarization

Vorticity/Partonic Interaction

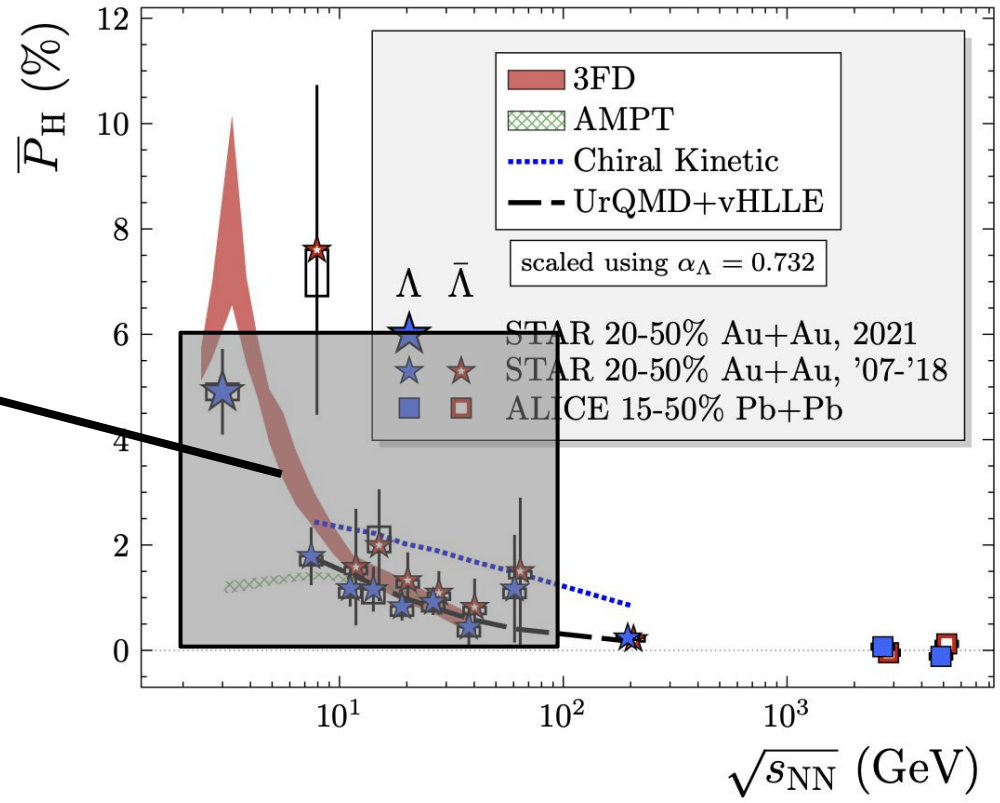
Unrelated plots saying different stories ?

Λ Transverse Polarization & Global Polarization

Phys. Rev. C 109, 055205



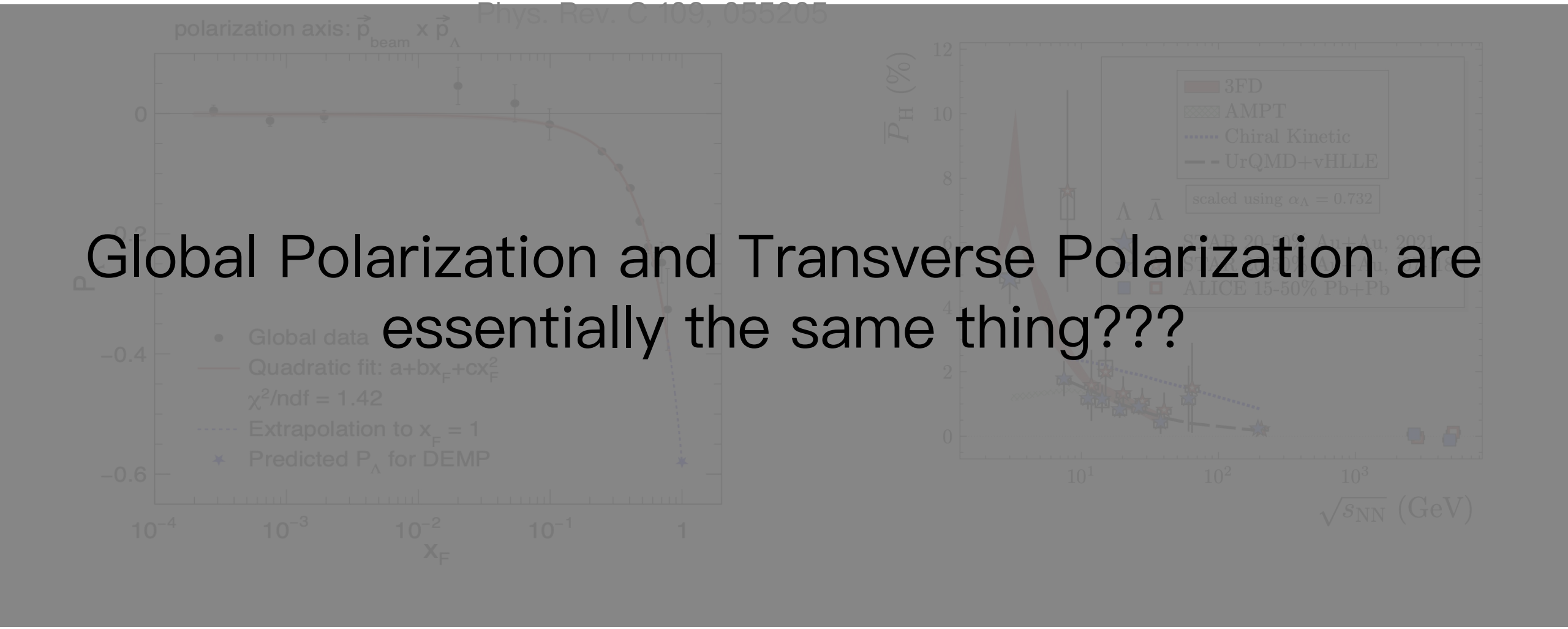
Phys. Rev. C 104, L061901



Λ measured by STAR TPC at this energy range has <xF> of 0.01 - 0.3.

Both are in a few %, similar in magnitude

Λ Transverse Polarization & Global Polarization

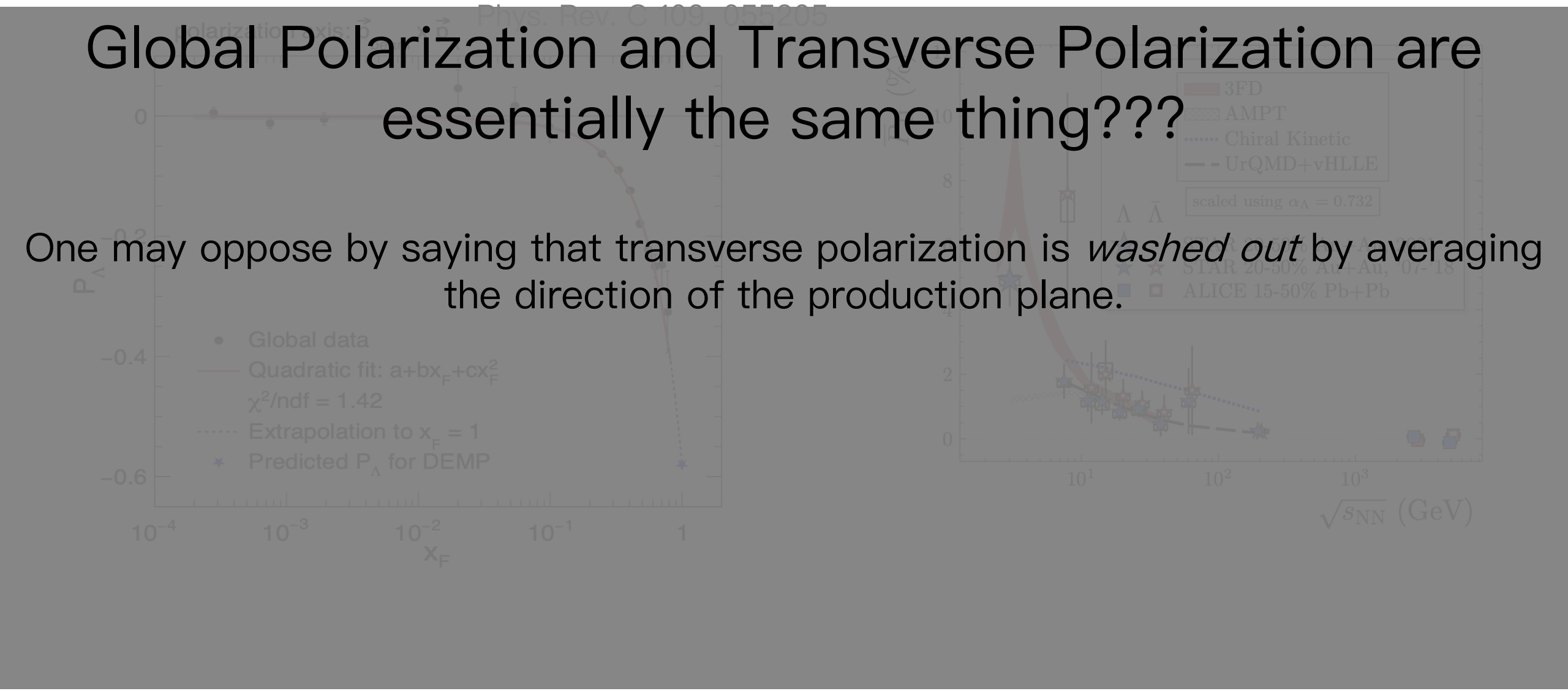


Global Polarization and Transverse Polarization are essentially the same thing???

Λ Transverse Polarization & Global Polarization

Global Polarization and Transverse Polarization are essentially the same thing???

One may oppose by saying that transverse polarization is *washed out* by averaging the direction of the production plane.



Λ Transverse Polarization & Global Polarization

Global Polarization and Transverse Polarization are essentially the same thing???

One may oppose by saying that transverse polarization is *washed out* by averaging the direction of the production plane.

Our prediction:

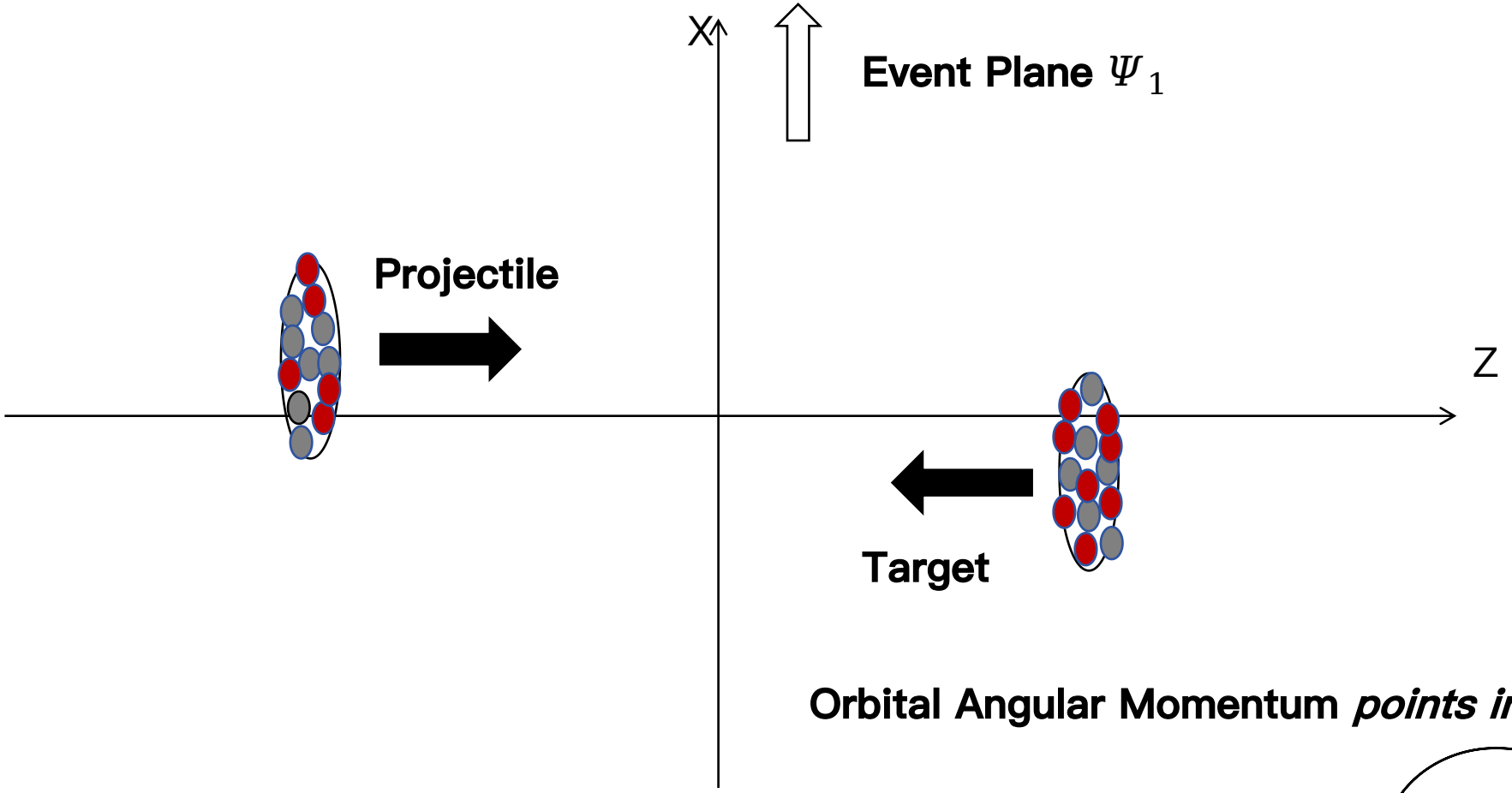
Won't be washed out.

The production plane is influenced by collective flow.

v1 flow can result in an alignment between production plane and reaction plane.

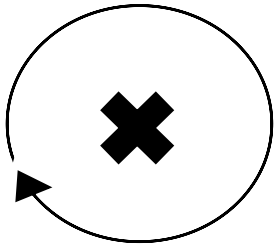
$$\hat{n}_{\mathrm{pp}} = \hat{p}_{\mathrm{beam}} \times \hat{p}_{\mathrm{T},\Lambda}$$

No vorticity, only Λ v1 flow + transverse polarization



Orbital Angular Momentum *points into the page*

$\vec{J}_{\mathrm{orbit}}$



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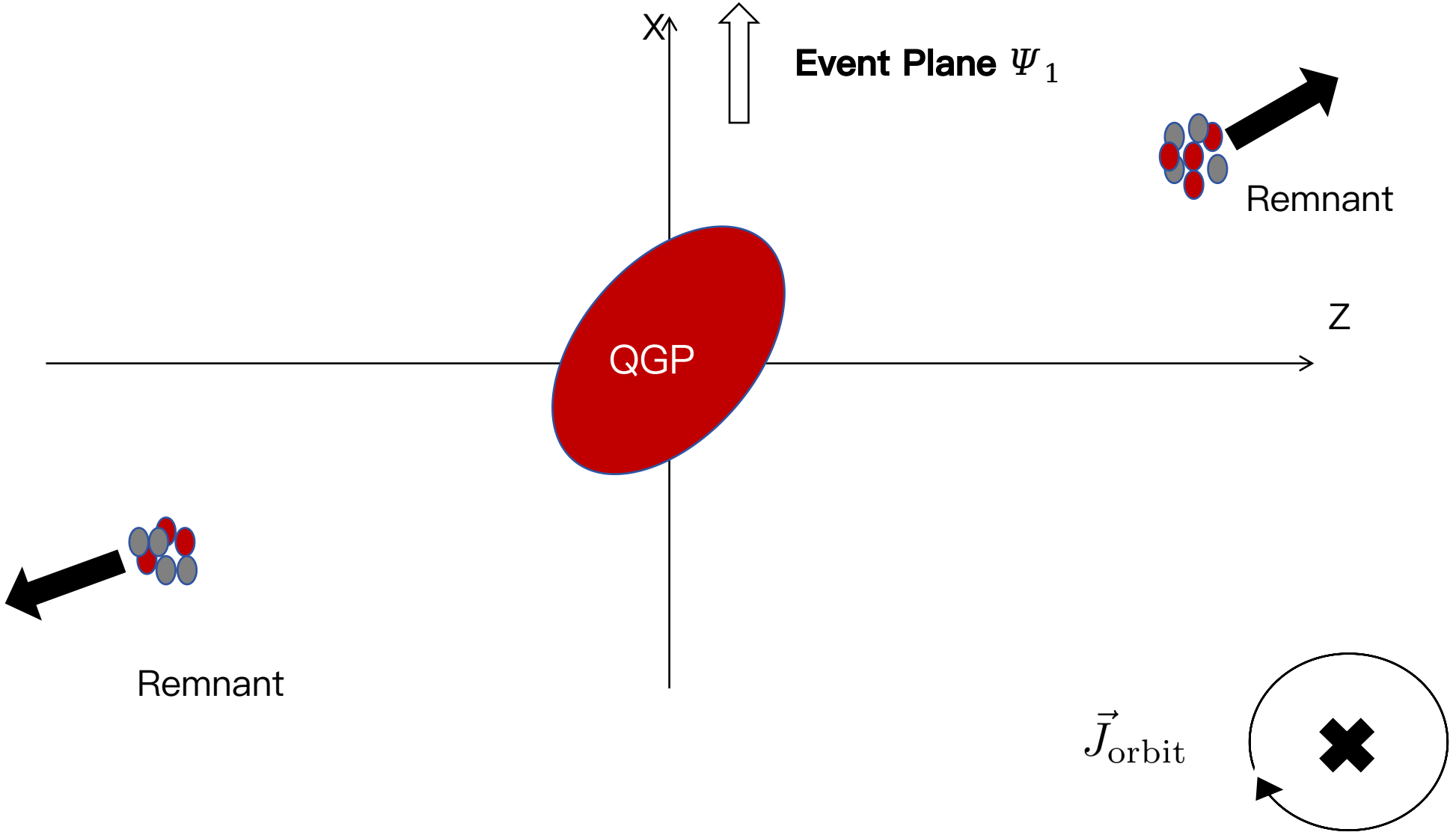

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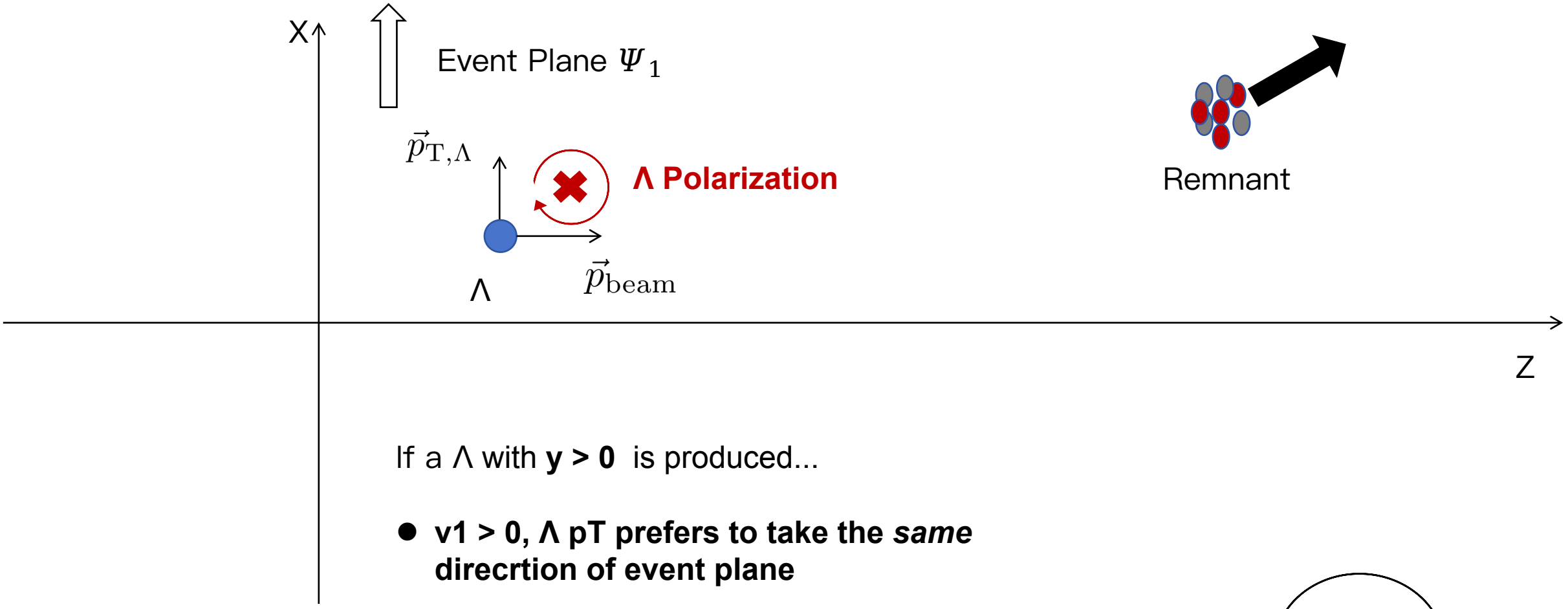
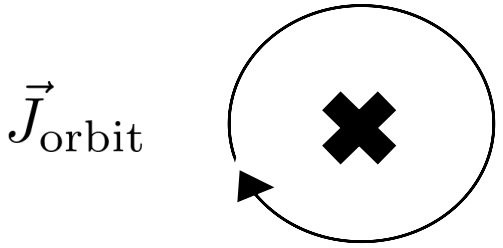


If a Λ with **y > 0** is produced...

- **v1 > 0, Λ pT prefers to take the *same* direcrtion of event plane**
- **Projectile nucleus is beam**

$$\hat{n}_{\mathrm{pp}} = \hat{p}_{\mathrm{beam}} \times \hat{p}_{\mathrm{T},\Lambda}$$

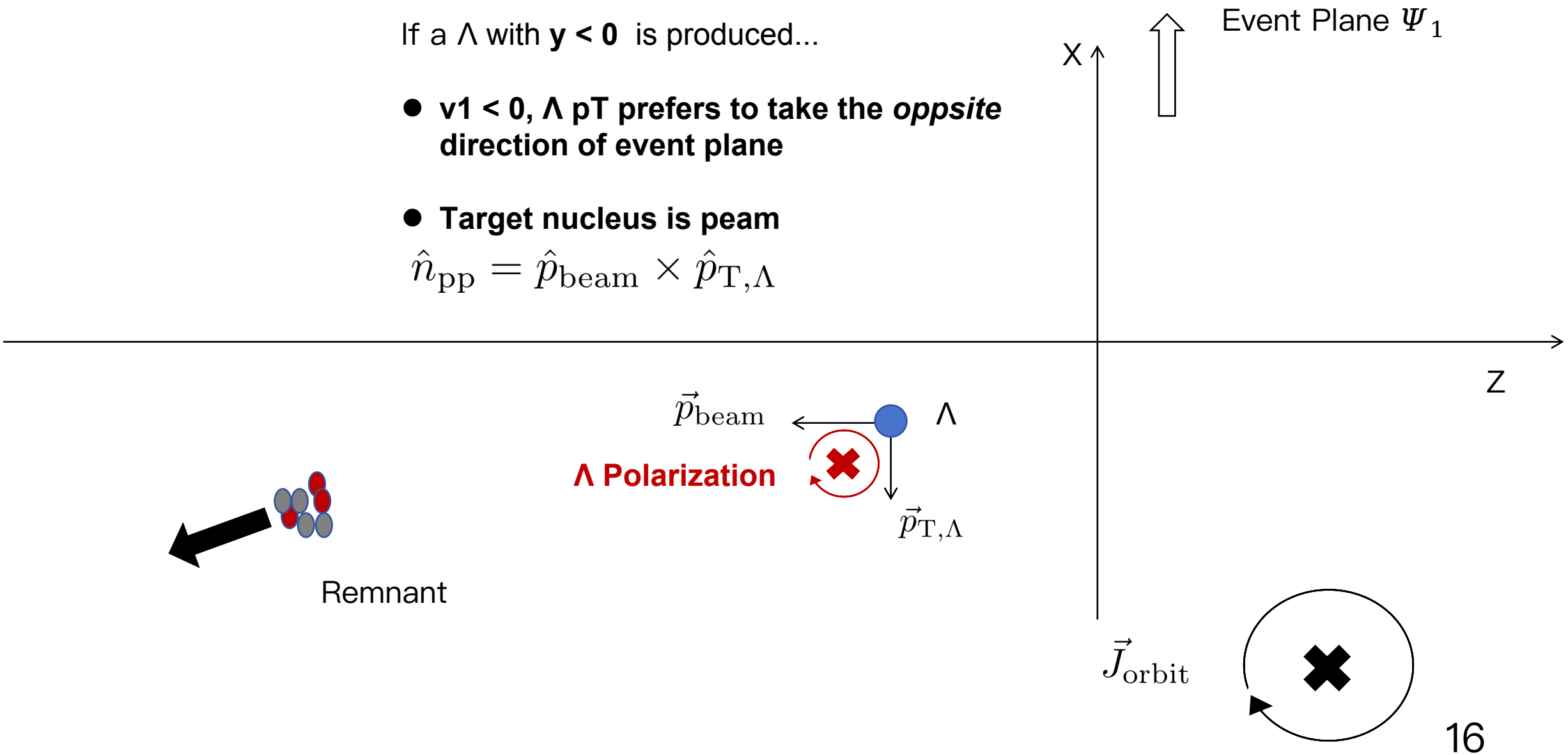


No vorticity, only Λ v1 flow + transverse polarization

If a Λ with **y < 0** is produced...

- **v1 < 0, Λ pT prefers to take the *oppsite* direction of event plane**
- **Target nucleus is peam**

$$\hat{n}_{\mathrm{pp}} = \hat{p}_{\mathrm{beam}} \times \hat{p}_{\mathrm{T},\Lambda}$$



No vorticity, only Λ v1 flow + transverse polarization

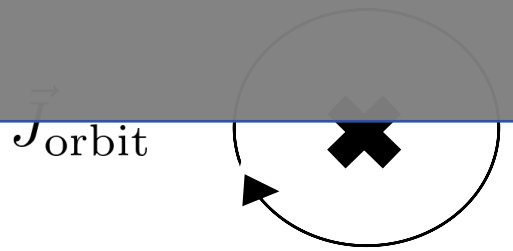
Transverse Polarization coupled with v1 flow

=

Global polarization ?

How much global polarization can be generated by this mechanism ?

Quantitive Assessment has the final word.



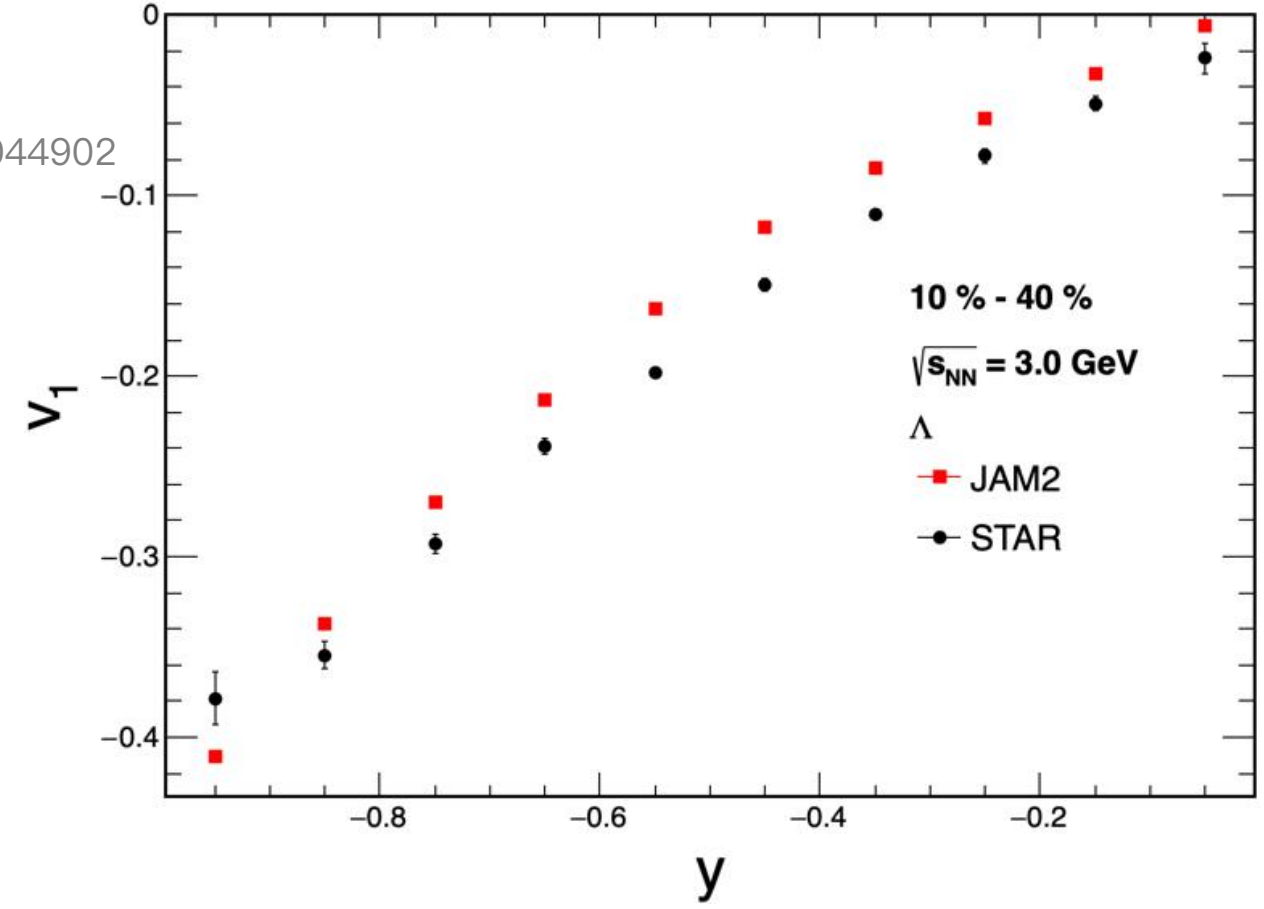
Simulation of Au+Au at 3 GeV

JAM2 Heavy Ion Event Generator

Phys. Rev. C 106, 044902

Jet AA Microscopic Transport Model 2

- Λ v1 Flow
  - Already reproduced by JAM2 generator



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Phys. Rev. C 106, 044902

Jet AA Microscopic Transport Model 2

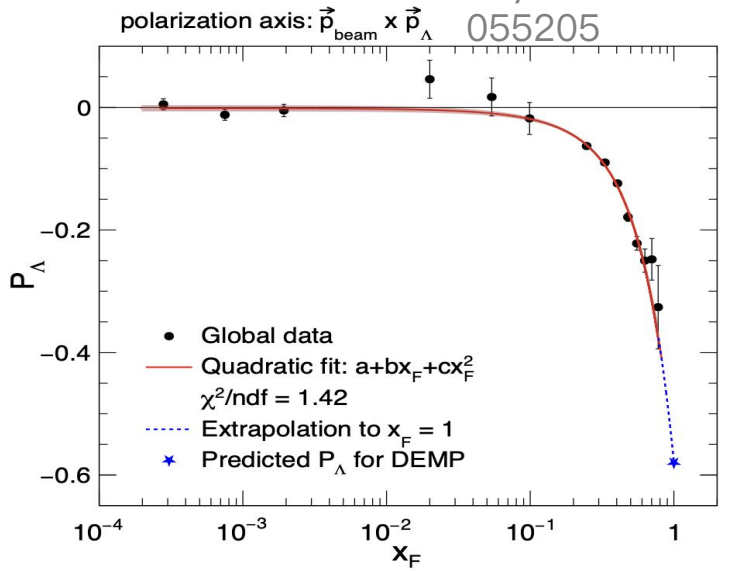
- **Λ v1 Flow**
  - Already reproduced by JAM2 generator
- **Λ Transverse Polarization**

Implemented by **a reweighting technique** based on Λ (decay) kinematic.

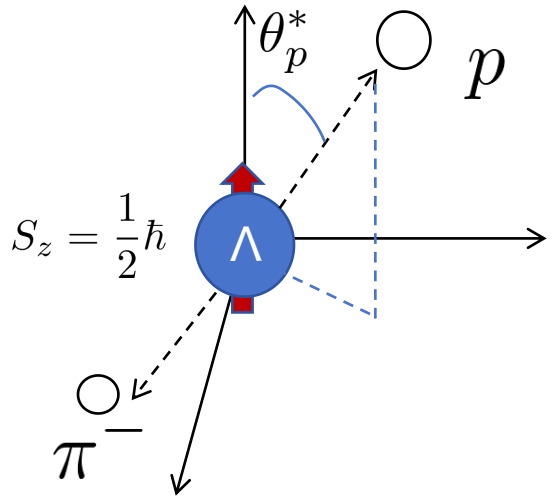
- **Calculate xF to determine P_Λ .**
- **Determine production plane.**
- **Relative angle between proton momentum and production plane.**
- **Λ is assigned a weight factor:**

$$\frac{1}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta_p^*)$$

Phys. Rev. C 109, 055205



$$\hat{n}_{\mathrm{pp}} = \hat{p}_{\mathrm{beam}} \times \hat{p}_{\mathrm{T},\Lambda}$$



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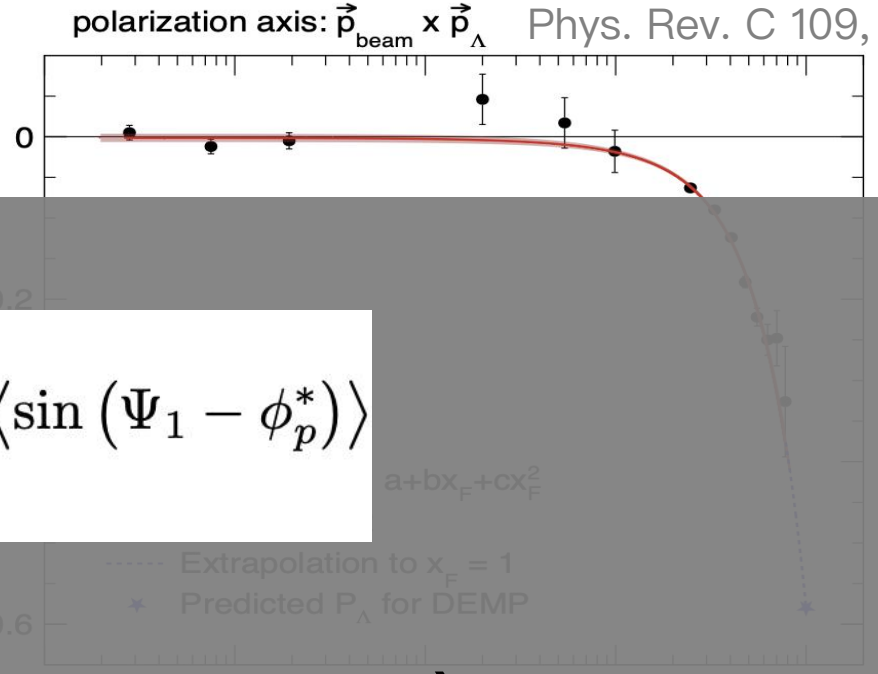

Phys. Rev. C 109, 055205

JAM2 Heavy Ion Event Generator

Jet AA Microscopic Transport

- Λ v1 Flow
  - Already reproduced by JAM2 generator
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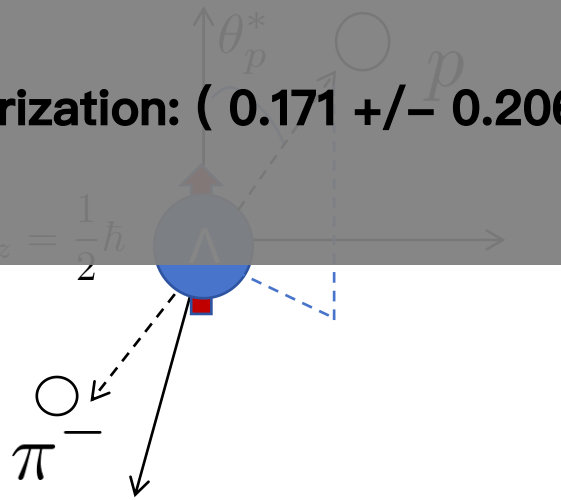
  - Implemented by **a reweighting technique** based on Λ (decay) kinematic.
    - Calculate xF to determine P_Λ
    - Determine production plane.
    - Relative angle between proton momentum and production plane.
  - **Λ is assigned a weight factor:**

$$\frac{1}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta_p^*)$$

$$\overline{P}_\Lambda \equiv \left\langle \vec{P}_\Lambda \cdot \hat{J} \right\rangle = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{\mathrm{EP}}^{(1)}} \left\langle \sin\left(\Psi_1 - \phi_p^*\right) \right\rangle$$

$$P_\Lambda = (2.553 \pm 0.206) \%$$

Without implementing Transverse Polarization: (0.171 +/− 0.206)%



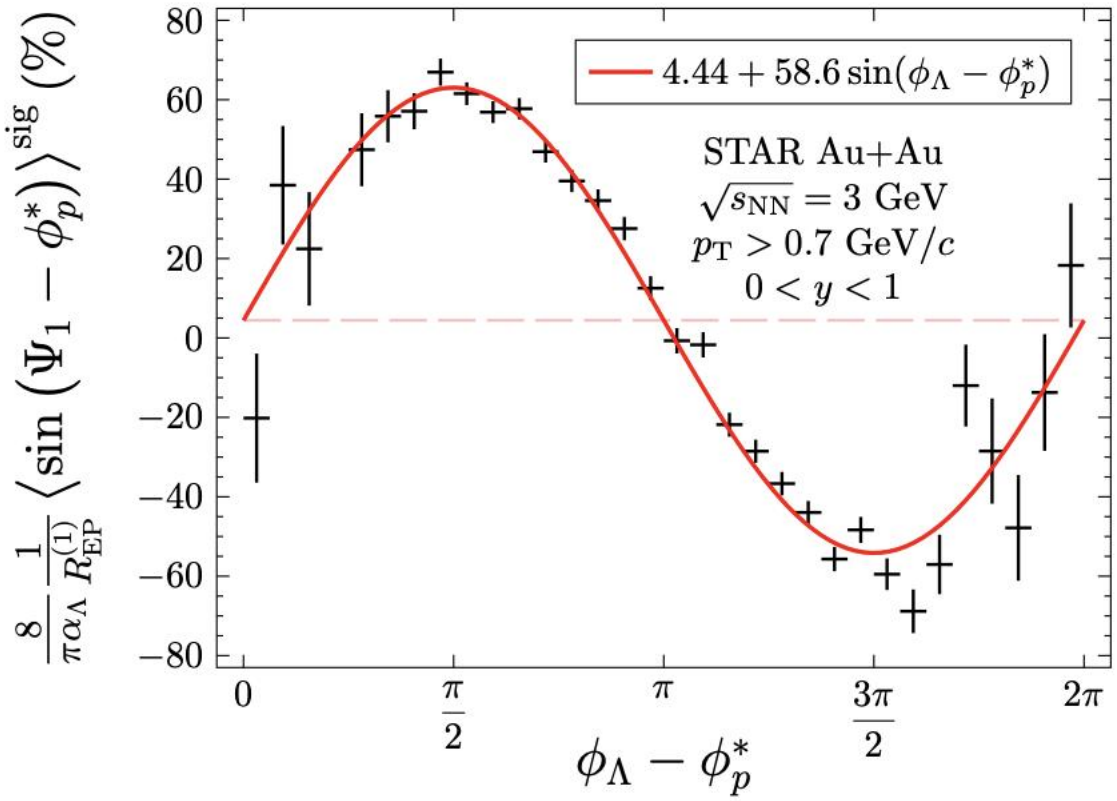
A Better Analysis Method by STAR

Phys. Rev. C 104, L061901

- **The Global Polarization is calculated as a function of $\phi_\Lambda - \phi_p^*$**
- **Sinusoidal fit is implemented:**

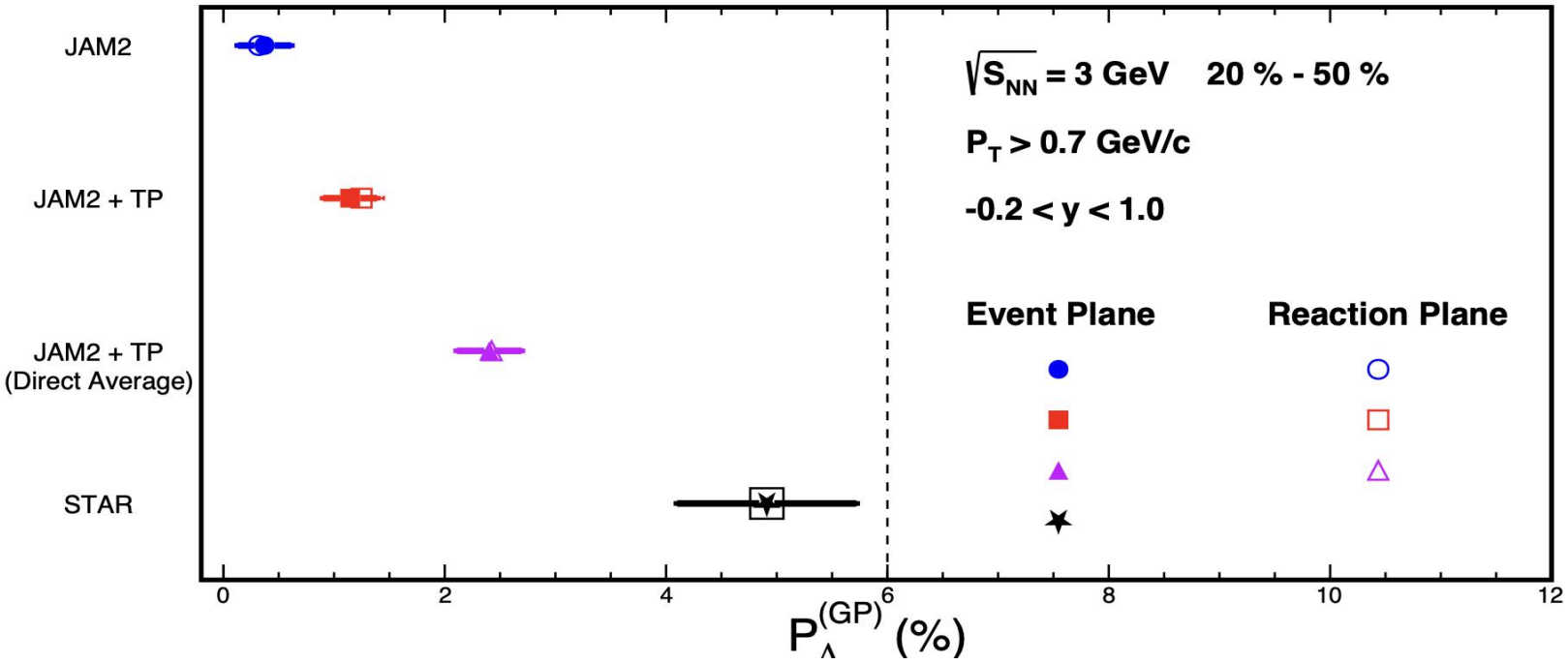
$$\frac{8}{\pi\alpha_\Lambda}\frac{1}{R_{\mathrm{EP}}^{(1)}}\left\langle \sin\left(\Psi_1 - \phi_p^*\right)\right\rangle^{\mathrm{sig}} = \boxed{\overline{P}_\Lambda} + c\sin(\phi_\Lambda - \phi_p^*),$$

- **The Global Polarization is extracted as the vertical shift.**



It is claimed that this analysis strategy can remove polarization with respect to production plane.

Transverse Polarization is NOT totally got rid of



"TP" means Transverse Polarization.

STAR Method

$$\frac{8}{\pi\alpha_\Lambda}\frac{1}{R_{\mathrm{EP}}^{(1)}}\left\langle \sin\left(\Psi_1-\phi_p^*\right)\right\rangle^{\mathrm{sig}} = \overline{P}_\Lambda + c\sin(\phi_\Lambda-\phi_p^*)$$

Direct Average

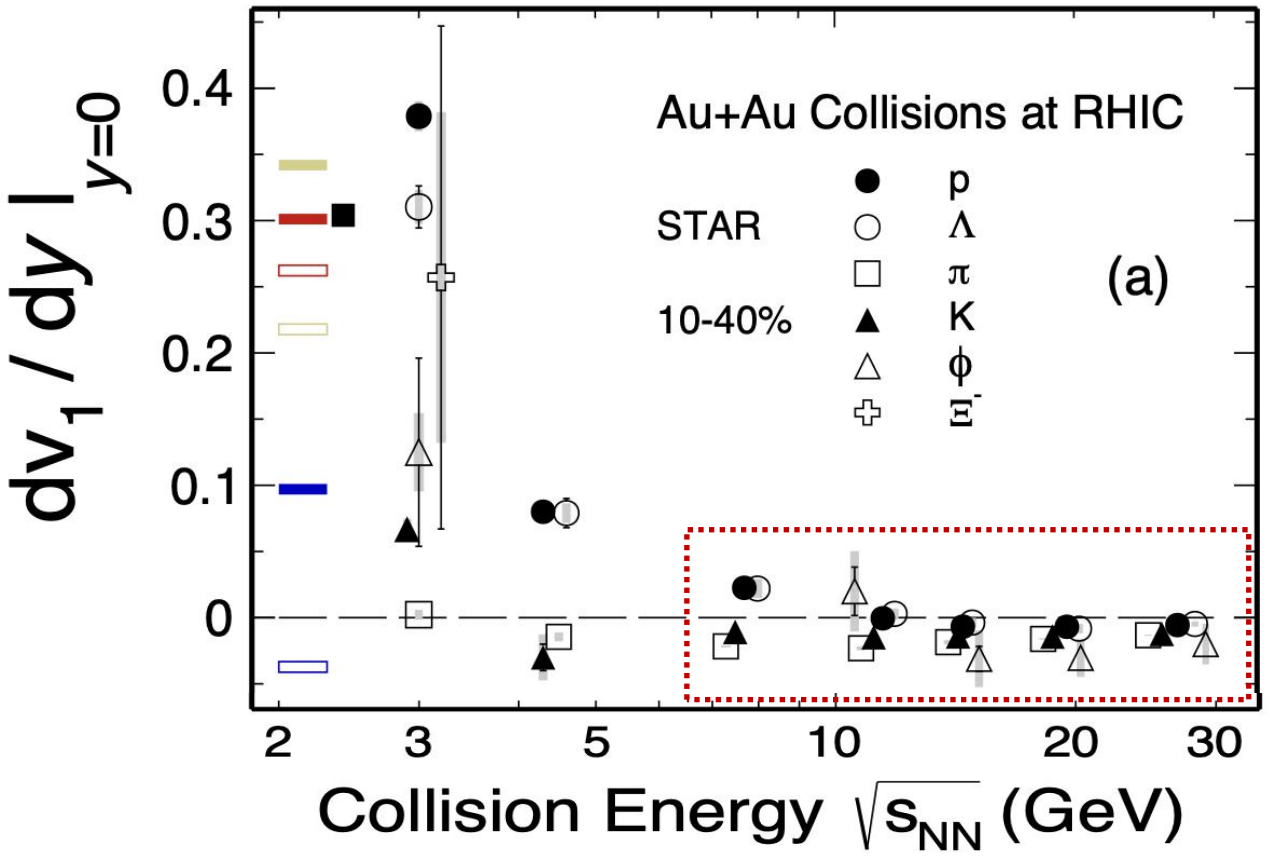
$$\overline{P}_\Lambda \equiv \left\langle \vec{P}_\Lambda\cdot\hat{J}\right\rangle = \frac{8}{\pi\alpha_\Lambda}\frac{1}{R_{\mathrm{EP}}^{(1)}}\left\langle \sin\left(\Psi_1-\phi_p^*\right)\right\rangle$$

- **Same analysis method, same kinematic cut, same centrality.**
- **Using STAR method, contribution from transverse polarization is reduced, but not completely got rid of.**
- **Production Plane Mechanism can enhance the global polarization by ~ 1%. Account for 23% +/– 6 % of STAR measurement.**

At Higher Energy ?

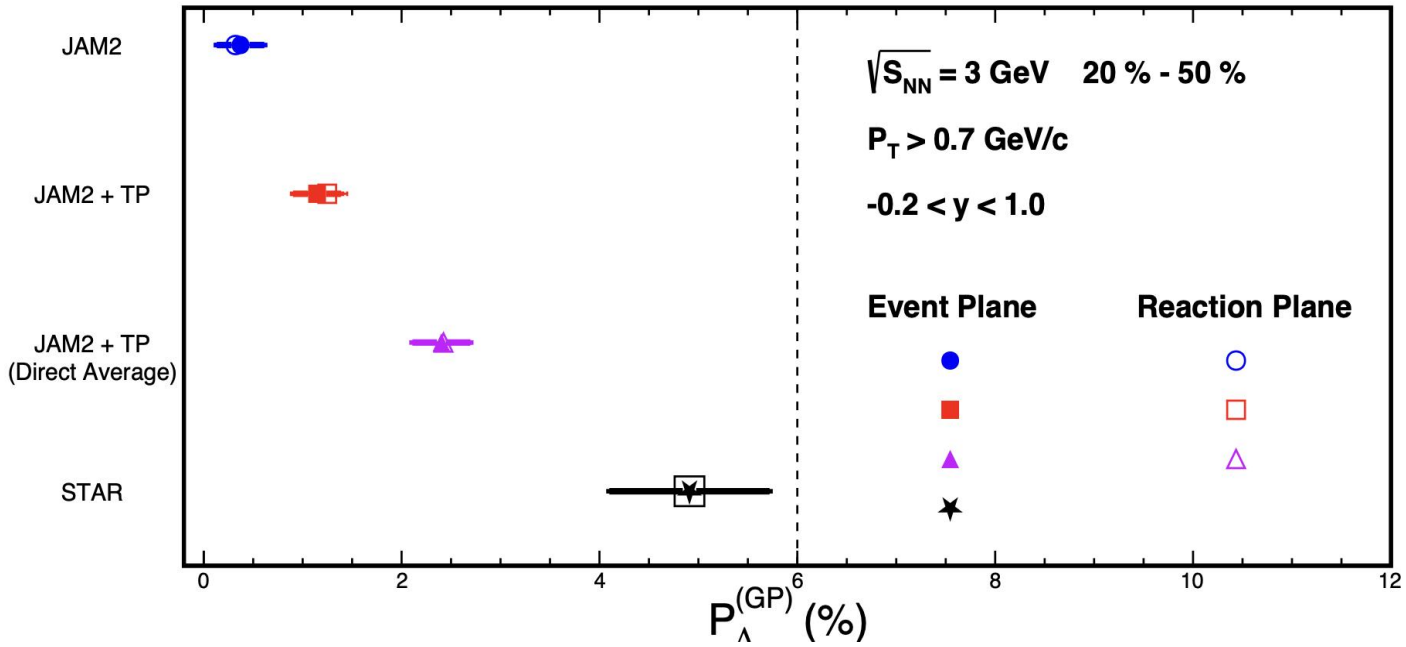
PLB,Volume 827, 10 April 2022, 137003

- **Magnitude**: The magnitude of v1 flow is too weak to produce large global polarization.
- **Sign:** The negative v1 above 10.5 GeV can't produce correct sign of global polarization.



At high energy HI collisions, Transverse Polarization can be negligible.

Summary

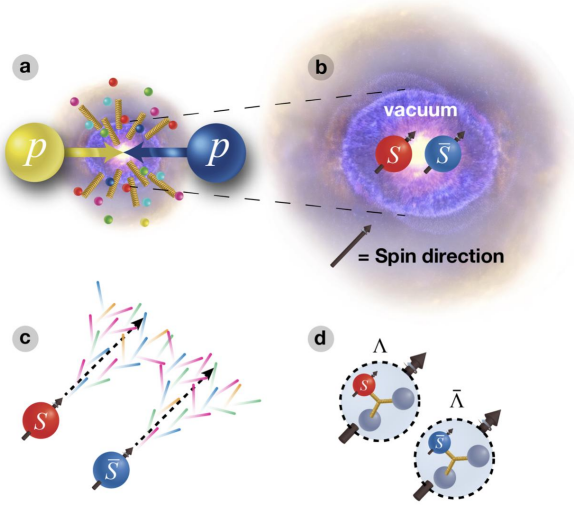


We present a mechanism that can:

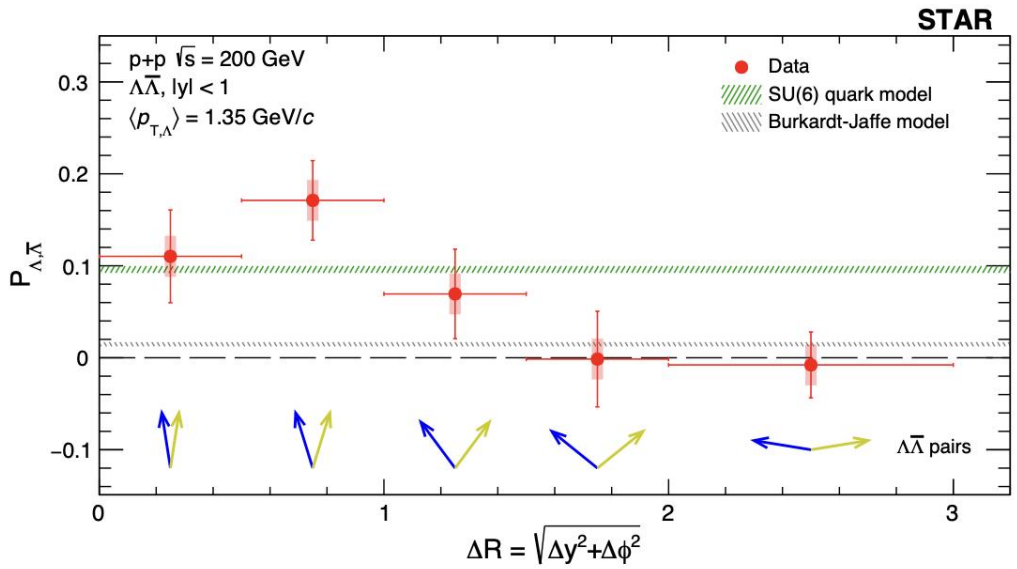
- **Generate the Λ Global Polarization by coupling transverse polarization to v1 flow.**
- **Large contribution to measurement at low-energy HICs, but negligible at high-energy HICs.**

Vorticity-Induced Global Polarization and Transverse Polarization can coexist. They can be developed at different stages of HICs.

New Source of Λ Hyperon Spin Alignment



Nature volume 650, pages 65–71 (2026)



New result from STAR collaboration at 200 GeV pp collisions:

- Not casued by voriticy/transverse polarzation.
- Originate from the maximally entangled quark pair in QCD vacumm

Stay tuned for new results!

Thank you !

We would like to thank Ashik Ikbal and Sooraj Radhakrishnan for discussions of JAM2 event generator, and Li Xu, Zhangbu Xu, Prithwish Tribedy, Arjun Kumar for reading the paper draft (arXiv 2603.19581).

We would like to point out : the idea that transverse polarization may enhance global polarization was already proposed in Liang and Wang's early paper of Global Polarization.

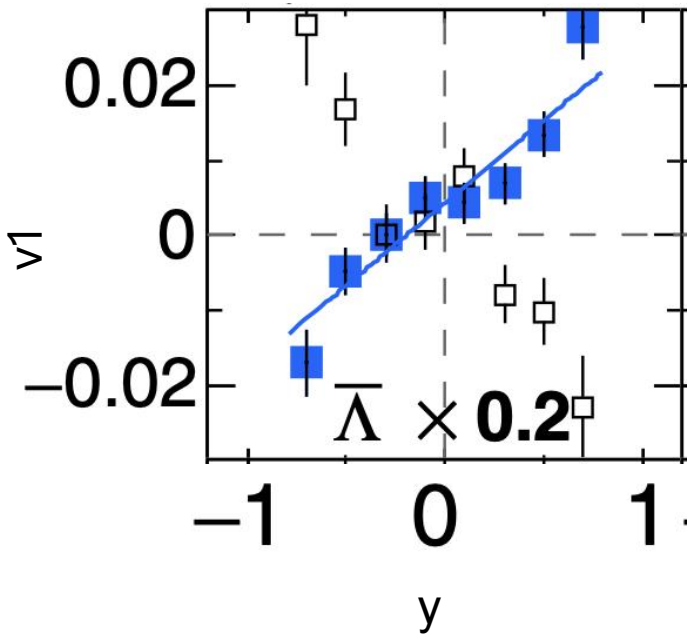
be estimated within a recombination model. (5) Since hyperon's production planes are randomly oriented with respect to the reaction plane of heavy-ion collisions, the observed hyperon polarization in $p + A$ collisions should not contribute to the global polarization as we have defined here, except at large rapidity region where directed flow is observed [13]. In this region, the nonvanishing $\langle p_x \rangle$ can provide an average production plane $\vec{n}_H$ for hyperons. According to the observed polarization pattern in $p + A$ [1], the global P_H will be enhanced for Λ, Ξ, and $\bar{\Xi}$ and reduced for Σ in large rapidity region. In addition, one also expects $P_\Lambda > P_{\bar{\Lambda}}$ due to the directed flow.

Phys. Rev. Lett. 96, 039901 (2006)

Backup

Λ v1 flow in heavy ion collisions

PRL 120, 062301 (2018)



Λ v1 flow as a function of rapidity at 7.7 GeV

$$\frac{dN}{d\phi_\Lambda} \propto 1 + 2v_1 \cos(\phi_\Lambda - \Psi_1)$$

At 7.7 GeV:

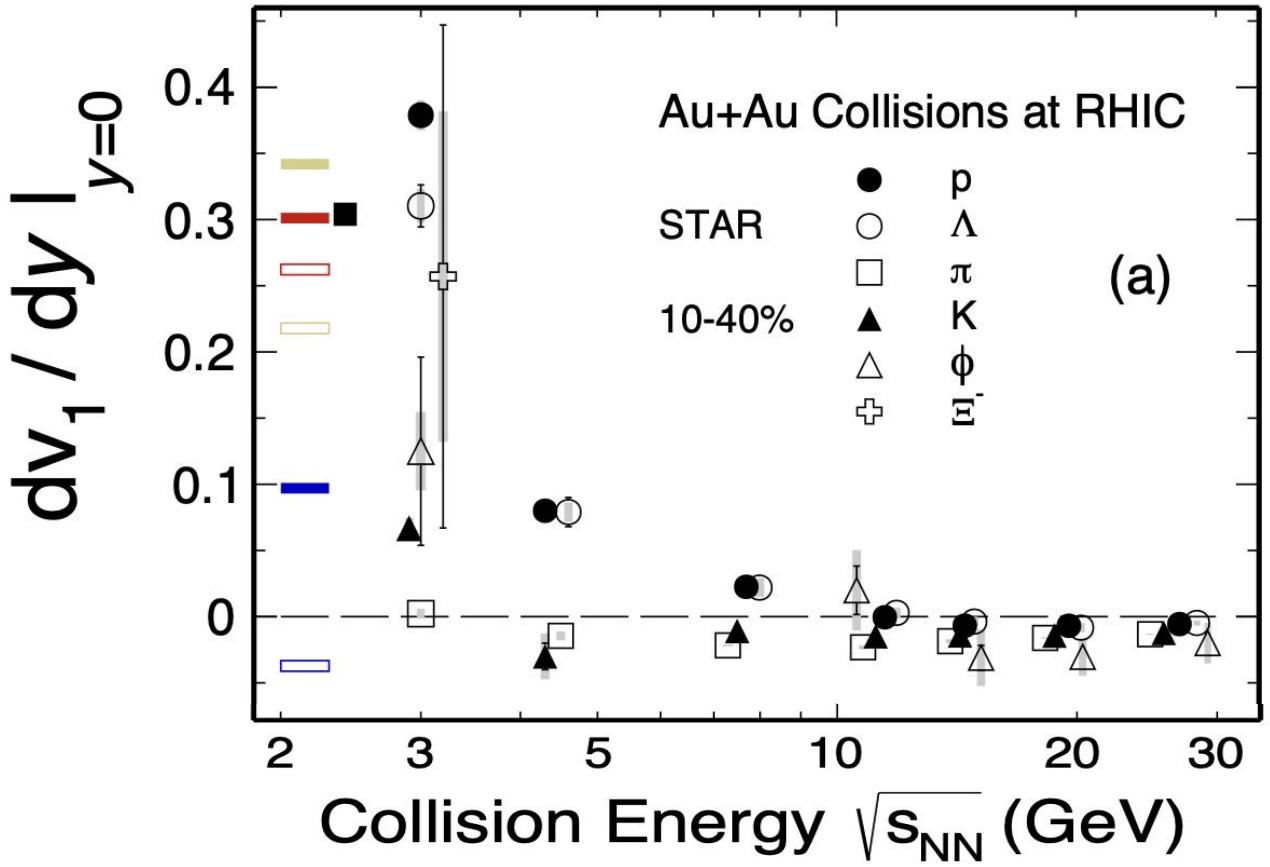
- At y > 0, v1 > 0, Λ prefers to take the same direction as event plane

$$\phi_\Lambda \approx \Psi_1$$

- At y < 0, v1 < 0, Λ prefers to take the opposite direction to event plane

$$\phi_\Lambda \approx \Psi_1 + \pi$$

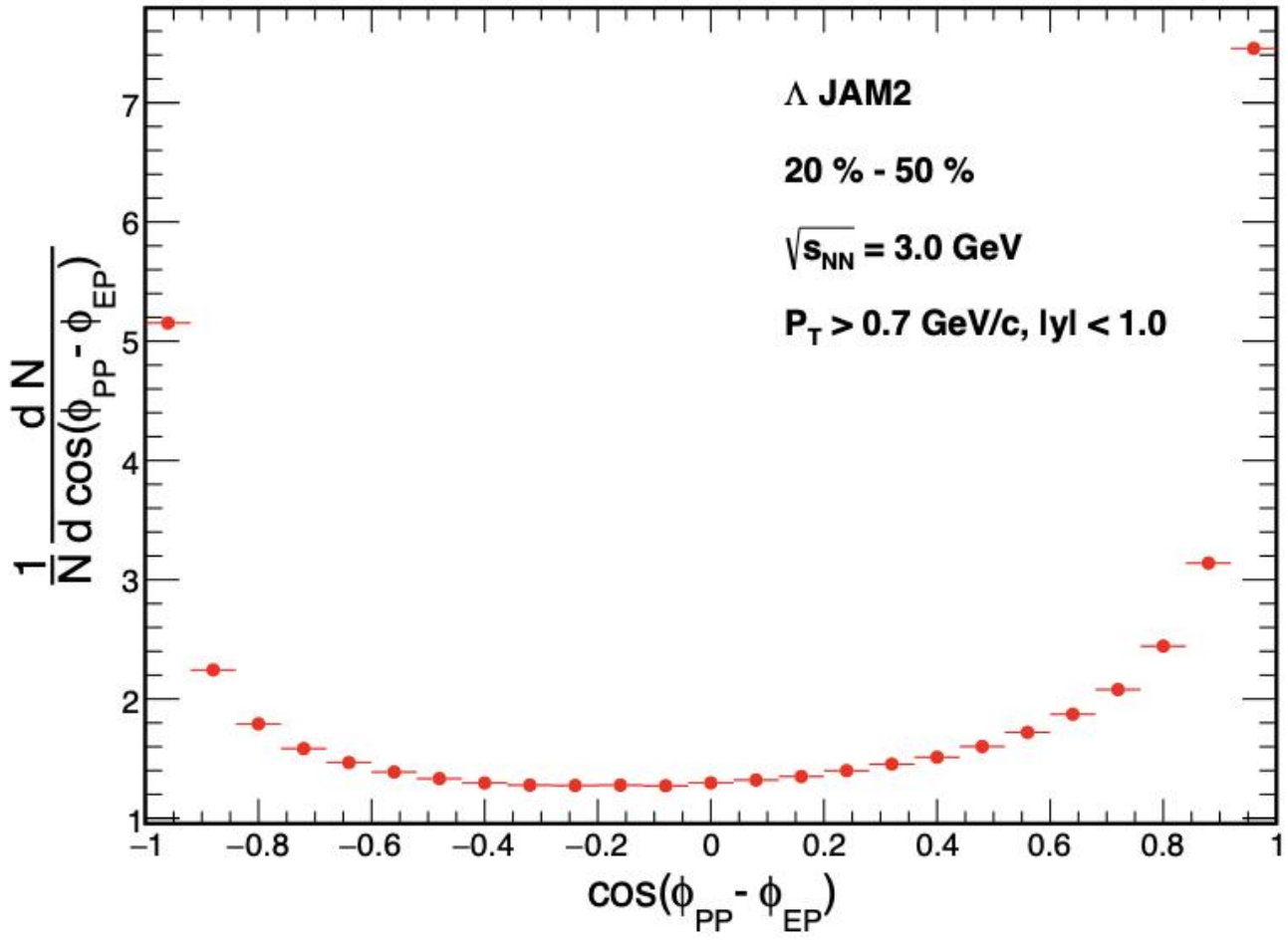
Λ v1 flow in heavy ion collisions



PLB,Volume 827, 10 April 2022, 137003

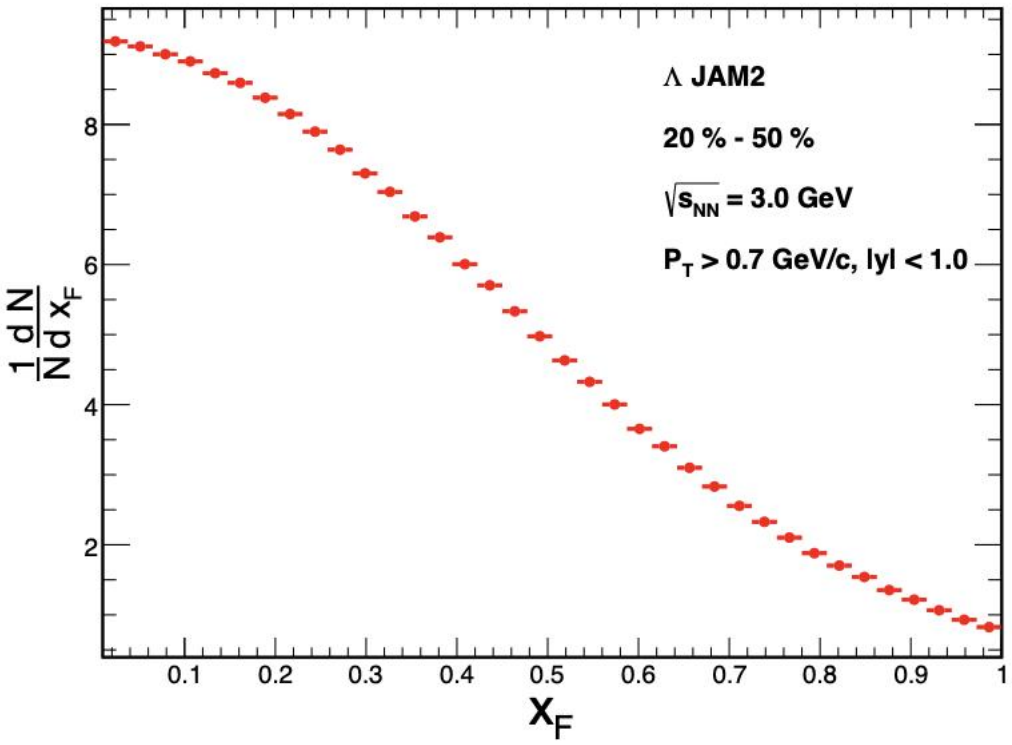
- The v1 slope decreases with collision energy.
- The slope sign changes at energy above 10.5 GeV.

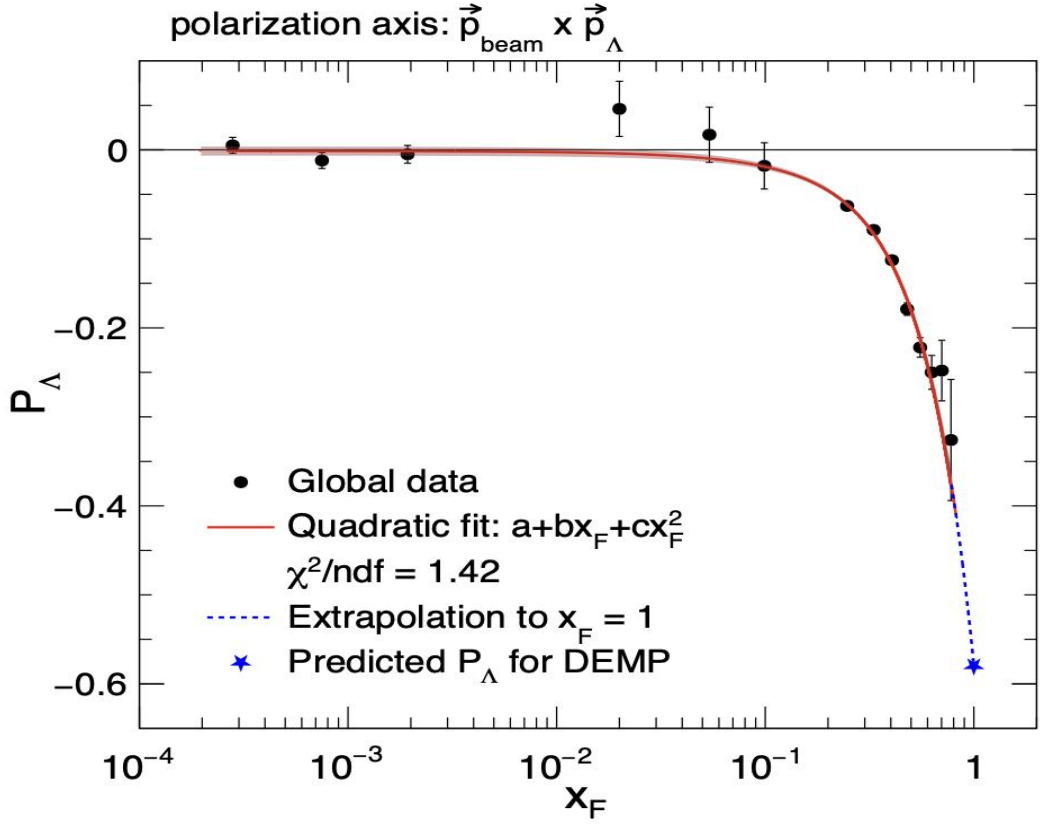
Correlation Between Production Plane and Reaction plane



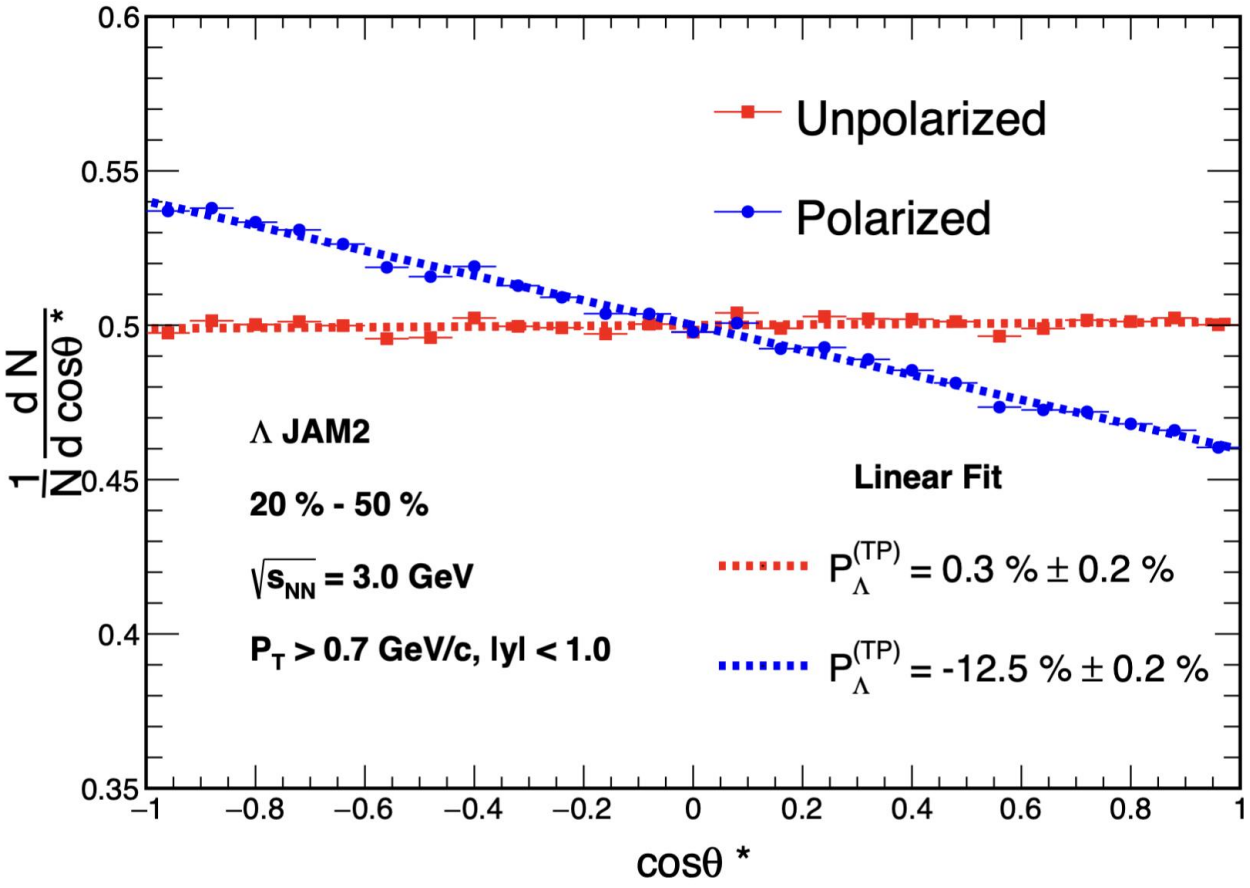
Lambda xF at 3GeV

Phys. Rev. C 109, 055205

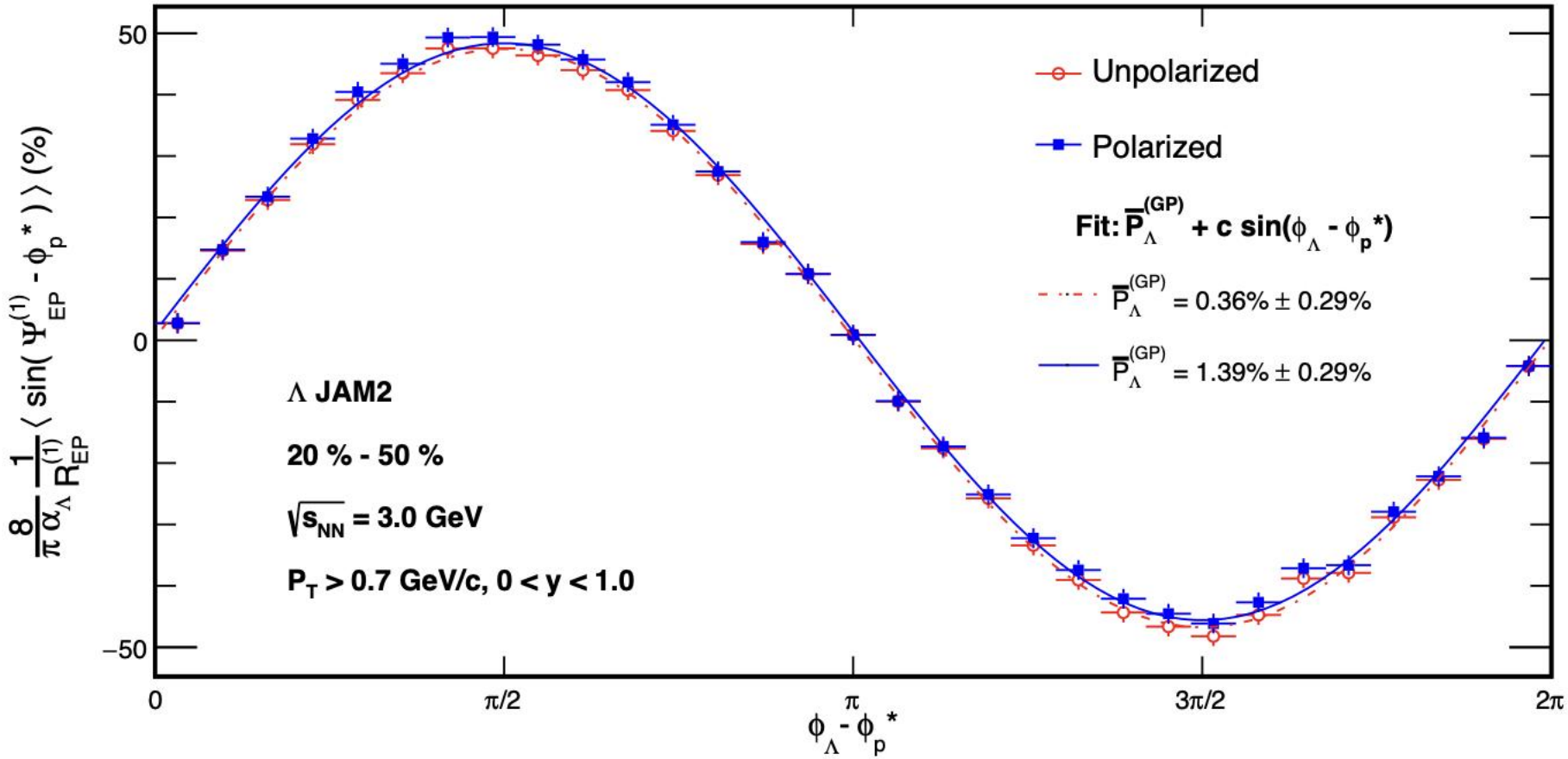




Reweighting Technique



JAM2 result with STAR method.



Models attempting to explain transverse polarization:

- *Lund semi-classical fragmentation model*: finite pT lambdas infers orbital angular momentum (ssbar) and s quark spin needs to balance that. The higher the pT, the larger the effect.
- *Thomas precession mechanism* — a semi-classical recombination model.
- *Single-pion exchange*
- *Interference from resonances decay.*
- *TMD polarizing Fragmentation Functions*

PRD 24, 2419,
PRL. 68, 907,
PLB Vol. 818, 10 July 2021, 136371
Phys. Rev. D 23, 1227(R) .....

Defense from $\overline{\Lambda}$ transverse polarization

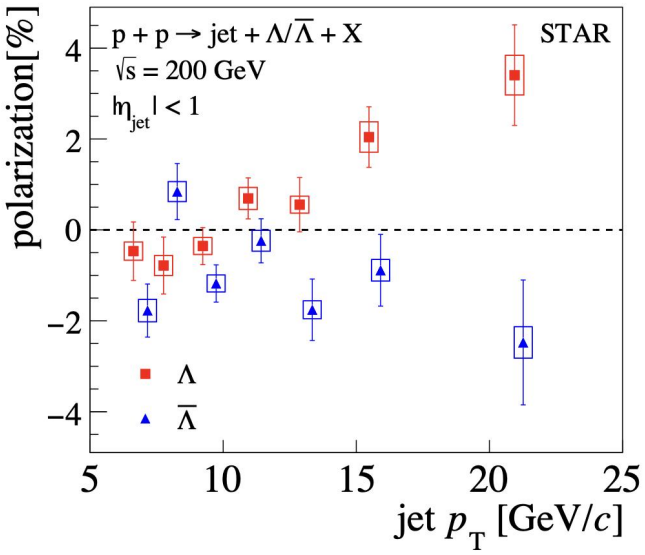
$\overline{\Lambda}$ is believed to unpolarized.

scenario 1

- **In Jet and ee, $\overline{\Lambda}$ shows evidences of polarization.**

- **But current measurements have large uncertainties. It is still possible that $\overline{\Lambda}$ is polarized with a few % magnitude, which is comparable to polarization observed at HICs.**

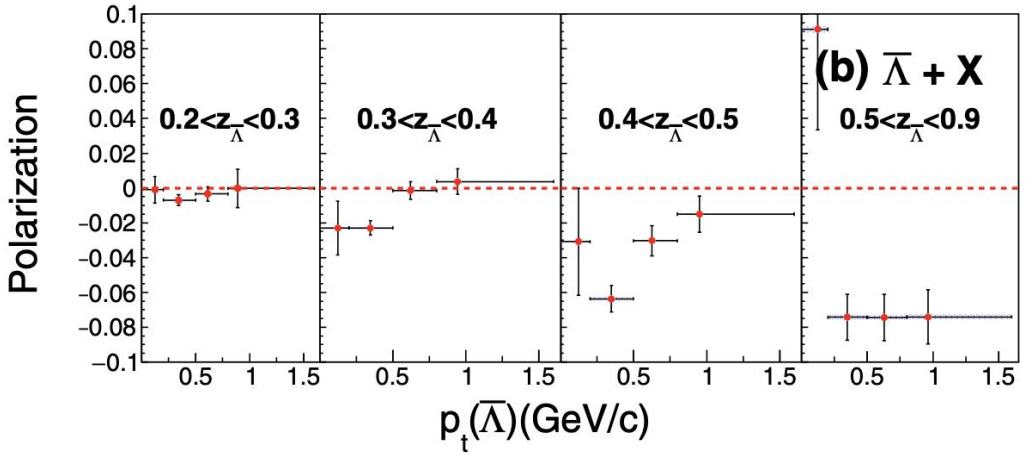
arxiv2509.17487



Jets in pp collisions

Λ: 0.24±0.19 (stat)±0.09 (sys)%

$\overline{\Lambda}$: −0.77±0.20 (stat)±0.09 (sys)%



e+e− collisions

PRL 122, 042001 (2019)

Defense from $\overline{\Lambda}$ transverse polarization

$\overline{\Lambda}$ is believed to unpolarized.

scenario 1

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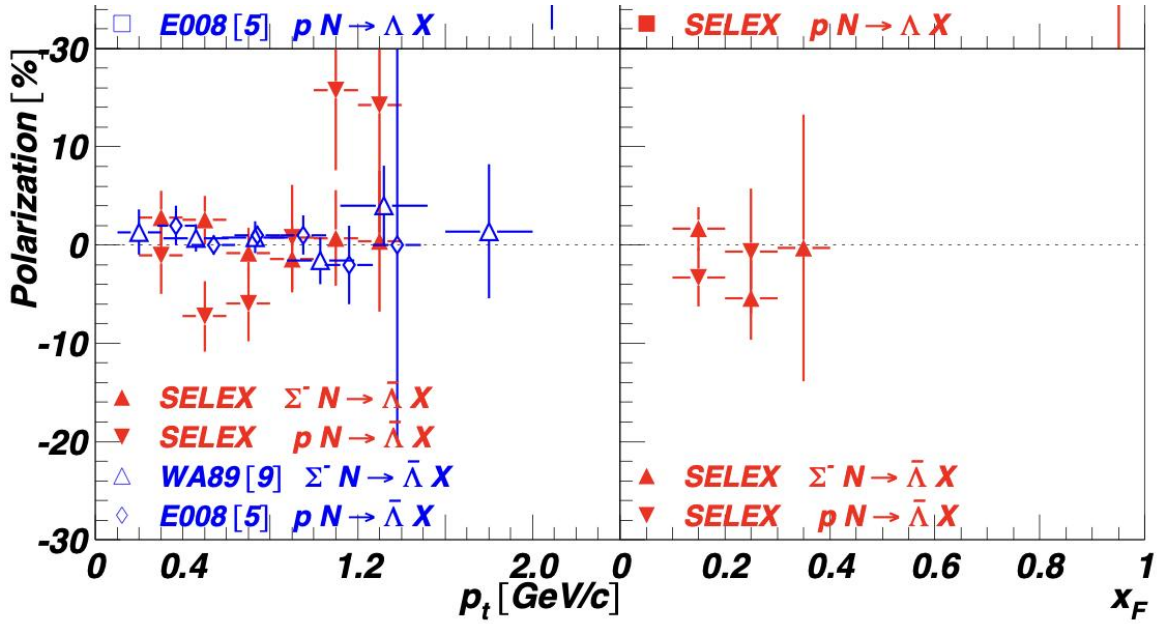
arXiv 0706.3660

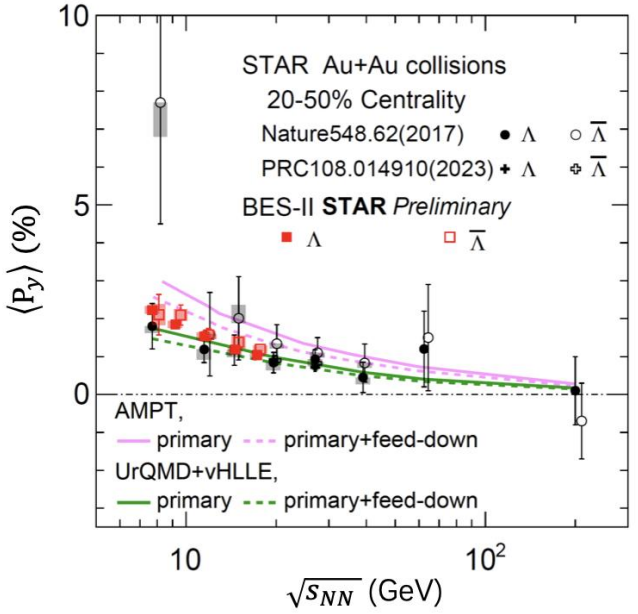


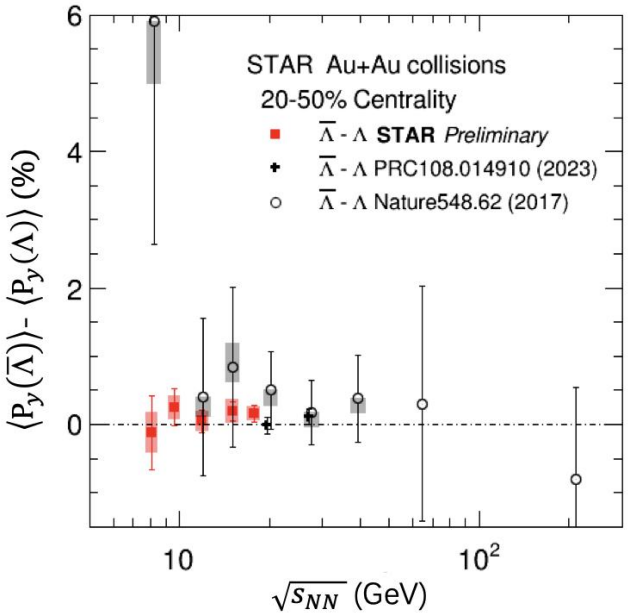
Defense from $\overline{\Lambda}$ transverse polarization

$\overline{\Lambda}$ is believed to unpolarized.

scenario 2

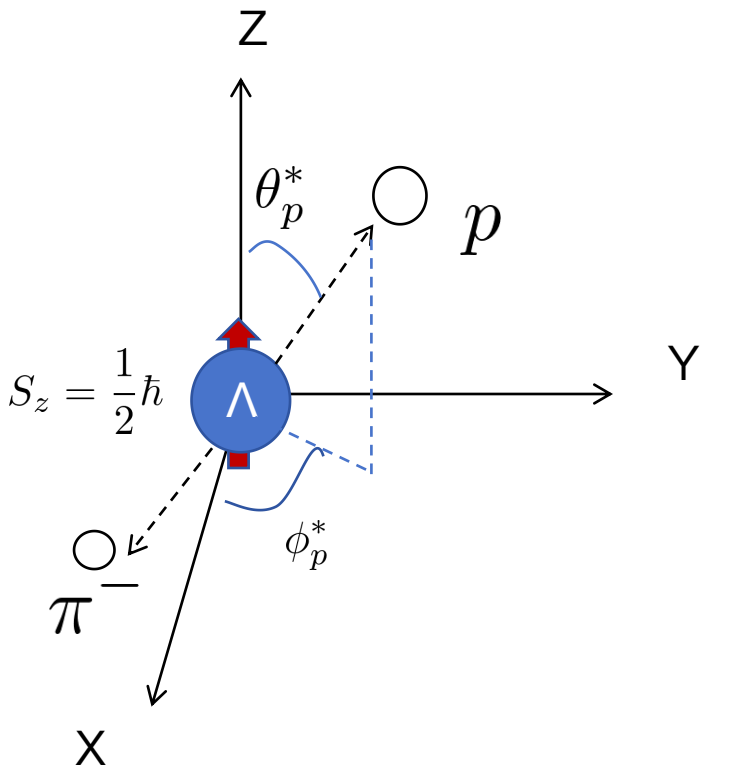
- **If $\overline{\Lambda}$ is unpolarized, a straightforward expectation is that Λ exhibits larger polarization than $\overline{\Lambda}$.**
- **But the separation is expected to be small (~0.1%) at collision energy 7.7 GeV due to small v1.**





arXiv:2412.09897

Λ spin is *self-analyzing*

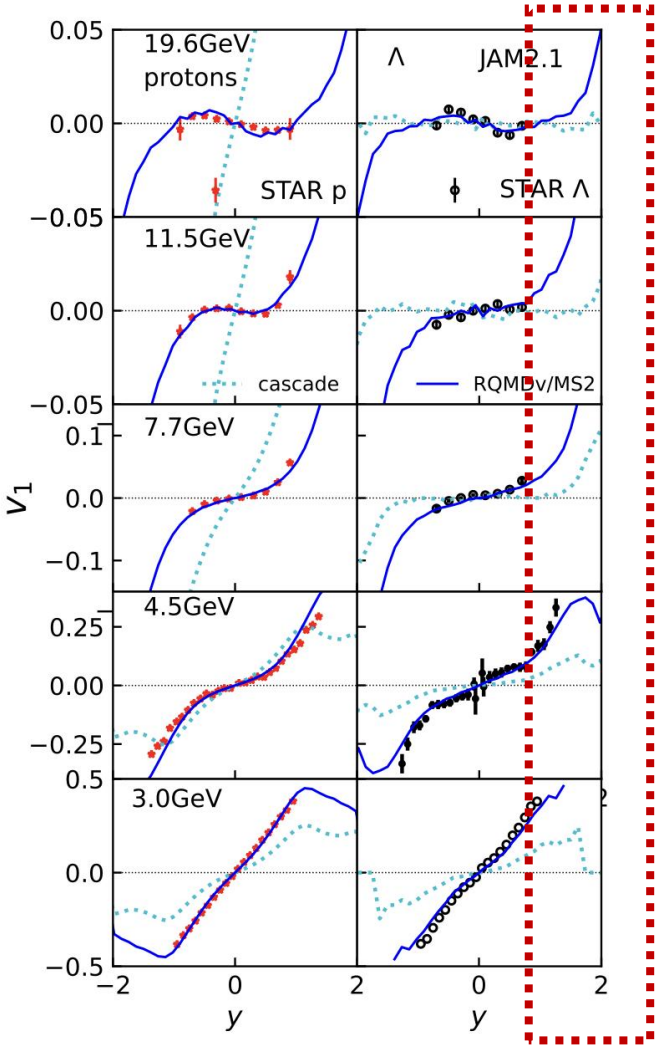


$$\frac{dN}{d\cos\theta_p^* d\phi_p^*} = \frac{1}{4\pi}(1 + \alpha_\Lambda \cos\theta_p^*)$$

Why 3 GeV HICs ?

We focus on 3 GeV HICs, besically because v1 flow is large within |y| < 1.0.

But, v1 flow is also large at forward region in high–energy HICs. The contribution from puzzle transverse lambda polarizaton can thus be large.



Phys. Rev. C 106, 044902

Transverse Polarization at low energy p pbar collisions

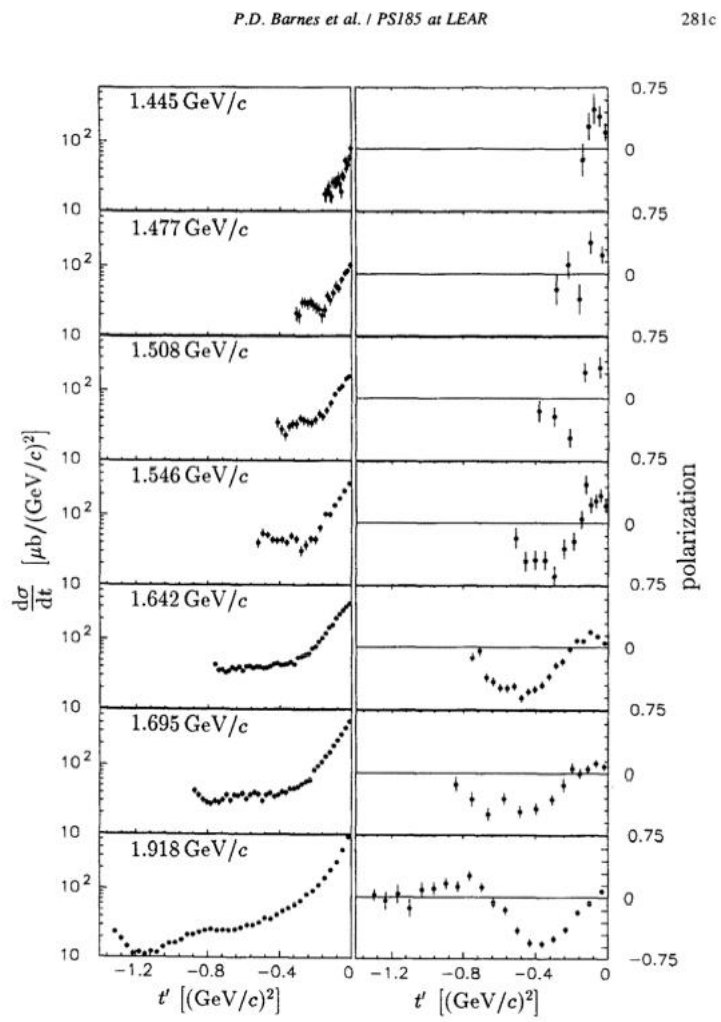
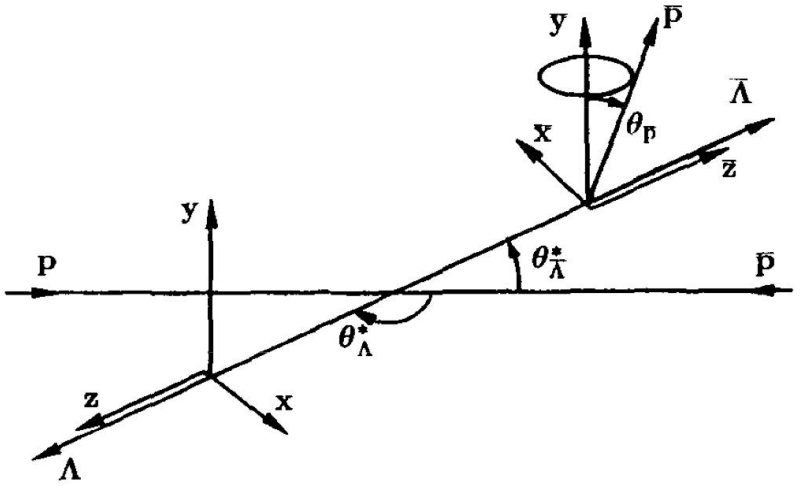


Figure 4. Differential cross sections (left) and polarizations (right) as functions of the momentum transfer at different beam momenta.

Figure 6. Coordinate system used for the determination of the spin observables. θ_p is the angle between the normal to the production plane and the direction of the decay nucleon.



$$P_y(\theta^*_\Lambda) = \frac{3}{\alpha_\Lambda} \cdot \frac{1}{N} \sum_N (\cos\theta_p)_y$$

The lambda and lambda_bar were analyzed independently and average afterward

Nuclear Physics A, Volume 558, 7 June 1993, Pages 277–286