INTERPRETATION OF Λ HYPERONS SPIN POLARIZATION MEASUREMENTS

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based on the paper: **2102.02890 [hep-ph]**
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Angular momentum in heavy-ion collisions

Non-central heavy-ion collisions create systems with large global orbital angular momenta

$$\boldsymbol{L}_{\text{init}} \sim 10^5\hbar$$

F. Becattini, F. Piccinini, J. Rizzo, PRC 77 (2008) 024906

Part of the angular momentum can be transferred from the orbital to the spin sector

$$\boldsymbol{J}_{\text{init}} = \boldsymbol{L}_{\text{init}} = \boldsymbol{L}_{\text{final}} + \boldsymbol{S}_{\text{final}}$$

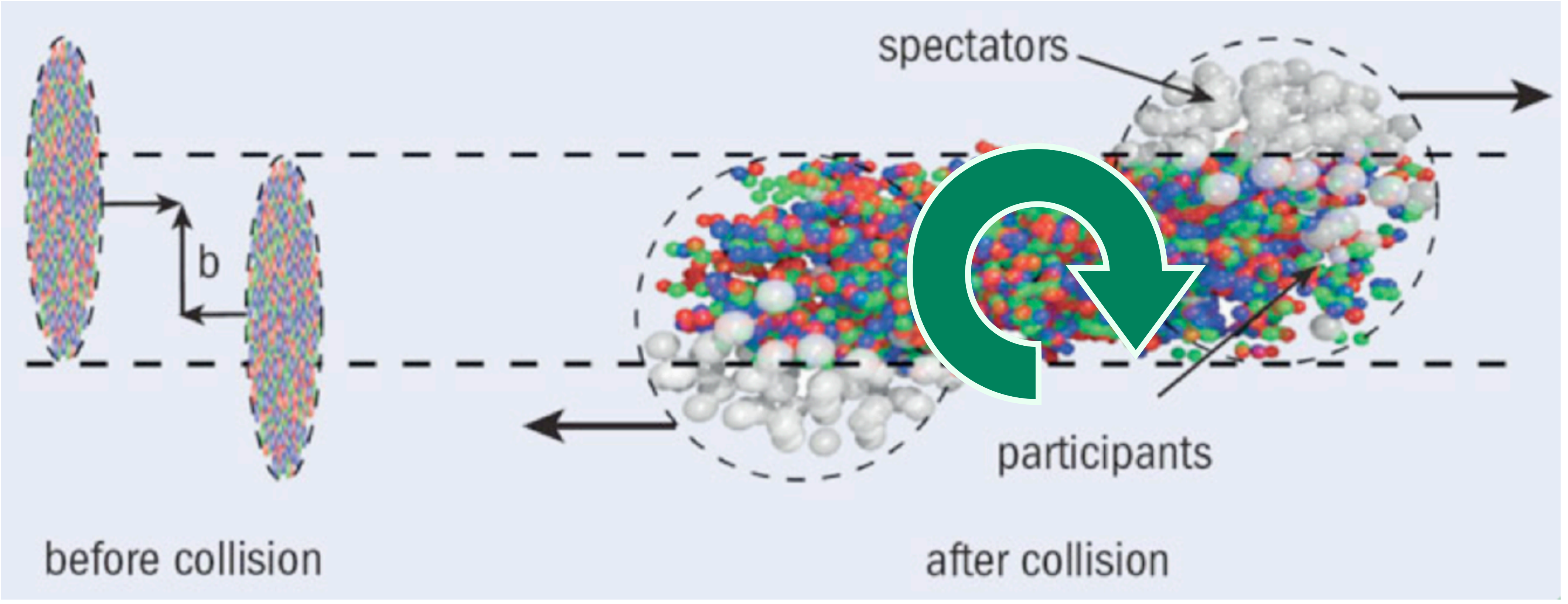
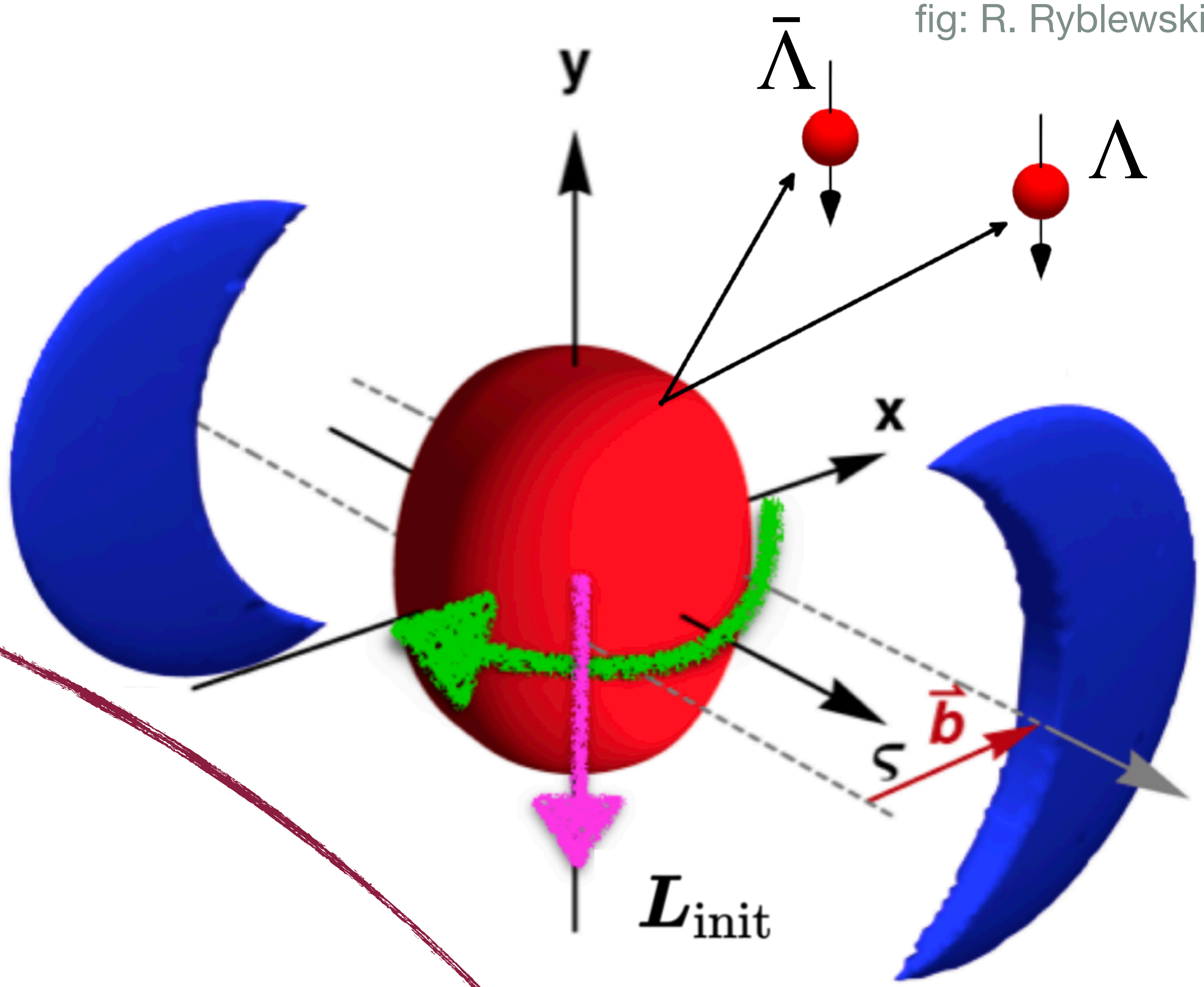


fig: M. Lisa, SQM 2016

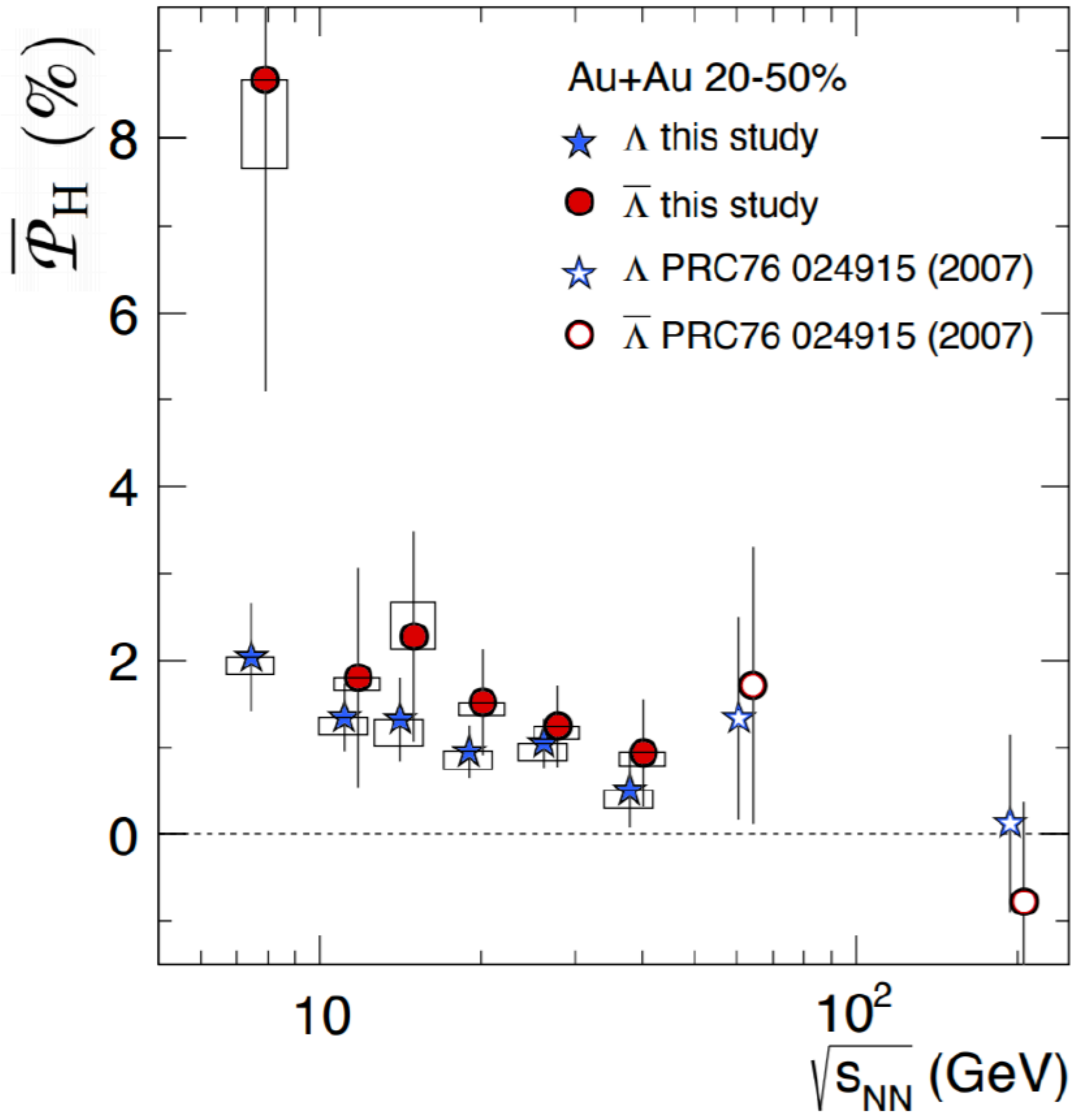
fig: R. Ryblewski



Emitted particles are expected to be polarized along the system's orbital angular momentum

Measurement of Λ and $\bar{\Lambda}$ spin polarization

fig: L. Adamczyk et al. (STAR) (2017), Nature 548 (2017) 62-65



Self-analysing parity-violating hyperon weak decay allows to measure Λ polarization

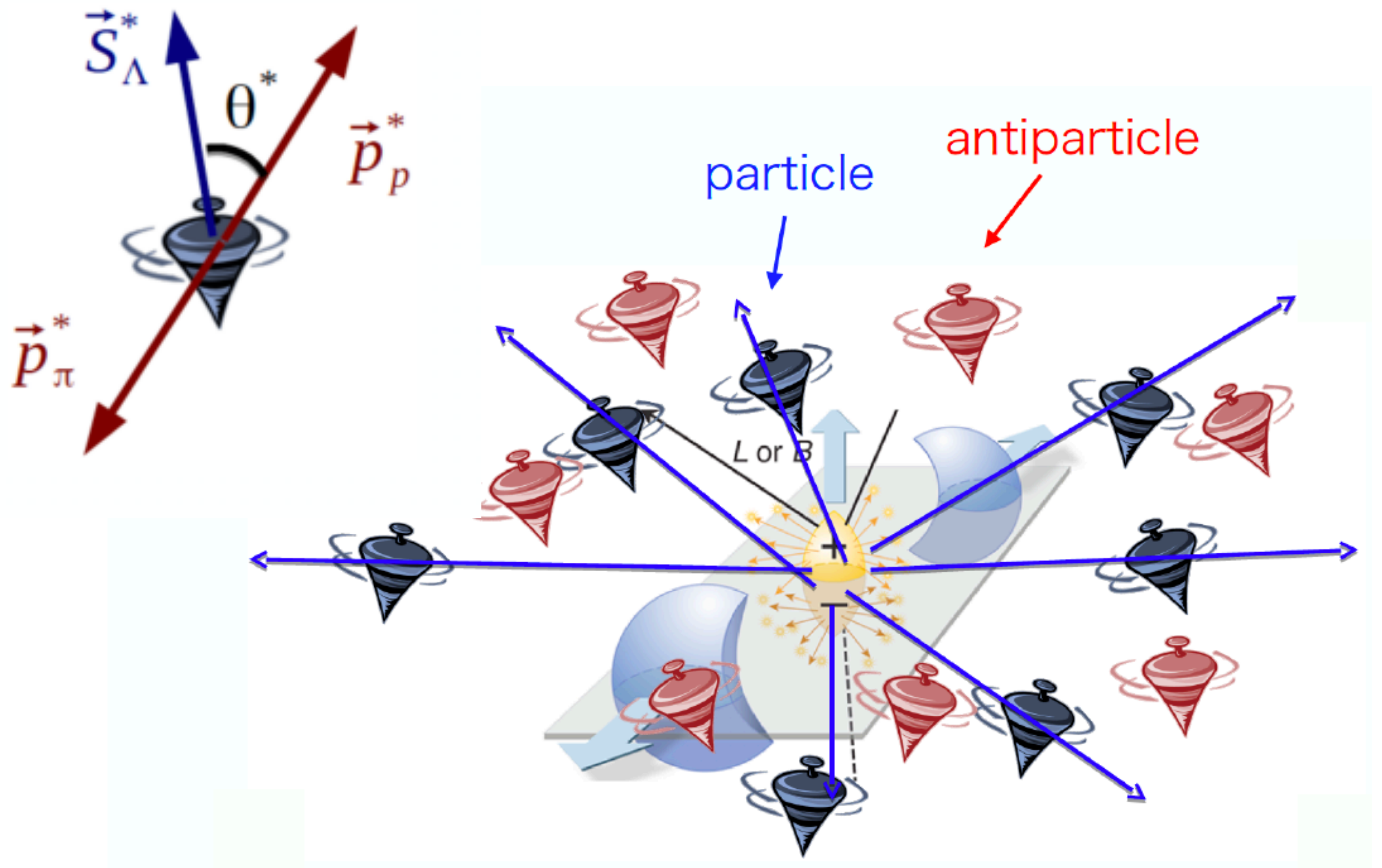


fig: T.Niida

. . . the hottest, least viscous – and now, most vortical – fluid produced in the laboratory . . .

$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T/\hbar \sim 0.6 - 2.7 \times 10^{22}\ \mathrm{s}^{-1}$$

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_{\mathrm{H}} \mathbf{P}_{\mathrm{H}} \cdot \mathbf{p}^*_{\mathbf{p}}\right)$$

Measurement of Λ and $\bar{\Lambda}$ spin polarization

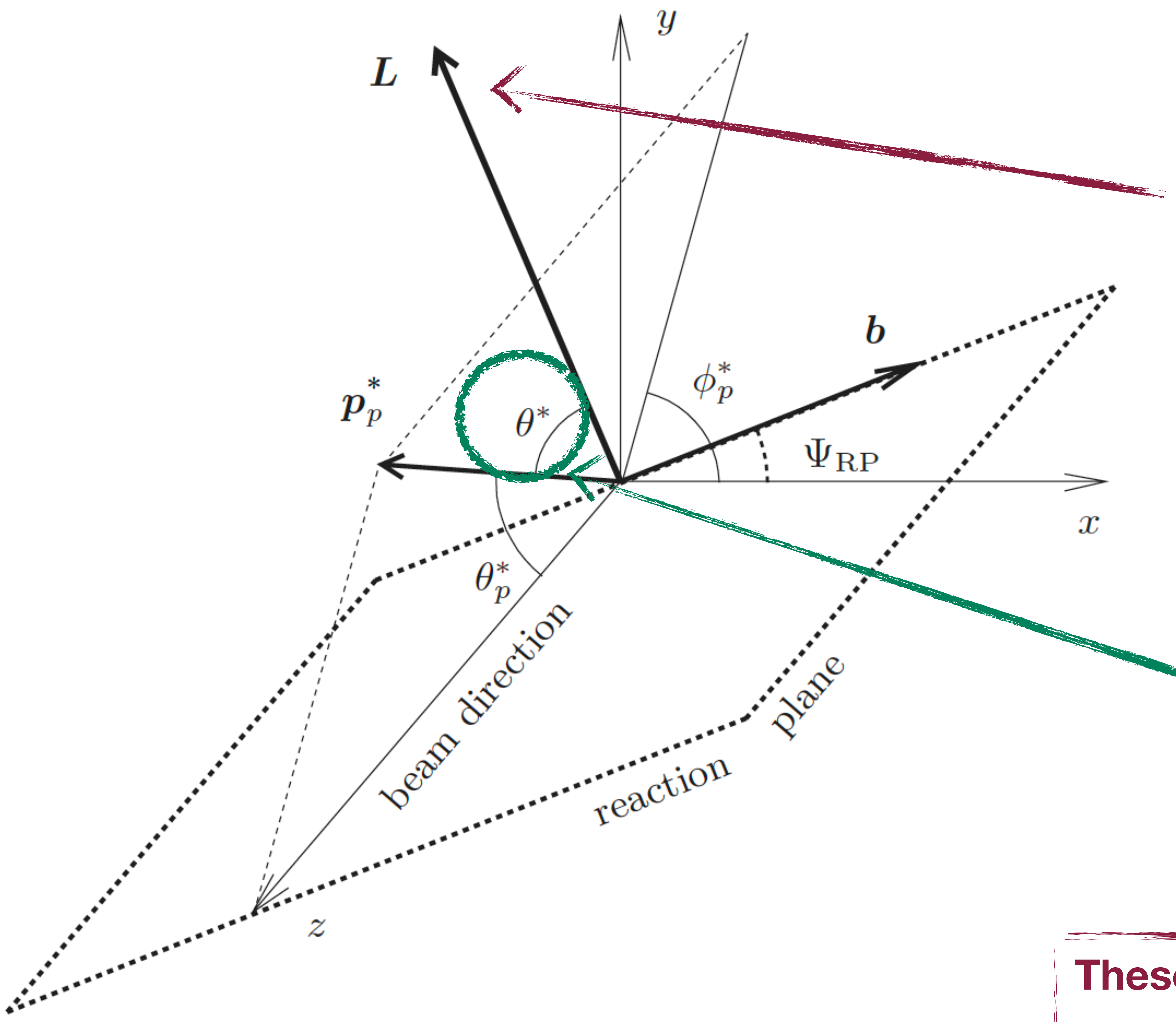


fig: B. I. Abelev et al. (STAR) PRC 76, 024915 (2007)

As the outcome of the spin polarization experiments, one cites the magnitude of the polarization along orbital angular momentum of the system defined in system's center-of-mass (COM) frame

However, to determine the magnitude of the polarization one studies momentum distributions of protons emitted in the weak decay of Lambdas which are measured in the Λ rest frame (ΛRF)

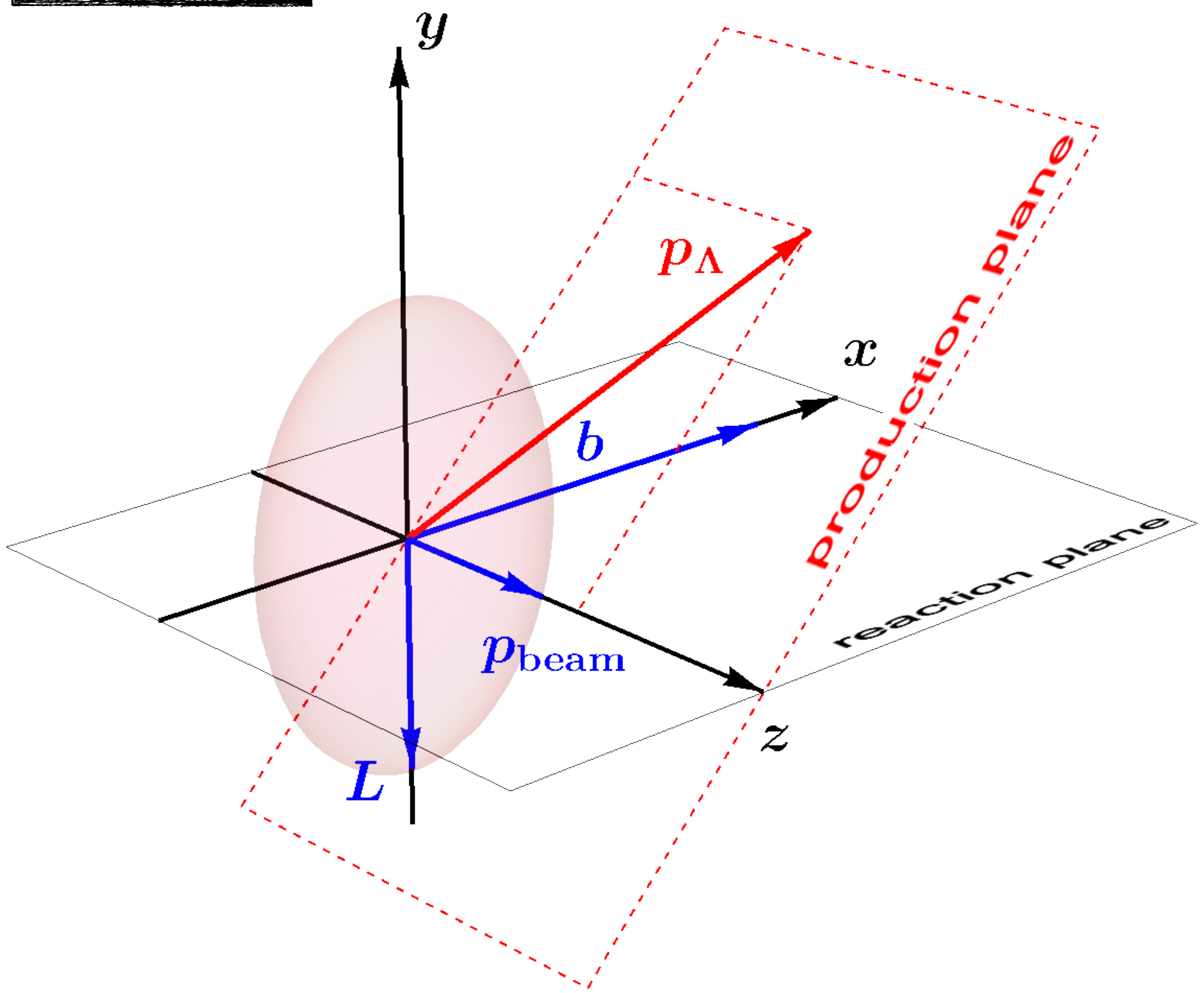
$$\frac{dN}{d\cos\theta^*} \sim 1 + \alpha_H P_H \cos\theta^*$$

These two frames are linked by a non-trivial Lorentz transformation. Interpretation of the results will depend on it!

CENTER-OF-MASS FRAME IN HEAVY-ION COLLISION

COM frame

fig: W. Florkowski, R.R., 2102.02890 [hep-ph]



NOTE: we assume here that Ψ_{RP} can be well measured

Transformation from COM to ΛRF

canonical boost

$$\mathcal{L}^{\mu}{}_{\nu}(-\boldsymbol{v}_\Lambda) = \begin{bmatrix} \frac{E_\Lambda}{m_\Lambda} & -\frac{p^1_\Lambda}{m_\Lambda} & -\frac{p^2_\Lambda}{m_\Lambda} & -\frac{p^3_\Lambda}{m_\Lambda} \\ -\frac{p^1_\Lambda}{m_\Lambda} & 1+\alpha p^1_\Lambda p^1_\Lambda & \alpha p^1_\Lambda p^2_\Lambda & \alpha p^1_\Lambda p^3_\Lambda \\ -\frac{p^2_\Lambda}{m_\Lambda} & \alpha p^2_\Lambda p^1_\Lambda & 1+\alpha p^2_\Lambda p^2_\Lambda & \alpha p^2_\Lambda p^3_\Lambda \\ -\frac{p^3_\Lambda}{m_\Lambda} & \alpha p^3_\Lambda p^1_\Lambda & \alpha p^3_\Lambda p^2_\Lambda & 1+\alpha p^3_\Lambda p^3_\Lambda \end{bmatrix}$$

$$\alpha \equiv 1/\left(m_\Lambda\left(E_\Lambda + m_\Lambda\right)\right)$$

$$p'^{\mu} = \mathcal{L}^{\mu}{}_{\nu}(-\boldsymbol{v}_\Lambda)\, p^{\nu}.$$

COM frame

$$p^\mu_\Lambda = \left(E_\Lambda, p^1_\Lambda, p^2_\Lambda, p^3_\Lambda\right)$$

$S'(\boldsymbol{p}_\Lambda)$
Λ rest frame

$$p'^{\mu}_\Lambda = (m_\Lambda, 0, 0, 0)$$

COM frame

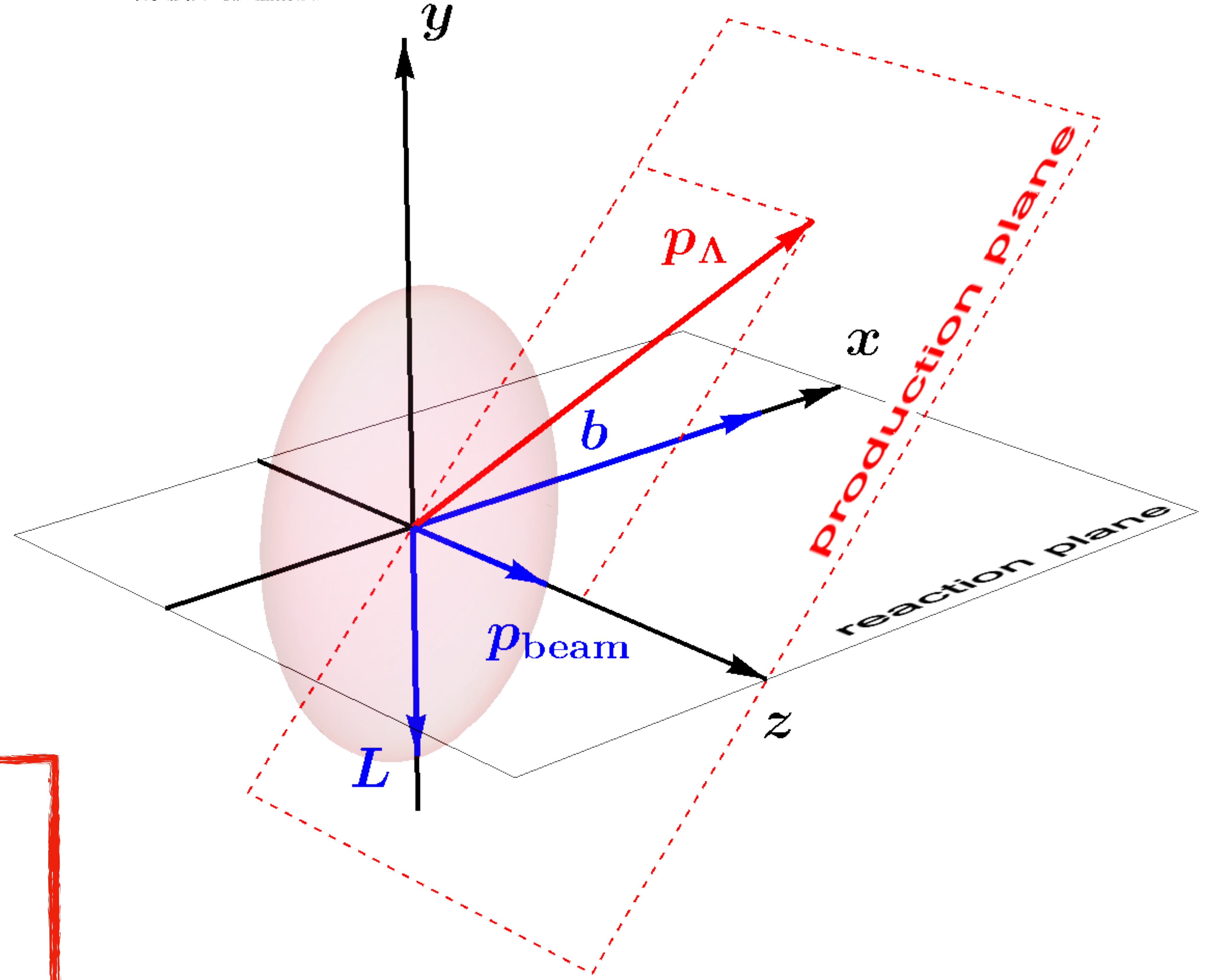


fig: W. Florkowski, R.R., 2102.02890 [hep-ph]

TRANSFORMATION OF ORBITAL ANGULAR MOMENTUM

In non-central heavy-ion collisions, a substantial orbital part is generated at the initial stage

$$J^{\mu\nu} = L^{\mu\nu} + S^{\mu\nu}$$

transforms like the spatial components of an antisymmetric tensor

$$L^k = -\frac{1}{2}\epsilon^{kij} L^{ij}$$

$$K^i = -L^{0i} = 0$$

COM frame

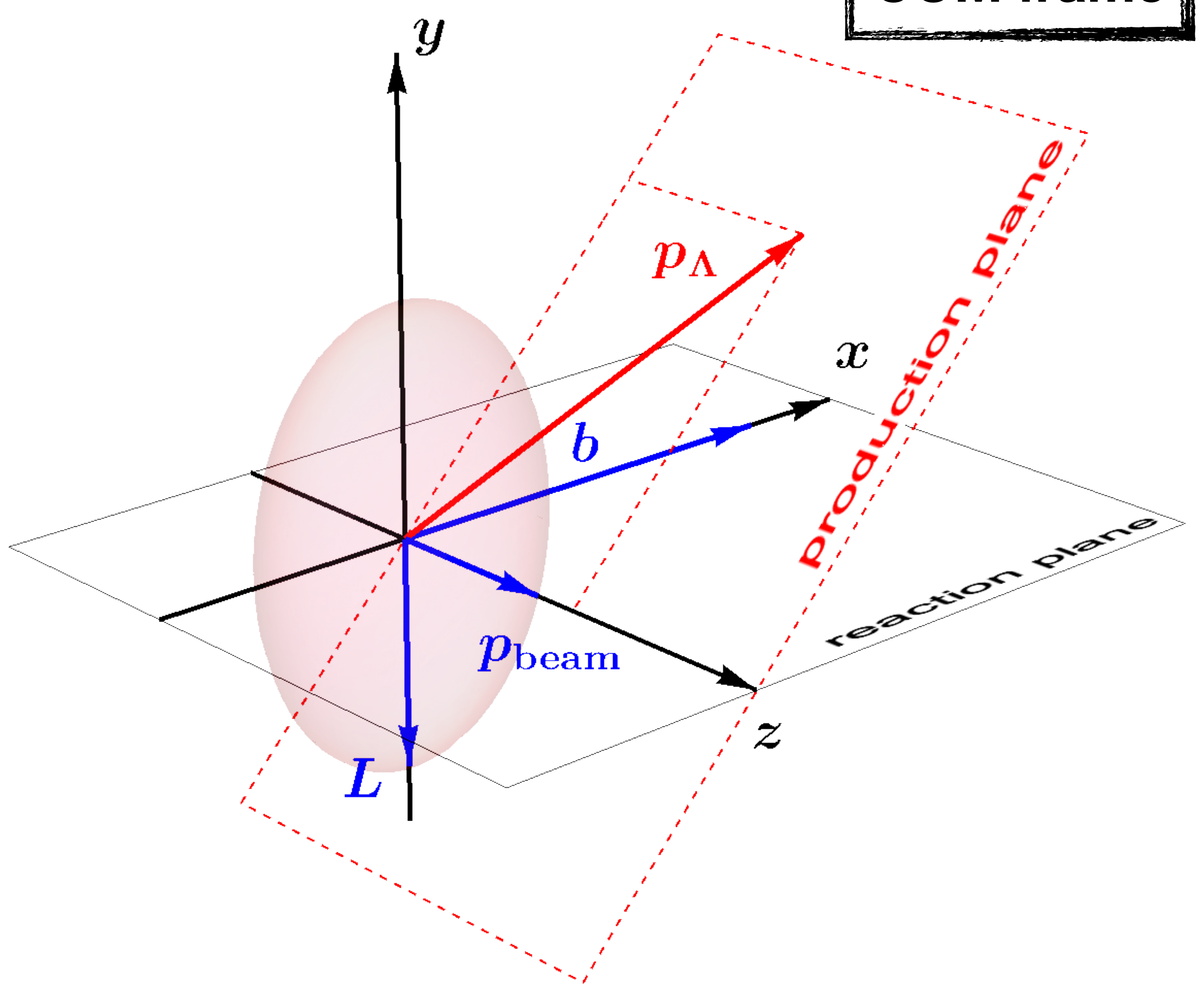


fig: W. Florkowski, R.R., 2102.02890 [hep-ph]

Λ in its rest frame “sees” different direction of angular momentum !

COM frame

$$\boldsymbol{L}$$

$$\boldsymbol{K} = 0$$

$S'(p_\Lambda)$
Λ rest frame

$$\gamma_\Lambda = E_\Lambda / m_\Lambda$$

$$\boldsymbol{L}' = \gamma_\Lambda \boldsymbol{L} - \frac{\gamma_\Lambda^2}{\gamma_\Lambda + 1} \boldsymbol{v}_\Lambda (\boldsymbol{v}_\Lambda \cdot \boldsymbol{L})$$

relativistic correction

Transformation of orbital angular momentum

COM frame

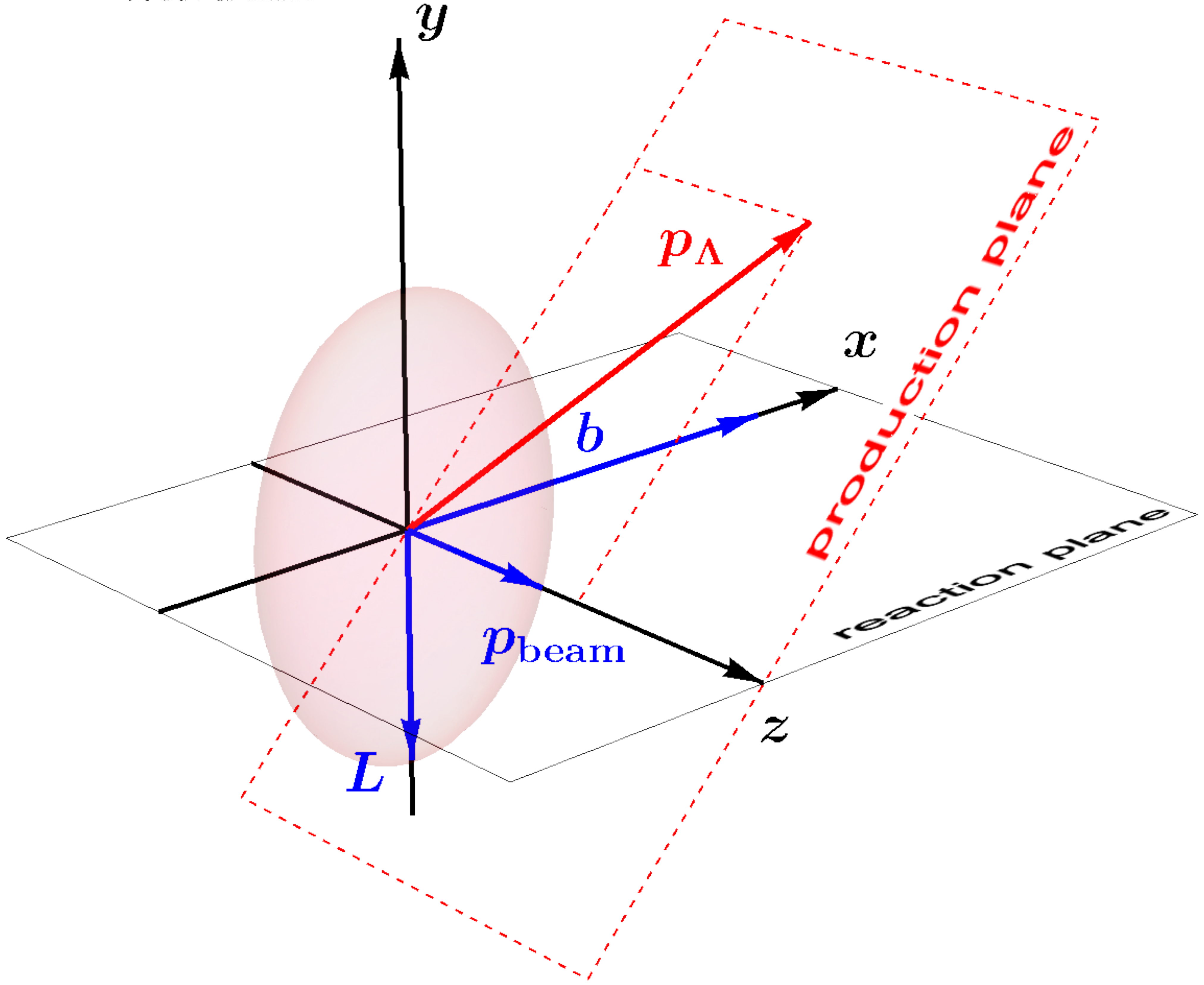


fig: W. Florkowski, R.R., 2102.02890 [hep-ph]

COM frame

$$\hat{\boldsymbol{L}} = \frac{\boldsymbol{L}}{L} = (0,-1,0) \qquad \hat{\boldsymbol{K}} = 0$$

$S'(p_\Lambda)$

Λ rest frame

$$\hat{L}'^1 = \left(1-(v_\Lambda^2)^2\right)^{-1/2} \frac{\gamma_\Lambda}{\gamma_\Lambda+1} v_\Lambda^1 v_\Lambda^2,$$

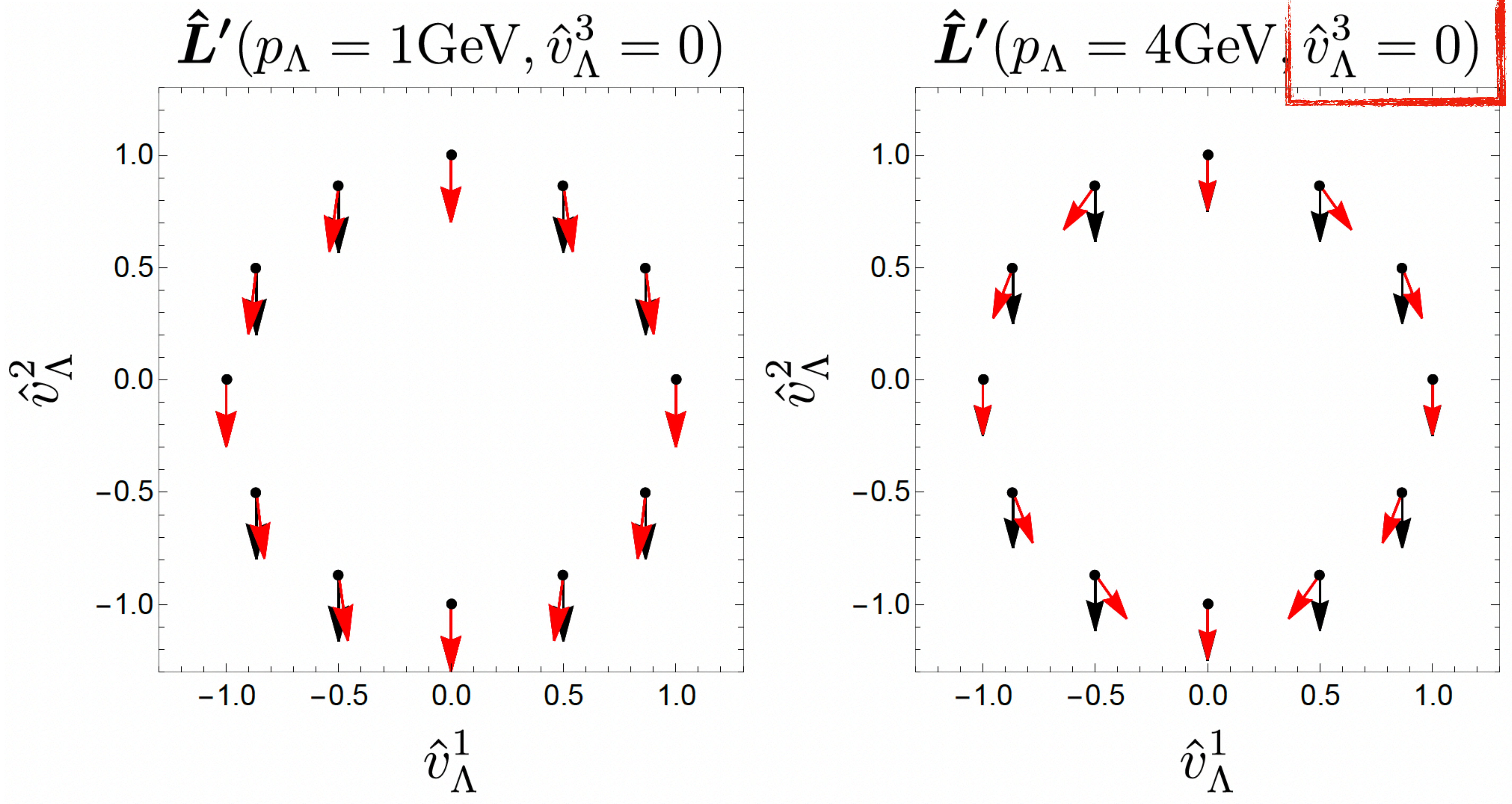
$$\hat{L}'^2 = \left(1-(v_\Lambda^2)^2\right)^{-1/2} \left(\frac{\gamma_\Lambda}{\gamma_\Lambda+1} v_\Lambda^2 v_\Lambda^2 - 1\right)$$

$$\hat{L}'^3 = \left(1-(v_\Lambda^2)^2\right)^{-1/2} \frac{\gamma_\Lambda}{\gamma_\Lambda+1} v_\Lambda^3 v_\Lambda^2.$$

$$\hat{\boldsymbol{K}}' = \frac{(v_\Lambda^3, 0, -v_\Lambda^1)}{\sqrt{(v_\Lambda^1)^2+(v_\Lambda^3)^2}}$$

Transformation of orbital angular momentum

midrapidity Λ's



COM frame

$$\hat{\boldsymbol{L}} = \frac{\boldsymbol{L}}{L} = (0, -1, 0) \qquad \hat{\boldsymbol{K}} = 0$$

$S'(p_\Lambda)$
Λ rest frame

$$\hat{L}'^1 = \left(1 - (v^2_\Lambda)^2\right)^{-1/2} \frac{\gamma_\Lambda}{\gamma_\Lambda + 1} v^1_\Lambda v^2_\Lambda,$$

$$\hat{L}'^2 = \left(1 - (v^2_\Lambda)^2\right)^{-1/2} \left(\frac{\gamma_\Lambda}{\gamma_\Lambda + 1} v^2_\Lambda v^2_\Lambda - 1\right)$$

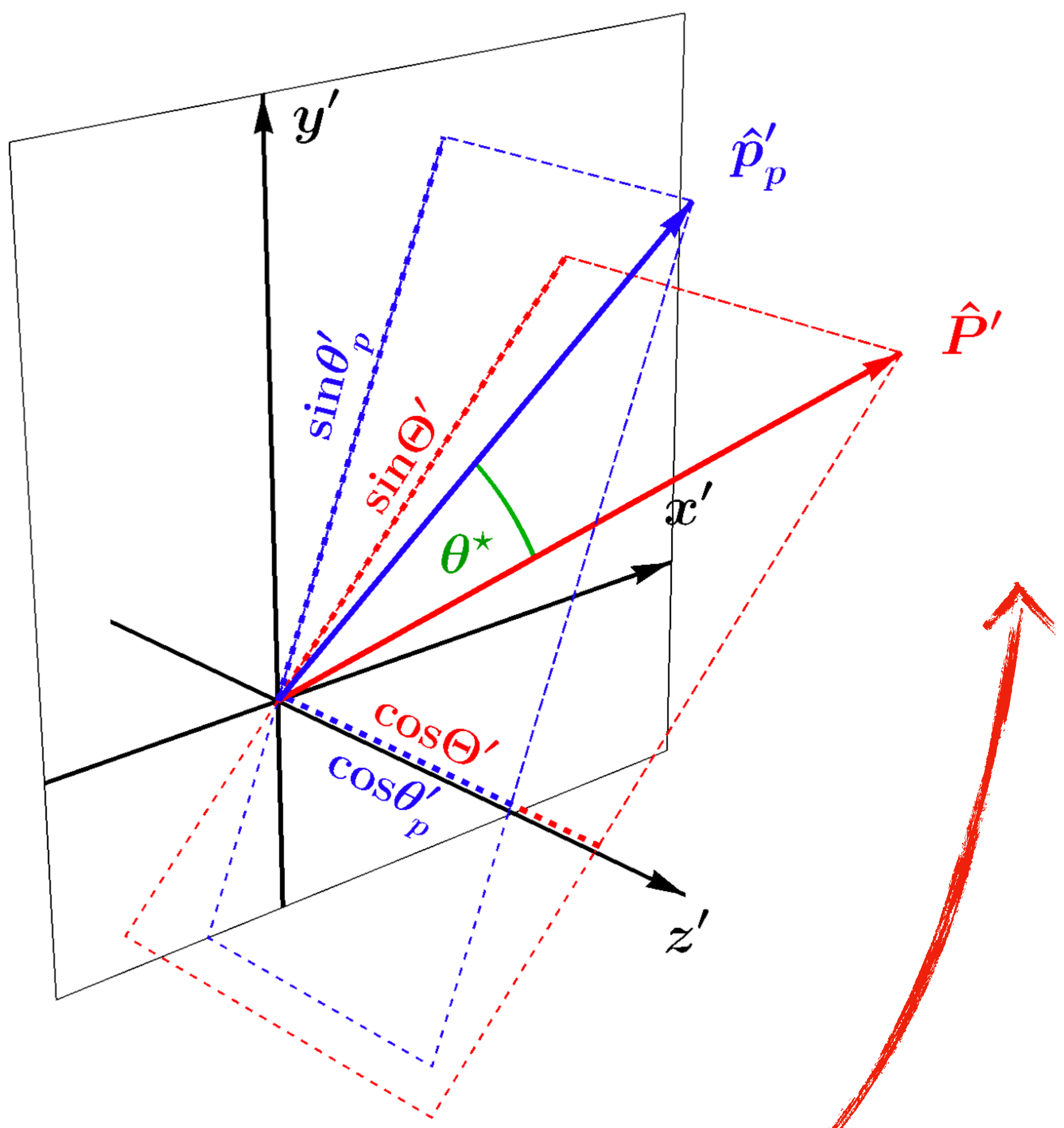
$$\hat{L}'^3 = \left(1 - (v^2_\Lambda)^2\right)^{-1/2} \frac{\gamma_\Lambda}{\gamma_\Lambda + 1} v^3_\Lambda v^2_\Lambda.$$

$$\hat{\boldsymbol{K}}' = \frac{(v^3_\Lambda, 0, -v^1_\Lambda)}{\sqrt{(v^1_\Lambda)^2 + (v^3_\Lambda)^2}}$$

change of the system's angular momentum direction due to relativistic effects

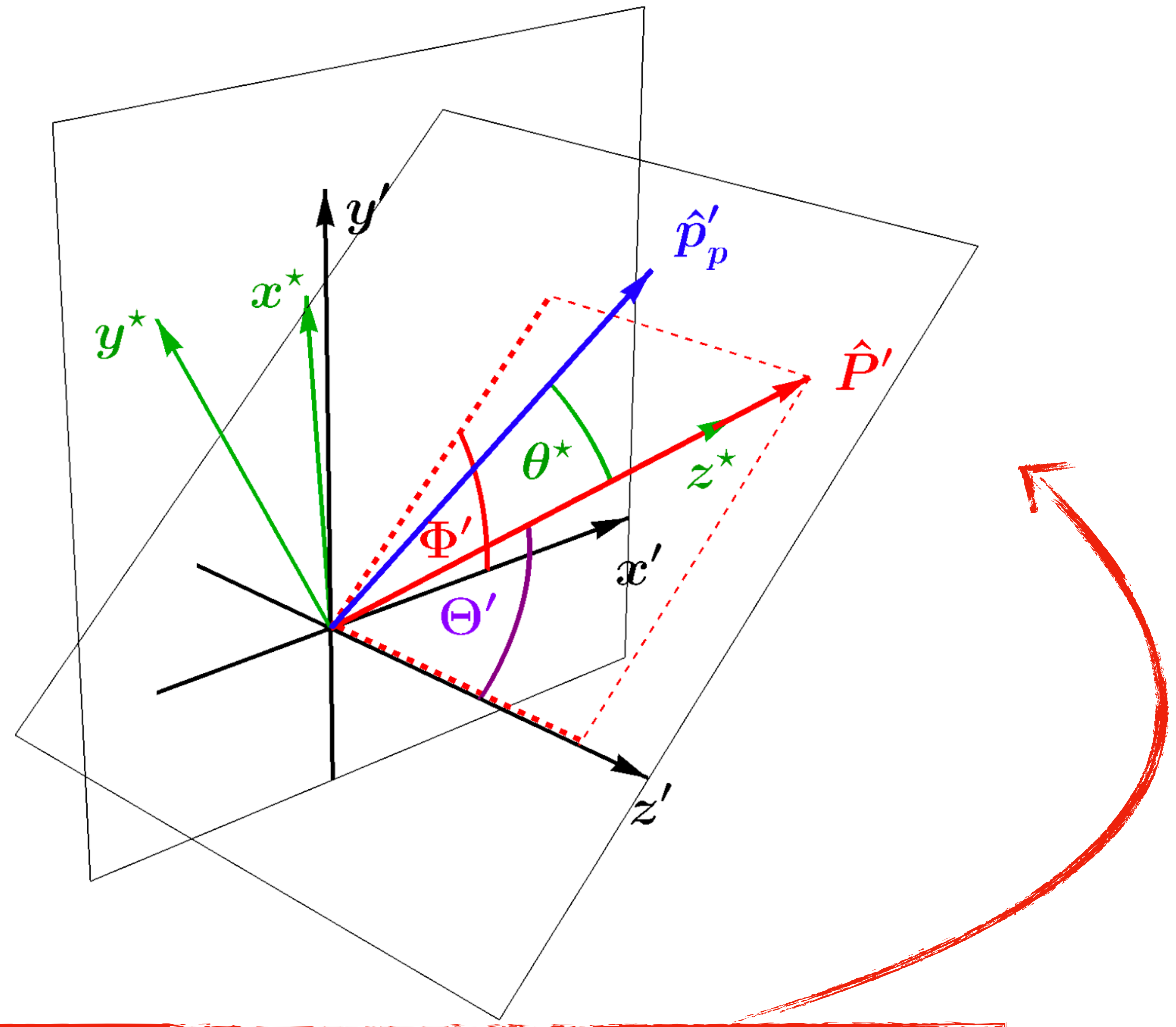
$S'(p_\Lambda)$ VS $S^*(p_\Lambda)$ Λ REST FRAMES AND THE WEAK DECAY

$S'(p_\Lambda)$
Λ rest frame



rotation

$S^*(p_\Lambda)$
Λ rest frame



$$\hat{\boldsymbol{P}}' = (\sin\Theta'\cos\Phi', \sin\Theta'\sin\Phi', \cos\Theta')$$

$$\hat{\boldsymbol{P}}^* = \mathcal{R}_{y'}(\Theta')\,\mathcal{R}_{z'}(\Phi')\,\hat{\boldsymbol{P}}' = (0,0,1)$$

$$\hat{\boldsymbol{p}}'_p = \left(\sin\theta'_p\cos\phi'_p, \sin\theta'_p\sin\phi'_p, \cos\theta'_p\right)$$

$$\begin{aligned}
\hat{p}^*_{p,x} &= \cos(\Phi' - \phi'_p)\sin\theta'_p\cos\Theta' - \cos\theta'_p\sin\Theta' \equiv \sin\theta^*\cos\phi^*, \\
\hat{p}^*_{p,y} &= -\sin(\Phi' - \phi'_p)\sin\theta'_p \equiv \sin\theta^*\sin\phi^*, \\
\hat{p}^*_{p,z} &= \cos(\Phi' - \phi'_p)\sin\theta'_p\sin\Theta' + \cos\theta'_p\cos\Theta' \equiv \cos\theta^*.
\end{aligned}$$

Λ WEAK DECAY LAW

$S^*(\boldsymbol{p}_\Lambda)$
Λ rest frame

$$\frac{dN_p^{\rm pol}}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_\Lambda \boldsymbol{P}^* \cdot \hat{\boldsymbol{p}}_p^*\right)$$

$$\hat{\boldsymbol{P}}' \cdot \hat{\boldsymbol{p}}_p' = \hat{\boldsymbol{P}}^* \cdot \hat{\boldsymbol{p}}_p^* = \cos\theta^*$$

$S'(\boldsymbol{p}_\Lambda)$
Λ rest frame

$$\frac{dN_p^{\rm pol}}{d\Omega'} = \frac{1}{4\pi}\left[1 + \alpha_\Lambda P\left(\cos(\Phi' - \phi_p')\sin\theta_p'\sin\Theta' + \cos\theta_p'\cos\Theta'\right)\right]$$

$$\langle \hat{p}'_{p,x}\rangle = \int \left(\frac{dN_p^{\rm pol}}{d\Omega'}\right)(\sin\theta_p')^2\cos\phi_p'\,d\theta_p'\,d\phi_p' = \frac{1}{3}P'\alpha_\Lambda\sin\Theta'\cos\Phi',$$

$$\langle \hat{p}'_{p,y}\rangle = \int \left(\frac{dN_p^{\rm pol}}{d\Omega'}\right)(\sin\theta_p')^2\sin\phi_p'\,d\theta_p'\,d\phi_p' = \frac{1}{3}P'\alpha_\Lambda\sin\Theta'\sin\Phi',$$

$$\langle \hat{p}'_{p,z}\rangle = \int \left(\frac{dN_p^{\rm pol}}{d\Omega'}\right)\sin\theta_p'\cos\theta_p'\,d\theta_p'\,d\phi_p' = \frac{1}{3}P'\alpha_\Lambda\cos\Theta'.$$

$$\langle\ldots\rangle = \int\left(\frac{dN_p^{\rm pol}}{d\Omega'}\right)(\ldots)\sin\theta_p' d\theta_p' d\phi_p'$$

the polarization vector can be obtained from the averaged values of the proton three-momentum components measured in $S'(\boldsymbol{p}_\Lambda)$

$$\boldsymbol{P}' = P'(\sin\Theta'\cos\Phi', \sin\Theta'\sin\Phi', \cos\Theta') = \frac{3}{\alpha_\Lambda}\left(\langle\hat{p}'_{p,x}\rangle, \langle\hat{p}'_{p,y}\rangle, \langle\hat{p}'_{p,z}\rangle\right)$$

Interpretation of the Λ polarization measurement

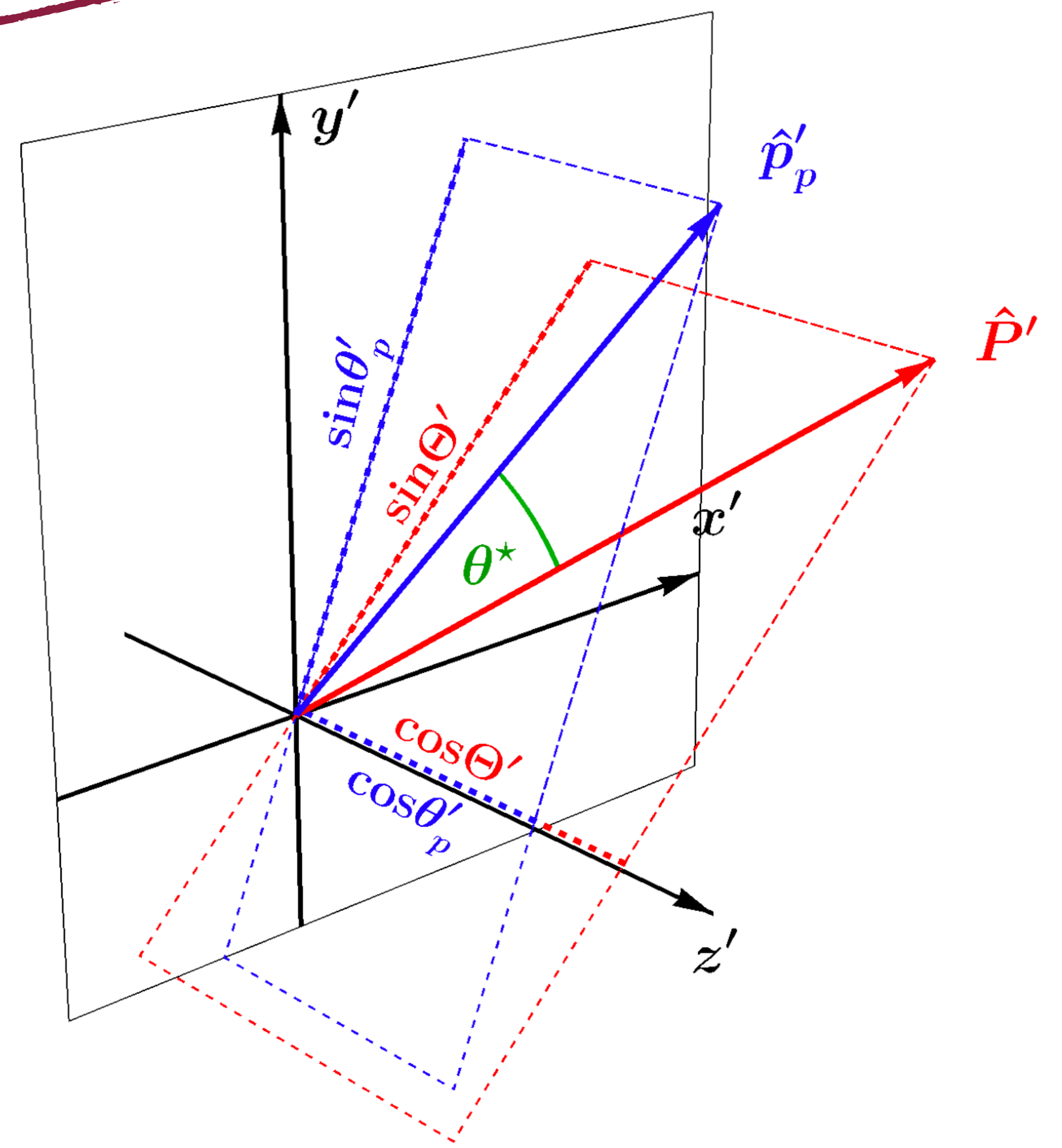
$$\langle \sin\phi'_p \rangle = \frac{\pi\alpha_\Lambda}{8} \underbrace{P' \sin\Theta' \sin\Phi'}$$

$$P_H = P' \sin\Theta' \sin\Phi'$$

$$\hat{\boldsymbol{P}}' = (\sin\Theta' \cos\Phi', \sin\Theta' \sin\Phi', \cos\Theta')$$

$$P_H = \frac{8}{\pi\alpha_\Lambda} \langle \sin\phi'_p \rangle$$

“y” component of the polarization three-vector measured in the ΛRF



not the component of the polarization along the orbital angular momentum, as the “y” directions is COM and ΛRF differ

it is tempting to measure also mean $\langle \cos\phi'_p \rangle$ — ratio of the two would give us information about the angle Φ'

$$\langle \cos\phi'_p \rangle = \frac{\pi\alpha_\Lambda}{8} P' \sin\Theta' \cos\Phi'$$

Correlation with global angular momentum

direction of the orbital angular momentum that is "seen" by the spin in the Λ rest frame

$$\hat{\boldsymbol{L}}' = \left(1 - (\boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}})^2\right)^{-1/2} \left(\hat{\boldsymbol{L}} - \frac{\gamma_\Lambda}{\gamma_\Lambda + 1} \boldsymbol{v}_\Lambda (\boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}})\right)$$

components of the polarization vector

$$\boldsymbol{P}' = \frac{3}{\alpha_\Lambda} \left(\langle \hat{p}'_{p,x} \rangle, \langle \hat{p}'_{p,y} \rangle, \langle \hat{p}'_{p,z} \rangle\right)$$

projection of the polarization vector along the direction of the global angular momentum

$$\hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' = \left(1 - (\boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}})^2\right)^{-1/2} \left(\hat{\boldsymbol{L}} \cdot \boldsymbol{P}' - \frac{\gamma_\Lambda}{\gamma_\Lambda + 1} \boldsymbol{v}_\Lambda \cdot \boldsymbol{P}' \ \boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}}\right)$$

the advantage of $\hat{L}' \cdot P'$ compared to $\hat{L} \cdot P'$ is that the spin polarization of each Λ irrespectively of its three-momentum in COM, is projected on the same physical axis corresponding to L in COM

Estimates of relativistic effects

let us assume that

$$\boldsymbol{P}' = P'\hat{\boldsymbol{L}} \quad \Rightarrow \quad \hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' = P'\left(1 - v_2^2\right)^{-1/2}\left(1 - \frac{v_2^2}{1+\sqrt{1-v^2}}\right) \equiv P' F_P(\boldsymbol{v})$$

$$v = \sqrt{v_1^2 + v_2^2 + v_3^2}$$

average value for Λ in momentum range (m,n) GeV

$$\langle \hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' \rangle_{m-n} = P' \frac{\int_{v_{(m)}}^{v_{(n)}} dv \int d\Omega \, F_P(\boldsymbol{v}) F_T(v)}{\int_{v_{(m)}}^{v_{(n)}} dv \int d\Omega \, F_T(v)}$$

$$F_T(v) = N\left[\exp\left(\frac{m_\Lambda}{T_{\rm eff}\sqrt{1-v^2}}\right) + 1\right]^{-1}$$

$$v_{(n)} = \tanh\left[\sinh^{-1}\left(\frac{n\,\mathrm{GeV}}{m_\Lambda}\right)\right]$$

$$T_{\rm eff} = 150 \;\; \mathrm{MeV}$$

$$\langle \hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' \rangle_{2-3} = 0.97 \;\; P'$$

$$\langle \hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' \rangle_{3-4} = 0.94 \;\; P'$$

$$\langle \hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' \rangle_{4-5} = 0.92 \;\; P'$$

$$\langle \hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' \rangle_{5-6} = 0.90 \;\; P'$$

relativistic effects may reach 10%
for the most energetic Λ studied at STAR

Including reaction plane dependence

$\Psi_{\rm RP} \neq 0$ ⇨ $\hat{\boldsymbol{L}} = -\left(\cos\left(\Psi_{\rm RP} + \pi/2\right), \sin\left(\Psi_{\rm RP} + \pi/2\right), 0\right)$

$$\hat{\boldsymbol{L}} \cdot \boldsymbol{P}' = -\frac{8}{\pi\alpha_\Lambda}\langle \sin(\phi'_p - \Psi_{\rm RP})\rangle = -\frac{8}{\pi\alpha_\Lambda}\int\left(\frac{dN_p^{\rm pol}}{d\Omega'}\right)\sin\left(\phi'_p - \Psi_{\rm RP}\right)\, d\Omega'$$

explicit dependence of the results on the reaction plane angle which is not directly measured

$$\left\langle \sin\left(\phi'_p - \Psi^{(1)}_{\rm EP}\right)\right\rangle_{\rm ev.} = \left\langle \sin\left(\phi'_p - \Psi_{\rm RP} - \left(\Psi^{(1)}_{\rm EP} - \Psi_{\rm RP}\right)\right)\right\rangle_{\rm ev} \equiv \left\langle \sin\left(\phi'_p - \Psi_{\rm RP}\right)\right\rangle_{\rm ev} R^{(1)}_{\rm EP}$$

$\langle \cos\Delta\Psi\rangle_{\rm ev.} \equiv R^{(1)}_{\rm EP}$ $\Delta\Psi \equiv \Psi^{(1)}_{\rm EP} - \Psi_{\rm RP}$ $\langle \sin\Delta\Psi\rangle_{\rm ev.} = 0$

$$\langle \hat{\boldsymbol{L}} \cdot \boldsymbol{P}'\rangle_{\rm ev.} = -\frac{8}{\pi\alpha_\Lambda}\langle \sin(\phi'_p - \Psi_{\rm RP})\rangle_{\rm ev.} = -\frac{8}{\pi\alpha_\Lambda}\frac{\langle \sin(\phi'_p - \Psi^{(1)}_{\rm EP})\rangle_{\rm ev.}}{R^{(1)}_{\rm EP}}$$

Including reaction plane dependence

$$\hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' = \left(1 - (\boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}})^2\right)^{-1/2} \left(\hat{\boldsymbol{L}} \cdot \boldsymbol{P}' - \frac{\gamma_\Lambda}{\gamma_\Lambda + 1} \boldsymbol{v}_\Lambda \cdot \boldsymbol{P}' \;\; \boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}}\right)$$

$$\hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' = \hat{\boldsymbol{L}} \cdot \boldsymbol{P}' - \frac{\gamma_\Lambda}{\gamma_\Lambda + 1} \boldsymbol{v}_\Lambda \cdot \boldsymbol{P}' \;\; \boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}} + \frac{1}{2}(\boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}})^2 \hat{\boldsymbol{L}} \cdot \boldsymbol{P}'$$

$$\langle \boldsymbol{v}_\Lambda \cdot \boldsymbol{P}' \;\; \boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}} \rangle_{\text{ev.}} = \frac{8}{\pi \alpha_\Lambda} \langle \cos(\phi_\Lambda - \phi'_p) \sin(\phi_\Lambda - \Psi_{\text{RP}}) \rangle_{\text{ev.}}$$

$$\frac{\langle \cos(\phi_\Lambda - \phi'_p) \sin(\phi_\Lambda - \Psi^{(1)}_{\text{EP}}) \rangle_{\text{ev.}}}{\langle \cos(\phi_\Lambda - \phi'_p) \cos \Delta\Psi \rangle_{\text{ev.}}}$$

Including reaction plane dependence

$$\hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' = \left(1 - (\boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}})^2\right)^{-1/2} \left(\hat{\boldsymbol{L}} \cdot \boldsymbol{P}' - \frac{\gamma_\Lambda}{\gamma_\Lambda + 1} \boldsymbol{v}_\Lambda \cdot \boldsymbol{P}' \;\; \boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}}\right)$$

$$\hat{\boldsymbol{L}}' \cdot \boldsymbol{P}' = \hat{\boldsymbol{L}} \cdot \boldsymbol{P}' - \frac{\gamma_\Lambda}{\gamma_\Lambda + 1} \boldsymbol{v}_\Lambda \cdot \boldsymbol{P}' \;\; \boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}} + \underbrace{\frac{1}{2}(\boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}})^2 \hat{\boldsymbol{L}} \cdot \boldsymbol{P}'}$$

$$\langle (\boldsymbol{v}_\Lambda \cdot \hat{\boldsymbol{L}})^2 \hat{\boldsymbol{L}} \cdot \boldsymbol{P}' \rangle_{\text{ev.}} = -\frac{8}{\pi \alpha_\Lambda} \boxed{\langle \sin^2(\phi_\Lambda - \Psi_{\text{RP}}) \sin(\phi'_p - \Psi_{\text{RP}}) \rangle_{\text{ev.}}}$$

$$\boxed{\langle \sin^2(\phi_\Lambda - \Psi^{(1)}_{\text{EP}}) \sin(\phi'_p - \Psi^{(1)}_{\text{EP}}) \rangle_{\text{ev.}}} = M_1 \langle \cos \Delta\Psi \cos(2\Delta\Psi) \rangle_{\text{ev.}} + (M_2 + M_3) \langle \cos \Delta\Psi \sin^2 \Delta\Psi \rangle_{\text{ev.}}$$

$$\boxed{\langle \sin(2(\phi_\Lambda - \Psi^{(1)}_{\text{EP}})) \cos(\phi'_p - \Psi^{(1)}_{\text{EP}}) \rangle_{\text{ev.}}} = (M_2 + 2(M_3 - 2M_1)) \langle \cos \Delta\Psi \cos(2\Delta\Psi) \rangle_{\text{ev.}} - 2(M_3 - 2M_1) \langle \cos^3 \Delta\Psi \rangle_{\text{ev.}},$$

$$\boxed{M_1 = \langle \sin^2(\phi_\Lambda - \Psi_{\text{RP}}) \sin(\phi'_p - \Psi_{\text{RP}}) \rangle_{\text{ev.}}}$$

$$M_2 = \langle \sin(2(\phi_\Lambda - \Psi_{\text{RP}})) \cos(\phi'_p - \Psi_{\text{RP}}) \rangle_{\text{ev.}},$$

$$M_3 = \langle \sin(\phi'_p - \Psi_{\text{RP}}) \rangle_{\text{ev.}}.$$

Summary

We have discussed the interpretation of the spin polarization measurements in relativistic heavy-ion collisions

We have shown that the appropriate interpretation of the relation between the spin direction (measured in the ΛRF) and the orbital angular momentum of the system (measured in the COM frame) requires that the direction of the angular momentum is boosted to the ΛRF

We have given the necessary formula that may be used to average the measured polarization of Λ with different momenta in the COM frame

THANK YOU FOR YOUR ATTENTION!