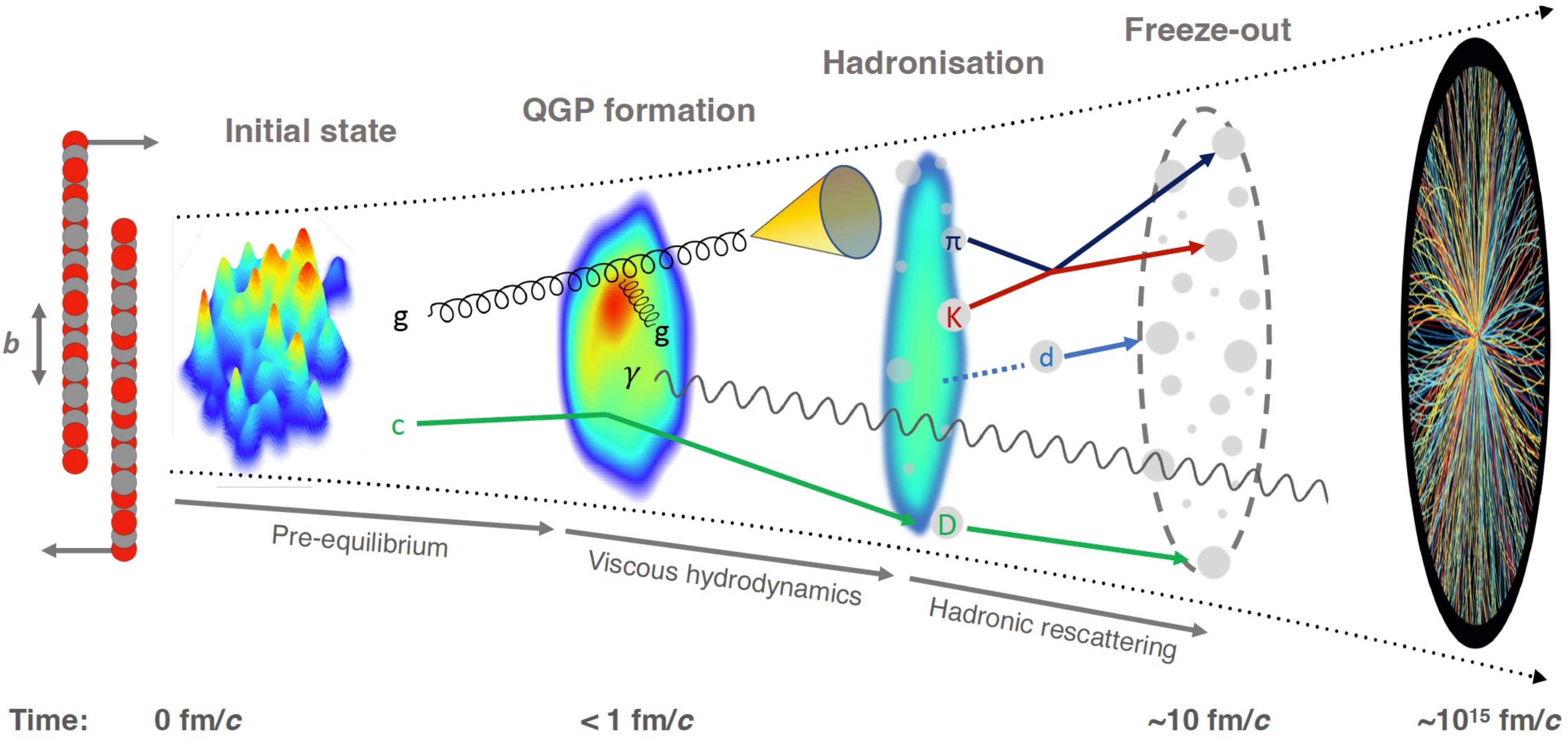
Recent results at the LHC on polarization and spin alignment

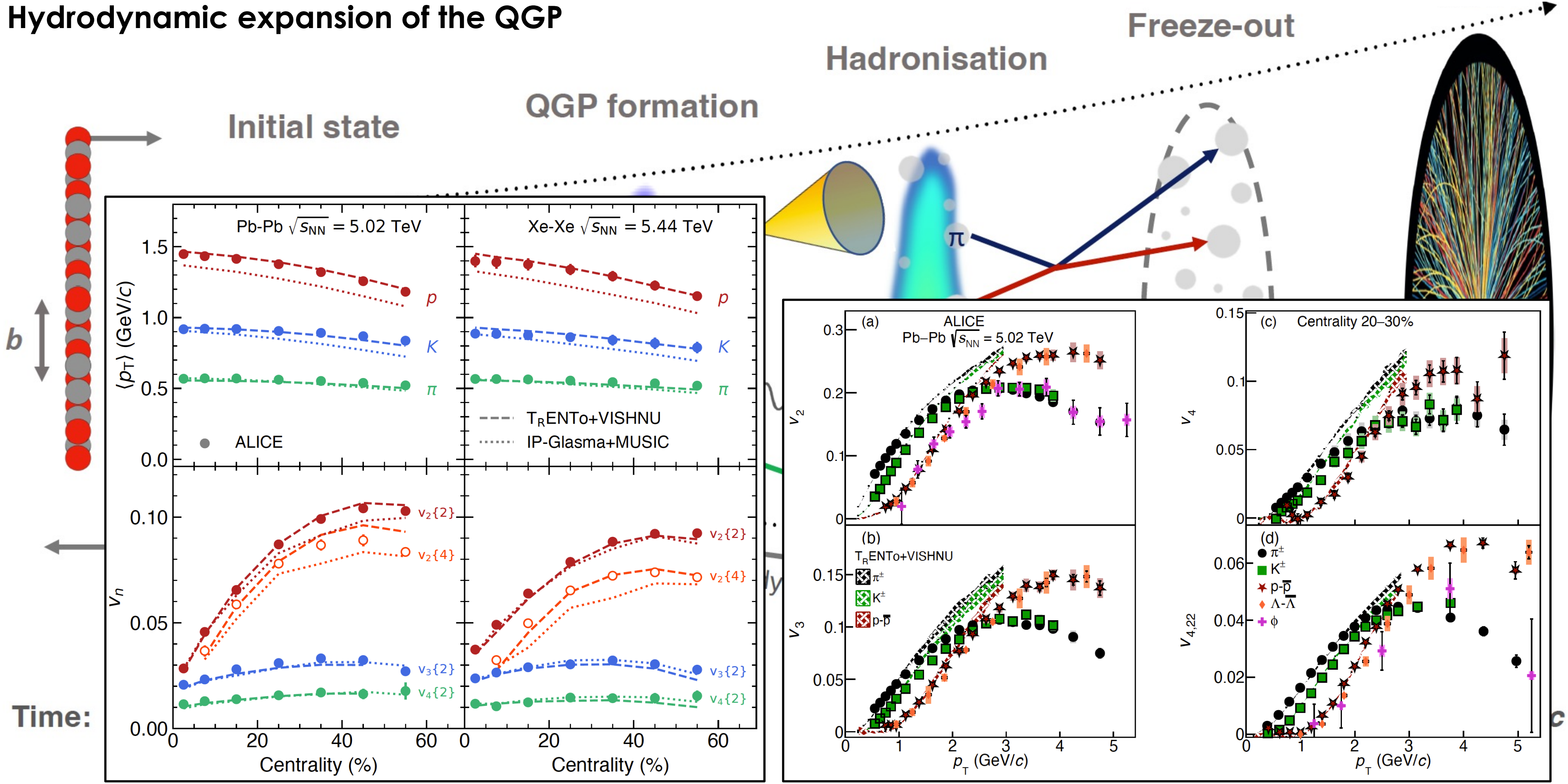
Sanghoon Lim
Pusan National University

Relativistic heavy-ion collision



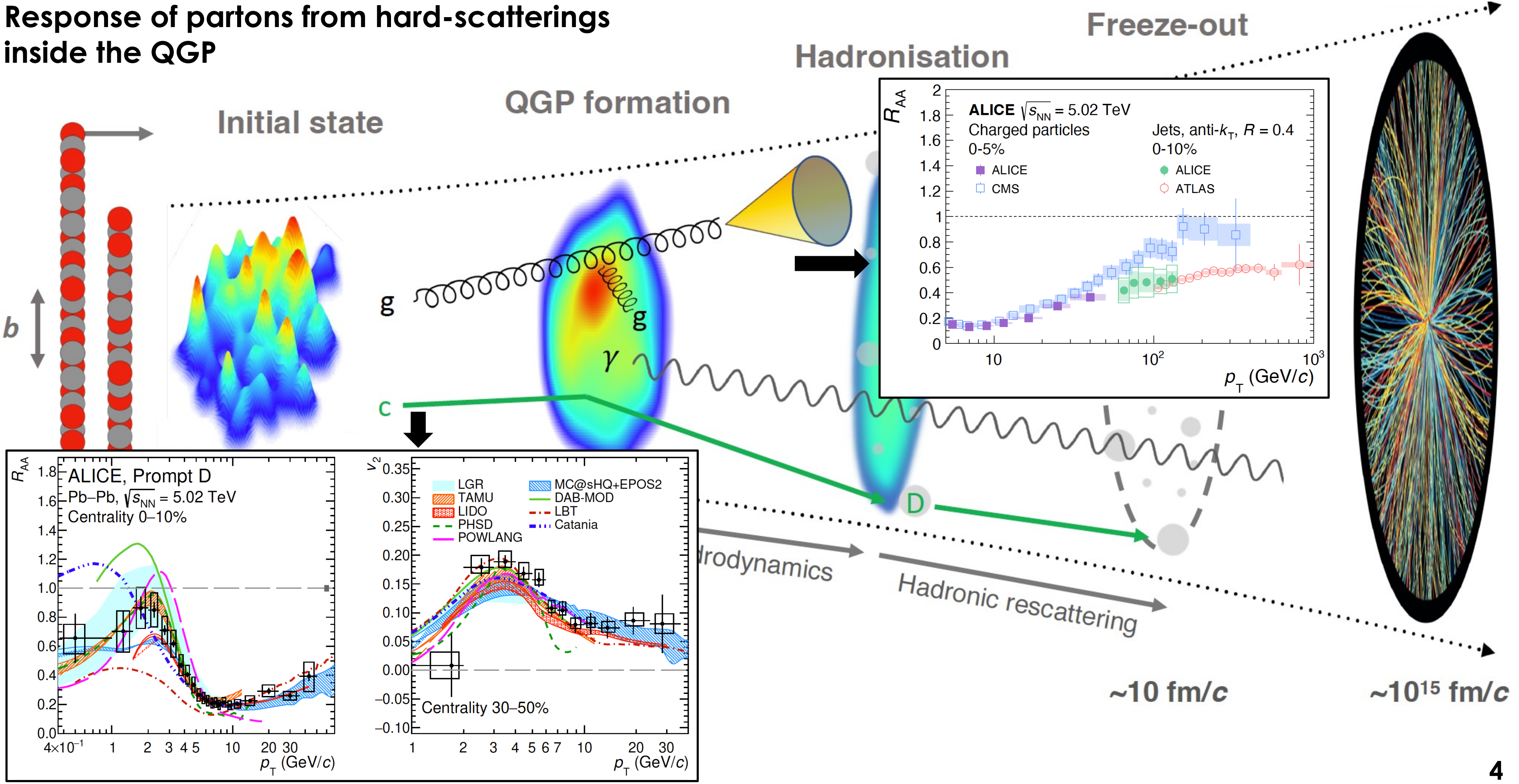
Relativistic heavy-ion collision

Hydrodynamic expansion of the QGP



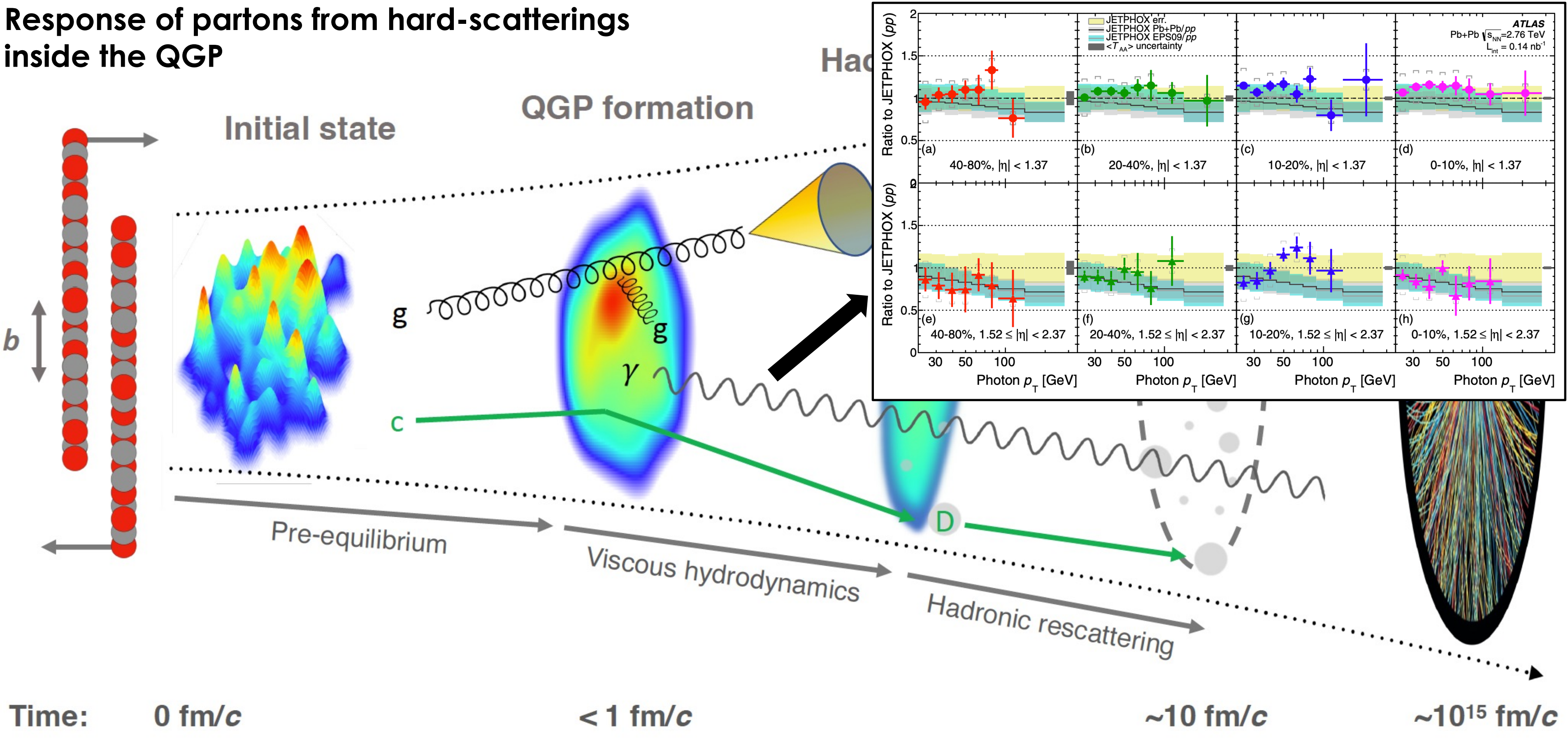
Relativistic heavy-ion collision

Response of partons from hard-scatterings inside the QGP



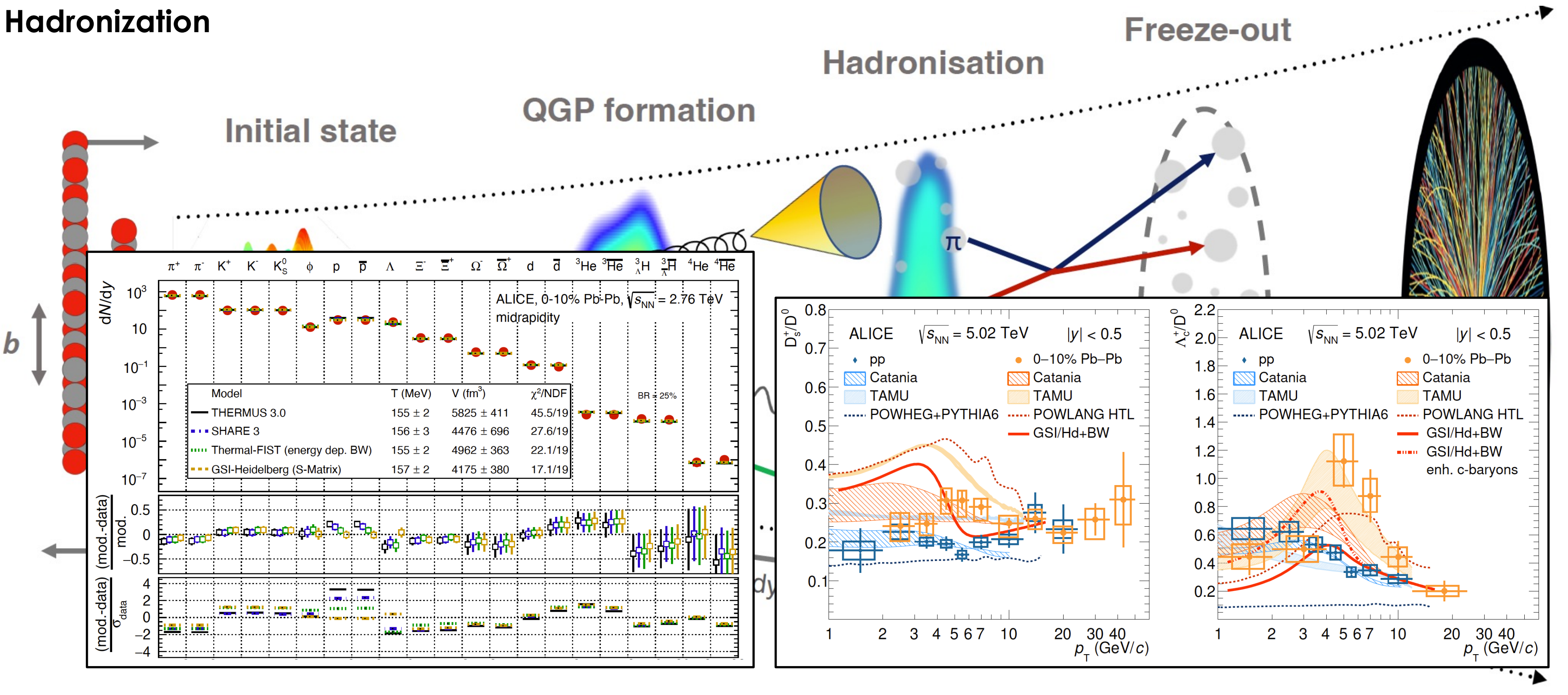
Relativistic heavy-ion collision

Response of partons from hard-scatterings inside the QGP



Relativistic heavy-ion collision

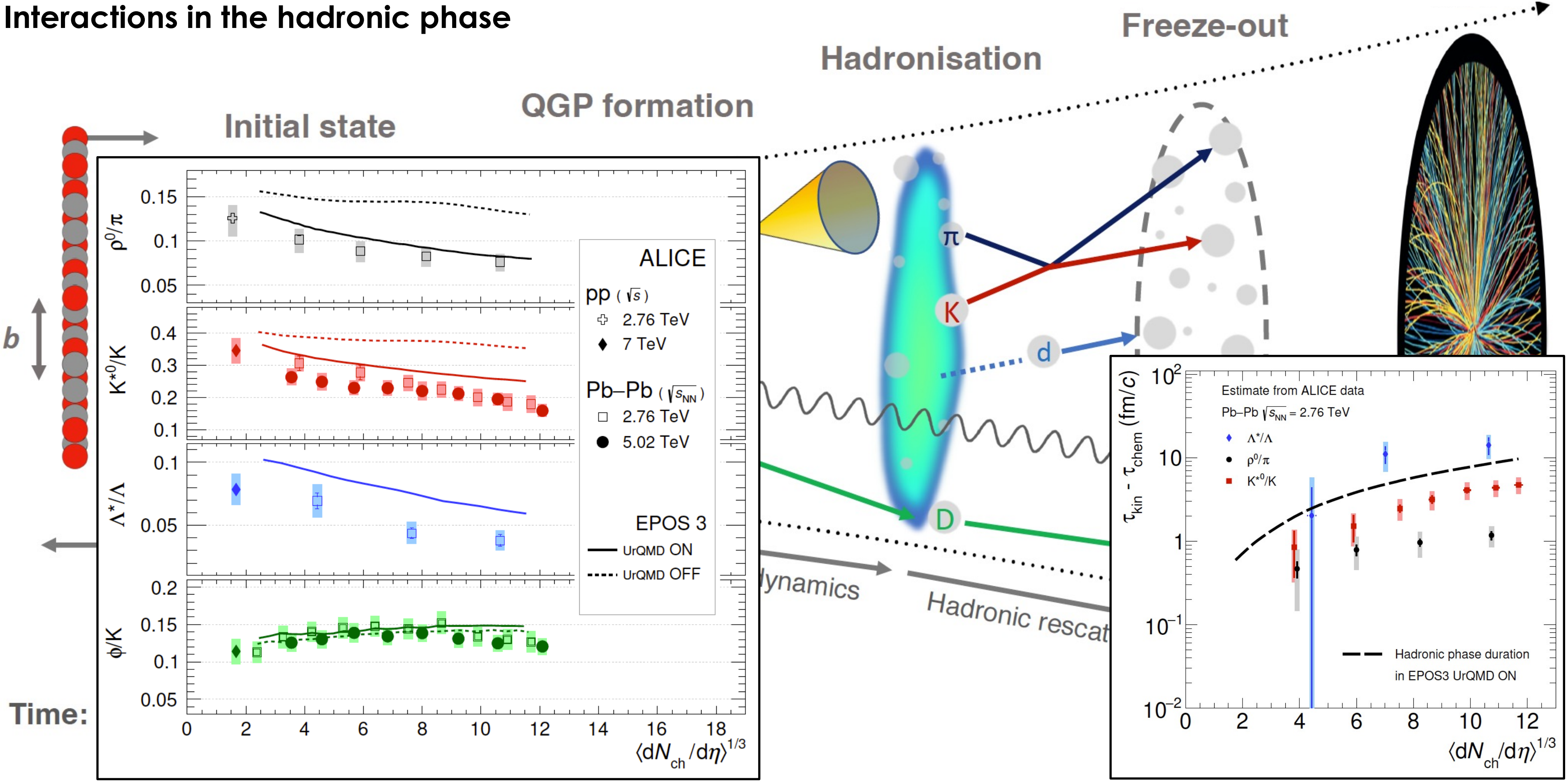
Hadronization



Time: 0 fm/c < 1 fm/c ~10 fm/c ~10^{15} fm/c

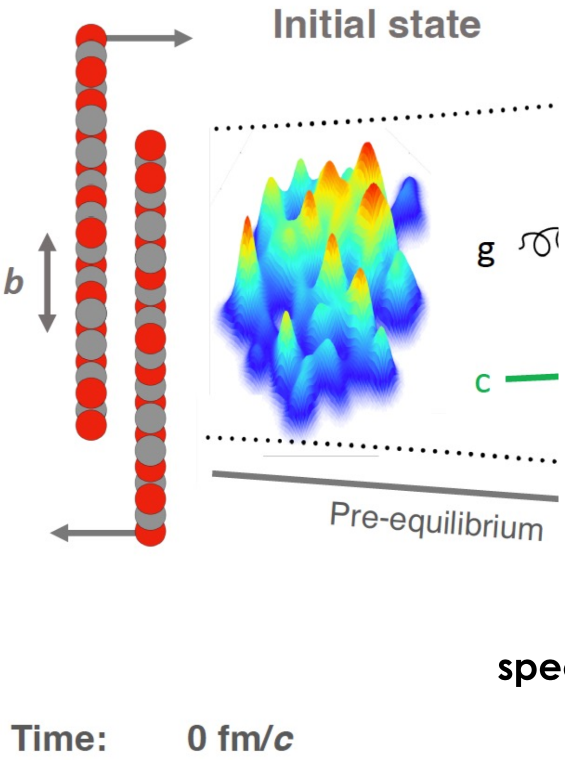
Relativistic heavy-ion collision

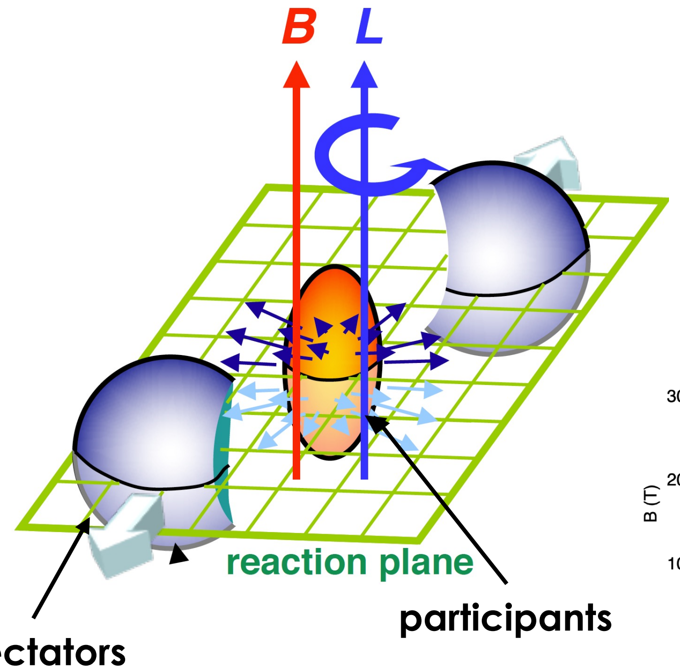
Interactions in the hadronic phase



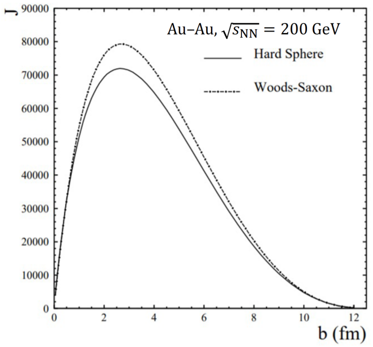
Relativistic heavy-ion collision

Strong magnetic field and vorticity at the initial state



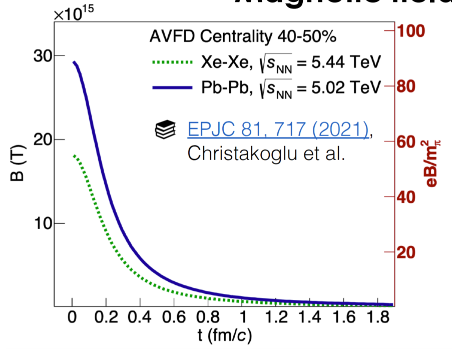


Angular momentum



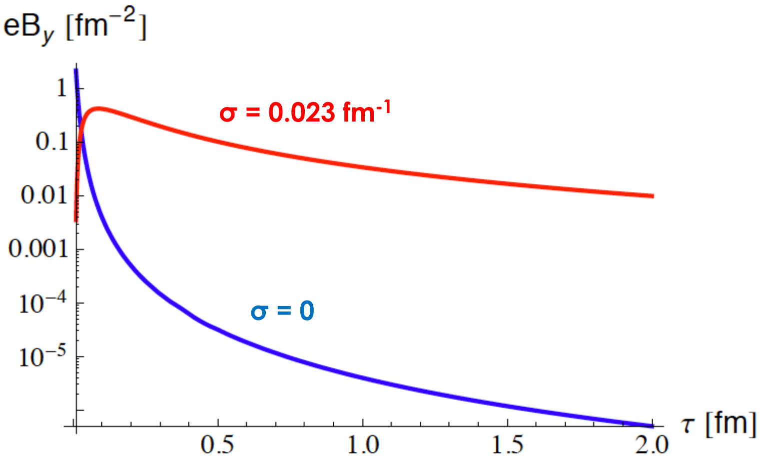
	ω (s⁻¹)
QGP	10^{22}
Pulsar	10^{2}
Tornado	10^{-1}

Magnetic field



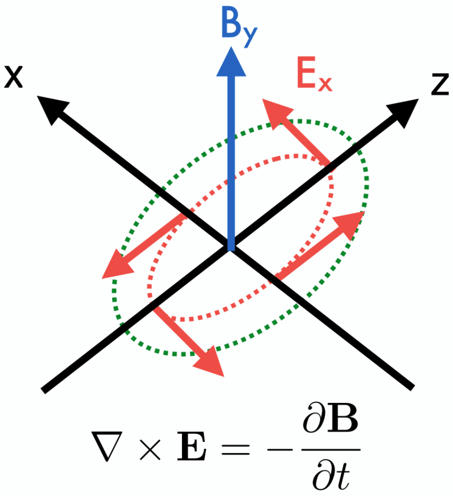
	B (T)
HICs	10^{16}
Pulsar	10^{11}
Earth	10^{-5}

Effects from the strong EM field

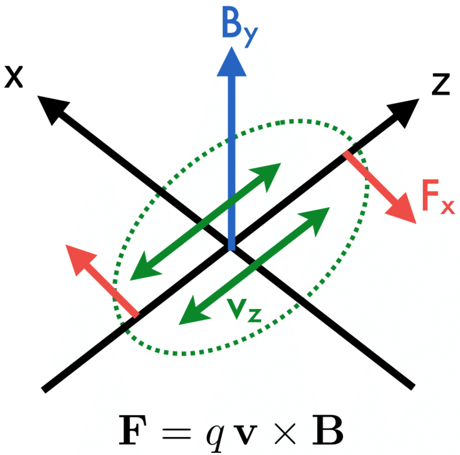


PRC 89, 054905 (2014)

- The decay time of the magnetic field is related to the conductivity of the QGP!

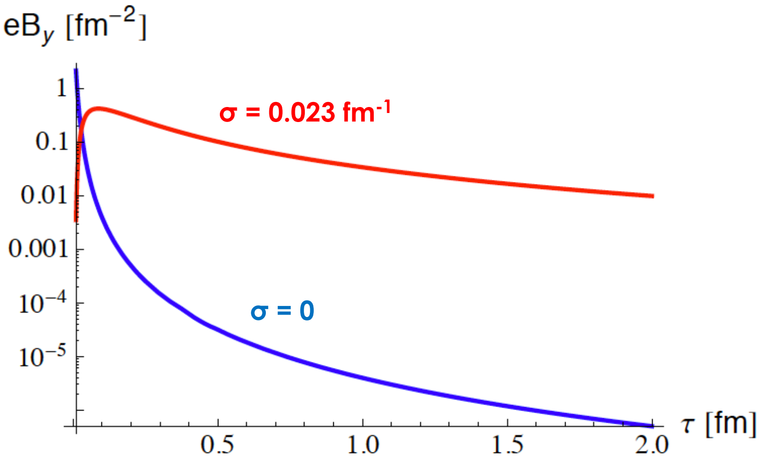


Electric field induced by decreasing B

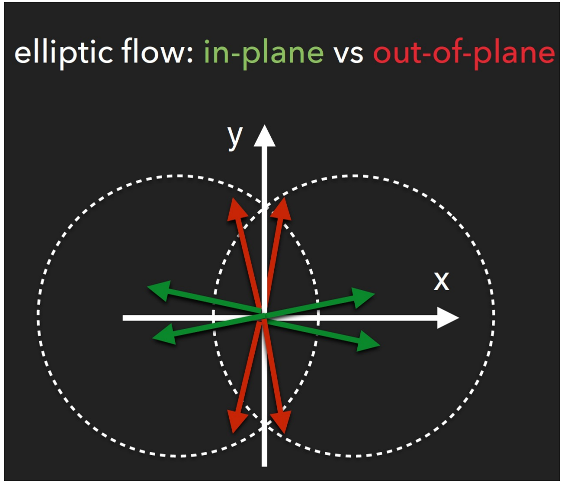


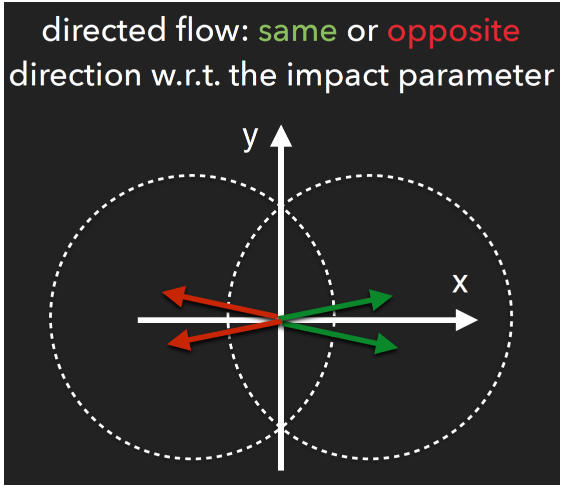
Lorentz force on moving charge

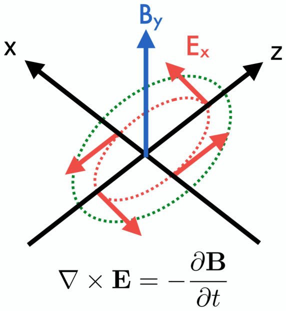
Effects from the strong EM field

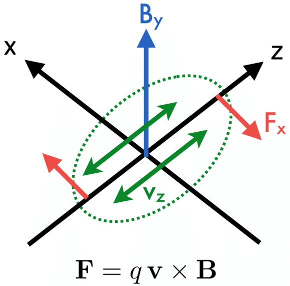


PRC 89, 054905 (2014)





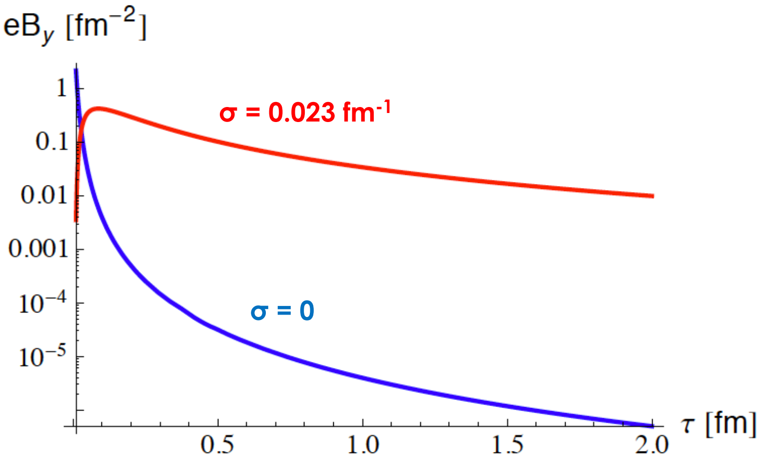




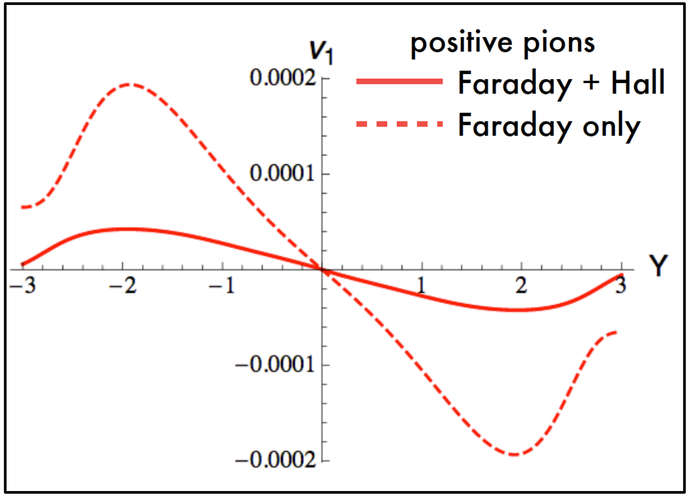
Competing effects!

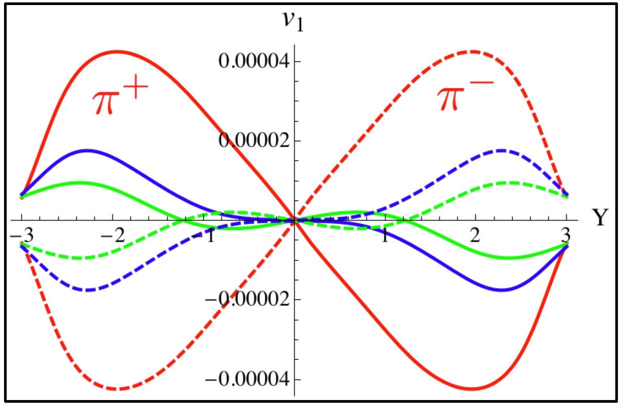
- The decay time of the magnetic field is related to the conductivity of the QGP!
- Charge-dependent directed flow can be used to calibrate the strength and duration of the magnetic field

Effects from the strong EM field

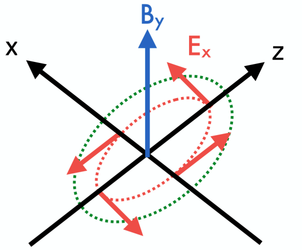


PRC 89, 054905 (2014)

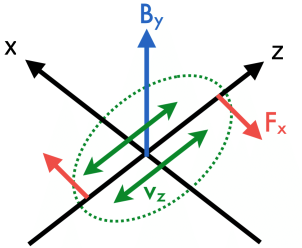




Pb-Pb 2.76 TeV p_T = 0.25, 0.5, 1.0 GeV/c^2



$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

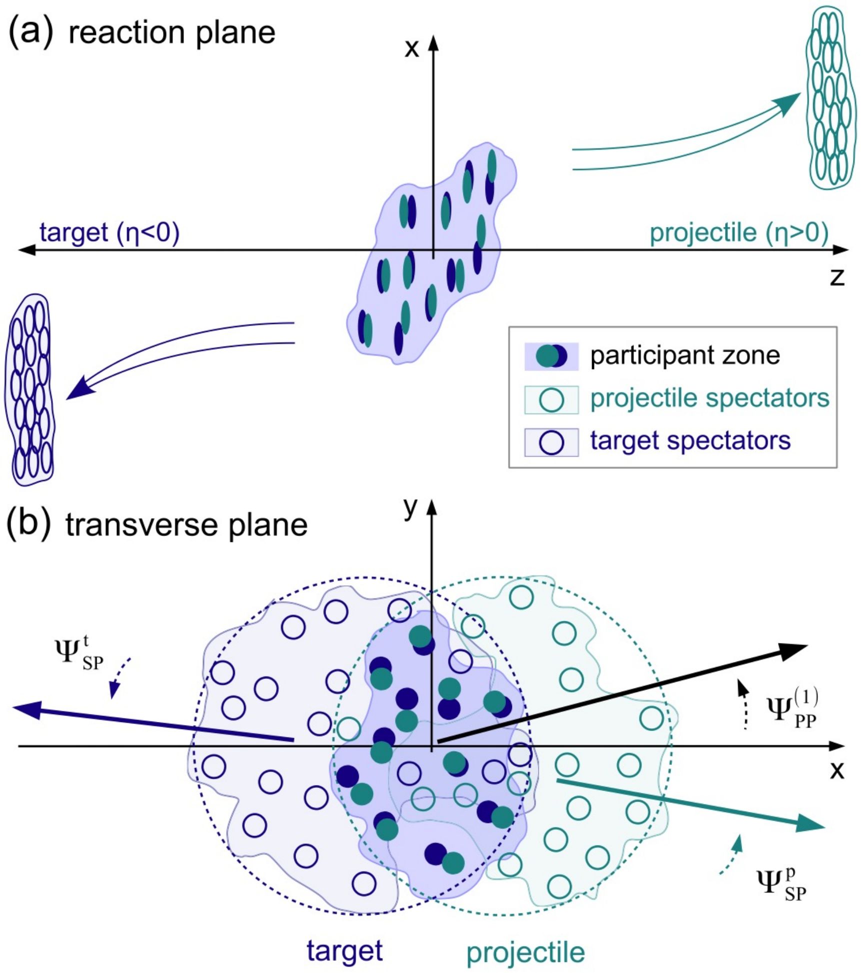


$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

Competing effects!

- The decay time of the magnetic field is related to the conductivity of the QGP!
- Charge-dependent directed flow can be used to calibrate the strength and duration of the magnetic field

Measurement of directed flow



$$v_1\{\Psi^p_{SP}\} = \frac{1}{\sqrt{2}}\left[\frac{\langle u_x Q^p_x\rangle}{\sqrt{|\langle Q^t_x Q^p_x\rangle|}} + \frac{\langle u_y Q^p_y\rangle}{\sqrt{|\langle Q^t_y Q^p_y\rangle|}}\right],$$

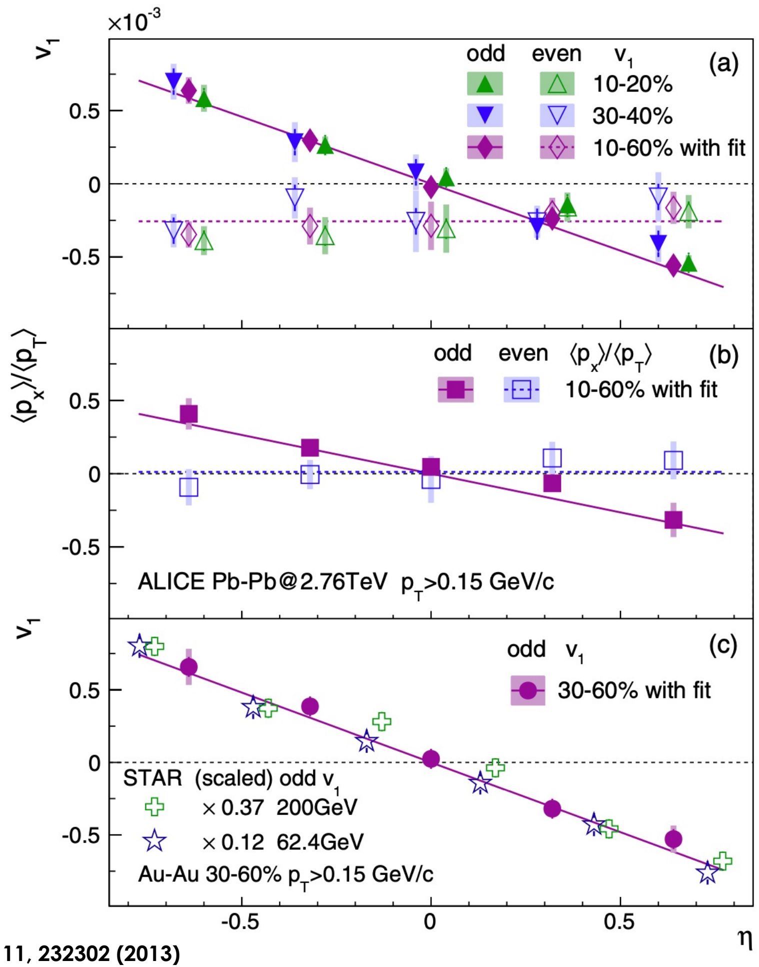
$$v_1\{\Psi^t_{SP}\} = -\frac{1}{\sqrt{2}}\left[\frac{\langle u_x Q^t_x\rangle}{\sqrt{|\langle Q^t_x Q^p_x\rangle|}} + \frac{\langle u_y Q^t_y\rangle}{\sqrt{|\langle Q^t_y Q^p_y\rangle|}}\right],$$

$$v_1^{odd}\{\Psi_{SP}\} = [v_1\{\Psi^p_{SP}\} + v_1\{\Psi^t_{SP}\}]/2$$

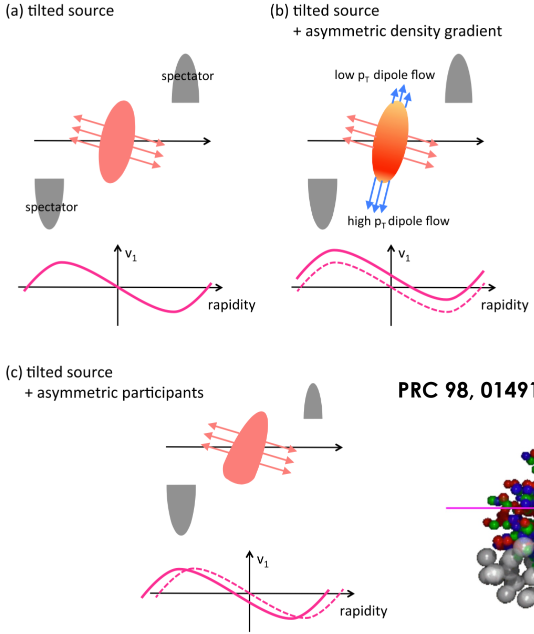
$$v_1^{even}\{\Psi_{SP}\} = [v_1\{\Psi^p_{SP}\} - v_1\{\Psi^t_{SP}\}]/2.$$

- Proxy of the reaction plane:
  Direction of the spectator neutron
  ➔spectator plane
- The energy of spectator neutrons is measured with Zero-Degree Calorimeters

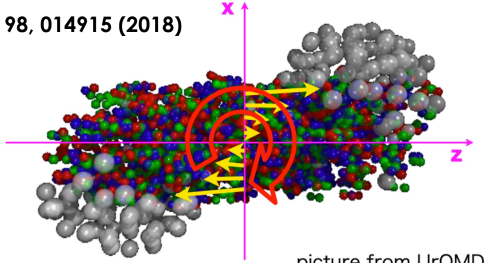
Measurement of directed flow



PRL 111, 232302 (2013)



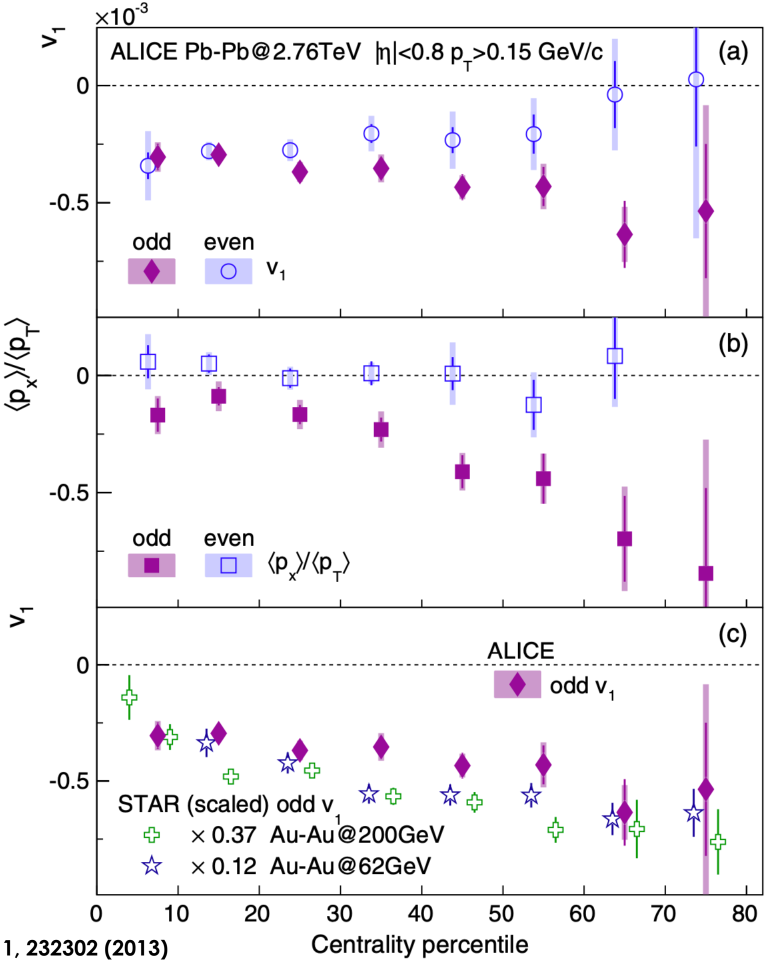
PRC 98, 014915 (2018)



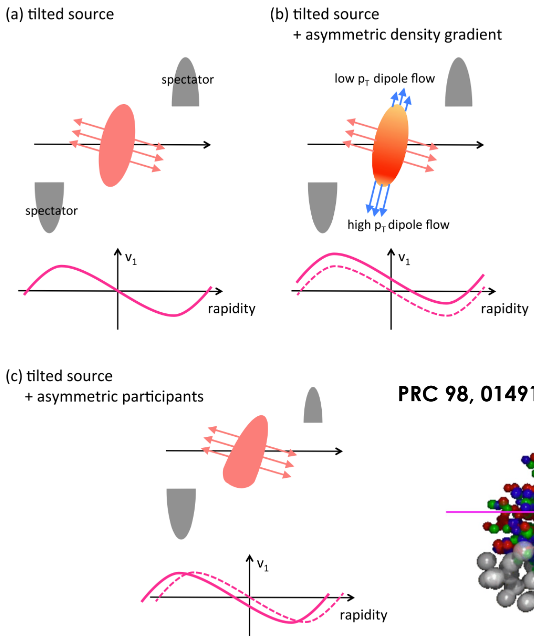
picture from UrQMD

- Vorticity (tilt) due to asymmetric initial velocity generates directed flow

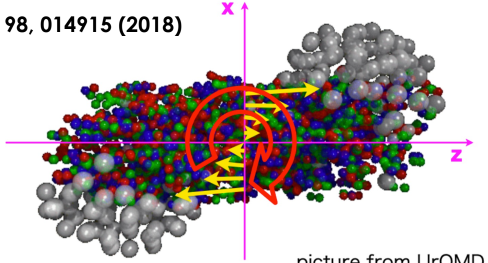
Measurement of directed flow



PRL 111, 232302 (2013)



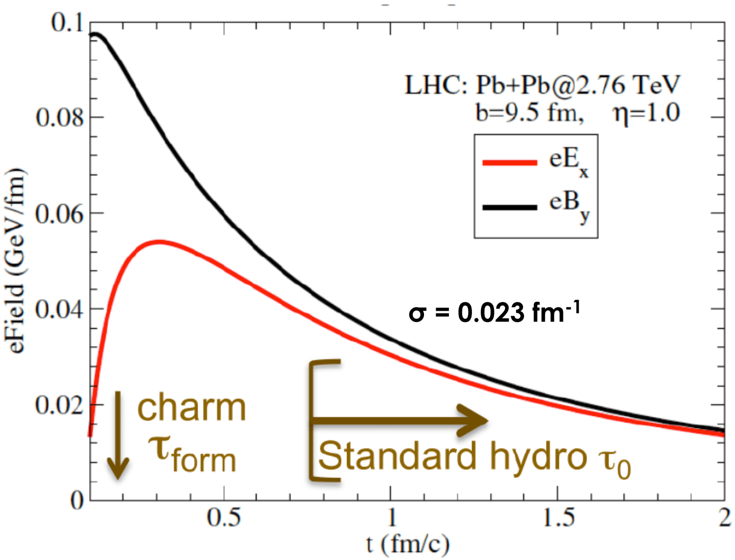
PRC 98, 014915 (2018)

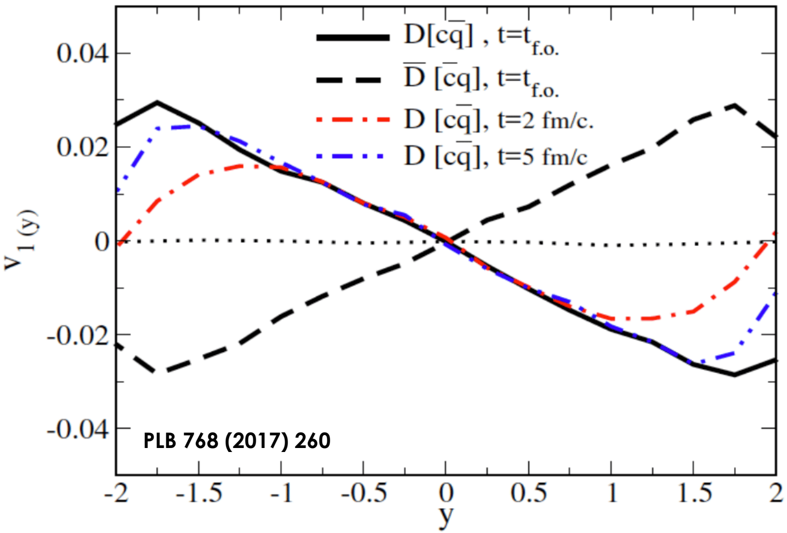


picture from UrQMD

- Vorticity (tilt) due to asymmetric initial velocity generates directed flow
- Significantly smaller magnitude than RHIC energies

Closer to the initial state using heavy flavor

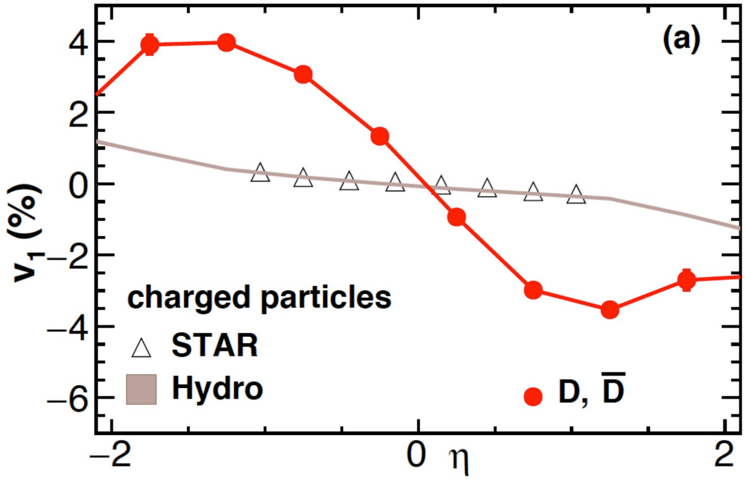


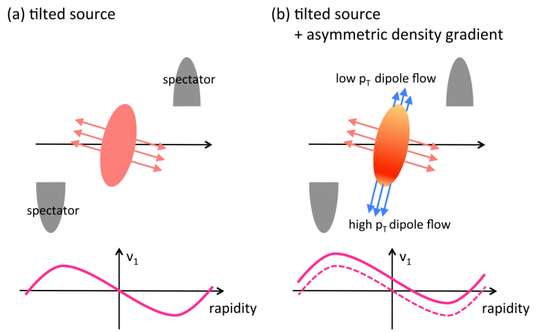


- The formation time of the charm quark is about 0.1 fm/c
  ➔When the magnetic field is maximum

- Directed flow of charm hadrons is expected to be larger than light hadrons

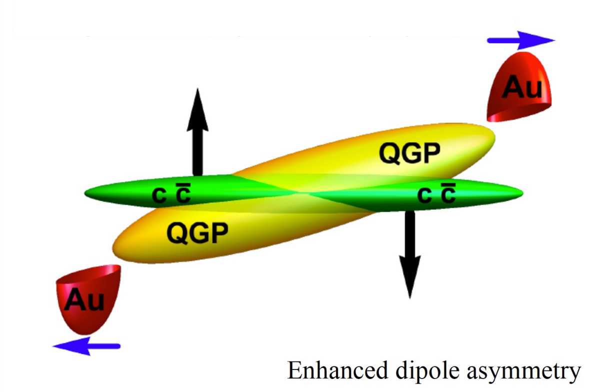
Closer to the initial state using heavy flavor



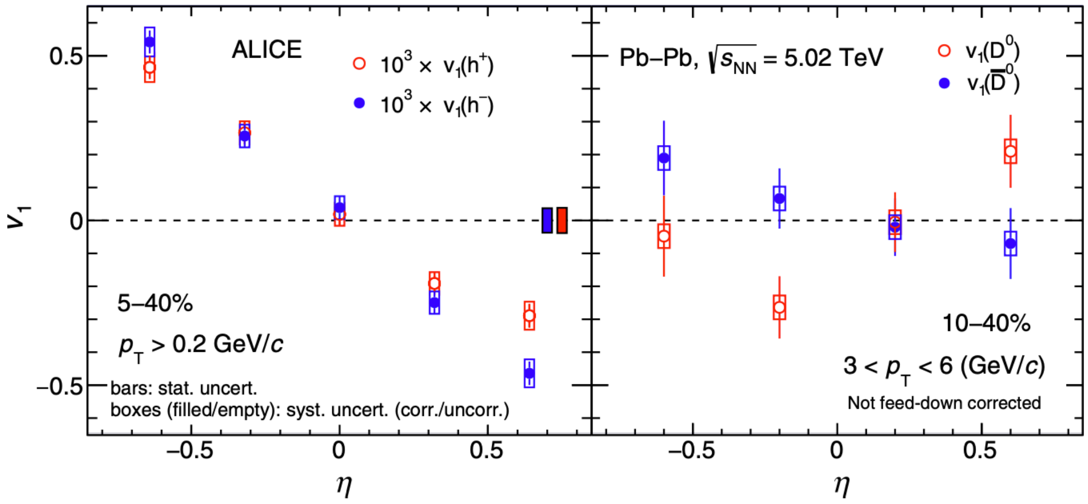


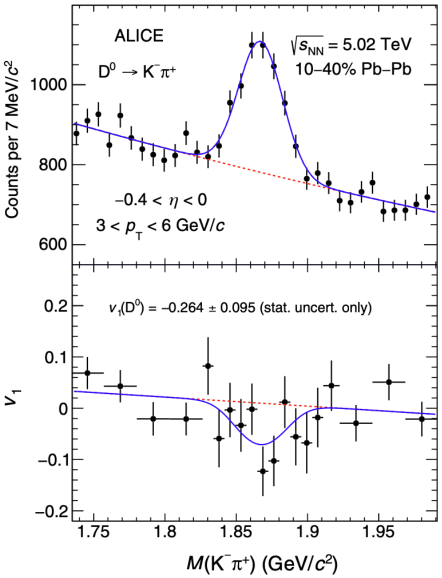
PRC 98, 014915 (2018)

- The formation time of the charm quark is about 0.1 fm/c
  ➔When the magnetic field is maximum
- Shifted from the bulk
  ➔Enhance dipole asymmetry resulting in a larger directed flow



PLB 798 (2019) 134955
PRL 120 192301 (2018)



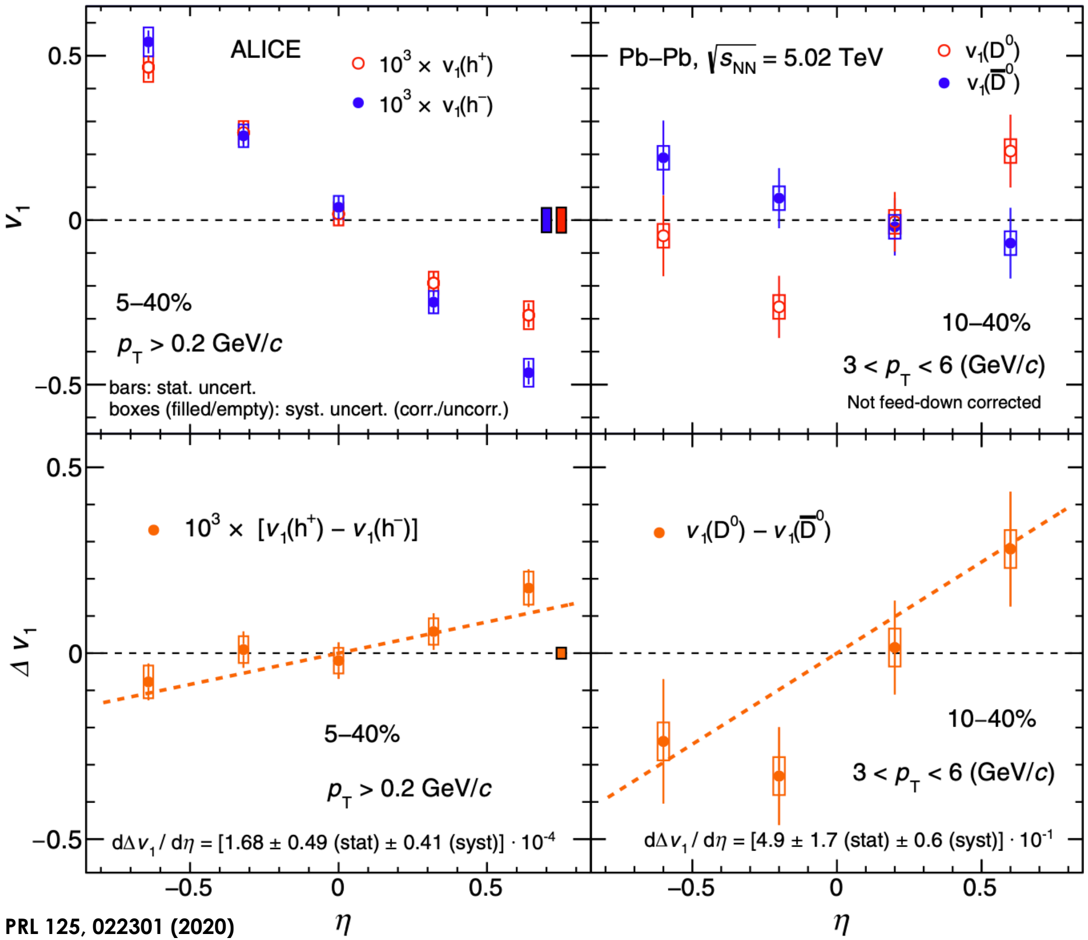


PRL 125, 022301 (2020)

$$N(M) = N_D(M) + N_{bg}(M),$$

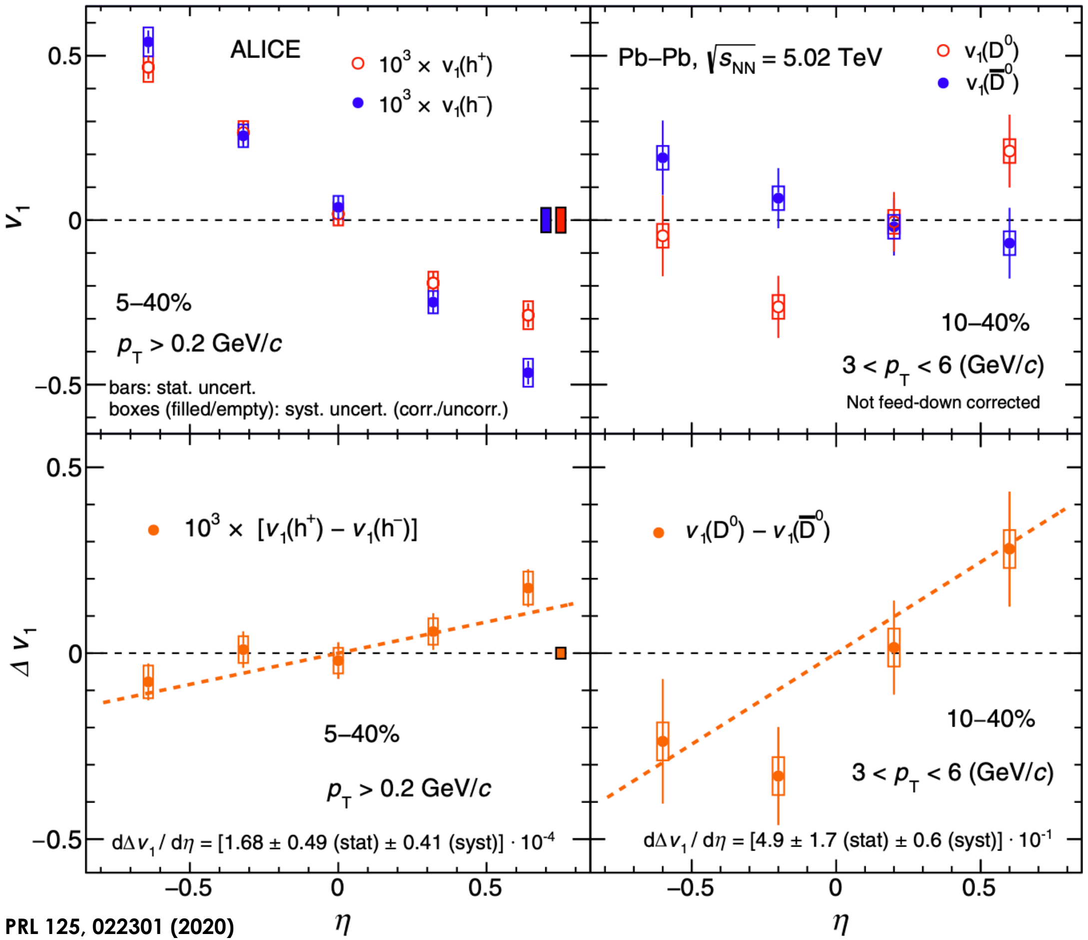
$$v_1(M) = [v_1^D N_D(M) + v_1^{bg}(M) N_{bg}(M)] / [N_D(M) + N_{bg}(M)]$$

- Much larger v_1 signal for D mesons than light hadrons
- Opposite rapidity dependence between D^0 and $\overline{D}^0$

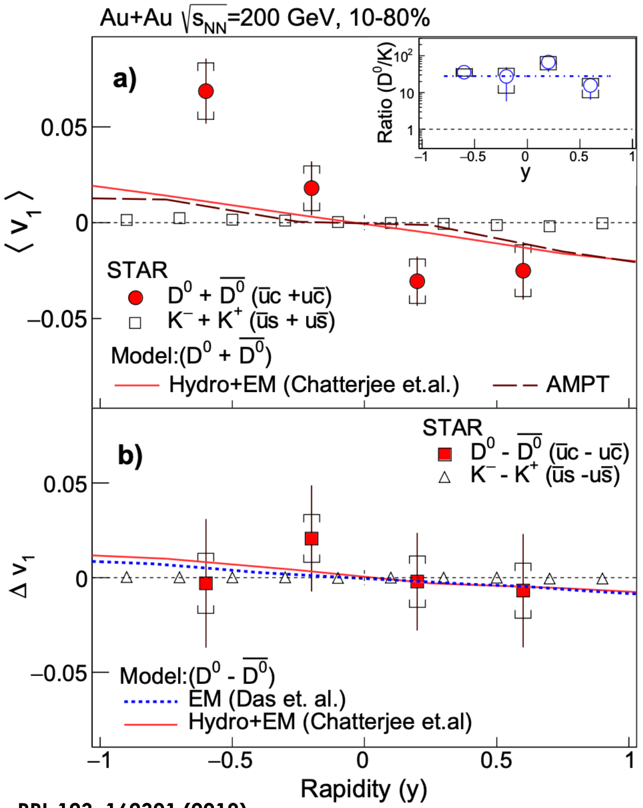


PRL 125, 022301 (2020)

Closer to the initial state using heavy flavor



PRL 125, 022301 (2020)



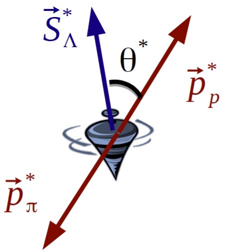
PRL 123, 162301 (2019)

- Parity violating weak decay:
  Daughter baryon is preferentially emitted in the direction of hyperon spin

- Polarization measurement:
  Take a projection of the daughter proton's momentum direction on the reference axis

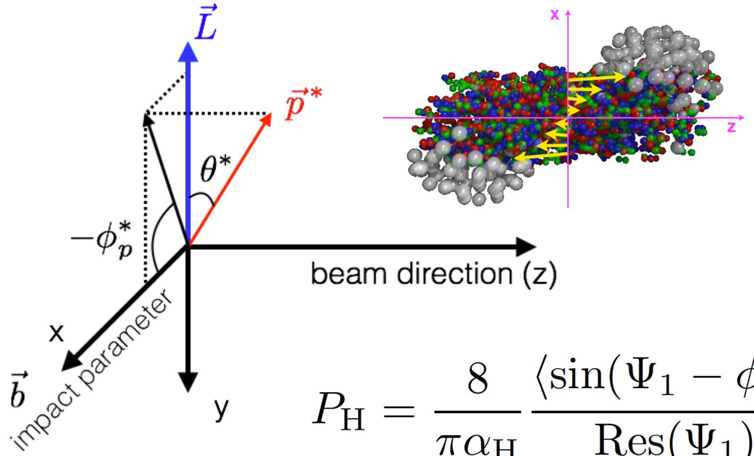
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\rm H}\mathbf{P}_{\rm H}\cdot\mathbf{p}_{\mathbf{p}}^*)$$

P_H: Λ polarization
p_p^*: proton momentum in the Λ rest frame
α_H: Λ decay parameter
($\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642\pm0.013$)



$$\Lambda \rightarrow p + \pi^-$$

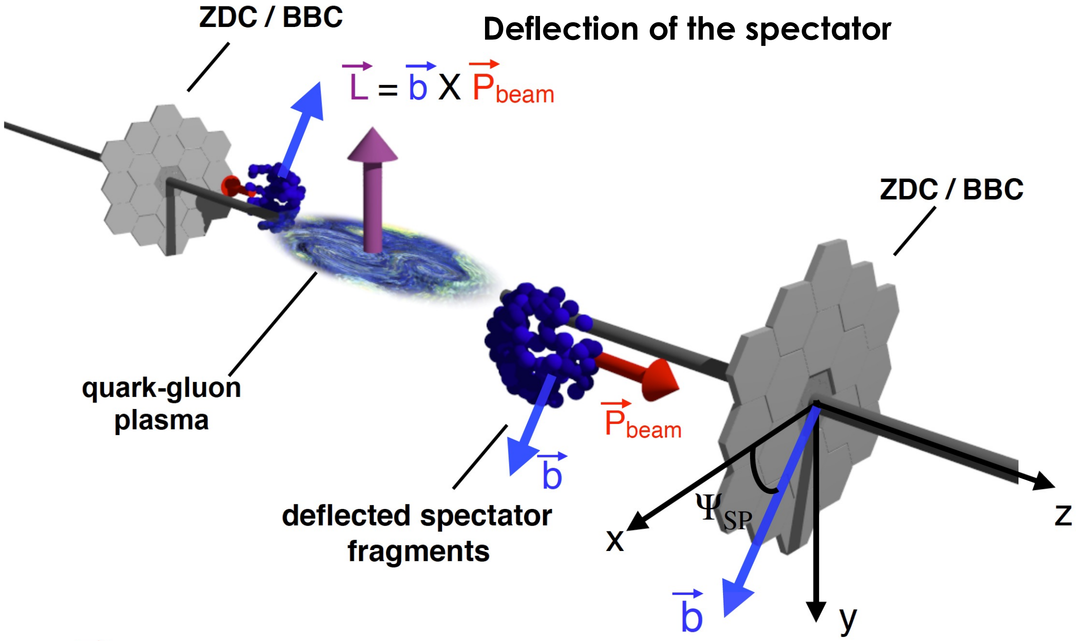
(BR: 63.9%, cτ~7.9 cm)



$$P_{\rm H} = \frac{8}{\pi\alpha_{\rm H}}\frac{\langle\sin(\Psi_1 - \phi_p^*)\rangle}{{\rm Res}(\Psi_1)}$$

Ψ_1: azimuthal angle of the impact parameter
ϕ_p^*: ϕ of daughter proton in Λ rest frame

Global hyperon polarization



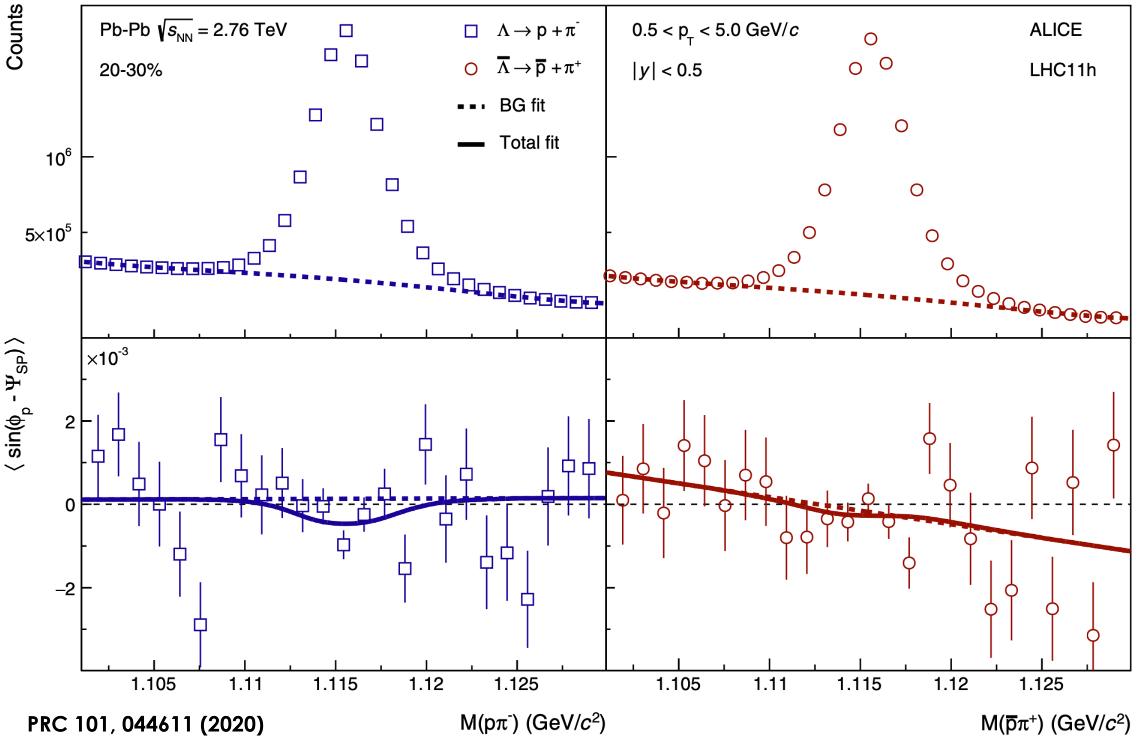
Global hyperon polarization

$$P_H = \frac{3}{\alpha_H}\langle(\hat{p}_p^* \cdot \hat{L})\rangle$$

$$P_\mathrm{H} = -\frac{8}{\pi\alpha_\mathrm{H}}\frac{\langle\sin(\varphi_\mathrm{p}^* - \Psi_\mathrm{SP})\rangle}{R_{SP}^1}$$

- $\vec{P}_{beam}$ = momentum of the projectile (moving toward positive rapidity: known)
- $\vec{b}$ = Impact parameter
- Ψ_SP = spectator plane angle (azimuthal angle of $\vec{b}$).
- φ_p^* = azimuthal angle of daughter proton in $\Lambda(\bar{\Lambda})$ rest frame
- R_SP^1 = Resolution of Ψ_SP

Global hyperon polarization



PRC 101, 044611 (2020)

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\varphi_p^* - \Psi_{SP}) \rangle}{R_{SP}^{(1)}}$$

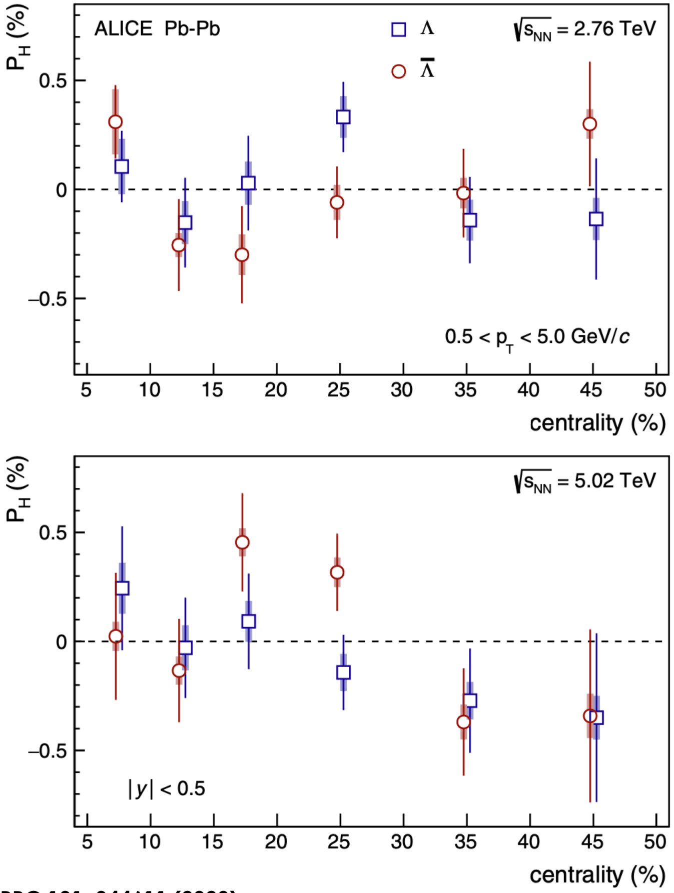
$$\langle \sin(\varphi_p^* - \Psi_{SP}) \rangle (M_{inv}) = [1 - f_{BG}(M_{inv})] \times S_H + f_{BG}(M_{inv}) \times L_{BG}(M_{inv})$$

f^S, f^{BG} signal, background fraction of Λ ($\bar{\Lambda}$)

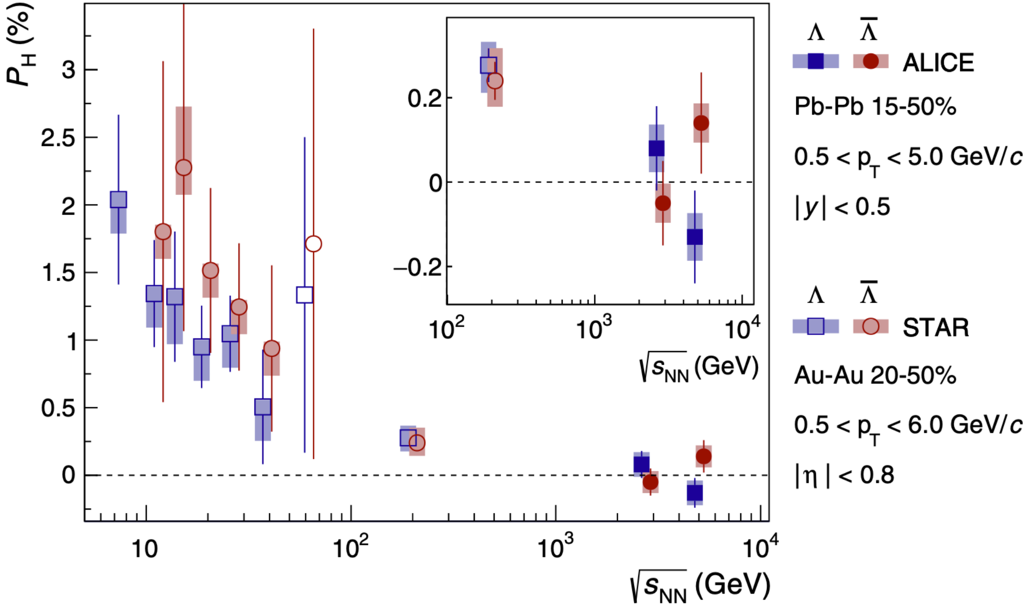
Q^S polarization signal

$Q^{BG}(M_{inv})$ Λ ($\bar{\Lambda}$) background contribution

Global hyperon polarization

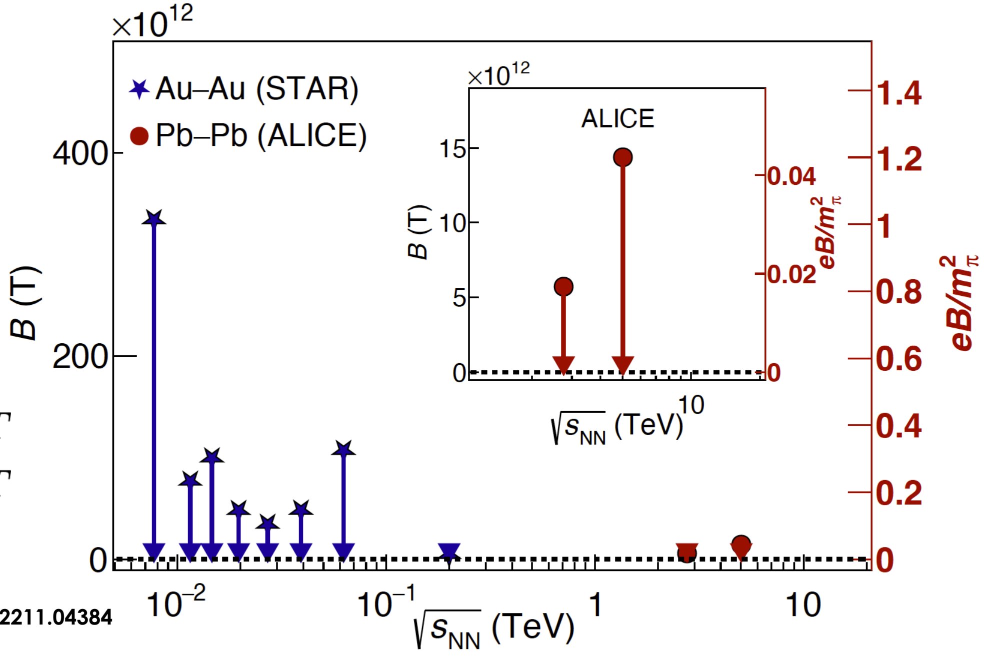


PRC 101, 044611 (2020)



- Consistent with zero within uncertainties
- Significantly smaller than RHIC energies: Decreasing trend with collision energy

Global hyperon polarization



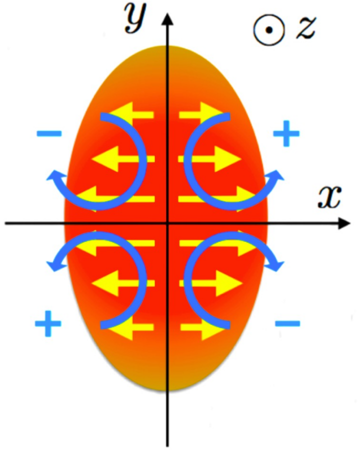
$$p_{\Lambda} \approx 0.5\omega/T + |\mu_{\Lambda}|B/T$$
$$p_{\bar{\Lambda}} \approx 0.5\omega/T - |\mu_{\Lambda}|B/T$$

arXiv:2211.04384

$\sqrt{s_{NN}}$	Centrality	P_{Λ} (%)	$P_{\bar{\Lambda}}$ (%)
2.76 TeV	5–15%	0.01 ± 0.13 (stat.) ± 0.04 (syst.)	0.09 ± 0.13 (stat.) ± 0.08 (syst.)
	15–50%	0.08 ± 0.10 (stat.) ± 0.04 (syst.)	-0.05 ± 0.10 (stat.) ± 0.03 (syst.)
5.02 TeV	5–15%	0.08 ± 0.18 (stat.) ± 0.08 (syst.)	-0.07 ± 0.18 (stat.) ± 0.03 (syst.)
	15–50%	-0.13 ± 0.11 (stat.) ± 0.04 (syst.)	0.14 ± 0.12 (stat.) ± 0.03 (syst.)
Average	15–50%	$\langle P_H \rangle (\%) \approx 0.01 \pm 0.06$ (stat.) ± 0.03 (syst.)	

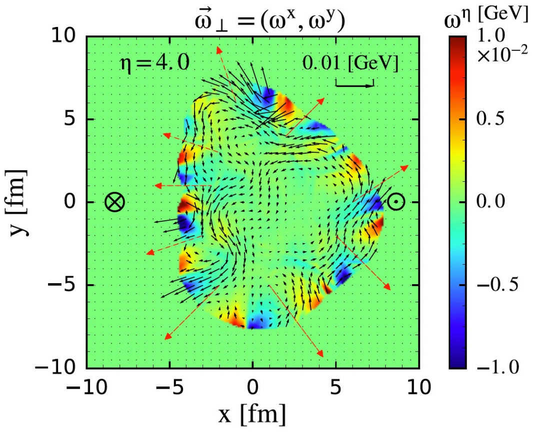
PRC 101, 044611 (2020)

Elliptic flow



$P_z(\phi) \approx sin(2\phi - 2\Psi_2)$

Non-uniform expansion of the QGP



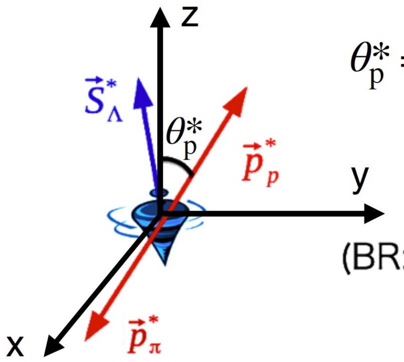
$P_z(\phi) \approx ?$ PRL 117, 192301 (2016)

- Local polarization along the z-axis:

$$P_z \approx \langle (\hat{p}_p^* \cdot \hat{z}) \rangle$$

$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle (\cos\theta_p^*)^2 \rangle} = \frac{3\langle \cos\theta_p^* \rangle}{\alpha_H}$$

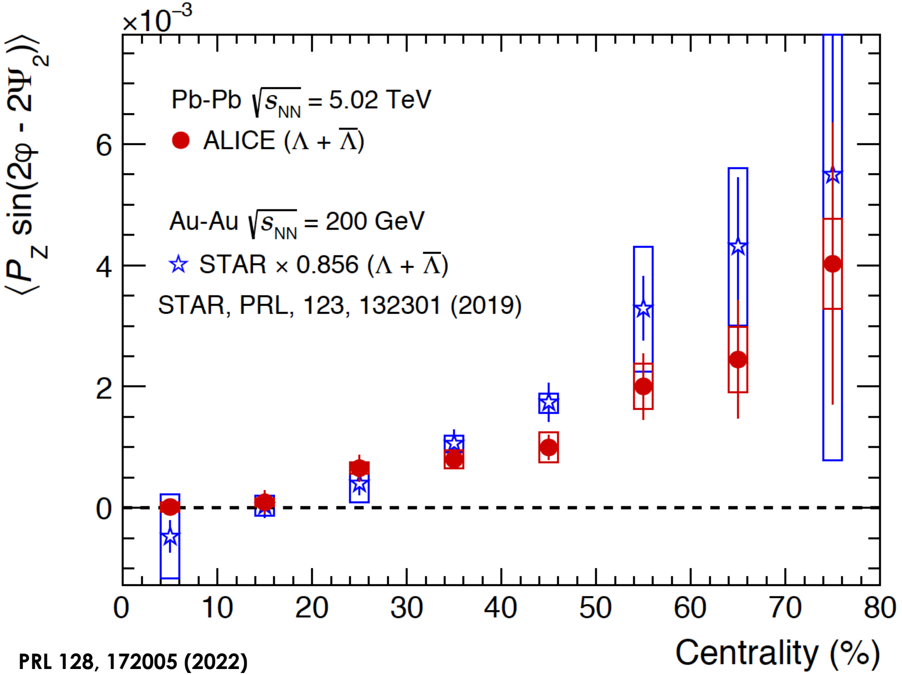
$$\boxed{P_{z,s2} = \langle P_z \sin(2\varphi - 2\Psi_2) \rangle}$$

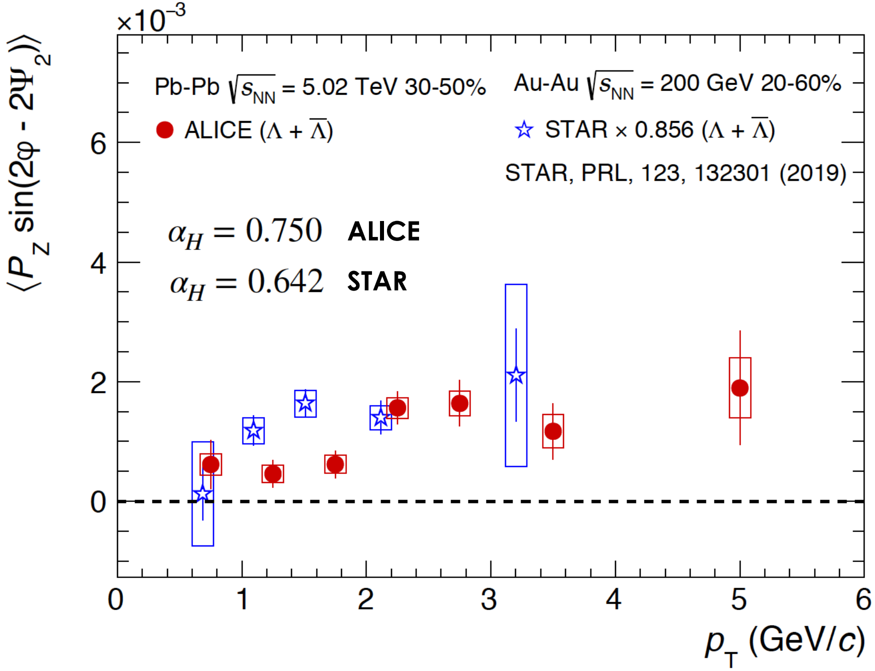


θ_p^* = polar angle of daughter baryon in hyperon rest frame

$$\Lambda \rightarrow p + \pi^-$$

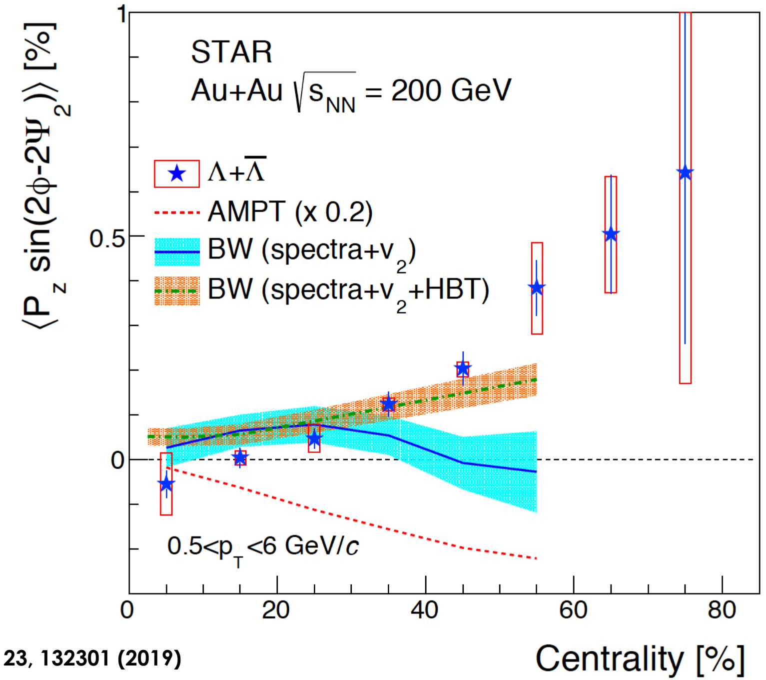
(BR: 63.9%, cτ~7.9 cm)



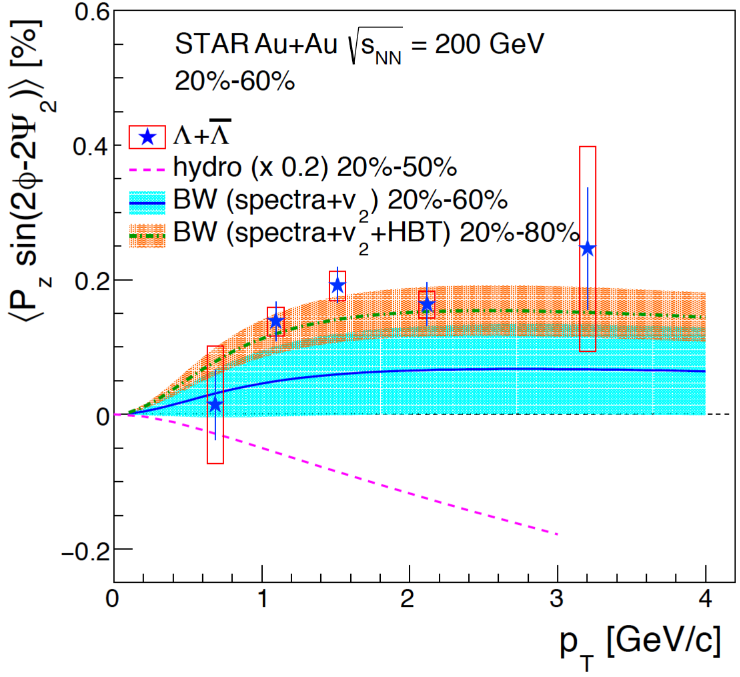


PRL 128, 172005 (2022)

- $P_{z,s2}$ (polarization along the beam axis) is similar between 200 GeV and 5.02 TeV

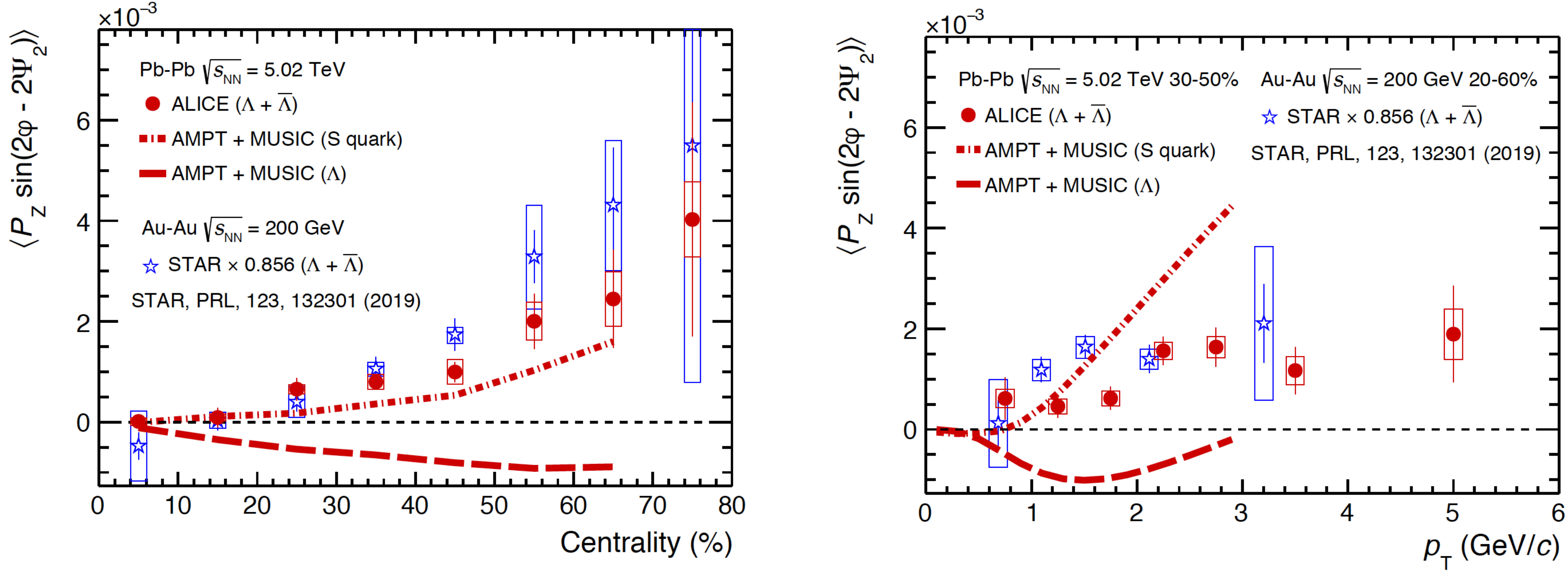


PRL 123, 132301 (2019)



- Blast-Wave model describe the $P_{z,s2}$ data
- Hydro and AMPT models, which can describe collective flow, show negative $P_{z,s2}$

Local polarization

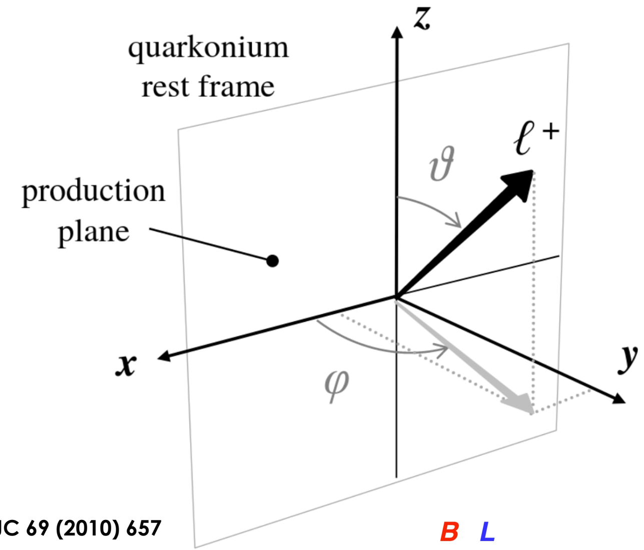


PRL 123, 132301 (2019)

- The AMPT+MUSIC-based model with fluid shear + thermal vorticity show a positive $P_{z,s2}$ in case of inheriting the spin information from the strange quark

Vector meson spin alignment

- Spin alignment of vector mesons (decay products) to the reference axis



EPJC 69 (2010) 657

- $W(\cos\theta) \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta$

ρ_{00} = spin density matrix element

$\rho_{00} = 1/3$ no spin alignment

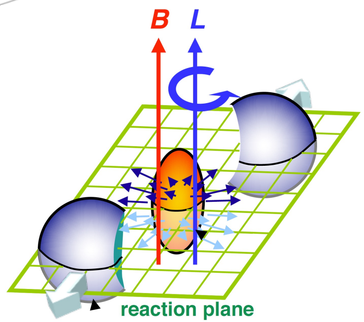
In quarkonia analyses:

- $W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\cdot(1+\lambda_\theta\cos^2\theta+\cdots)$

λ_θ = polarization parameter

$\lambda_\theta = 0$ no spin alignment

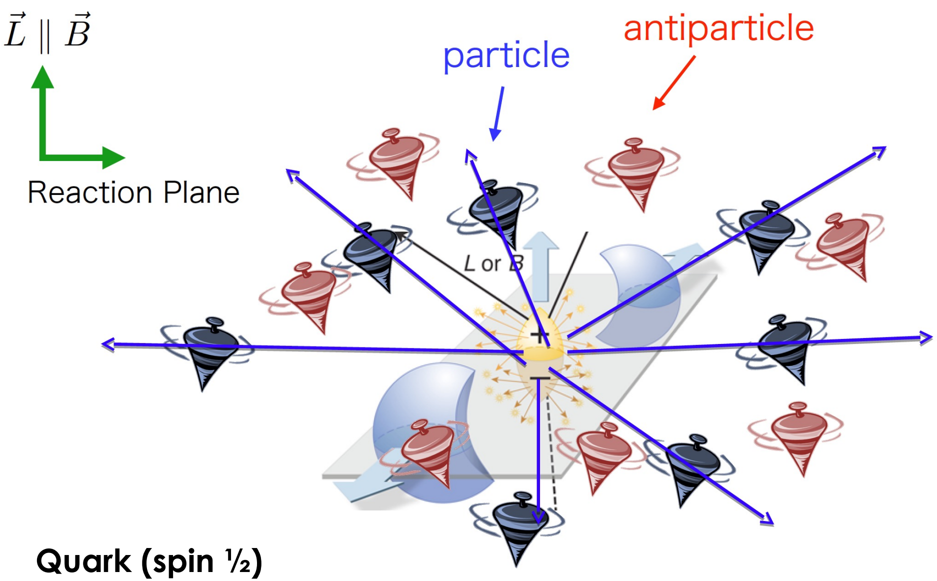
$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$



Reaction plane:
Axis orthogonal to the reaction plane in the center-of-mass frame

Helicity frame:
Direction of vector meson in the center-of-mass frame

Spin-orbit angular momentum interaction in HIC

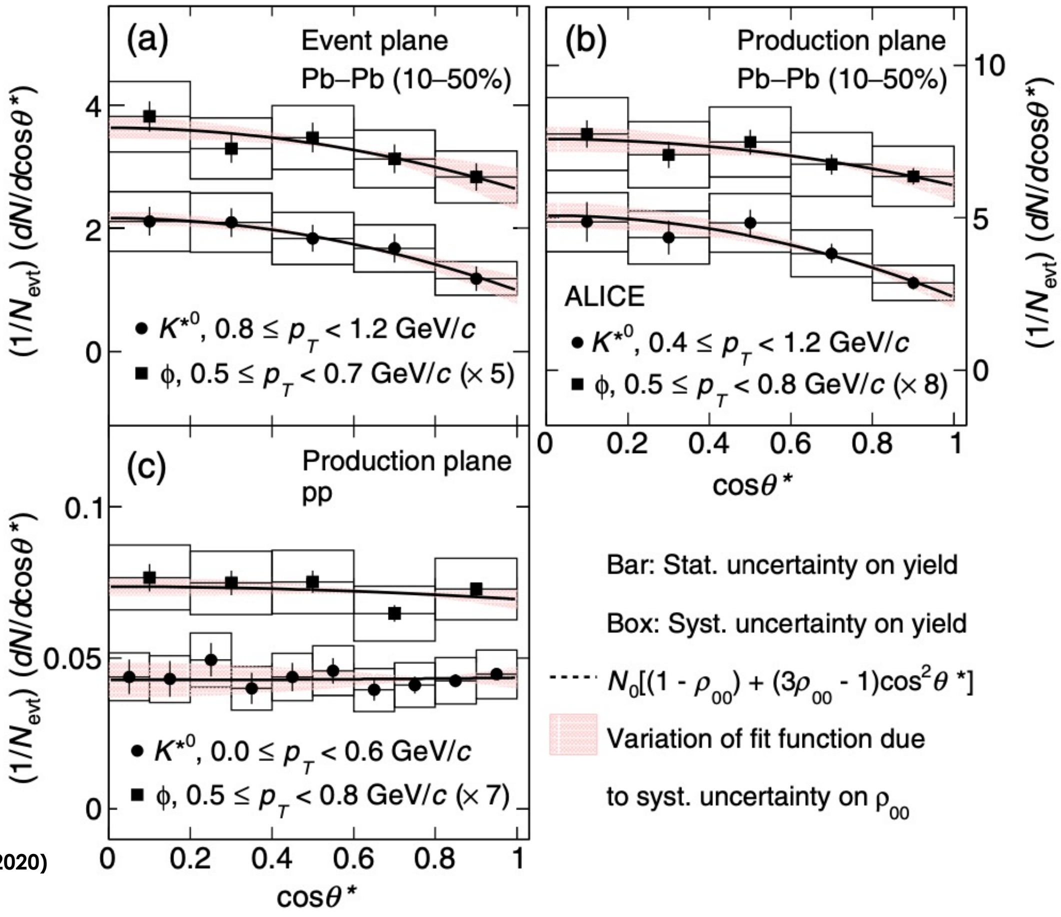


Quark (spin ½)
Vector meson (spin 1)

$$\frac{dN}{d\cos\theta^*} \propto [1 - \rho_{00} + \cos^2\theta^*(3\rho_{00} - 1)]$$

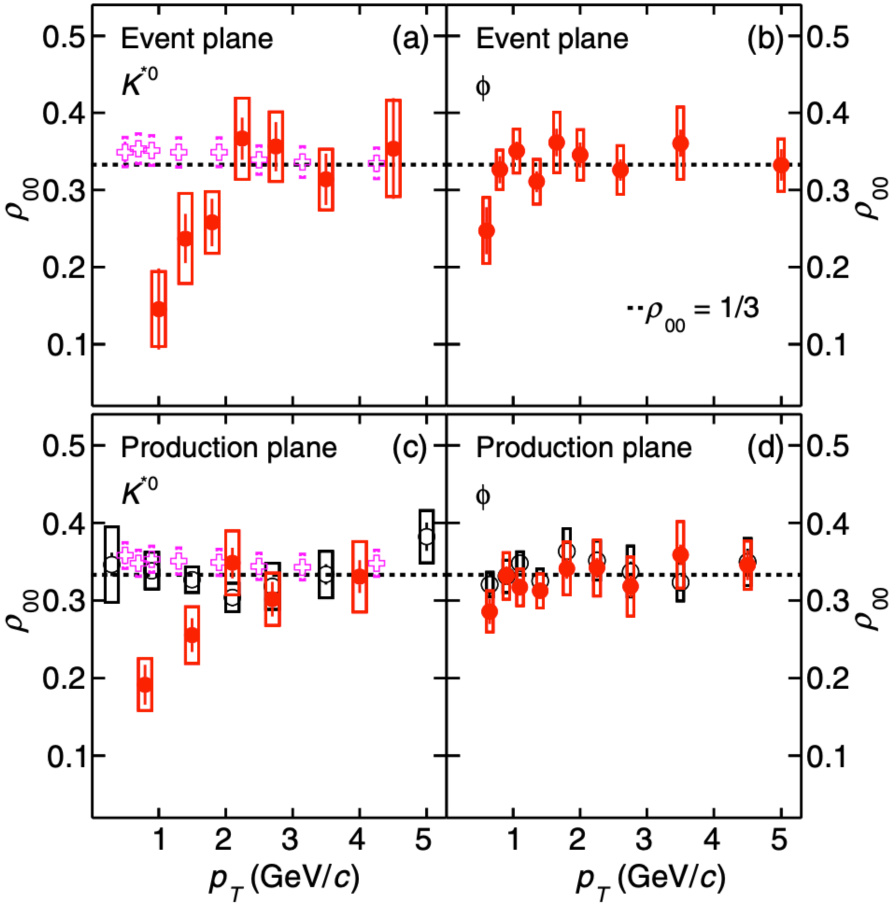
Physics process	Theory	Remarks	Reference
Vorticity (ω)	$\rho_{00}(\omega) < 1/3$	$\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta\omega)^2$	*F. Becattini et al., Phys. Rev. C 95 (2017) 054902*
Magnetic field (B)	$\rho_{00}(B) > 1/3$ $\sim \frac{1}{3} - \frac{1}{9}\beta\frac{q_1 q_2}{m_1 m_2}B^2$ $\rho_{00}(B) < 1/3$	Electrically neutral vector mesons Electrically charged vector mesons	*Y. Yang et. al., Phys. Rev. C 97 (2018) 034917*
Hadronization	$\rho_{00}(rec) < 1/3$ $\sim \frac{1-P_q P_q}{3+P_q P_q}$ $\rho_{00}(frag) > 1/3$ $\sim \frac{1+\beta P_q P_q}{3-\beta P_q P_q}$	Recombination Fragmentation	*Z. Liang et. al., Phys. Lett. B 629 (2005) 20 (2005)* *Z. Liang and X. N. Wang Phys.Rev.Lett. 94 (2005) 102301*
Coherent meson field	$\rho_{00} > 1/3$	ϕ mesons	*X. L. Sheng et. al., arXiv:1910.13684*

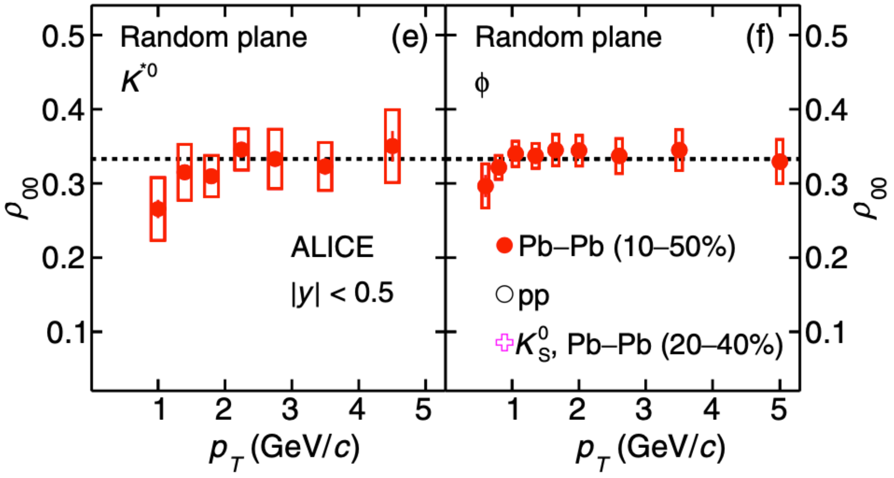
Vector meson spin alignment: K^{*0}, ϕ



PRL 125, 012301 (2020)

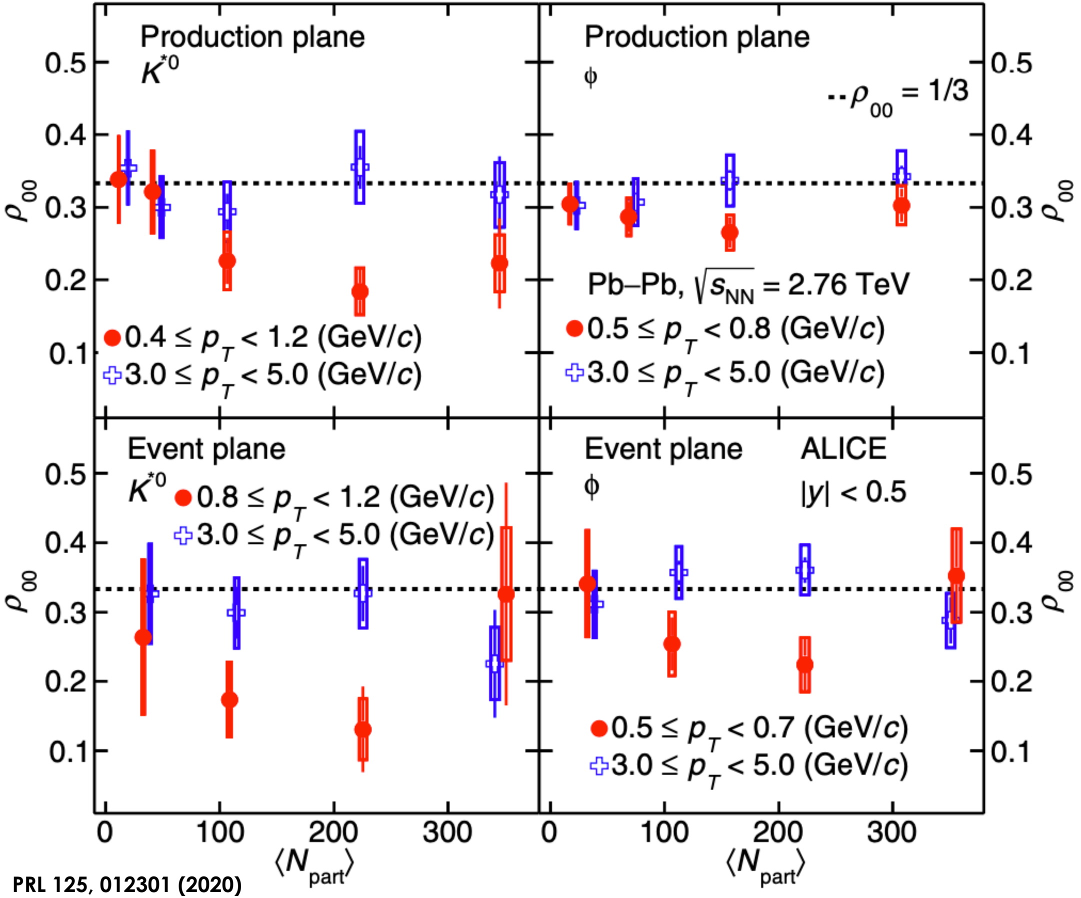
Vector meson spin alignment: K^{*0}, ϕ





- Spin alignment for K^{*0} and $\boldsymbol{\phi}$ at low p_T
- No spin alignment for K^0_S
- No spin alignment with random plane
- No spin alignment in pp collisions

Vector meson spin alignment: K^{*0}, ϕ



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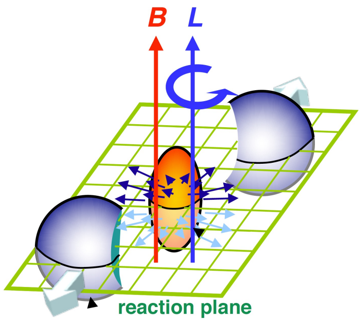
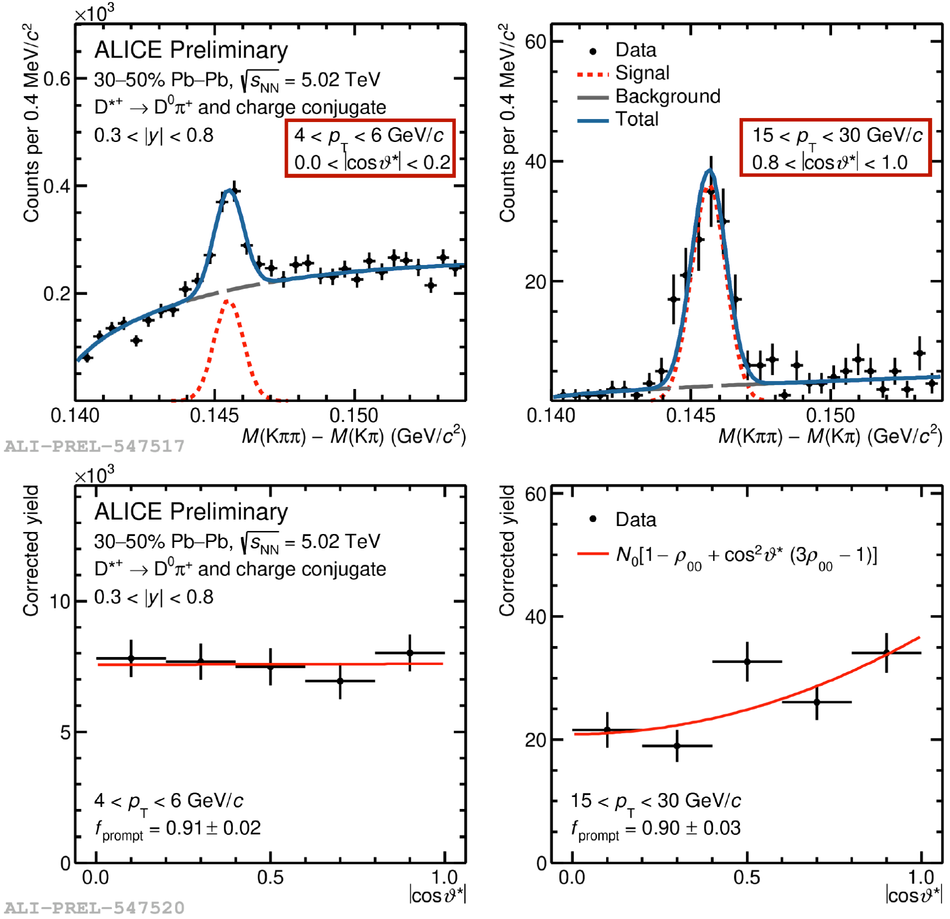
- Maximum effect in mid-central Pb-Pb collisions
- No spin alignment for high p_T at the entire centrality ranges

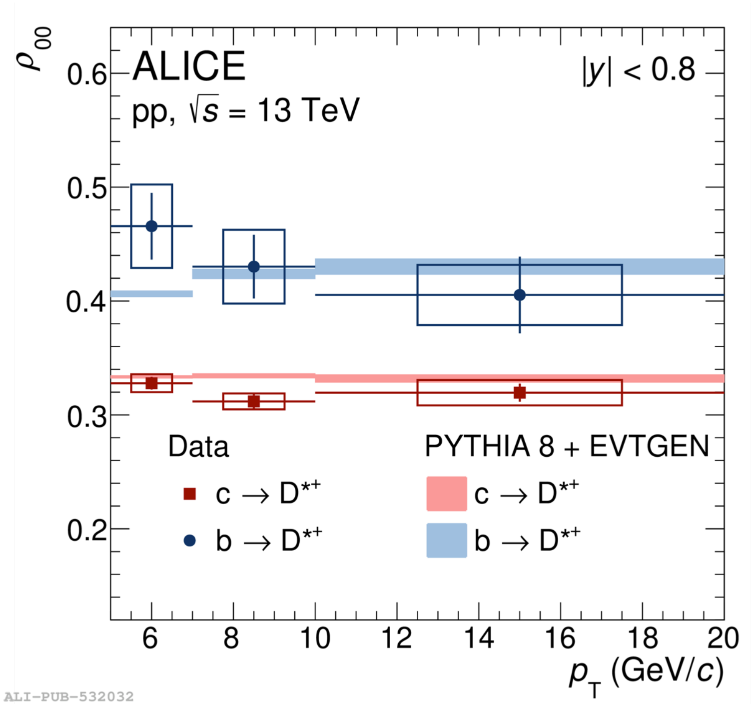


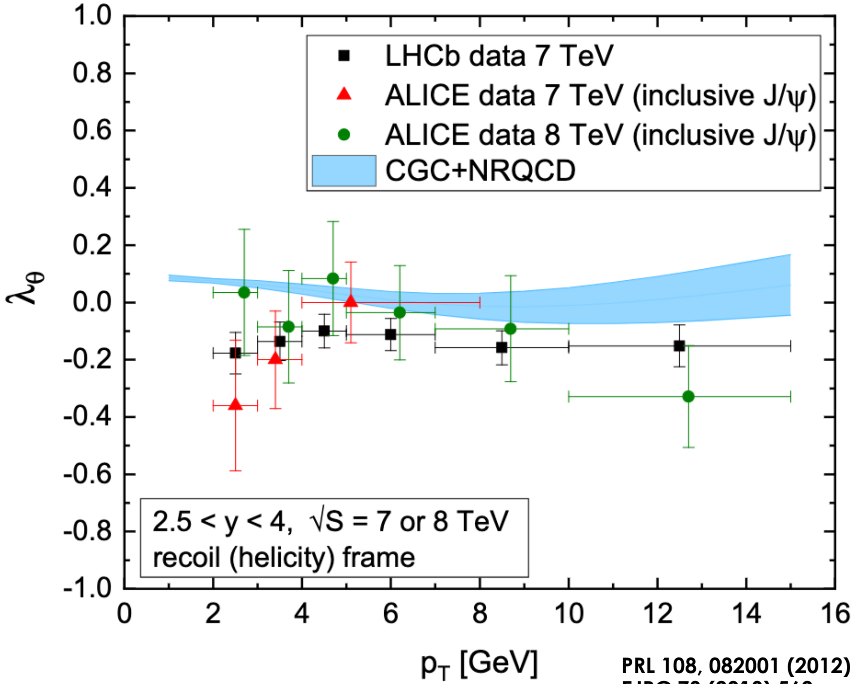
Vector meson spin alignment: D^{*+}, J/ψ



- Measurement of D^{*+} polarization with respect to the reaction plane
- ML technique to reduce background and non-prompt (B decay) contribution

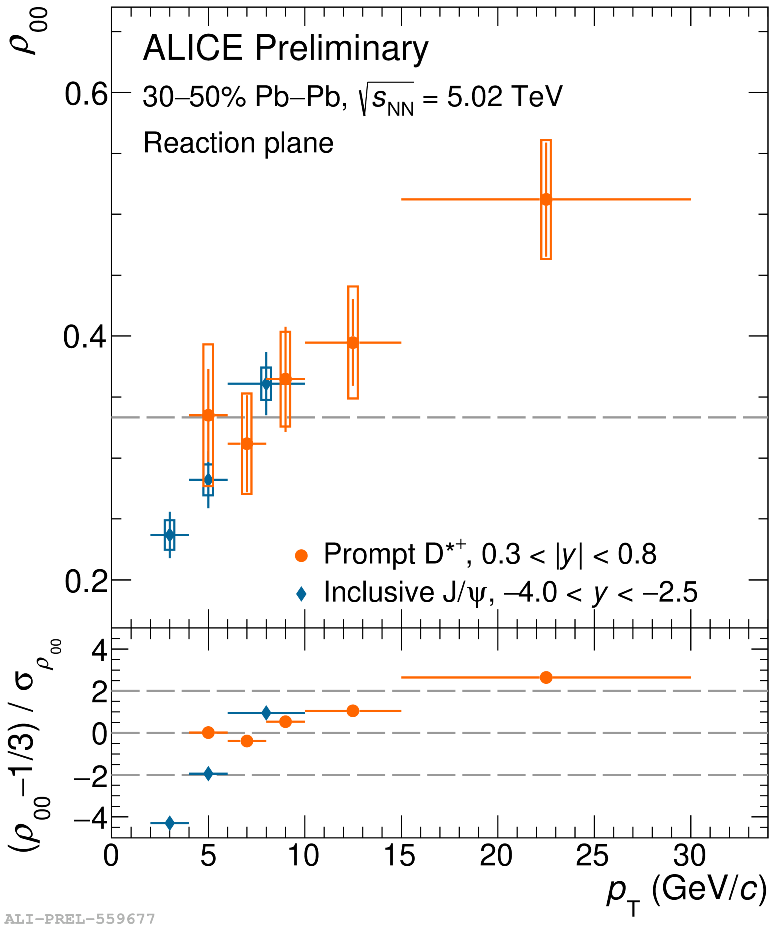
Vector meson spin alignment: D^{*+}, J/ψ



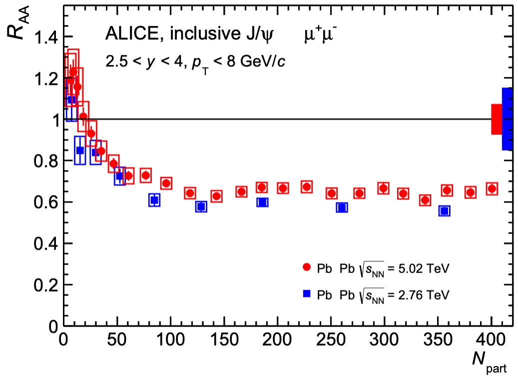


PRL 108, 082001 (2012)
EJPC 78 (2018) 562
EPJC 73 (2013) 11
JHEP 12 (2017) 110

- Results in pp collisions agree with zero polarization

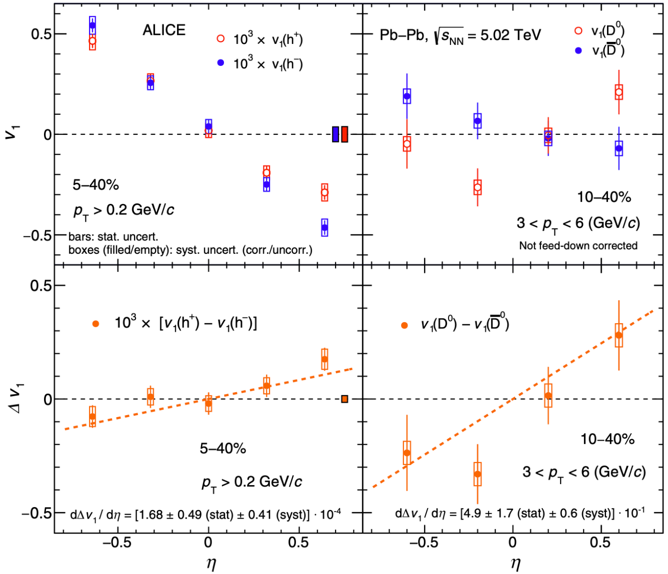


- Low p_T:
  $\rho_{00} < 1/3$ for J/ψ can be explained by recombination

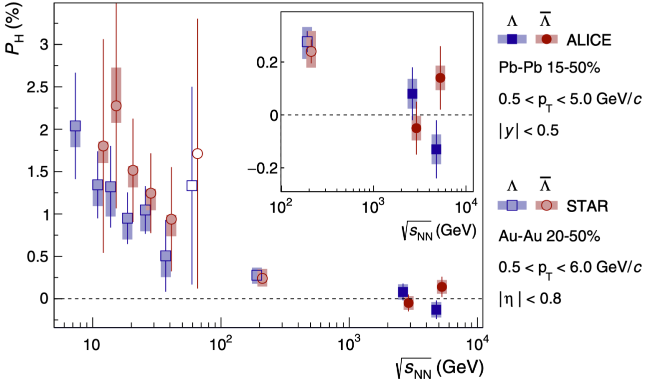


- High p_T:
  $\rho_{00} < 1/3$ for D*+ can be explained by fragmentation

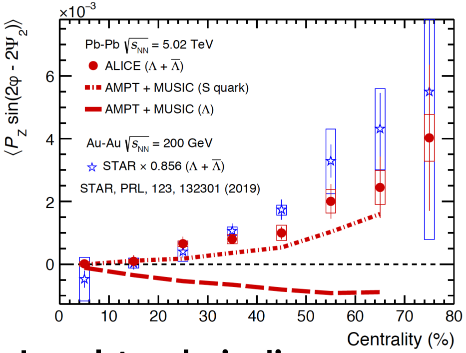
Summary



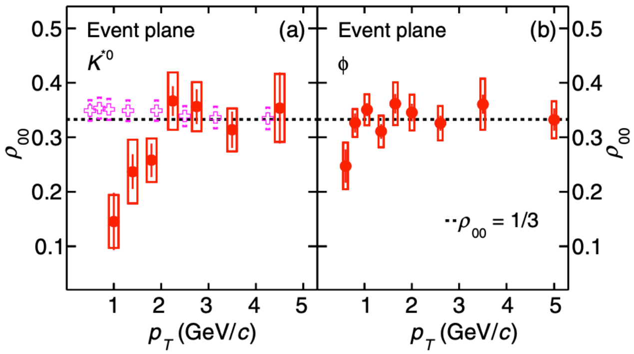
Directed flow:
Strong vorticity
Hint of a B-field effect?



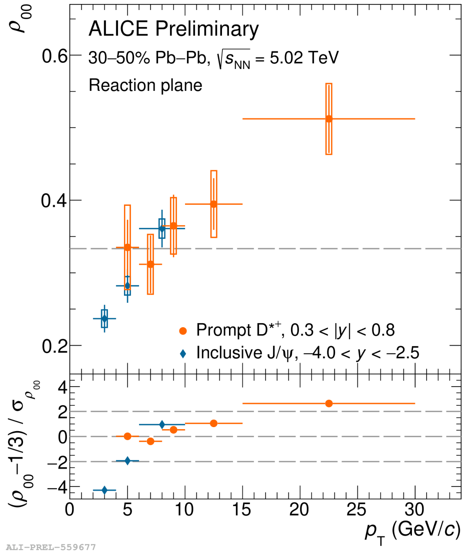
Global Λ polarization:
Very weak B-field effect



Local Λ polarization:
Need more models



Vector meson spin alignment:
Polarization at low p_T



BACKUP