On Hyperon Polarization in Heavy Ion Collisions

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- New mechanism of Strangeness Enhancement
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- Measurement of Global Polarization of Hyperons
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Introduction

Polarization of Hyperons in **unpolarized pp** and **pA** experiments

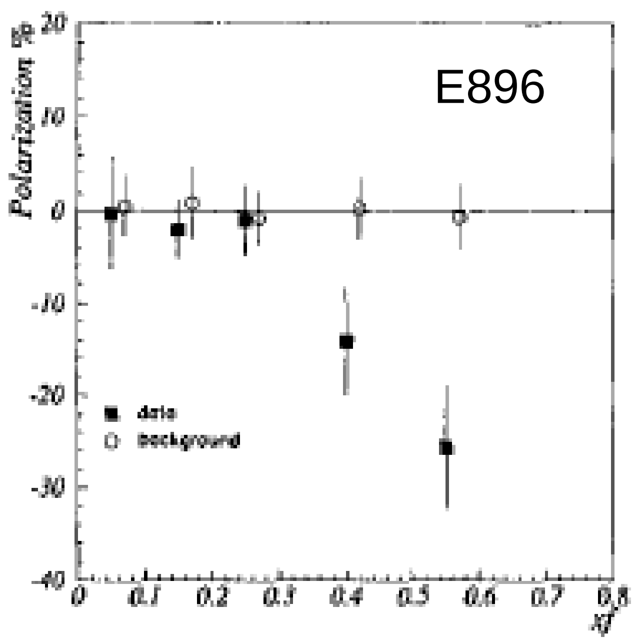
FNAL: p + Be → Λ + X at E_p = 300 GeV *G.Bunce, et. al, PRL, 36, 1113.*

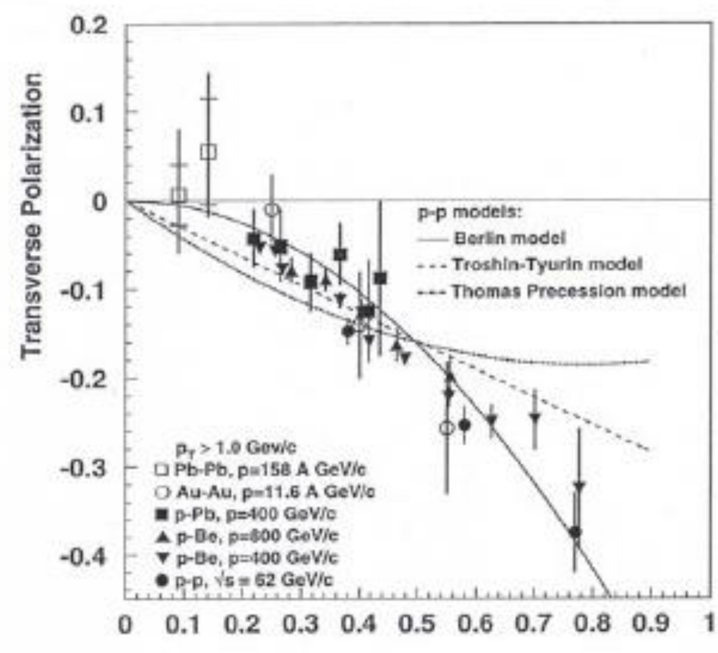
Are Hyperons polarized in HIC experiments?

E896 (AGS) Au+Au at E = 11 AGeV *R. Bellwied et al.*, Nucl. Phys., **A698** (2002) 499c.

Polarization in Au+Au is the same as in pp and pA !

$$dN/d\cos\Theta = A(cos\Theta)(1+\alpha P\cos\Theta),$$





Recombination Models: *Lund, DeGrand&Miettinen*

Introduction

- Polarization of **Λ**’s in **unpolarized pp**, **pA** and **AuAu** experiments was detected w,r,t, the **production plane.**
- Mechanism of polarization in all processes is the same.

Hyperons formed in QGP

Liang Z and Wang X N 2005 Phys. Rev. Lett. ***94 102301***

Global Polarization of Hyperons:

polarization w.r.t. the **reaction plane**

Global Hyperon Polarization E896 (AGS, $\sqrt{s}$ = 4.8 GeV)

+ (the same as in p

- **Global polarization in AuAu/PbPb – collisions**)
  - NA49 (SPS, $\sqrt{s}$ = 17.2 GeV) - no evidence
  - STAR (RHIC, $\sqrt{s}$ = 62, 200 GeV) - no evidence

Interpretation:

Formation of QGP randomizes orientation of *u*, *d*, *s* – quarks spins. Therefore the spins of hyperons have no preferred direction.

- **However**
  - ✓ Hyperon polarization was not measured w.r.t. the production plane!
  - ✓ It should exist in peripheral events, like in pp and pA collisions.

Global Hyperon Polarization E896 (AGS, $\sqrt{s} = 4.8$ GeV)

+ (the same as in p

Conjecture: Global polarization in HIC could take place at lower energies (CBM, NICA, BES RHIC).

Peculiarities of HIC at CBM, NICA, BES RHIC Energies

- Maximal density of baryonic matter
- ‘Horn’ effect – enhanced yield of strangeness.

Two reasons of the global polarization

- Strong magnetic field in semi-central events.
- Very large angular momentum of a nuclear matter in semi-central events.

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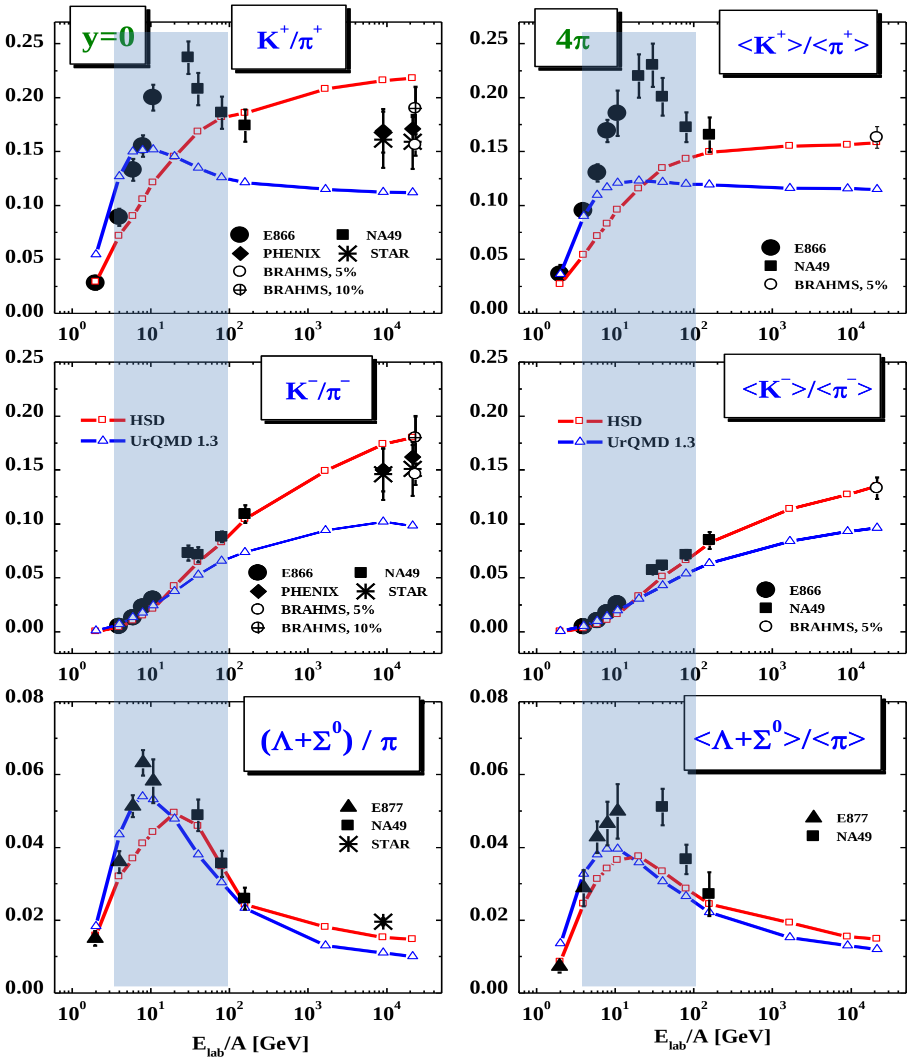
Strangeness enhancement (SE) in HIC at NICA energies

K/π and Λ/π ratio
in central PbPb/ AuAu collisions



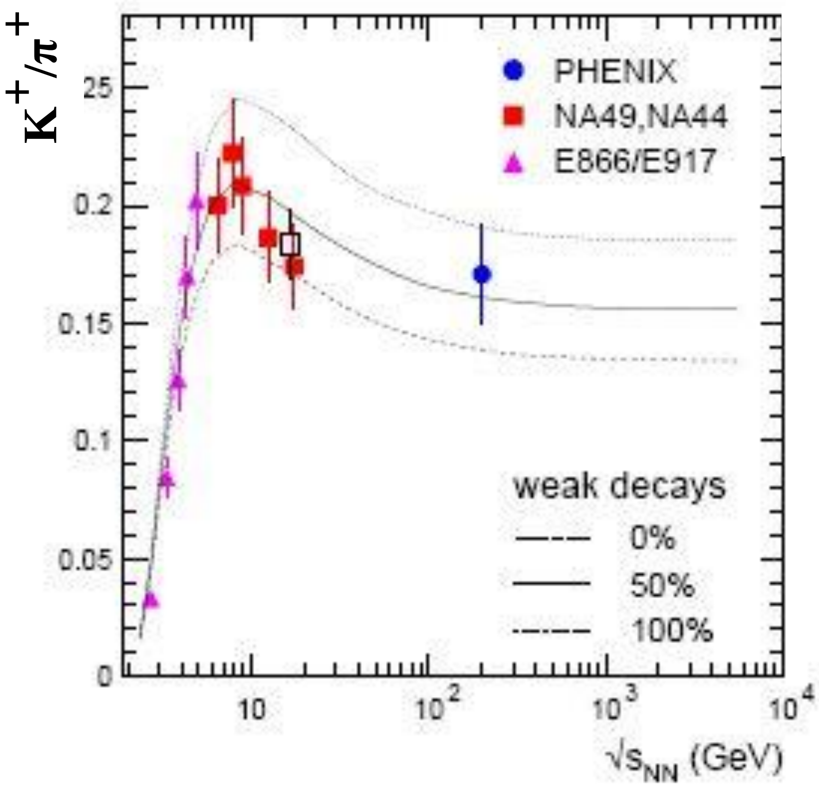
Clear evidence for horn structure in K^+/π^+ and $(\Lambda+\Sigma^0)/\pi$
Non-horn structure in K^-/π^-

Transport models fail to describe experimental data

NICA energy region is selected by blue bar

Why ‘horn’ structure takes place for K^+/π^+ but not for K^-/π^- ?

!



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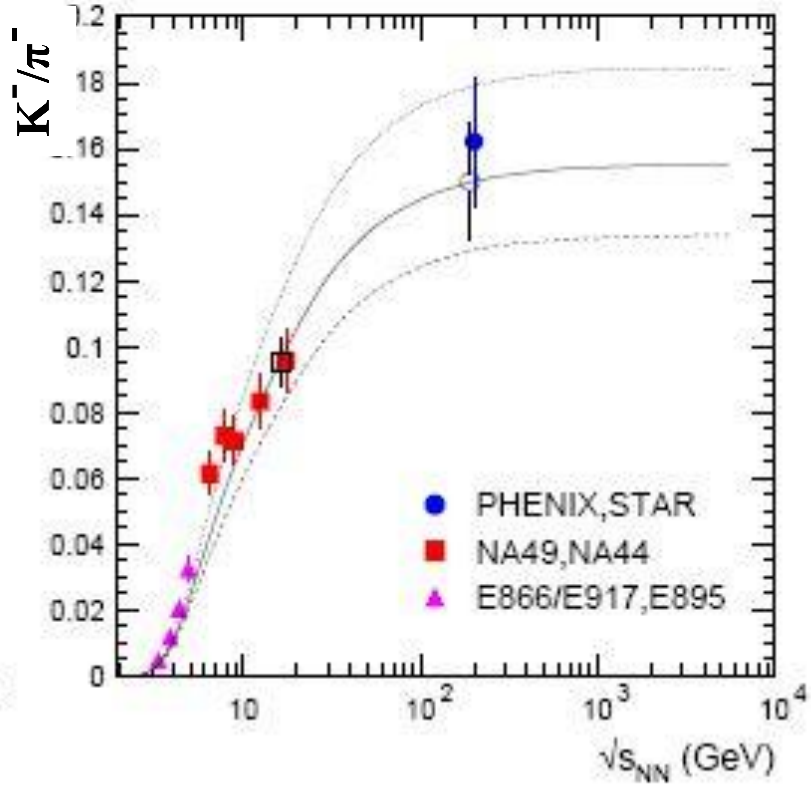
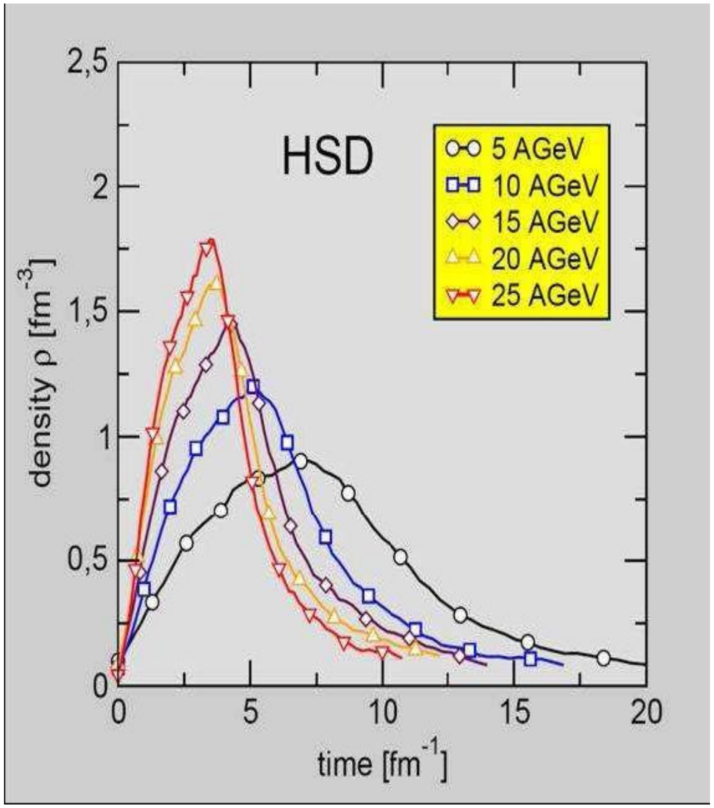


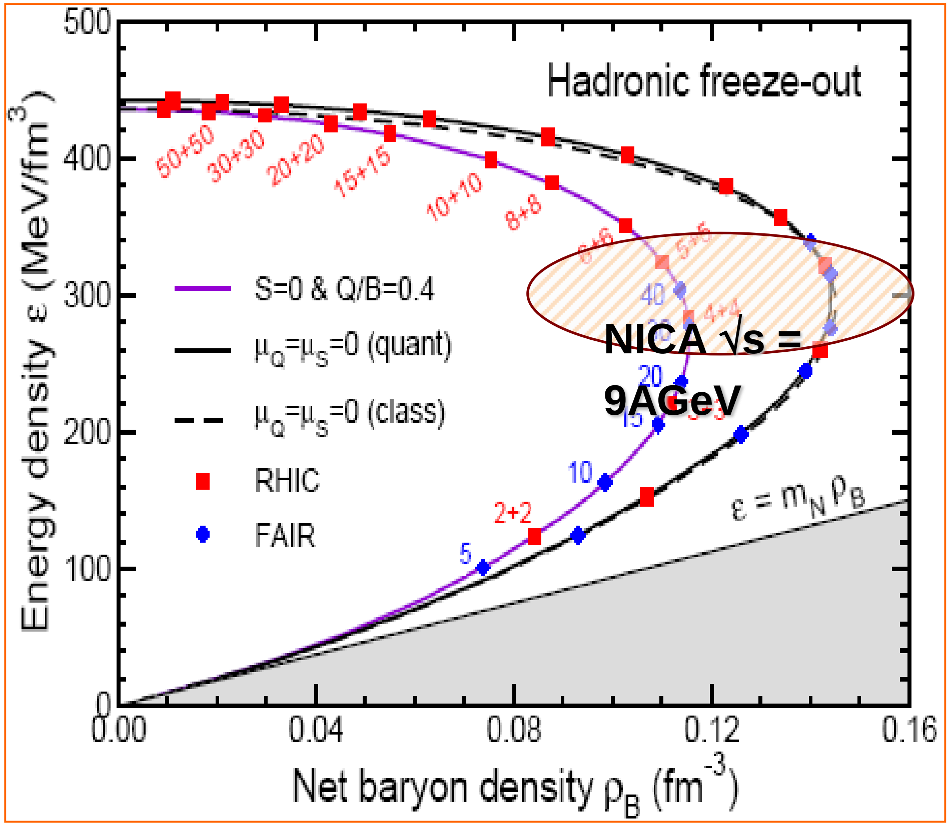
Baryon density in HIC

Baryon density evolution

At NICA energies ρ/ρ_0 ~ 5 - 10



Baryon density at freeze-out



New mechanism of Strangeness Enhancement (SE) in HIC

Conjectures:

- Baryonic matter compression → Strange Quark Pairs Condensation in $^3P_0$ - model of vacuum $\langle s\bar{s} \rangle$
- Strange Quark Pairs Condensation → Nucleons to Hyperons Transformation + Kaons Production
- Phase Transition: Nuclear Matter → Hypernucler Matter + Kaon Condensate

Proton Transformation channels

$$p(uud) \quad u,d \to s$$

$$\left.\begin{aligned} p(uud) &\to \Sigma^{+}(uus) + K^{0}(d\bar{s}) \\ &\to \Lambda^{0}(uds) + K^{+}(u\bar{s}) \end{aligned}\right\} S = 1$$

$$\left.\begin{aligned} &\to \Xi^{-}(dss) + 2K^{+}(u\bar{s}) \\ &\to \Xi^{0}(uss) + K^{0}(d\bar{s}) + K^{+}(u\bar{s}) \end{aligned}\right\} S = 2$$

$$\left.\to \Omega^{-}(sss) + 2K^{+}(u\bar{s}) + K^{0}(d\bar{s})\right\} S = 3$$

No K^{-} are producled

Neutron Transformation channels

$$n(udd), \quad u,d \rightarrow s$$

$$\left.\begin{aligned} n(ddu) &\rightarrow \Sigma^-(dds) + K^+(u\bar{s}) \\ &\rightarrow \Lambda^0(uds) + K^0(d\bar{s}) \end{aligned}\right\} S=1$$

$$\left.\begin{aligned} &\rightarrow \Xi^0(uss) + 2K^0(d\bar{s}) \\ &\rightarrow \Xi^-(dss) + K^0(d\bar{s}) + K^+(u\bar{s}) \end{aligned}\right\} S=2$$

$$\left.\rightarrow \Omega^-(sss) + 2K^0(d\bar{s}) + K^+(u\bar{s})\right\} S=3$$

No K^- are producled

Strangeness production in HIC

- **binary collisions -** competing mechanism of strangeness production

$$\sim 1/\lambda_{int} \sim \rho\sigma_{hN}$$

λ_{int} - mean free path

σ_{hN} - hadron-nucleon cross section

- **Nucleon transformation to a hyperon**

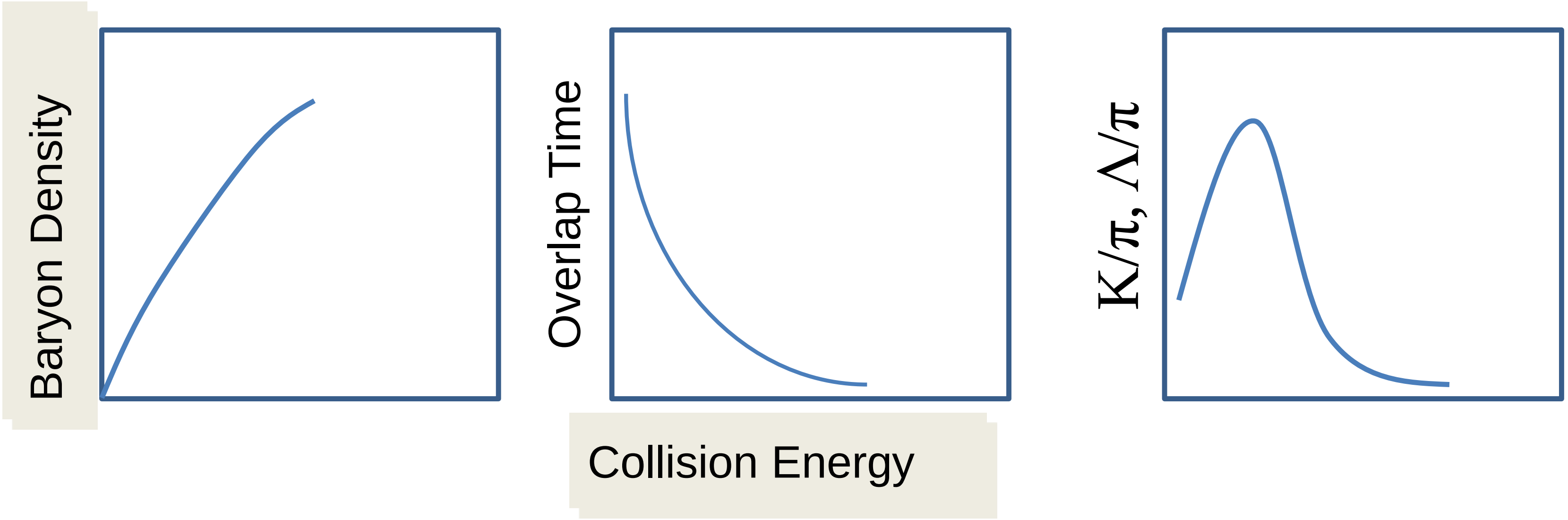
$$\sim (\tau_o/\tau_{re})\ f(\rho)$$

τ_o - overlap time

τ_{re} - rearrangement time

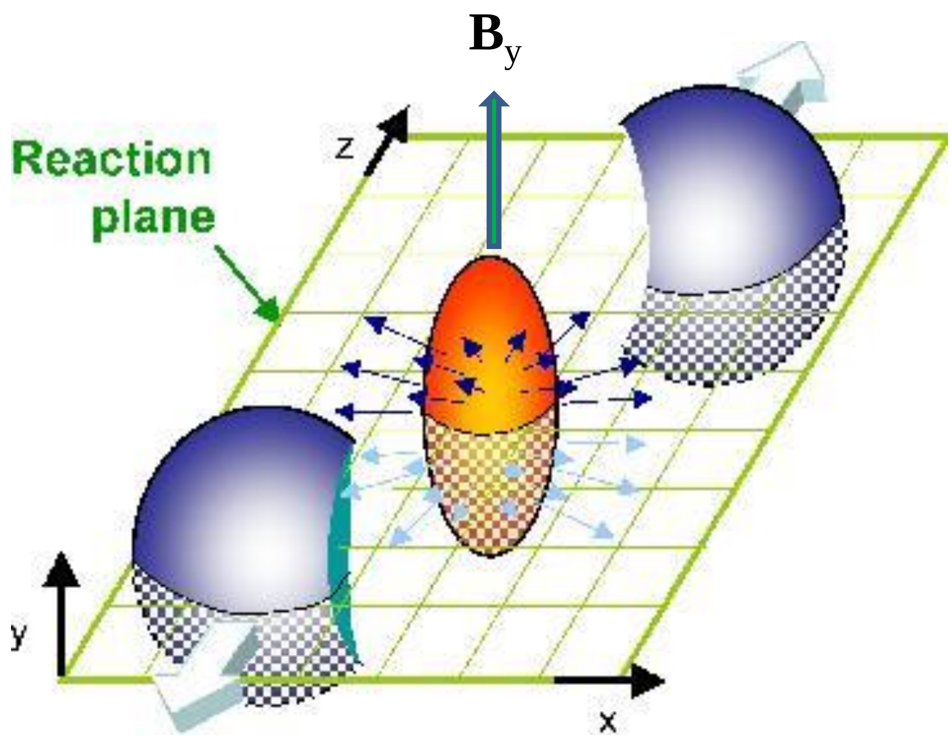
New SE Mechanism in HIC

K/π and Λ/π ratio

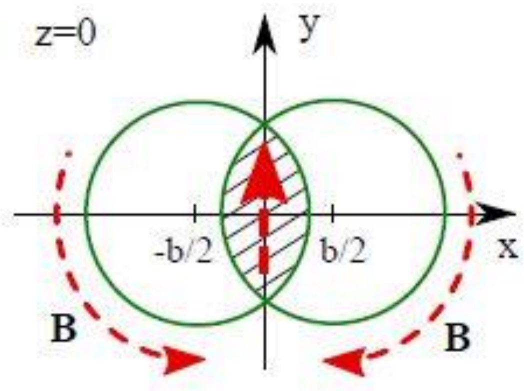


Global Polarization induced by Magnetic Field created in HIC ?
Au + Au: A = 197, Z = +79

Strong Magnetic Field



Magnetic Field created in HIC



$V.\,Skokov,\ et.\ al,\ arXive{:}nud\text{-}th/0907.1396$

$$e\vec{B}(t,\vec{x}') = \alpha_{\mathrm{EM}} \sum_i Z_i \frac{1\text{-}v_i^2}{(R_i - \vec{R}_i\vec{v}_i)^3}\left[\vec{v}_i \times \vec{R}_i\right]$$

At NICA energies $\sqrt{s_{\mathrm{NN}}} = 4 - 11\,GeV$

$\mathrm{Au} + \mathrm{Au}\ \ at\ b \approx 5\ fm$

$eB_y \approx 0.05 \div 0.075 m_\pi^2$,

$B_y \approx 10^{16}\,Gauss \approx 10^{12}\,Tesla$

Particle polarization in presence of magnetic field

Particles with spin 1/2 in magnetic field B_0

Energies of the states

$E_+ = -\mu B_0, \; E_- = \mu B_0,$

The ocupation numbers

$$n_+ = \exp\left(-\frac{E_+}{kT}\right)\left\{\exp\left(-\frac{E_+}{kT}\right) + \exp\left(-\frac{E_-}{kT}\right)\right\}^{-1}$$

$$n_- = \exp\left(-\frac{E_-}{kT}\right)\left\{\exp\left(-\frac{E_+}{kT}\right) + \exp\left(-\frac{E_-}{kT}\right)\right\}^{-1}$$

Polarization - the difference in ocupation of the states

$$\mathrm{P} = \frac{1}{2}n_+ - \frac{1}{2}n_- \approx \frac{1}{2}\frac{E_- - E_+}{kT}$$

Hyperon polarization in presence of magnetic field

$\sqrt{s} = 4$ -11 GeV
T ~ 100 MeV

Magnetic Field : $B_y \approx 10^{12}$ Tesla *V. Skokov et. al, Mod.Phys.Lett., 2009*

Nuclear magneton: $\mu_N = 3.15 \cdot 10^{-14}$ MeV/Tesla

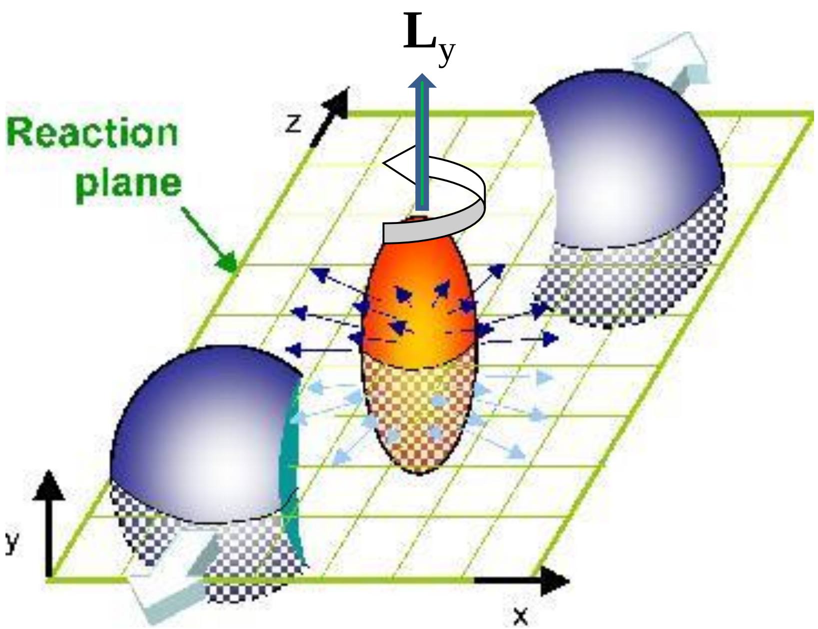
$E = -\boldsymbol{\mu_h}\, \mathbf{B}$

part	p	Λ	Σ^+	Σ^-	Ξ^0	Ξ^-	Ω^-
$\lvert\mu_h B_y\rvert$, (MeV)	0.091	0.019	0.077	0.037	0.039	0.020	0.064
P, (%)	0.2	0.04	0.15	0.07	0.07	0.04	0.13

Polarization induced by the magnetic field created in HIC is near zero.

Global Hyperon Polarization induced by Orbital Angular Momentum?

Large Orbital Angular Momentum



$$L_y \sim A\sqrt{s_{NN}}\, b/2$$

$$\mathrm{Au} + \mathrm{Au}$$

$$\text{RHIC energies } \sqrt{s} = 200\, GeV$$

$$at\ b \approx 5\ fm\ \ L_y \approx 5\times10^5$$

No evidence for Polarization at RHIC

$$Abelev, Phys. Rev. C76, 024915$$

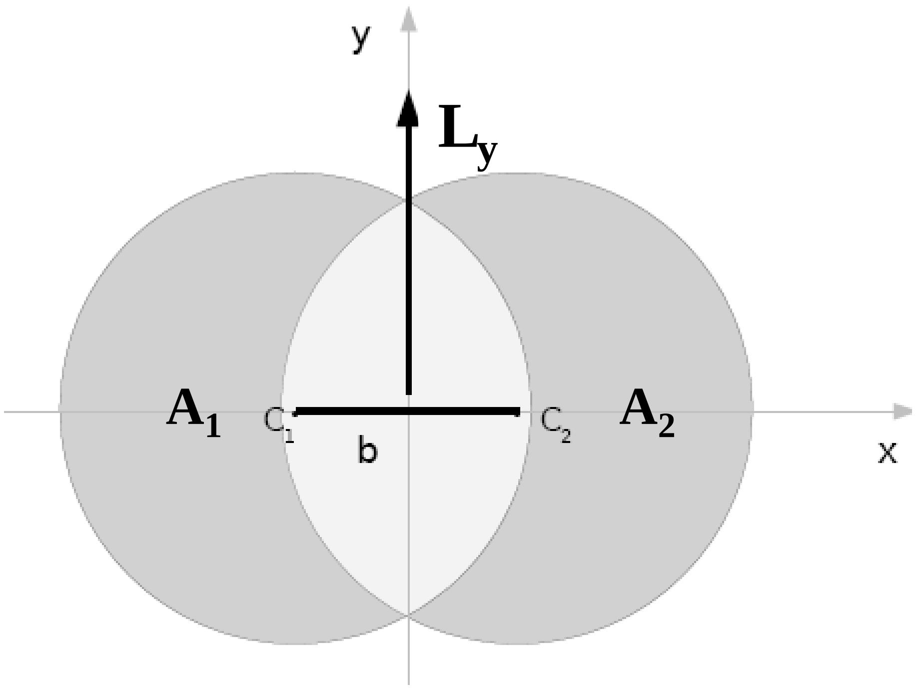
Proposal:

Hyperon Polarization can be observed at NICA, CBM and BES RHIC

$$\text{NICA energies } \sqrt{s} = 4\div11\, GeV$$

$$at\ b \approx 5\ fm\ \ L_y \approx 2.5\times10^4$$

Orbital Angular Momentum in HIC

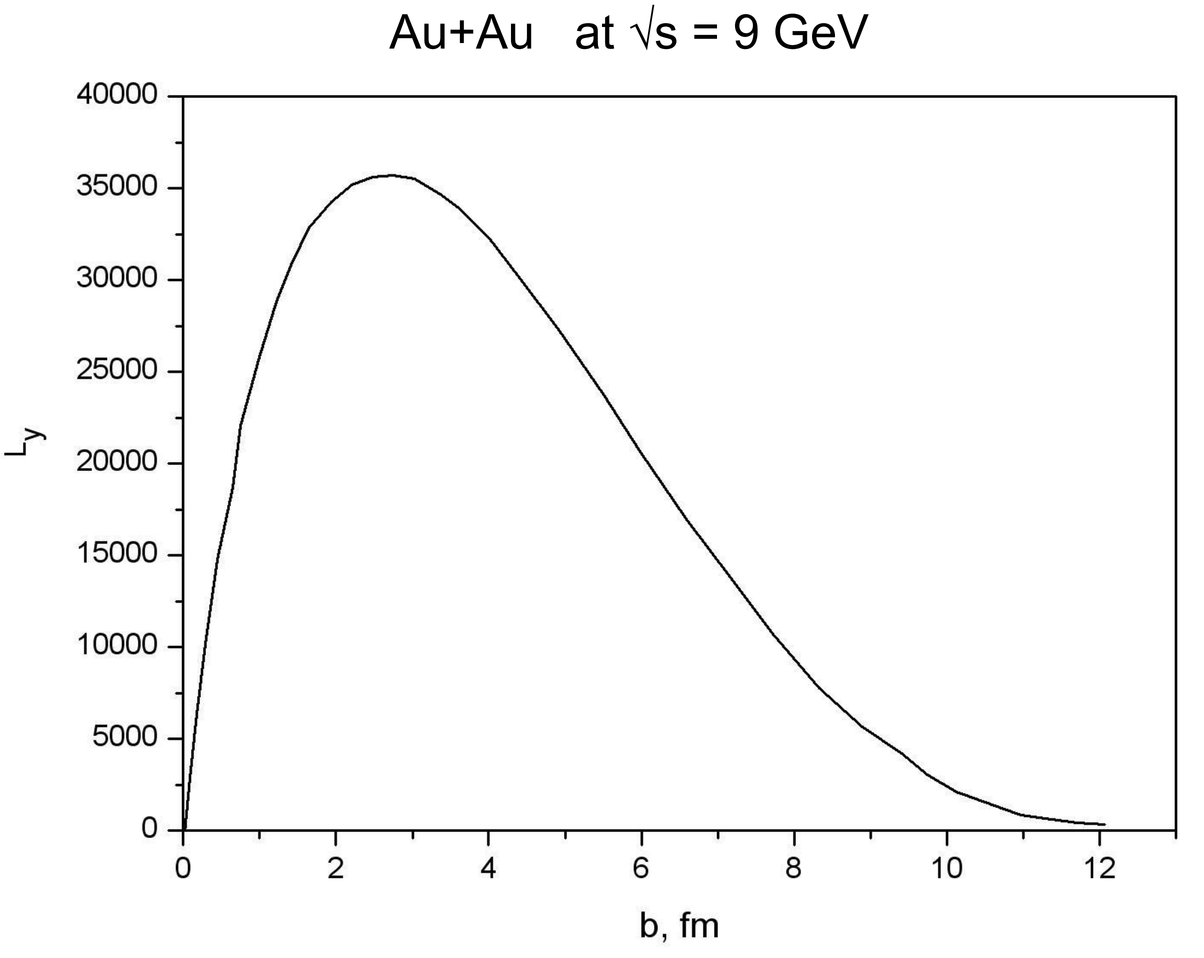


$$\frac{dp_z}{dxdy} = [T(x-b/2, y) - T(x+b/2, y)]\frac{\sqrt{s_{NN}}}{2}$$

$$T(x, y) = \int dz\, n(x, y, z)$$

$$L_y = \int xdxdy[T(x-b/2, y) - T(x+b/2, y)]\frac{\sqrt{s_{NN}}}{2}$$

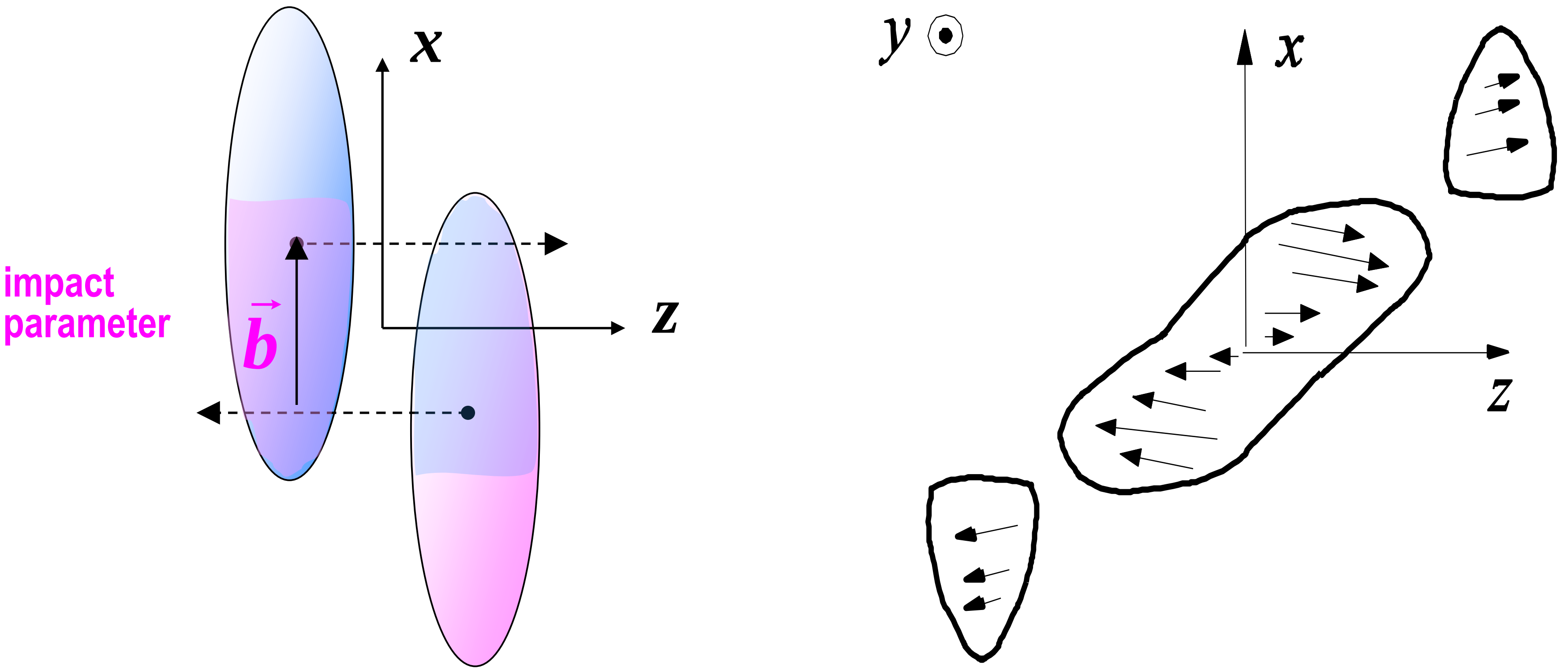
Orbital Angular Momentum in HIC



Global orbital angular momentum

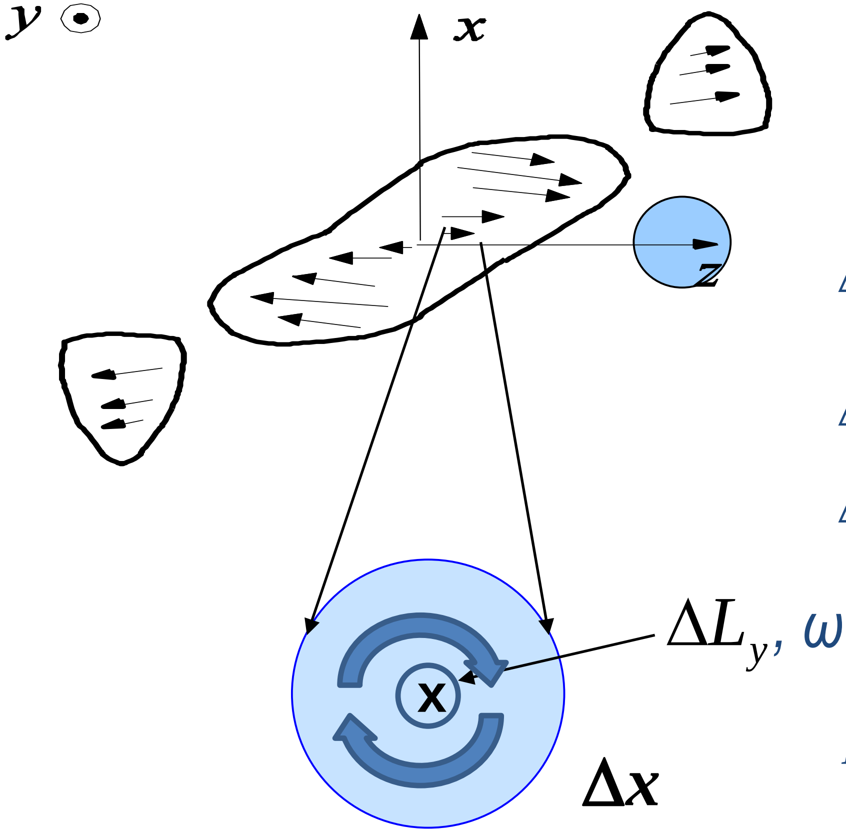
⇩

Gradient in p_z-distribution along the x-direction



Local Orbital Angular Momentum

Liang & Wang, arXive:nucl-th/0410079, 2004



$$\Delta p_z = \frac{dp_z}{dxdy} dxdy$$

$$\Delta L_y = -\Delta p_z \Delta x$$

$$\Delta x = 1\ fm$$

$$p_z(x,b,\sqrt{s}) = \frac{\sqrt{s}}{2c(s)} \frac{dN^P_{part}/dx - dN^T_{part}/dx}{dN^P_{part}/dx + dN^T_{part}/dx}$$

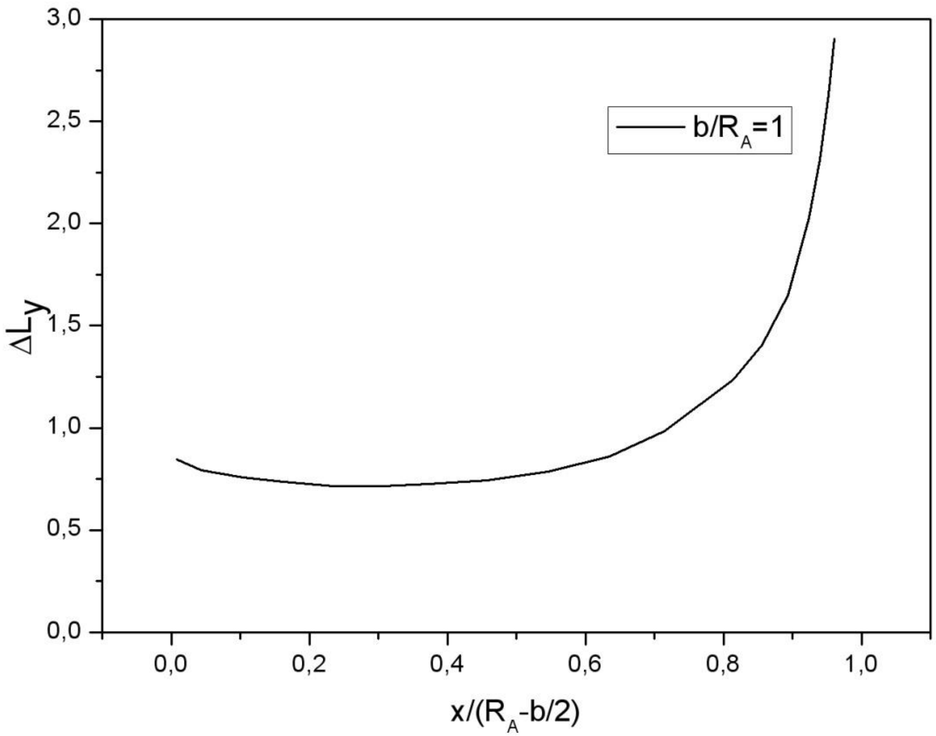
$$\Delta L_y = -\Delta p_z \Delta x = dp_z/dx\,(\Delta x)^2$$

Hydrodynamic analog:
non-vanishin local vorticity

$$\omega = (1/2)\nabla \times \mathbf{v}$$

Local Orbital Angular Momentum

Au+Au at $\sqrt{s}$ = 9 GeV, b = 6 fm



Hyperon polarization in HIC

- Particles in the overlap region of two colliding nuclei could be polarized due to the large orbital momentum created in the non-central HIC.
- **Proposal:**
- Hyperon Polarization can be observed at NICA, CBM and BES RHIC
- Why?

Global Polarization Hyperons in Non-Central HIC

- Hyperons could be polarized due to the large orbital momentum or/and strong magnetic field, created in the non-central HIC.
- Preferable (measurable) types of hyperons – Λ, Ξ^-, Ω^-:
  - $\Lambda \rightarrow p\pi^-$
  - $\Xi^- \rightarrow \Lambda\pi^-$
  - $\Omega^- \rightarrow \Lambda K^-$ (B.R. 68%)
- Global polarization are measured w.r.t. the reaction plane.
- Reaction plane is defined by a directed flow.

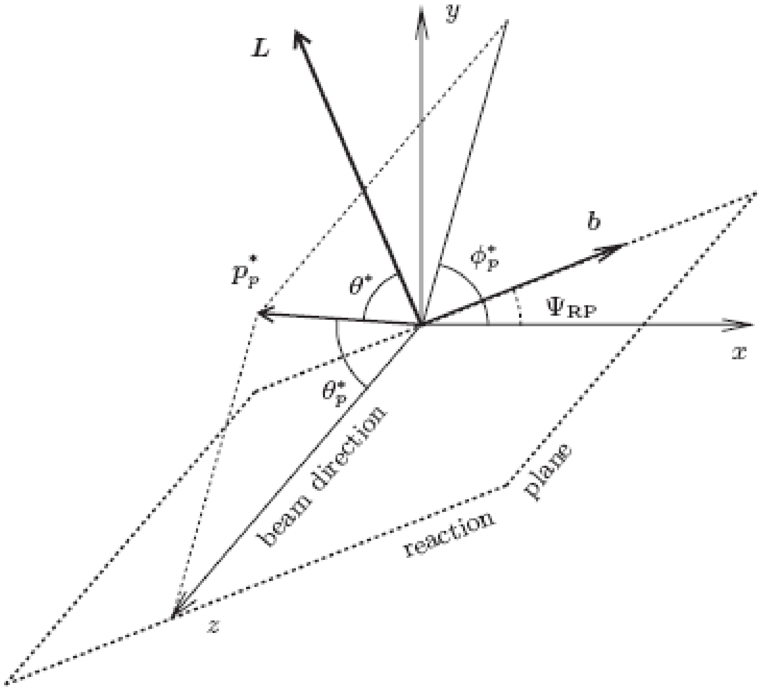
Measurement of Global Polarization

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

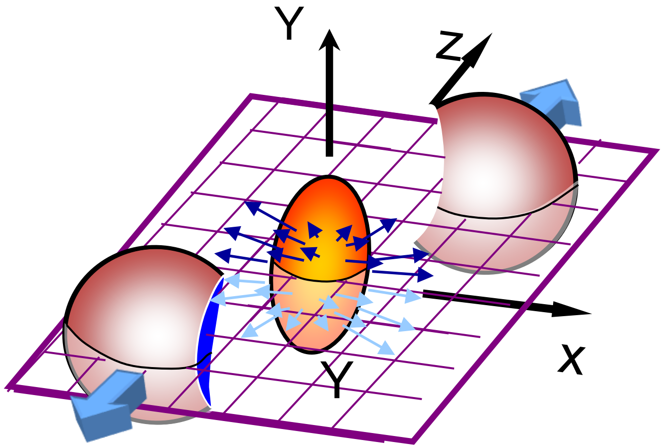
$$P_H = \frac{3}{\alpha_H}\langle\cos\theta^*\rangle.$$

$$P_H = \frac{8}{\pi\alpha_H}\langle\sin(\phi_p^* - \Psi_{\mathrm{RP}})\rangle.$$

$$v_1^H = \langle\cos(\phi_H - \Psi_{\mathrm{RP}})\rangle$$



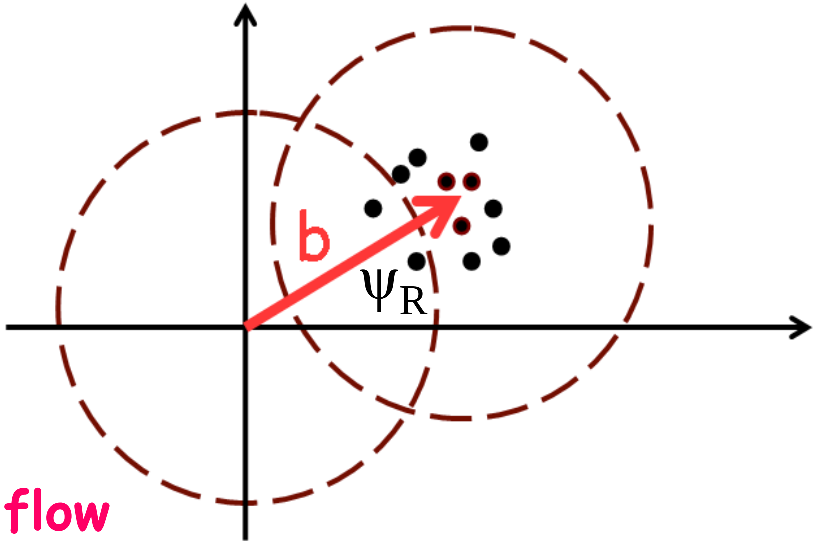
Reaction Plane vs. Collective Flow



Non-central HIC interaction in overlap region results in a **pressure gradient** =>
spatial asymmetry is converted to an asymmetry in momentum space => **collective flow**

Definitions: Flows

$$\frac{dN}{d\varphi} = \frac{N_{tot}}{2\pi}(1 + \sum 2v_n \cos(\varphi - \Psi_R))$$



1-st Fourier harmonics, v_1 → **directed flow**

2-nd Fourier harmonics, v_2 → **elliptic flow**

Ψ_r - Reaction Plane

$2v_n \cos[n(\varphi - \Psi_r)]$ - azimuthal asymmetry

$v_1 = \langle\cos[(\varphi - \Psi_r)]\rangle$ - direct flow

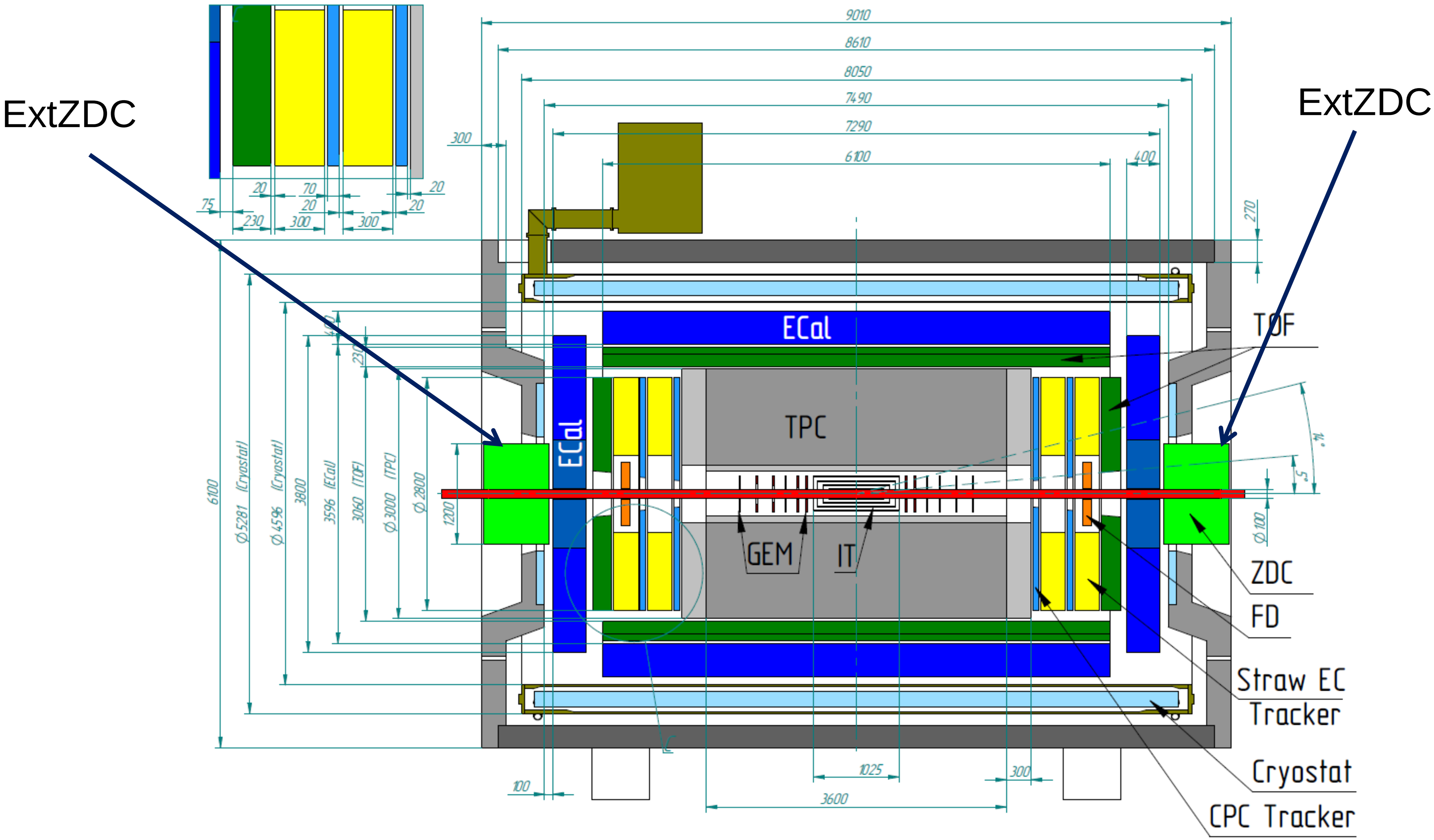
$v_2 = \langle\cos[2(\varphi - \Psi_r)]\rangle$ - elliptic flow

Conclusion

- Enhanced yield of Strangeness at $\sqrt{s} \sim 4 \div 10$ GeV may be a manifestation of the nucleon – hyperon phase transition in a dense baryonic matter.
- Global hyperon polarization could be preferably detected at this energy range (only!).

Thank you for attention!

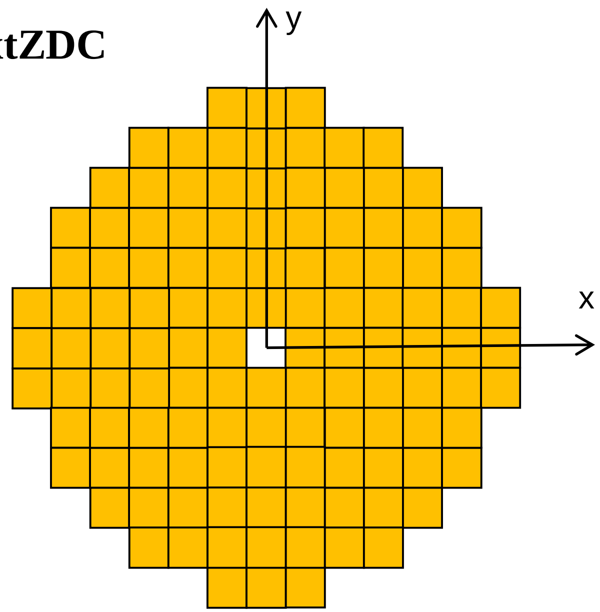
MPD layout



Length of TPC -340 cm, D=300cm

Extended ZDC detector

ExtZDC

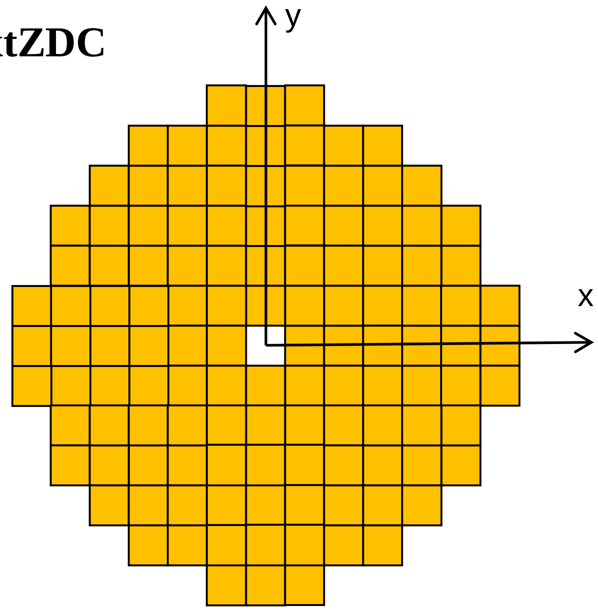


Simulation of Extended ZDC within mpdroot:

- $L \approx 120$ cm
- $5 < R < 61$ cm (radius of the inscribe circle)
- $d_{cell} = 5x5$ cm
- $z_0 = 365$ cm (distance from the int. point to ZDC)
- $0.8^o < \theta < 9.3^o$ (covered zenith angle)
- $2.5 < \eta < 5.0$ (covered pseudorapidity range)

RP reconstruction by Extended ZDC detector

ExtZDC



$$\varphi_{RP} = \arctan \frac{\sum \Delta E_{vis,i} y_i}{\sum \Delta E_{vis,i} x_i}$$

$$\delta\varphi_{RP} = \langle |\varphi_{EP} - \varphi_{RP}| \rangle = \langle \Delta\varphi_{RP} \rangle$$

$$R = \langle \cos(\Delta\varphi_{RP}) \rangle$$

- No particle identification
- Geant 3
- Systematic effect of magnetic field:

$\sim 1^o$ at 9 AGeV
increases to
$\sim 3^o$ at 3 AGeV

ZDC sizes and acceptances

D = 365 cm – distance from interaction point to ZDC

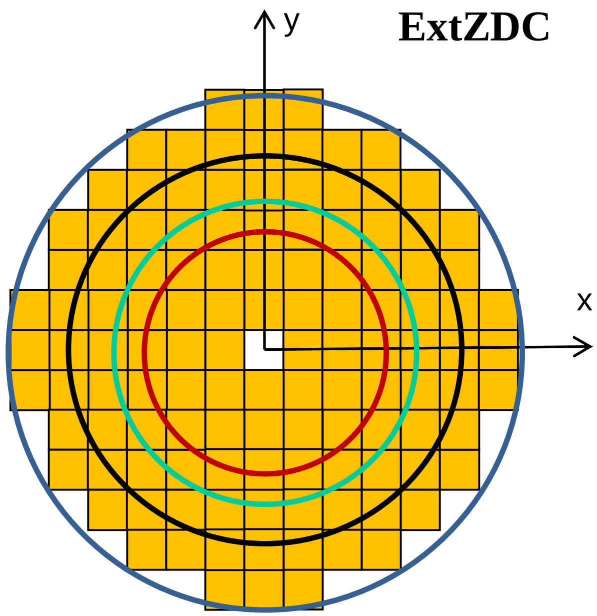
R_{hole} = 5 cm θ = 0.8° η = 5.0

R_{ZDC} = 61 cm θ = 9.54° η = 2.5 ÷ 5.0

R_{ZDC} = 50 cm θ = 7.84° η = 2.7 ÷ 5.0

R_{ZDC} = 41 cm θ = 6.4° η = 2.9 ÷ 5.0

R_{ZDC} = 33 cm θ = 5.26° η = 3.1 ÷ 5.0



RP resolution in MC-events for different acceptances of ZDC

RP resolution, R = <cos($\Delta\psi_1$)>

no particle identification