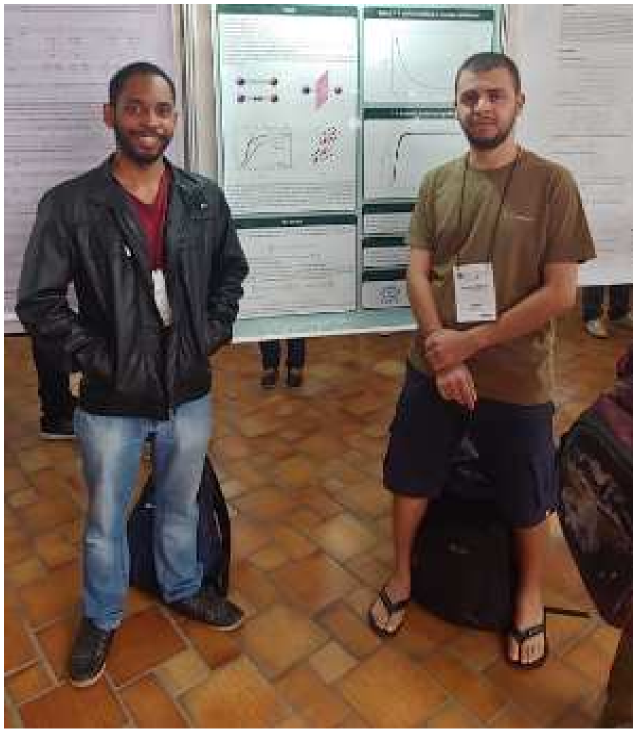
Spin 1 resonances as probes of spin-vorticity dynamics



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2305.02985 (PRD),2104.12941 (PRC) with Kayman Jhosef Carvalho Goncalves,Paulo Henrique de Moura and ongoing work with Kayman

The theoretical necessity of spin-vorticity non-equilibrium

The experimental necessity of spin 1 and higher (qubits vs qutrits)

From qutrits to non-equilibrium to data

Coalescence of light vector mesons

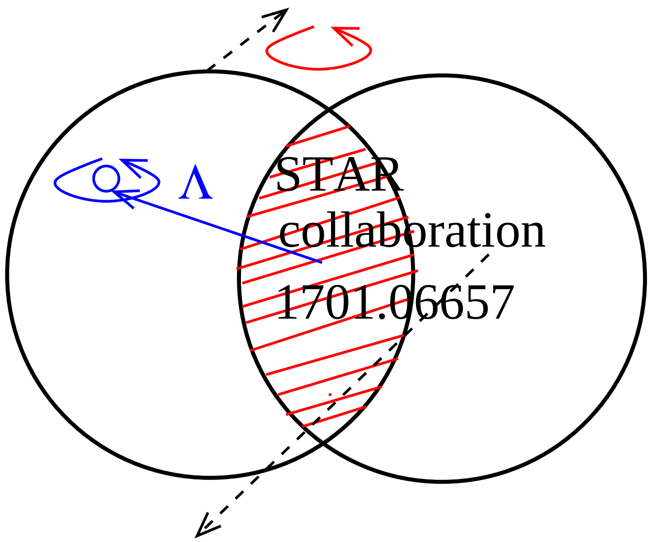
Blast wave estimates. What to look for?

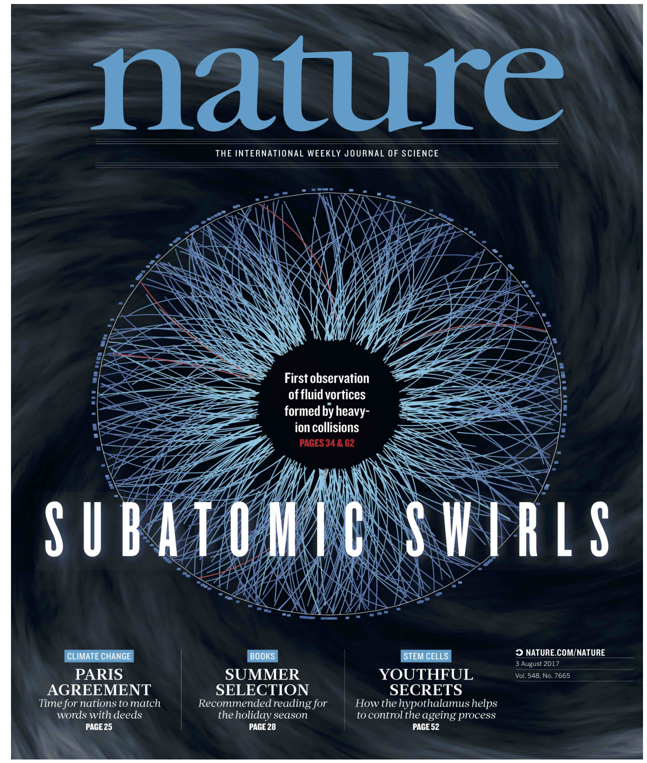
Quarkonia mass shifts

Melting a new mechanism for alignment
Correlate abundance and vorticity?

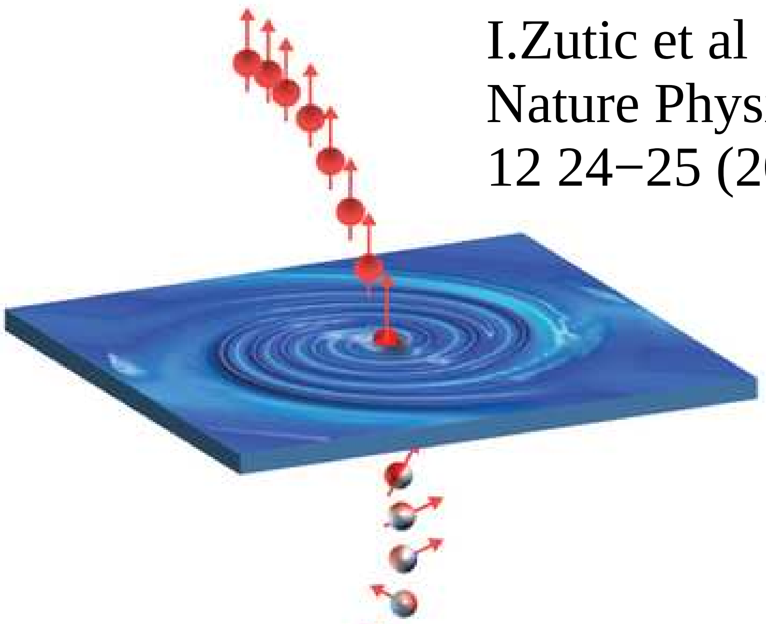
What to measure to get non-equilibrium

Hydrodynamics with spin

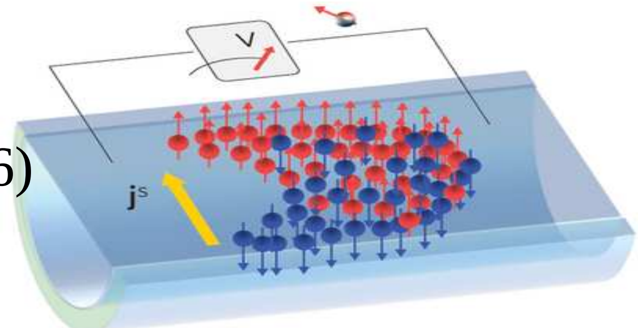


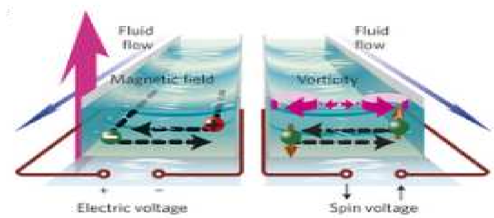


A remarkable experimental discovery, which opened a fascinating field of theoretical investigation.



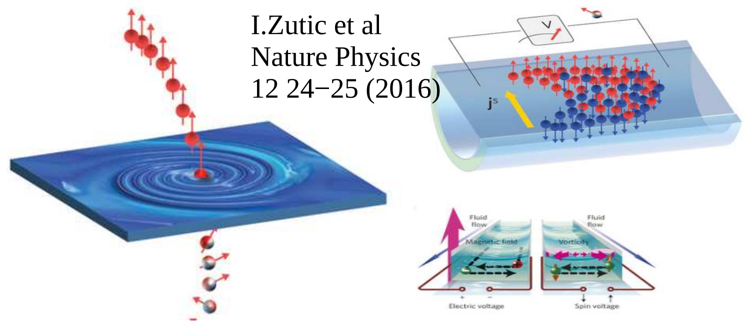
I.Zutic et al
Nature Physics
12 24−25 (2016)





What does a relativistic system look like where

- Close to local equilibrium (strongly coupled, many DoFs)
- Dofs have spin (not "colliding balls" but "shapes")



Unresolved very non-trivial statistical mechanics problem. Spin not the same as "small vortex".

Spin <u>quantum</u> microstate, how angular momentum is shared determines macroscopic entropy

Vorticity A <u>classical</u> collective excitation carrying angular momentum

So spin hydrodynamics means <u>backreaction</u> of microscopic DoFs on macroscopic perturbations!

Phenomenology so far:Becattini et al, 1303.3431

GC ensemble with angular momentum as a conserved quantity, fermions (1 species)

$$\exp\left(-\frac{p_\alpha u^\alpha}{T}\right) \to \exp\left(-\frac{p_\alpha u^\alpha}{T}\right)(\bar{u},\bar{v})\exp\left[\frac{\Sigma_{\mu\nu}\omega^{\mu\nu}}{T}\right]\begin{pmatrix} u \\ v \end{pmatrix}$$

And Fermi-Dirac statistics. Here

- $\omega^{\mu\nu}$ vorticity tensor
- $\Sigma^{\mu\nu}$ spin projection tensor $\sim \begin{pmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix}$

local equilibrium isentropic particle production with spin

Fits Λ global polarization

Doesen't fit local polarization (wrong phase).

- use T-vorticity but
- Symmetric shear and isothermal freeze-out but

equilibrium, local or global,about conserved charges!. Only circulation conserved is enthalpic ($\nabla \times [(e+p)\vec{u}]$ associated to angular momentum) not T-circulation or symmetric shear) so on a theory level there is something to understand

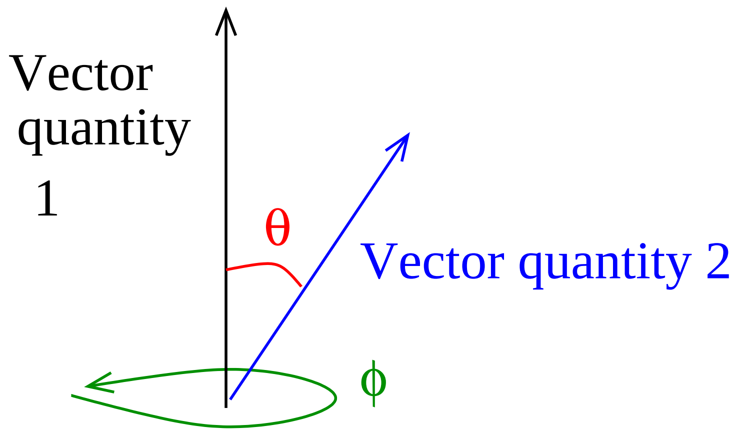
Underestimates and wrong sign for some spin-1 particles, $\phi, J/\Psi$

Investigation ongoing Toroidal vortex rings,jet-induced polarization,...

But... and this is the main point!

Theoretically This can not be the whole story! Perfect equilibrium between vorticity and spin acausal!

GT+Montenegro,1807.02796,GT,Montenegro,Tinti,1701.08263



Vorticity+spin must be aligned at equilibrium for entropy to have a well-defined minimum

But this cannot occur instantaneusly in a dynamical system

$$\tau_Y u_\alpha \partial^\alpha s_{\beta\gamma} + s_{\beta\gamma} = \omega_{\beta\gamma}$$

GT,Tinti,Montenegro dispersion relation quartic, non-causal (Ostrogradski's thm). GT,Montenegro : τ_Y Kramers-Konig dual to vortical susceptibility

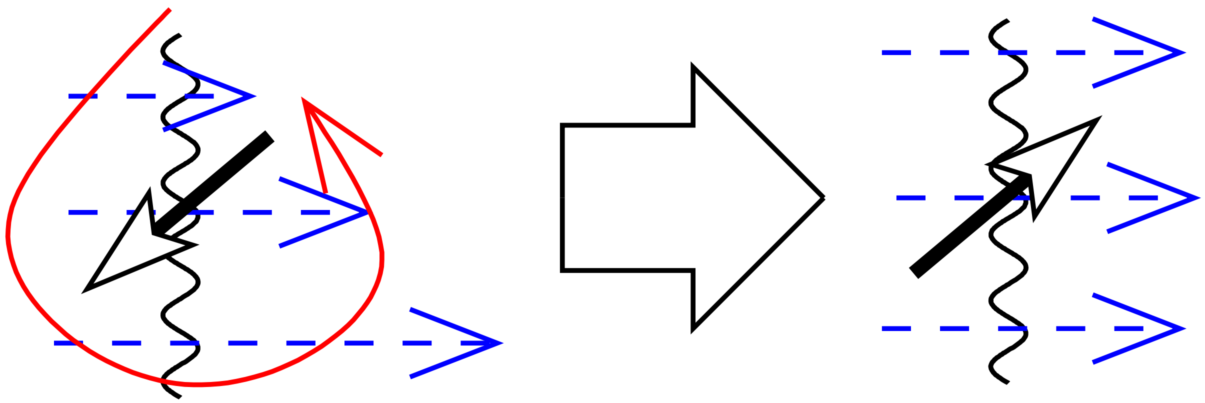
N. Weickgenannt et al transport with spin $\rightarrow$ non-local collision term

E.Speranza et al non-linear stability analysis

Ryblewski,Florkowski,... effective spin hydro

Qualitative picture :GT,D Montenegro, 1807.02796 lower limit to η/s in polarizeable fluids (anti-"ferrovortetic" or phase transition)

$$\tau_Y^2 \geq \frac{8c\chi^2(b_o,0)}{(1-c_s^2)b_o F'(b_o)} \quad , \quad \frac{\eta}{s} \geq T\tau_Y$$



Many attemps at quantitative picture Stephanov,Hongo,Florkowski,Ryblewski,Torrier
spin/vorticity nonequilibrium theoretically inevitable,Phenomenology needed!

Spin and vorticity: classical-quantum interaction

$$\rho_{spin} = \mathrm{Tr}_{bath}\left[\rho_{spin} \times \underbrace{\rho_{bath}}_{vorticity}\right]$$

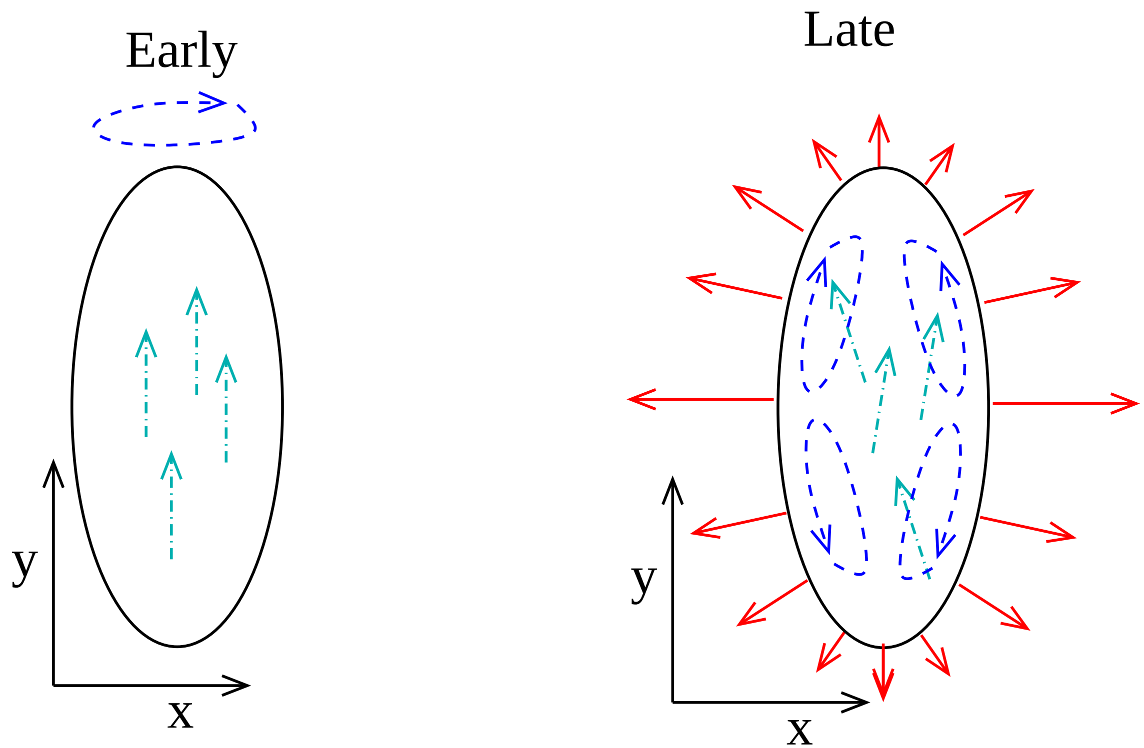
ρ_{spin} Mixed, evolves under Lindblad equation

ρ_{bath} Maximally mixed, evolves under classical equation of motion

H_{int} spin-orbit coupling

Cooper-Frye limit of maximal mixing

Need model-building for this



Global vorticity formed earlier,local vorticity later. Thus the former should be more equilibrated with vorticity than the latter! important consequences for Λ, vector meson . But we need more quantitative observables!

Why spin 1 resonances can help: spin 1/2 is a qbit of information

$$\rho = \begin{pmatrix} \rho_{1,1} & \rho_{1,-1} \\ \rho^*_{1,-1} & 1-\rho_{1,1} \end{pmatrix} \quad , \quad \underbrace{U^{-1}\rho U = \mathrm{Diag}\,(\alpha, 1-\alpha)}_{dU=\hat{I}-\delta\theta\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}-i\delta\phi\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}}$$

1 parameter,2 angles Whatever mechanism combines spin ($\equiv \phi$) and angular momentum ($\equiv \theta$) will result in some supoerposition of +1,-1

$$\frac{dN_{decay}}{d\theta} = 1 + \alpha\cos\theta \quad , \quad \alpha \sim \rho_{1,1}$$

Thus in practice any state indistinguishable from equilibrium $\rho_{equilibrium} \propto \begin{pmatrix} e^{w/T} & 0 \\ 0 & e^{-w/T} \end{pmatrix}$ Can study Dependence of α on y, p_T but need to fit many parameters. Need qualitative signature!

Spin 1 contains more information even if parity conserved! (Liang,Wang, nucl-th/0410079)

$$\frac{dN_{decay}}{d\theta d\phi} \propto \cos^2\theta \rho_{00} + \sin^2\theta \left(\frac{1-\rho_{00}}{2} + r_{1,-1}\cos(2\phi) + \alpha_{1,-1}\sin(2\phi) \right) +$$

$$+ \sin(2\theta)\left(r_{10}\cos\phi + \alpha_{10}\sin\phi \right)$$

Where

Variable	Element	coefficient $\times \frac{3}{4\pi}$
ρ_{00}	ρ_{00}	$\cos^2\theta$
$\frac{1-\rho_{00}}{2}$	$\frac{\rho_{11}+\rho_{-1-1}}{2}$	$\sin^2\theta$
r_{10}	$Re[\rho_{-10} - \rho_{10}]$	$\sin(2\theta)\cos(\phi)$
α_{10}	$Im[-\rho_{-10} + \rho_{10}]$	$\sin(2\theta)\sin(\phi)$
$r_{1,-1}$	$Re[\rho_{1,-1}]$	$\sin^2\theta\cos(2\phi)$
$\alpha_{1,-1}$	$Im[\rho_{1,-1}]$	$\sin^2\theta\sin(2\phi)$

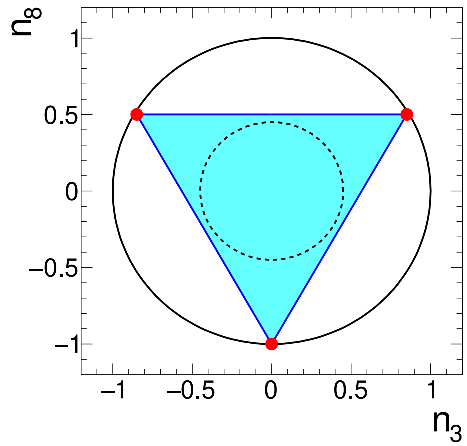
Small system Beam direction, momentum three parameters

$$\rho_{00} \equiv \frac{1+\lambda_\theta}{3+\lambda_\theta} \quad , \quad Re[\rho_{1,-1}] \equiv \frac{\lambda_\phi}{3+\lambda_\theta} \quad , \quad \mathrm{Re}\left[\rho_{-10}-\rho_{10}\right] \equiv \frac{\lambda_{\theta\phi}}{3+\lambda_\theta}$$

Large system Beam direction, momentum and impact parameter
2 additional parameters, $\mathrm{Im}[\rho_{1,-1}], \mathrm{Im}\left[\rho_{-10}-\rho_{10}\right]$ Crucial information about phases

(Wild idea : Perhaps can get new axis from cumulants in small systems?)

Spin-1 is a qutrit! Two vectors! Can be mixed $\rho^2 \neq \rho$ in all frames!



$$\rho_8(n_3, n_8) = \frac{1}{3} U^{-1}(\theta,\phi) \begin{pmatrix} 1+\sqrt{3}\,n_3+n_8 & 0 & 0 \\ 0 & 1-\sqrt{3}\,n_3+n_8 & 0 \\ 0 & 0 & 1-2n_8 \end{pmatrix} U(\theta,\phi)$$

Two parameters, two angles so generic state neither pure nor thermal! But what is angle ϕ? Need "objective" ebye definition! beam axis

From angular distributions to purity

$$\frac{dN_{decay}}{d\theta d\phi} \propto \cos^2\theta\rho_{00} + \sin^2\theta\left(\frac{1-\rho_{00}}{2} + r_{1,-1}\cos(2\phi) + \alpha_{1,-1}\sin(2\phi)\right) +$$

$$+\sin(2\theta)\left(r_{10}\cos\phi + \alpha_{10}\sin\phi\right)$$

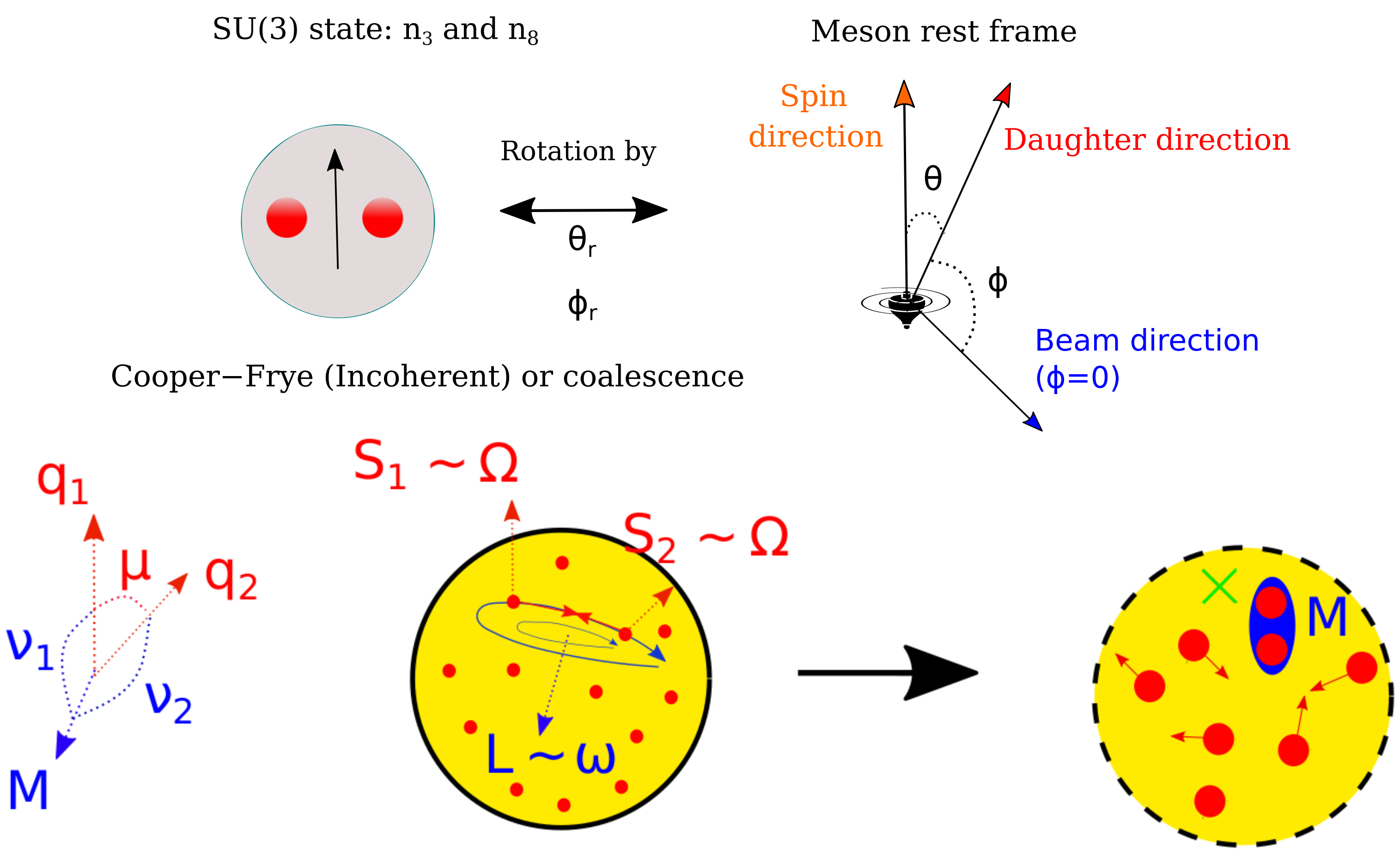
Matrix elements and purity directly related

$$\frac{1}{12}\left(3\left(n_8 - \sqrt{3}\, n_3\right)\cos\left(2\theta_r\right) - \sqrt{3}\, n_3 + n_8 + 4\right) = \rho_{00}$$

$$\frac{\left(n_8 - \sqrt{3}\, n_3\right)\sin\left(\theta_r\right)\cos\left(\theta_r\right)\cos\left(\phi_r\right)}{\sqrt{2}} = r_{10}$$

$$-\frac{\left(\sqrt{3}\, n_3 + 3n_8\right)\sin\left(\theta_r\right)\sin\left(\phi_r\right)}{3\sqrt{2}} = \alpha_{10} \quad , \quad \phi_r = -\frac{1}{2}\tan^{-1}\left(\frac{\alpha_{1,-1}}{r_{1,-1}}\right)$$

A concrete example: Coalescence K^*, ϕ



Cooper-Frye limit for some θ

$$\hat{\rho} = \frac{1}{N} U(\theta)^{+} \left(\begin{array}{ccc} e^{-w/T} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{w/T} \end{array} \right) U(\theta)$$

So all quantties related to ϕ_r compatible with zero

Non-equilibrium Non-trivial $\rho_{i \neq j}$ with two well-defined axes, θ_r, ϕ_r , whose exact nature depends on mechanism combining spin and vorticity

Coalescence in a rotating medium

THe expression of the vector meson density matrix in terms of the quark density matrices and the vorticity is straight-forwardly

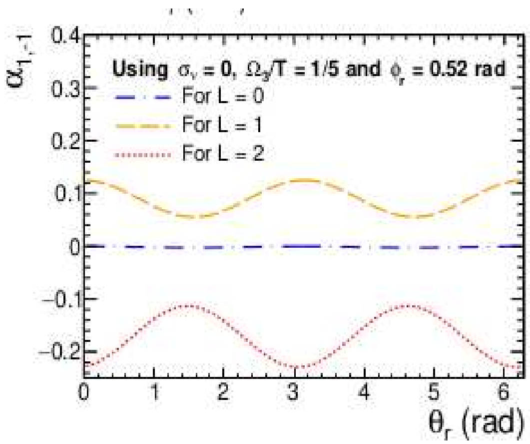
$$\left(\hat{\rho}^M\right)_{mn} = \sum_{ijkl} \left(P_{12}^L\right)_{ijklmn} U_S(\phi_r,\theta_r) \left(U_\omega(\mu_1,\nu_1)\rho^1(\Omega)U_\omega^{-1}(\mu_1,\nu_1)\right)_{ij} \times$$

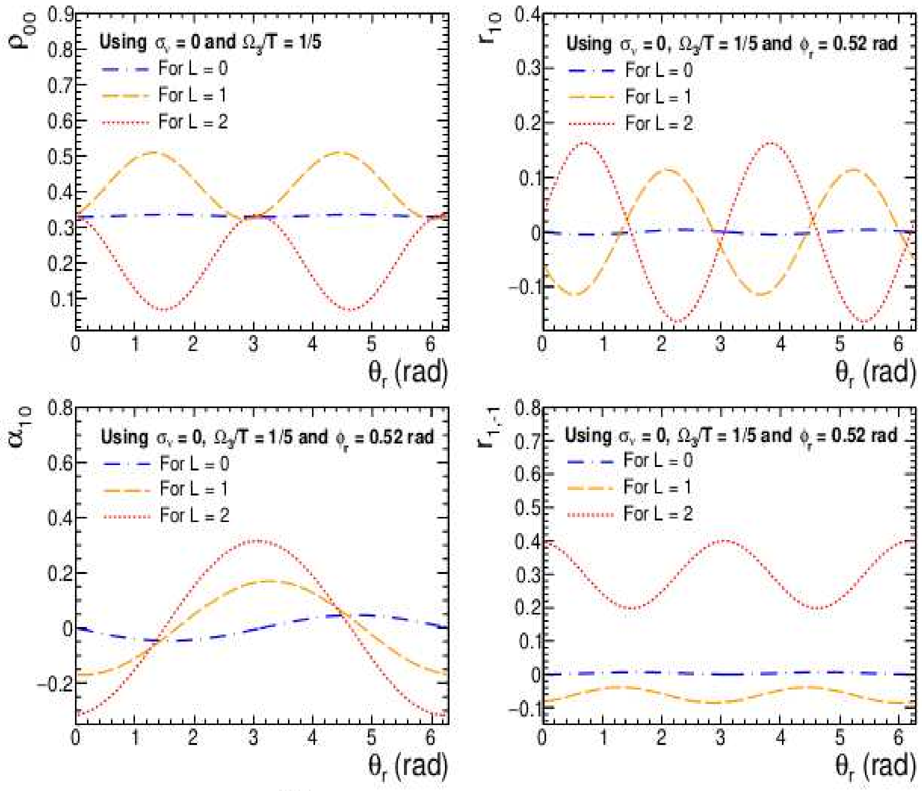
$$\times \left(U_\omega(\mu_2,\nu_2)\rho^2(\Omega)U_\omega^{-1}(\mu_2,\nu_2)\right)_{kl} U_S^{-1}(\phi_r,\theta_r)$$

Where $P_L(w)$ is the (unknown) probability to aquire a spin quantum number from vorticity and the rest are 6-j and C-G coefficients!

Big approximation : non-relativistic. But with constituent quarks and moderate p_T, y not bad

Golden signature:off-diagonal elements





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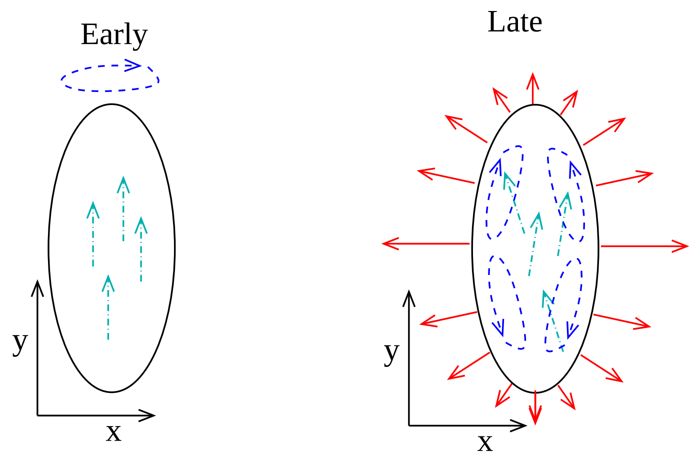
2104.12941

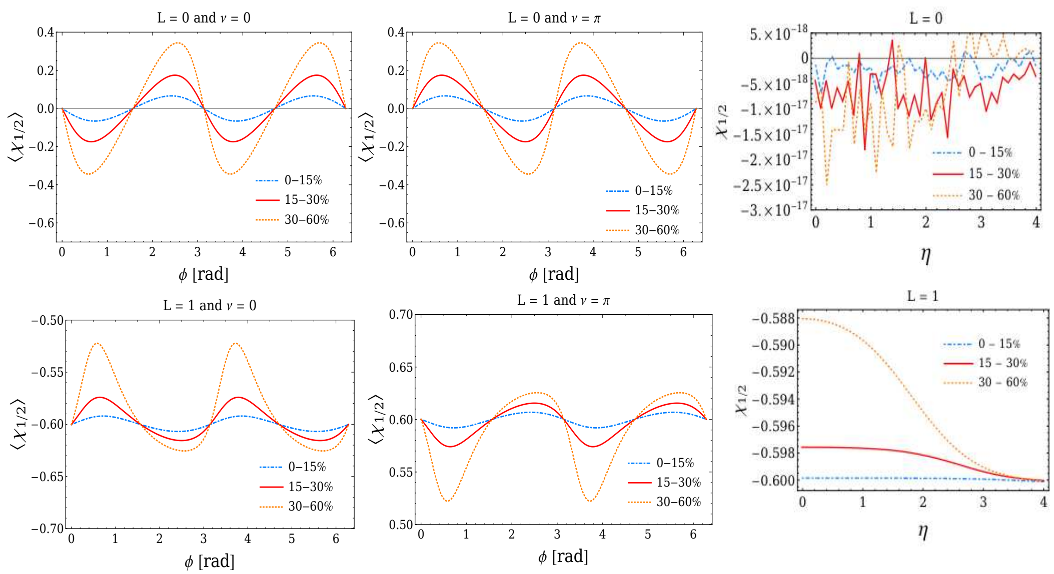
If ebye ϕ coefficients $\simeq 0$, Cooper-Frye, otherwise coalescence

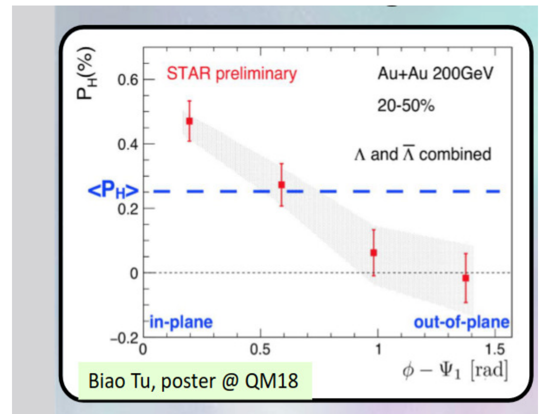
Towards more quantitative phenomenology: Blast wave model+coalescence

Use blast-wave model with vorticity, Florkowski et. al., 1904.00002



The idea: longitudinal polarization due to non-equilibrium between spin and vorticity Early polarization due to enthalpy gradients, "out of phase" late vorticity due to flow gradients "spin chemical potential" following initial circulation, fitted final vorticity,T,flow, coalesce using previous prescription spin 1 mesons and baryons? Transverse and longitudinal?



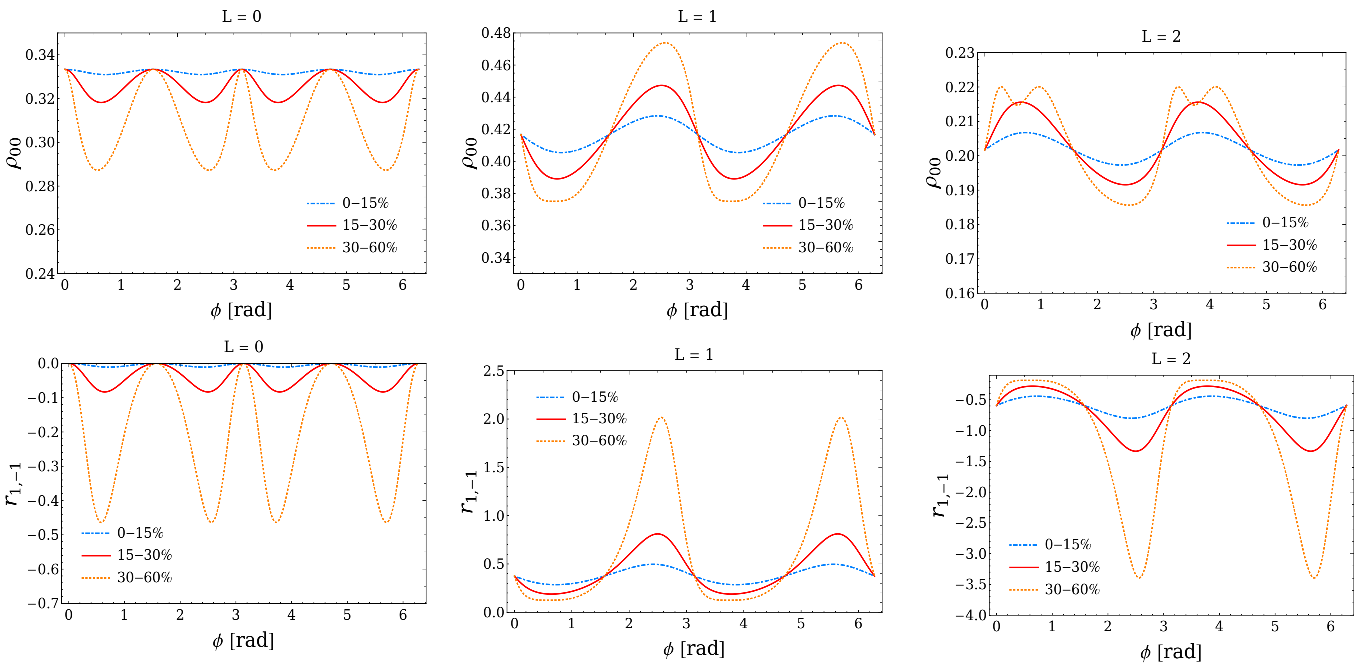


Non-zero meson spin alignment and small baryon polarization follow somewhat naturally but Not predictive (lots of parameters), in particular

Wigner function: if prefers ↑↑ , bayon polarization negative, if ↑↓ positive

$P(L)$: transfer of angular momentum from spin to voricity, decoherence problem, can in principle be calculated from linear response

Modulation generally big ($\gg \langle P \rangle$),so is preliminary STAR data!

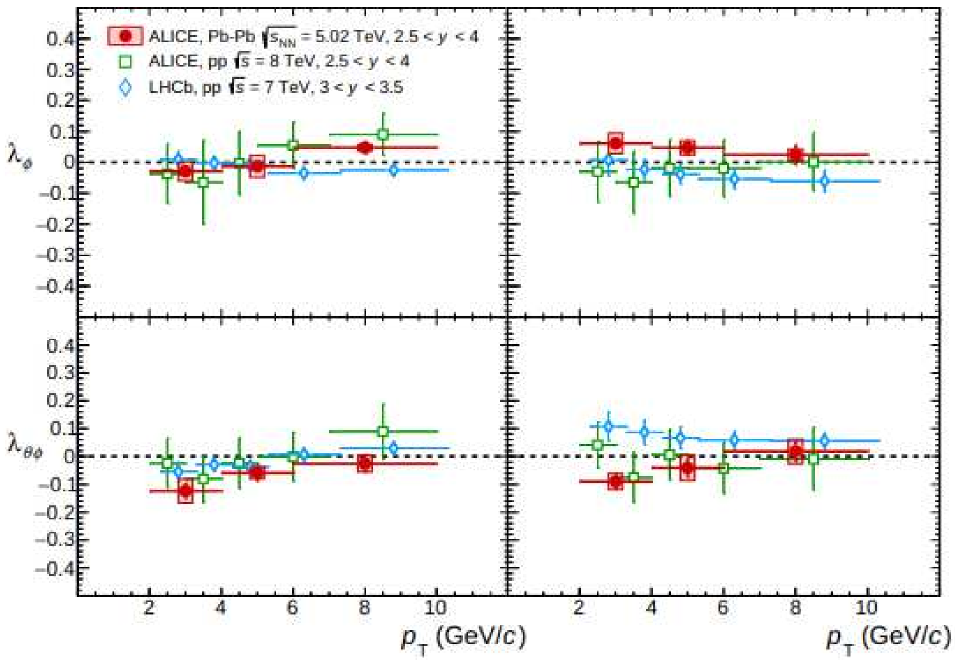


But if ρ_{00} and baryon polarization depend strongly on ϕ, it will become a viable explanation, partial-wave like analysis, And of course you have non-diagonal coefficients for spin 1 mesons too, and are non-zero for coalescence!

$$\rho_{00} \equiv \left\langle \cos^2 \theta_D \right\rangle \quad , \quad r_{1,-1} \equiv \left\langle \sin^2 \theta_D \cos(2\phi_D) \right\rangle \equiv \mathrm{Re}\rho 1, -1$$

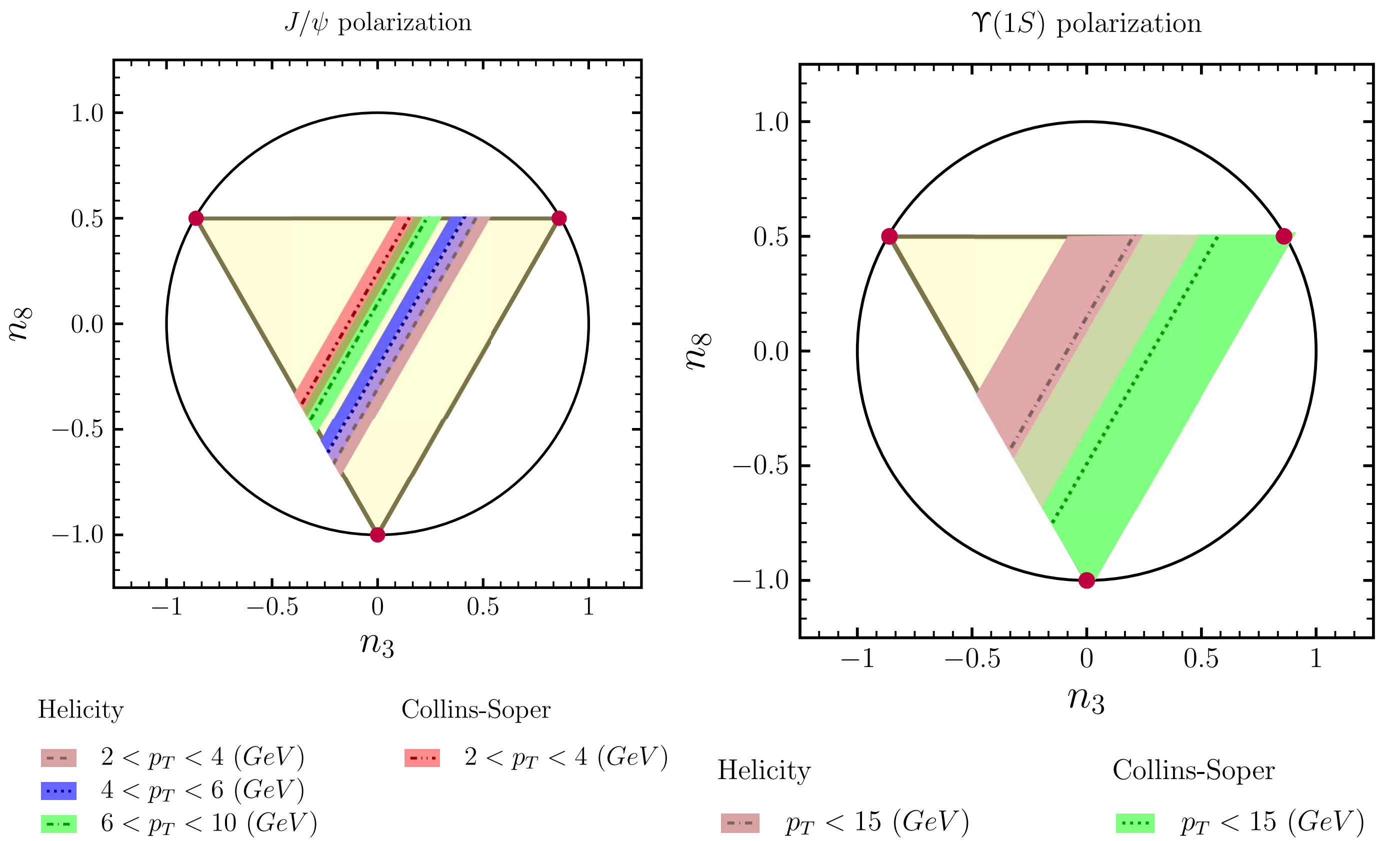
And then we discovered it was all measured... for quarkonium!

$$\rho_{00} = \frac{1+\lambda_\theta}{3+\lambda_\theta} \quad , \quad r_{1,-1} = \frac{\lambda_\phi}{3+\lambda_\theta} \quad , \quad r_{10} = \frac{\lambda_{\theta\phi}}{3+\lambda_\theta}$$

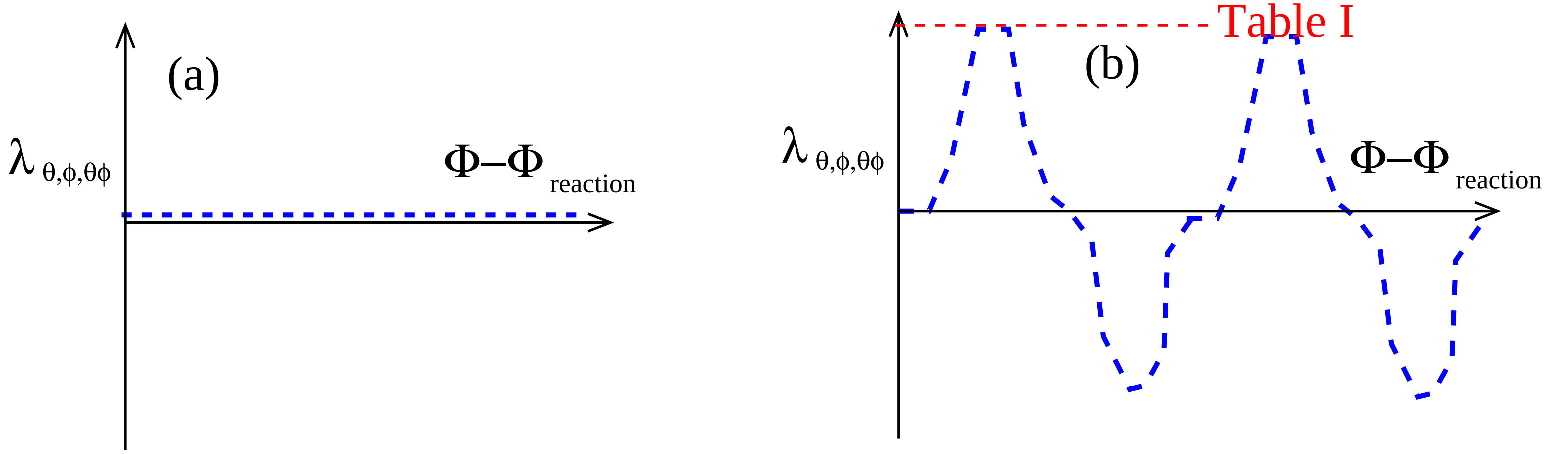


ALICE collaboration 2005.11128 PLB

Solving for $n_{1,8}$ gives close to maximally mixed state



Off-diagonal elements compatible with zero, Cooper-Frye! but...

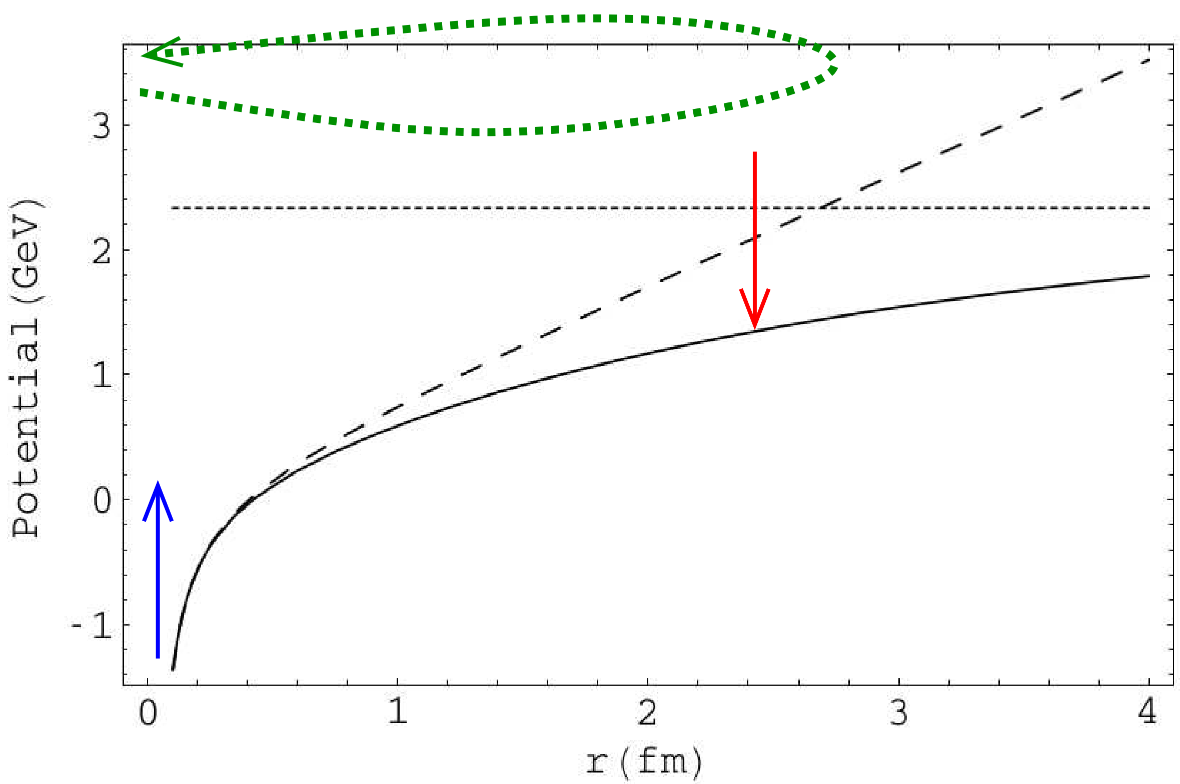


Remember spin-orbit non-equilibrium is all about interplay between eaaly (global) and late (local) axes. Need modulation in angle from reaction plane of λs!

Qualitatively one expects of diagonal elements to be "local", and ny harmonic function averages to zero. Is it zero in every azimuthal bin?

Getting more quantitative for Quarkonium

Rotating Cornell potential with spin orbit interaction



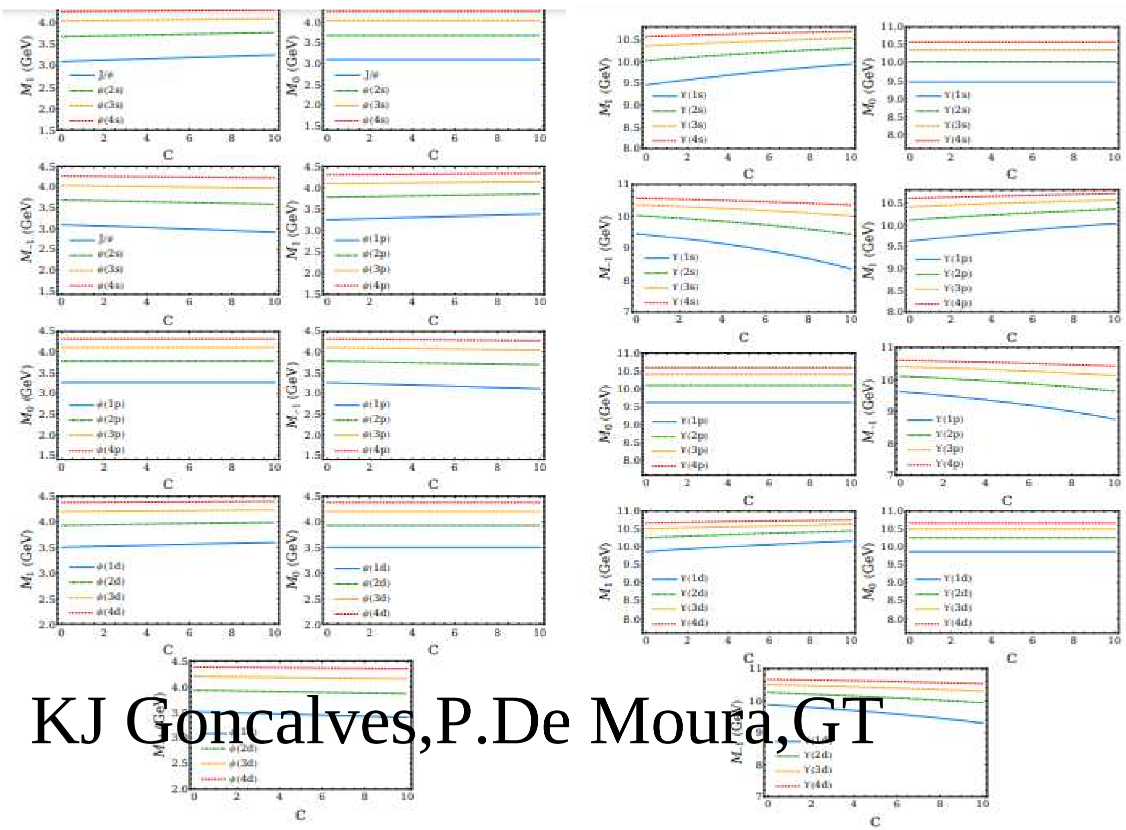
Rotating Cornell potential with spin orbit interaction

$$\begin{cases} \mathbf{P} = \mathbf{p_1} + \mathbf{p_2}, & \mathbf{p} = \mu \left(\frac{\mathbf{p_1}}{m_1} - \frac{\mathbf{p_2}}{m_2} \right) \\ \mu = \frac{m_1 \, m_2}{m_1 + m_2}, & \\ \mathbf{r_1} = \mathbf{R} + \frac{m_2}{m_1 + m_2}\mathbf{r}, & \mathbf{r_2} = \mathbf{R} - \frac{m_1}{m_1 + m_2}\mathbf{r} \end{cases}$$

$$\mathcal{H} = \frac{P^2}{2M} + \frac{p^2}{2\mu} - \mathbf{P} \cdot (\omega \times \mathbf{R}) - \mathbf{p} \cdot (\omega \times \mathbf{r}) - \omega \cdot (\mathbf{S}_1 + \mathbf{S}_2) + V(\mathbf{r})$$

With a Cornell-type potential. This way vorticity and spin interactions accounted for. Mass correction $\Delta E_{i,j}$ and Melting temperature from Debye formula. More realistic QFT/Open QM models?

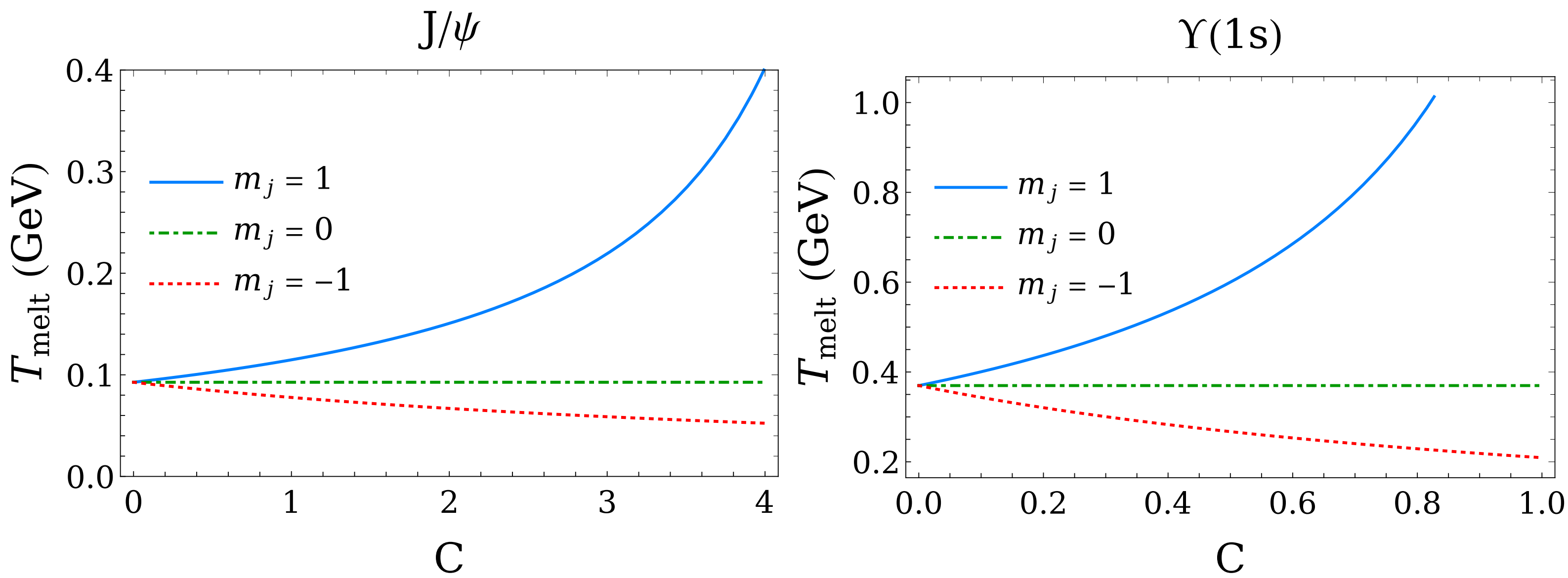
Mass becomes sensitive to relative direction of spin and vorticity



KJ Goncalves,P.De Moura,GT

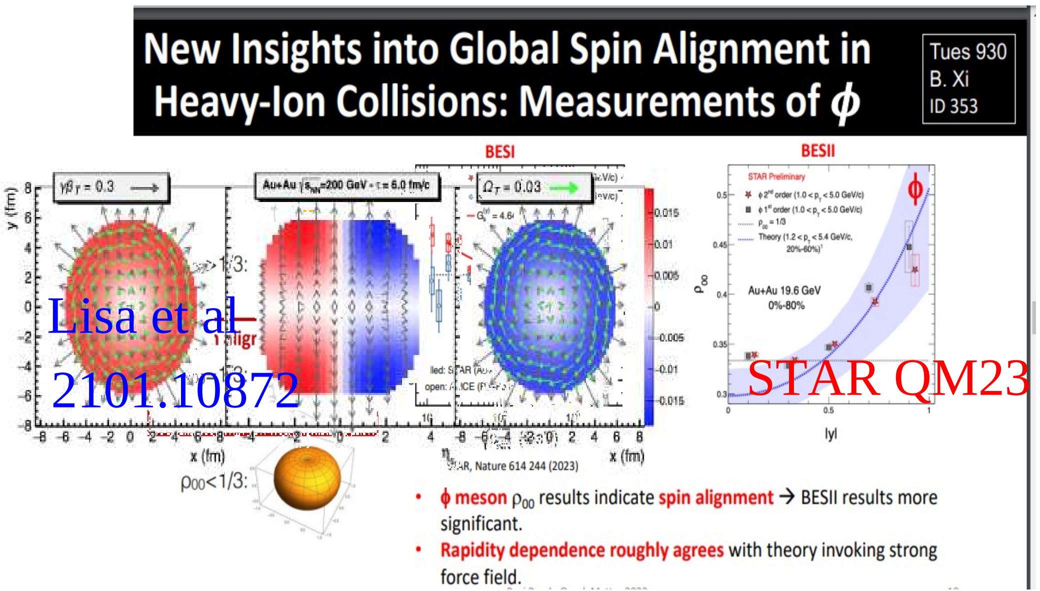
This is experimentally undetectable (widening), but...

One can get melting temperature from Debye formula!



Melting temperature depends non-monotonically on rotation <u>and</u> (anti)polarization. Could such "distillation" explain ϕ spin alignment? ϕ is quarkonium and only polarized survive! If confirmed by more realistic models (QFT,openQM) need abundance vs alignment scans with rapidity.

Can also have to do with quarkonium being more suppressed at higher rapidity (Which is also higher vorticity)



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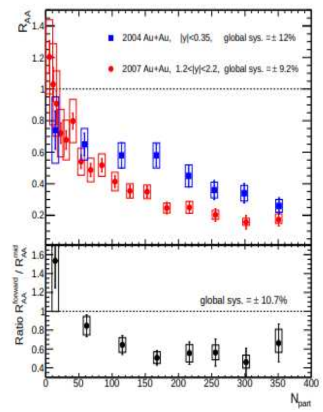
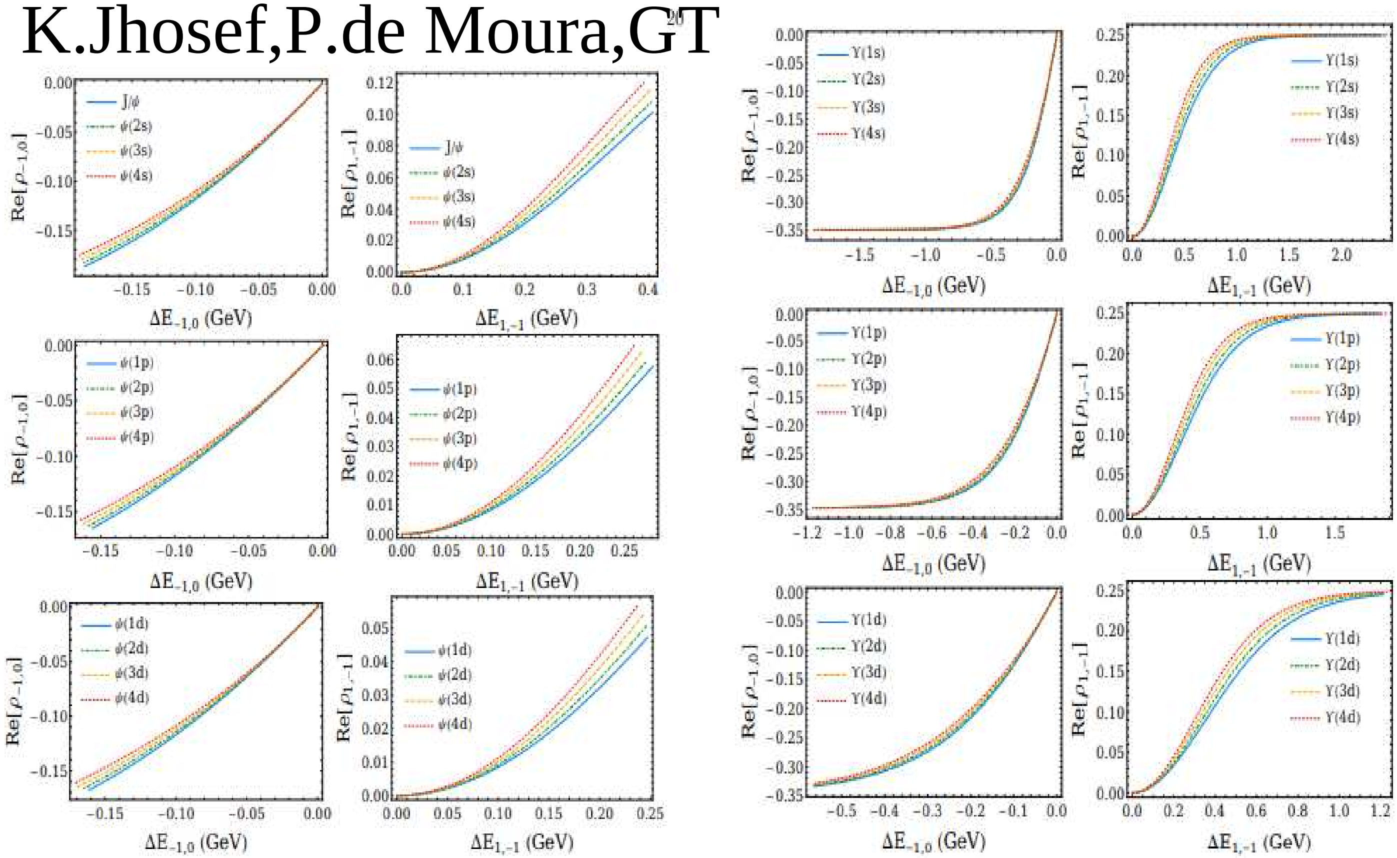


"Distillation" is an important effect qualitatively different from Cooper-Frye
Need: SUppression vs alignment in rapidity!

Correlation between invariant mass and off-equilibrium ρ!

K.Jhosef,P.de Moura,GT



Conclusions

Non-equilibrium between spin and vorticity theoretically well-established, need phenomenology

Spin and vorticity different objects

Cooper-Frye could be misleading

Spin1 vector mesons can serve as such a link because of a rich structure in their density matrix. Coalescence in vector mesons, potential models in quarkonia

To do baryon coalescence (can coalescence explain local polarization?), Ω (Spin 3/2), etc.

SPARE SLIDES