

Static Quark-Antiquark Interactions in Rotating SU(3) Gluodynamics

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under Rotation and Magnetic Fields**

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Non-central collisions create rotation

Impact parameter
 $b \neq 0$



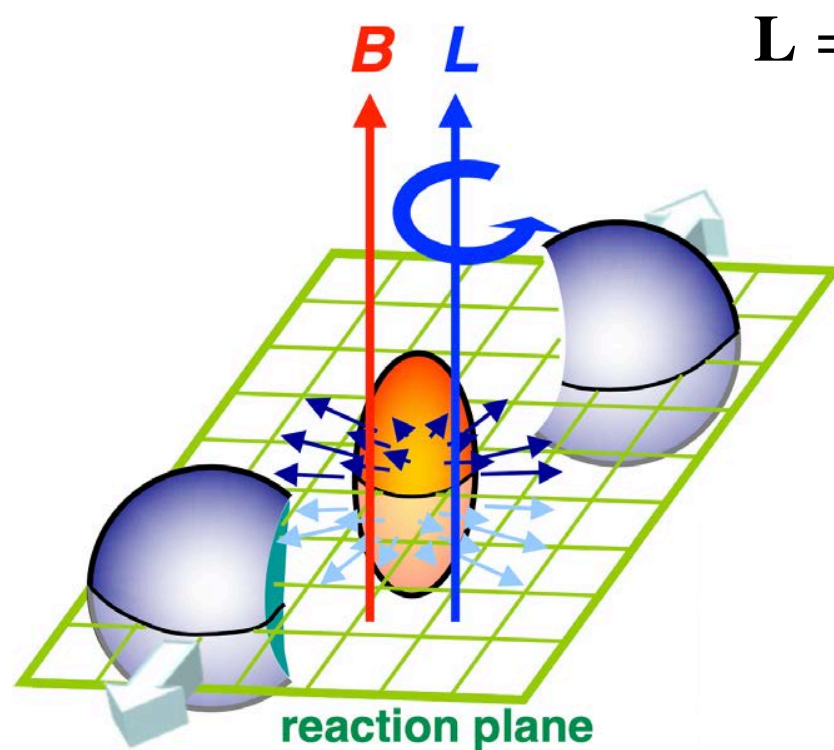
Large orbital
angular momentum



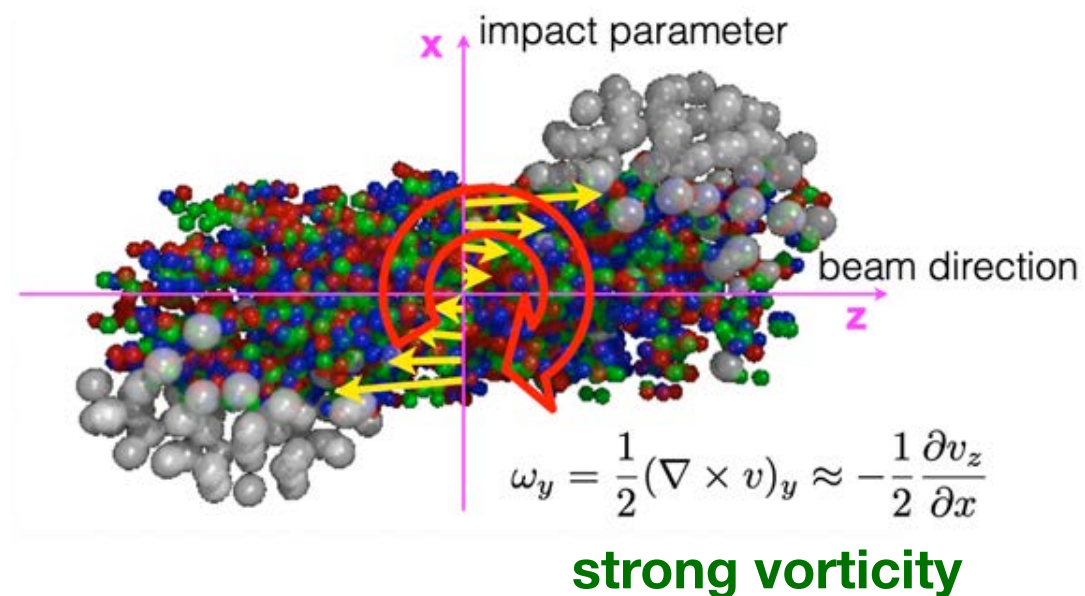
Shear flow



Vorticity in
QGP



$$\mathbf{L} = \mathbf{r} \times \mathbf{p} \sim 10^6 \hbar$$



Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005);
S. Voloshin, nucl-th/0410089 (2004)

- Non-central HICs generate large orbital angular momentum
- Part of it transferred to QGP, giving rise to strong vorticity

Experimental evidence of vorticity

- ◆ Vorticity polarizes quark spins (Barnett effect)



S. J. Barnett, Phys. Rev. 6, 239 (1915)

- ◆ Quark spin inherited by hyperons



- ◆ Measure global Λ and $\bar{\Lambda}$ polarization

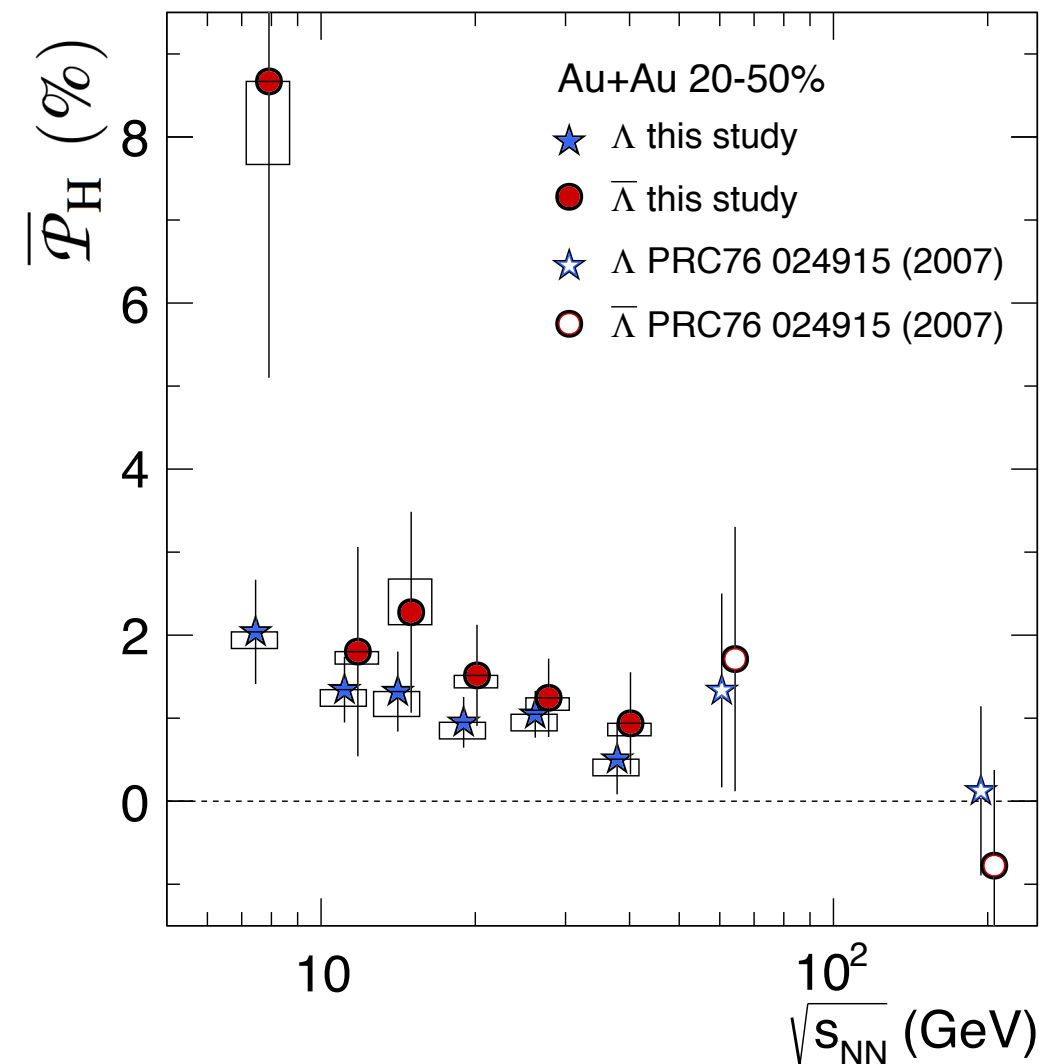


- ◆ Extract polarization from the decay angular distribution

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

hyperon polarization

STAR, Nature 548, 62 (2017)



Most vortical fluid ever observed:
 $\omega \sim 10^{22} s^{-1}$

Experimental bridge from HIC vorticity to QCD under rotation

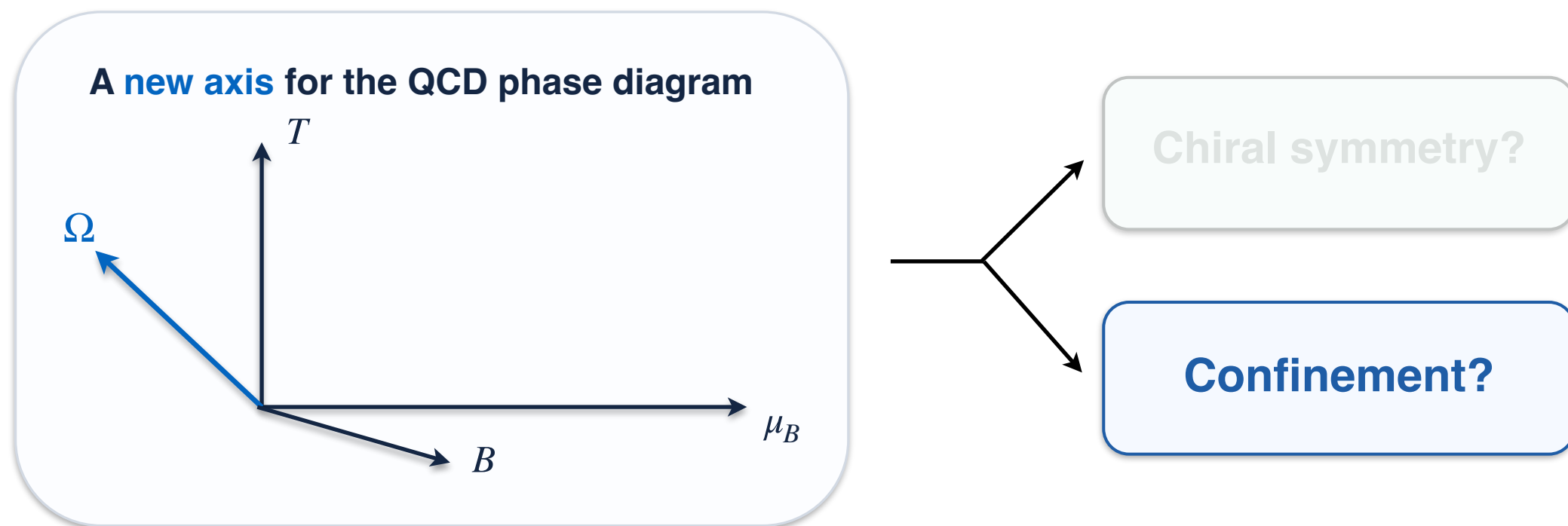
How does rotation affect QCD matter?

Angular velocity as a new thermodynamic parameter in the presence of rotation

Chen, Fukushima, Huang, Mameda, PRD 93, 104052 (2016)

$$\text{Hamiltonian: } H_{\text{rot}} = H - \Omega \cdot J$$

Rotation couples directly to total angular momentum



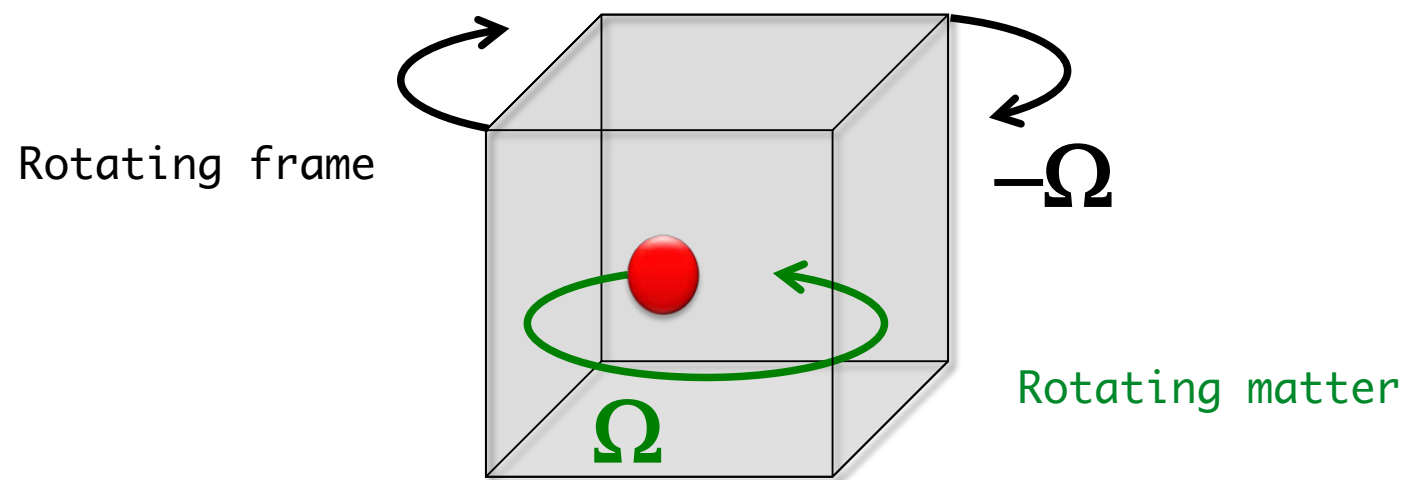
This work: confinement / color screening → static Q- $\bar{Q}$ interactions

A first-principles route to the rotating frame

Rotation = External gravity background

- ◆ Rotating matter in inertial frame $\longleftrightarrow$ Static matter in a co-rotating frame

A. Yamamoto and Y. Hirono, PRL. 111, 081601 (2013)



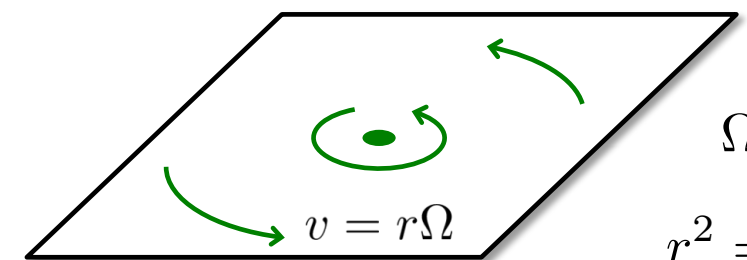
- ◆ Constructing rotating frame in Euclidean space

A. Yamamoto, PRD 90, 054510 (2014)

$$ds^2 = dX^2 + dY^2 + dZ^2 + d\tau^2$$

Change of line
element with rotation:

$$\begin{aligned} X &= x \cos(\Omega_I \tau) - y \sin(\Omega_I \tau) \\ Y &= x \sin(\Omega_I \tau) + y \cos(\Omega_I \tau) \\ Z &= z \end{aligned}$$



$$\begin{aligned} \Omega &= i\Omega_I \\ r^2 &= x^2 + y^2 \end{aligned}$$

$$ds^2 = dx^2 + dy^2 + dz^2 + (1 + \Omega_I^2 r^2) d\tau^2 + 2\Omega_I (x dy - y dx) d\tau$$

Lattice simulations with imaginary rotation

- ◆ Rotation appears through the spacetime metric

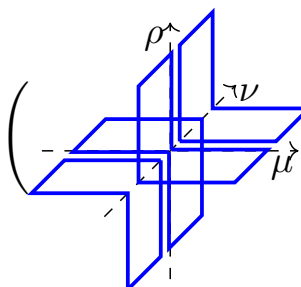
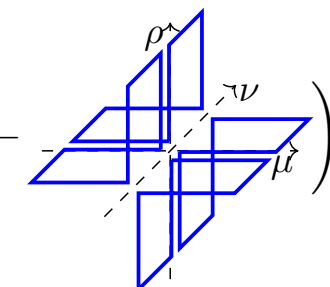
$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \longrightarrow g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & y\Omega_I \\ 0 & 1 & 0 & -x\Omega_I \\ 0 & 0 & 1 & 0 \\ y\Omega_I & -x\Omega_I & 0 & 1 + \Omega_I^2(x^2 + y^2) \end{pmatrix}$$

- ◆ Action remains the same form but with modified spacetime metric

$$S_{\text{YM}} = \frac{1}{2g_{\text{YM}}^2} \int d^4x \, g^{\mu\alpha} g^{\nu\beta} \text{Tr}[F_{\mu\nu} F_{\alpha\beta}]$$

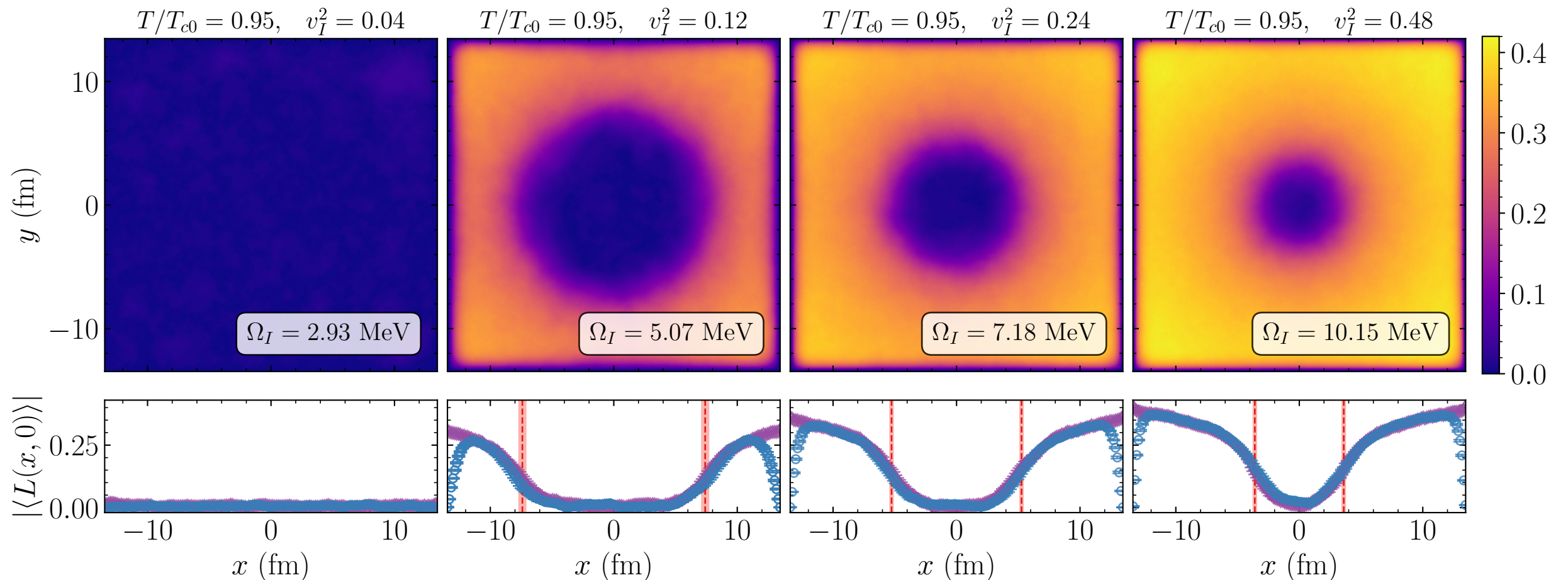
- ◆ Lattice discretization of the rotating-frame Yang--Mills action

$$S_G = \beta \sum_x \left\{ (1 + r^2 \Omega_I^2) \left(1 - \frac{1}{N_c} \text{ReTr} \bar{U}_{xy}\right) + (1 + y^2 \Omega_I^2) \left(1 - \frac{1}{N_c} \text{ReTr} \bar{U}_{xz}\right) + (1 + x^2 \Omega_I^2) \left(1 - \frac{1}{N_c} \text{ReTr} \bar{U}_{yz}\right) \right. \\ \left. + 3 - \frac{1}{N_c} \text{ReTr}(\bar{U}_{x\tau} + \bar{U}_{y\tau} + \bar{U}_{z\tau}) - \frac{1}{N_c} \text{ReTr} \left[y\Omega_I (\bar{V}_{xy\tau} + \bar{V}_{xz\tau}) - x\Omega_I (\bar{V}_{yx\tau} + \bar{V}_{yz\tau}) + xy\Omega_I^2 \bar{V}_{xzy} \right] \right\}$$

$$\bar{U}_{\mu\nu} = \frac{1}{4} \left(\begin{array}{cc} \boxed{} & \boxed{} \\ \boxed{} & \boxed{} \end{array} \right)_{\mu\nu} \longrightarrow \bar{U}_{\mu\nu} = \frac{1}{4} \left(\begin{array}{cc} \boxed{} & \boxed{} \\ \boxed{} & \boxed{} \end{array} \right)_{\mu\nu} + \bar{V}_{\mu\nu\rho} = \frac{1}{8} \left(\begin{array}{c} \text{Diagram 1} - \text{Diagram 2} \end{array} \right)$$



Previous lattice study on confinement under Ω_I

V.V. Braguta, M.N. Chernodub, and A.A. Roenko, PLB 855, 138783 (2024)



- The rotating plasma becomes radially inhomogeneous
- Radial coexistence of confining-like and deconfining-like regions
- Increasing Ω_I shrinks the confining core

Next: a closer look at static Q- $\bar{Q}$ interactions under rotation

Probes of $Q\bar{Q}$ -interactions

$T \simeq 0$: Wilson loop

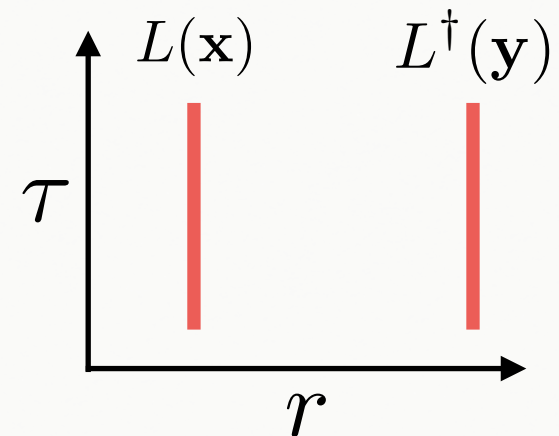
$$W(r, \tau)$$

$V(r)$ and $F(r)$ equivalent at $T = 0$,
but $V(r)$ requires less computations

$$aV_s(na) = \lim_{n_\tau \rightarrow \infty} \ln \frac{\langle W_s(n, n_\tau) \rangle}{\langle W_s(n, n_\tau + 1) \rangle}$$

Static potential $V(r)$

$T > 0$: Polyakov loop correlator

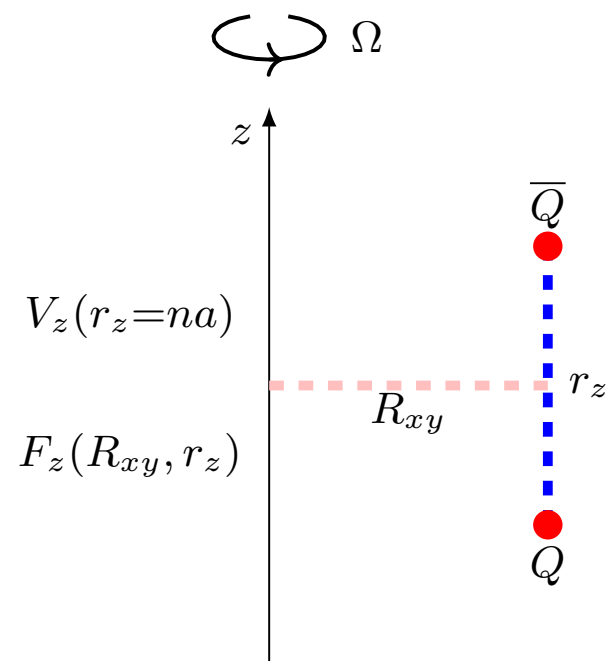


$$F(r) = -T \ln \langle L(\mathbf{x}) L^\dagger(\mathbf{y}) \rangle$$

Free energy $F(r)$

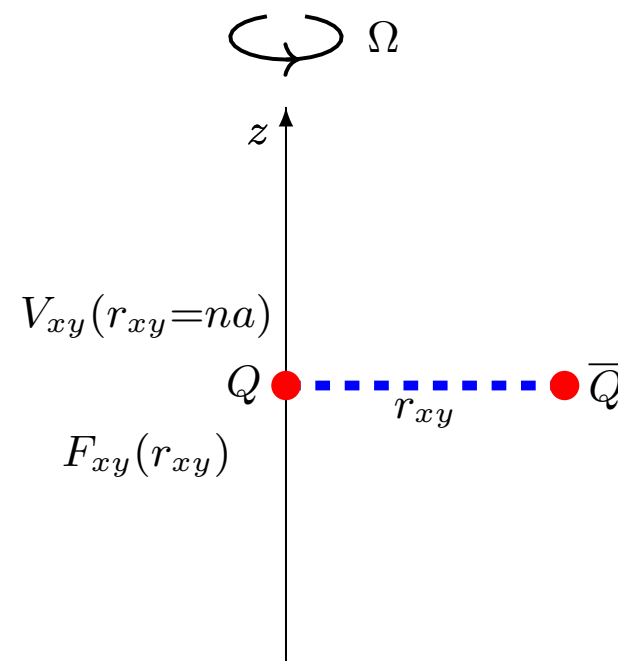
Static $Q\bar{Q}$ observables directly probe how
rotation modifies confinement and screening

Three geometries



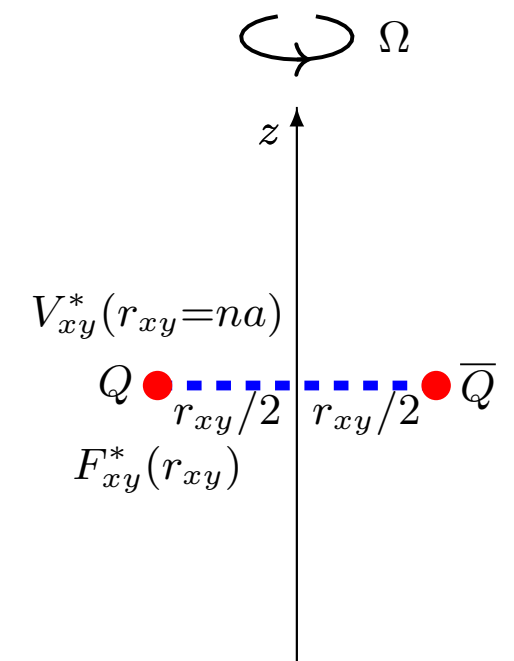
Orientation

Parallel or transverse to Ω ?



Separation

How far apart are Q and $\bar{Q}$?



Radial position

How far from the axis?

Rotation breaks the usual geometric equivalence of static Q - $\bar{Q}$ configurations

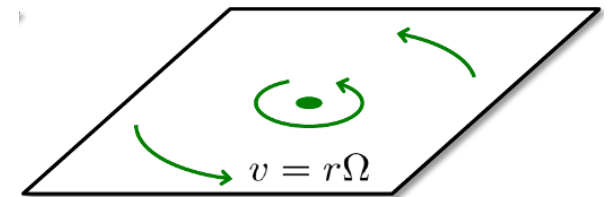
Workflow on the lattice

1. Background

Generate quenched SU(3) gauge configurations with rotation at Ω_I

2. Boundaries

PBC in Euclidean time τ and z , OBC in x and y



3. Measurements

Wilson loops at $T \simeq 0$, polyakov loop correlators at $T > 0$

4. Geometries

Longitudinal, on-axis transverse, and symmetric-transverse pairs

5. Boundary control

Identify a bulk region where boundary effects are negligible

6. Scan the response

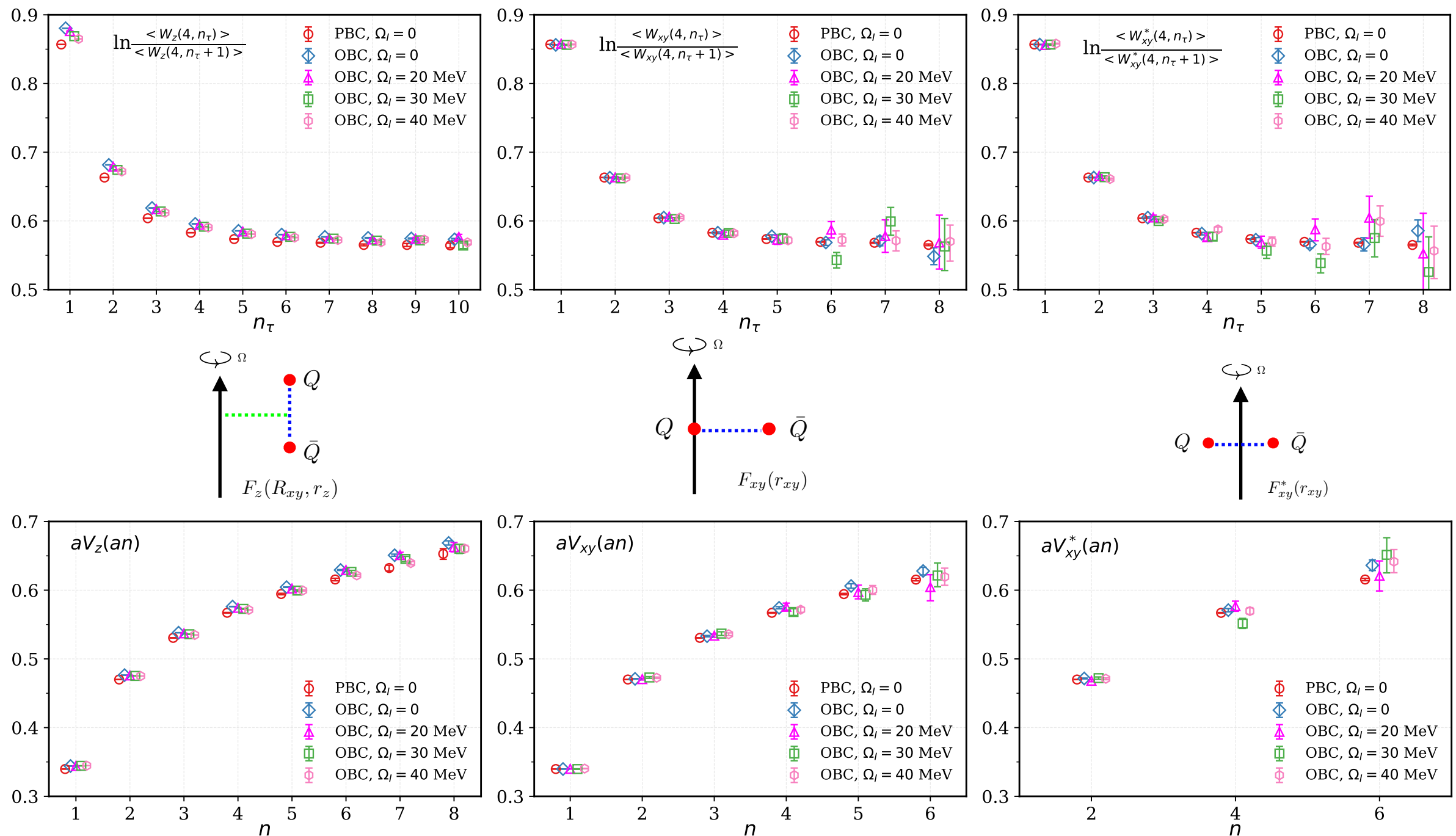
Dependence on Ω_I , temperature, separation and radius

Lattice setup

N_t	β	T/T_c	Ω_I [MeV]						
			0	10	15	20	25	30	40
64	6.5	~ 0	PBC:9 OBC:1	-	-	1	-	1	2
8	6.1	1.02	100	20	20	20	30	20	-
	6.12	1.05	100	20	20	20	30	20	
	6.14	1.09	100	40	20	20	30	20	
	6.17	1.14	100	20	20	40	30	20	
	6.2	1.19	100	20	40	40	32	40	
	6.3	1.38	100	20	40	10	24	40	

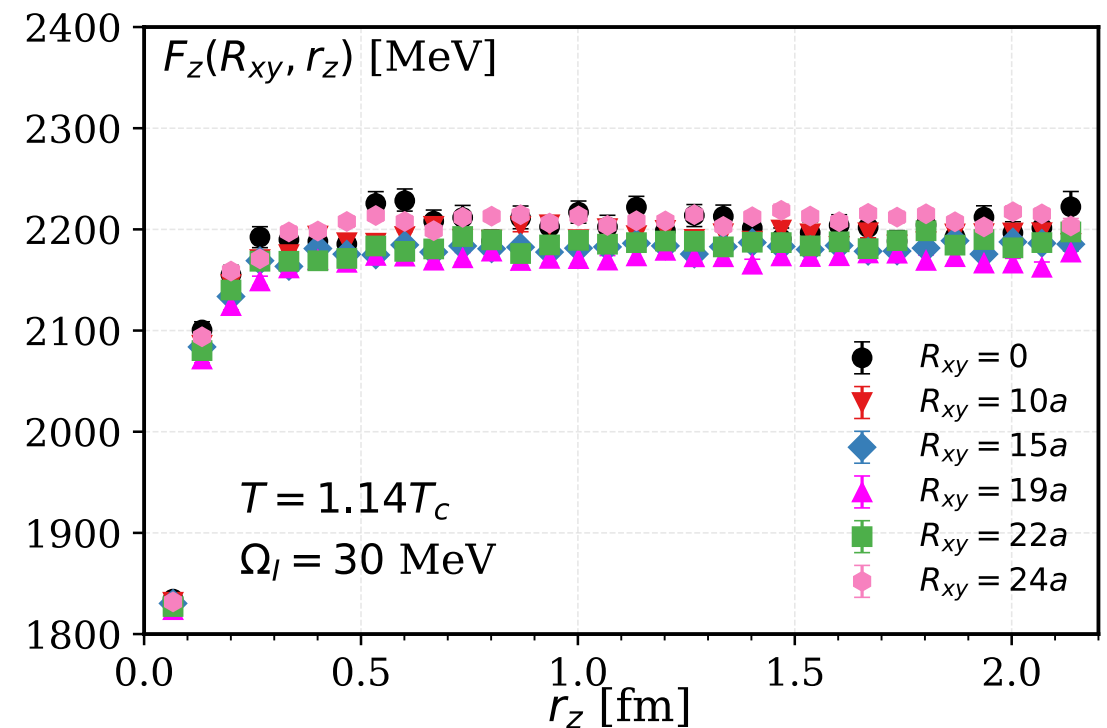
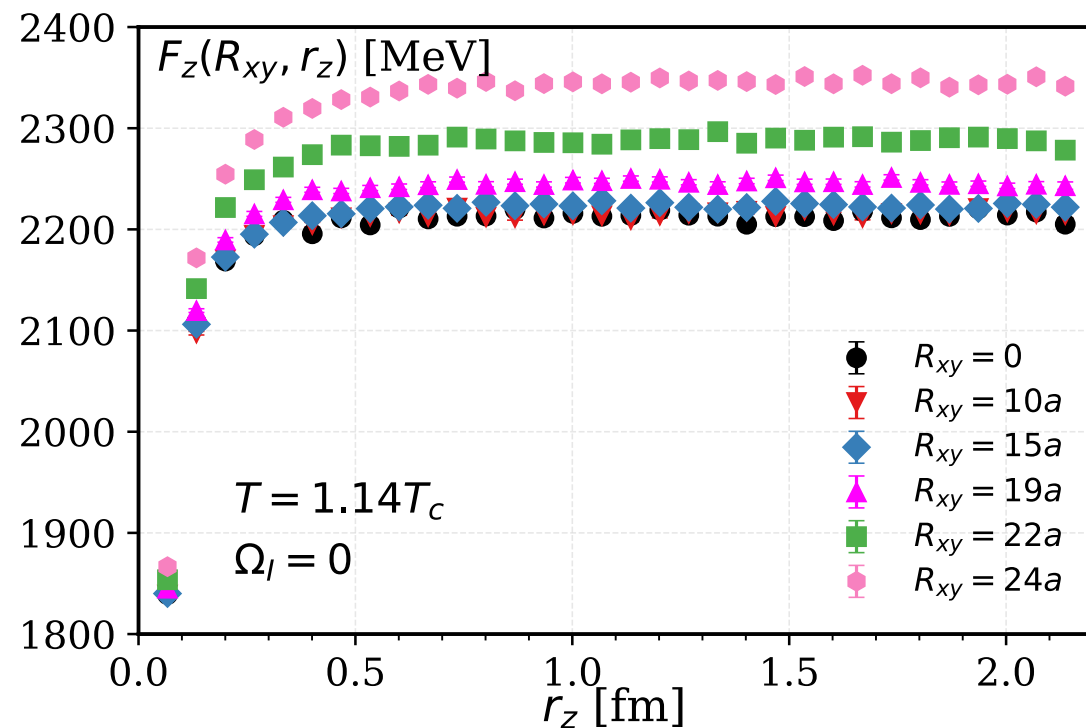
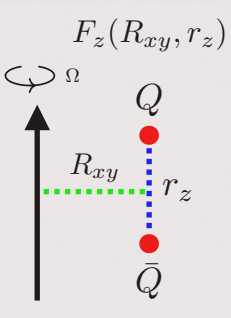
- No. of configurations in units of 1000
- One lattice spacing for each temperature
- Both zero and nonzero velocities at each temperature
- Focus on vicinity of T_c

$V(T = 0)$: no visible rotational effect



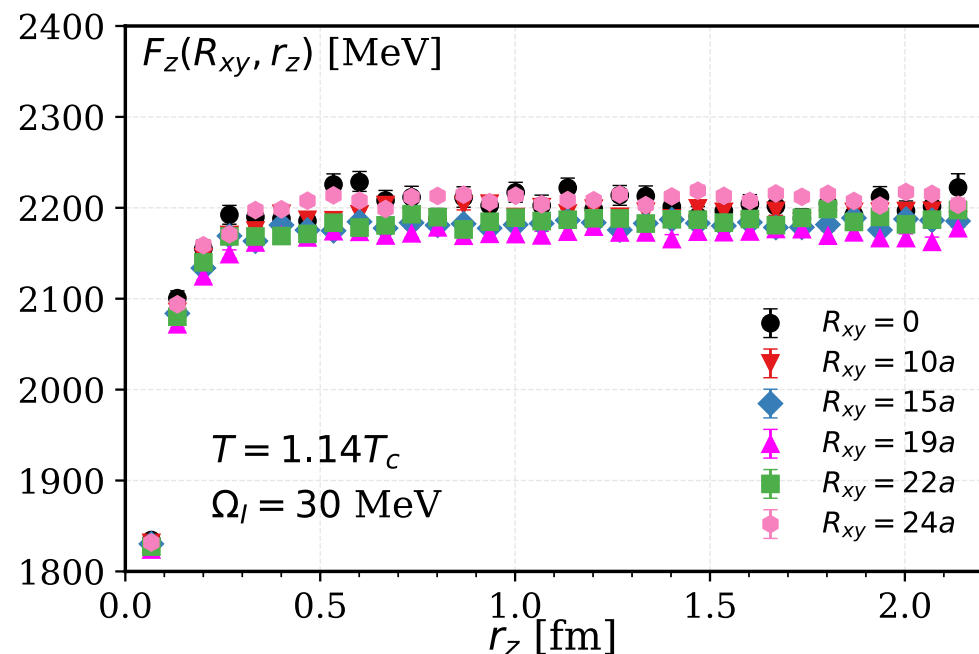
- Clear plateaus allow a **stable extraction** of the static potential
- OBC and PBC results at $\Omega_I = 0$ agree within errors $\rightarrow$ **boundary effects are mild**
- **No significant dependence on Ω_I** is resolved up to 40 MeV
- V_z , V_{xy} , and V_{xy}^* agree within uncertainties $\rightarrow$ no rotation-induced anisotropy

$F_z(R_{xy}, r_z)$: distance-dependent screening



- At fixed R_{xy} , $F_z(R_{xy}, r_z)$ approaches a plateau at large r_z
- Without rotation, the plateau already shows a strong R_{xy} dependence (OBC effects)
- With rotation, plateau values change, and spread with R_{xy} reduces
- At $T > 0$, free energy is sensitive to both r_z and R_{xy}

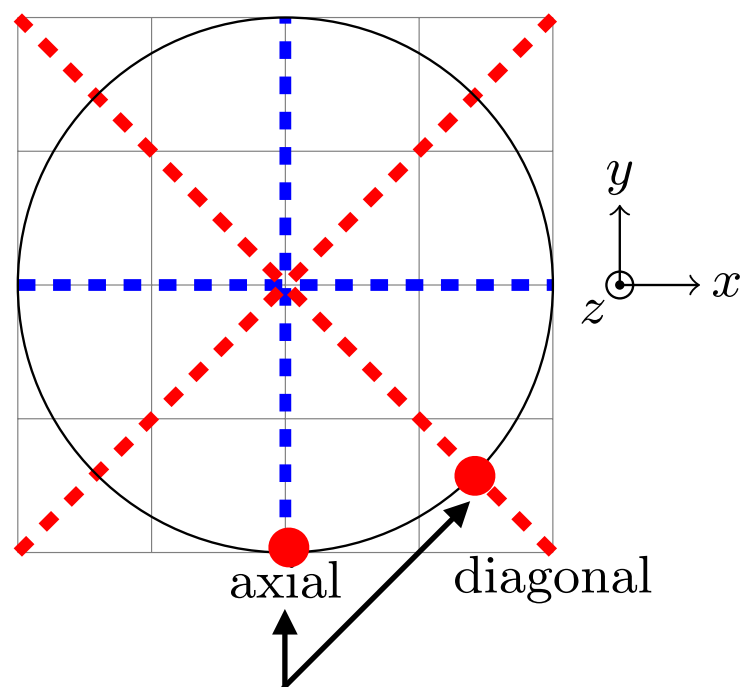
$F_z(R_{xy}, r_z)$: disentangle different effects



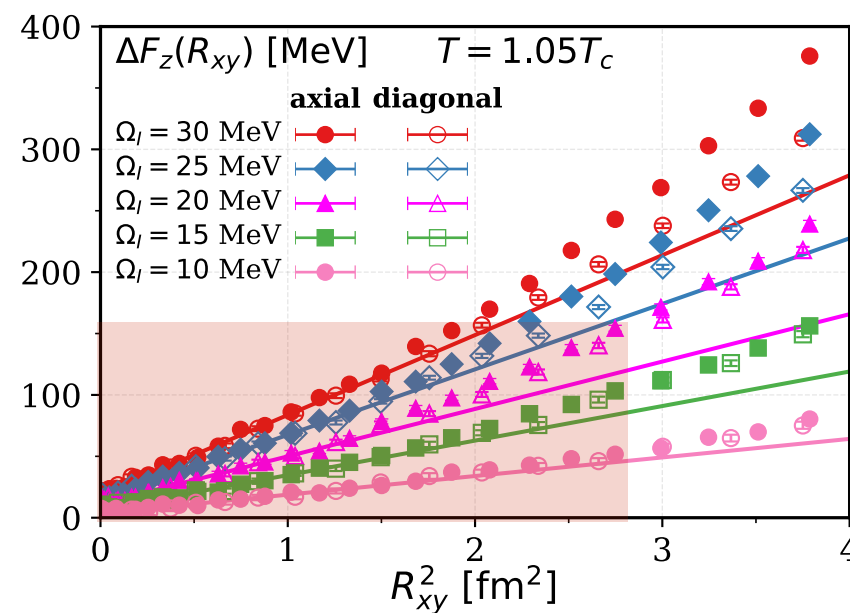
$F_z(R_{xy}, r_z)$ Depends on r_z and R_{xy} , with OBC contamination

- $r_z \rightarrow \infty$: removes the finite-separation dependence
- Subtract $\Omega_I = 0$: isolates the rotation-induced shift from backgrounds

$$\Delta F_z(R_{xy}) \equiv F_z(R_{xy}, \infty)|_{\Omega_I=0} - F_z(R_{xy}, \infty)|_{\Omega_I \neq 0}$$

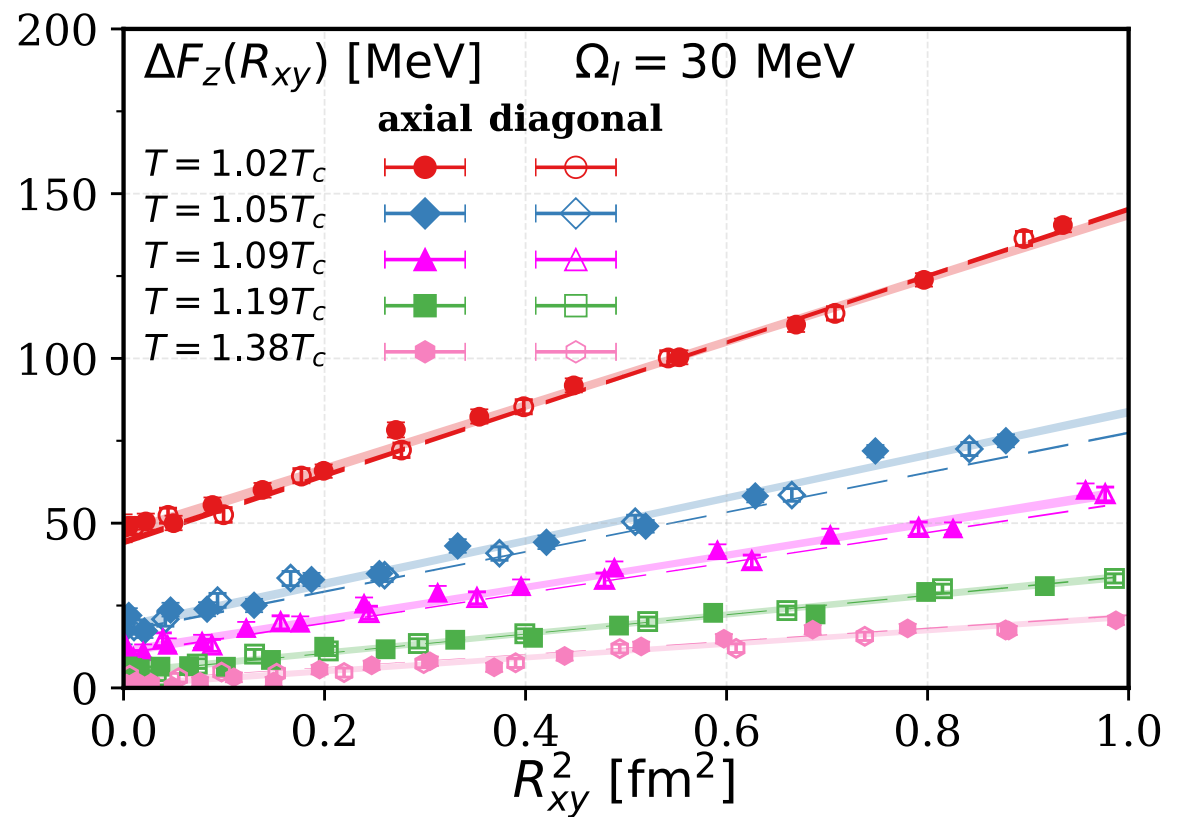
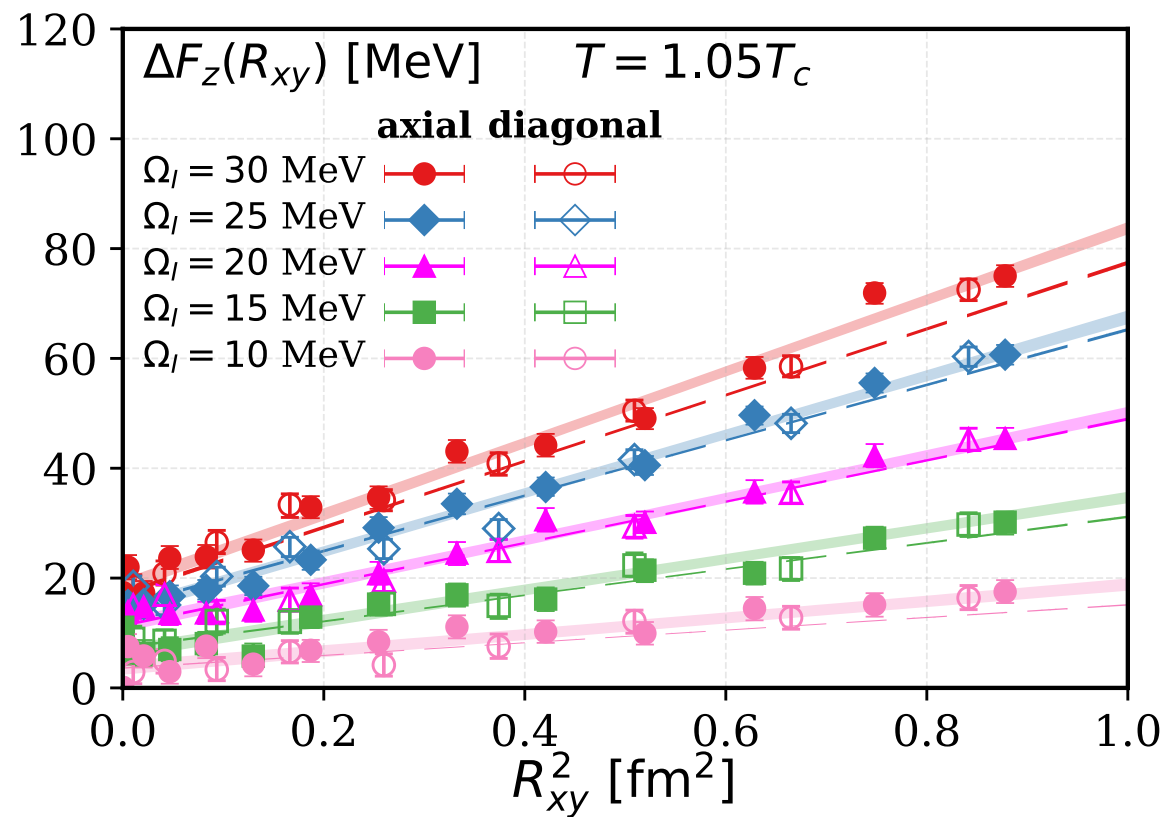


- Same R_{xy} , different boundary sensitivity



- Agreement at small R_{xy} defines the bulk region

$\Delta F_z(R_{xy})$: quadratic radial dependence

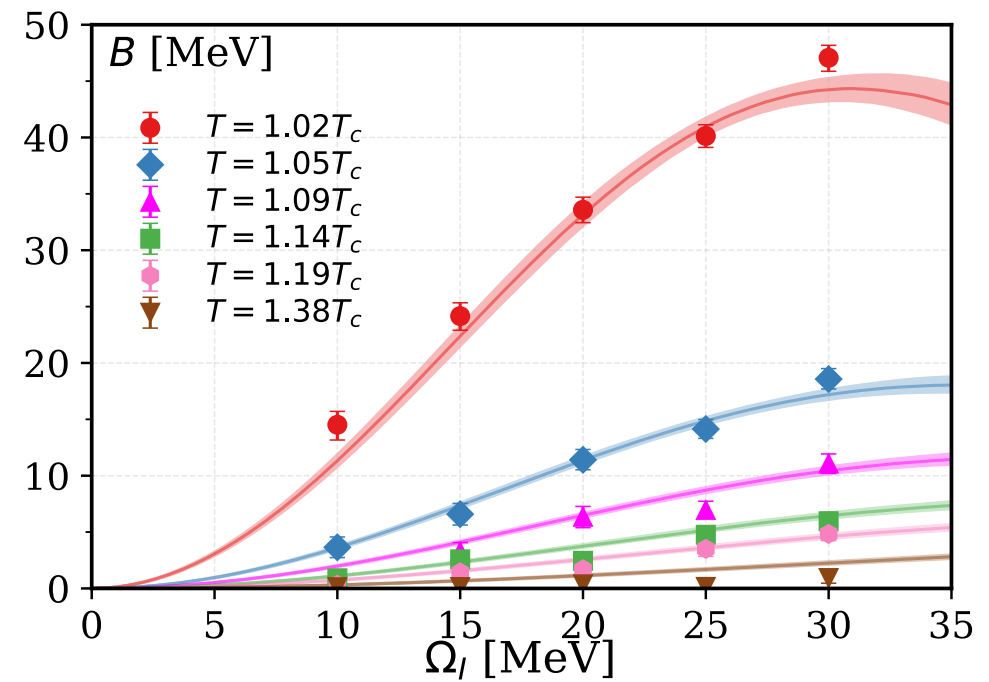
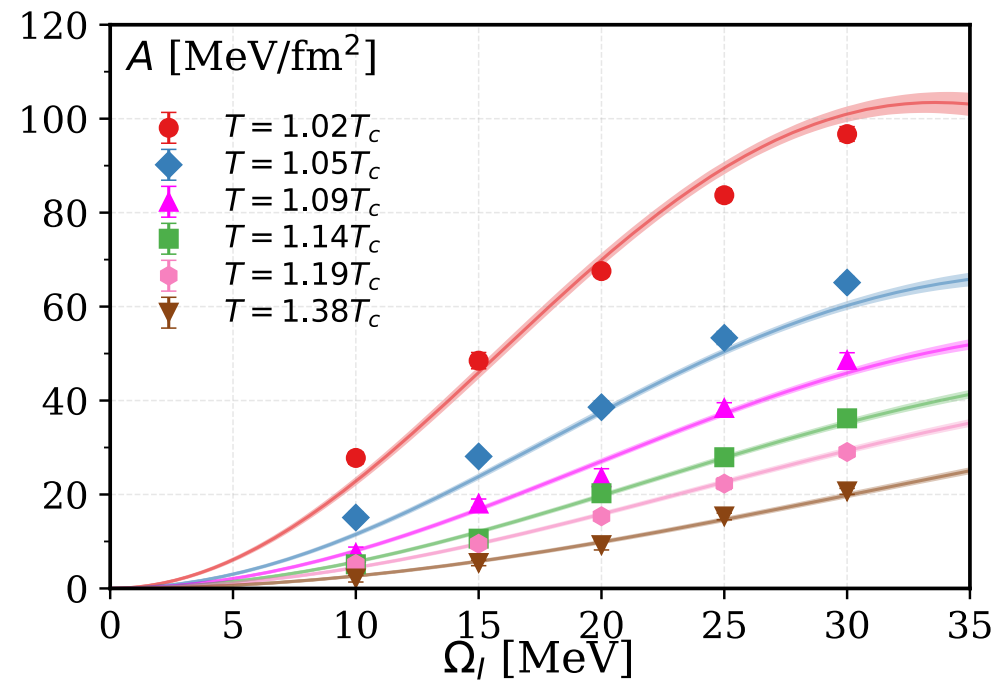


Symmetry under $\Omega \rightarrow -\Omega$: $\Delta F_z(R_{xy}) = \Omega_I^2 [c_2(T)R_{xy}^2 + c_0(T)]$

Global (dashed) and separate (solid) fit: $\Delta F_z(R_{xy}) = AR_{xy}^2 + B$

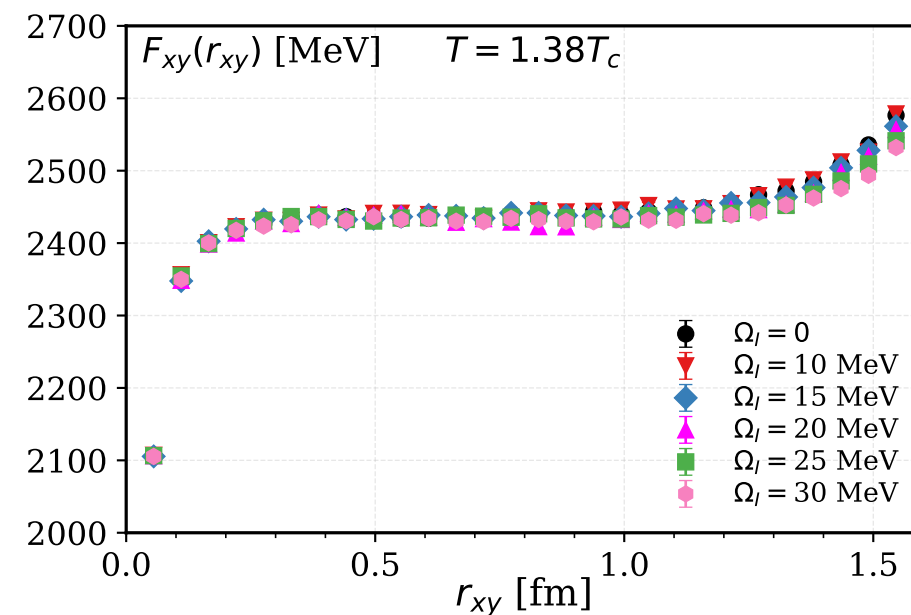
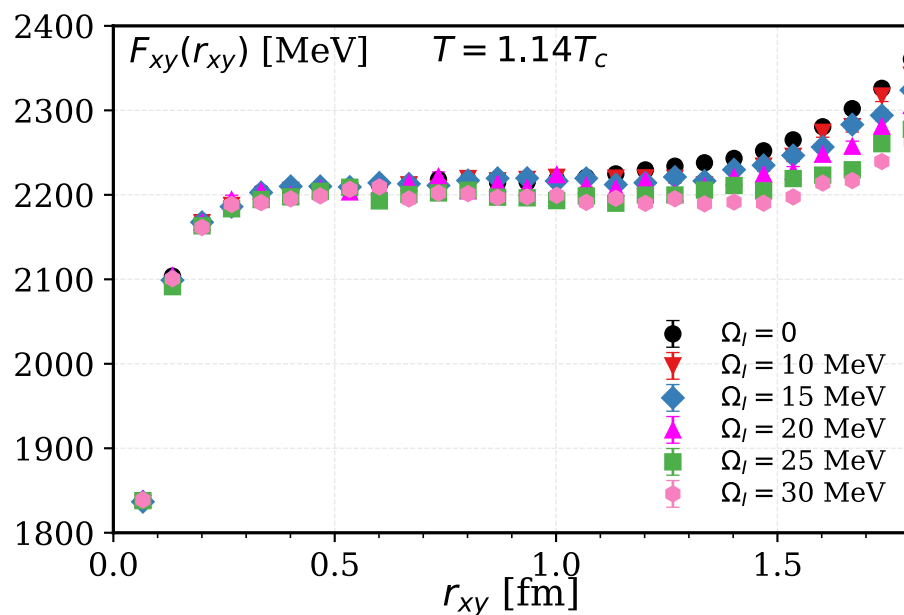
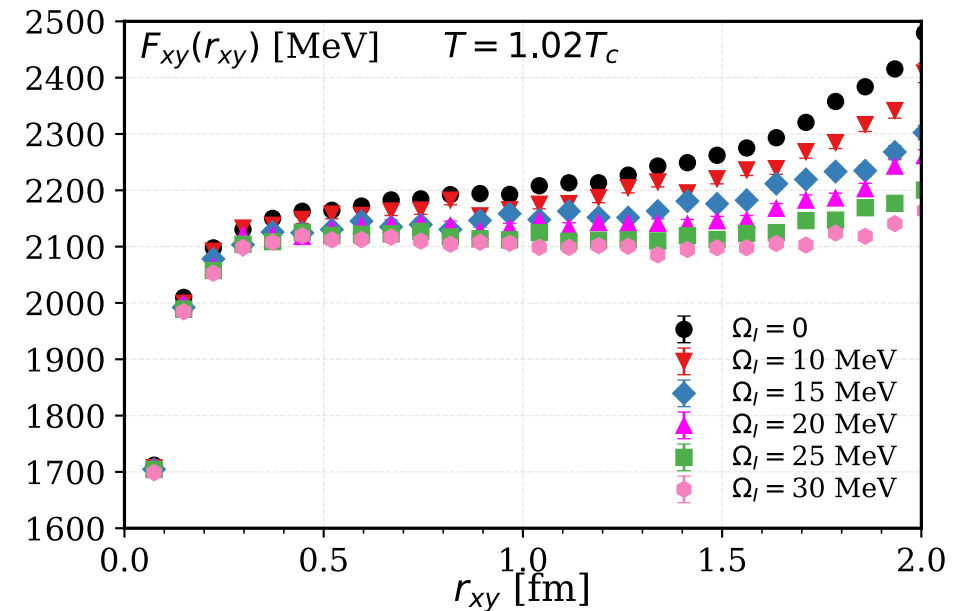
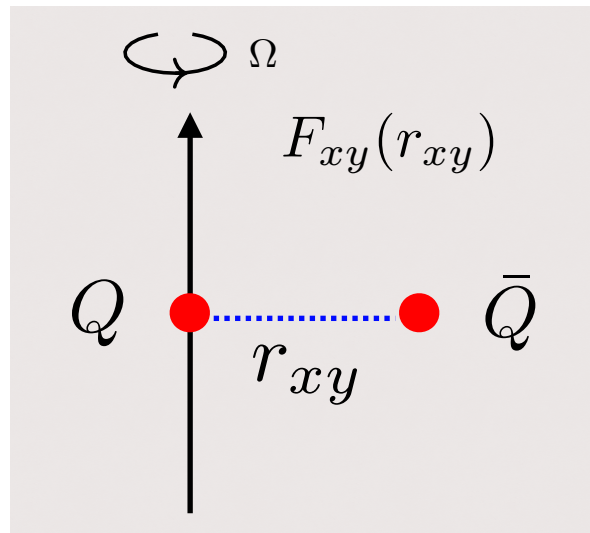
Consistent with the expected small- Ω_I expansion that predicts R_{xy}^2 dependence

$\Delta F_z(R_{xy})$: stronger rotation response near T_c



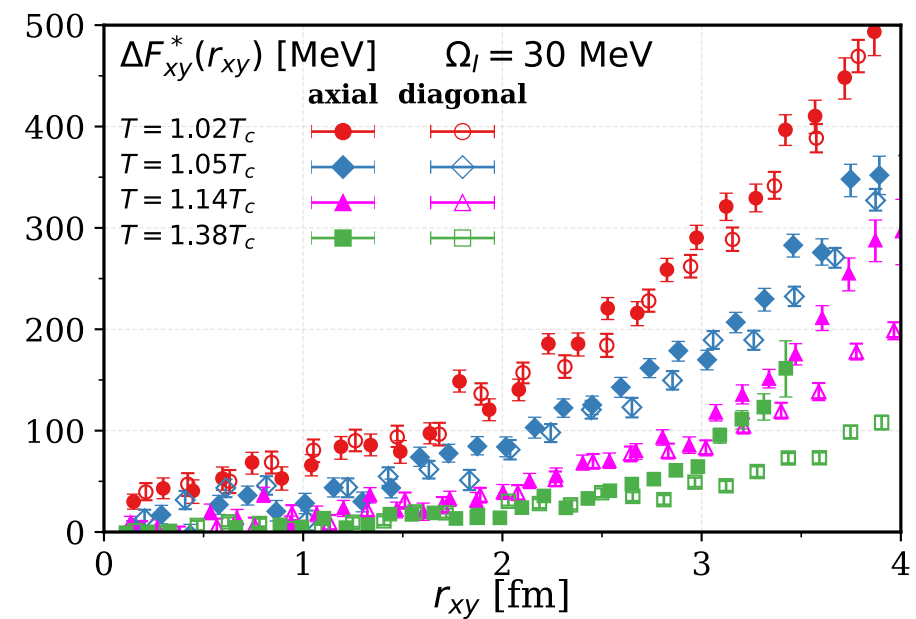
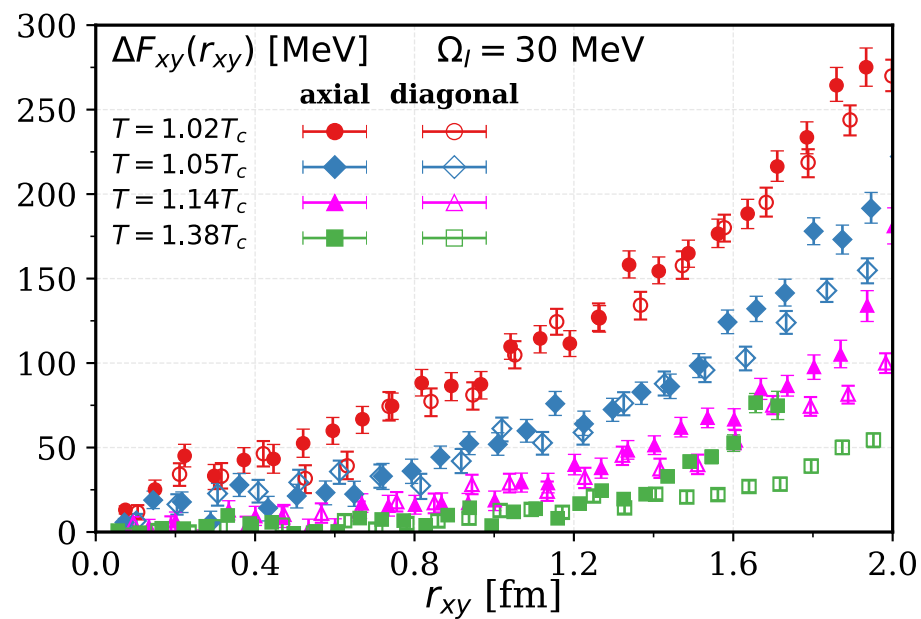
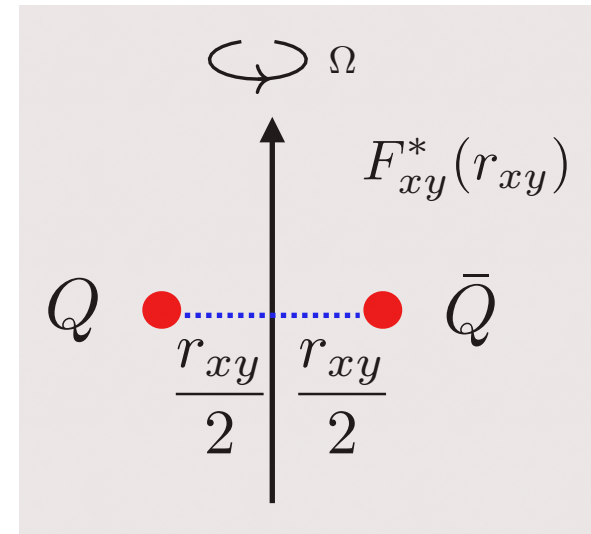
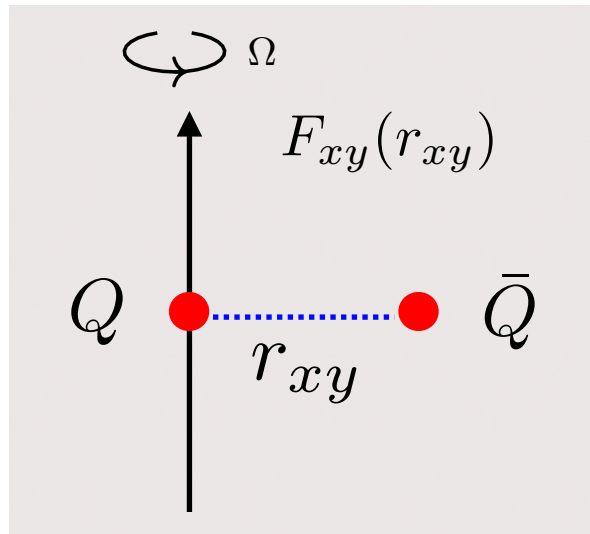
- Both A and B increase with Ω_I , but decrease with T
- Rotation response is strongest near T_c

$F_{xy}(r_{xy})$: suppressed by rotation



- $F_{xy}(r_{xy})$ decreases with increasing Ω_I
- Effect strongest near T_c , and weakens at higher T
- Same pattern as longitudinal channel

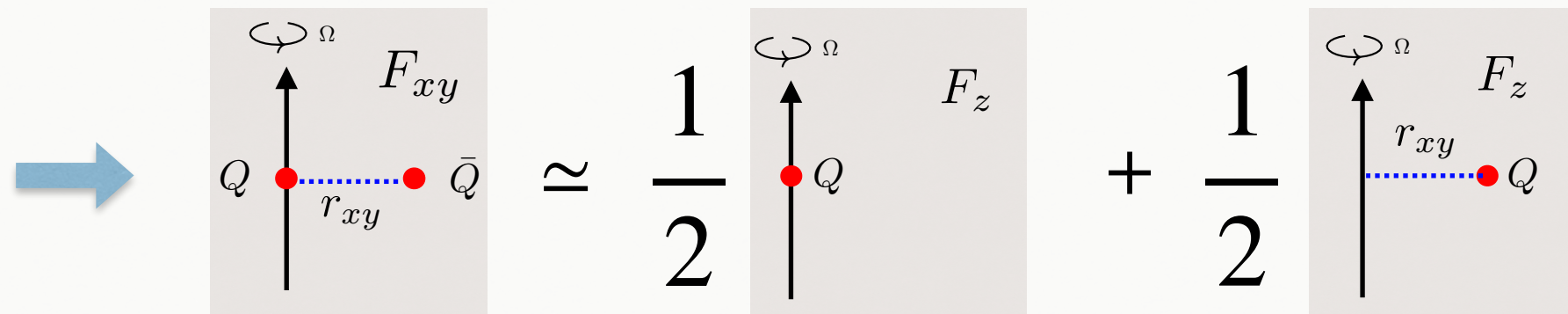
$\Delta F_{xy}(r_{xy})$ v.s. $\Delta F_{xy}^*(r_{xy})$



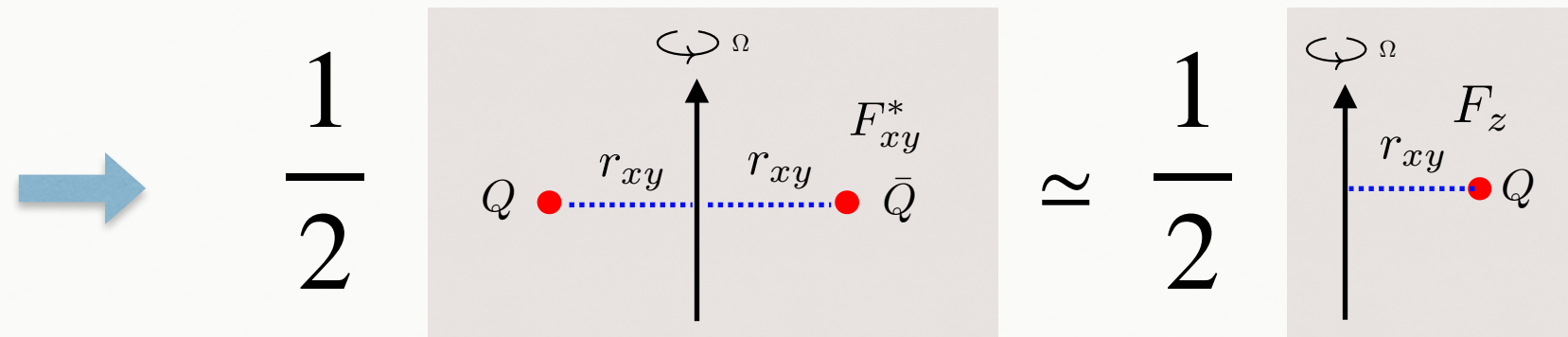
- Both shifts decrease with increasing T
- $\Delta F_{xy}^* > \Delta F_{xy}$ at comparable r_{xy}
- Response depends on radial arrangement

Single-source factorization

Single-source factorization at large separation: $F_Q(R_{xy}) \equiv \frac{1}{2} F_z(R_{xy}, \infty)$



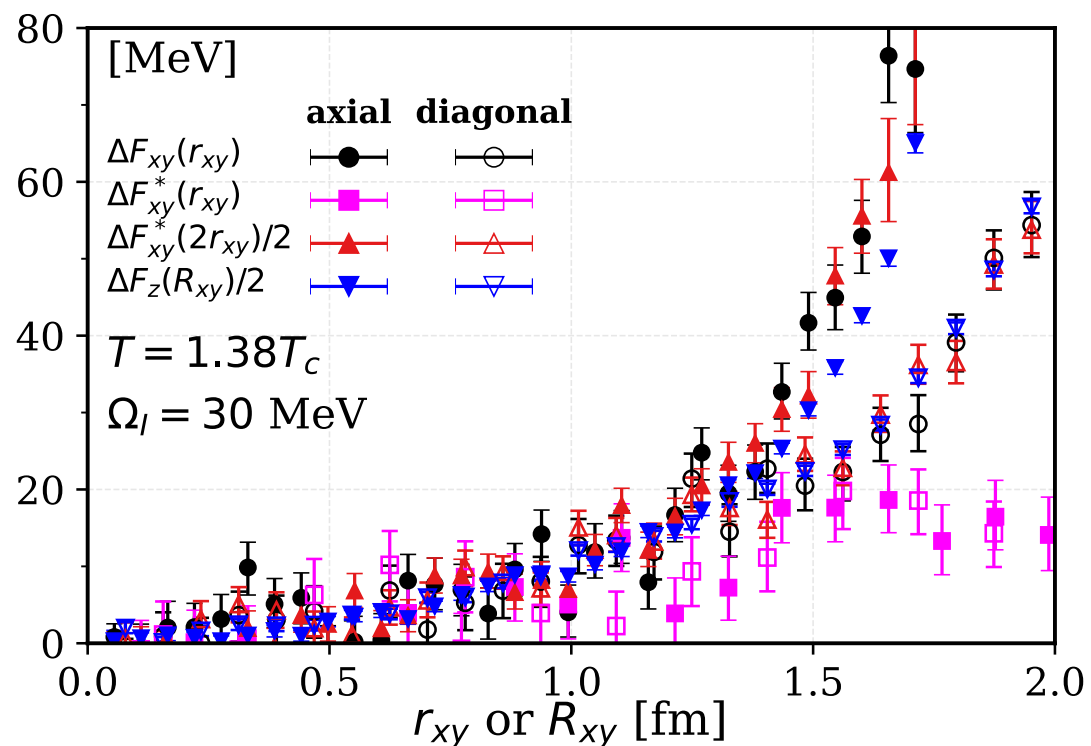
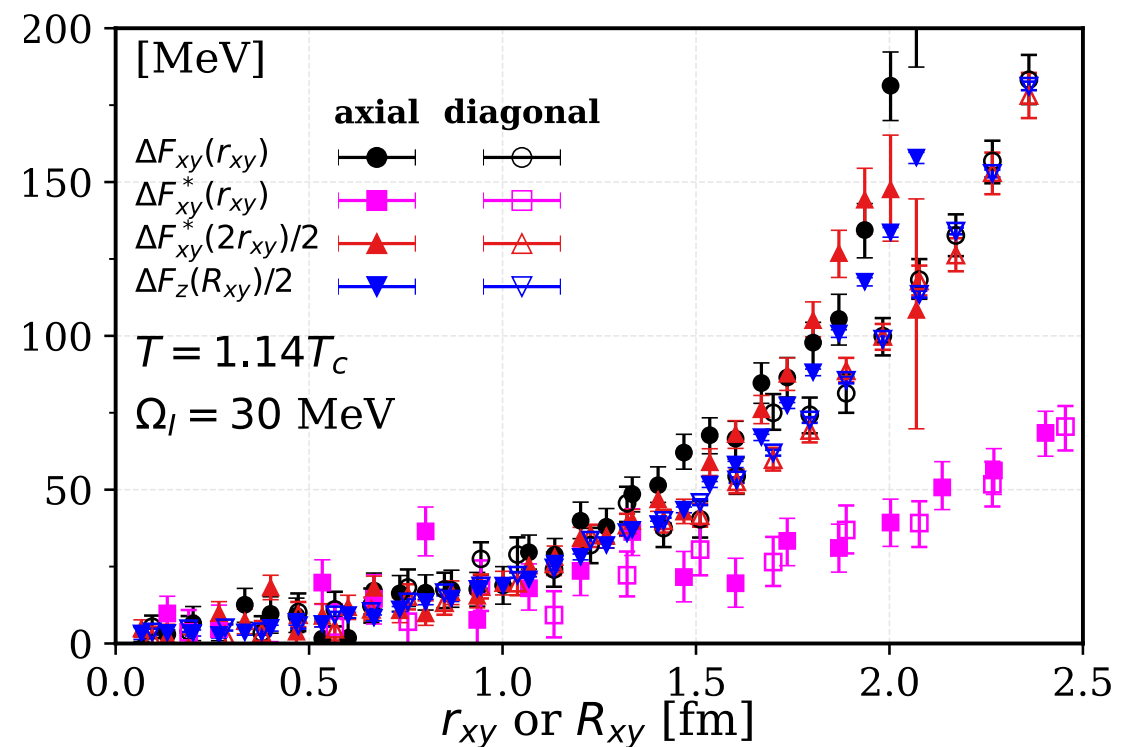
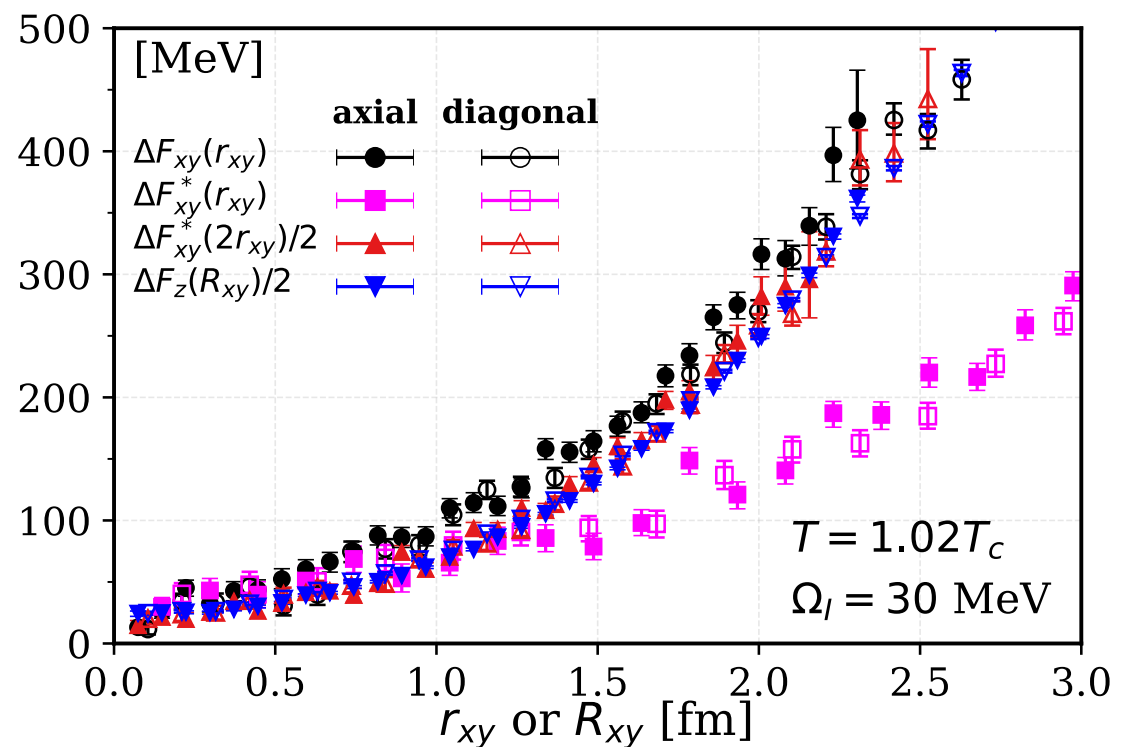
$$\Delta F_{xy}(r_{xy}) \simeq \frac{1}{2} [\Delta F_z(R_{xy} = 0) + \Delta F_z(R_{xy} = r_{xy})]$$



$$\frac{1}{2} \Delta F_{xy}^*(2r_{xy}) \approx \frac{1}{2} \Delta F_z(R_{xy} = r_{xy})$$

- Single-source factorization suggests scaling relations among the three geometries

Single-source scaling



- $\Delta F_{xy}^*(2r_{xy}) \approx \Delta F_z(R_{xy} = r_{xy})$ in the bulk region
- Supports the single-source interpretation
- Agreement persists across temperatures
- Deviations at large distance reflect growing OBC contamination

Conclusion

- ✓ $T \simeq 0$: no significant Ω_I dependence or anisotropy within present accuracy
- ✓ $T > T_c$: imaginary rotation suppresses the static free energies
- ✓ Longitudinal response: $\Delta F_z(R_{xy}) \sim R_{xy}^2 + \text{const.}$ in the bulk region
- ✓ Transverse response: sensitive to the radial arrangement of the static sources
- ✓ Bulk data are compatible with a radial single-source free-energy shift
- ✓ Rotation response is strongest near T_c and weakens at higher T