Theoretical aspects of spin physics at JINR

MexNICA Collaboration Winter meeting 2020

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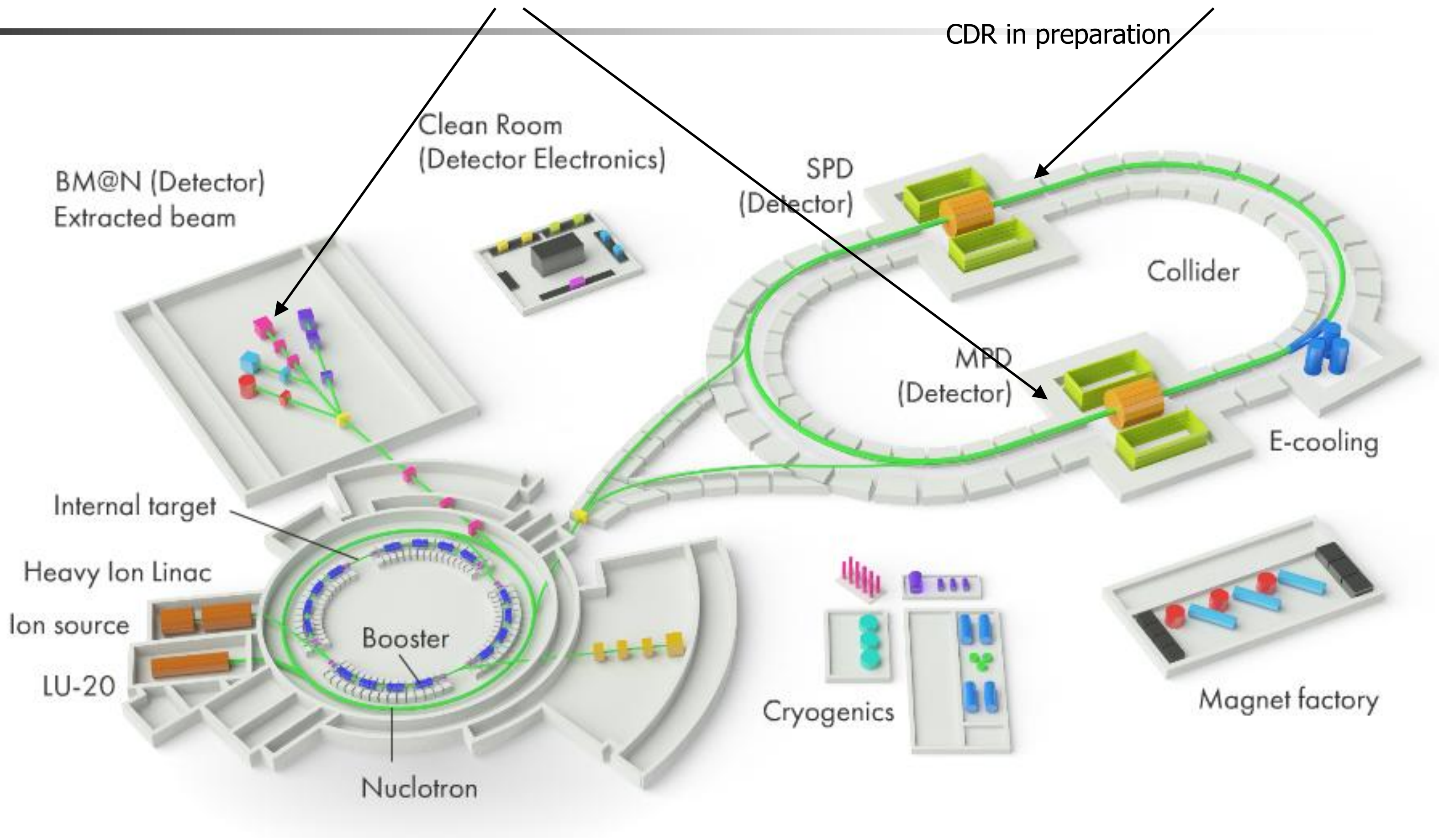
Outline

- Spin@NICA
- QCD factorization and hadron spin structure: types of spin-dependent NPQCD functions
- Single Spin Asymmetries in QCD - Sources of (I)FSI
- Hadronic vs Heavy-Ion physics: Scattering vs Reaction palne; FSI vs Dissipation
- Problems for NICA

Joint Institute for Nuclear Research, Dubna

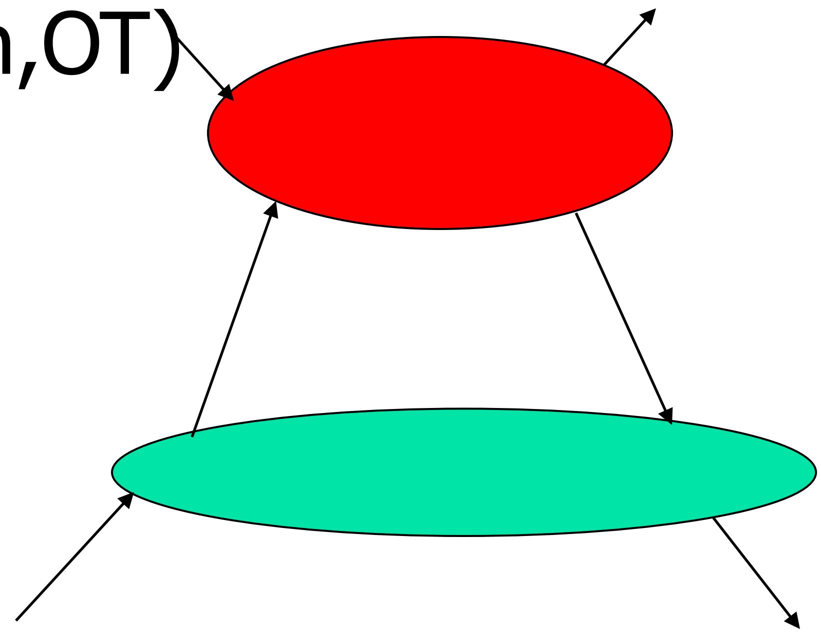
NICA: heavy ions and hadrons

CDR in preparation



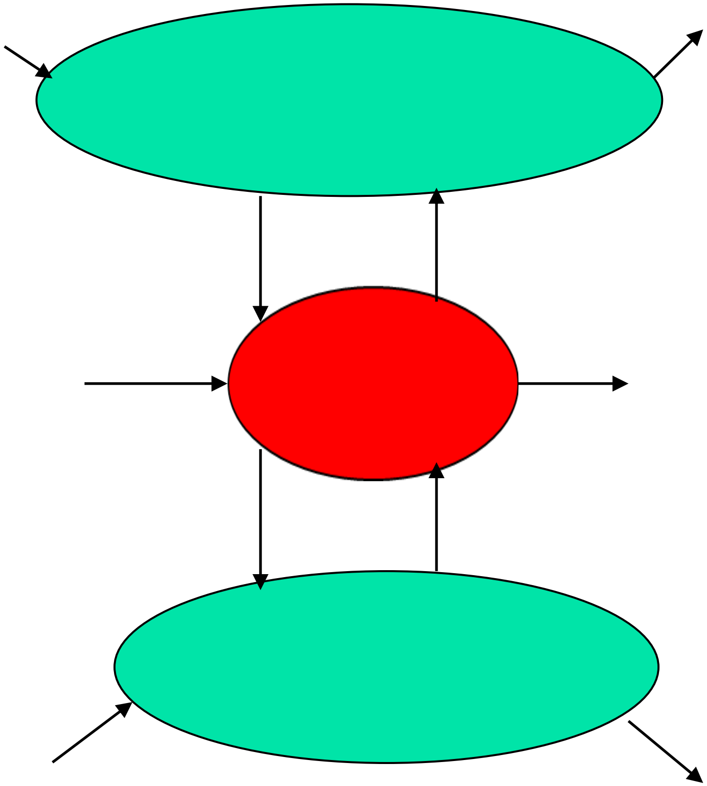
Factorization (lh-> DIS, DVCS)

- Short and large distances separated (JINR – Efremov, Radyushkin; Spin, Higher twist – Efremov,OT; DVCS- Anikin,OT)



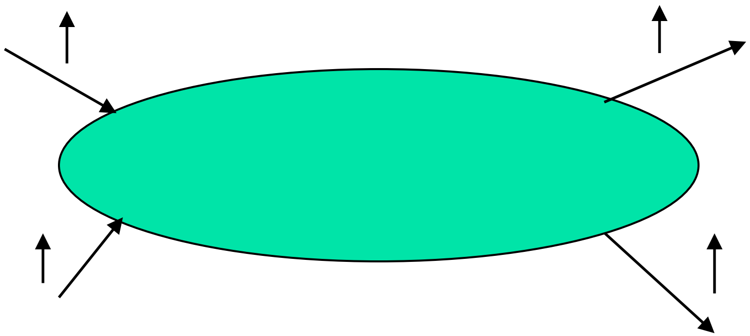
Factorization for DY – type Inclusive and Exclusive

- 2 hadrons participate



Types of parton distributions

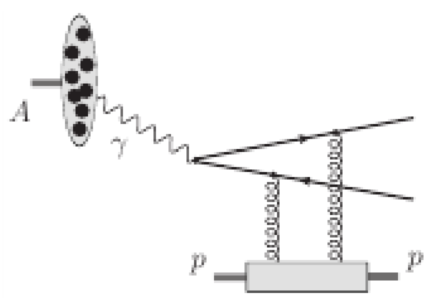
- Most general – Wigner function: non-symmetric partonic and hadronic momenta with transverse components
- Elliptic component related to elliptic flow



- The spin of both hadrons and partons fixed

Measurement of Wigner (GTMD) function

- Small x – lp (Hatta,Xiao,Yuan’16) or Ap UP (Hagiwara, Hatta, Pasechnik, Tasevsky, OT’17) collisions



- Larger x – UPC at SPD !?

Types of parton distributions - II

- Too rich structure of Wigner function
- Simplifications – Putting some (transverse) momenta to zero or average over some variables
- Hadronic moments equal - inclusive
- Allow for proof of QCD factorization is some cases (perturbative corrections are taken into account by some kind of evolution)

Collinear vs k_T factorization

- Collinear: NP longitudinal and pQCD transverse (GLAPD) evolution
- BFKL (also perturbative origin!) NP transverse and pQCD longitudinal evolution
- GI for off-shell partons? $(xP+ k_T)^2 < 0$
- Special BFKL vertices, effective action

TMD factorization

- BFKL (with non-linear unitarizaing modifications – CGC, BK) – low x regions
- k_T for larger x (relevant for SPD) – TMD factorization
- Another approach to GI: transverse momentum only in parton distributions
- Transition? Application of effective action at larger x
- Possible reason (Soffer,OT) : convex $x^a(1-x)^b$
- Approximate validity of Regge ~ x^a at rather large x~0.1

TMDs and GPDs

- Hadronic and partonic transverse momenta
- Variables $k_T^{\ 2}$ vs t
- Models (AdS/QCD) using overlap of LCWF – relation (Maji, Mondal, Chakrabarti, OT'15)

$$\frac{\partial}{\partial|t|}[\ln(\mathrm{GPD})] = \frac{(1-x)^2}{4}\frac{\partial}{\partial p_\perp^2}[\ln(\mathrm{TMD})].$$

Special interest to GPDs: pressure in proton

- Universal concept at all scales
- Similarity to stable macroscopic objects in all known cases
- Transition to HIC – similarity to hadronic physics (c.f. “Ridge”): small systems

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NATURE | www.nature.com/nature

https://doi.org/10.1038/s41586-018-0060-z

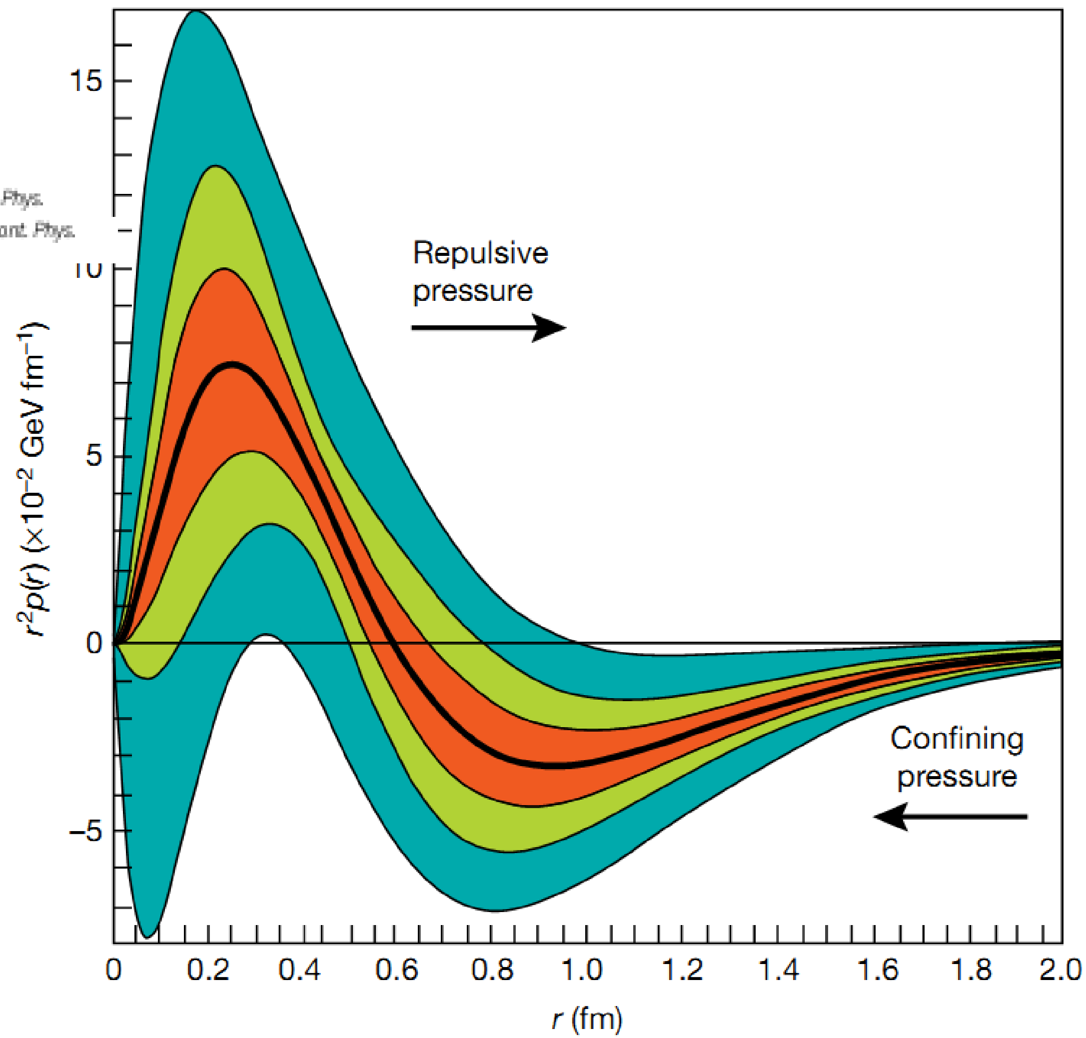
The pressure distribution inside the proton

V. D. Burkert[1]*, L. Elouadrhiri[1] & F. X. Girod[1]

5. Teryaev, O. V. Gravitational form factors and nucleon spin structure. *Front. Phys.*

5. Teryaev, O. V. Gravitational form factors and nucleon spin structure. *Front. Phys.* **11**, 111207 (2016).

15. Anikin, I. V. & Teryaev, O. V. Dispersion relations and QCD factorization in hard reactions. *Fizika B* **17**, 151–158 (2008).



Pressure –related to D-term (Poyakov'03) and to holographic SR (OT'05)

- Directly follows from double distributions

$$H(z,\xi) = \int_{-1}^{1} dx \int_{|x|-1}^{1-|x|} dy (F(x,y) + \xi G(x,y)) \delta(z - x - \xi y)$$

- Constant is the SUBTRACTION one - due to the (generalized) Polyakov-Weiss term G(x,y)

$$\Delta\mathcal{H}(\xi) = \int_{-1}^{1} dx \int_{|x|-1}^{1-|x|} dy \frac{G(x,y)}{1-y}$$

$$= \int_{-\xi}^{\xi} dx \frac{D(x/\xi)}{x - \xi + i\epsilon} = \int_{-1}^{1} dz \frac{D(z)}{z-1} = const$$

Also for exclusive DY! – OT'05 and work in progress

SR in energy plane (Anikin,OT'07)

- Finite subtraction implied

$$\mathrm{Re}\,\mathcal{A}(\nu, Q^2) = \frac{\nu^2}{\pi}\mathcal{P}\int_{\nu_0}^{\infty}\frac{d\nu'^2}{\nu'^2}\frac{\mathrm{Im}\,\mathcal{A}(\nu', Q^2)}{(\nu'^2-\nu^2)} + \Delta \qquad \Delta = 2\int_{-1}^{1} d\beta\,\frac{D(\beta)}{\beta-1}$$

$$\Delta^p_{\mathrm{CQM}}(2) = \Delta^n_{\mathrm{CQM}}(2) \approx 4.4, \qquad \Delta^p_{\mathrm{latt}} \approx \Delta^n_{\mathrm{latt}} \approx 1.1$$

- Numerically close to Thomson term for real proton (but NOT neutron) Compton Scattering!

- Duality (sum of squares vs square of sum; proton: 4/9+4/9+1/9=1)?!

From D-term to pressure

- Inverse -> 1st moment (model)
- Kinematical factor – moment of pressure C~<p r^4> (<p r^2> =0)

M.Polyakov'03

$$T^{Q}_{\mu\nu}(\vec{r},\vec{s}) = \frac{1}{2E}\int \frac{d^3\Delta}{(2\pi)^3}\, e^{i\vec{r}\cdot\vec{\Delta}}\, \langle p', S'|\hat{T}^{Q}_{\mu\nu}(0)|p, S\rangle$$

$$T_{ij}(\vec{r}) = s(r)\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\,\delta_{ij}\right) + p(r)\delta_{ij}$$

- Stable equilibrium C>0:

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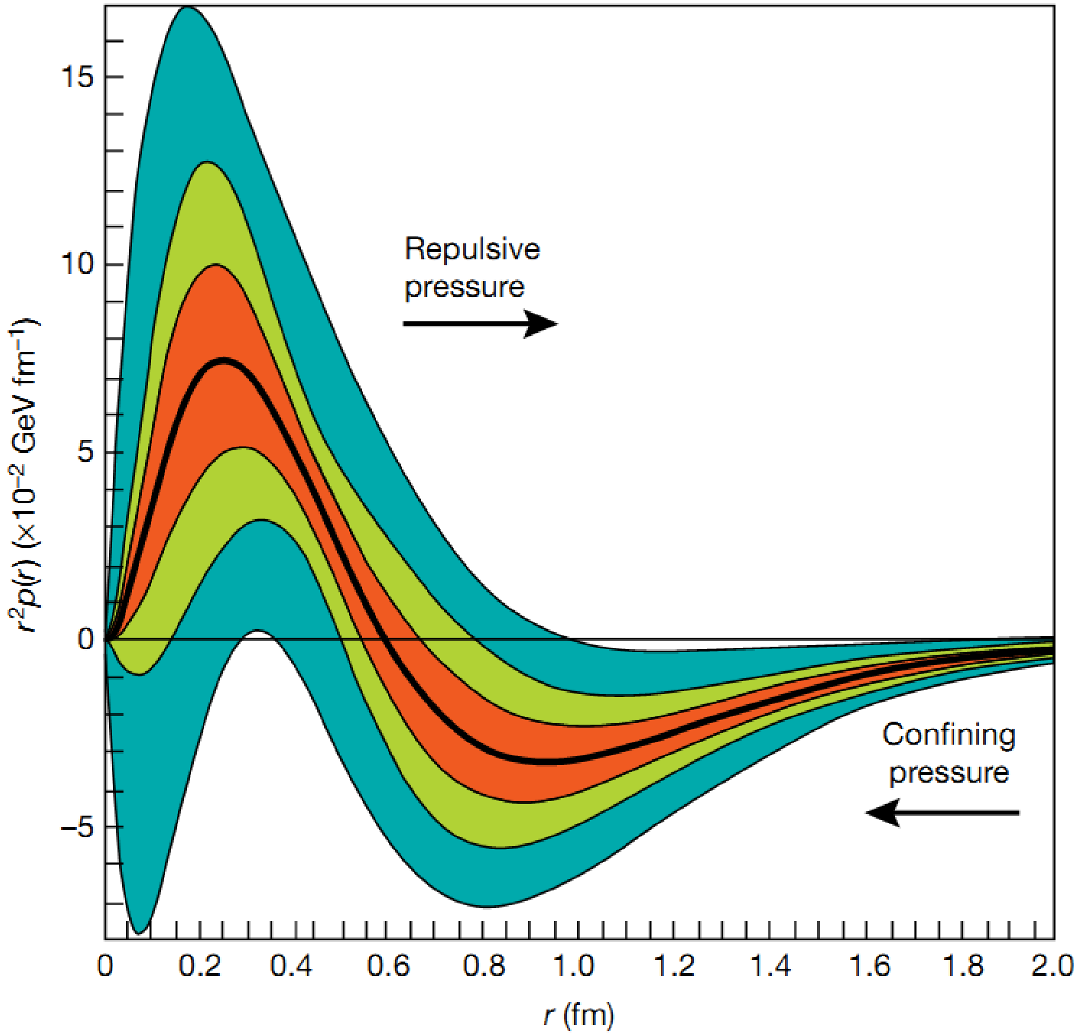
https://doi.org/10.1038/s41586-018-0060-z

The pressure distribution inside the proton

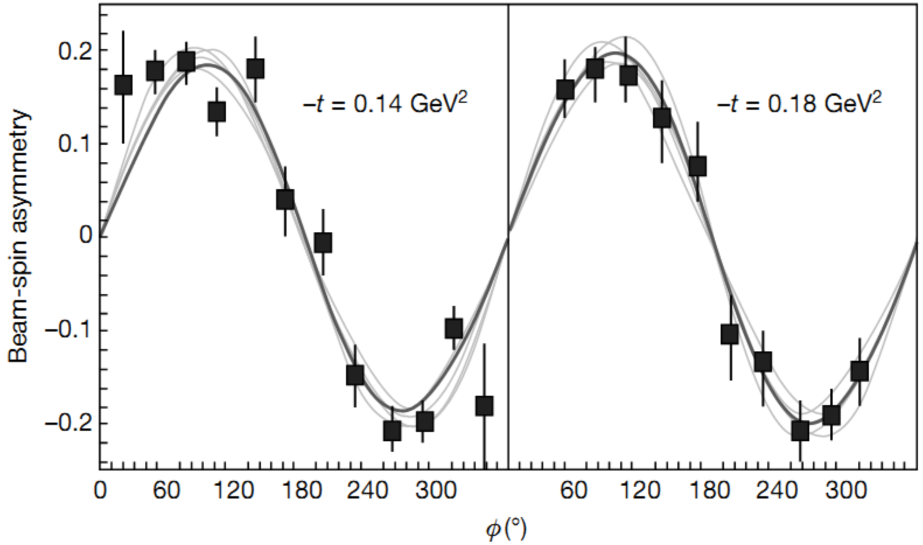
V. D. Burkert[1]*, L. Elouadrhiri[1] & F. X. Girod[1]

- Largest ever ($\sim\Lambda^4$QCD) $\sim 10^{35}$ pascals



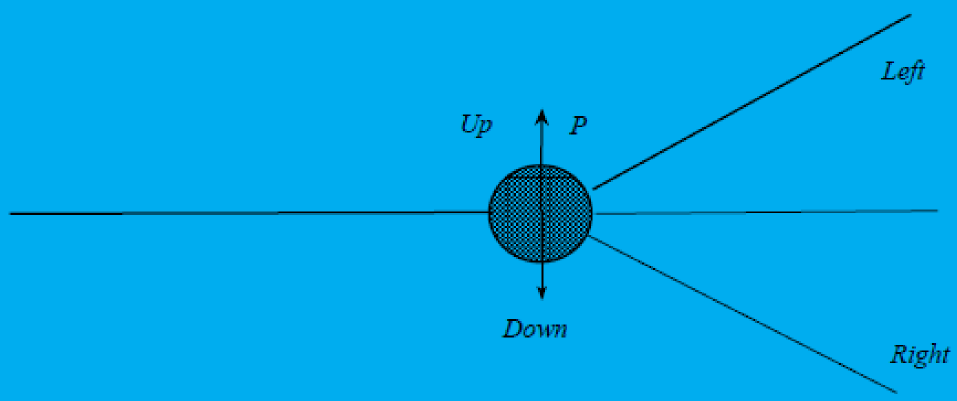
Experiment

- Jlab, TJNAF, CEBAF
- Very accurate data
- Imaginary part from Single Spin Asymmetry



Single Spin Asymmetries: simplest example

Simplest example - (non-relativistic) elastic pion-nucleon scattering $\pi \vec{N} \to \pi N$



$M = a + ib(\vec{\sigma}\vec{n})$ $\vec{n}$ is the normal to the scattering plane.

Density matrix: $\rho = \frac{1}{2}(1 + \vec{\sigma}\vec{P})$,

Differential cross-section: $d\sigma \sim 1 + A(\vec{P}\vec{n})$, $A = \frac{2Im(ab^*)}{|a|^2+|b|^2}$

Single Spin Asymmetries

Main properties:

– Parity: transverse polarization

– Imaginary phase – can be seen from T-invariance or technically - from the imaginary i in the (quark) density matrix

Various mechanisms – various sources of phases

Phases in QCD

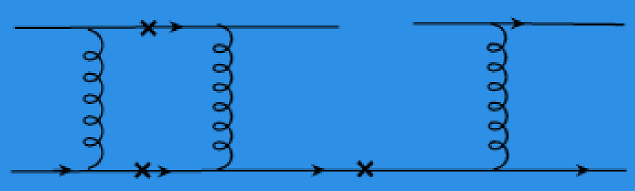
- QCD factorization – soft and hard parts-
- Phases form soft, hard and overlap
- Assume (generalized) optical theorem – phase due to on-shell intermediate states – positive kinematic variable (= their invariant mass)
- Hard: Perturbative (a la QED: Barut, Fronsdal (1960):

Kane, Pumplin, Repko (78) Efremov (78)

Perturbative PHASES IN QCD

QCD factorization: where to borrow imaginary parts?

Simplest way: from short distances - loops in partonic subprocess. Quarks elastic scattering (like $q - e$ scattering in DIS):

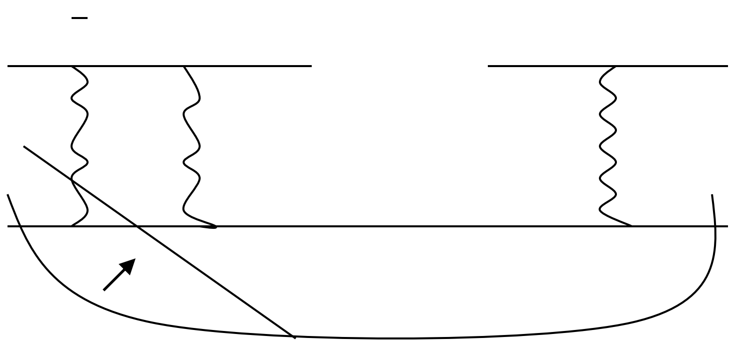


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

Large SSA "...contradict QCD or its applicability"

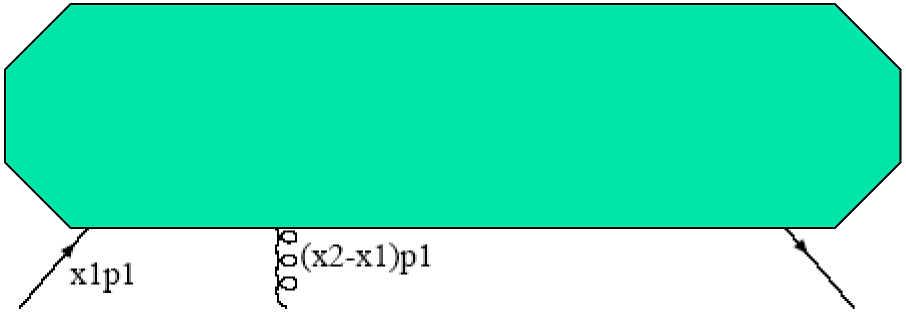
Short+ large overlap– twist 3

- Quarks – only from hadrons
- Various options for factorization – shift of SH separation (prototype of duality)



- New option for SSA: Instead of 1-loop twist 2 – Born twist 3: Efremov, OT (85, Ferminonc poles); Qiu, Sterman (91, GLUONIC poles)

Quark-gluon correlators

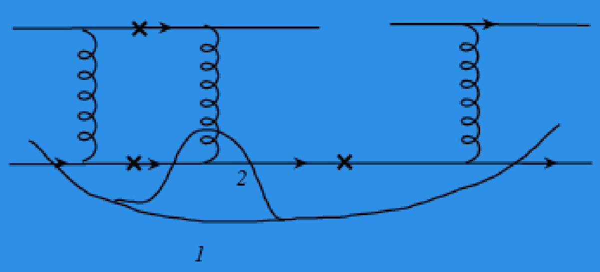


- Non-perturbative NUCLEON structure – physically mean the quark scattering in external gluon field of the HADRON.
- Depend on TWO parton momentum fractions
- For small transverse momenta – quark momentum fractions are close to each other- gluonic pole; probed if :
  $Q >> P_T >> M$

$$x_2 - x_1 = \delta = \frac{p_T^2 x_B}{Q^2 z}$$

Twist 3 correlators

Escape: QCD factorization - possibility to shift the borderline between large and short distances



At short distances - Loop $\rightarrow$ Born diagram

At Large distances - quark distribution $\rightarrow$ quark-gluon correlator.

Physically - process proceeds in the external gluon field of the hadron.

Leads to the shift of α_S to non-perturbative domain AND

"Renormalization" of quark mass in the external field up to an order of hadron's one

$$\frac{\alpha_S m p_T}{p_T^2 + m^2} \rightarrow \frac{M b(x_1, x_2) p_T}{p_T^2 + M^2}$$

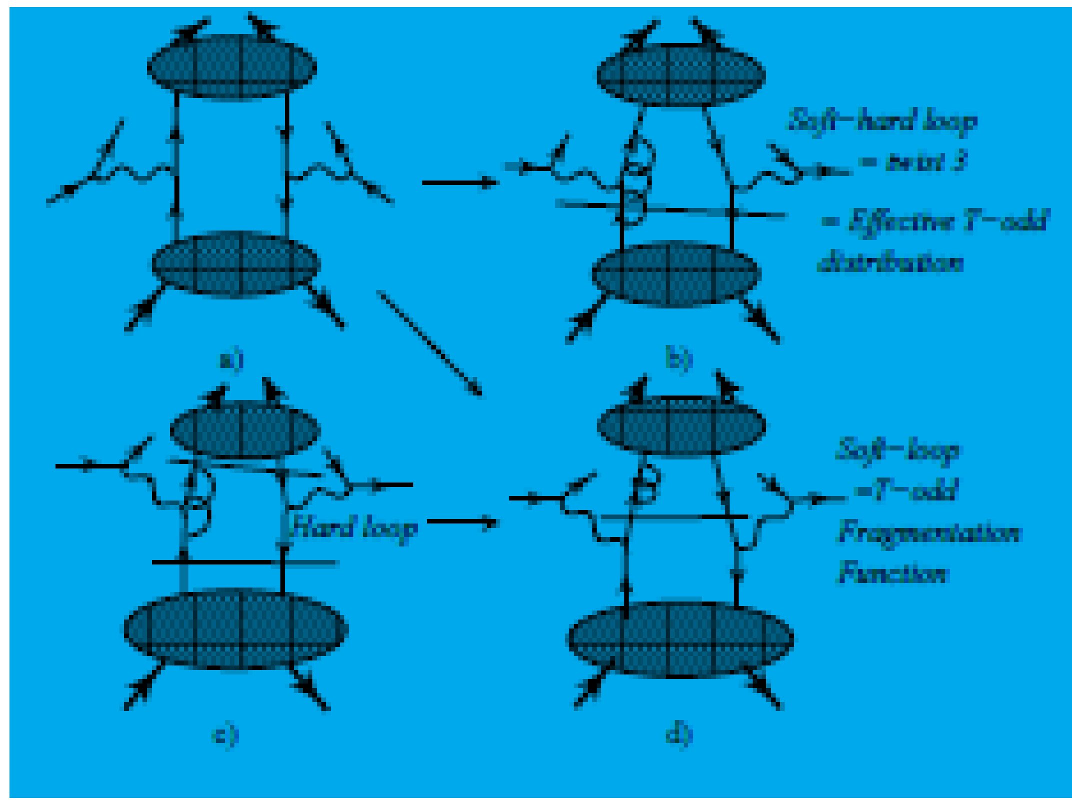
Further shift of phases completely to large distances - T-odd fragmentation functions. Leading twist transversity distribution - no hadron mass suppression.

Phases in QCD-Large distances in distributions

- Distributions: Sivers, Boer and Mulders – no positive kinematic variable producing phase
- QCD: Emerge only due to (initial of final state) interaction between hard and soft parts of the process
- Brodsky -Hwang-Schmidt model:the same SH interactions as twist 3 but non-suppressed by Q: Sivers function – leading (twist 2).
- Related in various complementary ways

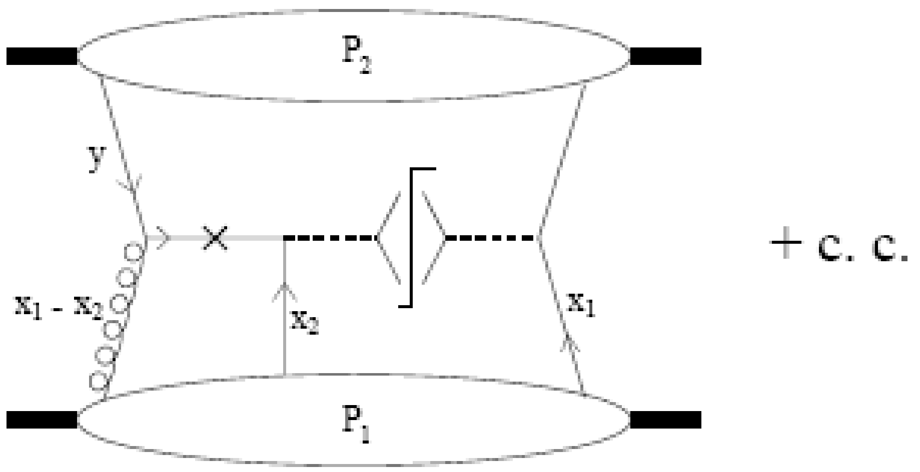
SSAs in SIDIS

- Various opportunities for phases generation



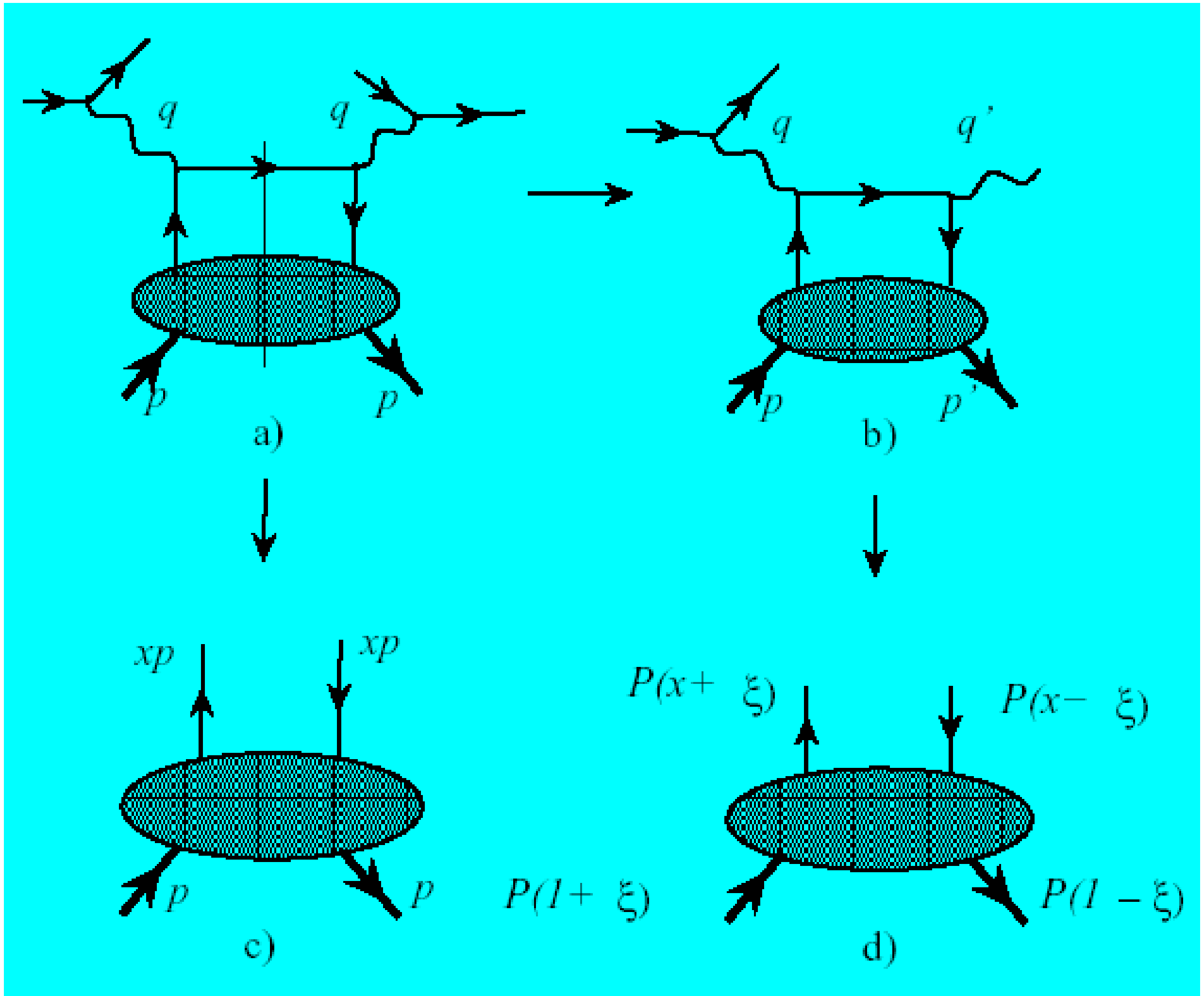
SSA in DY

- TM integrated DY with one transverse polarized beam– unique SSA – glu onic pole (Anikin,OT –factor 2)
- Important for lower M (SPD)

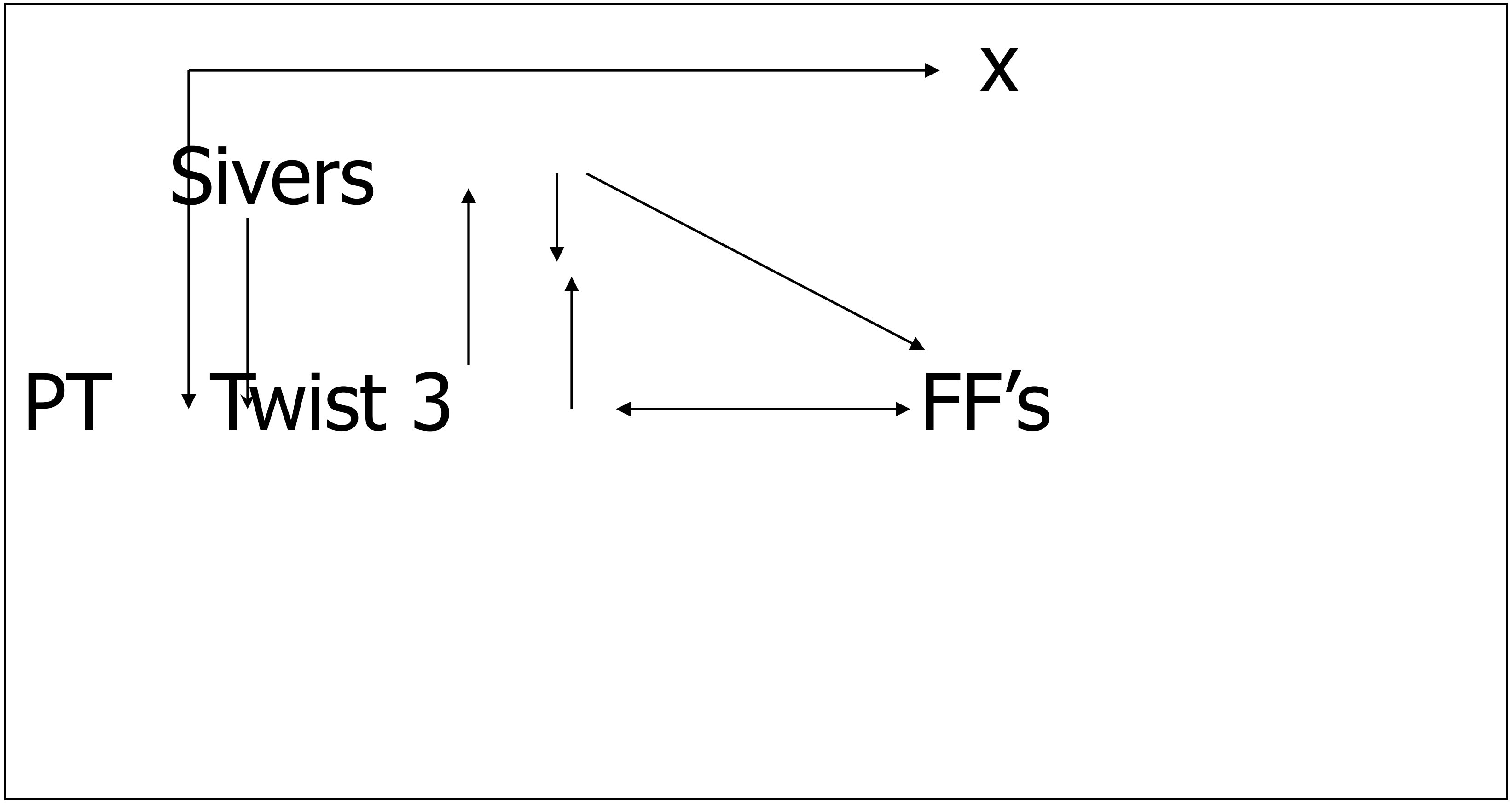


$$A = g\,\frac{\sin 2\theta\ \cos\phi\left[T(x,x) - x\frac{dT(x,x)}{dx}\right]}{M\left[1+\cos^2\theta\right]q(x)}$$

GPDs – another source of T-odd effects



Kinematical domains for SSA’s



Λ-polarisation

- Self-analyzing in weak decay (~20% refinement claimed by BESIII@DSPIN'19: ALL the measured polarization values to be reduced accordingly!)
- Directly related to s-quarks polarization: complementary probe of strangeness
- Widely explored in hadronic processes
- Disappearance-probe of QCD matter formation (Hoyer; Jacob, Rafelsky: '87): Randomization – smearing – no direction normal to the scattering plane

Global polarization

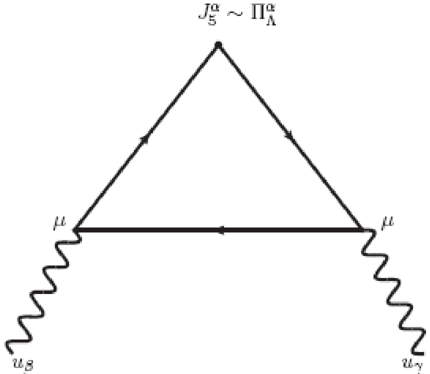
- Global polarization normal to REACTION plane (collective effect)
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Not found at RHIC
- How to transform rotation to spin?
- Mechanisms – reflected in kinematical dependencies of polarization
- Transition from inclusive to global (collectivization?)

Anomalous mechanism – polarization similar to CM(V)E

- 4-Velocity is also a GAUGE FIELD (V.I. Zakharov)

$$e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$$

- Triangle anomaly leads to polarization of quarks and hyperons (Rogachevsky, Sorin, OT '10)
- Analogous to anomalous gluon contribution to nucleon spin (Efremov,OT'88)
- 4-velocity instead of gluon field!



Energy dependence

- Coupling -> chemical potential

$$Q_5^s = \frac{N_c}{2\pi^2} \int d^3x \, \mu_s^2(x) \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- Field -> velocity; (Color) magnetic field strength -> vorticity;
- Topological current -> hydrodynamical helicity
- Large chemical potential: appropriate for NICA/FAIR energies

One might compare the prediction below with the right panel figures

O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

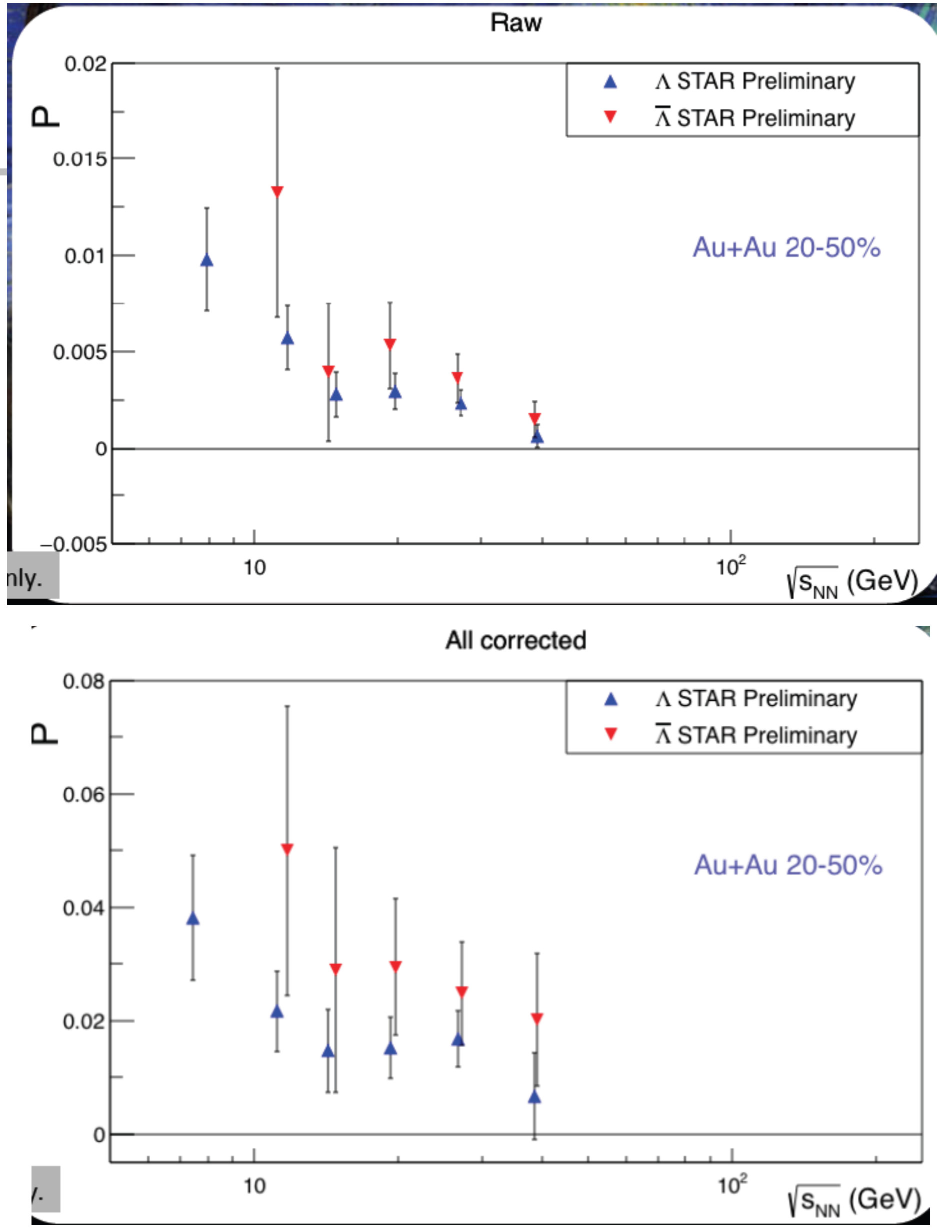
One would expect that polarization is proportional to the anomalously induced axial current [7]

$$j_A^{\mu} \sim \mu^2 \left(1 - \frac{2\mu n}{3(\epsilon + P)}\right) \epsilon^{\mu\nu\lambda\rho} V_\nu \partial_\lambda V_\rho, \qquad (6)$$

where n and ϵ are the corresponding charge and energy densities and P is the pressure. Therefore, the μ dependence of polarization must be stronger than that of the CVE, leading to the effect's increasing rapidly with decreasing energy.

This option may be explored in the framework of the program of polarization studies at the NICA [17] performed at collision points as well as within the low-energy scan program at the RHIC.

STAR collaboration , Nature (2017)



Microworld: where is the fastest possible rotation?

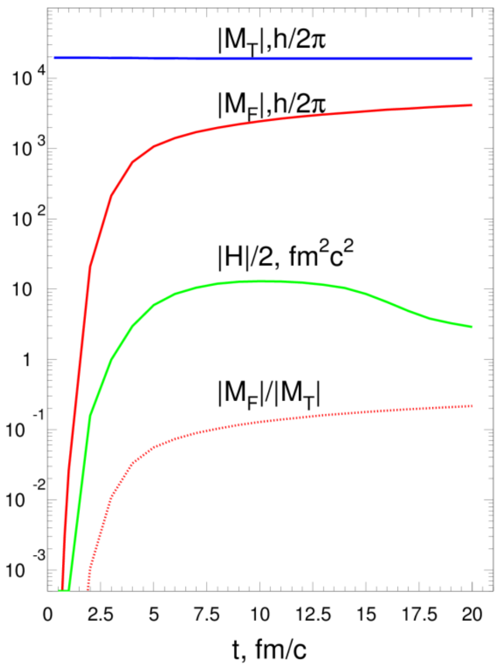
- Non-central heavy ion collisions (Angular velocity ~ c/Compton wavelength)
- ~25 orders of magnitude faster than Earth's rotation
- Calculation in kinetic quark - gluon string model (DCM/QGSM) – Boltzmann type eqns + phenomenological string amplitudes): Baznat, Gudima, Sorin, OT:
- PRC'13 (OAM, helicity separation+P@NICA~1%),
- 16 (femto-vortex sheets, NICA),
- 18 (antihyperons, gravitational anomaly, STAR)

Rotation in HIC and related quantities

- Non-central collisions – orbital angular momentum
- $L=\Sigma\, r \times p$
- Differential pseudovector characteristics – vorticity
- $\varpi = \mathrm{curl}\, v$
- Pseudoscalar – helicity
- $H \sim \langle (v\, \mathrm{curl}\, v) \rangle$
- Maximal helicity – Beltrami chaotic flows $v \parallel \mathrm{curl}\, v$

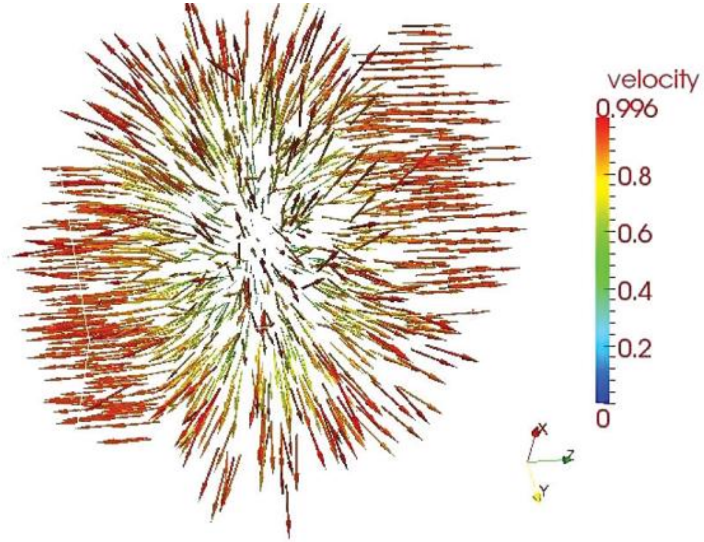
Angular momentum conservation and helicity

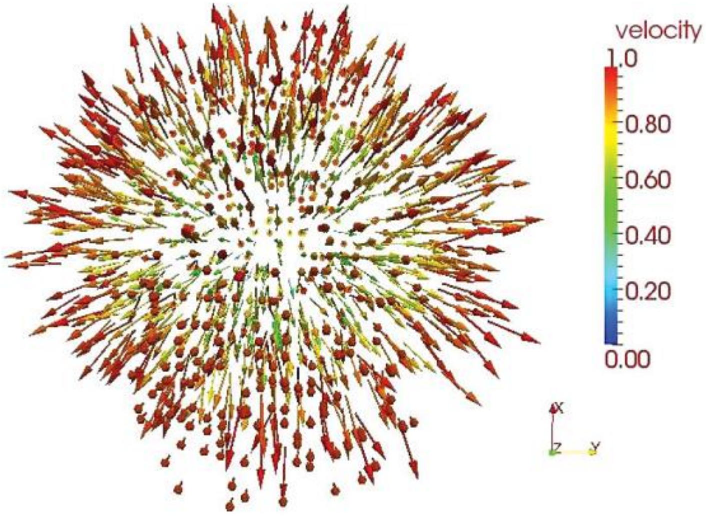
- Helicity vs orbital angular momentum (OAM) of fireball
- (~10% of total)
- Conservation of OAM with a good accuracy!



Distribution of velocity ("Little Bang")

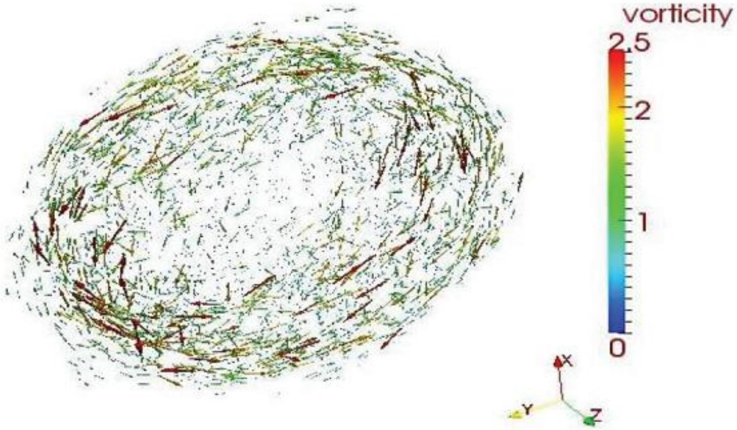
- 3D/2D projection
- z-beams direction
- x-impact paramater

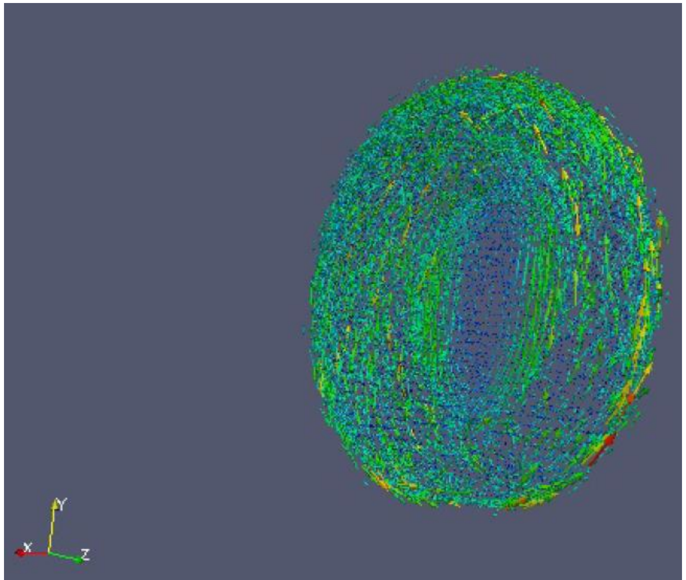


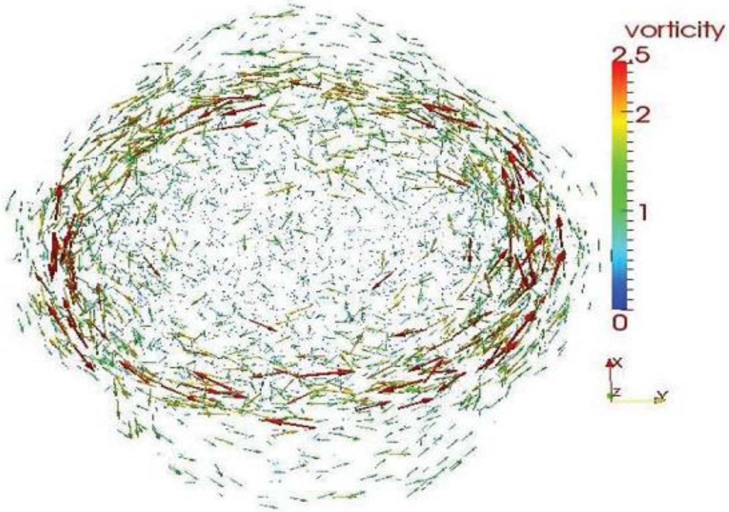


Distribution of vorticity ("Little galaxies")

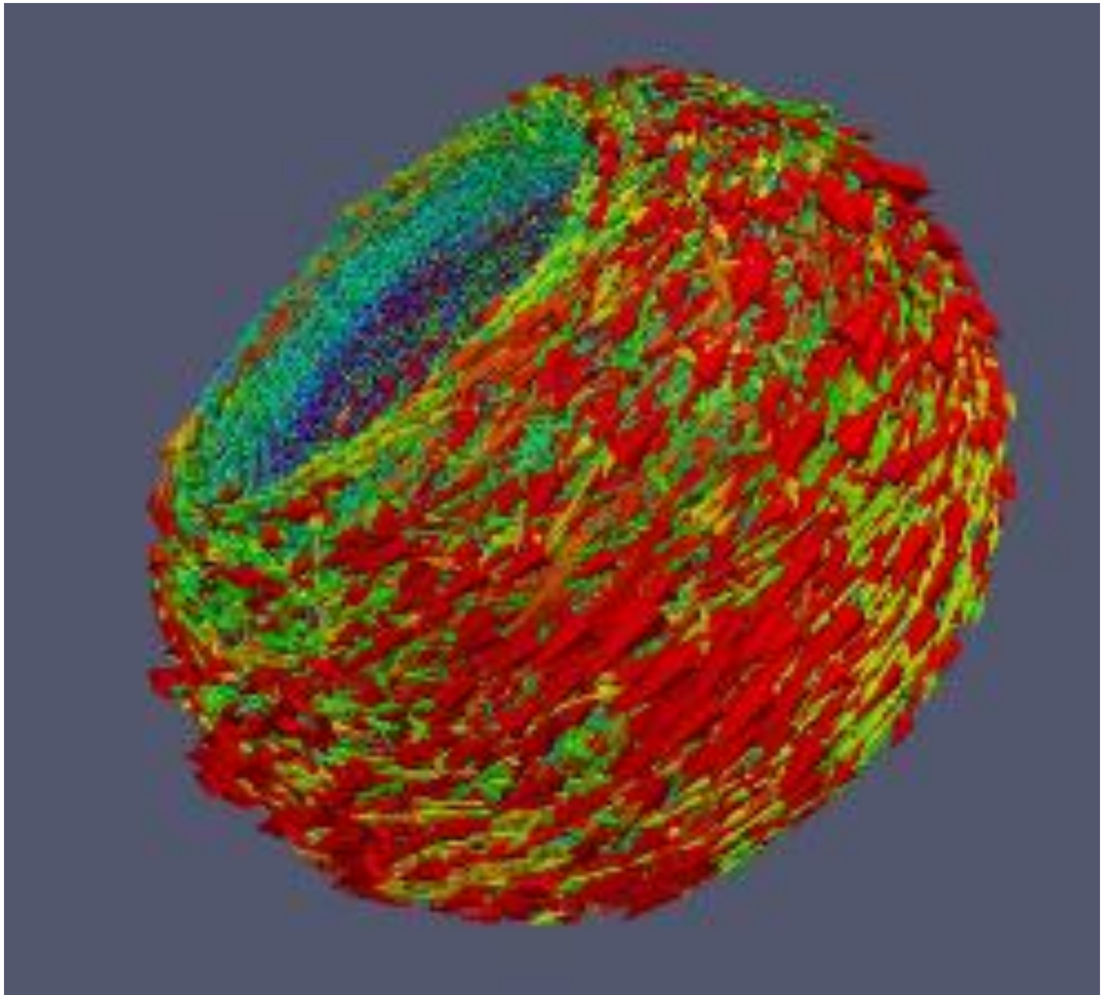
- Layer (on core - corona borderline) patterns (cf talk of A. Ayala)





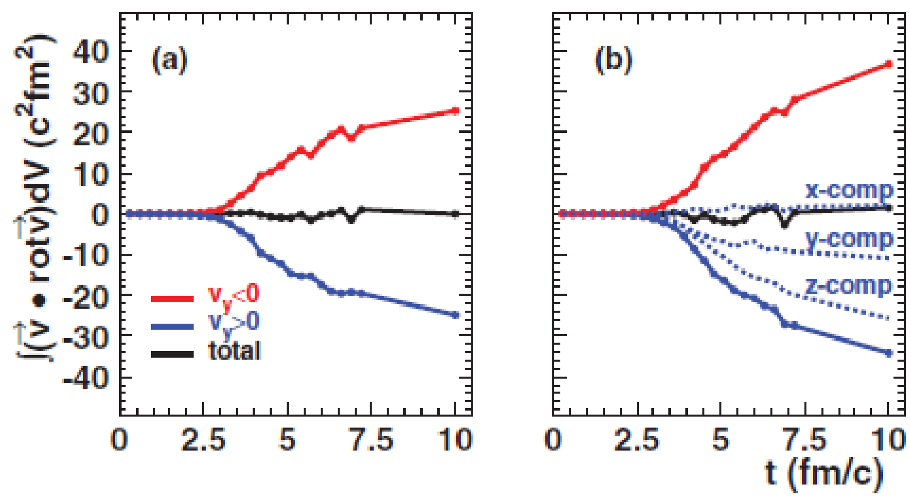


Vortex sheet (cf talk of A. Ayala)



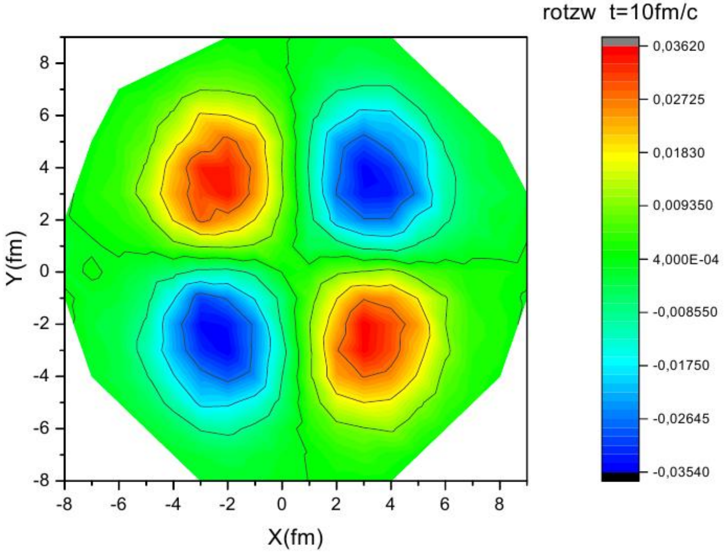
Helicity separation in QGSM **PRC88 (2013) 061901**

- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane – required by boost!
- Confirmed in HSD (OT, Usubov, PR**C92 (2015) 014906**
- **zz-> quadrupole structure**



Structure of vorticity

- y-component: constant vorticity, velocity changes sign
- **z-component: quadrupole structure of vorticity**



From axial charge to polarization (and from quarks to confined hadrons) – analog of Cooper-Frye

- Analogy of matrix elements and classical averages

$$< p_n|j^0(0)|p_n >= 2p_n^0 Q_n \qquad < Q >\equiv \frac{\sum_{n=1}^N Q_n}{N} = \frac{\int d^3x\, j^0_{class}(x)}{N}$$

- Axial current: charge -> polarization vector
- Lorentz boost: requires the sign change of helicity "below" and "above" the RP

$$\Pi^{\Lambda,lab} = (\Pi_0^{\Lambda,lab}, \Pi_x^{\Lambda,lab}, \Pi_y^{\Lambda,lab}, \Pi_z^{\Lambda,lab}) = \frac{\Pi_0^\Lambda}{m_\Lambda}(p_y, 0, p_0, 0)$$

$$< \Pi_0^\Lambda >= \frac{m_\Lambda \Pi_0^{\Lambda,lab}}{p_y} =< \frac{m_\Lambda}{N_\Lambda\, p_y} > Q_5^s \equiv< \frac{m_\Lambda}{N_\Lambda\, p_y} > \frac{N_c}{2\pi^2}\int d^3x\, \mu_s^2(x)\gamma^2\epsilon^{ijk}v_i\partial_j v_k$$

Axial charge and properties of polarization

- Antihyperons : same sign (C-even axial charge) and larger value (smaller N)

- More pronounced at lower energy. Baryon/antibaryon splitting due to magnetic field – increase (?!) with energy.
- Non-linear effects in H may be essential, cf vector mesons on the lattice: Luschevskaya, Solovjeva, OT: **JHEP 1709 (2017) 142 (longitudinal tensor polarization)**

Other approach to baryons in confined phase: vortices in pionic superfluid (V.I. Zakharov,OT: PRD96,09623)

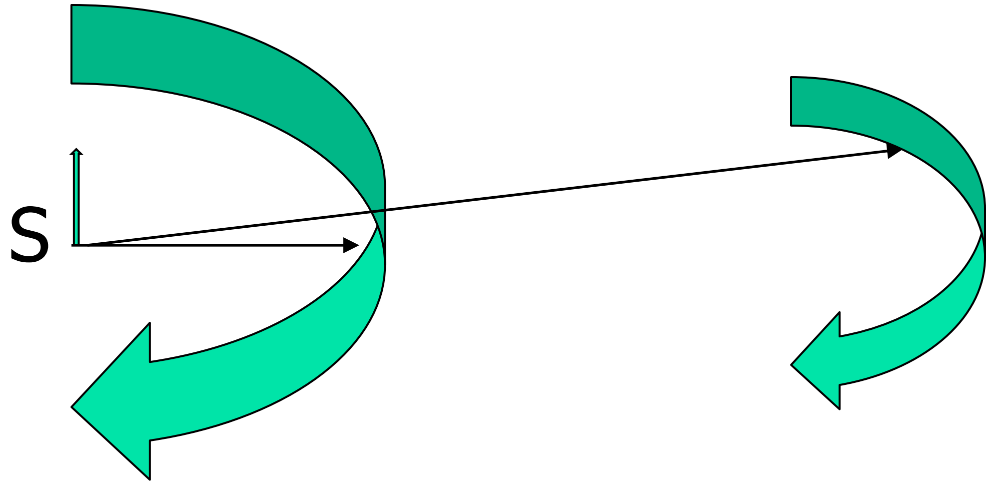
- Pions may carry the axial current due to quantized vortices in pionic superfluid (Kirilin,Sadofyev,Zakharov'12)

$$j_5^\mu = \frac{1}{4\pi^2 f_\pi^2}\epsilon^{\mu\nu\rho\sigma}(\partial_\nu\pi^0)(\partial_\rho\partial_\sigma\pi^0) \qquad \frac{\pi_0}{f_\pi} = \mu\cdot t + \varphi(x_i) \qquad \oint \partial_i\varphi dx_i = 2\pi n$$

$$\partial_i\varphi = \mu v_i$$

- Suggestion: core of the vortex- baryonic degrees of freedom- polarization
- Dissipation – counterpart of absorptive phases!

Core of quantized vortex

- Constant circulation – velocity increases when core is approached
- 

- Helium ($v < v_{sound}$) bounded by intermolecular distances
- Pions ($v<c$) –> (baryon) spin in the center

Anomalies due to chemical potential and temperature

- Induced axial charge

$$c_V = \frac{\mu_s^2 + \mu_A^2}{2\pi^2} + \frac{T^2}{6}, \quad Q_5^s = N_c \int d^3x \, c_V \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- Chemical potential im HIC is rapidly decreasing with energy
- T-dependent term is related to holographic gravitational anomaly (K. Landsteiner et al.)
- Coefficient (pi) ?

Rotated and accelerated frame: Wigner function and Zubarev density operator

- G. Prokhorov, V. Zakharov,OT '19:
- Imaginary chemical potential due to acceleration appears!

$$\langle j_\mu^5 \rangle = \frac{\omega_\mu + i\,\mathrm{sgn}(\omega a) a_\mu}{2(g_\omega - i g_a)} \int \frac{d^3 p}{(2\pi)^3}$$
$$\times \{ n_F(E_p - \mu - g_\omega/2 + i g_a/2)$$
$$- n_F(E_p - \mu + g_\omega/2 i g_a/2)$$
$$+ n_F(E_p + \mu - g_\omega/2 + i g_a/2)$$
$$- n_F(E_p + \mu + g_\omega/2 - i g_a/2) \} + \text{c.c.},$$

$$\rho = \frac{7\pi^2 T^4}{60} + \frac{T^2 a^2}{24} - \frac{17 a^4}{960\pi^2} = 2\int \frac{d^3p}{(2\pi)^3}\Big(\frac{|\mathbf{p}| + ia}{1 + e^{\frac{|\mathbf{p}|}{T} + \frac{ia}{2T}}} + \frac{|\mathbf{p}| - ia}{1 + e^{\frac{|\mathbf{p}|}{T} - \frac{ia}{2T}}} \Big)$$
$$+4\int \frac{d^3p}{(2\pi)^3} \frac{|\mathbf{p}|}{e^{\frac{2\pi|\mathbf{p}|}{a}} - 1} \qquad (T > T_U)$$

in red: *modifications* compared to the *Wigner function*

- In the first integral, the **acceleration** enters as an **imaginary chemical potential** $\pm\frac{ia}{2}$ [G.P., O. Teryaev, V. Zakharov, Phys. Rev. D 98, no. 7, 071901 (2018)].

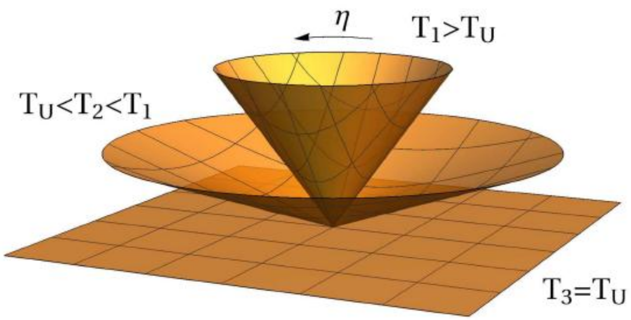
Statistics vs geometry

- Results for energy density of thermal system in Minkowski space coincide with the early known for the space with conical singularity (e.g. cosmic strings)

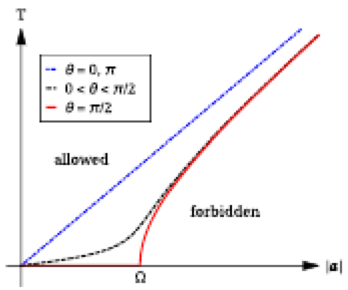
$$\rho_{s=0} = \frac{\pi^2 T^4}{30} + \frac{T^2|a|^2}{12} - \frac{11|a|^4}{480\pi^2},$$
$$\rho_{s=1/2} = \frac{7\pi^2 T^4}{60} + \frac{T^2|a|^2}{24} - \frac{17|a|^4}{960\pi^2}$$

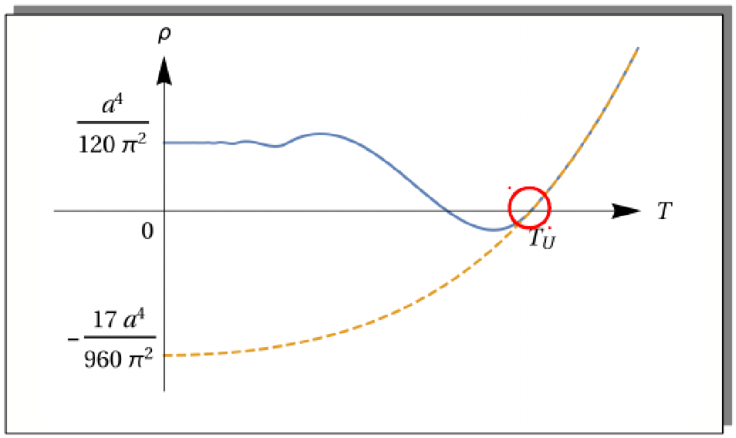
- Energy density turns to zero for $T=T_U=a/(2\pi)$ (~"physical conditions of renormalization". also simple explanation of coefficient)

Instability for high accelerations



- Normally $T>T_U$
- Fast accelration without thermalization: instability





- EP ~ fall to BH?
- Censorship: Origin for fast thermalization?

Lambda vs Antilambda and role of vector mesons

- Difference at low energies too large – same axial charge carried by much smaller number
- Strange axial charge may be also carried by K* mesons
- Λ - accompanied by (+,anti 0) K* mesons with two sea quarks – small corrections
- Anti Λ – more numerous (-,0) K* mesons with single (sea) strange antiquark
- Dominance of one component of spin results also in tensor polarization (P-even source) –revealed in dilepton anisotropies (Bratkovskaya, Toneev,OT'95)

Vector vs tensor polarization

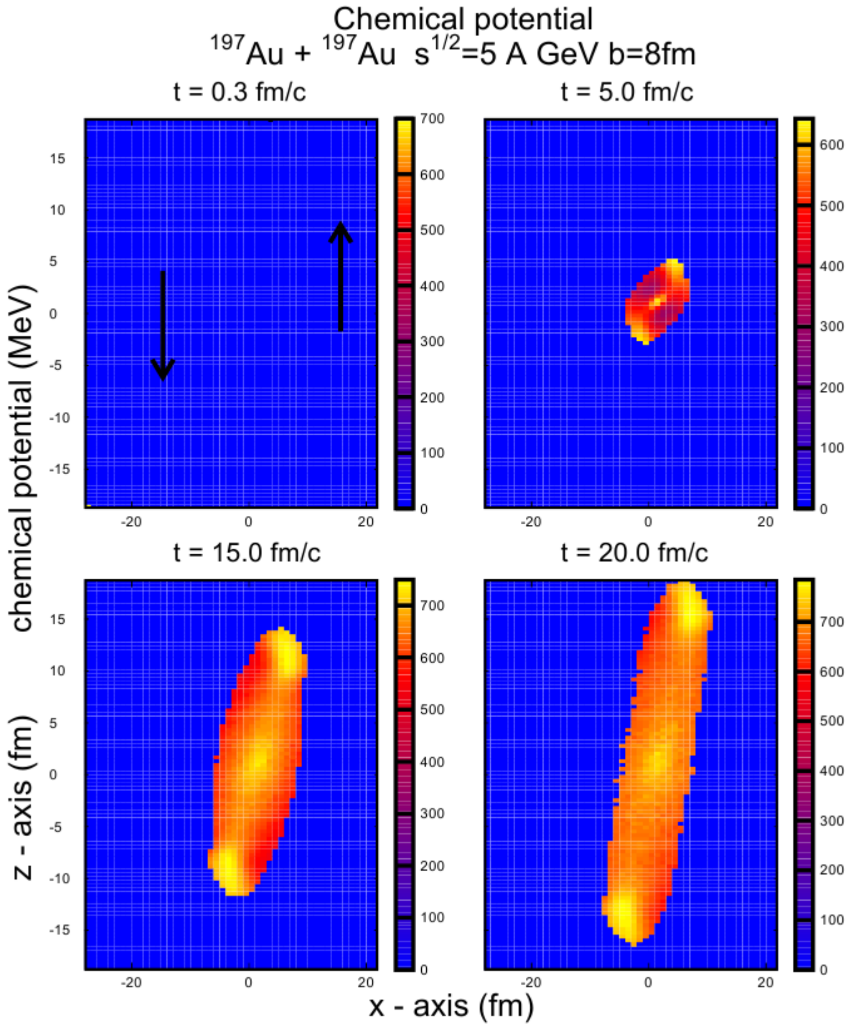
- P-odd vs P-even
- Related by invariants/density matrix positivity (Gavrilova,OT,PRD’19)
- Product vs correlation of polarizations $\langle P_1 \rangle \langle P_2 \rangle$ vs $\langle P_1 P_2 \rangle$
- Tensor may be larger than vector

Chemical potential and flavour dependence

- Way via axial current/charge differs from “direct” TD (spin is NOT thermalized)
- TD-Universal, “flavor-blind” (only mass-dependent) polarization
- Axial current: polarization depends on baryon structure
- Most pronounced at low energies
- Comparison of hyperons polarization (c.f. hadronic collisions)

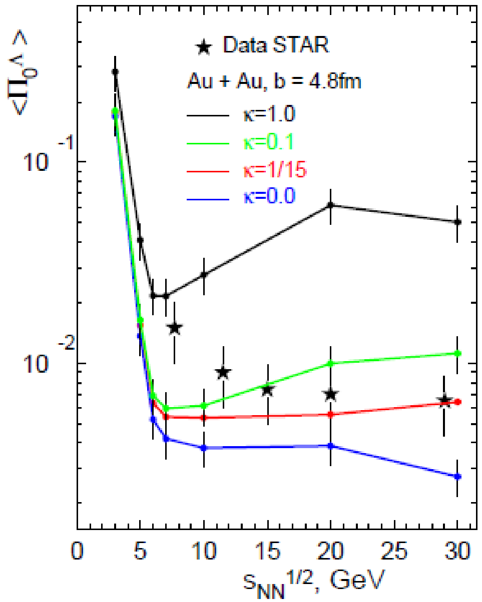
Chemical potential : Kinetics -> TD

- TD and chemical equilibrium
- Conservation laws
- Chemical potential from equilibrium distribution functions
- 2d section: y=0



The role of (gravitational anomaly related) T^2 term

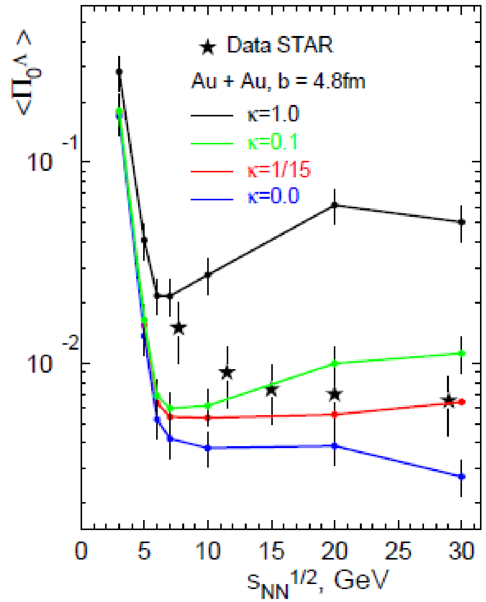
- Different values of coefficient probed



- LQCD suppression by collective effects supported

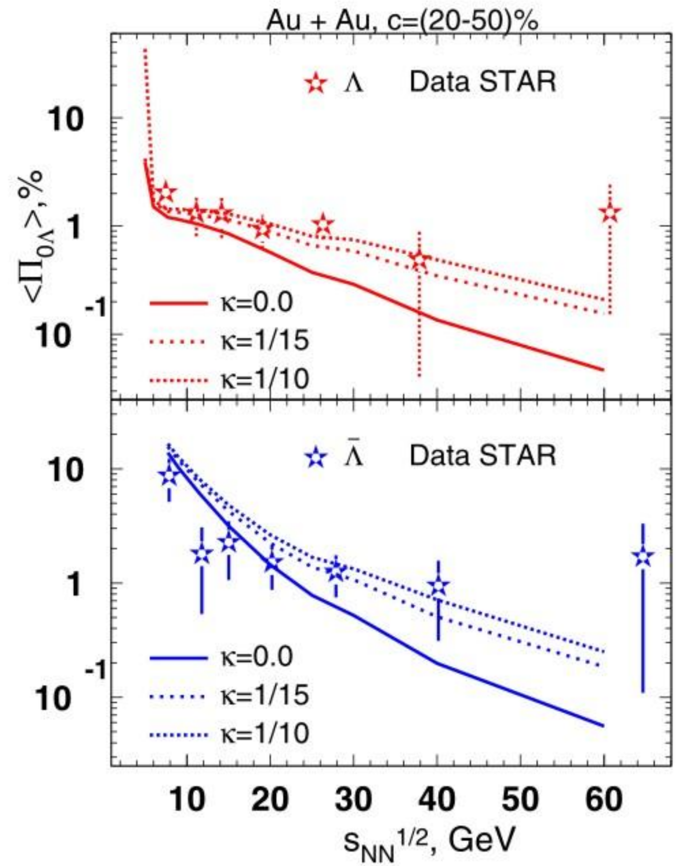
The role of (gravitational anomaly related) T^2 term

- Different values of coefficient probed



- LQCD suppression by collective effects supported

Λ vs Anti Λ



Au + Au, c=(20-50)%
Λ Data STAR
$\bar{\Lambda}$ Data STAR
κ=0.0
κ=1/15
κ=1/10
κ=0.0
κ=1/15
κ=1/10
$<\Pi_{0\Lambda}>$,%
10
1
10^{-1}
10
1
10^{-1}
10
20
30
40
50
60
$s_{NN}^{1/2}$, GeV

Problems for NICA

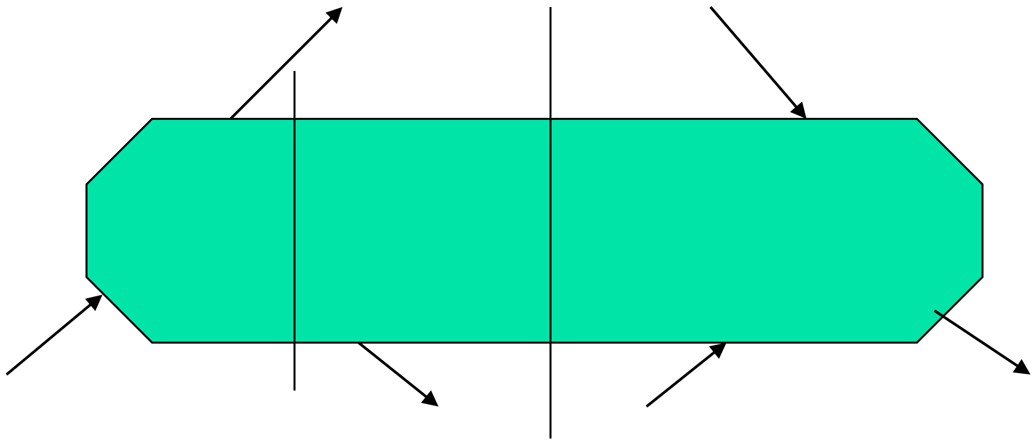
- Transition from inclusive to global/local polarization (talk of E. Nazarova)
- Vorticity in different models (talk of I. Maldonado)
- Polarization in TD/AVE (also for other baryons)
- Vector/tensor interplay
- Interplay with flows/correlations
- Effective gravity lab?!
- Relation of HIC/hadronic spin (MPD/SPD) – polarization for hadrons, light and heavy ions
- MexNICA is actively participating in MPD&BMN; SPD: – much welcomed

- BACKUP

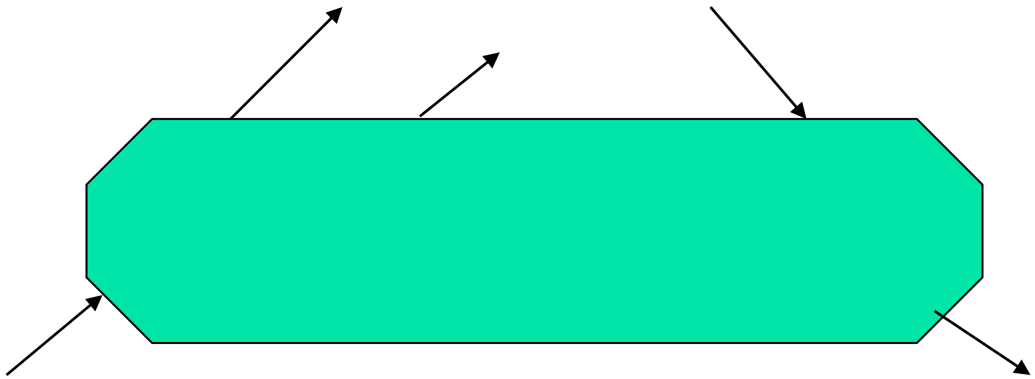
Fracture functions

- Common NP ingredient for FRAgmentation and struCTURE
- Structure functions – parton distributions
- Fracture functions – fractural (conditional,correlational,entangling?) parton distributions
- May be T-odd (Collins'95 –polarized beam jets; OT'01-T-odd Diffractive Distributions)
- Related by crossing to dihadron fragmentation functions

(T-odd) Fractural (conditional) parton distributions



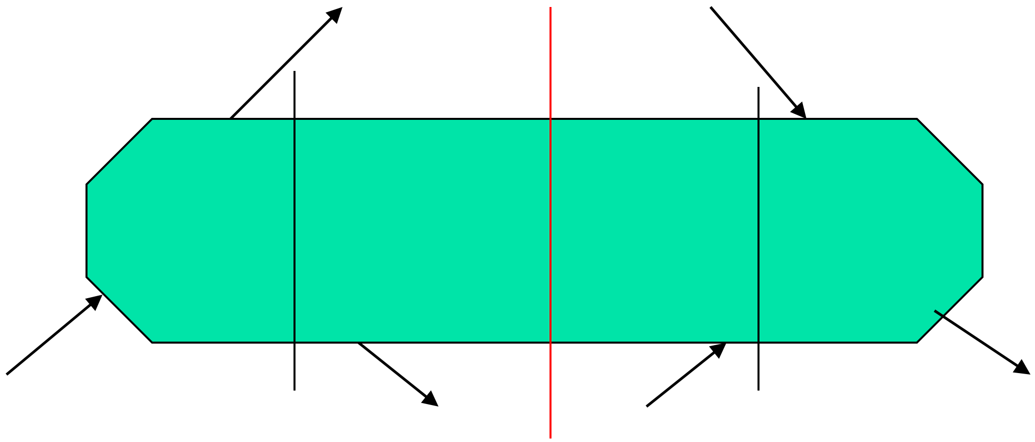
HT parton distributions



T-odd fracture function for hyperons polarization

- May be formally obtained from spin-dependent T-odd DIS (cf OT'99 for pions SSA-work in progress)
- Transverse spin in DIS – either transverse spin or transverse momentum of hyperon in SIDIS
- Both longitudinal and transverse polarizations appear
- SPD – extra hadrons (pions) with low TM

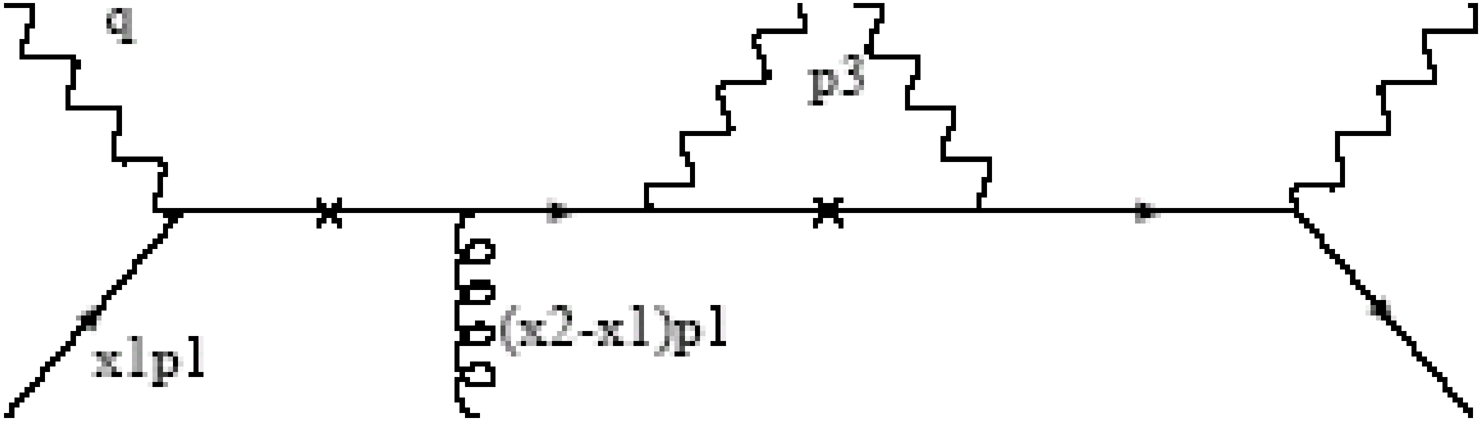
GPDs in exclusive limit of fractured distributions



Fractural PD

- **Frac´tur`al a.1.**Pertaining to, or consequent on, a fracture.

Twist 3 partonic subprocesses for SIDVCS



Real and virtual photons - most clean tests of QCD

- Both initial and final – real :Efremov, O.T. (85)
- Initial – quark/gluon, final - real : Efremov, OT (86, fermionic poles); Qui, Sterman (91, GLUONIC poles)
- Initial - real, final-virtual (or quark/gluon) – Korotkiian, O.T. (94)
- Initial –virtual, final-real: O.T., Srednyak (05; smooth transition from fermionic via hard to GLUONIC poles).

Sivers function and formfactors

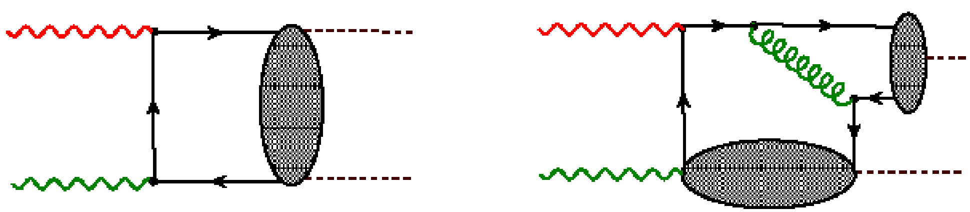
- Relation between Sivers and AMM known on the level of matrix elements (Brodsky, Schmidt, Burkardt)
- Phase?
- Duality for observables?
- Solution: SSA in DY

SSA in exclusive limit

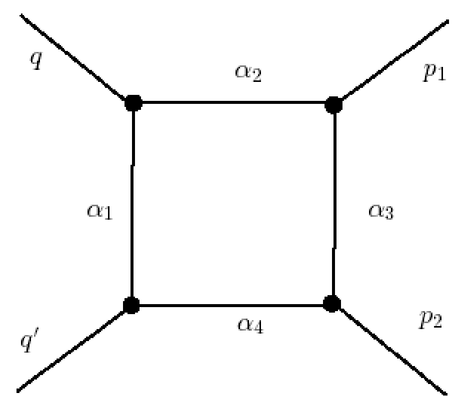
- Proton-antiproton – valence annihilation - cross section is described by Dirac FF squared
- The same SSA due to interference of Dirac and Pauli FF’s with a phase shift
- Exclusive large energy limit; x -> 1 : (d/dx)T(x,x)/q(x) -> Im F2/F1
- No suppression of large x – large E704 SSA
- Positivity: Twist 4 correction to q(x) may be important

mechanisms for exclusive amplitudes (Anikin, Cherednikov, Stefanis, OT, 08)

- 2 pion production : GDA (small s) vs TDA+DA (small t)

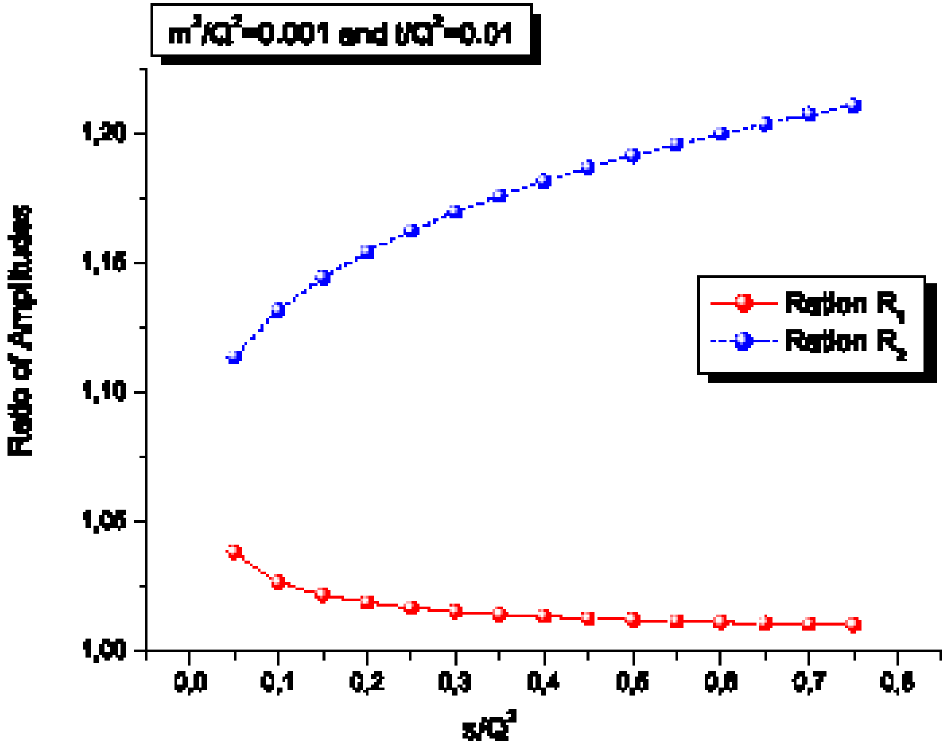


- Scalar model - asymptotics(Efremov, Ginzburg, Radyushkin…)



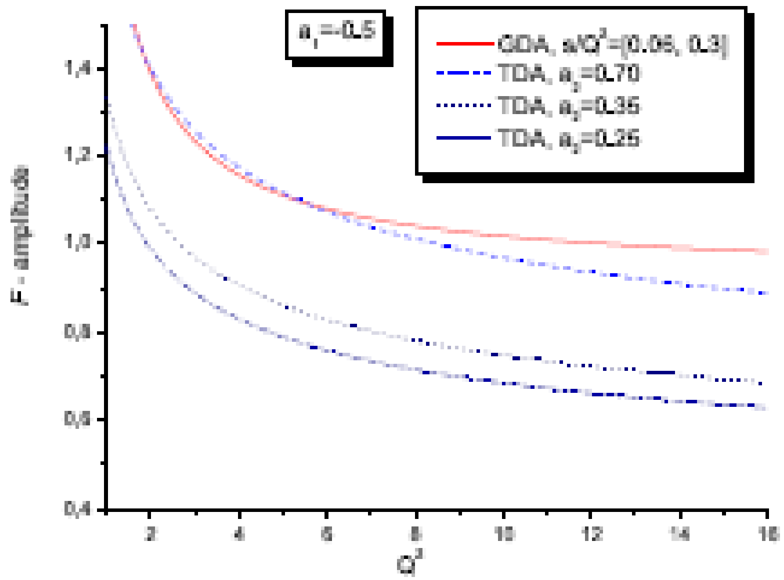
Duality in scalar model

- “Right” (TDA, red) and “wrong” (GDA, blue) asymptotics / exact result (>1- negative “Higher Twist”



Duality in QCD

- Qualitatively- surprisingly good, quantitatively - model-dependent



Duality and helicity amplitudes

- Holds if different mechanisms contribute to SAME helicity amplitudes
- Scalar- only one; QCD – L and T photons
- Other option : Different mechanisms – different helicity amplitudes (“unmatching”)
- Example -> transition from perturbative phase to twist 3 (m -> M)

Twist 3 factorization (Efremov, OT '84, Ratcliffe,Qiu,Sterman)

- Convolution of soft (S) and hard (T) parts

$$d\sigma_s = \int dx_1 dx_2 \frac{1}{4} Sp[S_\mu(x_1, x_2) T_\mu(x_1, x_2)]$$

- Vector and axial correlators: define hard process for both double (g_2) and single asymmetries

$$T_\mu(x_1, x_2) = \frac{M}{2\pi} (\hat{p}_1 \gamma^5 s_\mu b_A(x_1, x_2) - i \gamma_\rho \epsilon^{\rho\mu s p_1} b_V(x_1, x_2))$$

Twist 3 factorization -II

- Non-local operators for quark-gluon correlators

$$b_A(x_1,x_2)=\frac{1}{M}\int\frac{d\lambda_1 d\lambda_2}{2\pi}e^{i\lambda_1(x_1-x_2)+i\lambda_2 x_2}\langle p_1,s|\bar{\psi}(0)\hat{n}\gamma^5(D(\lambda_1)s)\psi(\lambda_2)|p_1,s\rangle,$$

$$b_V(x_1,x_2)=\frac{i}{M}\int\frac{d\lambda_1 d\lambda_2}{2\pi}e^{i\lambda_1(x_1-x_2)+i\lambda_2 x_2}\epsilon^{\mu s p_1 n}\langle p_1,s|\bar{\psi}(0)\hat{n}D_\mu(\lambda_1)\psi(\lambda_2)|p_1,s\rangle$$

- Symmetry properties (from T-invariance)

$$b_A(x_1,x_2)=b_A(x_2,x_1),\ \ b_V(x_1,x_2)=-b_V(x_2,x_1)$$

Twist-3 factorization -III

- Singularities

$$b_A(x_1,x_2) = \varphi_A(x_1)\delta(x_1 - x_2) + b^r_A(x_2,x_1).$$

$$b_V(x_1,x_2) = \frac{\varphi_V(x_1)}{x_1 - x_2} + b^r_V(x_1,x_2)$$

- Very different: for axial – Wandzura-Wilczek term due to intrinsic transverse momentum
- For vector-GLUONIC POLE (Qiu, Sterman '91) – large distance background

Sum rules

- EOM + n-independence (GI+rotational invariance) –relation to (genuine twist 3) DIS structure functions

$$\int_0^1 x^n \bar{g}_2(x)dx = \int_0^1 x^n \left(\frac{n}{n+1} g_1(x) + g_2(x)\right)dx =$$

$$-\frac{1}{\pi(n+1)} \int_{|x_1,x_2,x_1-x_2|\leq 1} dx_1 dx_2 \sum_f e_f^2 [\frac{n}{2} b_V(x_1,x_2)(x_1^{n-1} - x_2^{n-1}) +$$

$$b_A^r(x_1,x_2)\phi_n(x_1,x_2)], \quad \phi_n(x,y) = \frac{x^n - y^n}{x-y} - \frac{n}{2}(x^{n-1} - y^{n-1}), \quad n = 0, 2...$$

Sum rules -II

- To simplify – low moments

$$\int_0^1 x^2 \hat{g}_2(x)dx =$$
$$-\frac{1}{3\pi}\int_{|x_1,x_2,x_1-x_2|\leq 1} dx_1 dx_2 \sum_f e_f^2 b_V(x_1,x_2)(x_1-x_2)$$

- Especially simple – if only gluonic pole kept:

$$\int_0^1 x^2 \bar{g}_2(x)dx = -\frac{1}{3\pi}\int_{|x_1,x_2,x_1-x_2|\leq 1} dx_1 dx_2 \sum_f e_f^2 \varphi_V(x_1)$$
$$= -\frac{1}{3\pi}\int_{-1}^1 dx_1 \sum_f e_f^2 \varphi_V(x_1)(2-|x_1|)$$

Gluonic poles and Sivers function

- Gluonic poles – effective Sivers functions-Hard and Soft parts talk, but SOFTLY

- Implies the sum rule for effective Sivers function (soft=gluonic pole dominance assumed in the whole allowed x's region of quark-gluon correlator)

$$x f_T(x) = \frac{1}{2M} T(x,x) = \frac{1}{4} \phi_v(x)$$

$$\int_0^1 dx x^2 \bar{g}_2(x) = \frac{4}{3\pi} \int_0^1 dx x f_T(x)(2-x)$$

Compatibility of SSA and DIS

- Extractions of and modeling of Sivers function: – "mirror" u and d
- Second moment at % level
- Twist -3 g_2 - similar for neutron and proton and of the same sign – no mirror picture seen –but supported by colour ordering!
- Scale of Sivers function reasonable, but flavor dependence differs qualitatively.
- Inclusion of pp data, global analysis including gluonic (=Sivers) and fermionic poles
- HERMES, RHIC, E704 –like phonons and rotons in liquid helium; small moment and large E704 SSA imply oscillations
- JLAB –measure SF and g2 in the same run

CONCLUSIONS

- 3rd way from SF to GP – proof of Torino recipe supplemented by colour correlations
- Effective SF – small in pp - factorization in terms of twist 3 only
- Large x – E704 region - relation between SF, GP and time-like FF's

Outlook (high energies)

- TMD vs UGPD
- T-odd UGPD?
- T-odd (P/O) diffractive distribiutions

(analogs - also at small energies)

- Quark-hadron duality: description of gluon coupling to "exotic" objects in diffractive production via their decay widths

Relation of Sivers function to GPDs

- Qualitatively similar to Anomalous Magnetic Moment (Brodsky et al)
- Quantification : weighted TM moment of Sivers PROPORTIONAL to GPD E (**hep-ph/0612205**): $x f_T(x) : xE(x)$
- Burkardt SR for Sivers functions is now related to Ji SR for E and, in turn, to Equivalence Principle

$$\sum_{q,G} \int dx x f_T(x) = \sum_{q,G} \int dx x E(x) = 0$$

How gravity is coupled to nucleons?

- Current or constituent quark masses ?– neither!
- Energy momentum tensor - like electromagnertic current describes the coupling to photons

Equivalence principle

- Newtonian – “Falling elevator” – well known and checked
- Post-Newtonian – gravity action on SPIN – known since 1962 (Kobzarev and Okun’) – not yet checked
- Anomalous gravitomagnetic moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way

Gravitational formfactors

$$\langle p'|T^{\mu\nu}_{q,g}|p\rangle = \bar{u}(p')\Big[A_{q,g}(\Delta^2)\gamma^{(\mu}p^{\nu)} + B_{q,g}(\Delta^2)P^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha/2M]u(p)$$

- Conservation laws - zero Anomalous Gravitomagnetic Moment : $\mu_G = J$ (g=2)

$$P_{q,g} = A_{q,g}(0) \qquad A_q(0) + A_g(0) = 1$$

$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0)\right] \qquad A_q(0) + B_q(0) + A_g(0) + B_g(0) = 1$$

- May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons
- Describe interaction with both classical and TeV gravity – similar t-dependence to EM FF

Electromagnetism vs Gravity

- Interaction – field vs metric deviation

$$M = \langle P'|J_q^\mu|P\rangle A_\mu(q) \qquad M = \frac{1}{2}\sum_{q,G}\langle P'|T_{q,G}^{\mu\nu}|P\rangle h_{\mu\nu}(q)$$

- Static limit

$$\langle P|J_q^\mu|P\rangle = 2e_q P^\mu \qquad \sum_{q,G}\langle P|T_i^{\mu\nu}|P\rangle = 2P^\mu P^\nu$$

$$h_{00} = 2\phi(x)$$

$$M_0 = \langle P|J_q^\mu|P\rangle A_\mu = 2e_q M\phi(q) \qquad M_0 = \frac{1}{2}\sum_{q,G}\langle P|T_i^{\mu\nu}|P\rangle h_{\mu\nu} = 2M\cdot M\phi(q)$$

- Mass as charge – equivalence principle

Gravitomagnetism

- Gravitomagnetic field – action on spin – ½ from $M = \frac{1}{2}\sum_{q,G}\langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$

$\vec{H}_J = \frac{1}{2} rot\vec{g};\ \vec{g}_i \equiv g_{0i}$ spin dragging twice smaller than EM

- Lorentz force – similar to EM case: factor ½ cancelled with 2 from $h_{00} = 2\phi(x)$
Larmor frequency same as EM $\vec{H}_L = rot\vec{g}$
- Orbital and Spin momenta dragging – the same - Equivalence principle $\omega_J = \frac{\mu_G}{J} H_J = \frac{H_L}{2} = \omega_L$

Sivers function and Extended Equivalence principle

- Second moment of E – zero SEPARATELY for quarks and gluons –only in QCD beyond PT (OT, 2001) - supported by lattice simulations etc.. ->
- Gluon Sivers function is small! (COMPASS, STAR, Brodsky&Gardner)
- BUT: gluon orbital momentum is NOT small: total – about 1/2, if small spin – large (longitudinal) orbital momentum
- Gluon Sivers function should result from twist 3 correlator of 3 gluons: remains to be proved!

Generalization of Equivalence principle

- Various arguments: AGM $\approx$ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM, confirmed recently)