JINR contribution to physics program at NICA

The Conference "RFBR Grants for NICA"

20 October 2020

VBLHEP, JINR, Dubna, RUSSIA

Oleg Teryaev

VBLHEP and BLTP,

JINR, Dubna

RFBR for NICA and JINR

- Participation in the Russian-wide grants (talks)
- Interactions between the JINR labs (VBLHEP, BLTP, LIT, LNP…)
- Interaction with international scientific community
- Support of interdisciplinary aspects
- Two ways road

Outline

- Observable signals in detectors (based on the theoretical activity worldwide)

- Developing of physics with a feedback from NICA

- Hadronic vs Heavy-Ion physics
- Polarization: MPD/SPD

Prospects for the study of the strangeness production within PHQMD model

V. Kireyeu[1], J. Aichelin[2], V. Kolesnikov[1], E. Bratkovskaya[3,4], A. Zinchenko[1], V. Vasendina[1], A. Mudrokh[1]

The 5th International Conference on Particle Physics and Astrophysics
2020-10-08

1 – JINR, Dubna
2 – SUBATECH, Nantes
3 – GSI, Darmstadt
4 – Goethe Universität, Frankfurt am Main

PHQMD model

J. Aichelin, E. Bratkovskaya, A. Le Fèvre, V. Kireyeu, V. Kolesnikov, Y. Leifels, V. Voronyuk, and G. Coci, Phys. Rev. C 101, 044905

The goal: to develop a **unified n-body microscopic transport approach** for the description of heavy-ion dynamics and dynamical cluster formation from low to ultra-relativistic energies

Realization: combined model **PHQMD = (PHSD & QMD) & SACA**

Parton-Hadron-Quantum-Molecular Dynamics

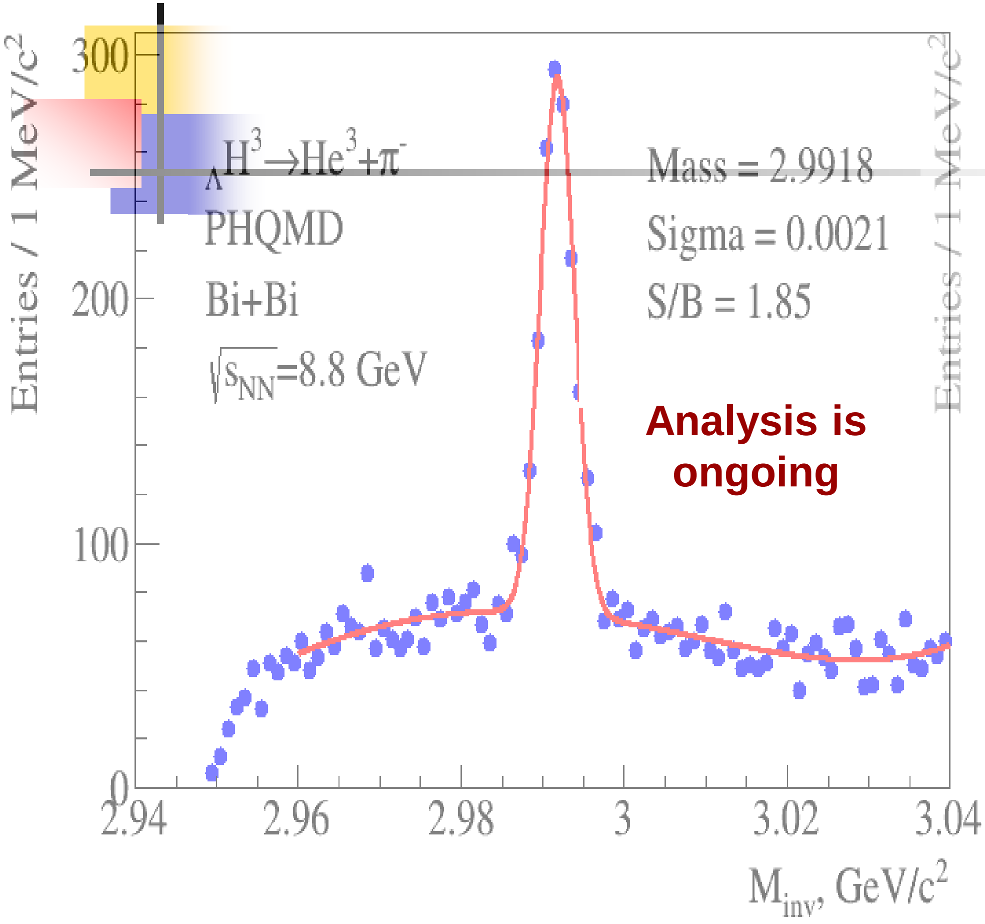
Initialization □ propagation of baryons:
QMD (Quantum-Molecular Dynamics)

Propagation of partons (quarks, gluons) and mesons
+ collision integral = interactions of hadrons and partons (QGP)
from PHSD (Parton-Hadron-String Dynamics)

Clusters recognition:
SACA (Simulated Annealing Clusterization Algorithm)
vs. MST (Minimum Spanning Tree)

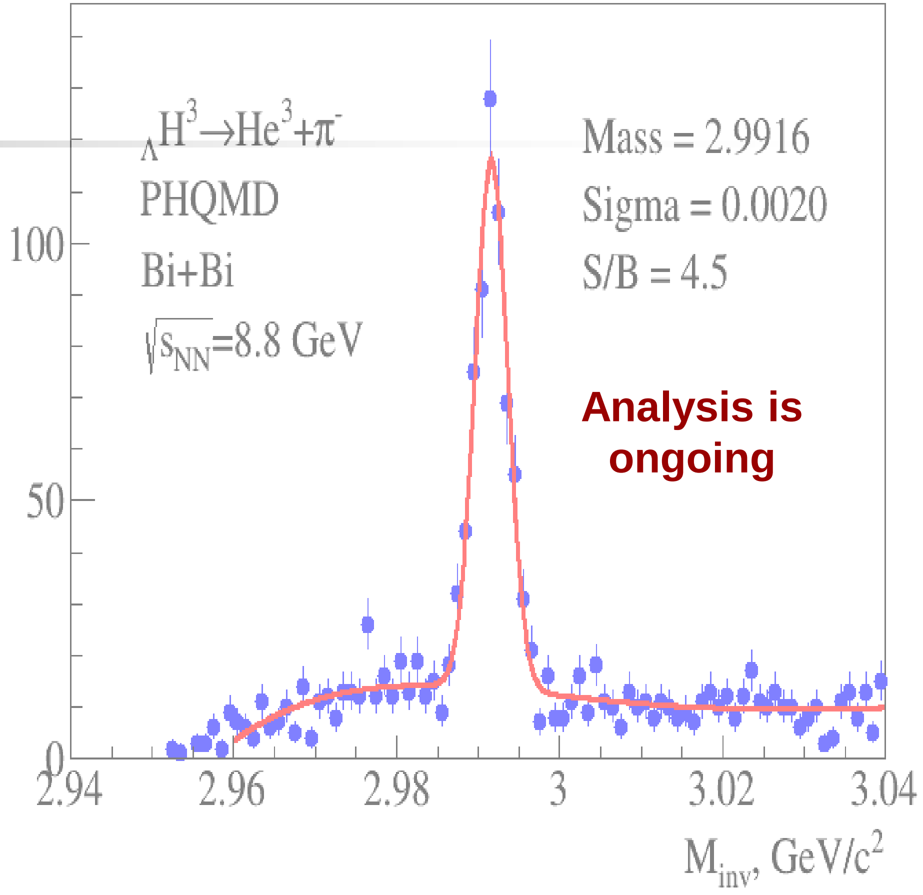
PHQMD: hypernuclei performance at MPD (ongoing analysis)

Reconstructed invariant mass spectra of ${}_{\Lambda}H^3$: 2-prong decay mode.



Analysis is ongoing

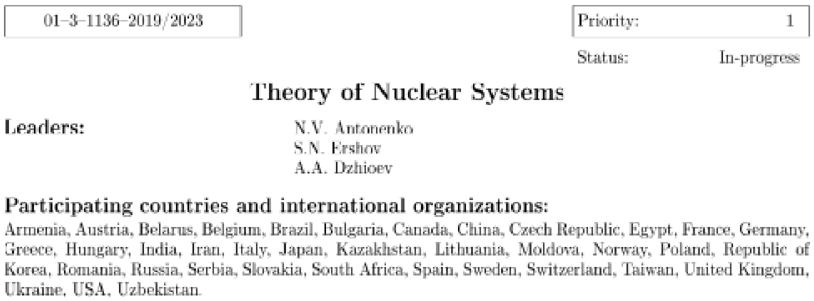
Soft cuts, **large contamination of misidentified daughters mainly from spallation reactions in the material**



Analysis is ongoing

Strong cuts, **better PID and lower contamination of wrongly identified specie, but lower efficiency**

BLTP

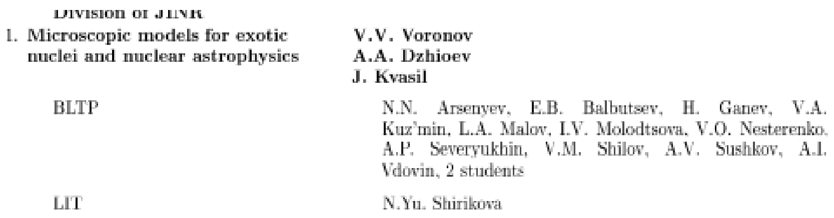


01–3–1136–2019/2023	Priority: 1
	Status: In-progress

Theory of Nuclear Systems

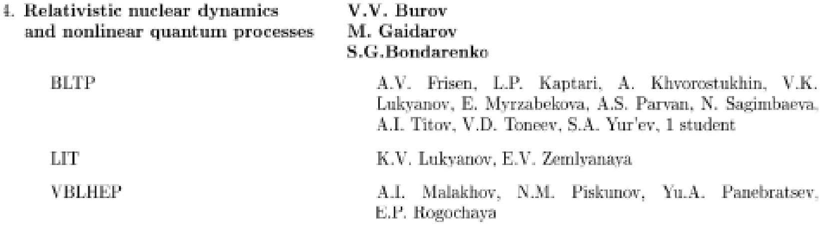
Leaders:
N.V. Antonenko
S.N. Ershov
A.A. Dzhioev

Participating countries and international organizations:
Armenia, Austria, Belarus, Belgium, Brazil, Bulgaria, Canada, China, Czech Republic, Egypt, France, Germany, Greece, Hungary, India, Iran, Italy, Japan, Kazakhstan, Lithuania, Moldova, Norway, Poland, Republic of Korea, Romania, Russia, Serbia, Slovakia, South Africa, Spain, Sweden, Switzerland, Taiwan, United Kingdom, Ukraine, USA, Uzbekistan.



Division of JINR

1. **Microscopic models for exotic nuclei and nuclear astrophysics**	**V.V. Voronov** **A.A. Dzhioev** **J. Kvasil**
BLTP	N.N. Arsenyev, E.B. Balbutsev, H. Ganev, V.A. Kuz'min, L.A. Malov, I.V. Molodtsova, V.O. Nesterenko, A.P. Severyukhin, V.M. Shilov, A.V. Sushkov, A.I. Vdovin, 2 students
LIT	N.Yu. Shirikova



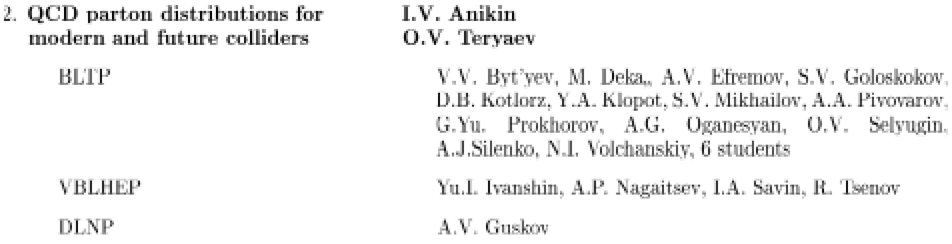
4. **Relativistic nuclear dynamics and nonlinear quantum processes**	**V.V. Burov** **M. Gaidarov** **S.G.Bondarenko**
BLTP	A.V. Frisen, L.P. Kaptari, A. Khvorostukhin, V.K. Lukyanov, E. Myrzabekova, A.S. Parvan, N. Sagimbaeva, A.I. Titov, V.D. Toneev, S.A. Yur'ev, 1 student
LIT	K.V. Lukyanov, E.V. Zemlyanaya
VBLHEP	A.I. Malakhov, N.M. Piskunov, Yu.A. Panebratsev, E.P. Rogochaya

01–3–1135–2019/2023	Priority: 1
	Status: New

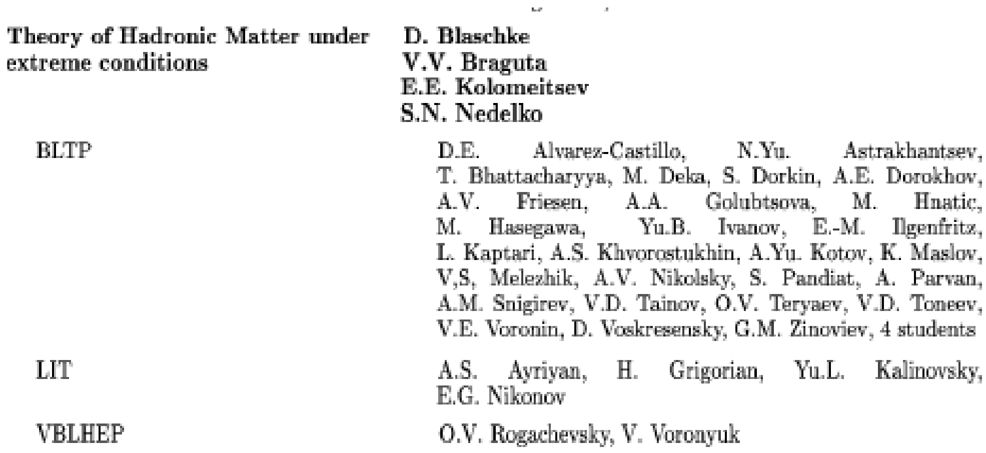
Fundamental Interactions of Fields and Particles

Leaders:
D.I. Kazakov
O.V. Teryaev

Participating countries and international organizations:
Armenia, Azerbaijan, Belarus, Bulgaria, Canada, CERN, Chile, China, Czech Republic, Finland, France, Georgia, Germany, Hungary, ICTP, Italy, Japan, Kazakhstan, Mexico, Mongolia, Netherlands, Norway, Portugal, Poland, Republic of Korea, Russia, Serbia, Slovakia, Spain, Sweden, Switzerland, USA, Ukraine, United Kingdom, Uzbekistan, Vietnam.



2. **QCD parton distributions for modern and future colliders**	**I.V. Anikin** **O.V. Teryaev**
BLTP	V.V. Byt'yev, M. Deka., A.V. Efremov, S.V. Goloskokov, D.B. Kotlorz, Y.A. Klopot, S.V. Mikhailov, A.A. Pivovarov, G.Yu. Prokhorov, A.G. Oganesyan, O.V. Selyugin, A.J.Silenko, N.I. Volchanskiy, 6 students
VBLHEP	Yu.I. Ivanshin, A.P. Nagaitsev, I.A. Savin, R. Tsenov
DLNP	A.V. Guskov



Theory of Hadronic Matter under extreme conditions	**D. Blaschke** **V.V. Braguta** **E.E. Kolomeitsev** **S.N. Nedelko**
BLTP	D.E. Alvarez-Castillo, N.Yu. Astrakhantsev, T. Bhattacharyya, M. Deka, S. Dorkin, A.E. Dorokhov, A.V. Friesen, A.A. Golubtsova, M. Hnatic, M. Hasegawa, Yu.B. Ivanov, E.-M. Ilgenfritz, L. Kaptari, A.S. Khvorostukhin, A.Yu. Kotov, K. Maslov, V,S, Melezhik, A.V. Nikolsky, S. Pandiat, A. Parvan, A.M. Snigirev, V.D. Tainov, O.V. Teryaev, V.D. Toneev, V.E. Voronin, D. Voskresensky, G.M. Zinoviev, 4 students
LIT	A.S. Ayriyan, H. Grigorian, Yu.L. Kalinovsky, E.G. Nikonov
VBLHEP	O.V. Rogachevsky, V. Voronyuk

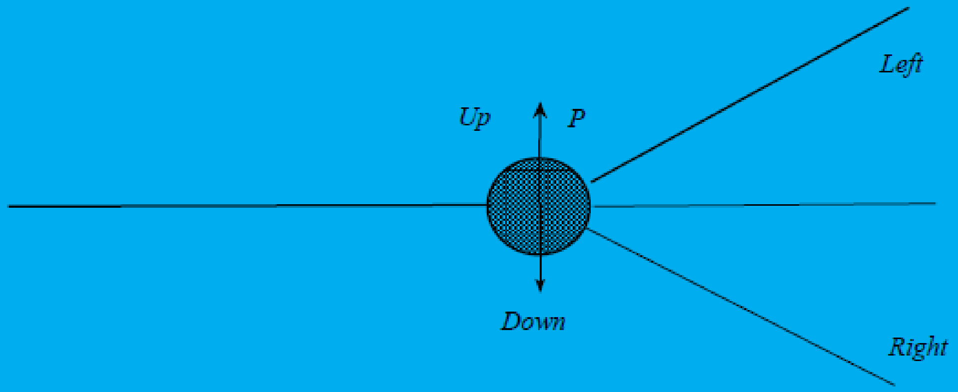
Seminar "Theory of Hadronic Matter under Extreme Conditions"
http://theor.jinr.ru/~klopot/seminarTHMUEC.html#16012020

- E.- M. Ilgenfritz, S. Nedelko, O.T.

- 127 talks
- 1st - 16.11.2011 **P.V. Buividovich (ITEP)** *"Nonrelativistic and Relativistic Hydrodynamics on the Lattice"*
  Abstract:
  Lattice discretization of kinetic Boltzmann equation is one of efficient ways for numerical simulations in viscous nonrelativistic hydrodynamics, which allows to consider turbulence, convection and other non-equilibrium processes. We consider the derivation of macroscopic hydrodynamical equations from continuum Boltzmann equation and from its lattice discretization. It turns out that numerical solution of Boltzmann equation on the lattice is simpler than the solution of the corresponding Navier-Stokes equation. We also consider the generalization of this approach to relativistic theory, in particular, to the simulations of quark-gluon plasma.

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

Λ-polarisation

- Self-analyzing in weak decay
- 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
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Search by STAR (Selyuzhenkov et al.'07) : polarization NOT found at % level!
- Maybe due to locality of LS coupling while large orbital angular momentum is distributed
- How to transform rotation to spin?

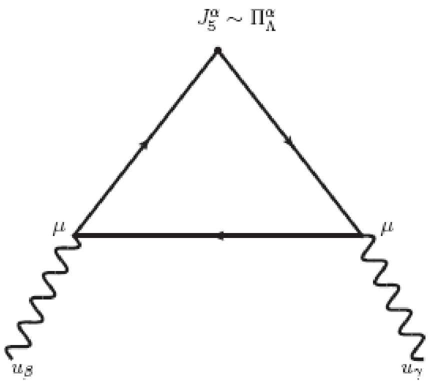
Anomalous mechanism – Axial Vortical Effect: polarization similar to CM(V)E

- 4-Velocity is also a GAUGE FIELD:

V.I. Zakharov (talk)

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

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



Gluonic spin

- Gluons contribute to the proton structure
- Mass (predominantly – most of visible Universe mass is “gluonic”)
- Longtudinal momentum (~50%)
- Spin (~10%)
- Orbital momentum, diverse transverse structure – SPD (talk of A. Guskov)

Axial Anomaly for HIC: Energy dependence

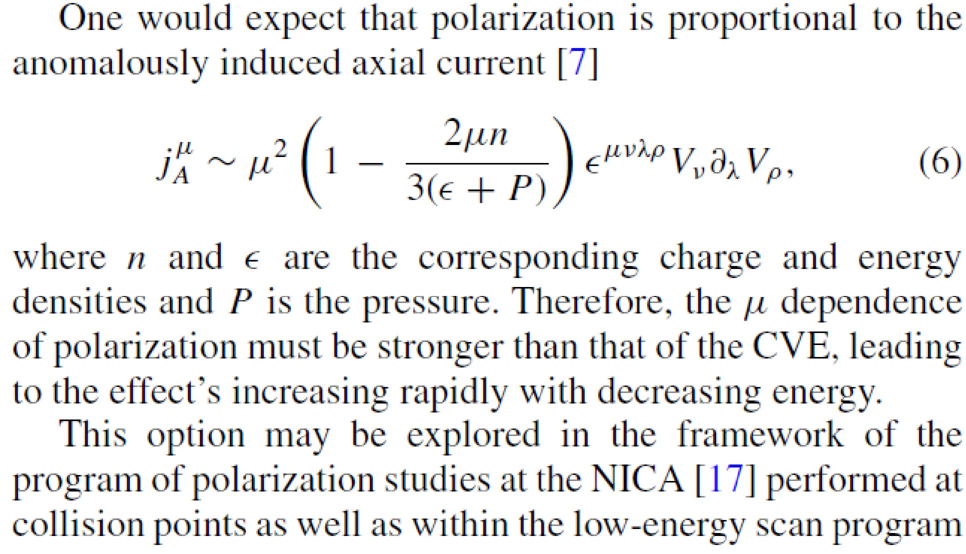
- Coupling -> chemical potential

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

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

One might compare the predictions 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)

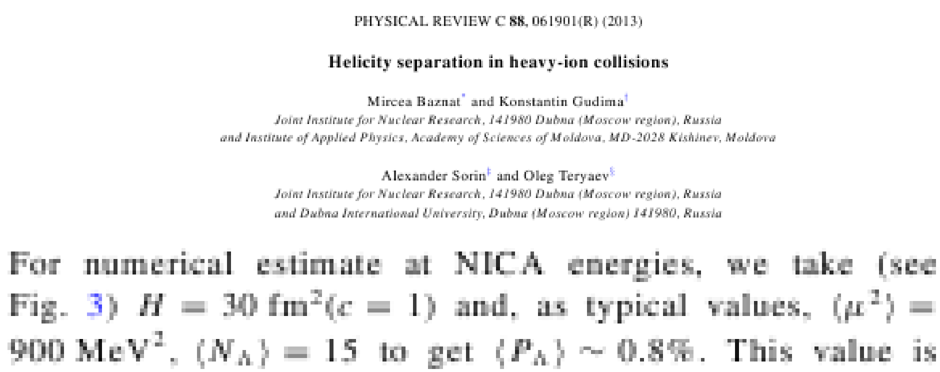


One would expect that polarization is proportional to the anomalously induced axial current [7]

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

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.



RAPID COMMUNICATIONS

PHYSICAL REVIEW C 88, 061901(R) (2013)

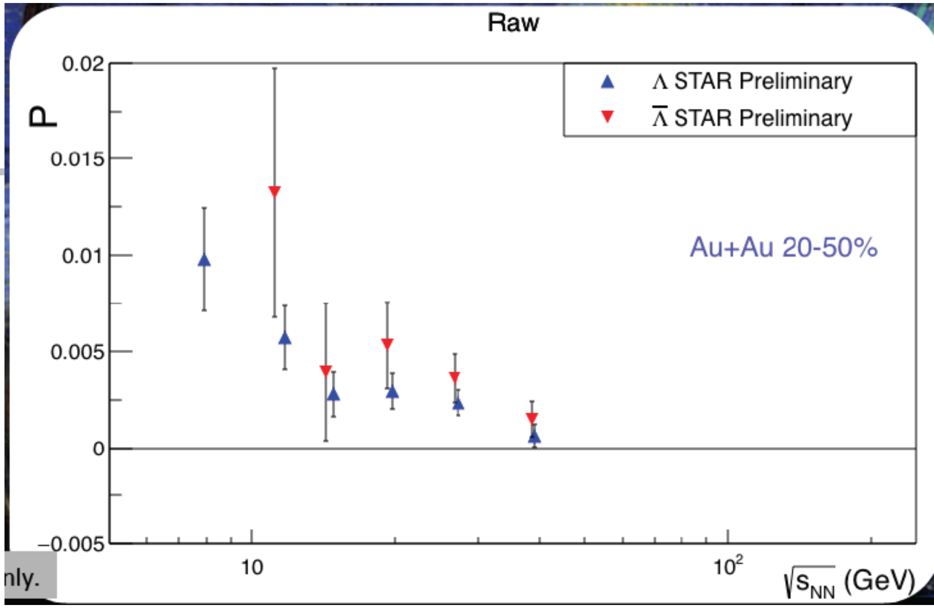
Helicity separation in heavy-ion collisions

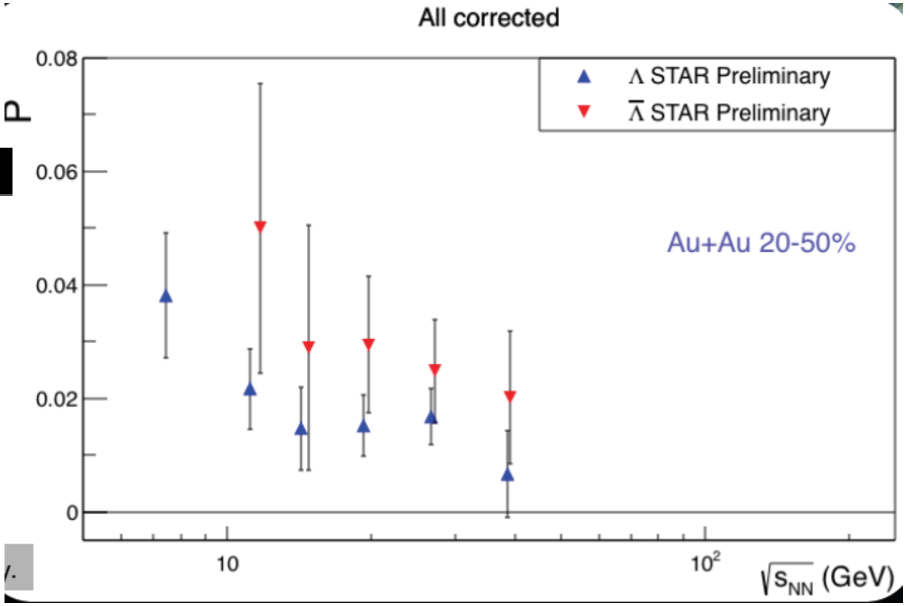
Mircea Baznat[*] and Konstantin Gudima[†]
Joint Institute for Nuclear Research, 141980 Dubna (Moscow region), Russia
and Institute of Applied Physics, Academy of Sciences of Moldova, MD-2028 Kishinev, Moldova

Alexander Sorin[‡] and Oleg Teryaev[§]
Joint Institute for Nuclear Research, 141980 Dubna (Moscow region), Russia
and Dubna International University, Dubna (Moscow region) 141980, Russia

For numerical estimate at NICA energies, we take (see Fig. 3) $H = 30\ \mathrm{fm}^2 (c = 1)$ and, as typical values, $\langle\mu^2\rangle = 900\ \mathrm{MeV}^2$, $\langle N_\Lambda\rangle = 15$ to get $\langle P_\Lambda\rangle \sim 0.8\%$. This value is

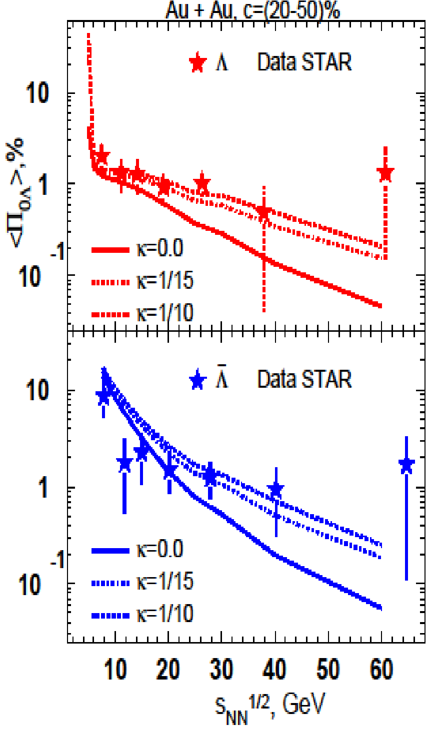
M. Lisa et al (STAR collaboration) Nature,2017



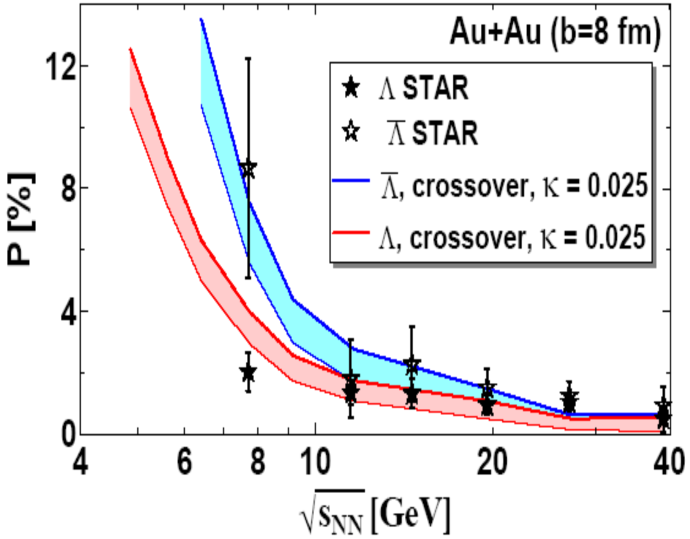


Polarization in various models of vorticity: 3-Fluid hydro (talk of Yu. Ivanov)

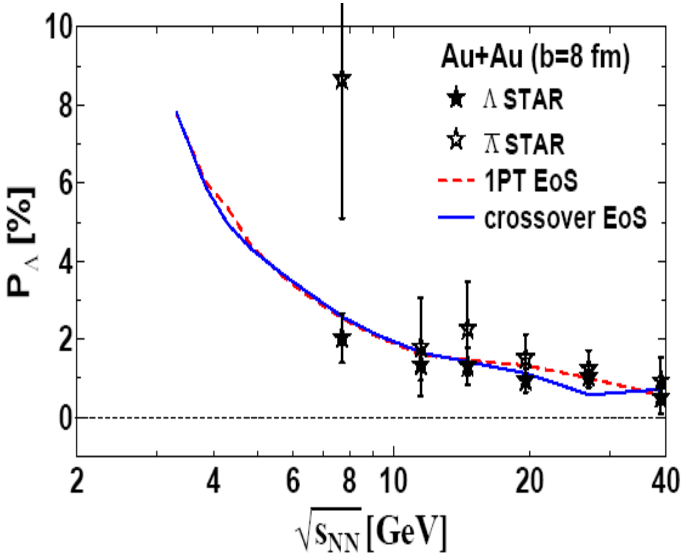
Baznat, Gudima, Sorin, Teryaev, PRC 97, 041902 (2018)



Ivanov, 2006.14328



Ivanov, Soldatov, PRC 102, 02491



NICA data will distinguish between AVE and thermodynamic predictions

Interdisciplinary aspects

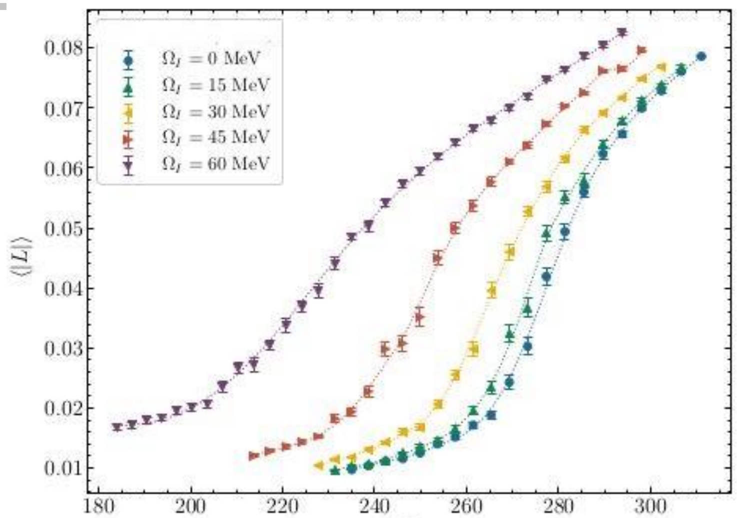
- Models for vorticity: PHSD, QGSM -> DCM-SMM (LIT)
- Condensed matter: semimetals, graphene, conductivity in magnetic field (similar to vector mesons alignment)
- Gravity : indirect way to probe the effects on Black Hole horizon; Instability: similar to fall into BH (talks of V.I. Zakharov, G. Prokhorov)
- Holography (talks of I. Arefeva, A. Golubtsova, K. Rannu, P. Slepov)
- Lattice: rotation of gluonic matter

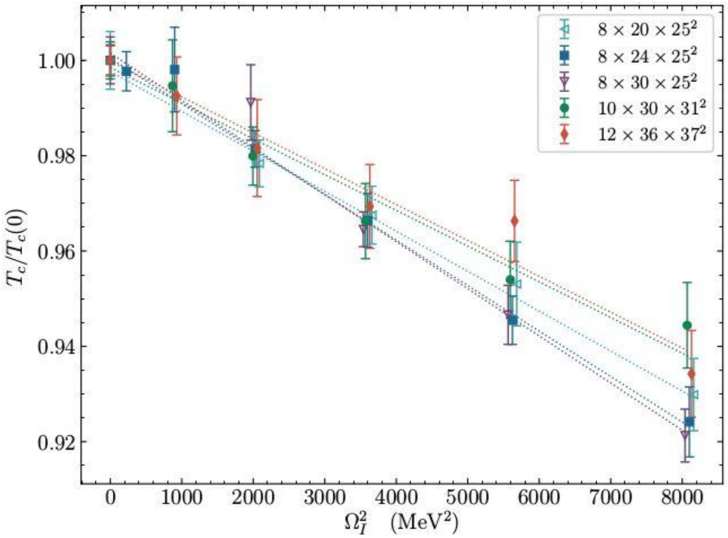
Lattice simulation of rotating gluodynamics (talks of V. Braguta, A. Roenko)

- Reference frame which rotates with QGP => Simulation with external gravitational field
- Sign problem => Simulation with imaginary angular velocity
- Periodic, Dirichlet, Neumann boundary conditions
- Critical temperature of confinement/deconfinement through measurement of Polyakov loop
- Results are well described by

$$\frac{T_c(\boldsymbol{\Omega})}{T_c(0)} = 1 + C_2\, \boldsymbol{\Omega}^2$$

- Critical temperature rises with angular velocity





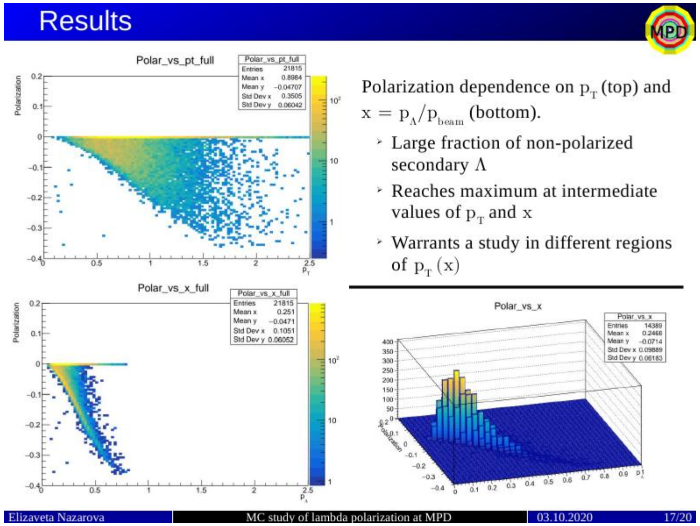
Inclusive polarization for MPD

Monte-Carlo study of $\Lambda(\bar{\Lambda})$ polarization at MPD

Elizaveta Nazarova[1], Alexander Zinchenko[1], Oleg Teryaev[1], Raimbek Akhat[1,2], Baznat Mircea[1,3] (?)

for the MPD collaboration

The 5th international conference on particle physics and astrophysics (ICPPA-2020)

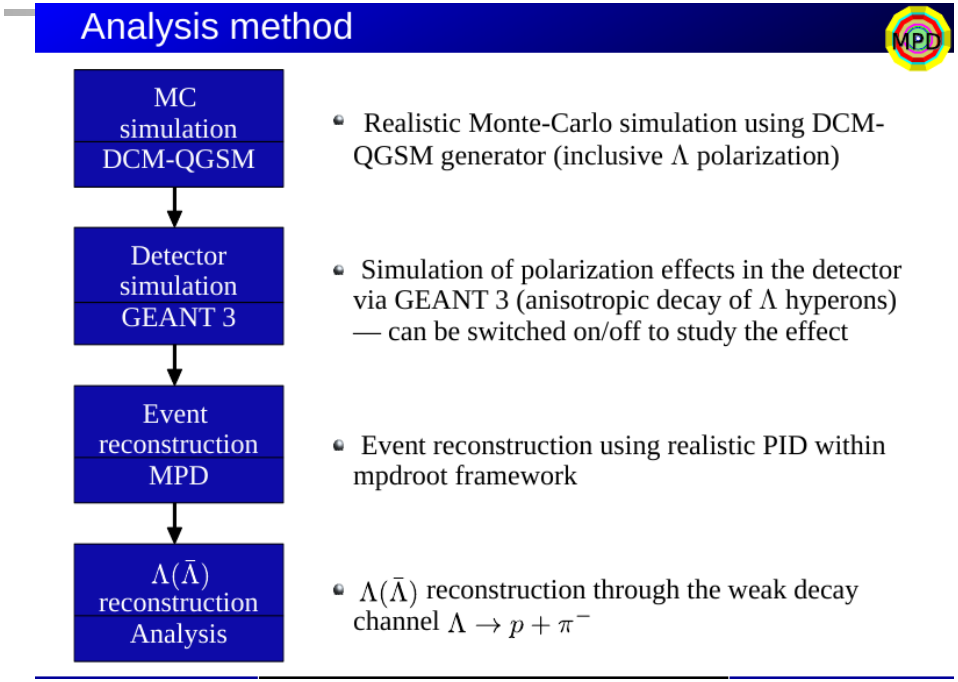


Results

Polarization dependence on p_T (top) and $x = p_\Lambda / p_{beam}$ (bottom).

- Large fraction of non-polarized secondary Λ
- Reaches maximum at intermediate values of p_T and x
- Warrants a study in different regions of p_T (x)

Elizaveta Nazarova | MC study of lambda polarization at MPD | 03.10.2020 | 17/20



Analysis method

MC simulation DCM-QGSM

- Realistic Monte-Carlo simulation using DCM-QGSM generator (inclusive Λ polarization)

Detector simulation GEANT 3

- Simulation of polarization effects in the detector via GEANT 3 (anisotropic decay of Λ hyperons) — can be switched on/off to study the effect

Event reconstruction MPD

- Event reconstruction using realistic PID within mpdroot framework

$\Lambda(\bar{\Lambda})$ reconstruction Analysis

- $\Lambda(\bar{\Lambda})$ reconstruction through the weak decay channel $\Lambda \to p + \pi^-$

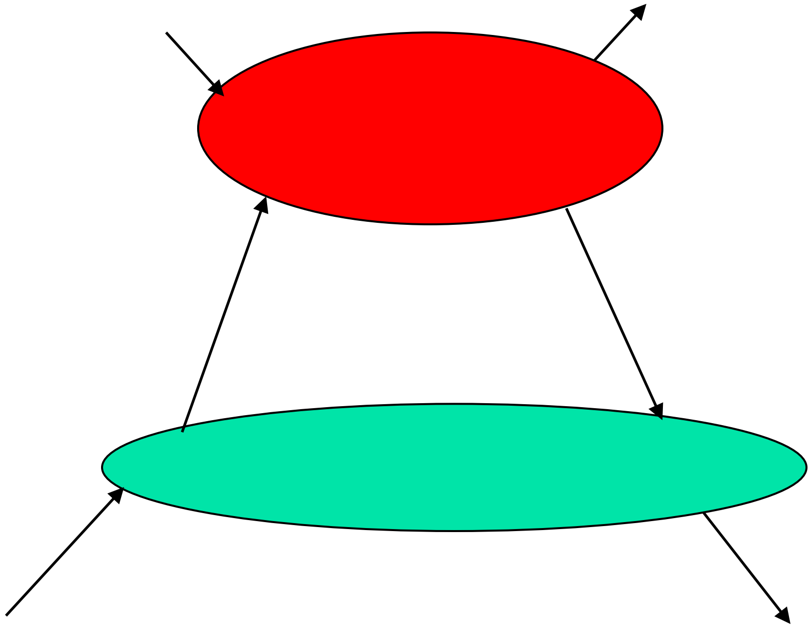
Conclusions

- JINR physicists actively participate in the realization and development of NICA physics program

- NICA program and its support by RFBR is stimulating the interactions inside and outside JINR and progress in interdisciplinary research

Factorization (lh-> DIS, DVCS)

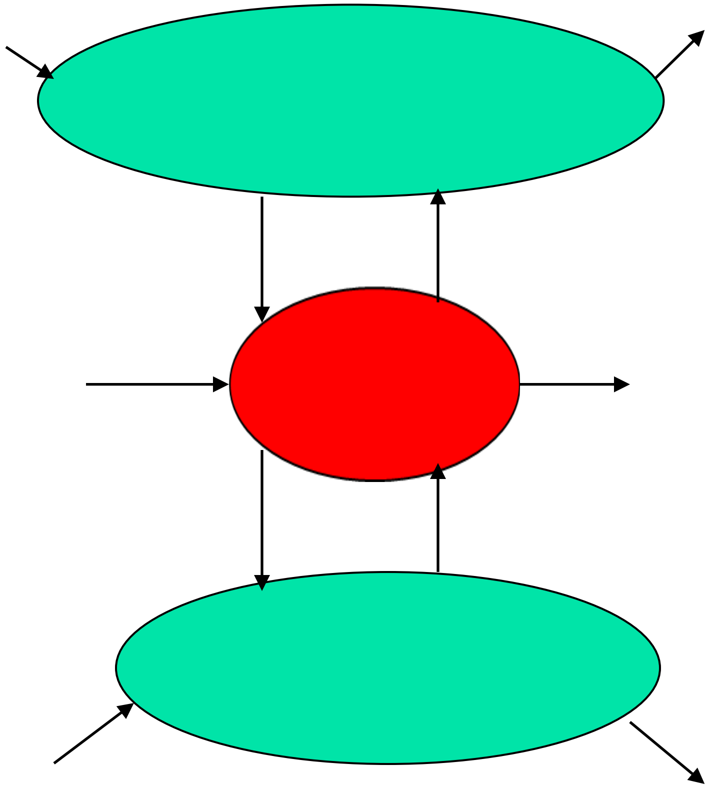
- Short and hard distances separated (JINR – Efremov, Radyushkin; Higher twist – Efremov,OT; DVCS-Anikin,OT)



BACKUP

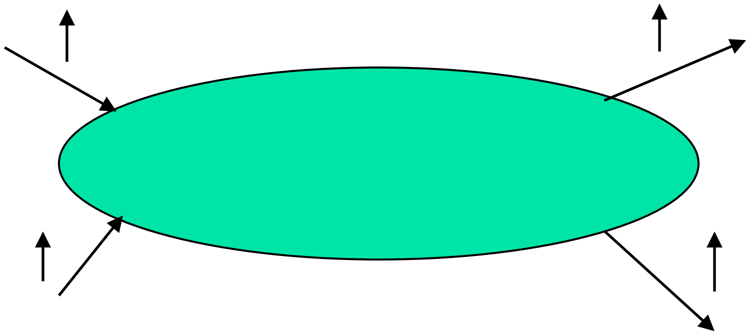
Factorization for DY – type Inclusive and Exclusive (talk of S. Goloskokov)

- 2 hadrons participate



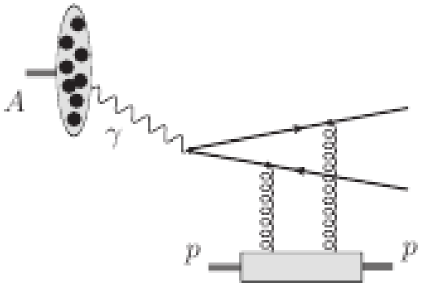
Types of parton distributions

- Most general – Wigner function: non-symmetric partonic and hadronic momenta with transverse components
- 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 (R.Tsenov)!?

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 (talk of V. Saleev)
- 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”)

LETTER

NATURE | www.nature.com/nature

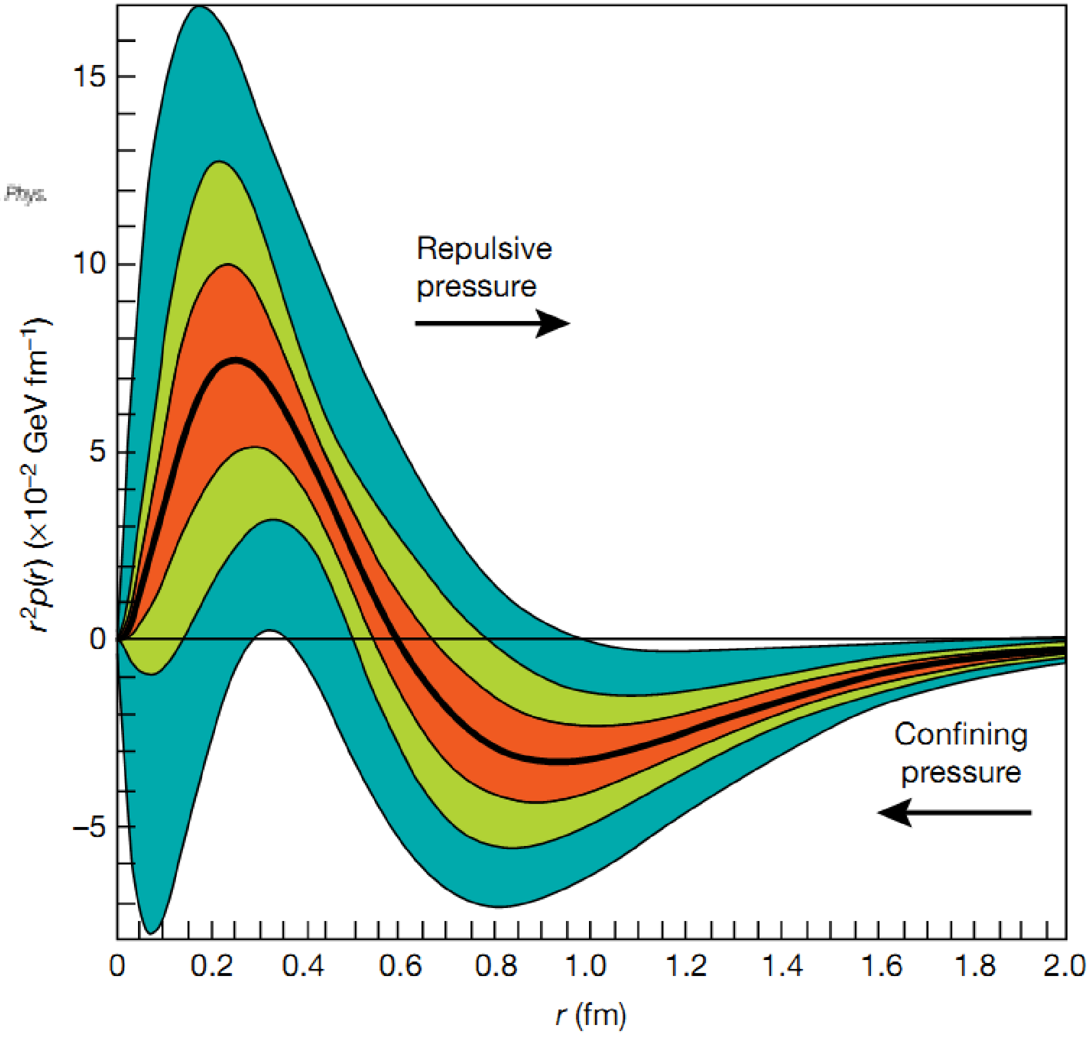
https://doi.org/10.1038/s41586-018-0060-z

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.* **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)

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

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

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:

LETTER

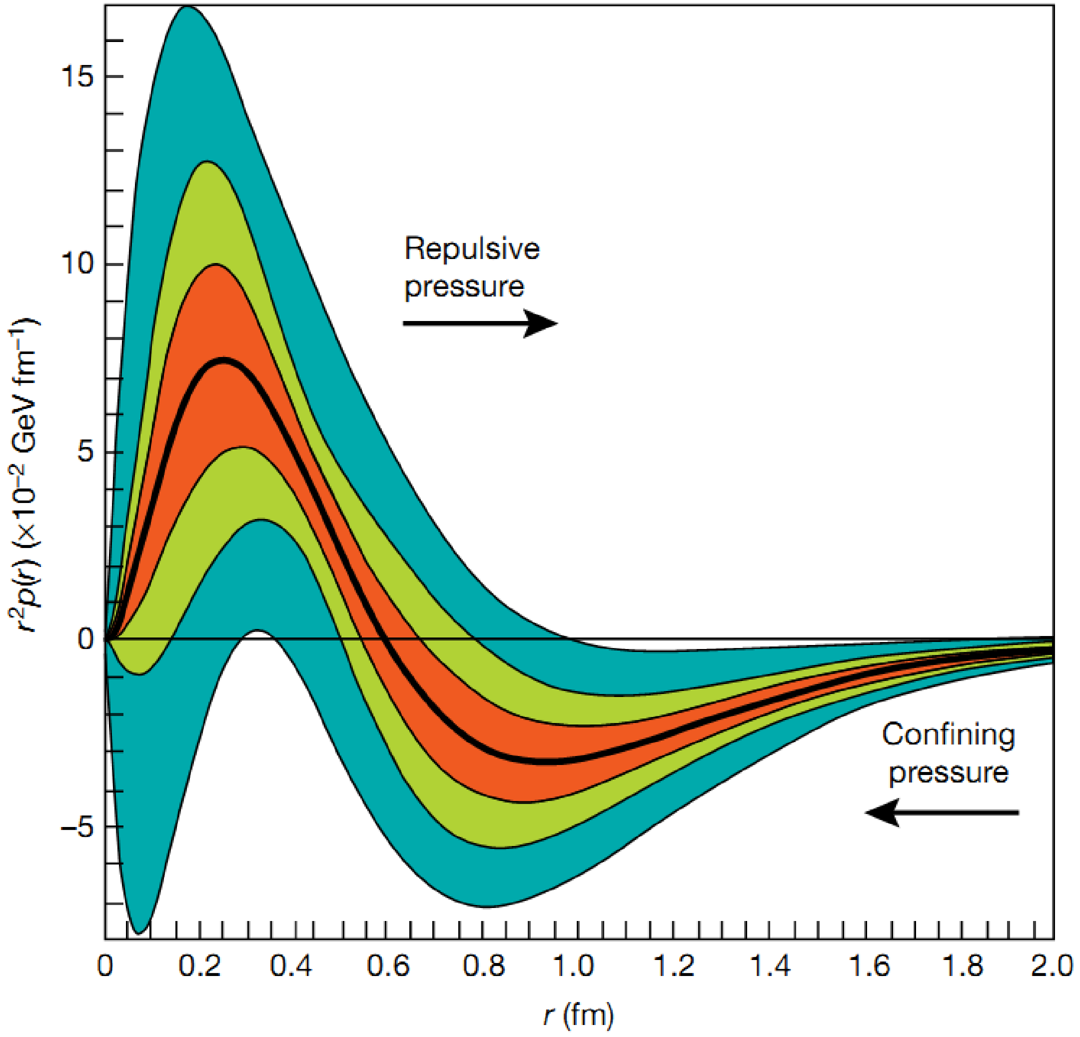
NATURE | www.nature.com/nature

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

The pressure distribution inside the proton

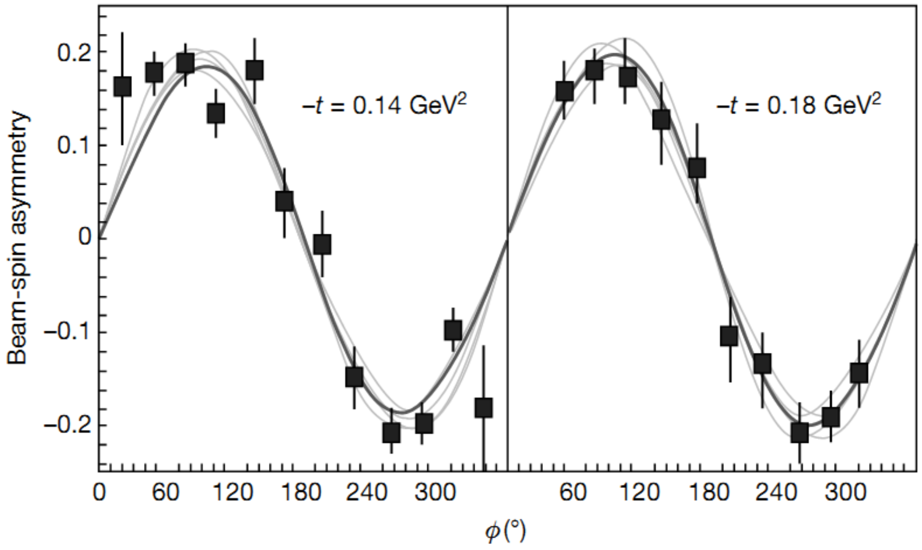
V. D. Burkert[1]*, L. Elouadrhiri[1] & F. X. Girod[1]

- Largest ever (~Λ^4QCD) ~10^{35} pascals



Experiment

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



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

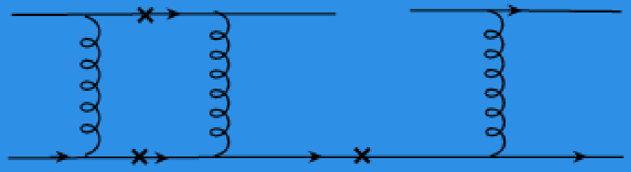
(1960):

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):

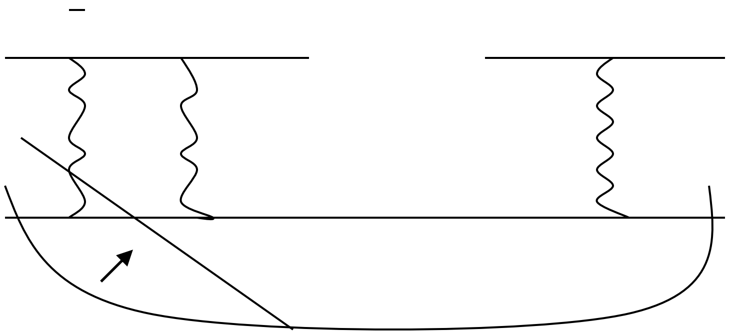


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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

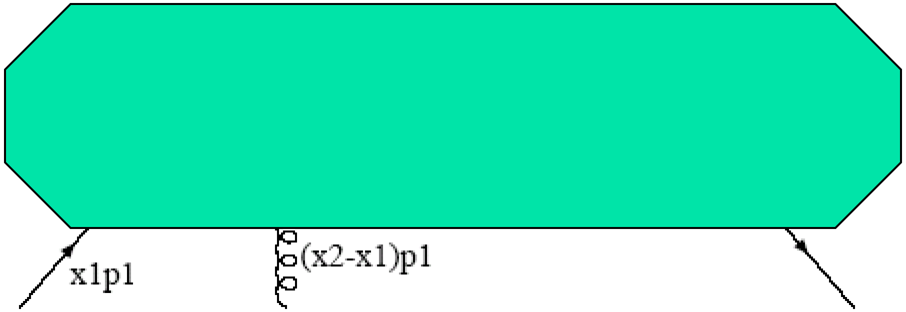
Short+ large overlap– twist 3

- 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

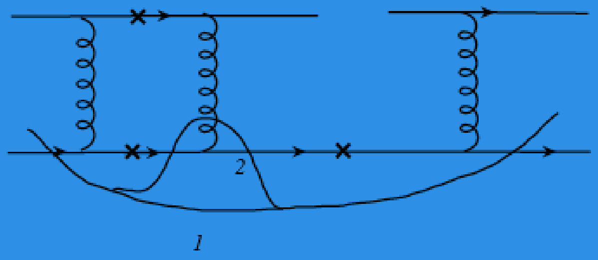


- Non-perturbative NUCLEON structure – physically mean the quark scattering in external gluon field of the HADRON.
- Depend on TWO parton momentum fractions
- For small transverse momenta – quark momentum fractions are close to each other- gluonic pole; probed if : $Q >> P_T >> M$

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

Twist 3 correlators

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



At short distances - Loop → Born diagram

At Large distances - quark distribution → 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

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

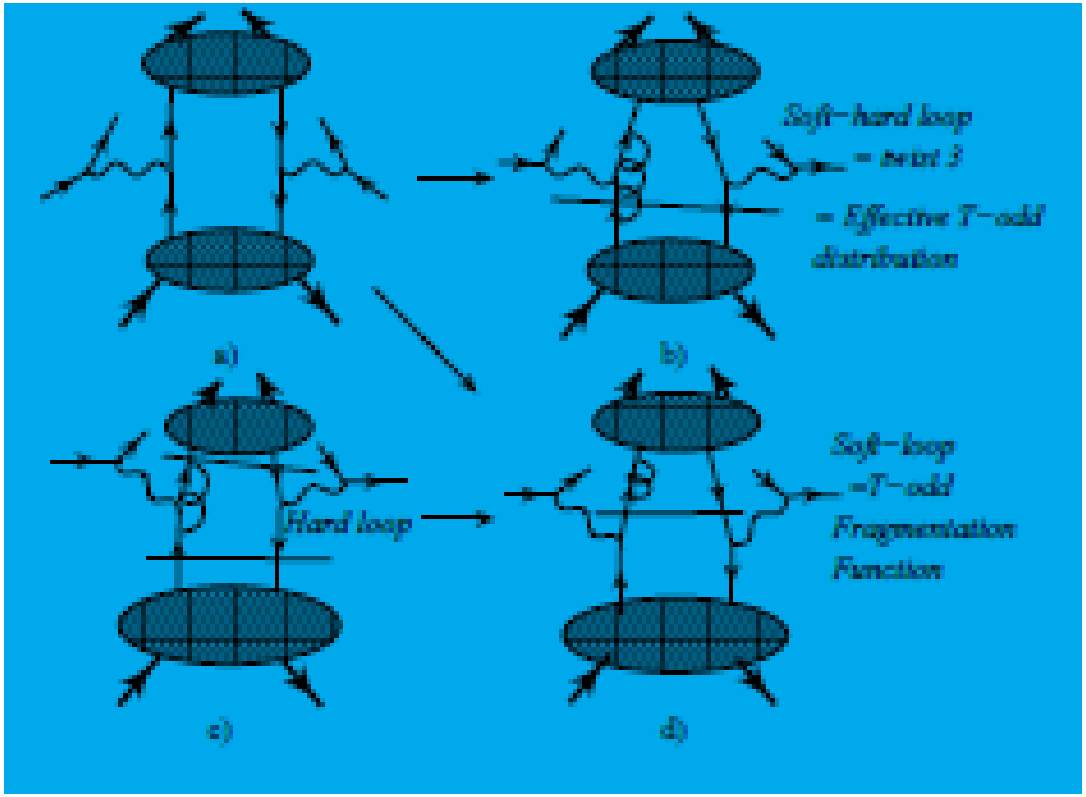
Further shift of phases completely to large distances - T-odd fragmentation functions. Leading twist transversity distribution - no hadron mass suppression.

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

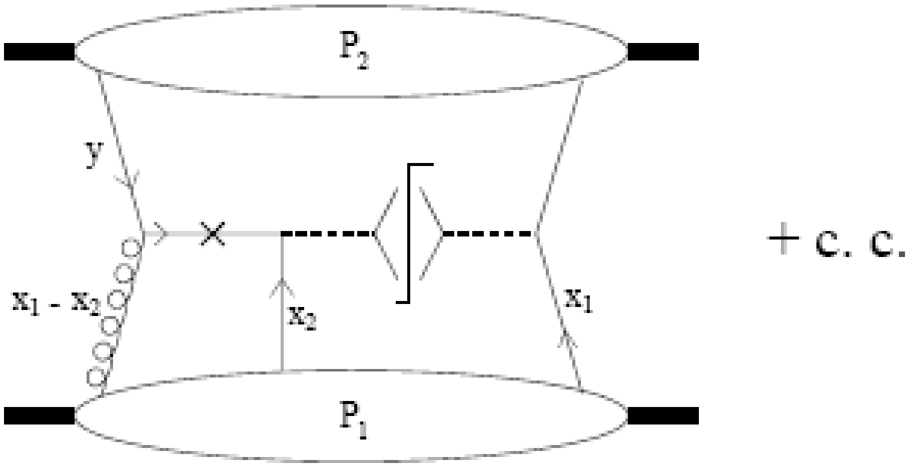
SSAs in SIDIS

- Various opportunities for phases generation



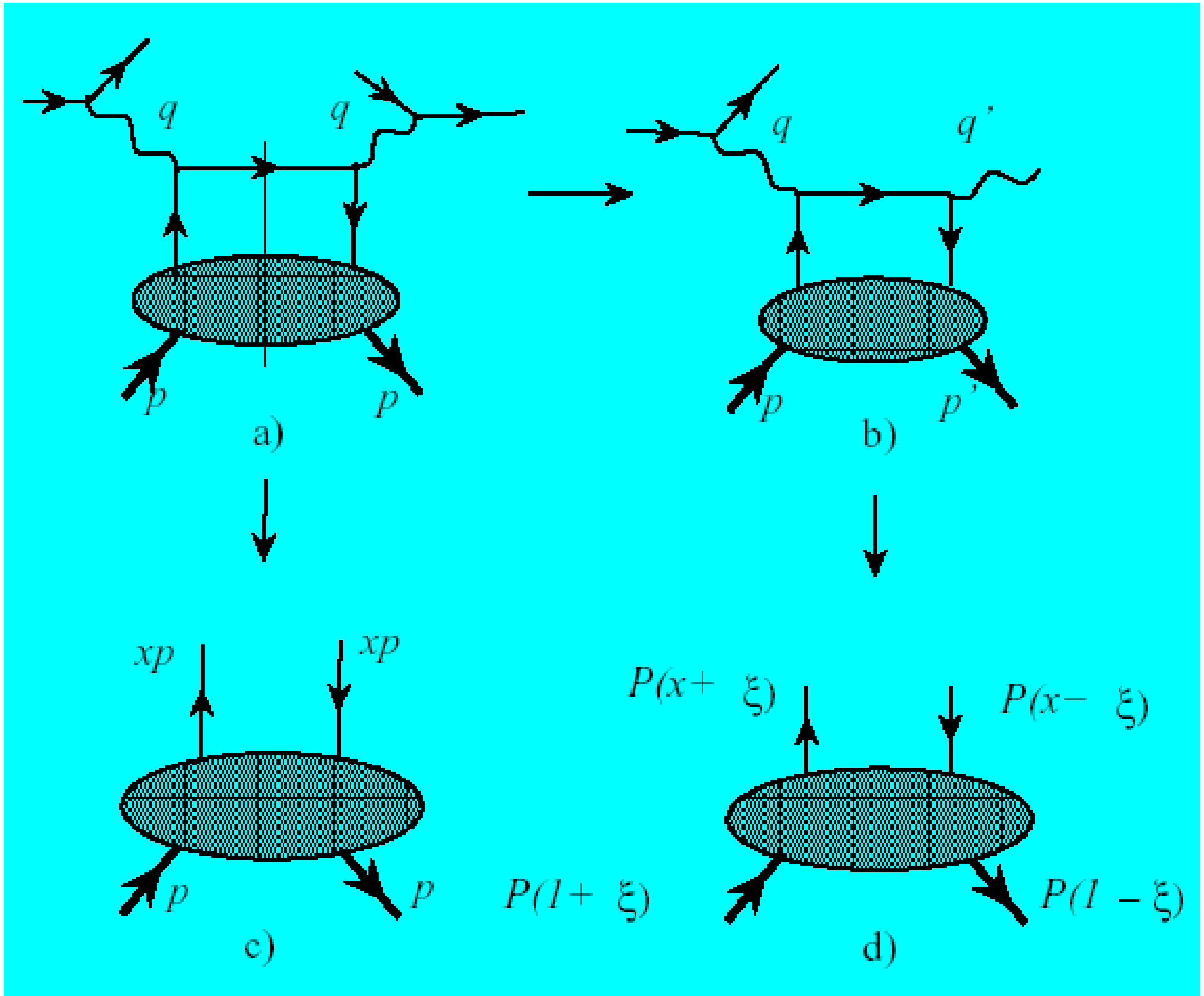
SSA in DY

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

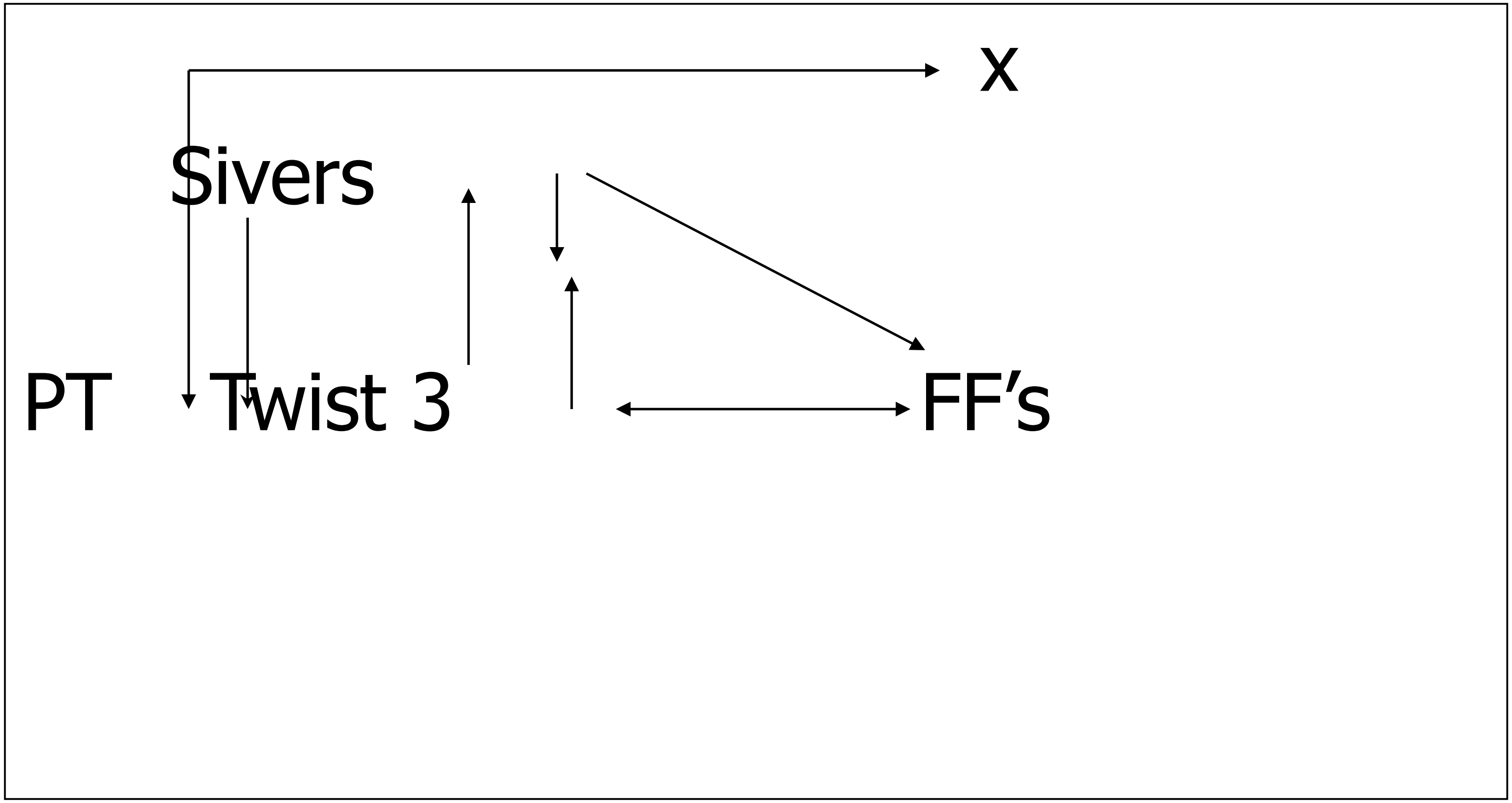


$$A = g\,\frac{\sin 2\theta\ \cos\phi\left[T(x,x) - x\frac{dT(x,x)}{dx}\right]}{M\left[1+\cos^2\theta\right]q(x)}$$

GPDs – another source of T-odd effects



Kinematical domains for SSA’s



x

Sivers

PT Twist 3 FF’s

Global polarization

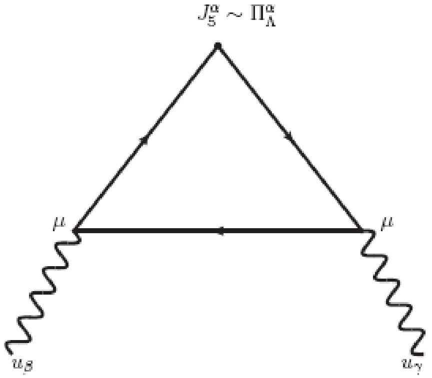
- Global polarization normal to REACTION plane
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Search by STAR (Selyuzhenkov et al.’07) : polarization NOT found at % level!
- Maybe due to locality of LS coupling while large orbital angular momentum is distributed
- How to transform rotation to spin?

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

M. Lisa, for the STAR collaboration , QCD Chirality Workshop, UCLA, February 2016;
SQM2016, Berkeley, June 2016

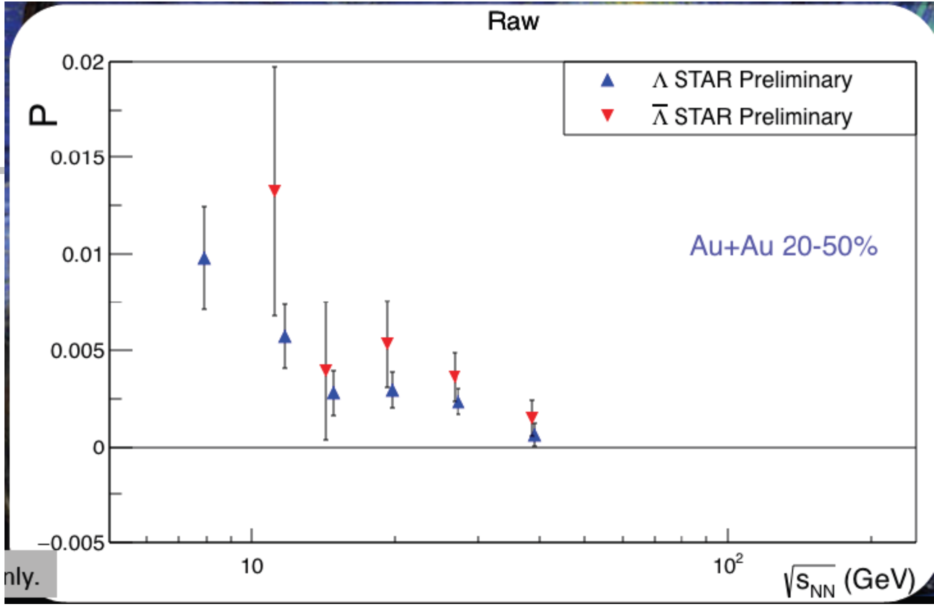
O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

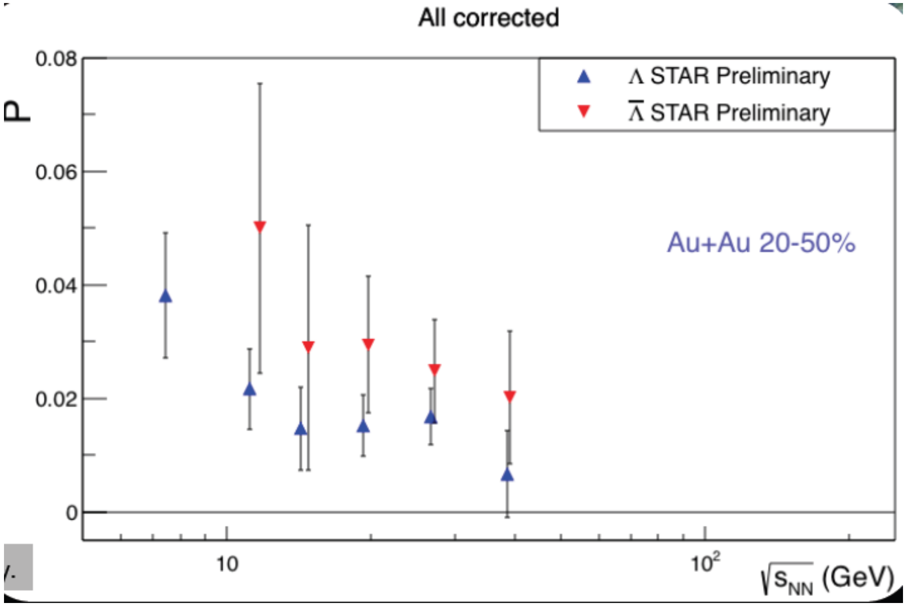
One would expect that polarization is proportional to the anomalously induced axial current [7]

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

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.

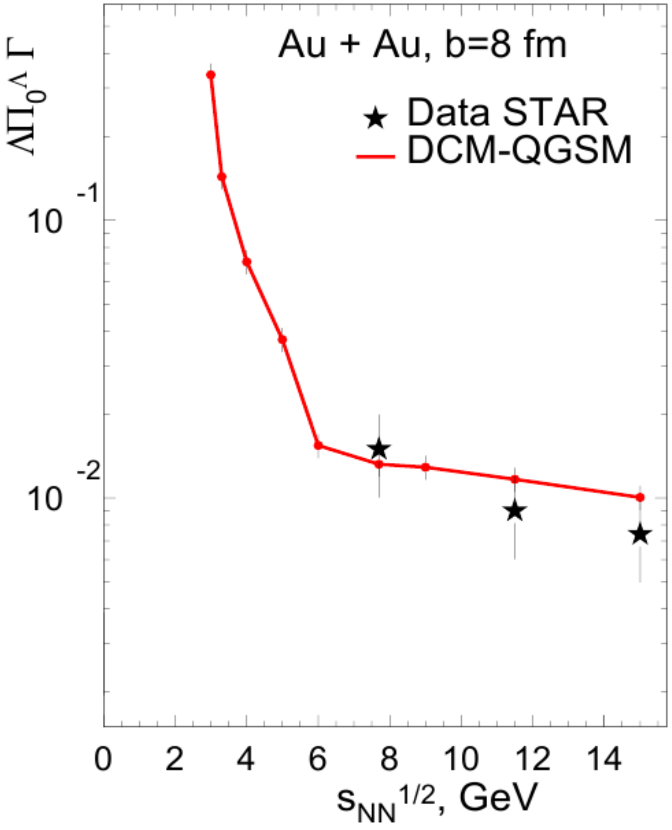




Another NATURE article

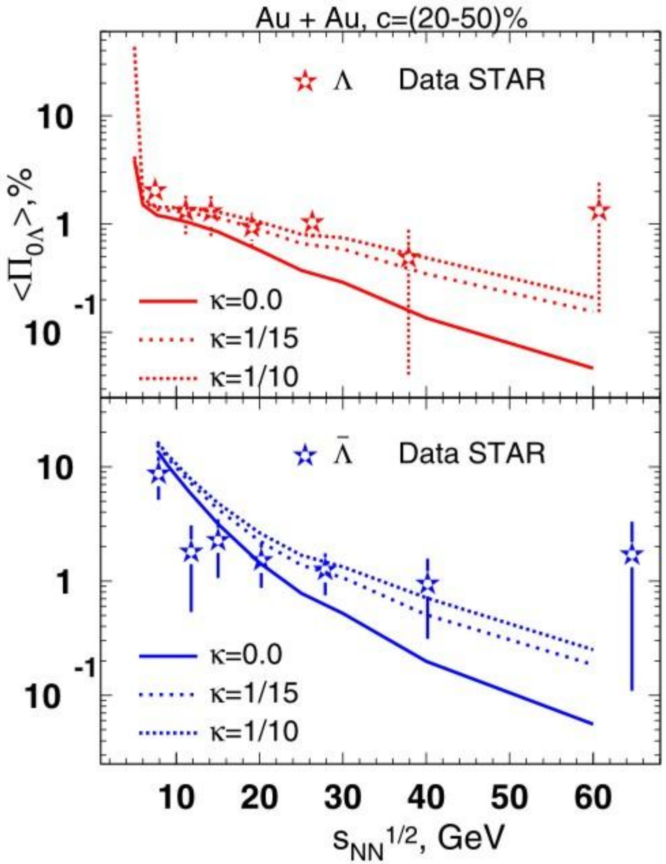
- **Global Λ hyperon polarization in nuclear collisions**
- The STAR Collaboration
- Journal name:Nature Volume: 548, Pages:62–65 Date published: (03 August 2017

Energy dependence (Baznat, Gudima, Sorin,OT)



- Growth at low energy
- Close to STAR data!
- Baryon-antibaryon successfully described - but a lot of work ahead

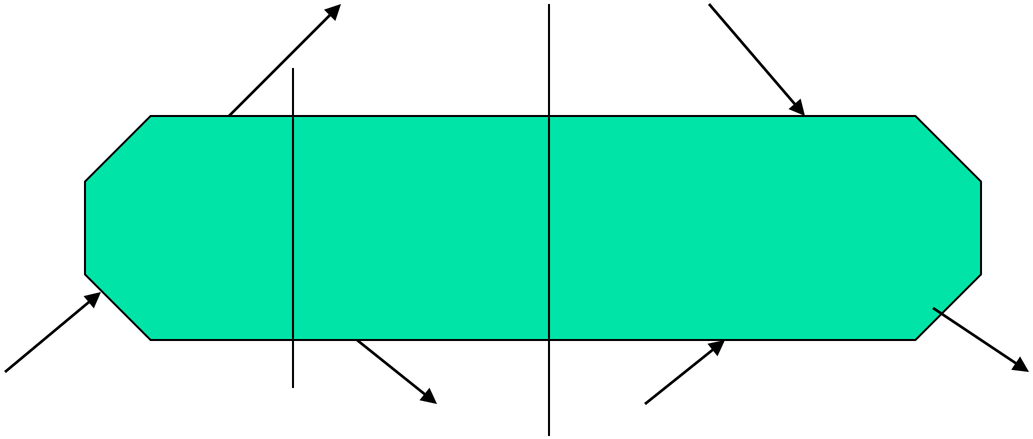
Λ vs Anti Λ


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

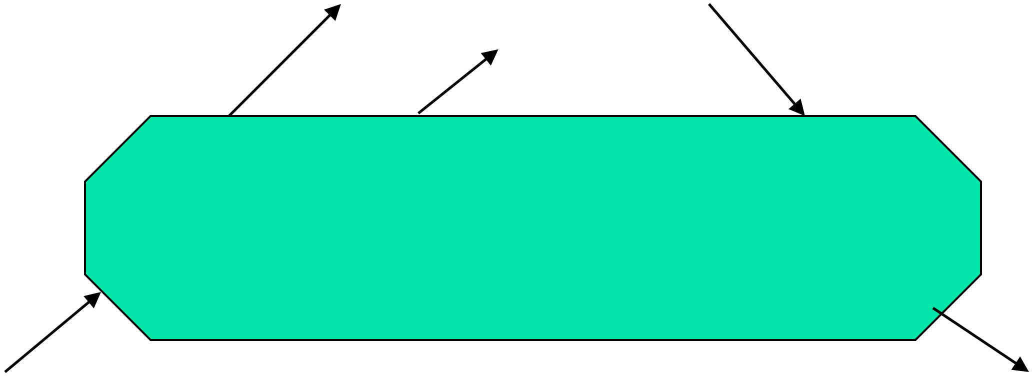
Fracture functions

- 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



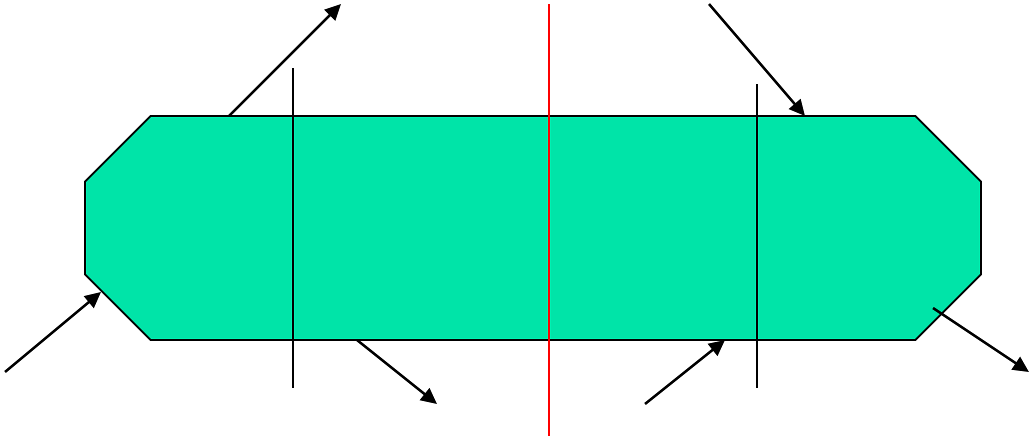
HT parton distributions



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



Problems for NICA

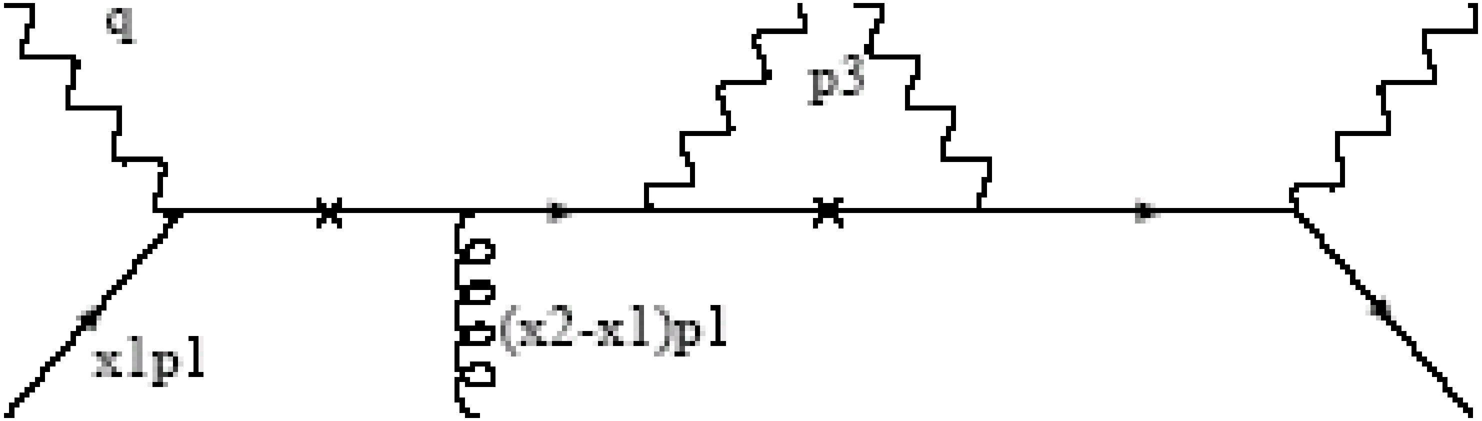
- SPD LoI: TMDs@DY
- TMDs – J/Ψ, ɣ
- GPDs: Exlusive DY-type (smaller x-section but lower background)
- GPDs from TMDs (pressure?!)
- Fracture – SSAs with extra hadrons
- Relation of HIC/hadronic spin (MPD/SPD) – polarization for hadrons, light and heavy ions

- BACKUP

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

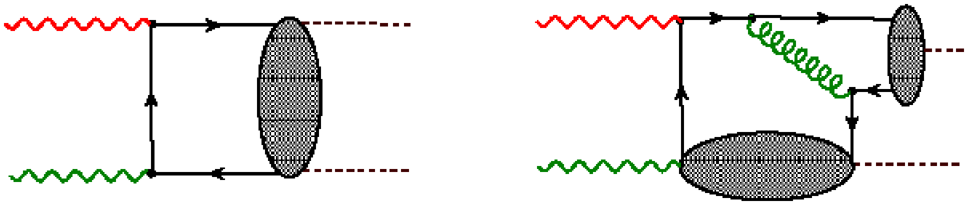
- Relation between Sivers and AMM known on the level of matrix elements (Brodsky, Schmidt, Burkardt)
- Phase?
- Duality for observables?
- Solution: SSA in DY

SSA in exclusive limit

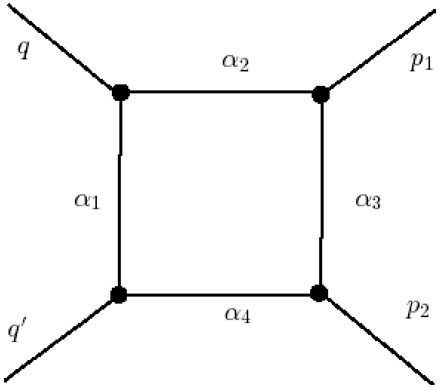
- Proton-antiproton – valence annihilation - cross section is described by Dirac FF squared
- The same SSA due to interference of Dirac and Pauli FF's with a phase shift
- Exclusive large energy limit; x -> 1 : (d/dx)T(x,x)/q(x) -> Im F2/F1
- No suppression of large x – large E704 SSA
- Positivity: Twist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

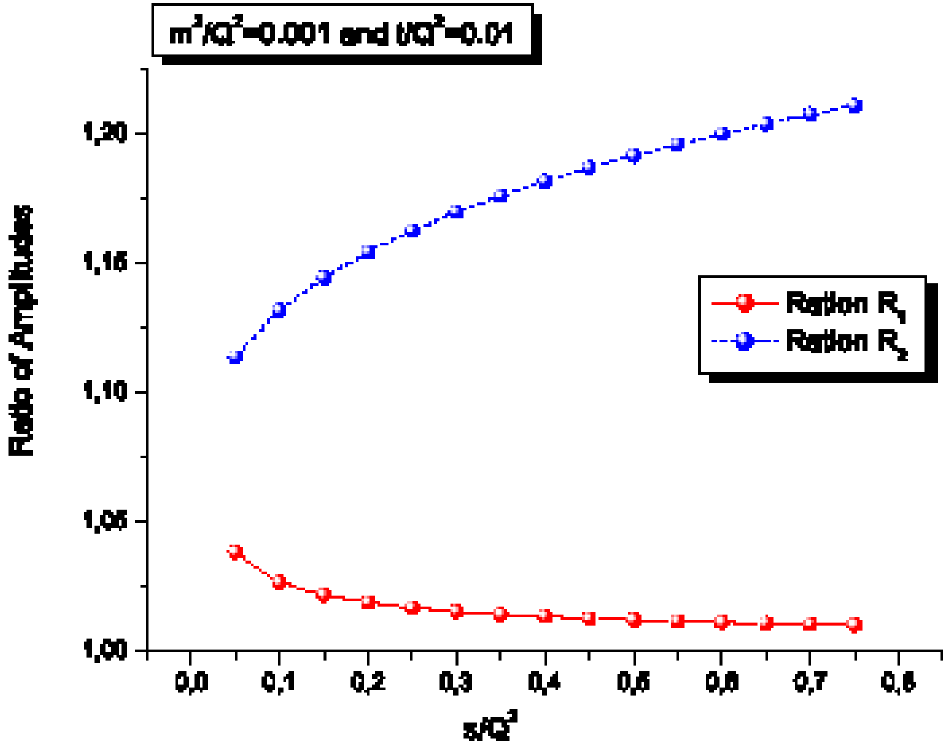


- Scalar model - asymptotics(Efremov, Ginzburg, Radyushkin…)



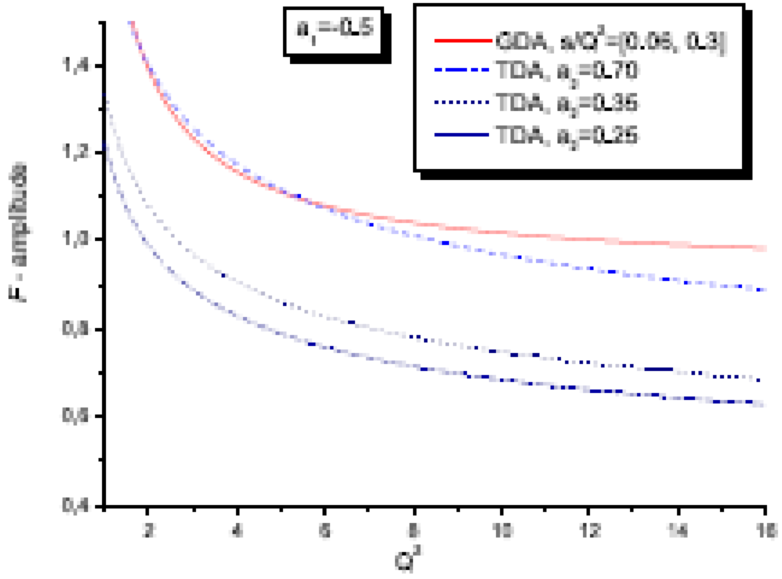
Duality in scalar model

- “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

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

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

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

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)

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

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

- 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

$$M = \langle P'|J_q^\mu|P\rangle A_\mu(q) \qquad M = \frac{1}{2}\sum_{q,G}\langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$$

- 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 ≈ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM, confirmed recently)