(@COMPASS&NICA)

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Outline

- Angular distributions and positivity
- (Very) simple theory for LT
- Semi-exclusive pion-nucleon DY (COMPASS) and pion DA
- Exclusive DY (COMPASS,NICA) and TDA
- Transverse SSA in DY: contour gauge and factor 2
- BG-type duality in DY(@COMPASS&PANDA): Sivers function and time-like formfactors
- NICA&DY
- Spin effects in HIC

QCD factorization mechanisms

- Hard and Soft parts may change simultaneously for transition to diffferent kinematical domains
- Various factorization mechanisms (duality, matching,...)
- Exclusivity for DY (TMD)pdf's->GPDs

Positivity for dilepton angular distribution

- Angular distribution

$$d\sigma \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi + \rho \sin 2\theta \sin\phi + \sigma \sin^2\theta \sin 2\phi$$

- Positivity of the matrix (= hadronic tensor in dilepton rest frame)

$$M_0 = \begin{pmatrix} \frac{1-\lambda}{2} & \mu & \rho \\ \mu & \frac{1+\lambda-\nu}{2} & \sigma \\ \rho & \sigma & \frac{1+\lambda+\nu}{2} \end{pmatrix}$$

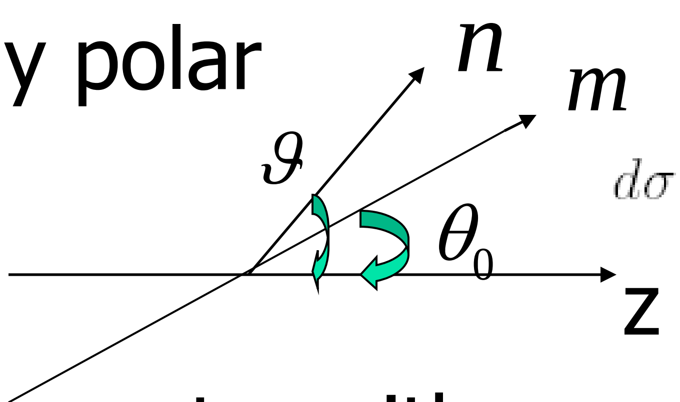
$$|\lambda| \le 1,\ |\nu| \le 1+\lambda,\ \mu^2 \le \frac{(1-\lambda)(1+\lambda-\nu)}{4}$$

$$\rho^2 \le \frac{(1-\lambda)(1+\lambda+\nu)}{4},\ \sigma^2 \le \frac{(1+\lambda)^2-\nu^2}{4}$$

- + cubic – det $M_0 > 0$
- 1st line – Lam&Tung by SF method

Kinematic azimuthal asymmetry from polar one by rotation ($\sim k_T$)

Only polar



$$d\sigma \propto 1+\lambda_0(\vec{n}\vec{m})^2 = 1+\lambda_0\cos^2\theta_{nm}^2$$

asymmetry with respect to m!

$$\cos\theta_{nm} = \cos\theta\cos\theta_0 + \sin\theta\sin\theta_0\cos\phi$$

- azimuthal angle appears with new

$$\lambda = \lambda_0\frac{2-3\sin^2\theta_0}{2+\lambda_0\sin^2\theta_0}$$

$$\nu = \lambda_0\frac{2sin^2\theta_0}{2+\lambda_0\sin^2\theta_0}$$

Matching with pQCD results (J. Collins, PRL 42,291,1979)

- Direct comparison: $\tan^2 \theta_0 = (k_T/Q)^2$
- Off-shellness effects for colliding (anti)quarks – cancel in GI set
- New ingredient – expression for μ
- Linear in k_T
- Saturates positivity constraint!
- Tests by J.-C. Peng,J.Roloff:often close to saturation
- Extra probe of transverse momentum

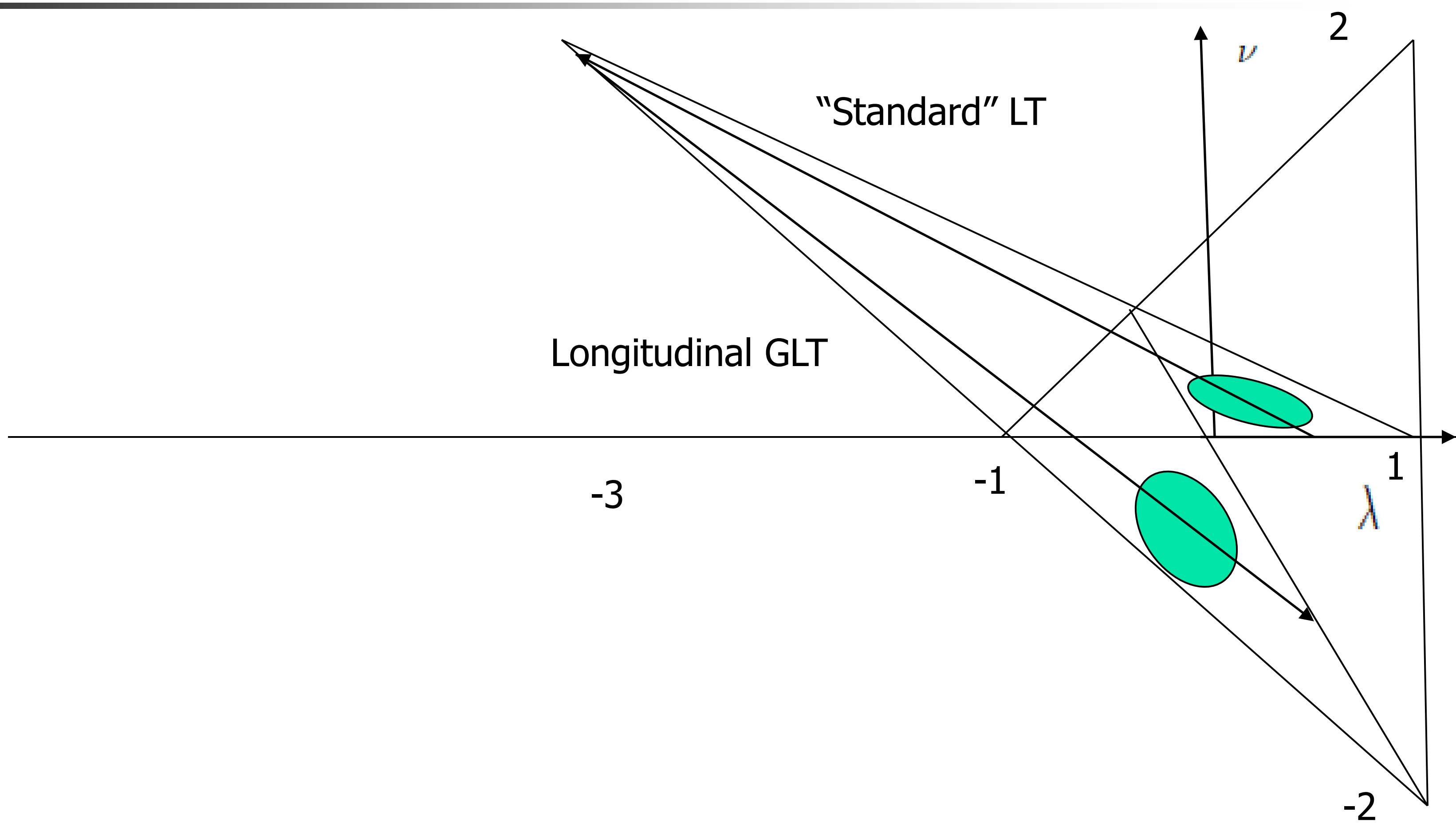
Generalized Lam-Tung relation (OT'05)

- Relation between coefficients (high school math sufficient!)

$$\lambda_0 = \frac{\lambda + \frac{3}{2}\nu}{1 - \frac{1}{2}\nu}$$

- Reduced to standard LT relation for transverse polarization (λ_0 =1)
- LT - contains two very different inputs: kinematical asymmetry+transverse polarization

Positivity domain with (G)LT relations

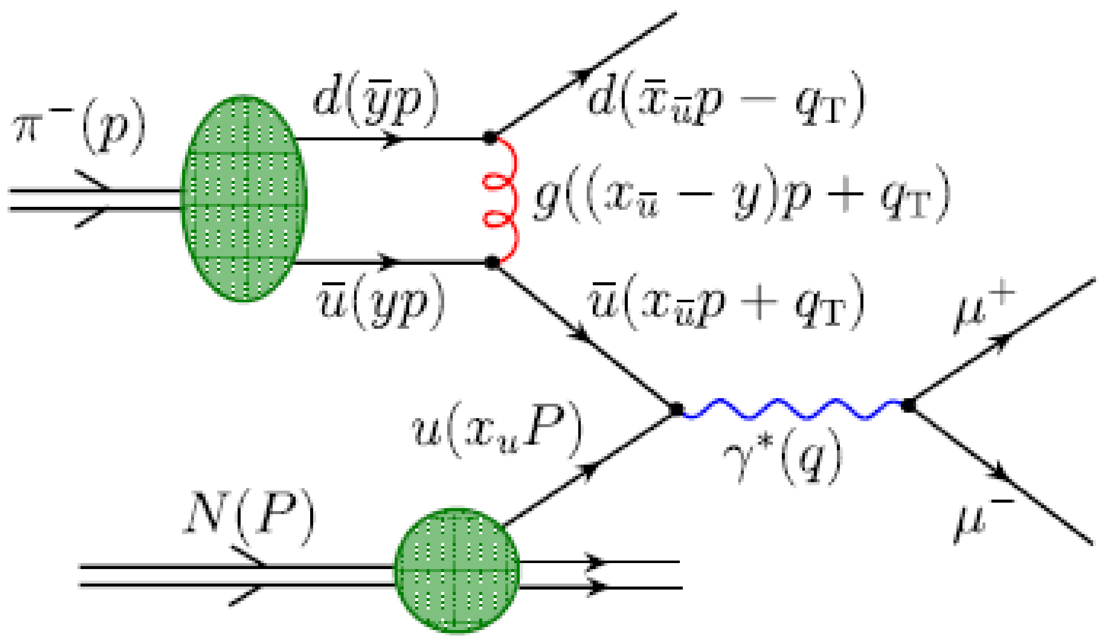


LT violation

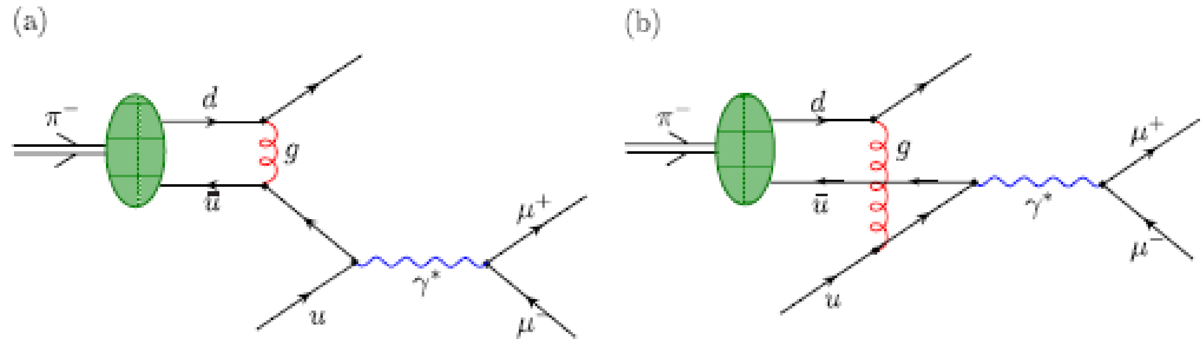
- Azimuthal asymmetries at fundamental level required
- Privileged plane
- NLO-gluon emission
- BM-quark spins

- Off-shell quarks (NLO,HT)

Semi-Exclusive DY (large x_F) - Pion participates through Distribution Amplitude (Light-cone WF)



GI ->



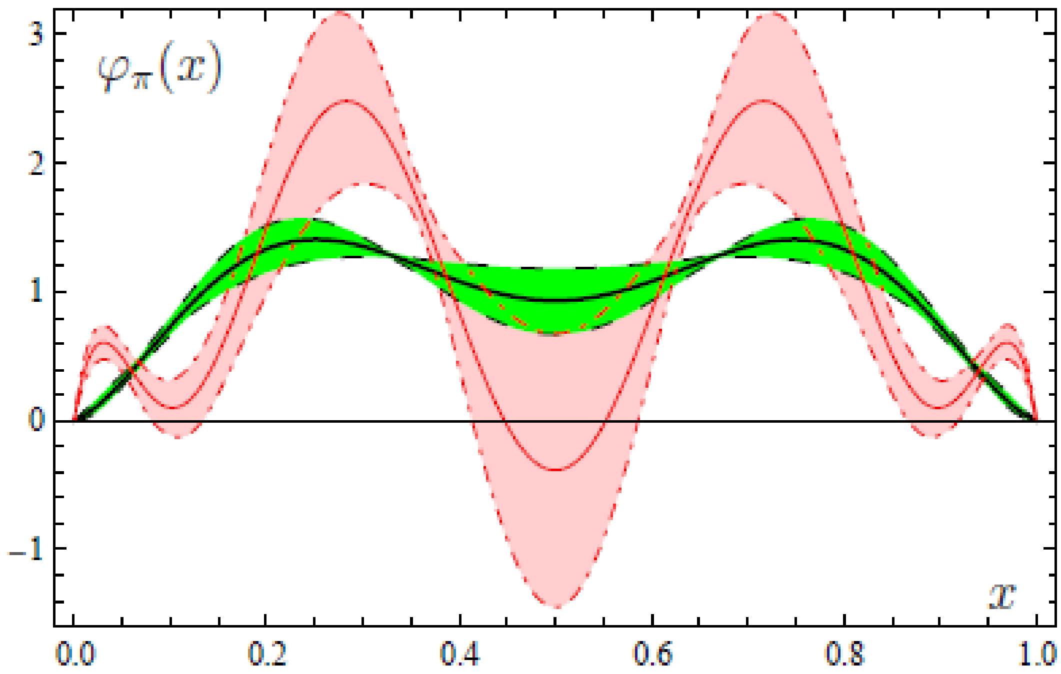
- Colour GI -> second diagram -> phase
- Unpolarized – Brandenburg, Brodsky, Mueller(94)
- Longitudinally polarized –> SSA – Brandenburg, Mueller, OT(95)
- Refined DA – Bakulev, Stefanis,OT(07)

Pion DA

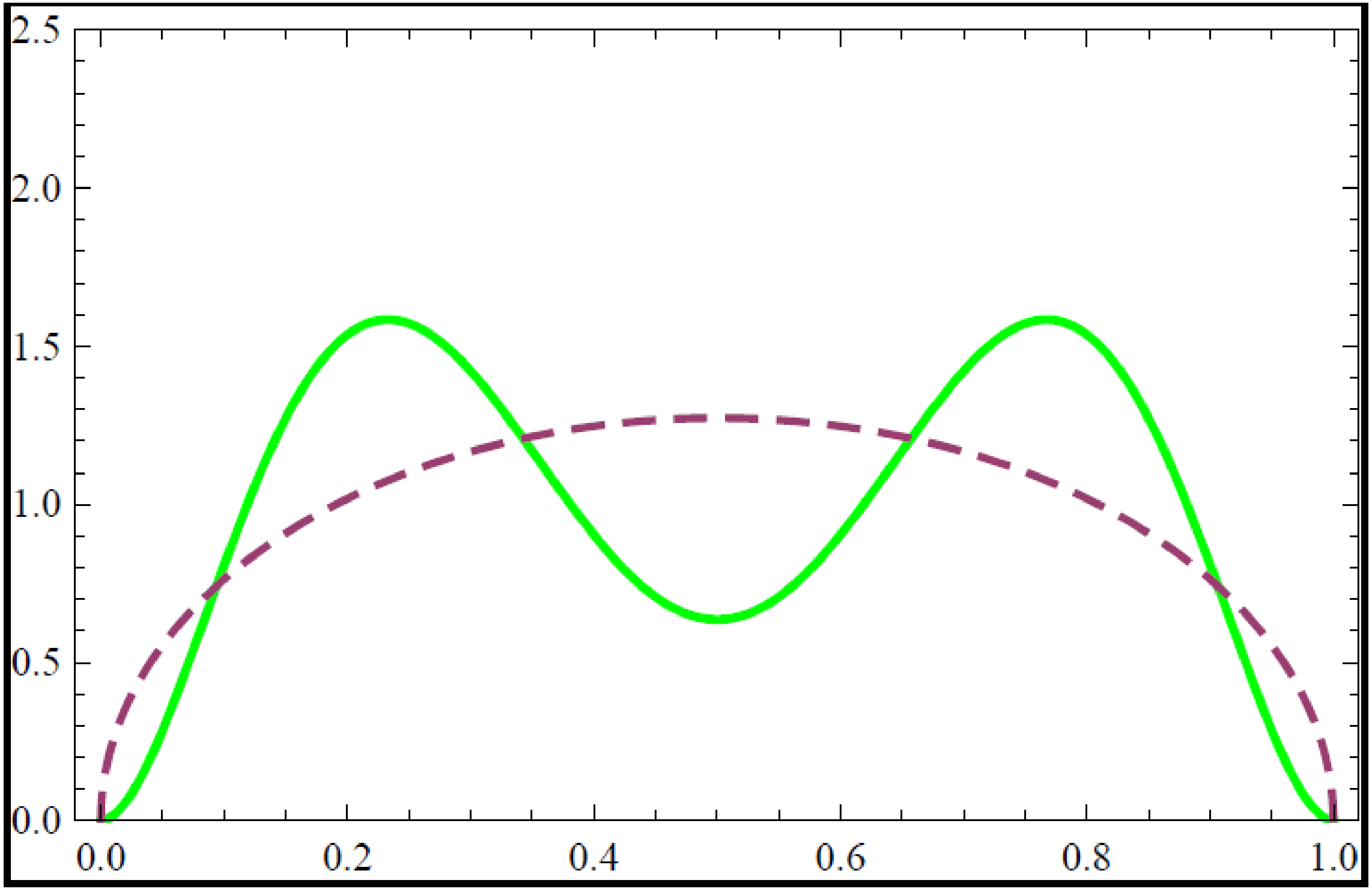
- Element of ERBL factorization
- Describes probability amplitude for the (anti) quark carrying given light-cone momentum fraction
- Interest recently increased due to BaBar data for pion-photon transition formfactor-simplest exclusive process

Pion DA

- (Conservative) model of Bakulev, Mikhailov, Stefanis vs (3D) fit



Comparison to holographic model



Angular distributions – probes of DA

- Unpolarized

$$F = \int_0^1 dy \frac{\varphi(y, \tilde{Q}^2)}{y},$$

$$I(\tilde{x}) = \int_0^1 dy \frac{\varphi(y, \tilde{Q}^2)}{y(y + \tilde{x} - 1 + i\varepsilon)}$$

$$\tilde{x}(x_L, \rho) \equiv \frac{x_L + \sqrt{x_L^2 + 4(1 + \rho^2)\tau}}{2(1 + \rho^2)}.$$

$$\rho \equiv Q_T/Q$$

$$x_L = 2Q_L/\sqrt{s} < 1$$

$$\lambda(\tilde{x}, \rho) = \frac{2}{N}\{(1 - \tilde{x})^2[(>\mathrm{Im}I(\tilde{x}))^2 + (F + \mathrm{Re}I(\tilde{x}))^2] - (4 - \rho^2)\rho^2\tilde{x}^2F^2\}, \quad (2.19)$$

$$\mu(\tilde{x}, \rho) = -\frac{4}{N}\rho\tilde{x}F\{(1 - \tilde{x})[F + \mathrm{Re}I(\tilde{x})] + \rho^2\tilde{x}F\}, \quad (2.20)$$

$$\nu(\tilde{x}, \rho) = -\frac{8}{N}\rho^2\tilde{x}(1 - \tilde{x})F[F + \mathrm{Re}I(\tilde{x})], \quad (2.21)$$

$$N(\tilde{x}, \rho) = 2\{(1 - \tilde{x})^2[(\mathrm{Im}I(\tilde{x}))^2 + (F + \mathrm{Re}I(\tilde{x}))^2] + (4 + \rho^2)\rho^2\tilde{x}^2F^2\} \quad (2.22)$$

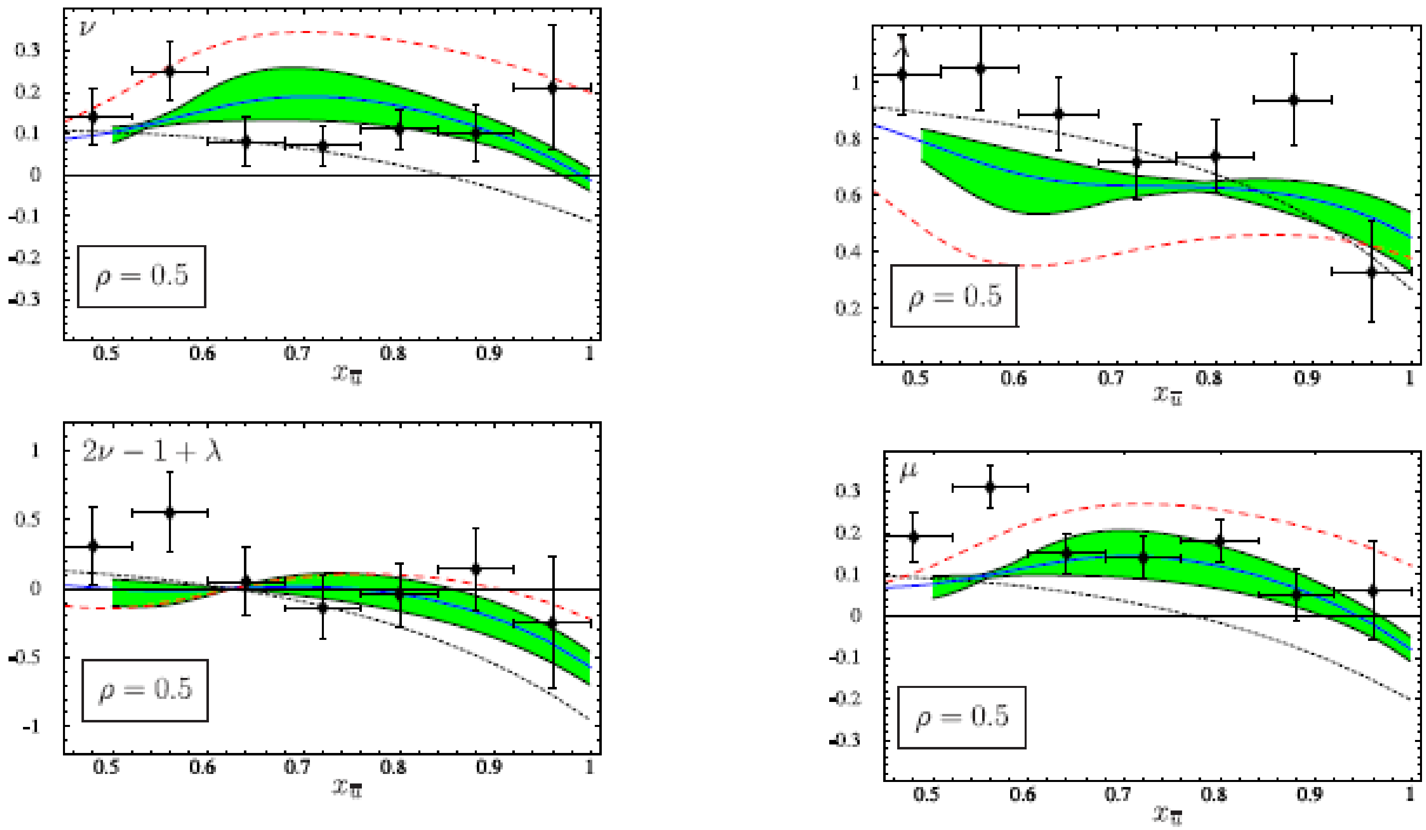
- Polarized

$$\bar{\mu}(\tilde{x}, \rho) = \frac{-2\pi s_\ell \rho\tilde{x}F\varphi(\tilde{x}, \tilde{Q}^2)}{(1 - \tilde{x})^2[(F + \mathrm{Re}I(\tilde{x}))^2 + \pi^2\varphi(\tilde{x})^2] + (4 + \rho^2)\rho^2\tilde{x}^2F^2}\bar{\mu}_{\mathrm{nucl}},$$

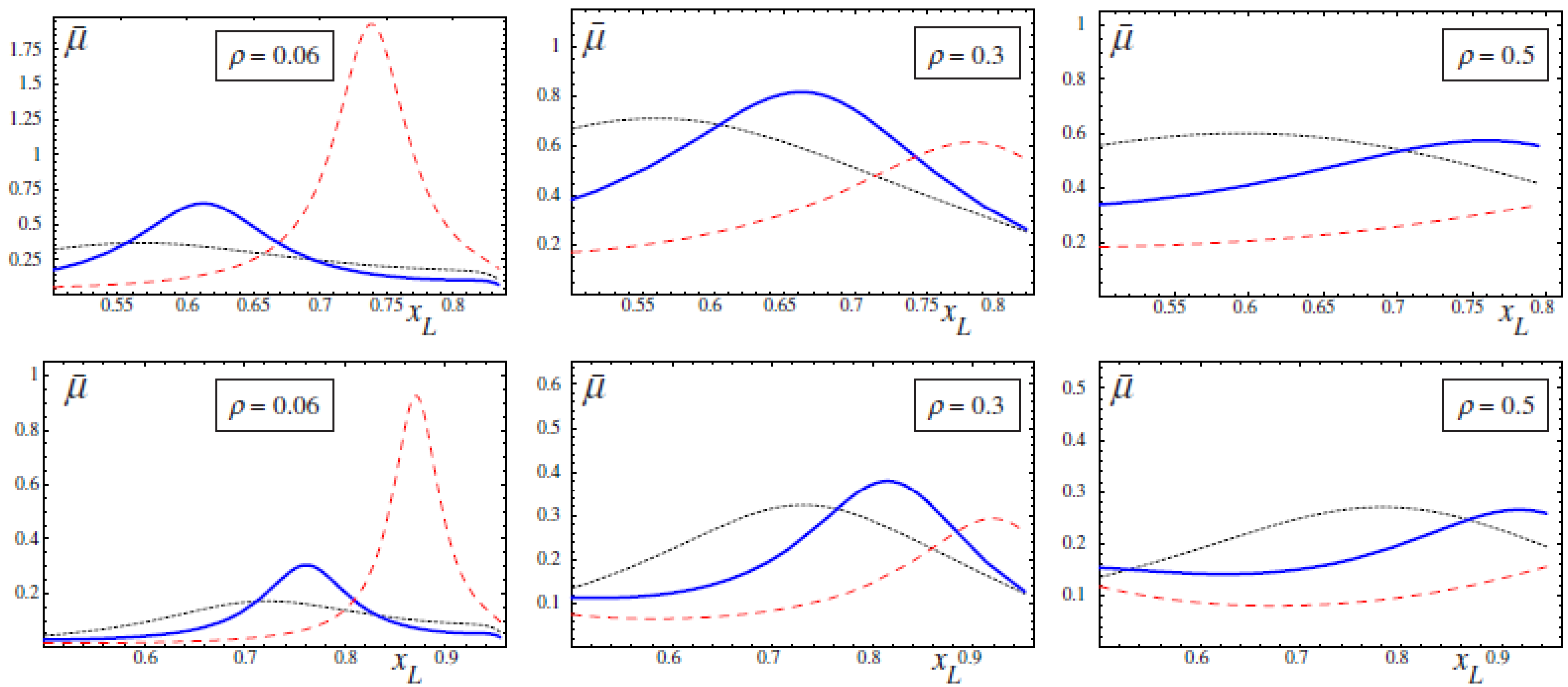
$$\bar{\mu}_{\mathrm{nucl}} \equiv \frac{\frac{4}{9}\Delta q_u^v(x_p; \mu^2) + \frac{4}{9}\Delta q_u^s(x_p; \mu^2) + \frac{1}{9}\Delta q_d^s(x_p; \mu^2)}{\frac{4}{9}q_u^v(x_p; \mu^2) + \frac{4}{9}q_u^s(x_p; \mu^2) + \frac{1}{9}q_d^s(x_p; \mu^2)},$$

$$\bar{\nu}(\tilde{x}, \rho) = 2\rho\bar{\mu}(\tilde{x}, \rho),$$

Asymmetries vs data

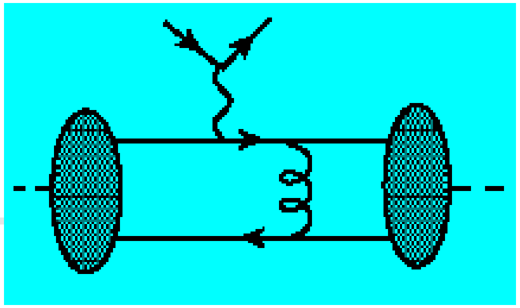


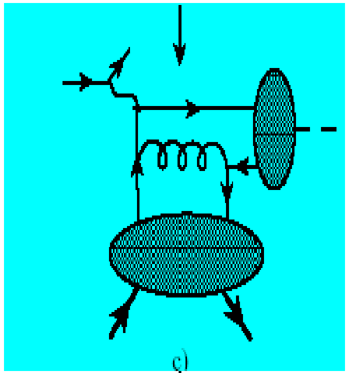
Polarization -> scanning of DA

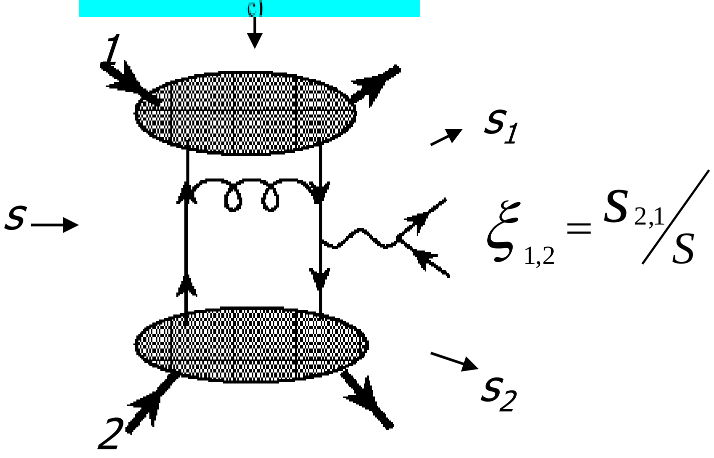


From semi-to pure exclusive

- Simplest case - pion FF(ERBL)
- Change DA to GPD-exclusive electroproduction (talks of Delia,Nicole,Volker)
- Time from right to left-exclusive DY (DAxGPD)-Pire,Szymanowski
- Second DA->GPD-another mechanism- OT'05 (problems with factorization -analytic continuation to be performed)







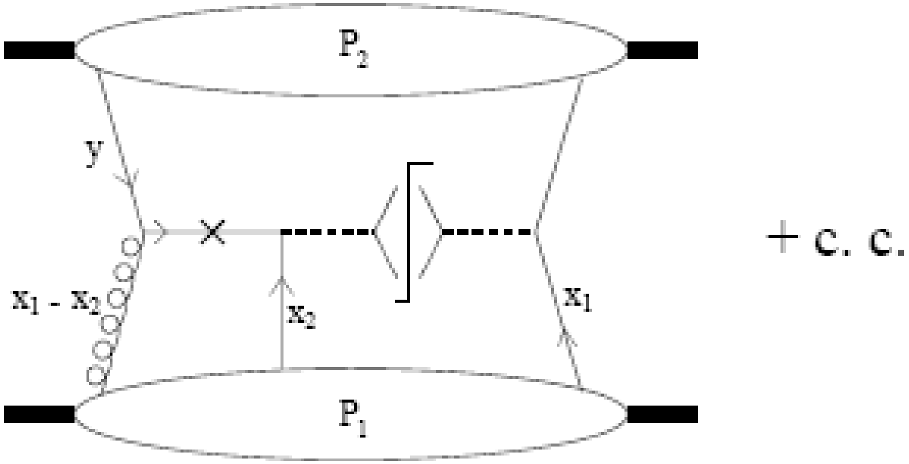
Properties of exclusive DY

- Polarization T->L
- Difference in sign between imaginary parts of electroproduction and DY-> exclusive analog of famous Sivers function sign change
- Final proton is not mandatory – small missing mass (cf Hoyer et al)~at rest for fixed target-possible at COMPASS (talk of O.Denisov)
- PP(NICA): TDA p->pp (to be compared with p->D)
- Test of scaling in various momenta
- Estimates for COMPASS ~ 10^3 events
- Exclusive limit with antiproton beam – relation to time-like FF's

SSA in DY

- TM integrated DY with one transverse polarized beam – unique SSA – gluonic pole (Hammon, Schaefer, OT) – "factor 2" problem

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



- Positivity: twist 4 in denominator reqired

Contour gauge in DY: (Anikin,OT arXiv:1003.1482 and PLB)

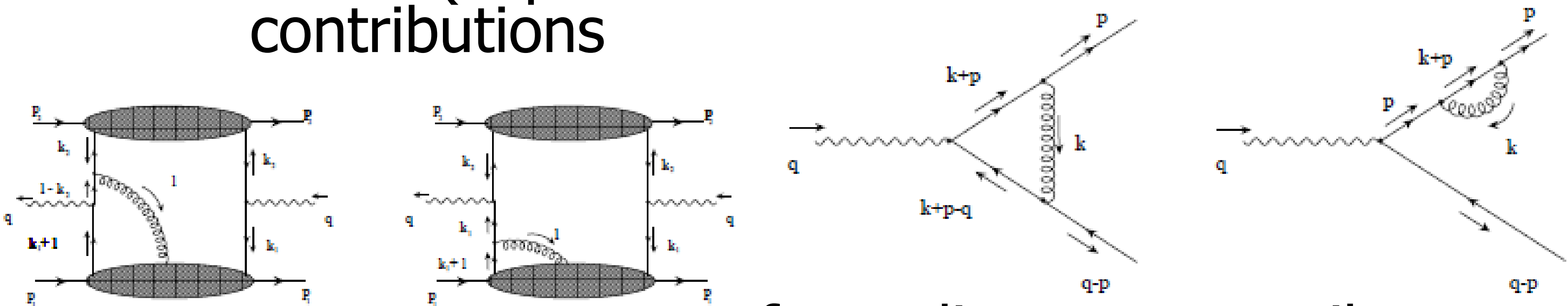
- Motivation of contour gauge – elimination of link $[-\infty^-, 0^-] = 1$

$$[-\infty^-, 0^-] = Pexp\Big\{-ig\int_{-\infty}^{0} dz^-\, A^+(0,z^-,\vec{0}_T)\Big\}$$

- Appearance of infinity – mirror diagrams subtracted rather than added
- Field $A^\mu(z) = \int_{-\infty}^{\infty} d\omega^- \theta(z^- - \omega^-) G^{+\mu}(\omega^-) + A^\mu(-\infty)$
- Gluonic pole appearance $B^V(x_1, x_2) = \frac{T(x_1, x_2)}{x_1 - x_2 + i\epsilon}$
- cf naïve expectation $B^V(x_1, x_2) = \frac{\mathcal{P}}{x_1 - x_2} T(x_1, x_2)$
- Source of phase?!

Phases without cuts

- EM GI (experience from q2 DVCS) – 2 contributions



- Cf PT – only one of two diagrams contribute to SSA and required for GI
- NP tw3 analog - GI only if GP absent
- GI with GP – “phase without cut”

Analogs/implications

- Analogous pole – in gluon GPD
- Prescription – also process-dependent: 2-jet diffractive production (Braun et al.)
- Analogous diagram for GI – Boer, Qiu(04)
- Our work besides consistency proof – factor 2 for asymmetry (missed before)
- GI $Z_\mu = \widehat{p}_{1\,\mu} - \widehat{p}_{2\,\mu}$ (zq)=0
- Naïve $\widehat{p}_{1\,\mu} \Longrightarrow \widehat{p}_{1\,\mu} - q_\mu \frac{\widehat{p}\cdot q}{Q^2} = \frac{p_{1\,\mu} - p_{2\,\mu}}{2}.$
- But! Metz&Zhou 2->1/2 (“factor of 2 puzzle” in addition to sign puzzle)

Sivers function and formfactors

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

BG/DYW type duality for DY SSA in exclusive limit

- Proton-antiproton DY – 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 (Rekalo,Brodsky)
- Exclusive large energy limit; x -> 1 : T(x,x)/q(x) -> Im F2/F1
- Both directions – estimate of Sivers at large x and explanation of phases in FF's

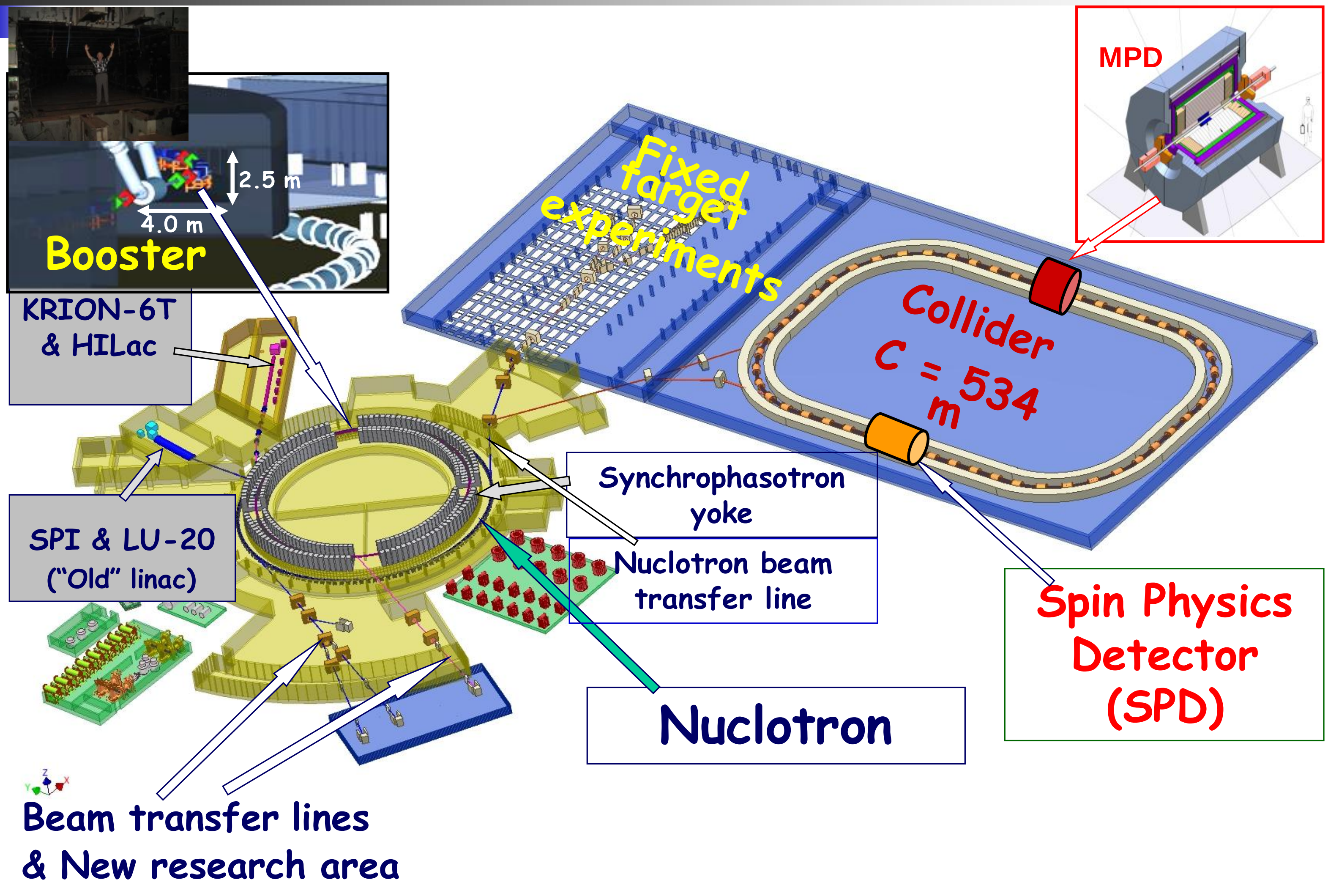
NICA Project

The goal of the NICA project is construction at JINR of the new accelerator facility that consists of

- cryogenic heavy ion source,
- source of polarized protons and deuterons,
- "old" linac LU-20,
- a new heavy ion linear accelerator,
- a new Booster-synchrotron,
- the existing proton synchrotron Nuclotron,upgraded to Nuclotron-M,
- two new superconducting storage rings of the collider,
- new set of transfer channels.

http://nica.jinr.ru

NICA@JINR (slides by A. Nagaytsev)



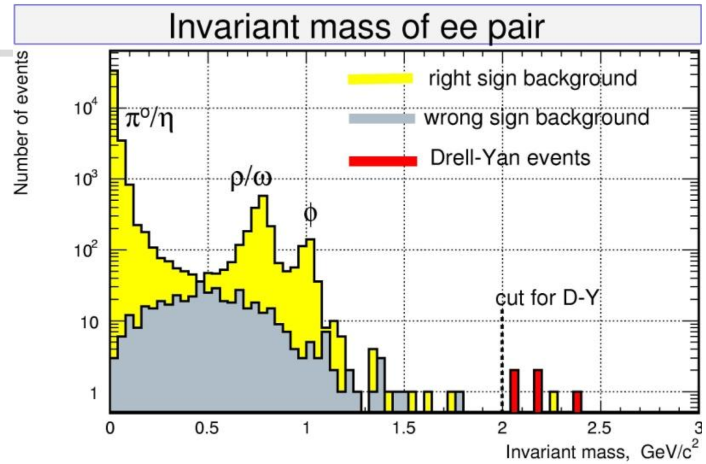
Spin Physics at NICA. Proposed measurements

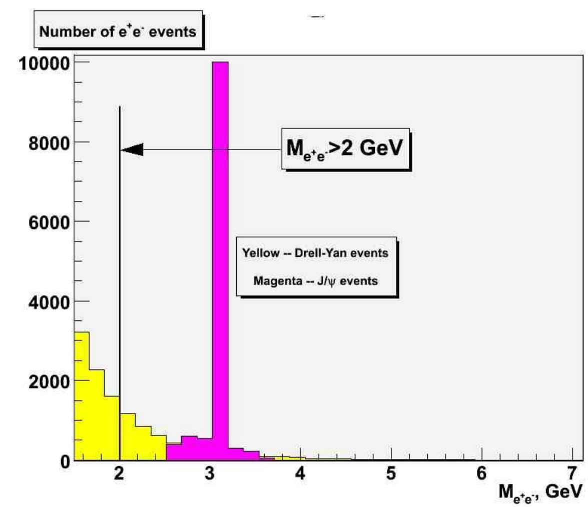
Estimations were done for 1 month of data taking.
For 3 years of data taking: we expect to take ~100K DY events

	σ_{DY}, total, nb	L, $cm^{-2}s^{-1}$	K events
PAX, √s=14.6 GeV	2	10^{30}	~10
	1	10^{30}	5
NICA, √s=20	1.3	10^{30}	7

Cut on Q, GeV	1.5	1.6	1.7	1.8	1.9	2.0
NICA, √s=20 GeV						
σ_{DY}, total, nb	2.5	1.9	1.6	1.3	1.1	0.9
# per month (in K)	14	11	9	7	6	5
NICA, √s=26 GeV						
σ_{DY}, total, nb	3.3	2.7	2.3	1.9	1.6	1.3
# per month (in K)	18	15	13	10	9	7
PAX, √s=14.6 GeV						
σ_{DY}, total, nb	5.1	4.3	3.5	2.9	2.5	2.1
# per month (in K)	24	21	17	14	12	10

√s , GeV	20	26	√s , GeV	20	26
$\sigma_{J/\psi}$, $B_{\mu\mu}$, nb	10	16	σ_{DY} , nb	0.9	1.3
# per month (in K)	55	88	# per month (in K)	5	7

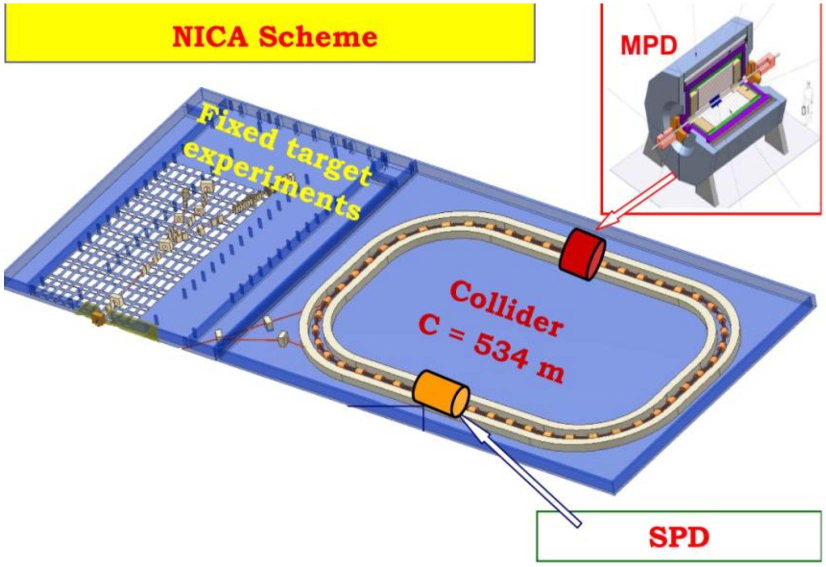




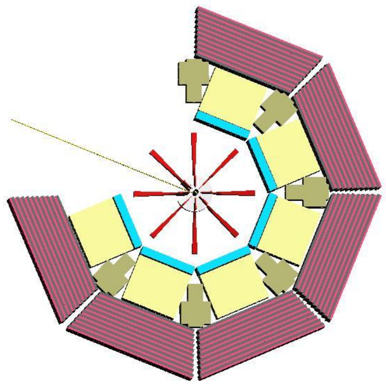
Spin Physics at NICA. SPD Detector

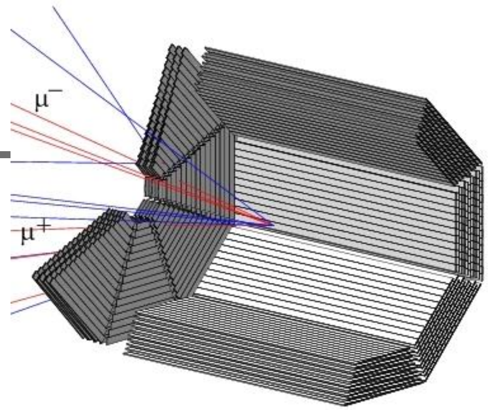
Important requirements for detector (SPD) :

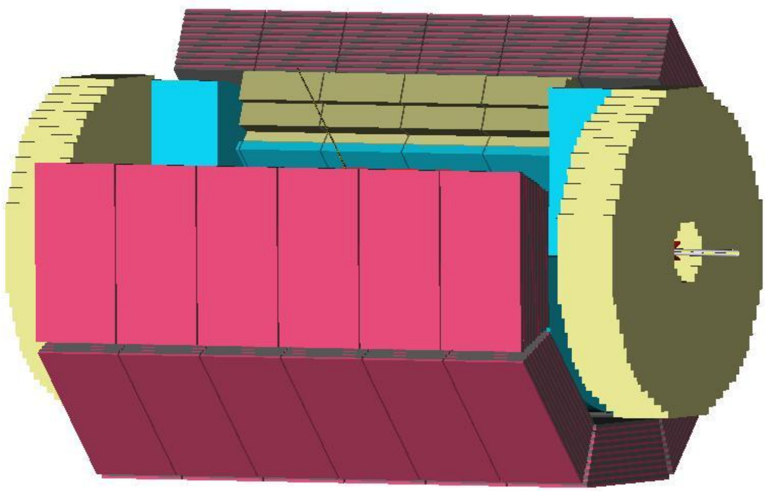
1) 4 π geometry
2) Precision vertex reconstrustion
3) Advanced tracking system
4) Good angular resolution – very important for azimuthal spin asymmetries measurements in the wide kinematical region
5) Particle identification



Spin Physics at NICA. SPD Detector







SPD Barell is about 1.9 m in radius

SPD lenght is about 5 m

Preliminary scheme of the SPD:

- Toroid magnet system

  about 60 cm in radius
- Silicon or MicroMega (Vertex)
- Drift chambers (DC)
- EM Calorimeter (EMC)

  inner radius is about 80 cm

  outer radius is about 130 cm
- Range System (RS)

  (PANDA Moun System, JINR contrib.)

  inner radius is about 130 cm

  outer radius is about 180 cm
- Trigger counters
- EndCap detectors with RS, tracking system and EMC

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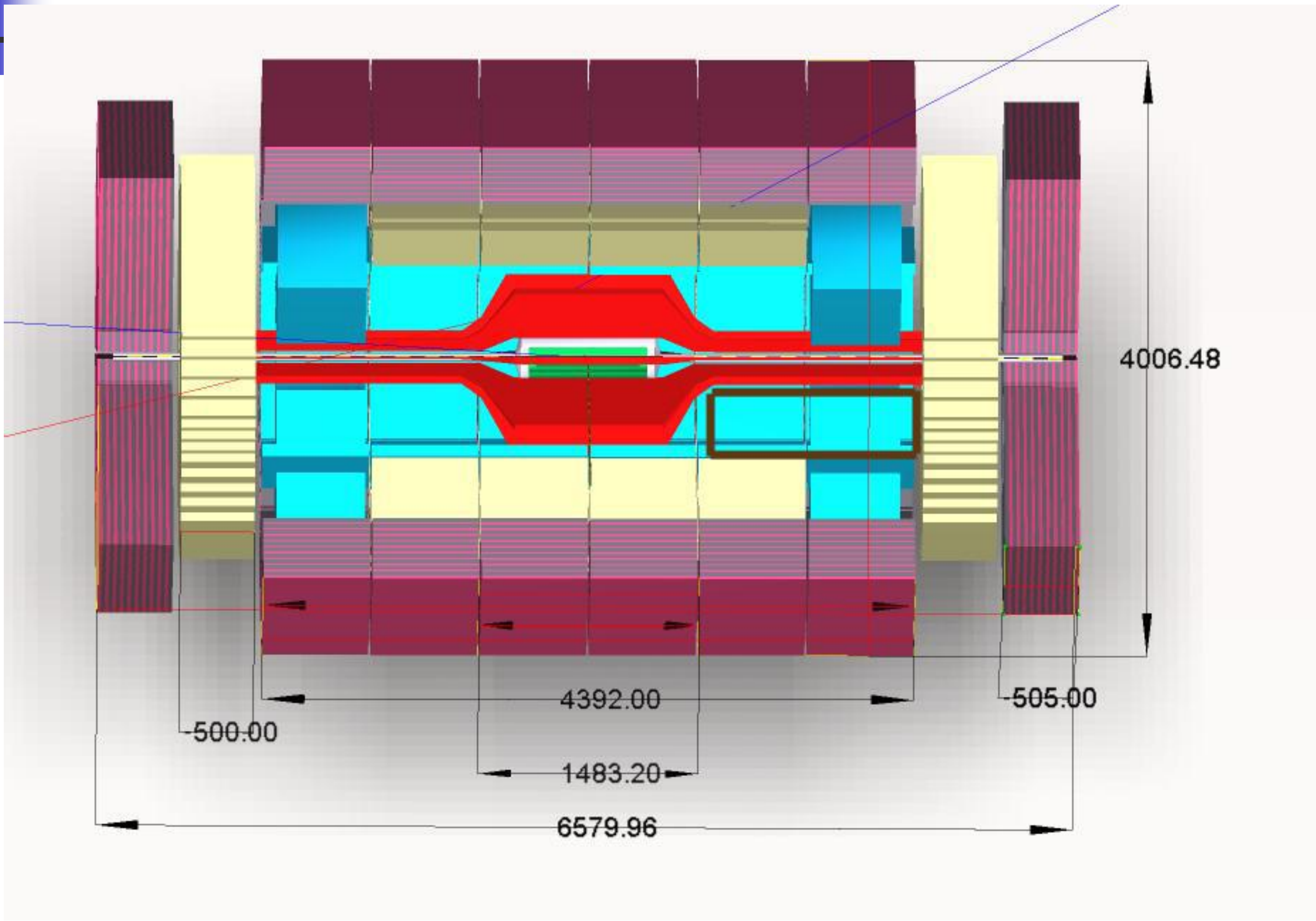
SPD

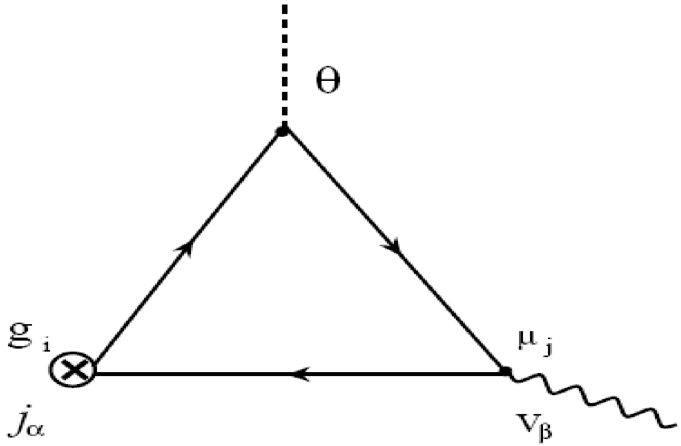


Spin physics at MPD

- Multi Purpose Detector – studies of heavy-ion collisions
- Possible to use also with p/D beams
- Spin-related studies (exclusive, exotics, spin-dpendent DY with associated particles
- Spin effects in HIC – vorticity
- In-between nucleon OAM (talks of Masashi, Elliot, Matthias, Cedric) and classical rotation

Anomaly in medium – new external lines in VVA graph

- Gauge field -> velocity
- Chiral Vortical Effect
- Kharzeev, Zhitnitsky (07) – EM current
- Straightforward generalization: any (e.g. baryonic) current – neutron asymmeries@NICA - Rogachevsky, Sorin, OT - **Phys.Rev.C82:054910,2010**.



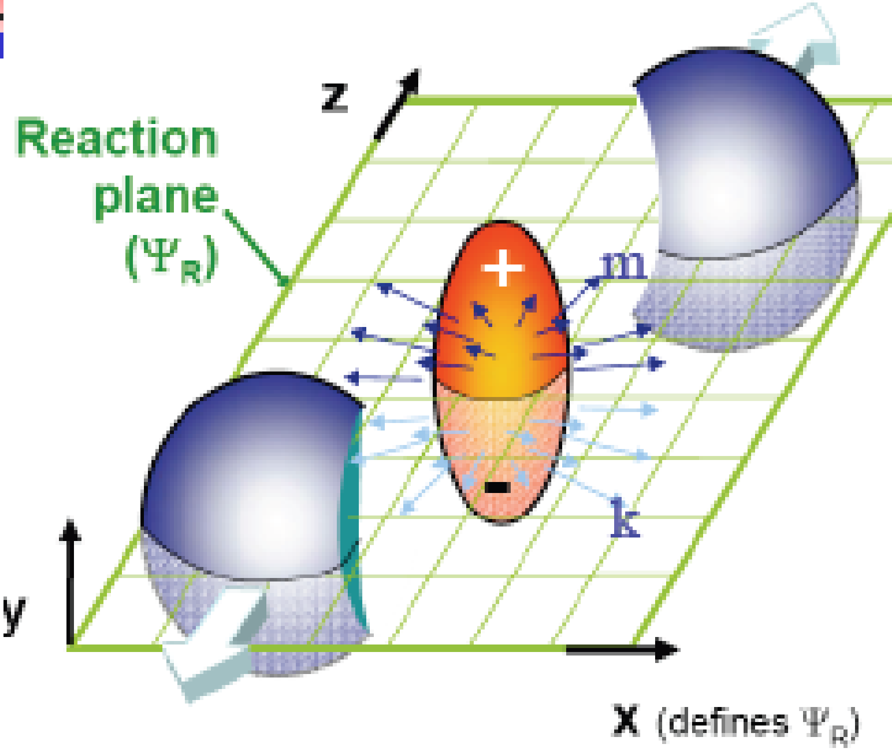
Baryon charge with neutrons – (Generalized) Chiral Vortical Effect

- Coupling: $e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$

- Current: $J_e^\gamma = \frac{N_c}{4\pi^2 N_f} \varepsilon^{\gamma\beta\alpha\rho} \partial_\alpha V_\rho \partial_\beta (\theta \sum_j e_j \mu_j)$
- - Uniform chemical potentials: $J_i^\nu = \frac{\sum_j g_{i(j)} \mu_j}{\sum_j e_j \mu_j} J_e^\nu$
- - Rapidly (and similarly) changing chemical potentials:

$$J_i^0 = \frac{|\vec{\nabla} \sum_j g_{i(j)} \mu_j|}{|\vec{\nabla} \sum_j e_j \mu_j|} J_e^0$$

Charge asymmetry w.r.t. reaction plane: how to detect it?



$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle =$$
$$= \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B^{in}] - [\langle a_\alpha a_\beta \rangle + B^{out}].$$

S.Voloshin, hep-ph/0406311

A sensitive measure of the asymmetry:

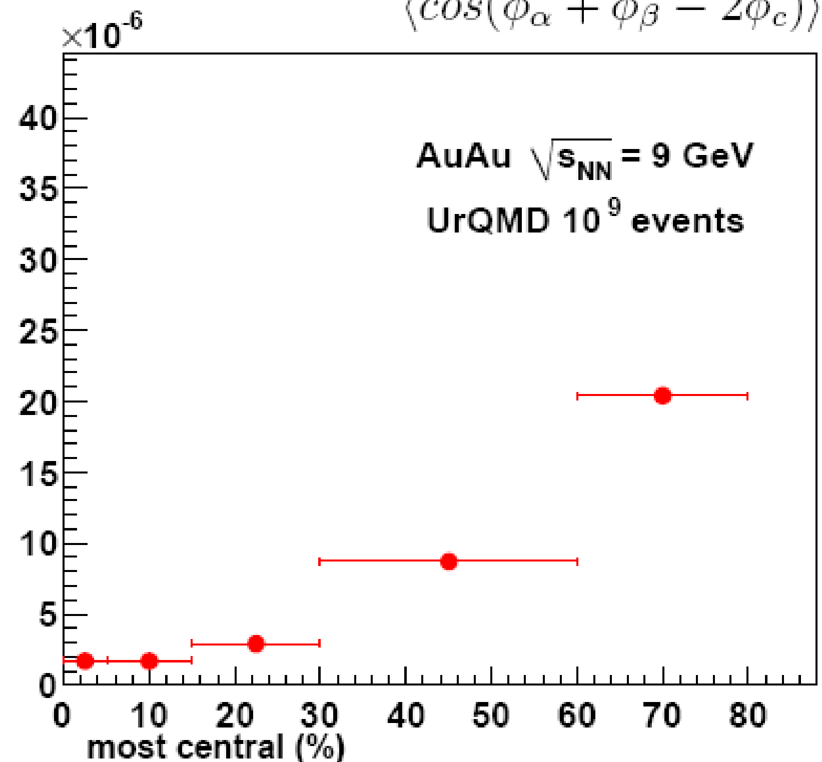
$$a^k a^m = \langle \sum_{ij} \sin(\varphi_i^k - \Psi_R)\ \sin(\varphi_j^m - \Psi_R) \rangle$$

Expect $a^+ a^+ = a^- a^- > 0; \quad a^+ a^- < 0$

Estimates of statistical accuracy at NICA MPD (months of running)

- UrQMD model : $Au + Au$ at $\sqrt{s_{NN}} = 9$ GeV
- 2-particles -> 3-particles correlations
  no necessity to fix the event plane
- 2 neutrons from mid-rapidity $(|\eta| < 1)$
- +1 from ZDC $(|\eta| > 3)$

$\langle cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle$



New sources of Λ polarization coupling to rotation

- Bilinear effect of vorticity – generates quark axial current (Son, Surowka)
- Strange quarks - should lead to Λ polarization
- Proportional to square of chemical potential – small at RHIC – may be probed at FAIR & NICA

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

Conclusions

- (Semi)exclusive limits of DY – interesting theoretically
- Feasibility at various experiments remains to be studies

- NICA@JINR has a possibility studies of various spin physics in hadronic and HIC
- New suggestions welcomed
- Better to see once than to hear 100 times; WELCOME to SPIN 2012