Selected topics in Drell-Yan theory: from twist 3 SSA to exclusive limit

Trento, ECT*, Dilepton Workshop, September 27, 2016

Igor Anikin , Oleg Teryaev

JINR, Dubna

based on

PLB690, 519 (2010); EPJC75, 184 (2015); PLB751 495 (2015); PoS QNP2012,055(2012); AIP Conf.Proc. 1654 (2015) 060007

Outline

- SSA in QCD
- Twist-3 Single Spin asymmetries and DY
- Contour gauge and factor 2
- Gluonic poles and physical fields
- Burkardt sum rules
- Elastic limit: Sivers function and formfactors
- Conclusions

Single Spin Asymmetries

- S(pxq): “Naïve” T-odd
- Real T-reflection – interchange of initial and final particles
- May lead to the sign change due to phase of <f|S|i>, compensating “naïve” T-oddness
- Phases – mimic T-violation
- Sign of iε -measures time direction
- Manifestation of real T(CP) violations in BAU – due to cuts of GUT diagrams!

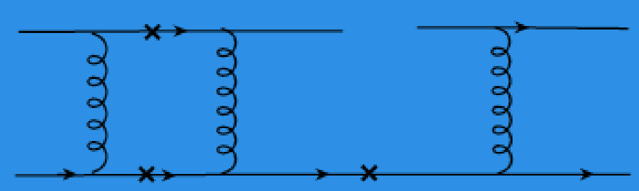
"Effective" T-reflection in QCD

- Phases = cuts in Soft or Hard variables due to (generalized) optical theorem
- Various manifestations in hadronic physics:
- No cuts<->S/H cuts: SL(T)FF<->TL(T)FF
- Scuts <-> Hcuts: SLTFF <->TL(T)FF to pairs e.g. (γ*γ->MM)<->(γ*->γMM)
- Hcuts in scaling region:cuts cancellation (see my talk on Dterm) – sign changes: SIDIS<->DY(Sivers fctn sign) ; DVCS <->TCS; DVMP<->exclusive DY; DDVCS(2 cuts in the same process)

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):

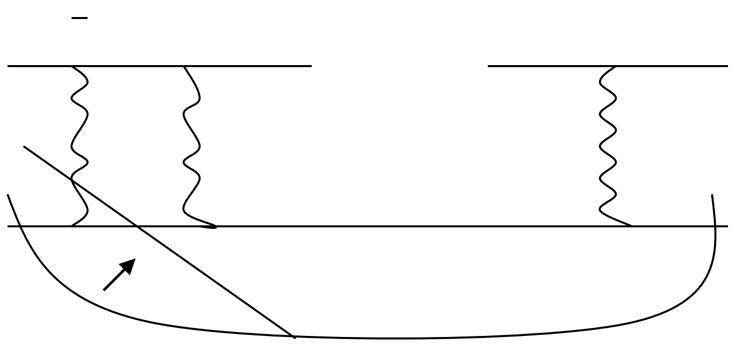


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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

Short+ large overlap– twist 3

- Quarks – only from hadrons
- Various options for factorization – shift of SH separation



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

Gluonic poles and Sivers function

- Both require Initial or Final State Interaction
- Twist-3: suppression like 1/Q
- "Compensated" by gluonic pole (~gauge link) – unsuppressed by 1/Q FSI (Brodsky, Hwang, Schmidt)
- Moment of Sivers function – twist 3 gluonic pole strength (Boer, Mulders, Pijlman)
- TMD – infinite tower of twists projected by the relevant moments (Ratcliffe,OT)

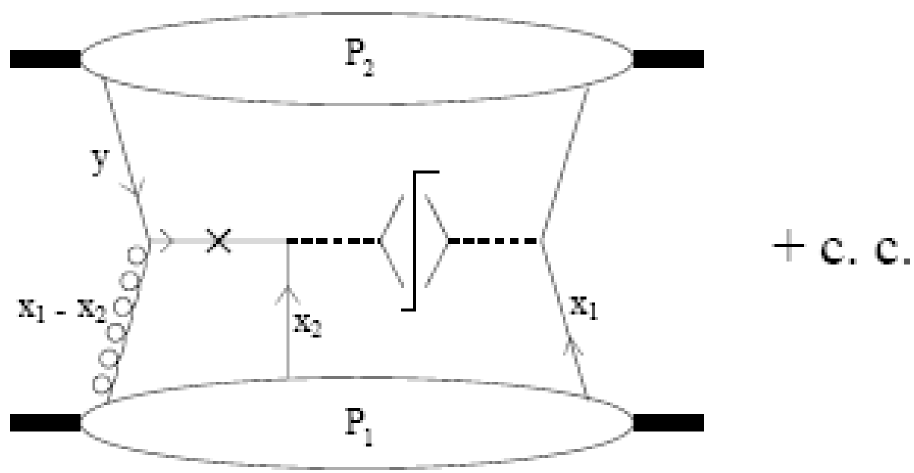
Twist 3 and gauge invariance

- Required to provide GI set of diagrams, maintain EMGI for g2 (80’s: Efremov, OT; Bukhvostov, Kuraev, Lipatov; Balitsky,Braun)
- $S_T \to \Delta_T$: EMGI for DVCS – twist 3 GPDs (talk of S. Liuti) first appeared (Anikin, Pire, OT’98; Polyakov, Kivel et al…); twist 4 - talk of V. Braun

SSA due to gluonic pole in DY

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

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



- Denominator to be modified due to density matrix positivity

Contour gauge in DY: (Anikin,OT,Phys.Lett. B690 (2010) 519-525)

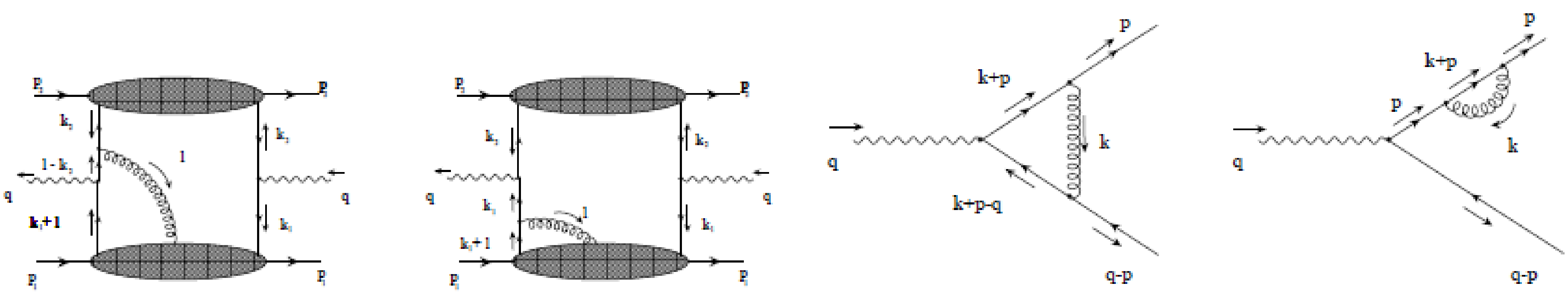
- Motivation of contour gauge – elimination of link $[-\infty^-, 0^-] = 1$

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

- Field $A^\mu(z) = \int_{-\infty}^{\infty} d\omega^- \theta(z^- - \omega^-) G^{+\mu}(\omega^-) + A^\mu(-\infty)$
- EOM: Gluonic pole appearance $B^V(x_1, x_2) = \frac{T(x_1, x_2)}{x_1 - x_2 + i\epsilon}$
- cf naïve expectation $B^V(x_1, x_2) = \frac{\mathcal{P}}{x_1 - x_2} T(x_1, x_2)$
- How to check that?

Gauge invariance

- EM GI (experience from g2,DVCS) – 2 contributions



- SSA in on shell PT – only one diagram for GI
- NP tw3 analog - GI only if GP absent
- GI with GP – “phase without cut ” (in subprocess)

Analogs/implications

- Analogous pole – in gluonic GPDs
- Braun, Ivanov,Schafer, Szymanowski'04 – universal GI result for on-shell quark target for different prescriptions in different ways
- Analogous diagram for GI – Boer, Qiu(04)
- Besides consistency proof – factor 2 for asymmetry (missed before)

$$\overline{\mathcal{W}}^{\mathrm{GI}}_{\mu\nu} = \overline{\mathcal{W}}^{(1)}_{\mu\nu} + \overline{\mathcal{W}}^{(2)}_{\mu\nu} = -\frac{2}{q^2}\varepsilon_{\nu S^T p_1 p_2} Z_\mu \bar{q}(y_B) T(x_B, x_B)$$

$$\widehat{p}_{1\,\mu} \Longrightarrow \widehat{p}_{1\,\mu} - q_\mu \frac{\widehat{p}\cdot q}{Q^2} = \frac{p_{1\,\mu} - p_{2\,\mu}}{2}\,.$$

$$Z_\mu = \widehat{p}_{1\,\mu} - \widehat{p}_{2\,\mu}$$

Feynman gauge (Anikin,OT'15)

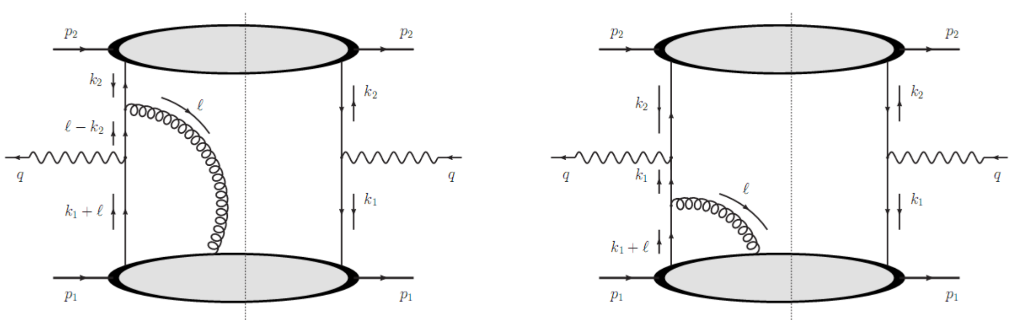
- Standard

$$\overline{W}^{(\text{Stand.})}_{\mu\nu} + \overline{W}^{(\text{Stand.},\, \partial_\perp)}_{\mu\nu} = \bar{q}(y) \Bigg\{ \qquad (14)$$

$$-\frac{p_{1\,\mu}}{y}\, \varepsilon_{\nu S^T - p_2} \int dx_2 \frac{x_1 - x_2}{x_1 - x_2 + i\epsilon} B^{(1)}(x_1, x_2)$$

$$-\left[\frac{p_{2\,\nu}}{x_1}\varepsilon_{\mu S^T - p_2} + \frac{p_{2\,\mu}}{x_1}\varepsilon_{\nu S^T - p_2}\right] x_1 \int dx_2 \frac{B^{(2)}(x_1, x_2)}{x_1 - x_2 + i\epsilon}$$

$$+\frac{p_{1\,\mu}}{y}\, \varepsilon_{\nu S^T - p_2} \int dx_2 \frac{B^{(\perp)}(x_1, x_2)}{x_1 - x_2 + i\epsilon} \Bigg\},$$



- and non-standard $\overline{W}^{(\text{Non-stand.})}_{\mu\nu} = \bar{q}(y) \frac{p_{2\,\mu}}{x_1} \varepsilon_{\nu S^T - p_2} \times$ pieces

$$\int dx_2 \Big\{ B^{(1)}(x_1, x_2) + B^{(2)}(x_1, x_2) \Big\}$$

EM GI – gluon poles not in PARTICULAR sructures

- Correlators

$$B^{(1)}(x_1,x_2) = \frac{T(x_1,x_2)}{x_1 - x_2 + i\varepsilon} \Longleftarrow \mathcal{F}_2\Big[\langle p_1, S^T|\bar{\psi}(\eta_1)\,\gamma^+\,A^T(z)\,\psi(0)|S^T, p_1\rangle\Big]\,,$$

$$B^{(2)}(x_1,x_2) \Longleftarrow \mathcal{F}_2\Big[\langle p_1, S^T|\bar{\psi}(\eta_1)\,\gamma^\perp\,A^+(z)\,\psi(0)|S^T, p_1\rangle\Big]\,,$$

$$B^{(\perp)}(x_1,x_2) \Longleftarrow \mathcal{F}_2\Big[\langle p_1, S^T|\bar{\psi}(\eta_1)\,\gamma^+\,(\partial^\perp\;A^+(z))\,\psi(0)|S^T, p_1\rangle\Big]\,.$$

- Gluon-pole free:

$(B^{(2)}(x_1,x_2) = -B^{(2)}(x_2,x_1))$, obeys $B^{(2)}(x,x) = 0.$

Possible interpretation (new)

- Decomposition of Gluon Angular momentum (Y. Hatta)

Complete decomposition

Chen, Lu, Sun, Wang, Goldman (2008)
Wakamatsu (2010)
Y.H. (2011)

$$M^{\mu\nu\lambda}_{\text{quark-spin}} = -\frac{1}{2}\epsilon^{\mu\nu\lambda\sigma}\bar{\psi}\gamma_5\gamma_\sigma\psi\,,$$
$$M^{\mu\nu\lambda}_{\text{quark-orbit}} = \bar{\psi}\gamma^\mu(x^\nu iD^\lambda_{\text{pure}} - x^\lambda iD^\nu_{\text{pure}})\psi\,,$$
$$M^{\mu\nu\lambda}_{\text{gluon-spin}} = F^{\mu\lambda}_a A^{\nu a}_{\text{phys}} - F^{\mu\nu}_a A^{\lambda a}_{\text{phys}}\,;$$
$$M^{\mu\nu\lambda}_{\text{gluon-orbit}} = F^{\mu\alpha}_a\Big(x^\nu(D^\lambda_{\text{pure}}A^{\text{phys}}_\alpha)_a - x^\lambda(D^\nu_{\text{pure}}A^{\text{phys}}_\alpha)_a\Big)$$

where (my choice) $A^\mu_{phys} = \frac{1}{D^+}F^{+\mu}$ $\quad D^\mu_{pure} = D^\mu - iA^\mu_{phys}$

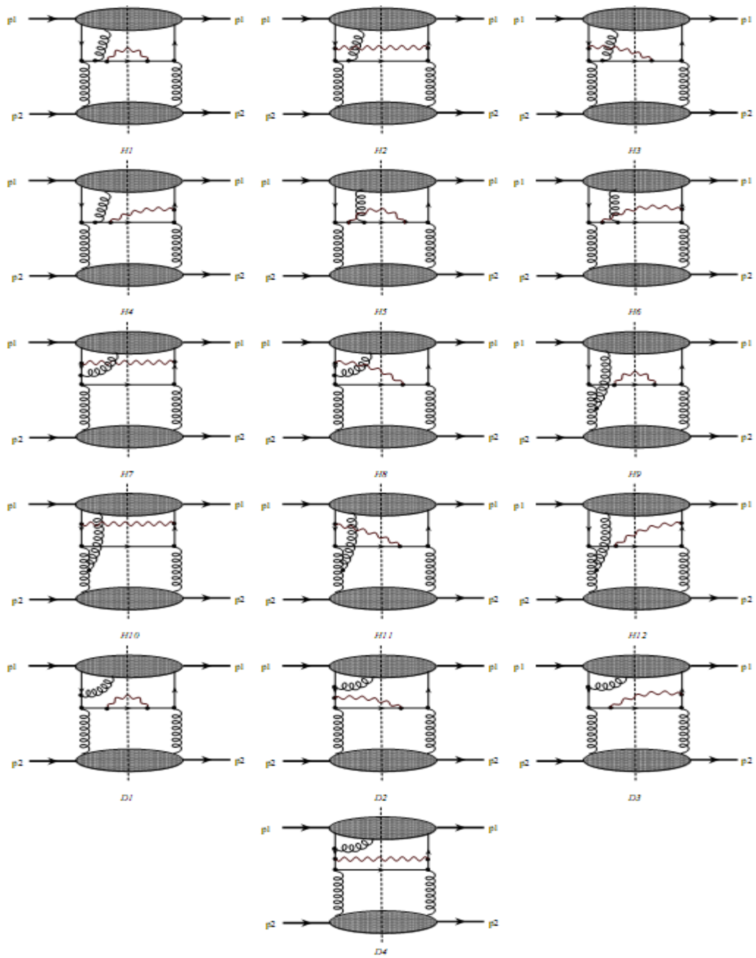
- Field (axial gauge)= physical

- Poles – only from physical fields

Direct photon production (Anikin, OT, Eur.Phys.J. C75 (2015) 5, 184)

- Gluonic poles from 4 diagrams
- Standard (H10) also enhanced by factor 2 from nonstandard ones

$$dW(\text{diag.H1}) + dW(\text{diag.H7}) + dW(\text{diag.D4}) = dW(\text{diag.H10}).$$



Burkardt SR and Energy-Momentum tensor (OT'14)

- Consider twist 3 (= relevant moment of Sivers function being infinite tower of twists) gluonic pole
- EMT forward matrix element: no spin-dependent structure $p^{\rho}\epsilon^{\mu S p n}$

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

$$\sum \int\int dx_1 dx_2 \frac{T(x_1,x_2)}{x_1-x_2} = 0$$

- Naively: Valid identically due to symmetry properties implied by T-invariance)
- However: pole should get imaginary part due to EMGI and related contour gauge – analog of force calculation in original Burkardt' derivation

Pole prescription and Burkardt SR

- Pole prescription (dynamics!) provides ("T-odd") symmetric part!

$$\sum \int \int dx_1 dx_2 \frac{T(x_1, x_2)}{x_1 - x_2 + i\varepsilon} = 0$$

- SR:

$$\sum \int dx T(x, x) = 0$$

- Gluonic poles for 3 gluon correlators should be related to gluon Sivers function – natural but not yet proved!

Validity for each flavour

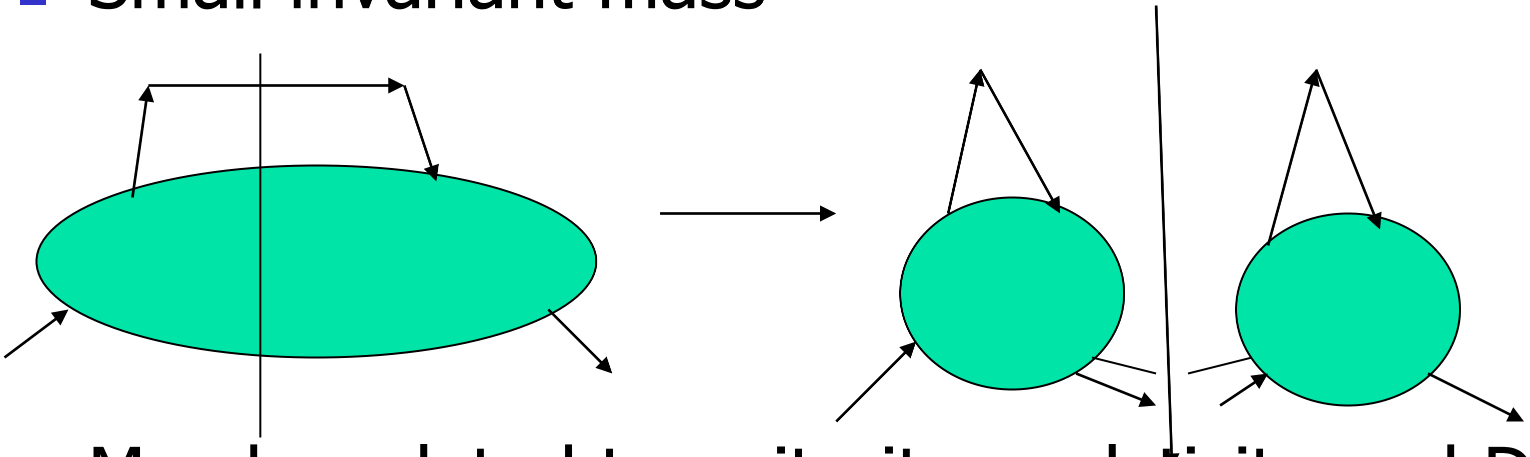
- Can it be valid separately for each quark flavour: nodes (Boer, Prokudin)?
- Valid if structures forbidden for TOTAL EMT do not appear for each flavour
- Structure contains besides S gauge vector n: GI separation of EMT – forbidden: SR valid separately!

Burkardt SR and Equivalence Principle

- Absence of s/n-dependent part for EMT matrix element
- Coupling to gravity - Equivalence Principle (OT'99)
- Provides another interpretation of Ji's SR and momentum SR (Efremov,OT'82) for tensor spin structure function (OT'99,'08)
- Validity for each flavour – extension of EP; for Ji's SR – only for sum of quarks

Exclusive limit : DIS and space-like (transitional and elastic) FFs

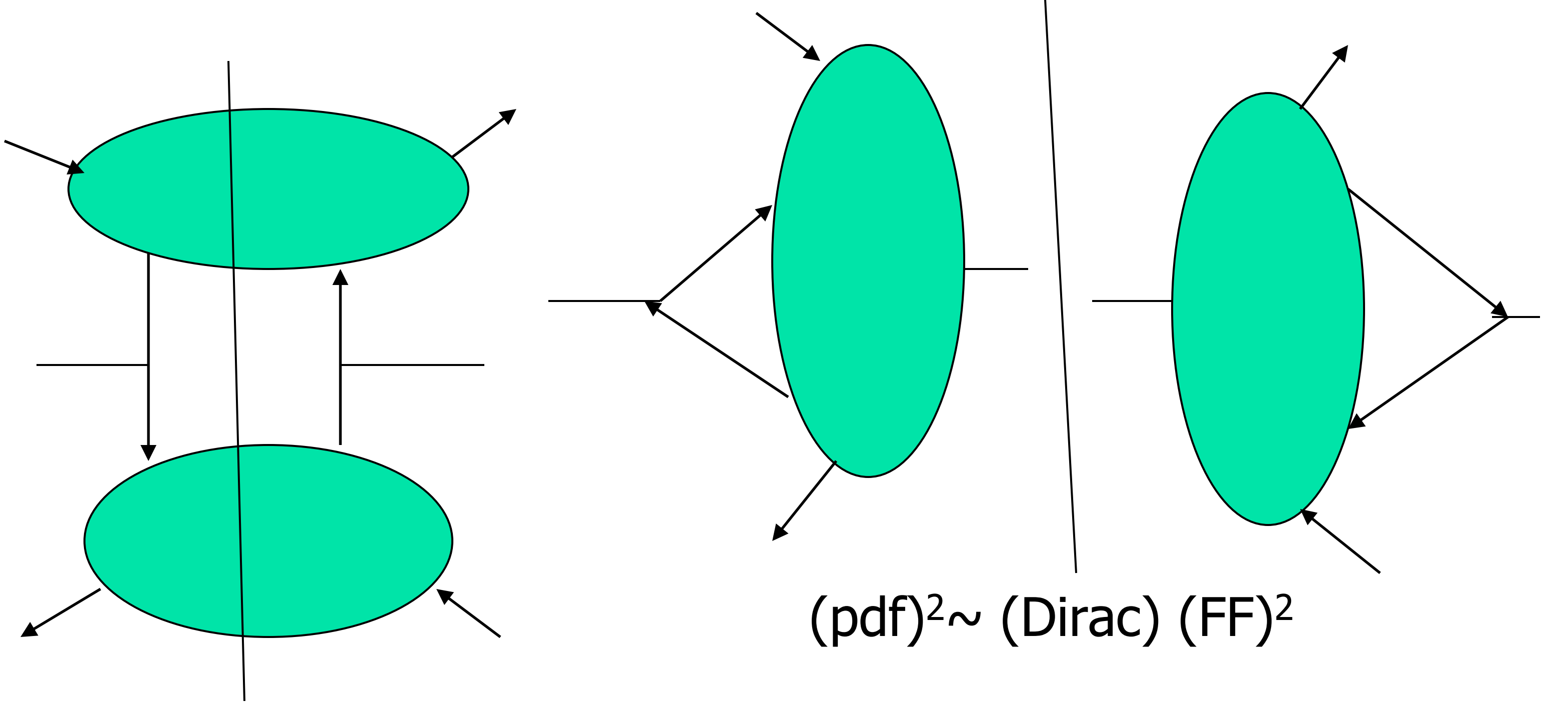
- Small invariant mass



- May be related to unitarity analyticity and DR (OT'05)
- Relation between x ->1 and large Q^2
- pdf ~ $(FF)^2$
- Elastic(DYW) or Transition(BG)

Exclusive limit of DY and time-like FFs (OT'14)

- (Proton-antiproton) DY at small s - Q^2 -elastic FF(DYW)



- (pdf)^2~ (Dirac) (FF)^2

- Other beams – baryon number conservation – time-like transition FFs (BG)

Comparing space-like and time-like FFs

- "Duality intervals" - from mass to x-space
- DIS: $(P+q)^2 = (P_f + \delta P_{DIS}))^2 = (M + \mu_{DIS})^2$ μ_{DIS} ~ pion related scale
- Deviation of $x_B (\equiv 1 - \delta_{DIS})$ from 1

$$\delta_{DIS} \sim 2M\mu_{DIS}/Q^2.$$

- DY: $(P_1 + P_2)^2 = (q + \delta P_{DY})^2$
- Deviation of $\tau = Q^2/s(\equiv 1 - \delta_{DY})$ from 1

$$\delta_{DY} \sim 2\mu_{DY}/Q$$

FFs from duality intervals

- DIS: $F^2_{SL} \sim \int_0^{\delta_{DIS}} d\bar{x} f(\bar{x}) \quad x = 1 - \bar{x}$
- DY: $F^2_{TL} \sim \int_0^{\delta_{DY}} d\bar{x}_1 d\bar{x}_2 f(\bar{x}_1) f(\bar{x}_2) \delta(\delta_{DY} - \bar{x}_1 - \bar{x}_2)$
- Proton-antiproton DY –same parton distributions $f(\bar{x}) = C\bar{x}^a$

$$F^2_{SL}(Q^2) \sim \frac{C}{a+1}\left(\frac{2M\mu_{DIS}}{Q^2}\right)^{a+1} ; \; F^2_{TL}(Q^2) \sim \frac{C^2}{2(a+1)}\left(\frac{4\mu^2_{DY}}{Q^2}\right)^{a+1}$$

- Pion: a=1 supported

SL vs TL

- Same Q-dependence
- Normalization –defined by distribution scale (~5) and duality intervals
- Asymptotically coincide – scales close to QCDSR pion duality interval (rather than pion mass) similar (equal?!) for DIS and DY)!?

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 – analyticity - cross section is described by Dirac FF squared
- The SSA similar to twist 3 one- due to interference of Dirac and Pauli FF's with a phase shift (Rekalo,Brodsky)
- Exclusive large energy limit; x -> 1 : $T(x,x)/q(x) \to \text{Im}\, F2/F1(Q^2 \sim M^2(1-x))$
- Both directions – estimate of Sivers at large x and explanation of phases in FF's

Conclusions

- SSA in DY : EM GI brings phases without cuts and factor 2 –tests at COMPASS, NICA
- Direct photon production – analogous modification of gluonic poles
- Feynman gauge: Gluonic poles due to physical field only
- Burkardt sum rule with hidden phase: relation to energy momentum-tensor and equivalence principle
- Exclusive limit – transition FFs
- Sivers function ~ (Im $F_1F_2^*$)

Where to measure?

- J-PARC, COMPASS,..
- NICA@JINR (talk of A.V.Efremov)
- http://nica.jinr.ru/

- Recent view