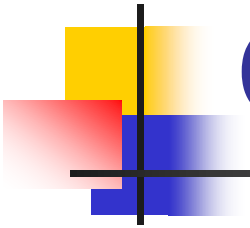
Mechanisms of (semi-)Exclusive DY processes

KEK Workshop on hadron physics with high momentum hadron beams at J-PARC March 13 2015

Oleg Teryaev

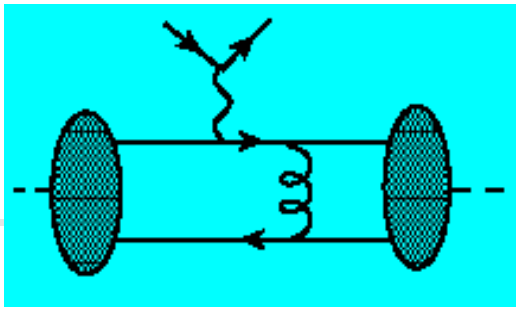
JINR, Dubna



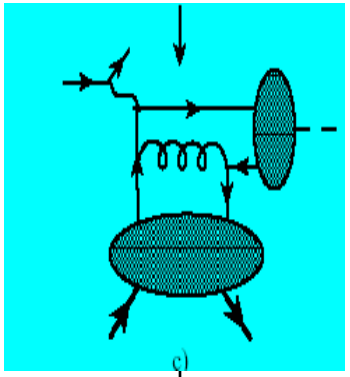
Outline

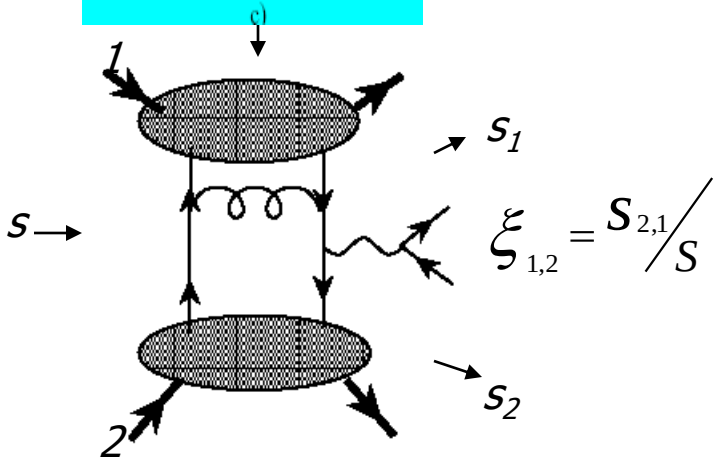
- Exclusive hard processes: analyticity and factorization
- Interference between exclusive lepton pair production mechanisms
- Transverse SSA in DY: contour gauge and factor 2
- DYW/BG-type duality in DY: SSA, Sivers function and time-like formfactors

Ways to to exclusive DY

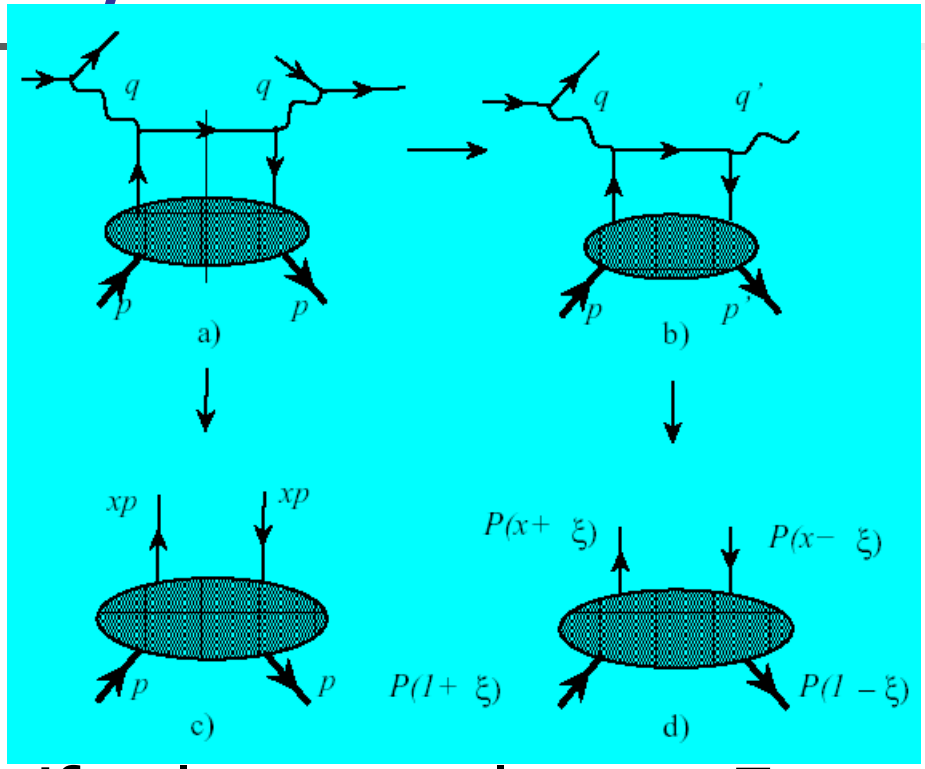


- Simplest case - pion FF(ERBL)
- Change DA to GPD- exclusive electroproduction (Frankfurt,Strikman)
- $M_{DY} \sim M_{DVCS} F_{pi\ g\ g^*}$
- Time from right to left- exclusive DY (DAxGPD)- Berger,Diehl,Pire
- Phase sign change: c.f. Sivers for SIDIS/DY
- Analytic properties ~ factorization (not completely lear yet)
- Second DA->GPD-another mechanism- OT'05 (problems with factorization -analytic continuation to be performed)





QCD Factorization for DIS and DVCS/DVMP



- Manifestly spectral

$$\mathcal{H}(x_B) = \int_{-1}^{1} dx \frac{H(x)}{x - x_B + i\epsilon}$$

- Extra dependence on ξ

$$\mathcal{H}(\xi) = \int_{-1}^{1} dx \frac{H(x,\xi)}{x - \xi + i\epsilon},$$

Unphysical regions

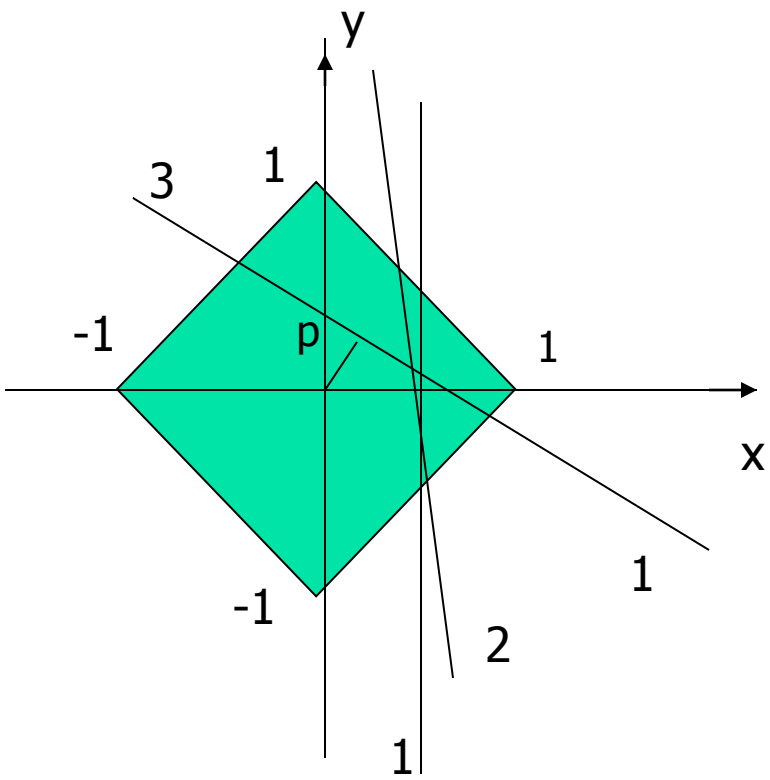
- DIS : Analytical function – if $1 \leq |X_B|$ polynomial in $1/x_B$
- DVCS – additional problem of analytical continuation of $H(x,\xi)$
- Solved by using of Double Distributions Radon transform

$$H(x_B) = -\int_{-1}^{1} dx \sum_{n=0}^{\infty} H(x) \frac{x^n}{x_B^{n+1}}$$

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

Double distributions and their integration

- Slope of the integration line- skewness
- Kinematics of DIS: $\xi = 0$ ("forward") - vertical line (1)
- Kinematics of DVCS: $\xi < 1$ - line 2
- Line 3: $\xi > 1$ unphysical region - required to restore DD by inverse Radon transform: tomography

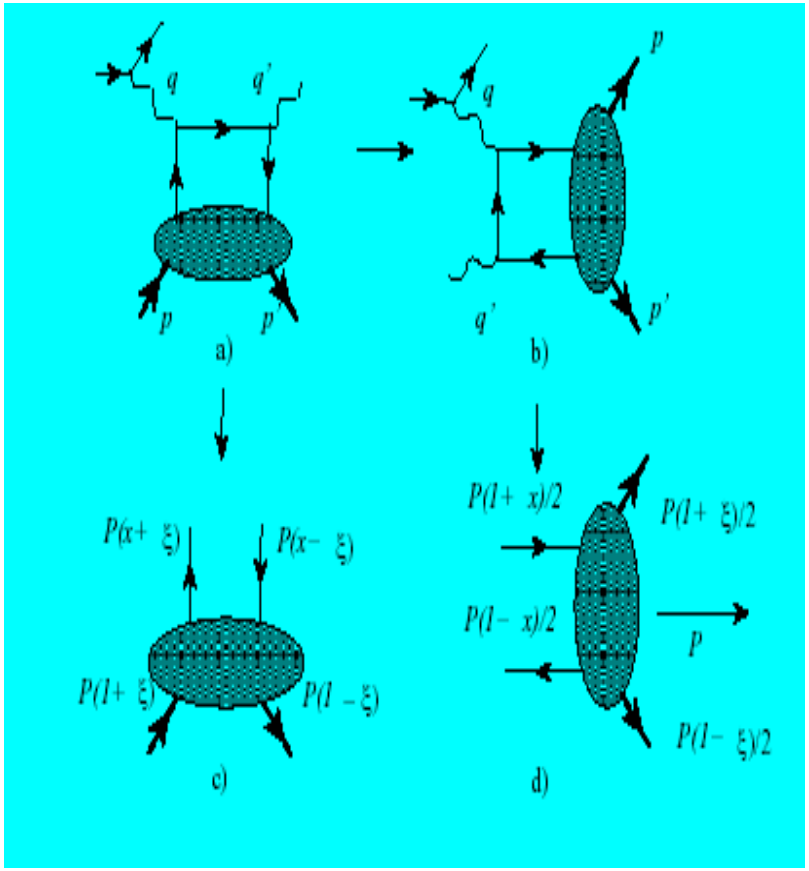


$$f(x,y) = -\frac{1}{2\pi^2}\int_0^\infty \frac{dp}{p^2}\int_0^{2\pi} d\phi |cos\phi| (H(p/cos\phi + x + ytg\phi, tg\phi) - H(x + ytg\phi, tg\phi)) =$$

$$= -\frac{1}{2\pi^2}\int_{-\infty}^\infty \frac{dz}{z^2}\int_{-\infty}^\infty d\xi (H(z + x + y\xi, \xi) - H(x + y\xi, \xi))$$

Crossing for DVCS and GPD

- DVCS -> hadron pair production in the collisions of real and virtual photons
- GPD -> Generalized Distribution Amplitudes



GDA -> back to unphysical regions for DIS and DVCS

- Recall DIS

$$H(x_B) = -\int_{-1}^{1} dx \sum_{n=0}^{\infty} H(x) \frac{x^n}{x_B^{n+1}}$$

- Non-positive powers of x_B

- DVCS

$$H(\xi) = -\int_{-1}^{1} dx \sum_{n=0}^{\infty} H(x,\xi) \frac{x^n}{\xi^{n+1}}$$

- Polynomiality (general property of Radon transforms): moments - integrals in x weighted with x^n - are polynomials in 1/ ξ of power $n+1$
- As a result, analyticity is preserved: only non-positive powers of ξ appear

Holographic property (OT'05)

- Factorization Formula ->

$$\mathcal{H}(\xi) = \int_{-1}^{1} dx \frac{H(x,\xi)}{x - \xi + i\epsilon}$$

- Analyticity ("dynamical") -> Imaginary part -> Dispersion relation:

$$\mathcal{H}(\xi) = \int_{-1}^{1} dx \frac{H(x,x)}{x - \xi + i\epsilon}$$

$$\Delta\mathcal{H}(\xi) \equiv \int_{-1}^{1} dx \frac{H(x,x) - H(x,\xi)}{x - \xi + i\epsilon}$$

- "Holographic" equation (DVCS AND VM)

$$= \sum_{n=1}^{\infty} \frac{1}{n!} \frac{\partial^n}{\partial \xi^n} \int_{-1}^{1} H(x,\xi) dx (x - \xi)^{n-1} = const$$

Holographic property - II

- Directly follows from double distributions

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

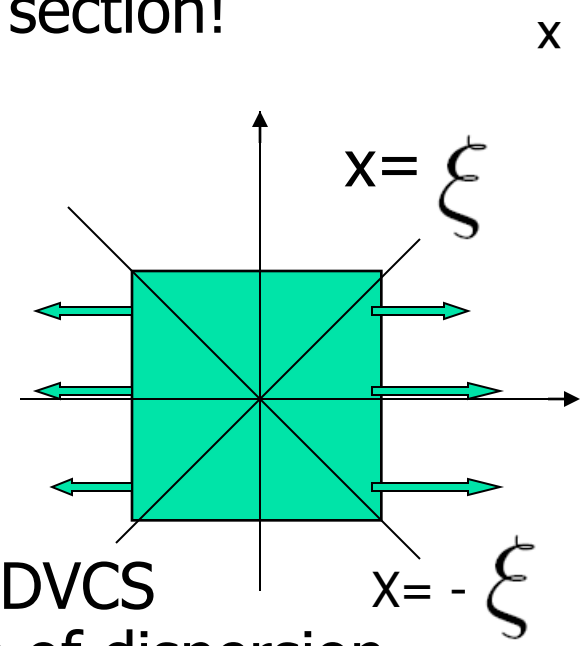
- Constant is the SUBTRACTION one - due to the (generalized) Polyakov-Weiss term G(x,y)

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

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

Holographic property - III

- 2-dimensional space -> 1-dimensional section!
- Momentum space: any relation to holography in coordinate space ?!



- ERBL ⟶ "GDA" region
- Strategy (now adopted) of GPD's studies: start at diagonals

(through SSA due to imaginary part of DVCS amplitude) and restore by making use of dispersion relations + subtraction constants

DY?!

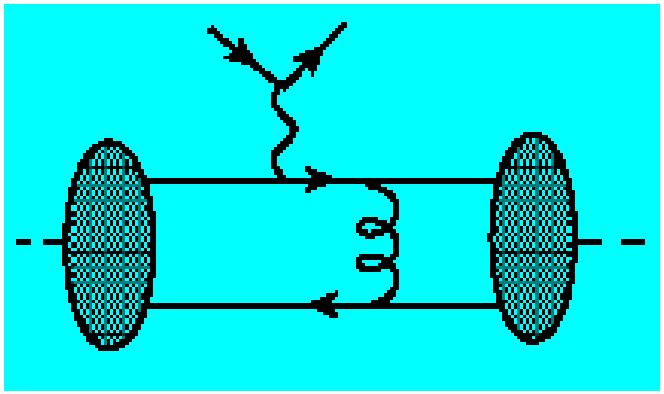
Time-like amplitudes and analyticity

- Extra cuts in Q^2 appear
- Scaling: $F(Q^2/s) = F(-Q^2/-s)$: cuts cancellation (cf inclusive electron-positron annihilation)
- $F(Q^2/u) = F(-Q^2/-u)$ – cuts in Q^2 has a form of cuts in u (opposite pole prescription) – diagonals on holographic plot interchanged
- Factorization proof: start in unphysical region in skewness where factorization holds (cuts cancelled but what about NLO?! – nonfactorizable corrections!?) and continue to physical region

“Dispersive” factorizaton proof

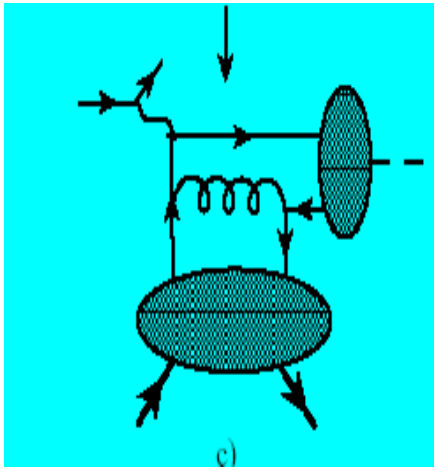
- Starting from (Pion) form factor- 2 DA’s –no cuts

$$F \sim (\int dx \frac{\phi(x)}{1-x})^2$$



- 1 DA -> GPD :Exclusive mesons production: Factorization = DR + D-subtraction
- (DVMP/DY) - +/-

$$M \sim \int dx \frac{\phi(x)}{1-x} \int dx \frac{H(x,\xi)}{x-\xi+i\varepsilon}$$



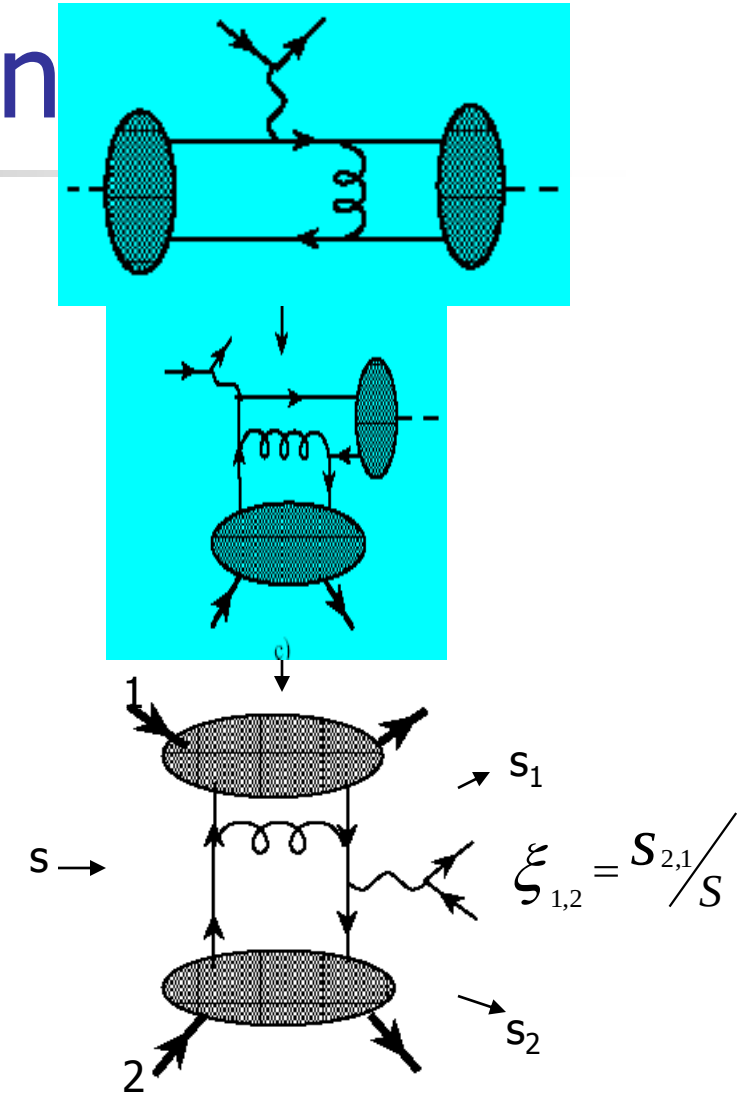
Next step: 2 DA's -> 2 GPD's- Double Diffraction

- Exclusive double diffractive DY process
- Analytic continuation:

$$M \sim \int dx \frac{H(x,\xi_1)}{x-\xi_1 \pm i\varepsilon} \int dy \frac{H(y,\xi_2)}{y-\xi_2 \mp i\varepsilon}$$

- DIFFERS from direct calculation – NO factorization in physical region

$$M \sim \int\int dx dy \frac{H(x,\xi_1)H(y,\xi_2)}{(x-\xi_1)(y-\xi_2)+i\varepsilon}$$



Double Diffraction: properties and problems

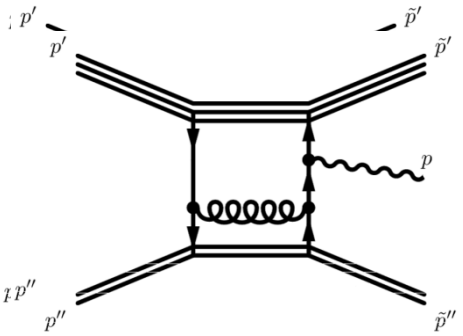
- Holographic equation: DR contains double and single (linear in D-term) dispersion integrals as well as subtraction (quadratic in D-term)
- $F(Q^2/s) \rightarrow F(s_i/s), F(s_i/s_j)$
- Analytic continuation for

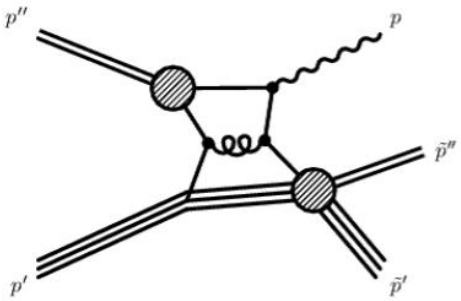
various cuts is still unclear. Possible cancellation of cuts – real amplitude?

Interference effects

- Interference with pure EM (FFxFF) production of (C-even) lepton pair contains only real IR safe part of the amplitude and gives rise to charge asymmetry (Pivovarov,OT, work in progress)
- The way to extract GPDxGPD in central region from inclusive DY

Interference with DGP(TDA) mchanism

- 

(16 diagrams)
- 

(8 diagrams)

Interference in exclusive DY

- In the forward region interference with BDP-like mechanism with TDA (Pivovarov,OT'14)

$$\frac{d\sigma}{\mathrm{d}^3\tilde{p}'\mathrm{d}^3\tilde{p}''} = \frac{\alpha_{(em)}\alpha_{(s)}^2}{2^6 N_c^4 \pi^2 \tilde{\varepsilon}'\tilde{\varepsilon}''} \cdot \frac{1}{(p', p'')^2} \cdot$$

$$\cdot \left[\frac{8s^2}{s_1 s_2}|I_1|^2 + \frac{8s}{s_1+s_2-s}|I_2|^2 + 4s\left(\frac{1}{s_2} + \frac{s}{s_1(s_1+s_2-s)}\right)(I_1^* I_2 + I_2^* I_1)\right] \cdot$$

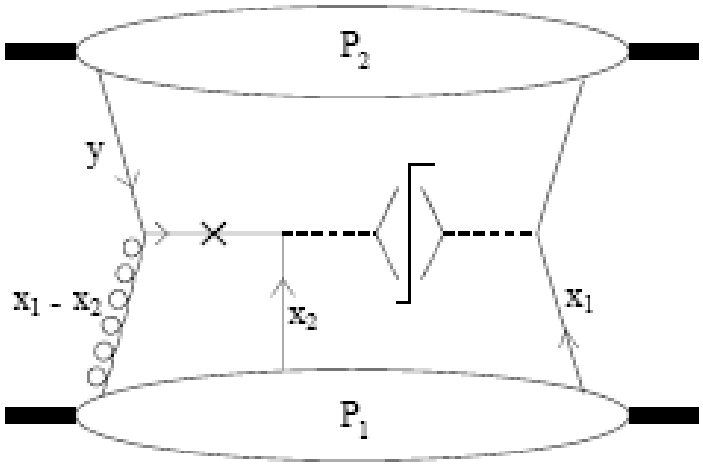
$$\cdot \delta(q^2 - m_\gamma^2)$$

SSA in DY

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

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

- Twist 3 – energy should not be too large(J-PARC)



+ c. c.

Contour gauge in DY (Anikin,OT, **PLB690 (2010) 519; Direct photons - arXiv: 1501.05900**)

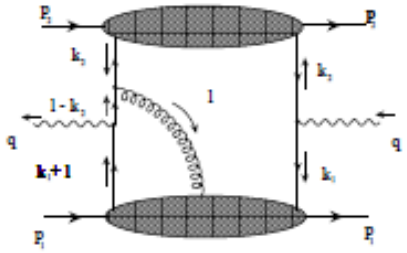
- Motivation of contour gauge – elimination of link $[-\infty^-, 0^-] = 1$
- Field $[-\infty^-, 0^-] = Pexp\left\{-ig\int\limits_{-\infty}^{0} dz^- A^+(0, z^-, \vec{0}_T)\right\}$

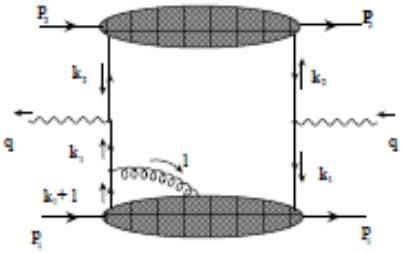
$$A^\mu(z) = \int\limits_{-\infty}^{\infty} d\omega^- \theta(z^- - \omega^-) G^{+\mu}(\omega^-) + A^\mu(-\infty)$$

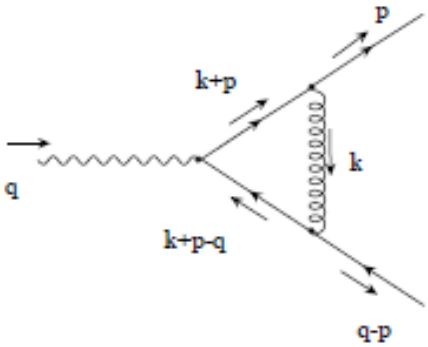
- Gluonic pole appearance $B^V(x_1, x_2) = \dfrac{T(x_1, x_2)}{x_1 - x_2 + i\epsilon}$
- cf naïve expectation $B^V(x_1, x_2) = \dfrac{\mathcal{P}}{x_1 - x_2} T(x_1, x_2)$
- Source of “Hidden” phase

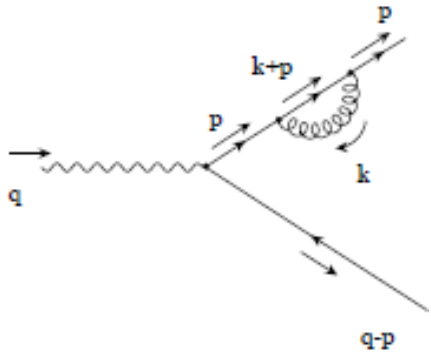
New phases and (EM) gauge invariance

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



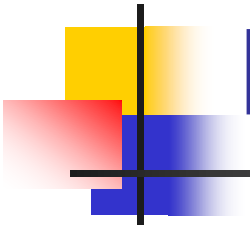






- Cf PT – only one of two diagrams contribute to SSA and required for GI
- NP tw3 analog - GI only if GP absent

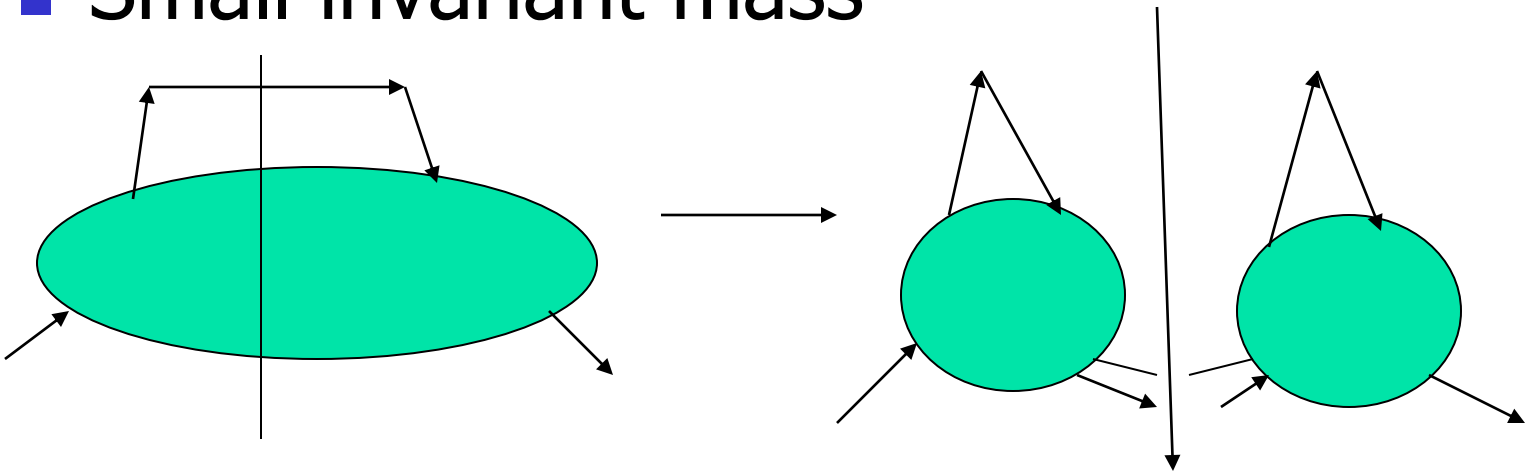
Hidden phase



- Analogous to Beliitsky, Ji, Yuan finding for gauge link?! (GP/Sivers relation – Boer,Mulders,Pijlman; Ji, Qiu, Vogelsang, Yuan)
- Plasma physics: phase of naively real poles - Landau damping
- GP – "Hidden phases" – experimental tests@J-PARC?!

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

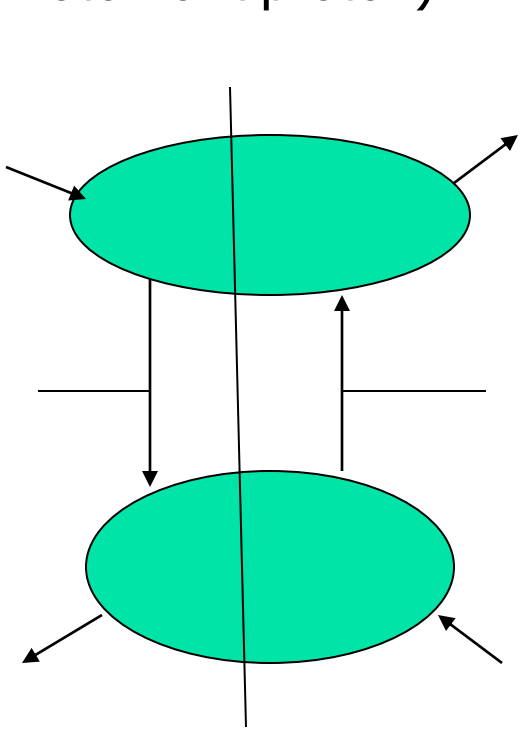
- Small invariant mass

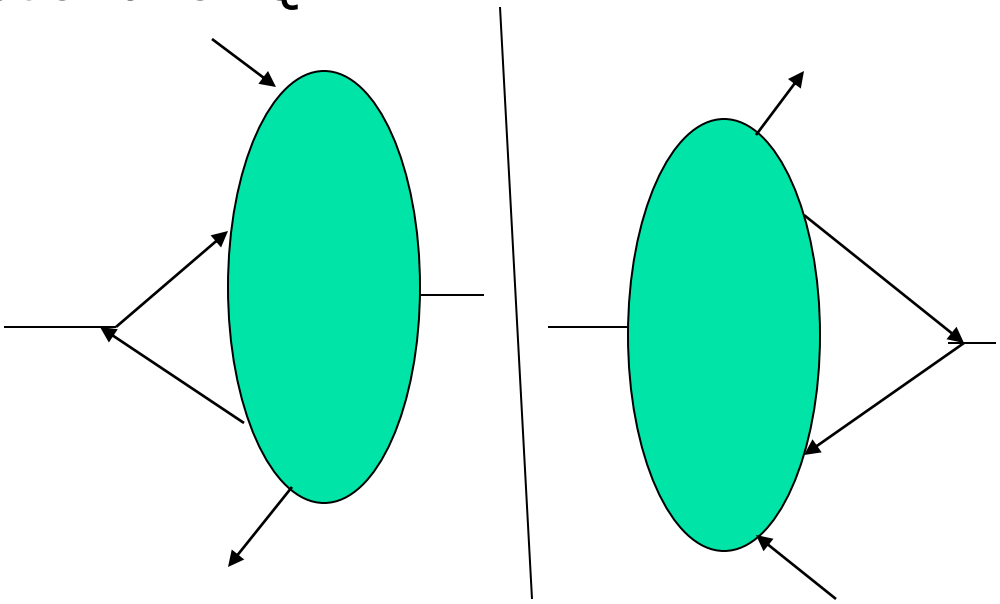


- May be related to unitarity analyticity and DR (OT'05)
- Relation between x ->1 and large Q^2
- pdf ~ $(FF)^2$

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

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





- $(pdf)^2 \sim$ (Dirac) $(FF)^2$

- Other beams – baryon number conservation – time-like transition FFs

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

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

DR: FFs from duality intervals

- DIS: $F_{SL}^2 \sim \int_0^{\delta_{DIS}} d\bar{x} f(\bar{x}) \quad x = 1 - \bar{x}$

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

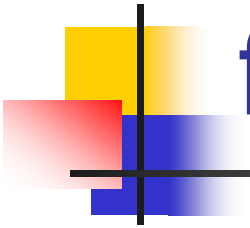
$$F_{SL}^2(Q^2) \sim \frac{C}{a+1}\left(\frac{2M\mu_{DIS}}{Q^2}\right)^{a+1}; \; F_{TL}^2(Q^2) \sim \frac{C^2}{2(a+1)}\left(\frac{4\mu_{DY}^2}{Q^2}\right)^{a+1}$$

- 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)!?
- Experimental tests at J-PARC – like BG tests in DIS@Jlab – lower energy pion beams

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 (analyticity?!) 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 : $T(x,x)/q(x) \rightarrow \mathrm{Im}\, F2/F1(Q^2 \sim M^2(1-x))$
- Both directions – estimate of Sivers at large x and explanation of phases in FF's

CONCLUSIONS/OUTLOOK

- Analyticity - natural way of factorization proof. DY – holds due to cuts cancellation, but possible problems at NLO
- Interference and QCD induced charge asymmetry is possible for lepton pairs production
- SSA@DY factor 2 (“Landau damping”) – can it be tested at J-PARC?
- BG/DYW for FF’s – J-PARC at lower energy?