Angular distributions in inclusive and exclusive Drell-Yan processes

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Outline

- Angular distributions of lepton pairs and density matrix
- Simple geometrical model of azimuthal angular distributions
- Geometrical model and LHC data

- Semi-exclusive DY and pion distribution amplitude
- Exclusive DY and GPDs

- Generalizing Bloom-Gilman duality to DY process

- Conclusions

Dilepton angular distribution and virtual photon density matrix

- 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): OT'10

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

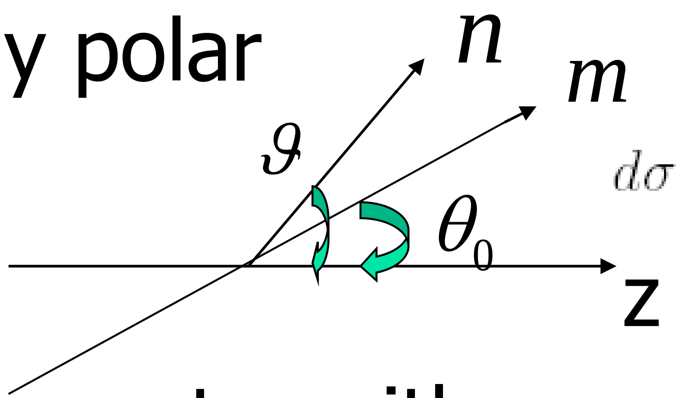
$$|\lambda| \le 1,\ |\nu| \le 1+\lambda,\ \mu^2 \le \frac{(1-\lambda)(1+\lambda-\nu)}{4}$$

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

- + 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

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

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

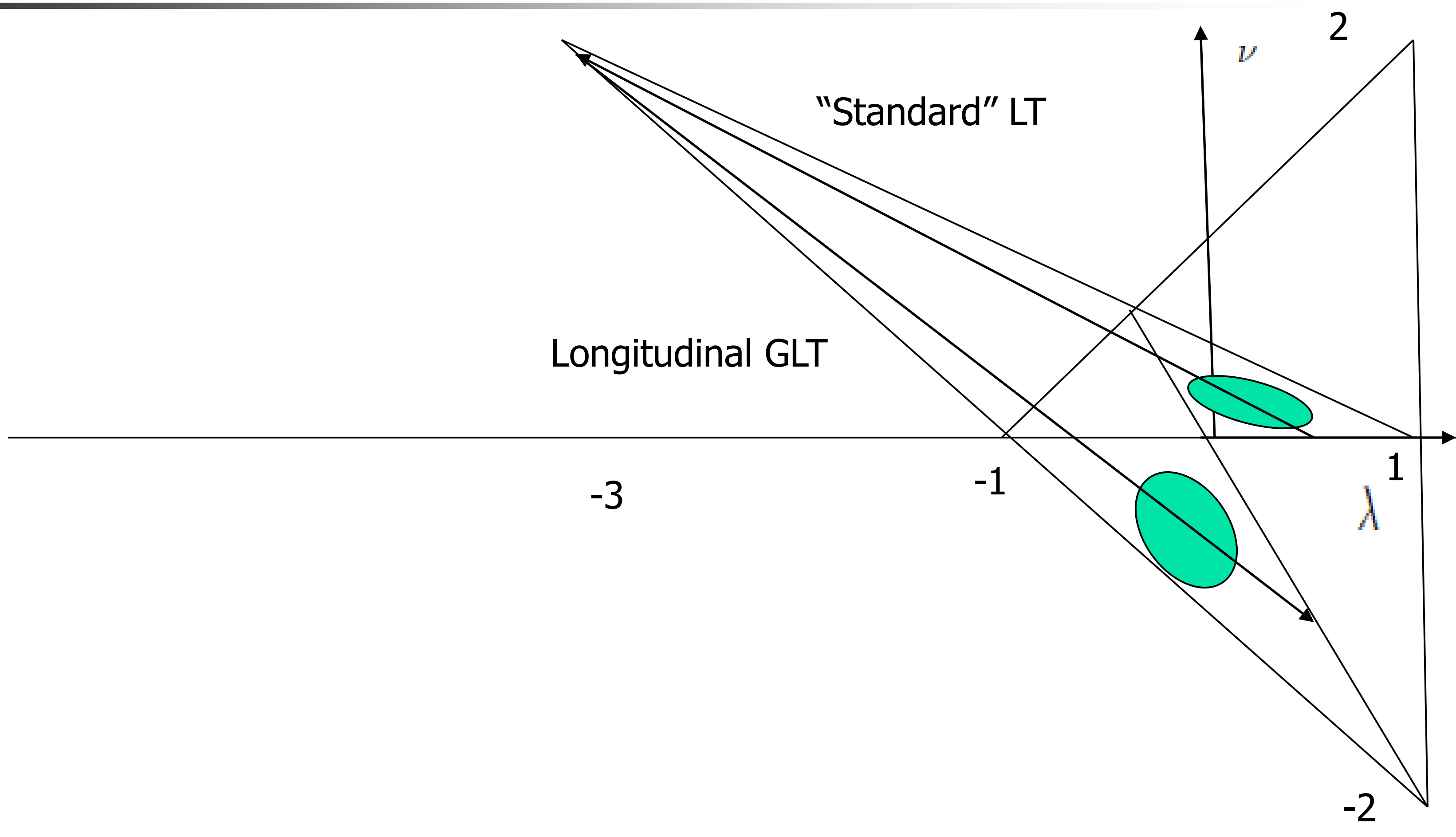
Generalized Lam-Tung relation (OT'05)

- 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



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

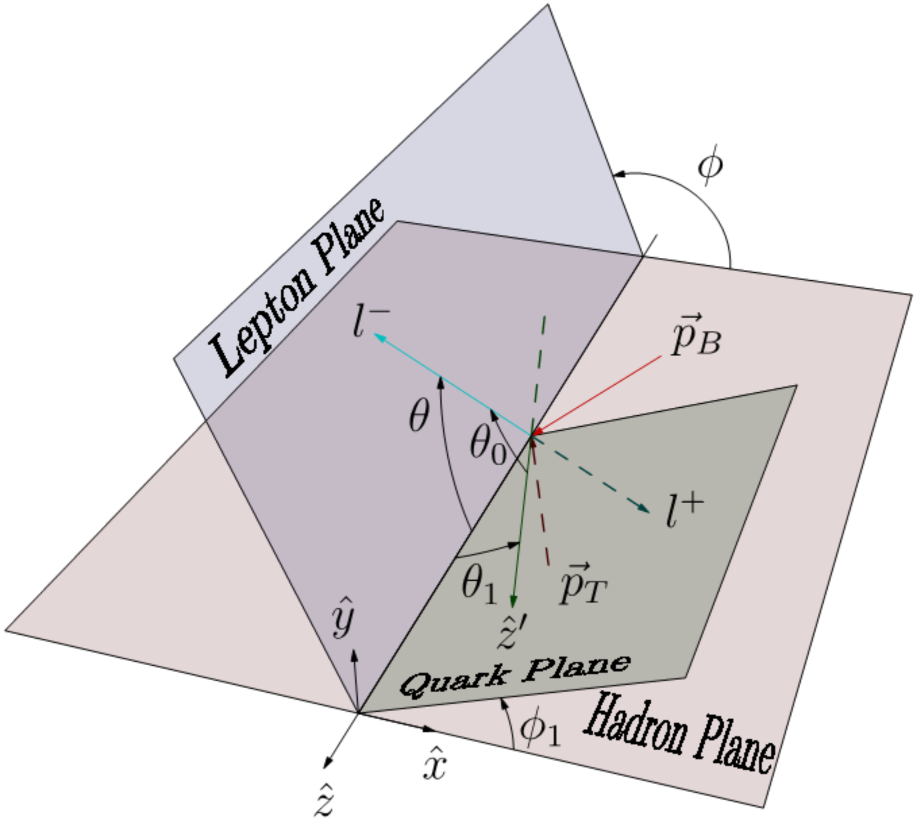
- Direct comparison: $\tan^2 \theta_0 = (k_T/Q)^2$
- Off-shellness effects for colliding (anti)quarks – cancel in GI set
- New ingredient – expression for μ
- Linear in k_T
- Saturates positivity constraint!
- Extra probe of transverse momentum

Geometric model vs FNAL and LHC data on Z production

- Interpretation of Angular Distributions of Z-boson Production at Colliders; Jen-Chieh Peng,Wen-Chen Chang, Randall Evan McClellan, and Oleg Teryaev; 1511.09893 and PLB

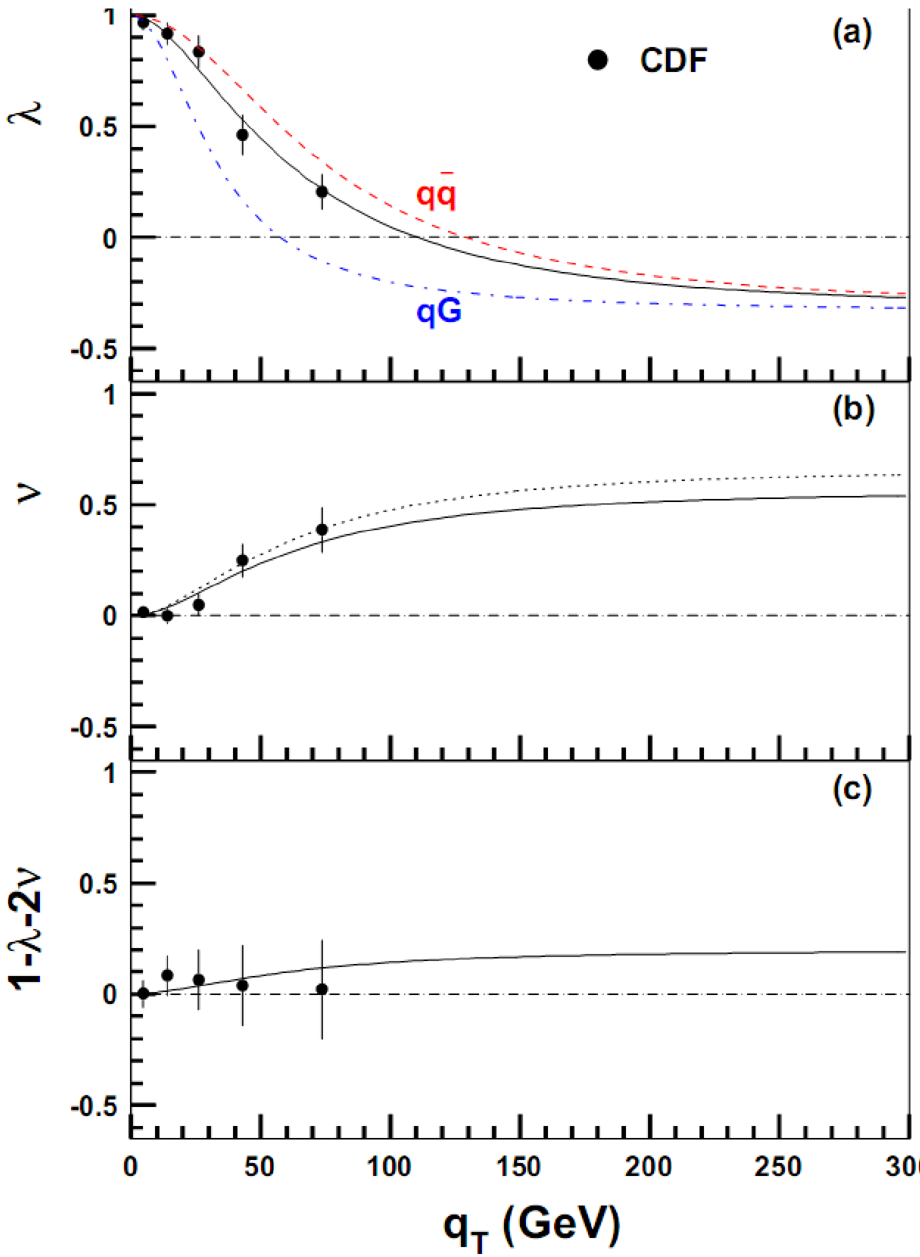
- Geometrical picture

- Non-coplanarity – disbalance of quark and hadron planes



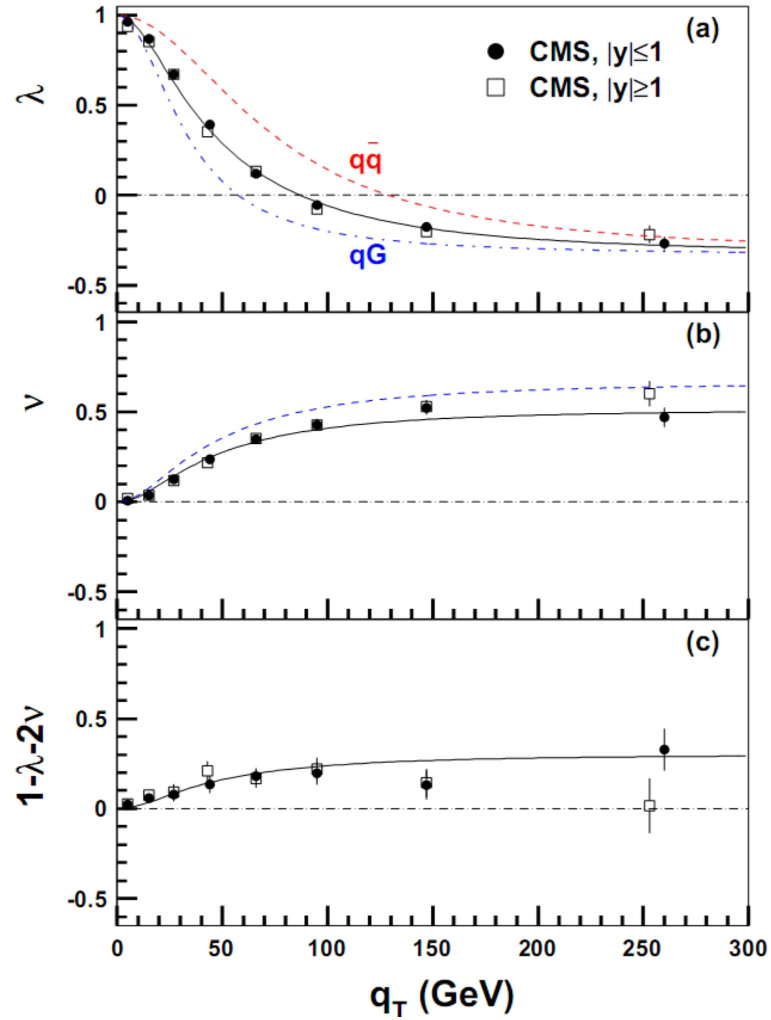
CDF (1.96 TeV) data

- qq-72.5%
- qG-27.5%
- < cos $2\varphi_1$> =0.85±0.17

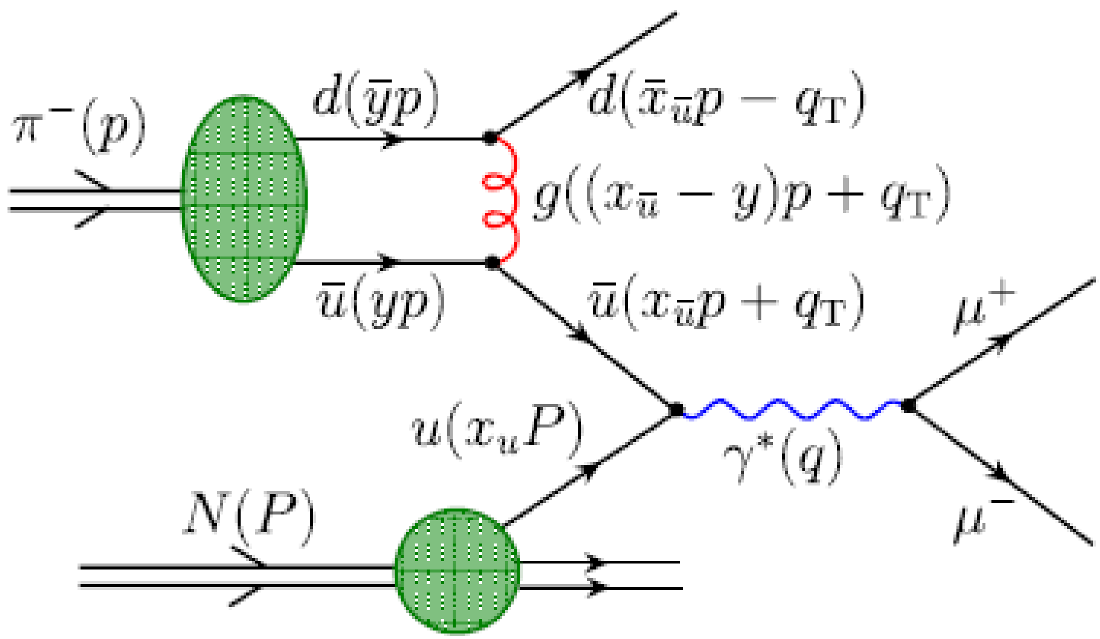


CMS (8 TeV) data

- Necessity to account for
- qq - 41.5(1.6)% (reggeized quarks?!)
- qG - 58.5(1.6)%
- $< \cos 2\varphi_1 > = 0.77$



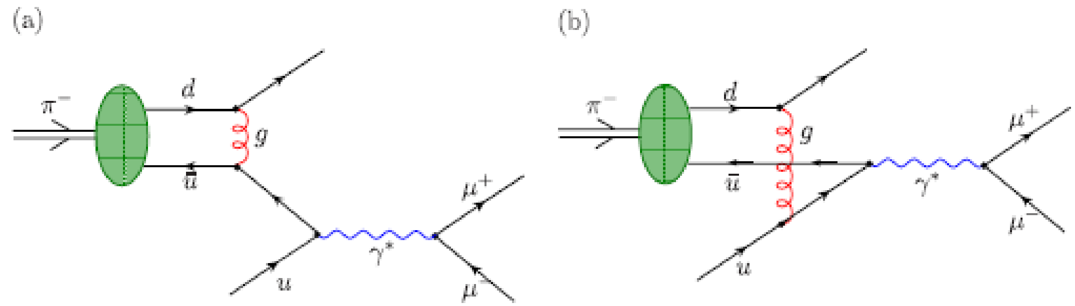
Semi-Exclusive DY (large x_F) - Pion participates through Distribution Amplitude (Light-cone WF)



When transition to exclusivity happen?

- Pion pdf $\sim(1-x)^a$
- HT $\sim (\langle 1/x \rangle f/Q)^2$
- Transition: $(1-x)^a \sim (\langle 1/x \rangle f/Q)^2$
- Strongly depends on pion pdf (large x dependence) and DA

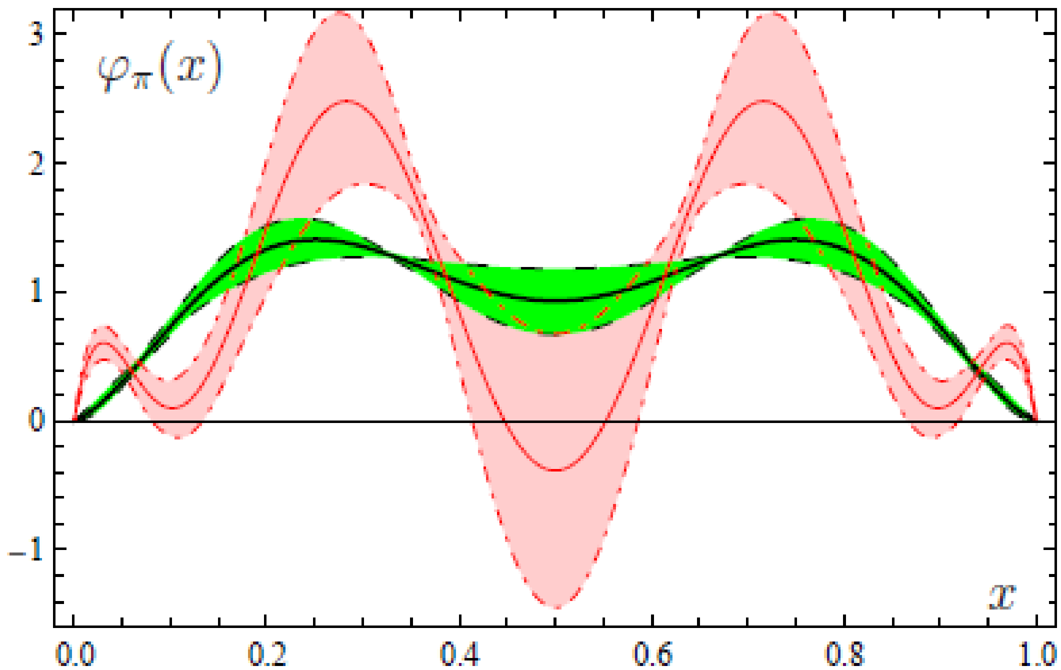
GI -> phase



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

Pion DA

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



Angular distributions – probes of DA

- Unpolarized

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

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

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

$$\rho \equiv Q_T/Q$$

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

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

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

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

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

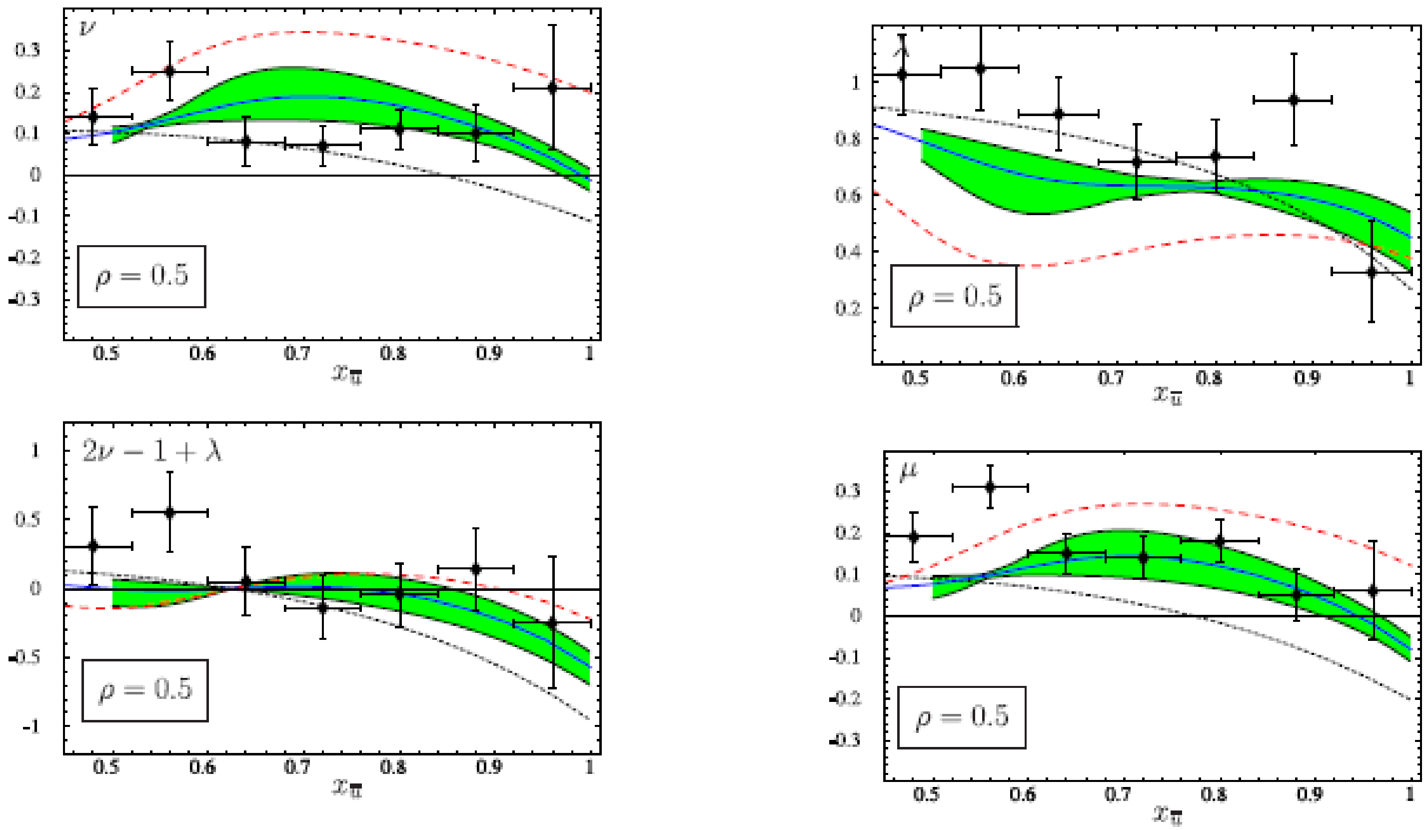
- Polarized

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

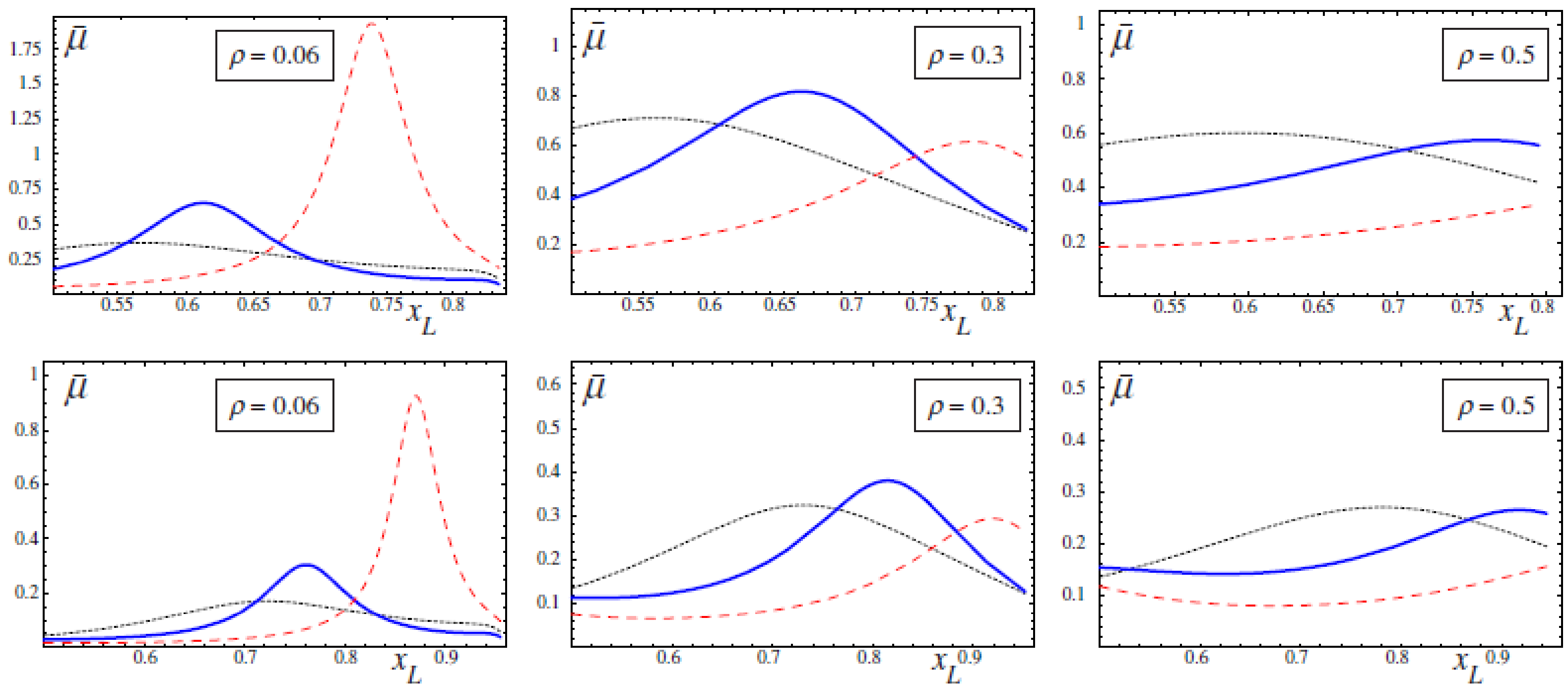
$$\bar{\mu}_{\mathrm{nucl}} \equiv \frac{\frac{4}{9}\Delta q_u^v(x_p; \mu^2) + \frac{4}{9}\Delta q_u^s(x_p; \mu^2) + \frac{1}{9}\Delta q_d^s(x_p; \mu^2)}{\frac{4}{9}q_u^v(x_p; \mu^2) + \frac{4}{9}q_u^s(x_p; \mu^2) + \frac{1}{9}q_d^s(x_p; \mu^2)},$$

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

Asymmetries vs E615 data



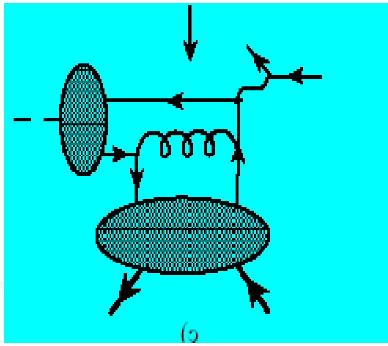
Polarization -> scanning of DA



Light-cone momenta in exclusive DY

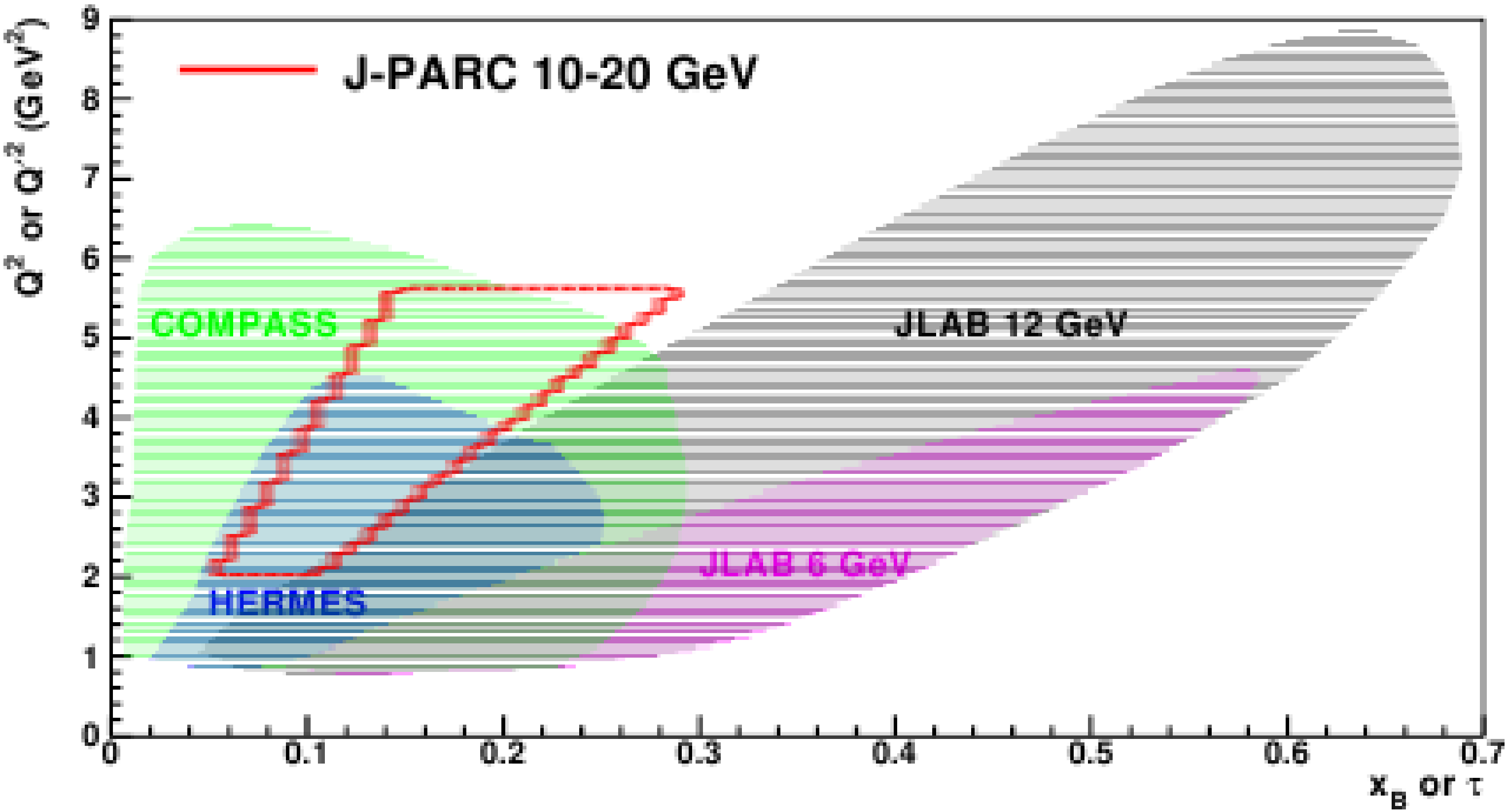
- Massive lepton pair – always requires that virtual photon carry both + and – light-cone momenta fractions
- Exclusive limit – limited number of final hadrons (typically 1 or 2)
- Mechanism may be labeled by light-cone momenta of final hadrons: 0,1,2 may carry large LC moments fractions

Ways to exclusive DY: classical



- “Classical”: 1 hadron in final state carrying sizable LC momentum fraction: GPD*(π)DA
- Meson-nucleon DY only
- Version: 2 hadrons in final state carrying the same (+ or -) LCM fraction and having low invariant mass TDA*(π)DA
- Factorization is it the same as for DVMP? Note DVMP problems and necessity of intrinsic TM
- Energy decrease (pion pole): small at COMPASS, suggested for J-PARC

ExDY@J-PARC (Takahiro Sawada, Wen-Chen Chang, Shunzo Kumano, Jen-Chieh Peng, Shinya Sawada, Kazuhiro Tanaka), 1605.00364 and PRC

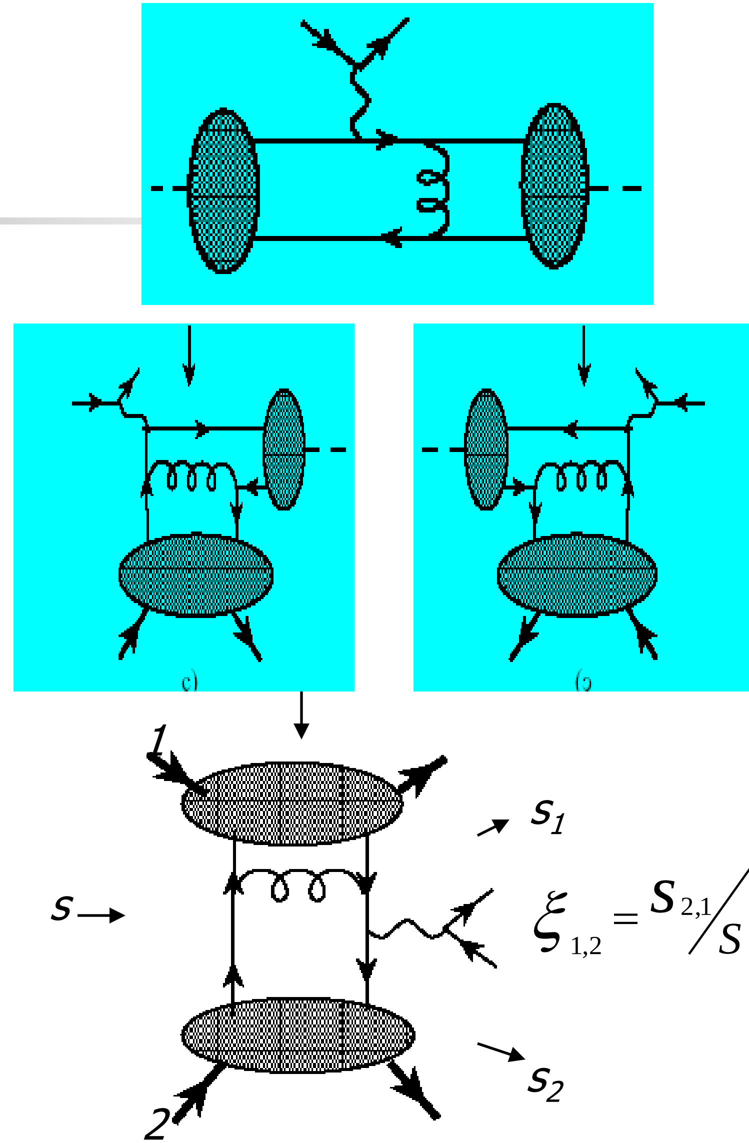


New ways to exclusive DY

- 2 hadrons in final state carrying different (+ and -) LCM fractions and having large invariant mass: GPD*GPD
- Also for pp
- No energy decrease: from NICA to LHC?
- 0,1,2 hadrons in final state carrying small LCM fractions: transition FFs and Bloom-Gilman-type duality in time-like region

Diagrammatics to exclusive DY

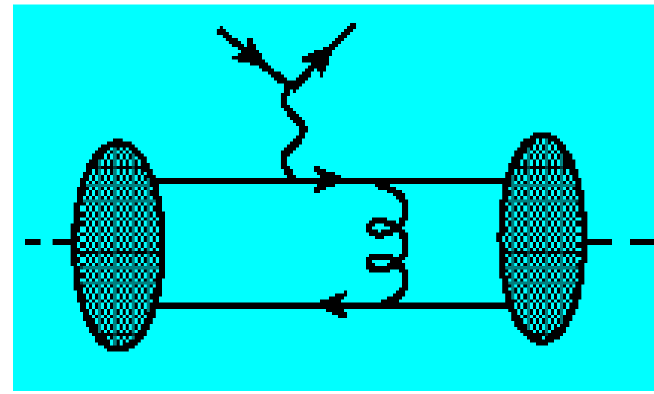
- Simplest case - pion FF(ERBL)
- Change DA to GPD - exclusive electroproduction
- $M_{DY} \sim M_{DVCS} F_{pi\ g\ g*}$
- Time from right to left- exclusive DY (DAxGPD)- Berger,Diehl,Pire
- Phase sign change: c.f. Sivers for SIDIS/DY
- Second DA->GPD-another mechanism- OT'05
- Longitudinal polarization
- Problems with factorization - analytic continuation may be used)



“Dispersive” factorizaton proof

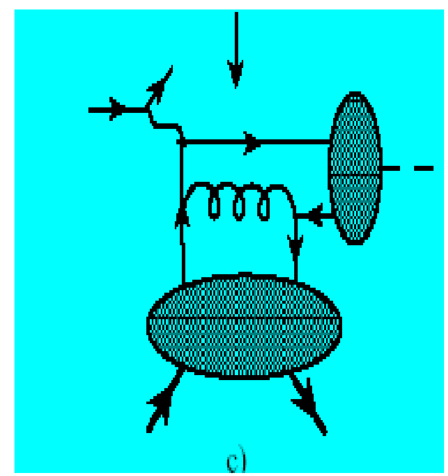
- Starting from (Pion) form factor- 2 DA’s –no cuts

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



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

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



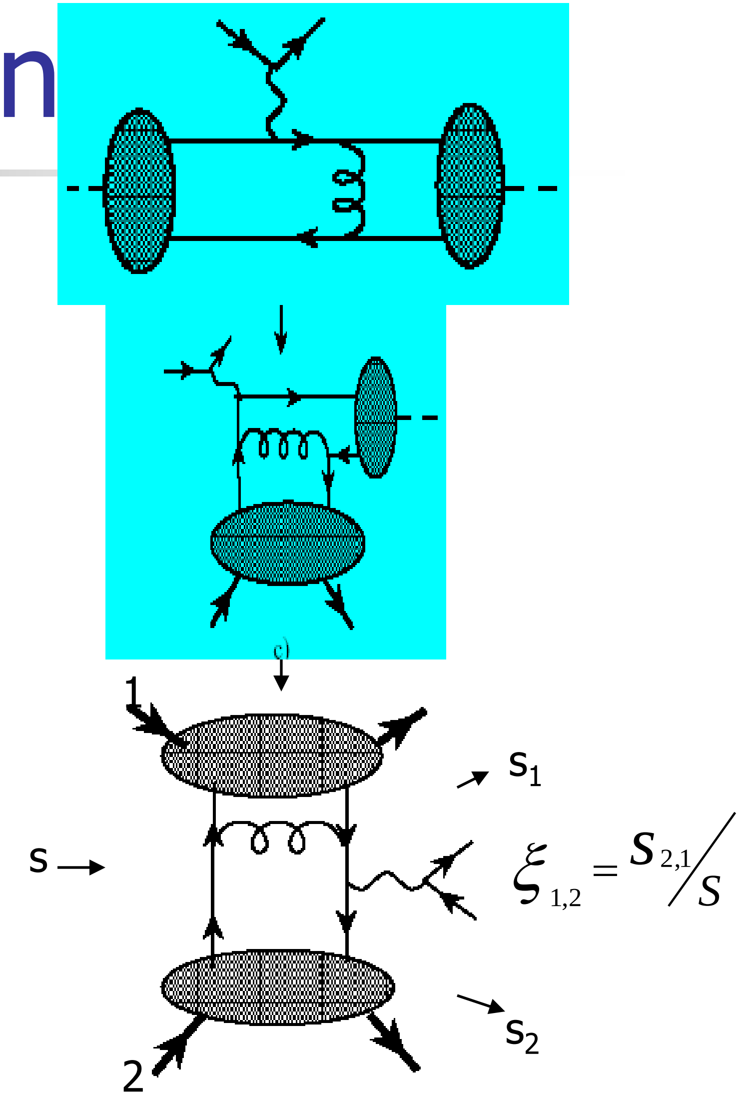
Next step: 2 DA's -> 2 GPD's- Double Diffraction

- Exclusive double diffractive DY process
- Analytic continuation:

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

- DIFFERS from direct calculation – NO factorization in physical region

$$M \square \int\int dxdy \frac{H(x,\xi_1)H(y,\xi_2)}{(x-\xi_1)(y-\xi_2)+i\varepsilon}$$



Intrinsic TM for various exclusive DY mechanisms

- Collinear GPDs – typically too large contribution to DVMP
- Intrinsic TM for meson WF (GK model)
- Neglected in GPD – more hope for "factorization" (product of Compton FFs) in GPD*GPD

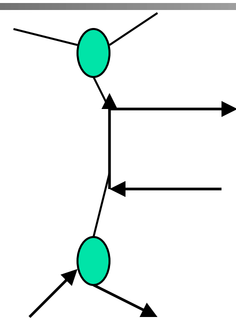
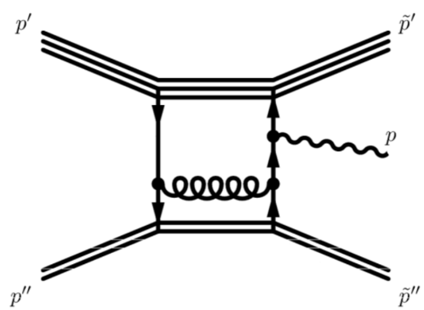
Kinematical regions

- (Nucleon GPD)x(pion Compton FF) – very forward region
- (Nucleon GPD)x(pion Compton GPD) – all x_F
- How to select? – interference with EM (Nucleon FF)x(pion FF)

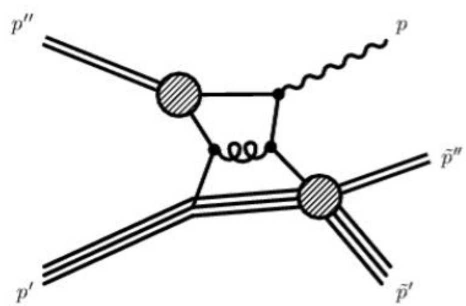
Interference effects

- 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 (work in progress)
- Both for pion-nucleon and pp
- The way to extract GPDxGPD in central region from inclusive DY

Interference of EM, GPD and TDA (for pion-nucleon DY) mechanisms

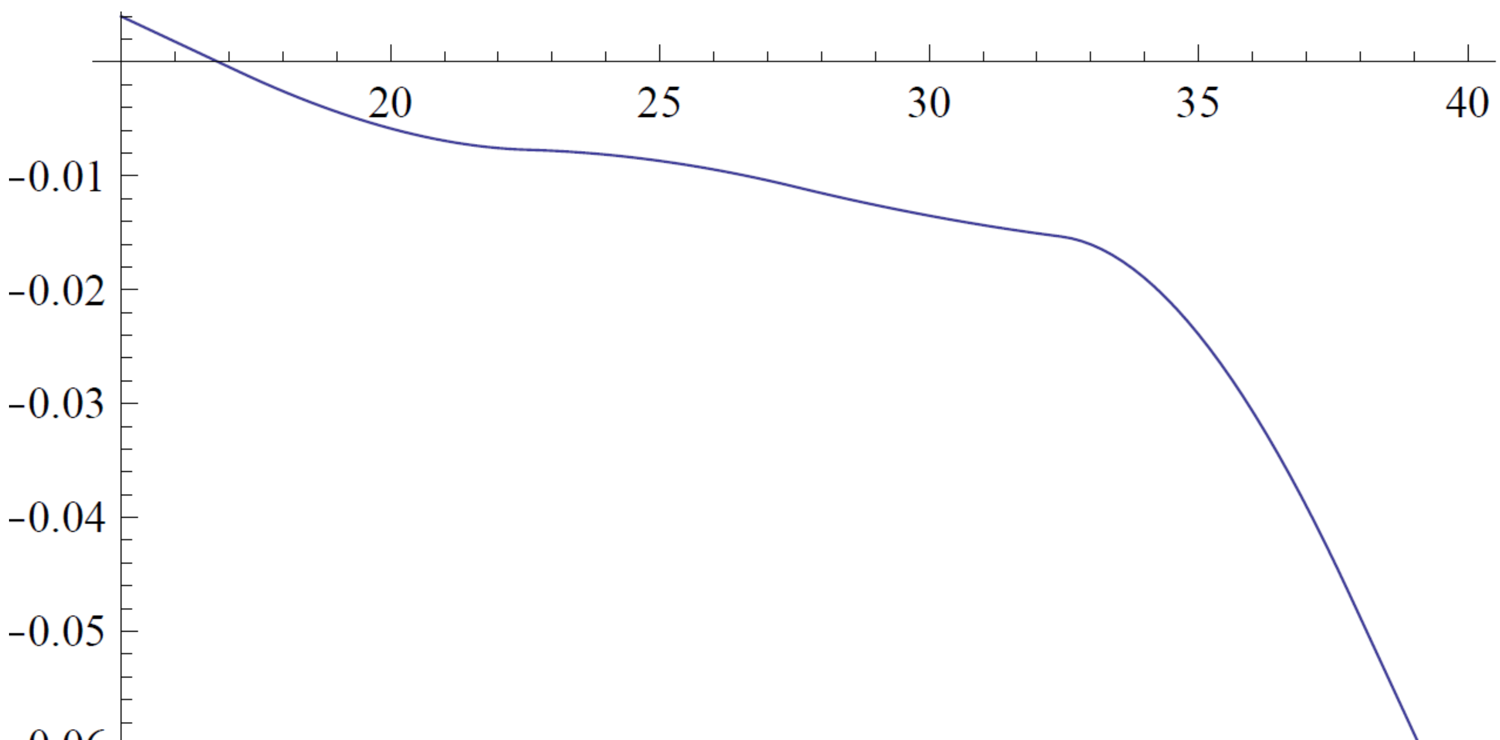
- 
  (2 diagrams)
- 

  (16 diagrams)
- (8 diagrams)

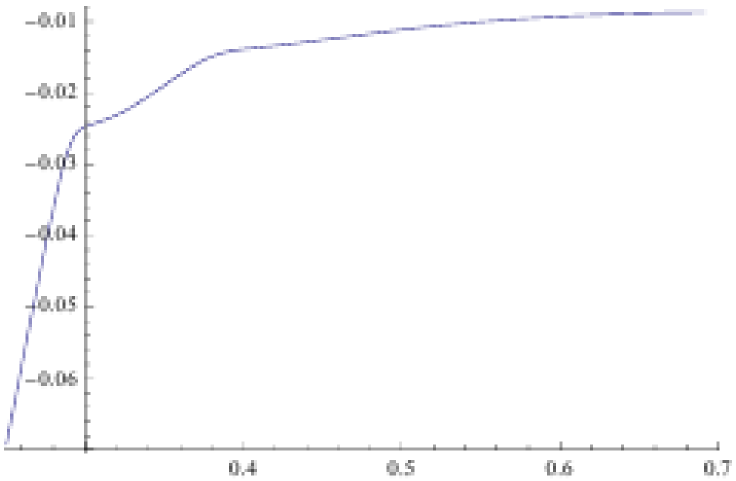


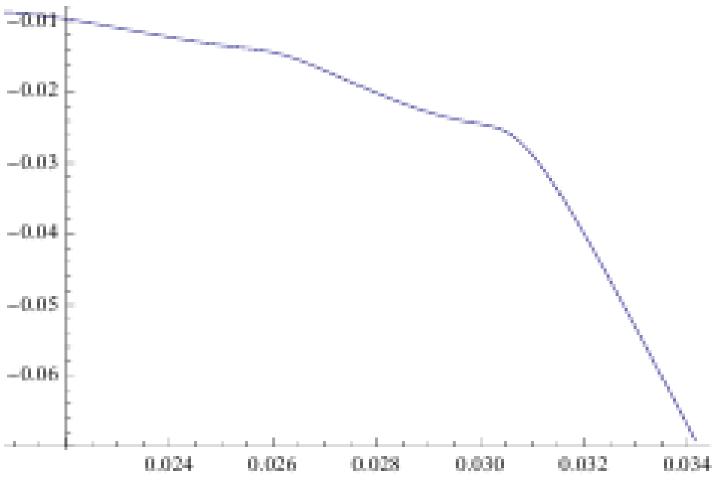
Interference with EM mechanism

- Charge asymmetry (muon-antimuon interchange) vs cm muon angle



(Anti)muon Lab frame asymmetry



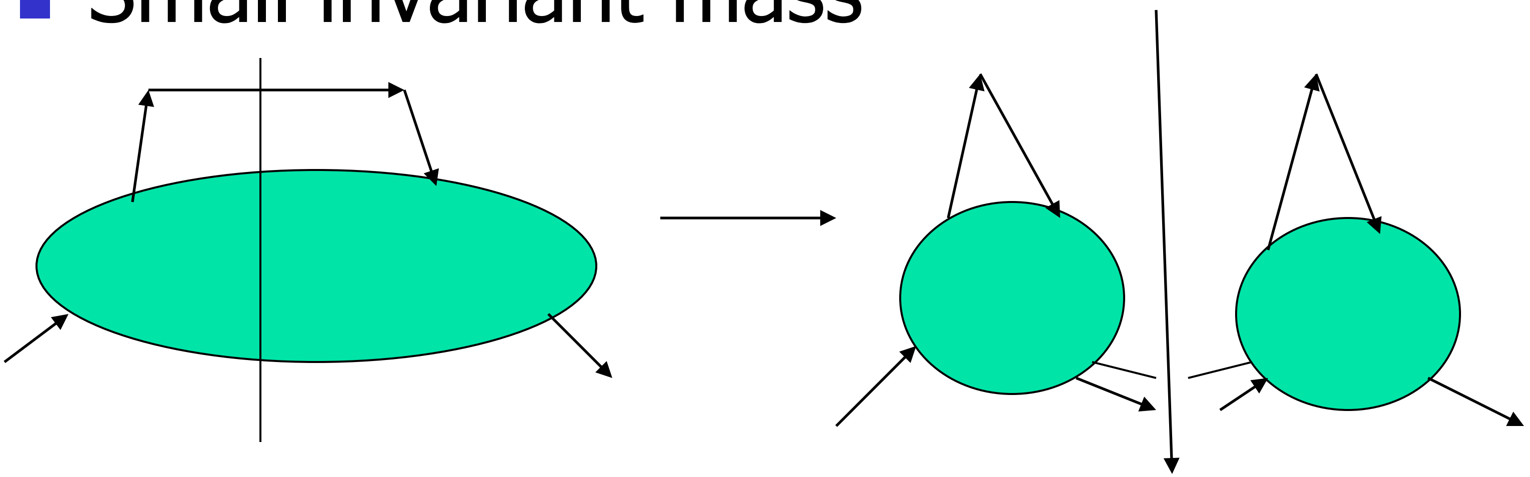


Exclusive large x limit

- Consider the dilepton carrying the most of collision energy; small number of hadrons in the central region; correspond to large x of pdf's
- DIS – Bloom Gilman duality, Drell-Yan-West relations
- Is there any analog for DY?

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

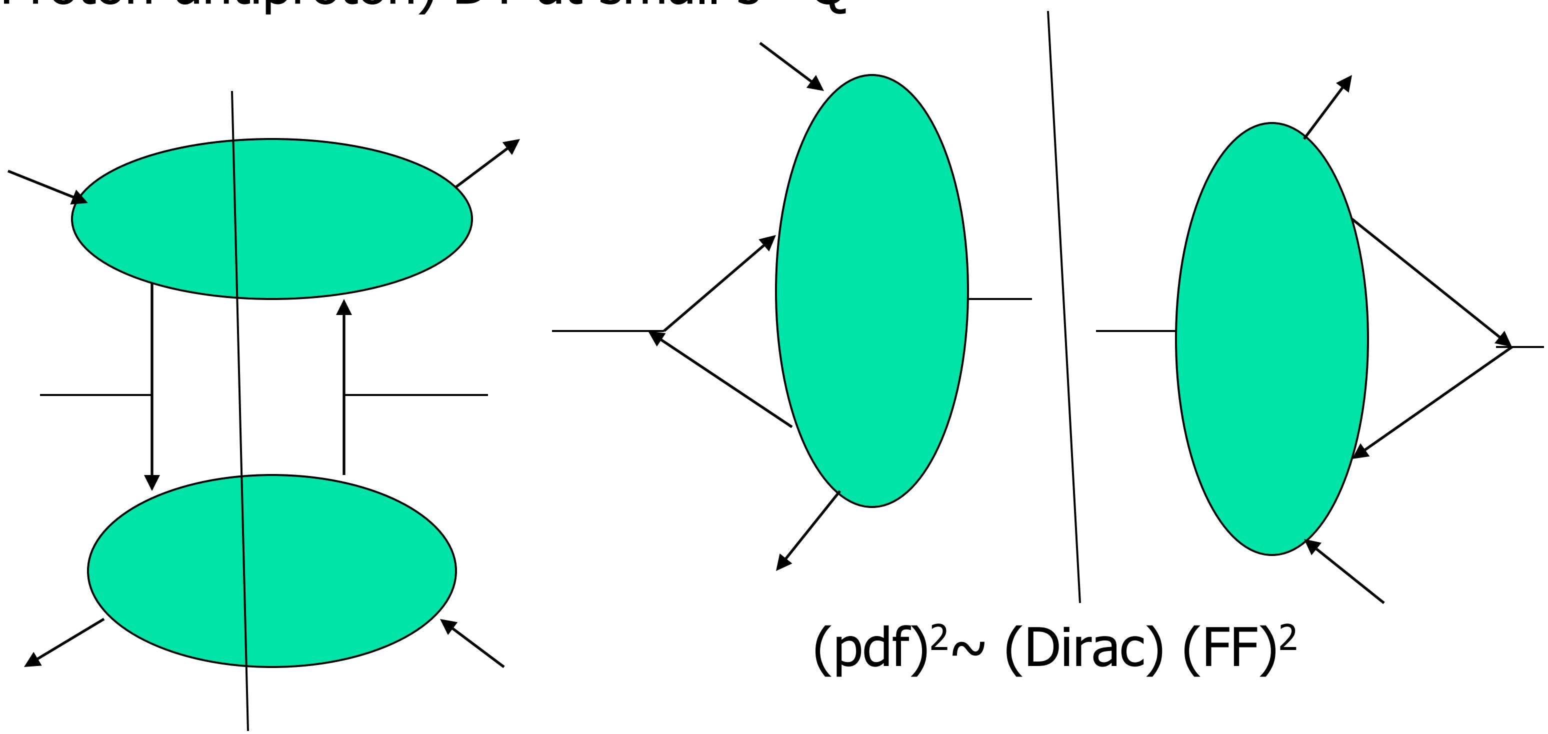
- Small invariant mass



- 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'12)

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



- (pdf)^2~ (Dirac) (FF)^2
- Other beams – baryon number conservation – time-like transition FFs
- Tests similar to tests of BG@JLab?!

Comparing space-like and time-like FFs

- "Duality intervals" - from mass to LC x-space
- DIS: $(P+q)^2 = (P_f + \delta P_{DIS}))^2 = (M + \mu_{DIS})^2$ μ_{DIS} ~ pion mass 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: $$F^2_{SL} \sim \int_0^{\delta_{DIS}} d\bar{x} f(\bar{x}) \qquad x = 1 - \bar{x}$$
- 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 (lensing function)?
- 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 : $T(x,x)/q(x) \rightarrow \text{Im } F2/F1(Q^2 \sim M^2(1-x))$
- Both directions – estimate of Sivers at large x and explanation of phases in FF's

CONCLUSIONS/OUTLOOK

- Angular asymmetries are related to virtual photon density matrix and are the sensitive test of dynamics
- Geometric model – applicable for LHC/FNAL
- Semi-explusive DY – sensitive to pion DA
- Exclusive DY – GPD's
- Interference and QCD induced charge asymmetry for lepton pairs production at LHC/COMPASS/J-PARC
- Generalization of BG/DYW for time-like (transition) FF's – natural physical interpretation of Sivers function

NICA (Nuclotron based Ion Colider fAcility)

– the flagship project in HEP

of Joint Institute for Nuclear Research (JINR)(slides by A. Sorin)

Main targets of "NICA Complex":

- ***study of hot and dense baryonic matter***
- *investigation of nucleon spin structure,*

  polarization phenomena
- *development of accelerator facility for HEP @ JINR providing*

  intensive beams of relativistic ions from p to Au

  polarized protons and deuterons

  with energy up to

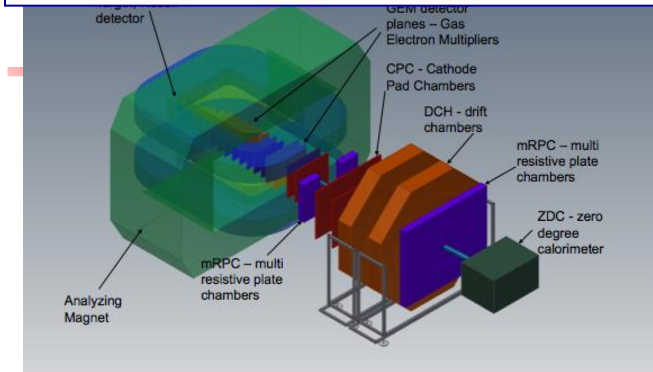
  $\sqrt{S_{NN}}$ = *11 GeV (Au*$^{79+}$ **, L ~ 10**^{32} cm^{-2} c^{-1}*)*

  $\sqrt{S}$ =*27 GeV (p,* L ~ **10**^{32} cm^{-2} c^{-1})

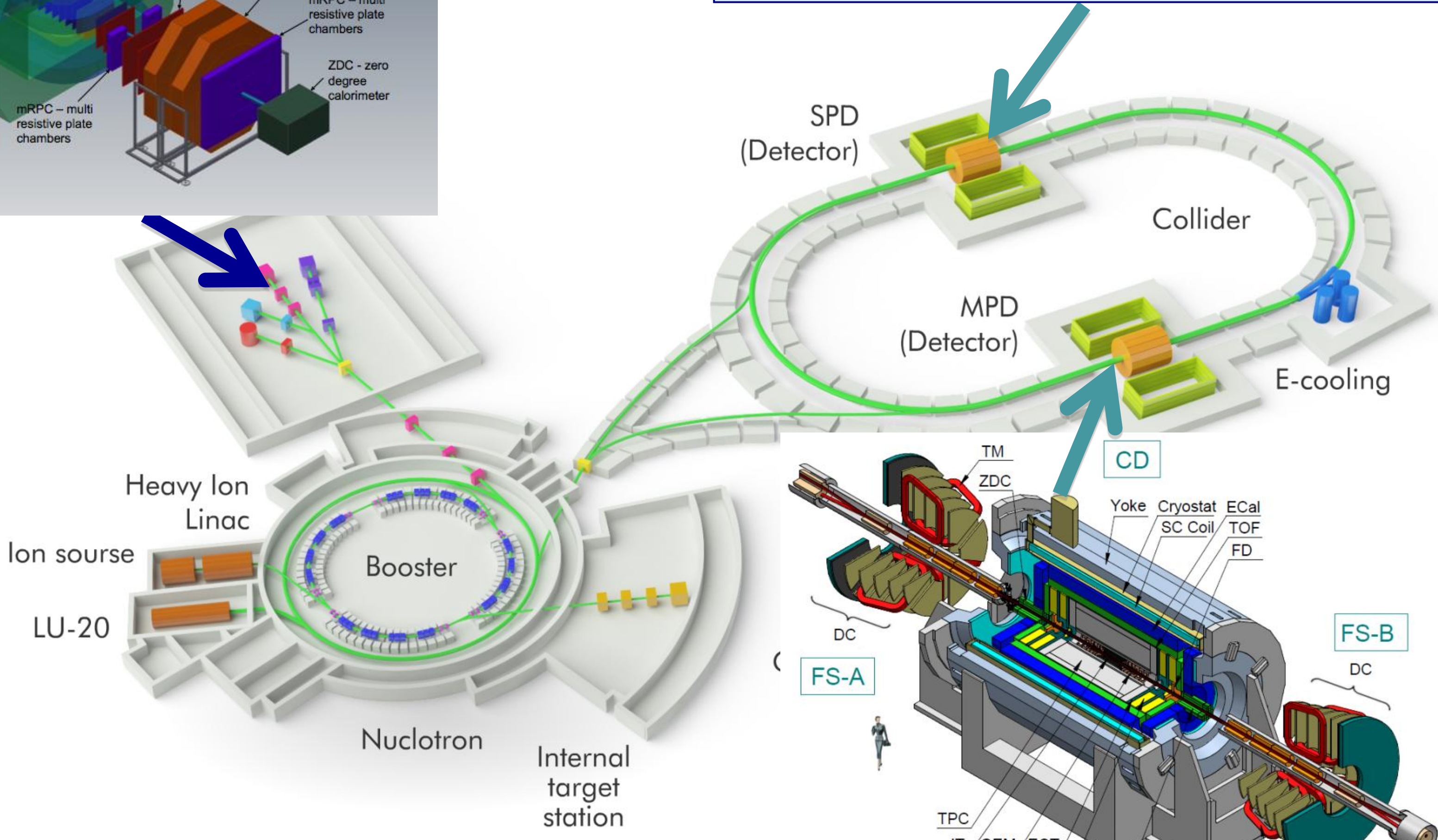

NICA
Volga
river

NICA Complex

Baryonic Matter at Nuclotron (BM@N)



SPD (Spin Physics Detector)



MultiPurpose Detector (MPD)

All basic parts of the **NICA complex** are at the stages of fabrication or **TDR** approval.

The major milestones for the commissioning:

accelerator complex

start-up configuration – **2019**
the design configuration – **2023**

BM@N

the I stage – **2017**
the II stage – **2019**

MPD

the I stage – **2019**
upgraded (IT + end-cups) – **2023**

SPD *project is under preparation*