Single Spin asymmetries in Longitudinally Polarized SIDIS

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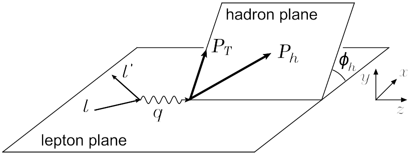
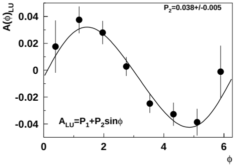
1. Introduction — experimental observables
2. Twist-3 TMD distribibutions in spectator diquark model
3. Longitudinally polarized beam and target SSAs
    - Beam spin asymmetry
    - Longitudinal target spin asymmetry

Longitudinally polarized beam SSA

- Longitudinally polarized lepton beam off unpolarized nucleon target:

$$e^{\rightarrow}(l) + N(P) \rightarrow e(l') + h(P_h) + X$$





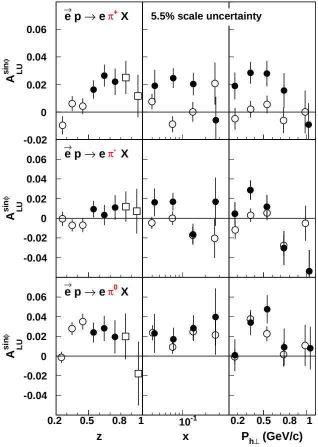
- Beam single spin asymmetry (SSA) of pion in SIDIS:

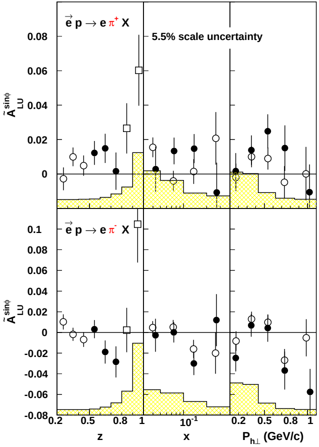
$$A(\phi)_{LU} = \frac{1}{P}\frac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow}}, \qquad A_{LU}^{\sin\phi} = \frac{2}{PN}\sum_{i=1}^{N} \sin\phi_i$$

- Measured by CLAS (04', 14') and HERMES (06') for neutral and charged pions.
- Preliminary data for kaon and proton from HERMES.

Experimental measurements of Beam SSA—-HERMES 27.6 GeV

- Beam SSAs of $\pi^{\pm}$, π^0 measured by HERMES, PLB648,164(2007). $A_{LU}^{\sin\phi}$&$\tilde{A}_{LU}^{\sin\phi}$: VM contribution included &subtracted:

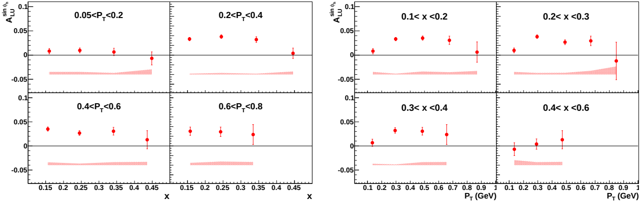




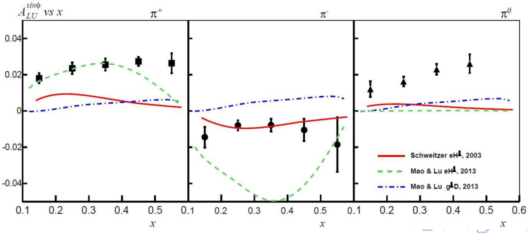
- $E_{beam} = 27.6$ GeV

Experimental measurements of beam SSA

- Beam SSA of π^0 ($E_{beam} = 5.776$ GeV) measured by CLAS, PLB704,397(2011):



- Beam SSA of charged and neutral pions at 5.5 GeV (CLAS Collaboration, 2014)



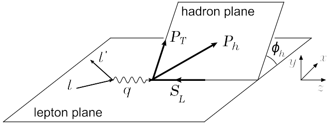
Longitudinally polarized target SSA

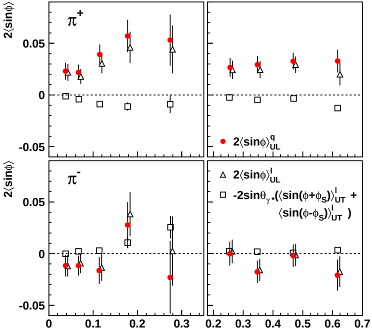
- Unpolarized lepton beam off longitudinally polarized nucleon target:

$$e(l) + N^{\Rightarrow}(P) \to e(l') + h(P_h) + X$$

- Longitudinal target SSA:

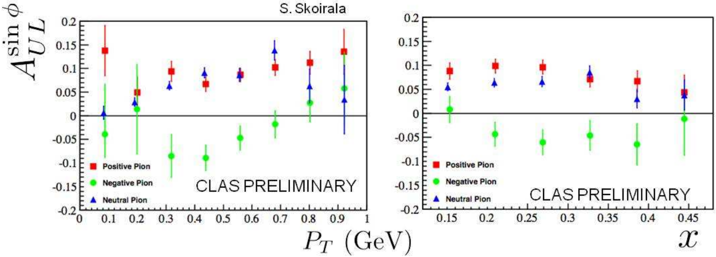
$$A(\phi)_{UL} = \frac{1}{P}\frac{N^{\Rightarrow} - N^{\Leftarrow}}{N^{\Rightarrow} + N^{\Leftarrow}}, \qquad A_{UL}^{\sin\phi} = \frac{2}{PN}\sum_{i=1}^{N}\sin\phi_i$$





Longitudinally polarized target SSA

- CLAS prelimenary results (QCD-N'12)



Mechanism for $A_{LU}^{\sin\phi}$ and $A_{UL}^{\sin\phi}$

- Longitudinal spin-dependent structure functions:

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_\parallel\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \cdots\Big\}$$

- Most of data are in the region $P_T < 1$ GeV, where TMD formalism is a natural choice.
- TMD framework at leading-twist can not account those SSAs
- $A_{LU}^{\sin\phi}$ and $A_{UL}^{\sin\phi}$ may be interpreted by the TMD twist-3 distribution functions or TMD fragmentation functions.
- Although TMD factorization at subleading-twist has not been established, here we assume the tree-level TMD factorization at twist-3 is valid.

Mechanism for $A_{LU}^{\sin\phi}$ and $A_{UL}^{\sin\phi}$

- Beam spin asymmetry:

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{p}_{\boldsymbol{T}}}{zM_h}\left(\frac{M_h}{M}\,f_1\,\frac{\tilde{G}^{\perp}}{z}+x\,eH_1^{\perp}\right)\right.$$
$$\left.+\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{k}_{\boldsymbol{T}}}{M}\left(\frac{M_h}{M}\,h_1^{\perp}\,\frac{\tilde{E}}{z}+x\,g^{\perp}D_1\right)\right]$$

- Longitudinal target spin asymmetry

$$F_{UL}^{\sin\phi} = \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{p}_{\boldsymbol{T}}}{zM_h}\left(x\,h_L H_1^{\perp}+\frac{M_h}{M}\,g_{1L}\,\frac{\tilde{G}^{\perp}}{z}\right)\right.$$
$$\left.+\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{k}_{\boldsymbol{T}}}{M}\left(x\,f_L^{\perp}D_1-\frac{M_h}{M}\,h_{1L}^{\perp}\,\frac{\tilde{H}}{z}\right)\right]$$

- Involving twist-3 TMD distribution functions and fragmentation functions

Twist-3 TMDs

- quark-quark correlator at twist-3 (Bacchetta et.al, 06):

$$\begin{aligned}\Phi(x,k_T) = \ldots + \frac{M}{2P^+}\Big\{ & e - i\, e_s\, \gamma_5 - e_T^{\perp}\, \frac{\epsilon_T^{\rho\sigma} k_{T\rho} S_{T\sigma}}{M} \\ & + f^{\perp}\, \frac{\not{k}_T}{M} - f_T'\, \epsilon_T^{\rho\sigma} \gamma_\rho S_{T\sigma} - f_s^{\perp}\, \frac{\epsilon_T^{\rho\sigma} \gamma_\rho k_{T\sigma}}{M} \\ & + g_T'\, \gamma_5\, \not{S}_T + g_s^{\perp} \gamma_5 \frac{\not{k}_T}{M} - g^{\perp} \gamma_5\, \frac{\epsilon_T^{\rho\sigma} \gamma_\rho k_{T\sigma}}{M} \\ & + h_s\, \frac{[\not{n}_+, \not{n}_-]\gamma_5}{2} + h_T^{\perp}\, \frac{[\not{S}_T, \not{k}_T]\gamma_5}{2M} + i\, h \frac{[\not{n}_+, \not{n}_-]}{2} \Big\}\end{aligned}$$

T-even

$q \setminus N$	U	L	T
U	$f^{\perp}$		
L		$g_L^{\perp}$	g_T, $g_T^{\perp}$
T	e	h_L	h_T, $h_T^{\perp}$

T-odd

$q \setminus N$	U	L	T
U		$f_L^{\perp}$	f_T, $f_T^{\perp}$
L	$g^{\perp}$		
T	h	e_L	e_T,$e_T^{\perp}$

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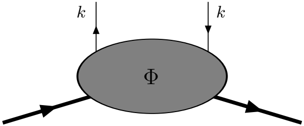
Status on model calculation of twist-3 TMDs

- So far no available fitting for twist-3 TMDs
- Model calculations provide primary information of twist-3 TMDs
- Commonly used models:
    - bag model
    - chiral soliton model
    - spectator diquark model
    - light-cone constituent quark model

spectator diquark model



- Correlator can be calculated by inserting a complete set of final states

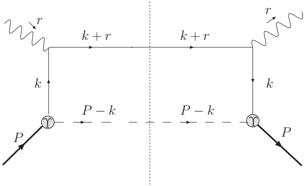
$$\Phi \sim \sum_X \int d^3 P_X < PS|\bar{\psi}(0)X >< X|\psi(0)|PS >$$

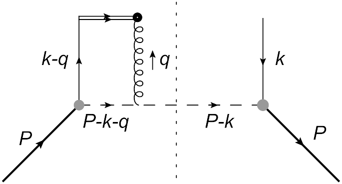
- In spectator diquark model, the unobserved (spectator) final states $|X>$ are truncated and are approximated by the diquark states $|qq\rangle$, which have certain quantum numbers (scalar or vector particle)
- the nucleon-quark-diquark effective vertex

$$< X|\psi(0)|PS >\approx \begin{cases} \frac{i}{\not{k}-m}\Upsilon_s(k^2)U(P,S), & \text{scalar diquark;} \\ \frac{i}{\not{k}-m}\Upsilon_v^{\mu}(k^2)U(P,S), & \text{axial-vector diquark.} \end{cases}$$

spectator diquark model

- Diagram to calculate $\Phi(x, k_T)$ in DIS





- T-even TMDs

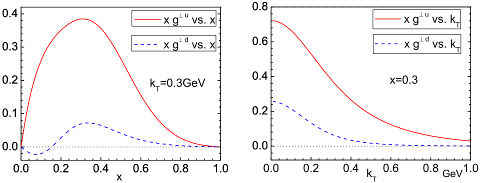
$$\frac{M}{P^+} e(x, \boldsymbol{k}_T^2) = \frac{1}{2}\,\mathrm{Tr}[\Phi]$$
$$S_L \frac{M}{P^+} h_L(x, \boldsymbol{k}_T^2) = \frac{1}{2}\,\mathrm{Tr}[\Phi i\sigma^{+-}\gamma_5]$$

- T-odd TMDs

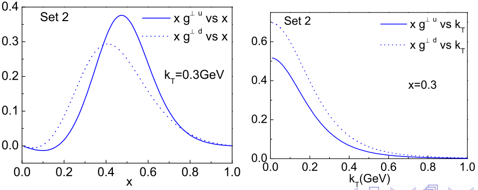
$$\frac{\epsilon_T^{\alpha\rho} k_{T\rho}}{P^+}\, g^{\perp}(x, \boldsymbol{k}_T^2) = -\frac{1}{2}\,\mathrm{Tr}[\Phi\gamma^{\alpha}\gamma_5]$$
$$S_L \frac{\epsilon_T^{\alpha\rho} k_{T\rho}}{P^+}\, f_L^{\perp}(x, \boldsymbol{k}_T^2) = -\frac{1}{2}\,\mathrm{Tr}[\Phi\gamma^{\alpha}].$$

Selected results of T-odd TMDs — $g^{\perp}(x, k_T^2)$

- Two sets of TMDs are calculated, by choosing different polarization sum of the vector diquark, as well as different relation between quark flavors and diquark types
- Results of $xg^{\perp}(x, k_T^2)$ in set 1

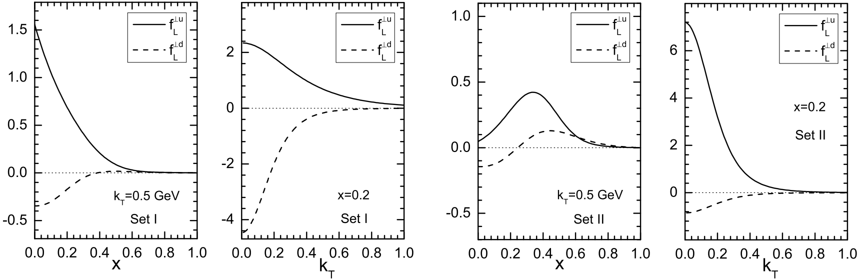


- results of $xg^{\perp}(x, k_T^2)$ in set 2



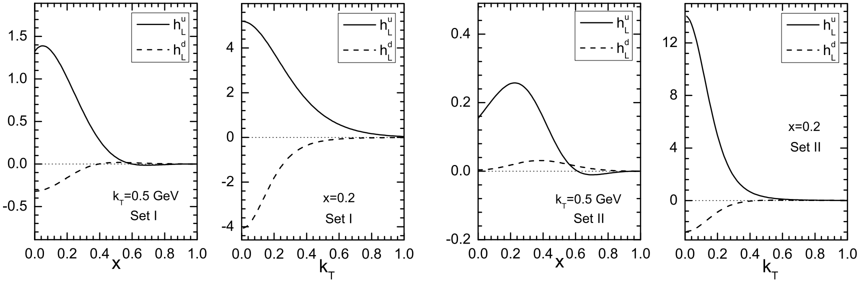
Selected results of T-odd TMDs — $f_L^\perp(x, k_T^2)$

- results of $f_L^\perp(x, k_T^2)$ in two different sets



Selected results of T-even TMDs — h_L

- results of $h_L(x, k_T^2)$ in two different sets



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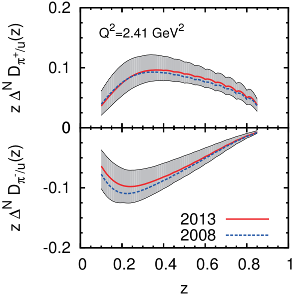
Beam SSA of π^0

$$F_{LU}^{\sin\phi} \approx \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{k}_{\boldsymbol{T}}}{M}\left(x\,g^{\perp}D_1\right)-\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{p}_{\boldsymbol{T}}}{M_h}\left(x\,eH_1^{\perp}\right)\right]$$

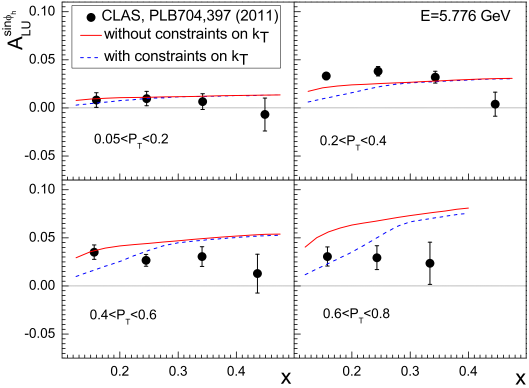
- Isospin symmetry ⇒ in π^0 production, $eH_1^{\perp}$ term is negligible:

$$H_1^{\perp\pi^0/q} = (H_1^{\perp fav} + H_1^{\perp unf})/2 \approx 0$$

- Recent extraction of Collins function (Anselmino et.al, arXiv:1303.3822):

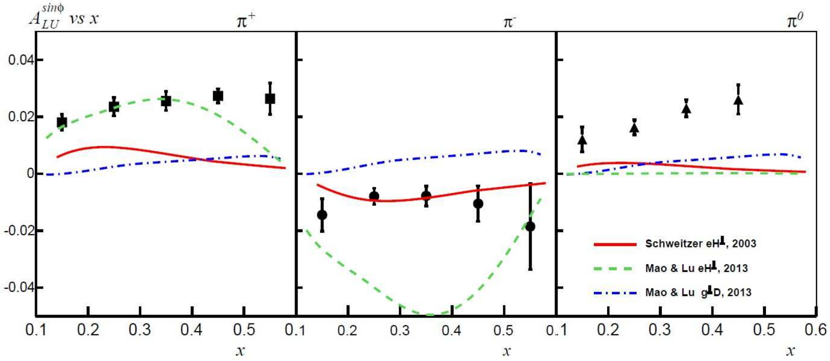


Beam SSA of π^0 vs x at CLAS (5.776GeV) in set 1



- T-odd distribution $g^{\perp}$ is crucial for beam SSA of neutral pion

Beam SSA of charged and neutral pion production at CLAS in set 2



- Data from CLAS Collaboration (2014)
- T-even distribution e contribute significant for beam SSA of positive pion

Longitudinal target spin asymmetry at HERMES (27.6 GeV)

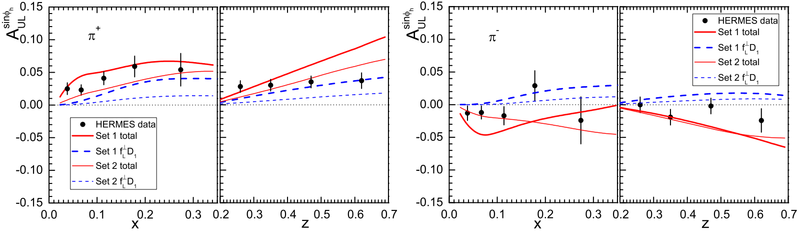
- $\sin\phi_h$ asymmetry (target is longitudinally polarized):

$$A_{UL}^{\sin\phi_h} = \frac{F_{UL}^{\sin\phi_h}}{F_{UU}}$$

- In Wandura-Wilzeck approximation:

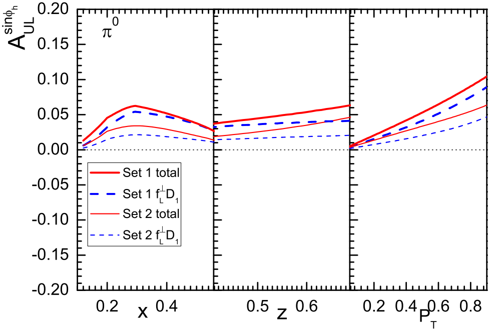
$$F_{UL}^{\sin\phi} \approx \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{p}_{\boldsymbol{T}}}{zM_h}\,x\,h_L H_1^{\perp} + \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{k}_{\boldsymbol{T}}}{M}\,x\,f_L^{\perp} D_1\right]$$

- longitudinal target spin asymmetry at HERMES (27.6 GeV):



A_{UL} for π^0 at CLAS

- A_{UL} for π^0 at CLAS

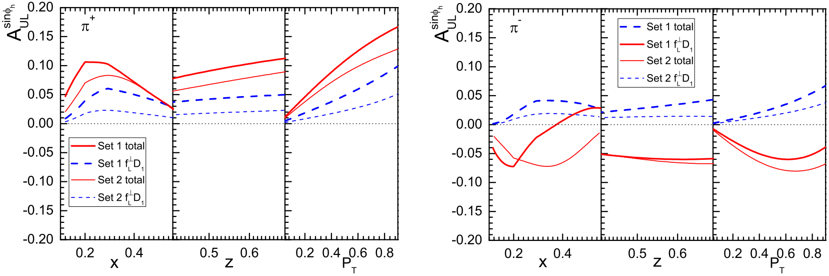


- Kinematics at CLAS:

$$E_e = 5.5\,\mathrm{GeV}, \quad 0.1 < x < 0.6, \quad 0.4 < z < 0.7,$$
$$Q^2 > 1\,\mathrm{GeV}^2, \quad P_T > 0.05\,\mathrm{GeV}, \quad W^2 > 4\,\mathrm{GeV}^2.$$

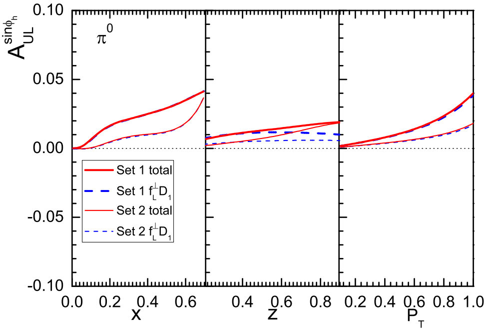
A_{UL} for charged pion at CLAS

- A_{UL} for charged pion at CLAS



A_{UL} for π^0 at COMPASS

- A_{UL} for π^0 at COMPASS

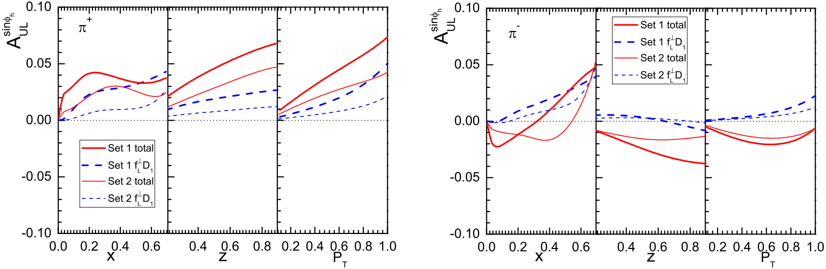


- Kinematics at COMPASS:

$$0.004 < x < 0.7, \quad y > 0.1, \quad 0.2 < z < 0.9,$$
$$x_F > 0, \quad Q^2 > 1\,\mathrm{GeV}^2, \quad 0.1\mathrm{GeV} < P_T < 1\,\mathrm{GeV},$$
$$5\,\mathrm{GeV} < W < 18\,\mathrm{GeV}.$$

A_{UL} for charged pion at COMPASS

- A_{UL} for charged pion at COMPASS



Summary & Conclusion

- Twist-3 TMDs distributions of u and d valence quarks are calculated in the spectator diquark model.
- Twist-3 TMDs play important roles in longitudinal beam and target SSAs.
- T-odd twist-3 distributions are essential for the SSA of π^0 production.

Summary & Conclusion

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- Twist-3 TMDs play important roles in longitudinal beam and target SSAs.
- T-odd twist-3 distributions are essential for the SSA of π^0 production.

Thank you for your attention