Transverse single-spin asymmetries of very forward neutral pion

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Outline

- *Introduction*
- *Inclusive* $pp^{\uparrow} \to \pi^0 X$ *scattering*
- *Invariant cross section in the triple-Regge limit*
- *Transverse single-spin asymmetry*
- *Results*
- *Summary*

Introduction

Introduction

- The transverse single-spin asymmetry(TSSA) is one of the crucial observables in high-energy physics for understanding particle production mechanisms and hadron spin structure.
- Large p_T (> 2 GeV/c) TSSA has been investigated by QCD-based approaches: (i.e., Transverse Momentum Distributions(TMDs), Collinear twist-3 factorization, …)
- Sizable transverse single-spin asymmetries in the very forward direction have been continuously reported for the few decades [1,2].
- Recently the TSSA of very forward neutral pion was measured in RHICf experiment [3].

TSSA :

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

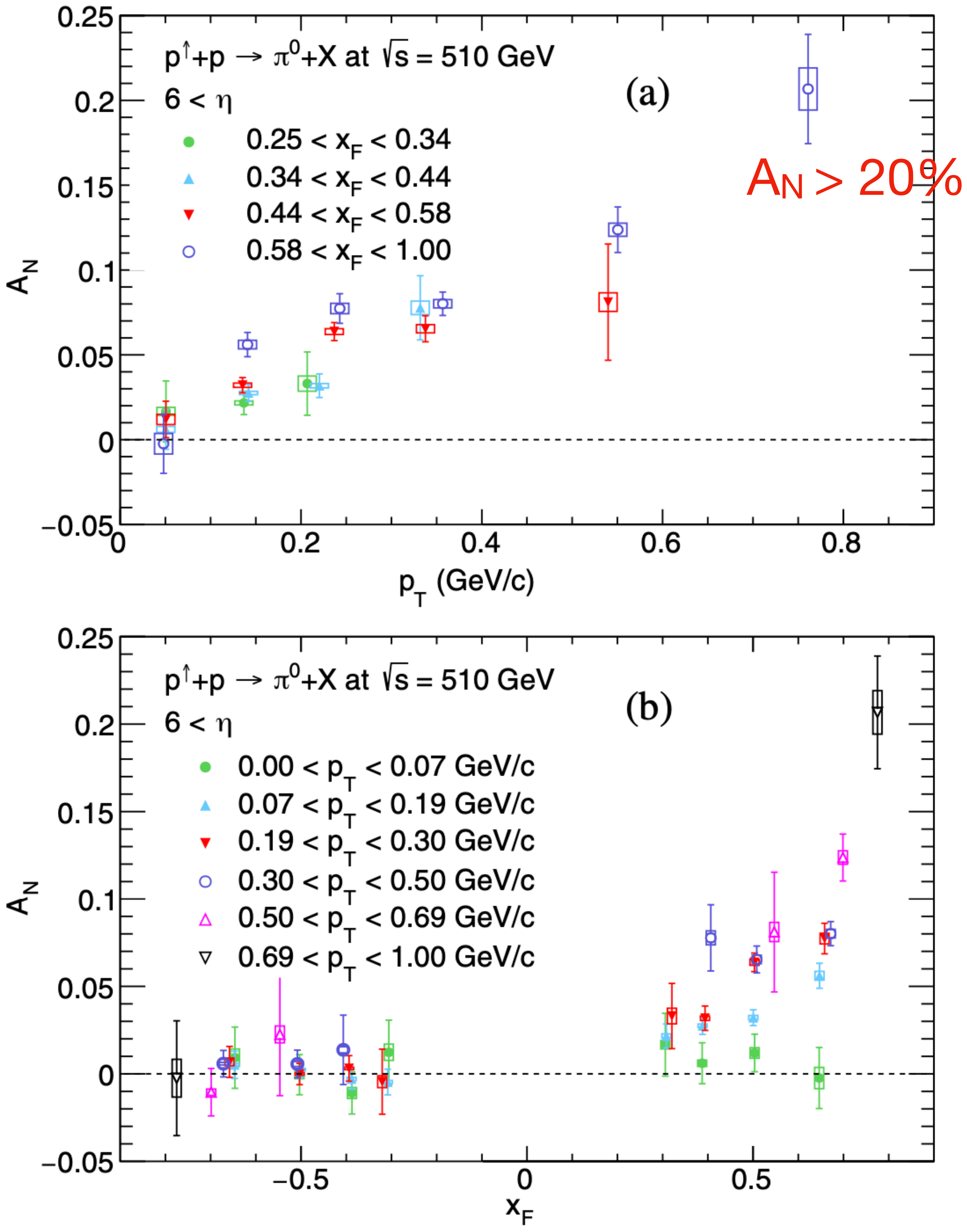
Transversely polarized proton beam

[1] Y. Fukao *et al.*, Phys. Lett. B650 (2007) 325

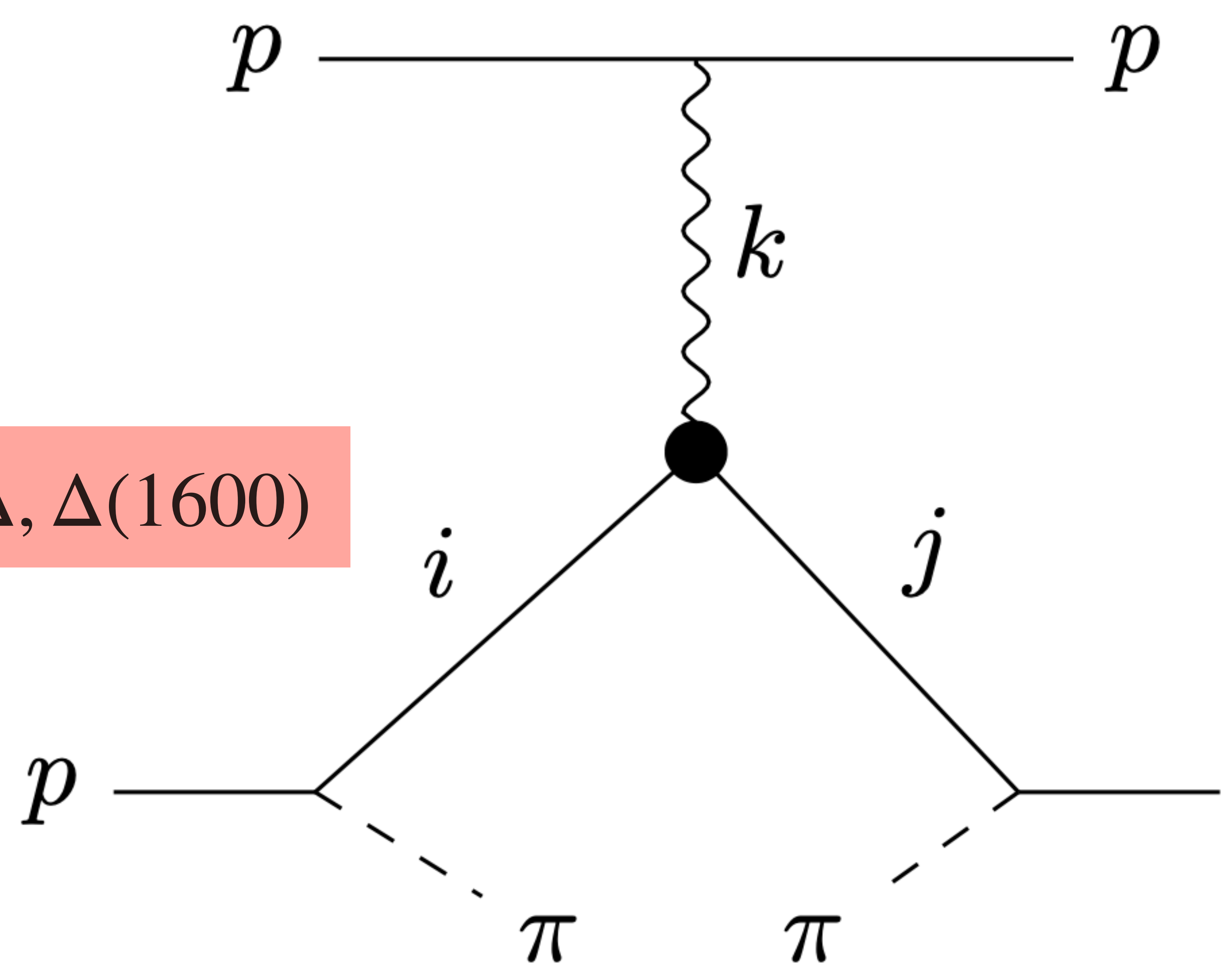
[2] K. Tanida *et al.*(PHENIX Collaboration), J.Phys.Conf.Ser.295(2011)

[3] M.H. Kim *et al.*, Phys. Rev. Lett. 124 (2020) 124

- Since the produced particles have very large values of pseudorapidity and low p_T, it is believed that they are produced via diffractive processes.



$A_N > 20\%$



$p, N^*(1520), \Delta, \Delta(1600)$

- The interferences between baryon trajectories yield the transverse single-spin asymmetry.
- Since the RHICf energy is sufficiently large, $d\sigma$ can be approximated to the triple-Regge diagram.

Inclusive $pp^{\uparrow} \to \pi^0 X$ scattering

Kinematics

Inclusive $pp^{\uparrow} \to \pi^0 X$ reaction:

- **Kinematics for single diffractive(SD) process**

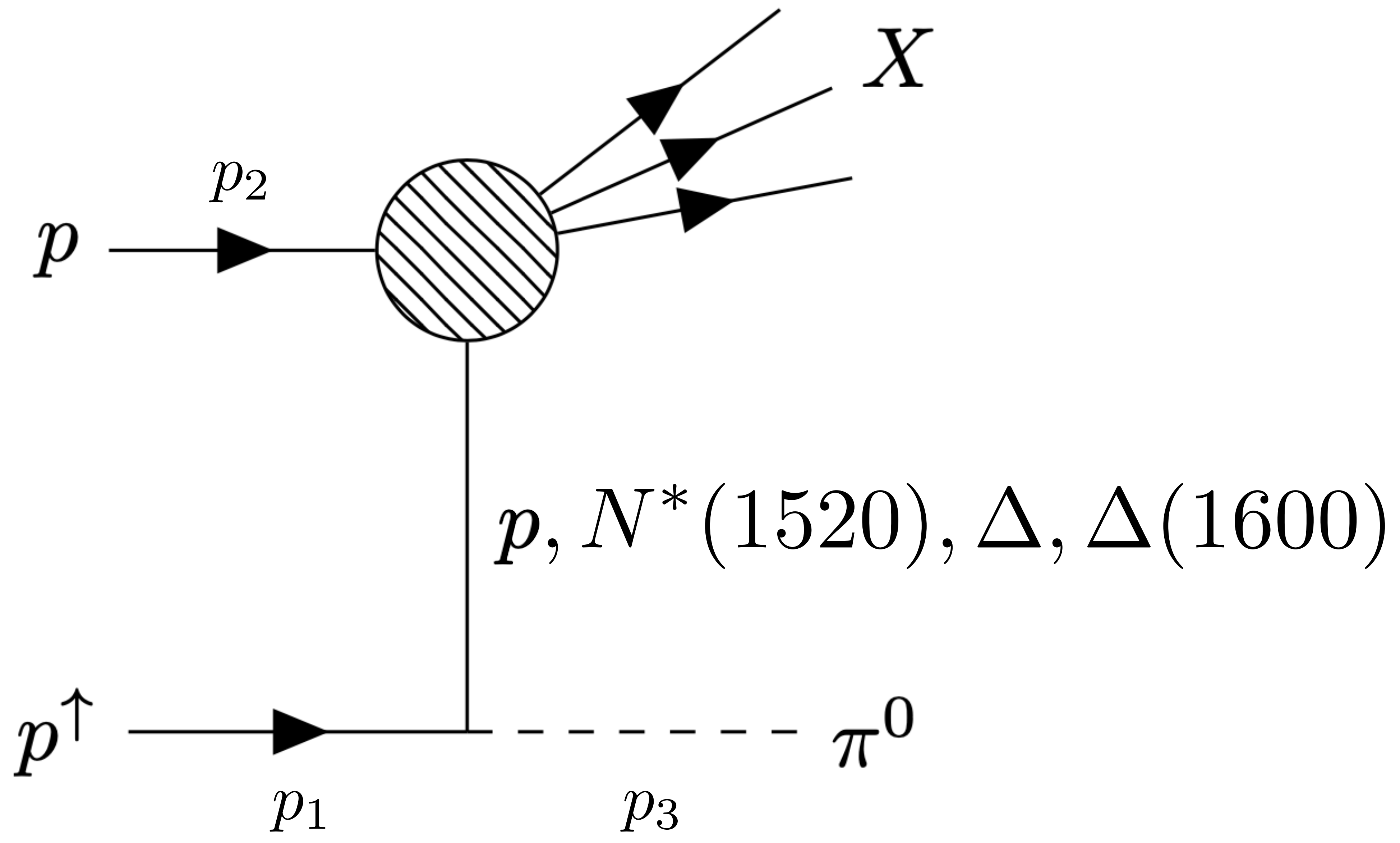
$$(s, M_X^2 \gg m_i^2, \text{ and } |\mathbf{p}_T| < 1 \text{ GeV})$$

$$p_1 = (E_1, 0, 0, p_z), \quad p_2 = (E_2, 0, 0, -p_z), \quad p_3 = (E_3, \boldsymbol{p}_T, p_z')$$

$$M_X^2 \equiv (p_1 + p_2 - p_3)^2$$

Feynman variable : $x_F = \frac{p_z'}{p_z} \simeq 1 - \frac{M_X^2}{s}$

The squared momentum transfer : $t = (p_1 - p_3)^2 \simeq (1 - x_F)m_N^2 - \frac{\boldsymbol{p}_T^2}{x_F}$



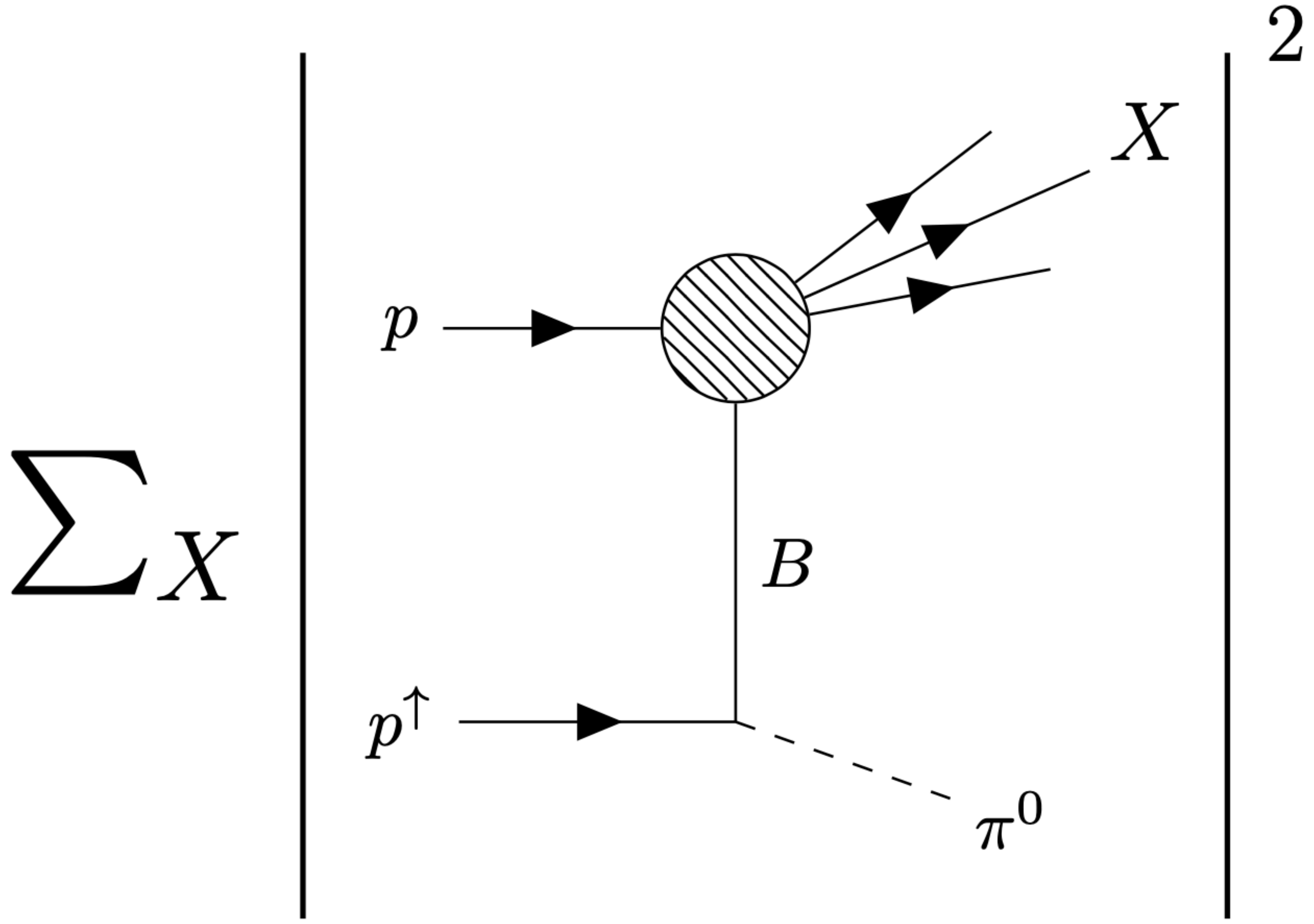
<u>The SD processes can be described in terms of s, x_F, and p_T^2.</u>

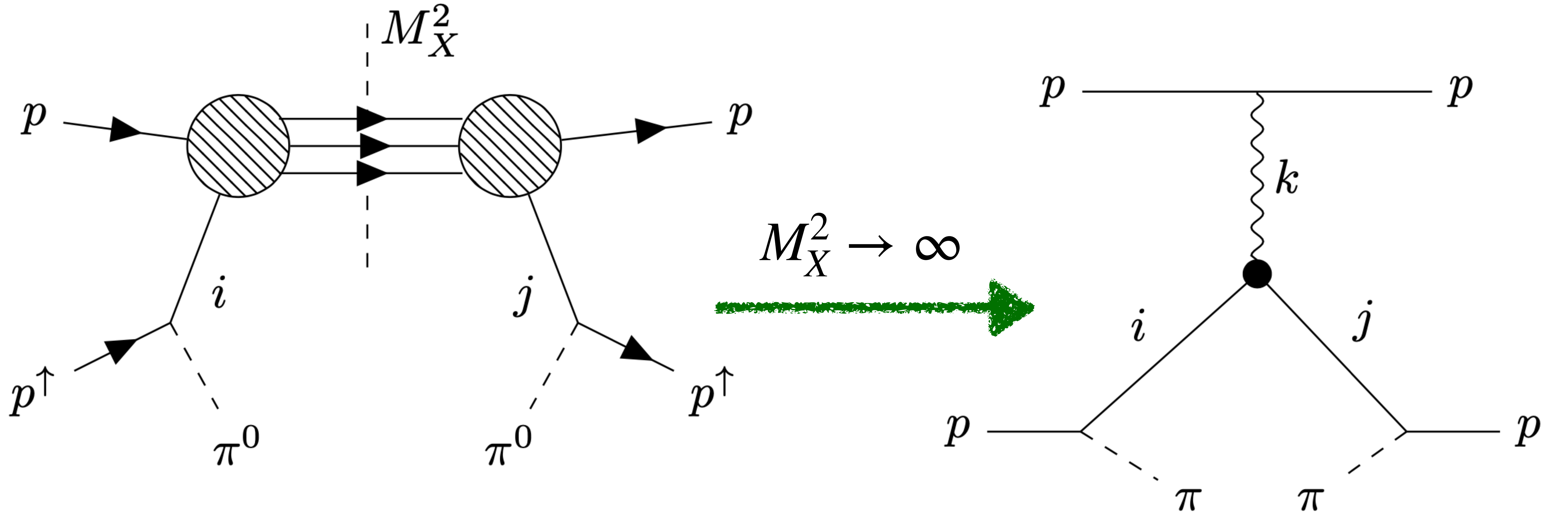
Invariant cross section in the triple-Regge limit

Invariant differential cross-section

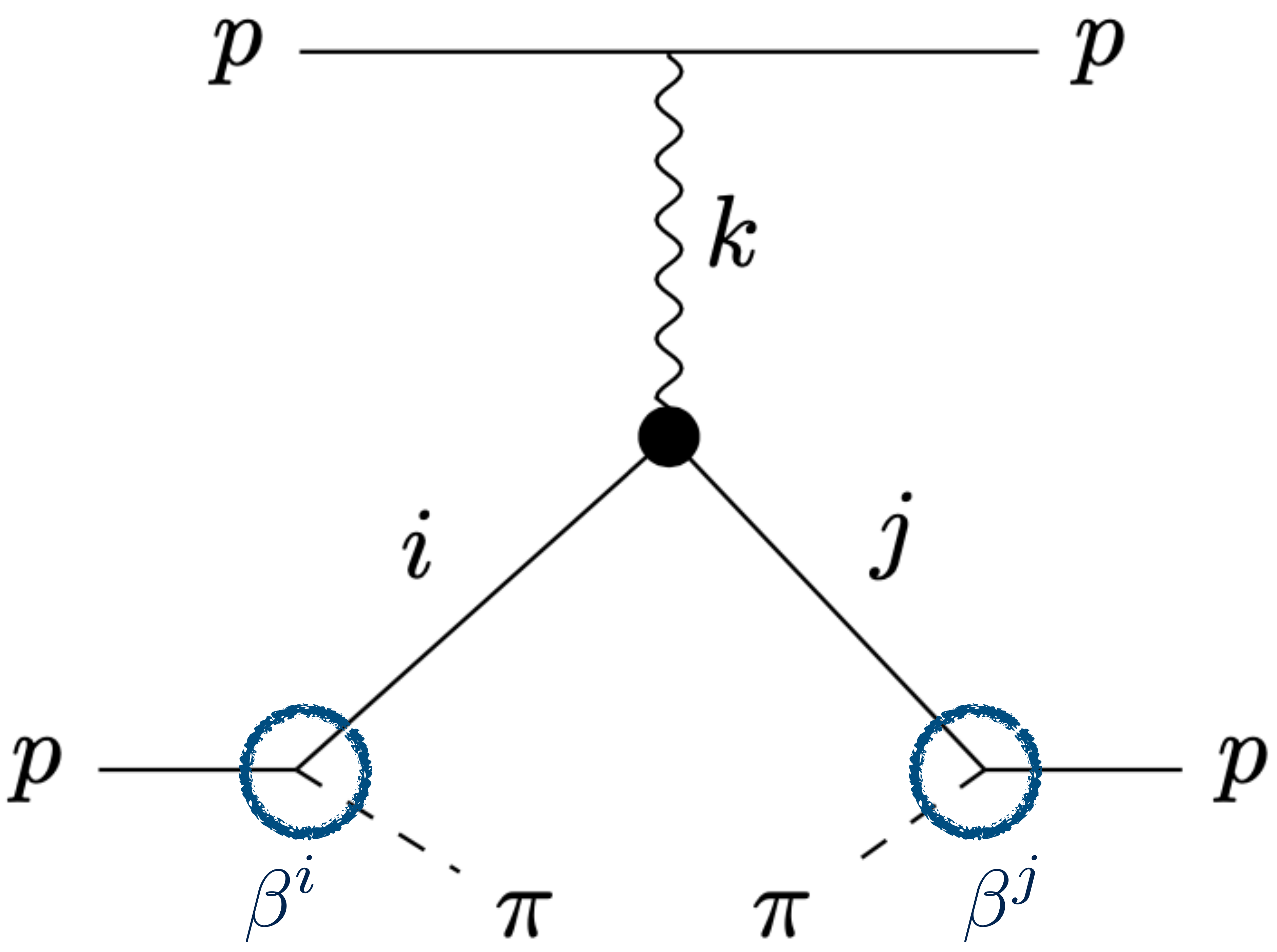
- The Lorentz-invariant differential cross section of π^0 :

$$d\sigma^h \equiv E\frac{d^3\sigma^h}{d^3\boldsymbol{p}} = \frac{1}{s}\sum\left|A^{\mathrm{tot}}_{p\to\pi^0}(s,p_T;h)\right|^2$$





$$d\sigma^h = \frac{1}{s}\sum_{i,j}\sum_{\lambda,\mu}\beta^i_{h\lambda}\beta^{j*}_{h\mu}\mathcal{P}_i\mathcal{P}^*_j\sum_k G^{ij}_k(t)\gamma^{pp}_k(0)\left(\frac{M_X^2}{s_0}\right)^{\alpha_k(0)}$$



Residue functions with Born approximation

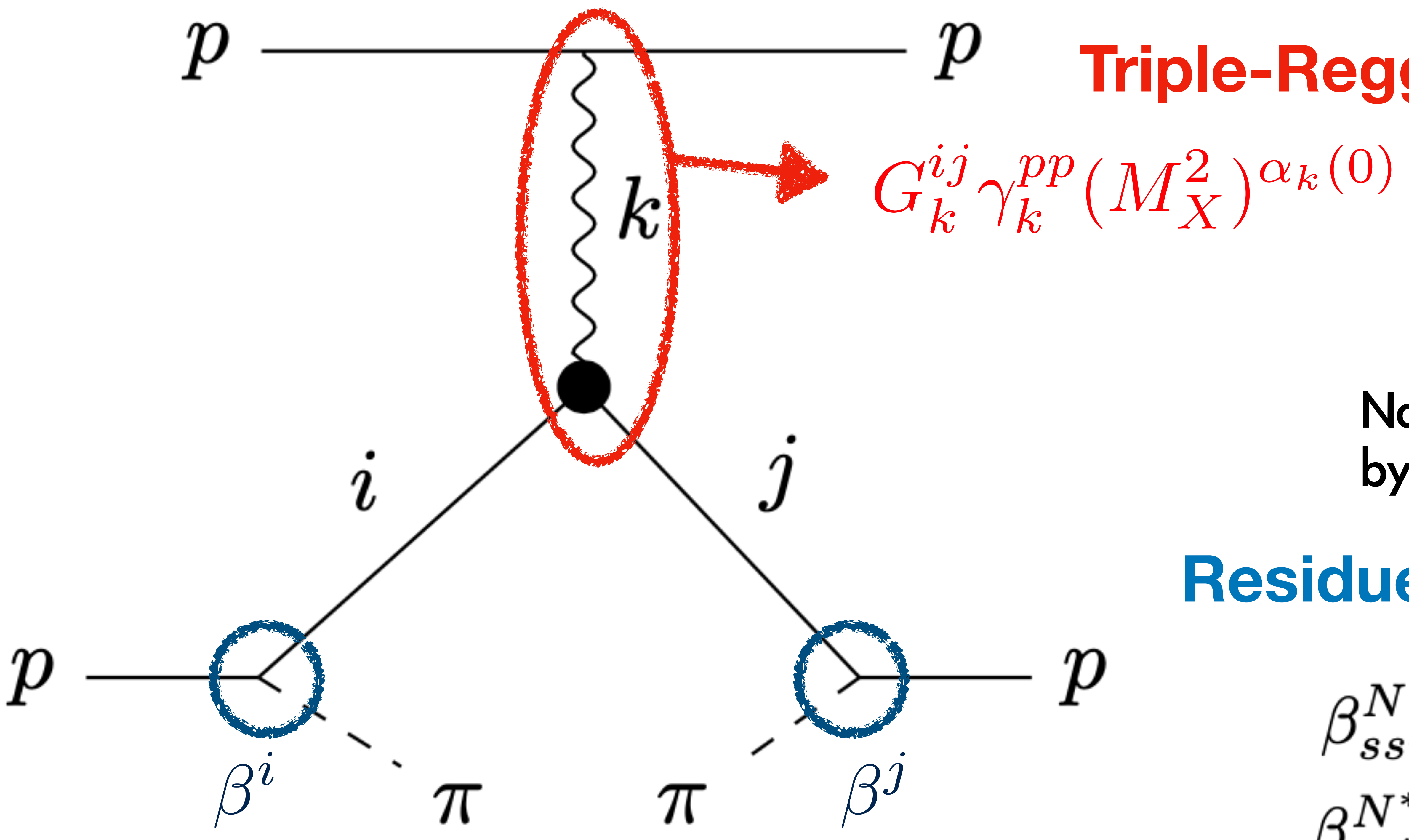
$$\beta^N_{ss'}(p_T) = \bar{u}_N(s',q)\not{k}\gamma_5 u_p(s,p),$$

$$\beta^{N^*}_{ss'}(p_T) = i\bar{u}^\mu_{N^*}(s',q)(k_\mu + a\gamma_\mu\not{k})\gamma_5 u_p(s,p)),$$

$$\beta^{\Delta}_{ss'}(p_T) = \bar{u}^\mu_{\Delta}(s',q)(k_\mu + a\gamma_\mu\not{k})u_p(s,p),$$

$$\beta^{\Delta^*}_{ss'}(p_T) = \bar{u}^\mu_{\Delta^*}(s',q)(k_\mu + a\gamma_\mu\not{k})u_p(s,p),$$

$$d\sigma^h = \frac{1}{s}\sum_{i,j}\sum_{\lambda,\mu}\beta^i_{h\lambda}\beta^{j*}_{h\mu}\mathcal{P}_i\mathcal{P}^*_j\sum_k G^{ij}_k(t)\gamma^{pp}_k(0)\left(\frac{M_X^2}{s_0}\right)^{\alpha_k(0)}$$



Triple-Regge coupling and ppk vertex function

$$\gamma^{pp}_k(t_{pp}=0) = \sum_\lambda \beta^k_{\lambda\lambda}(0)$$

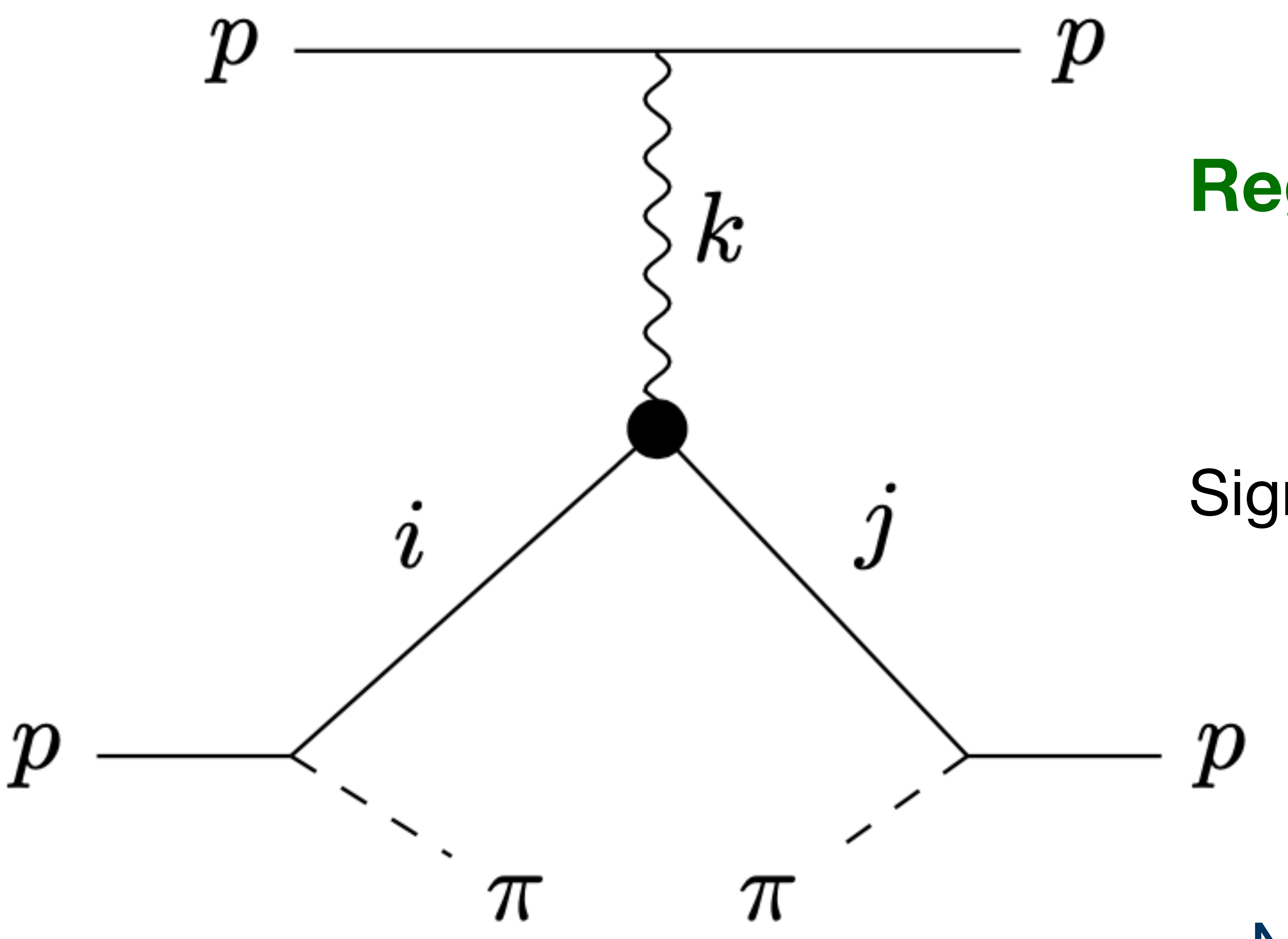
No momentum transfer between the unpolarized proton by the generalized optical theorem.

Residue functions with Born approximation

$$\beta^N_{ss'}(p_T) = \bar{u}_N(s',q)\not{k}\gamma_5 u_p(s,p),$$
$$\beta^{N^*}_{ss'}(p_T) = i\bar{u}^\mu_{N^*}(s',q)(k_\mu + a\gamma_\mu\not{k})\gamma_5 u_p(s,p)),$$
$$\beta^\Delta_{ss'}(p_T) = \bar{u}^\mu_\Delta(s',q)(k_\mu + a\gamma_\mu\not{k})u_p(s,p),$$
$$\beta^{\Delta^*}_{ss'}(p_T) = \bar{u}^\mu_{\Delta^*}(s',q)(k_\mu + a\gamma_\mu\not{k})u_p(s,p),$$

$$d\sigma^h = \frac{1}{s}\sum_{i,j}\sum_{\lambda,\mu}\beta^i_{h\lambda}\beta^{j*}_{h\mu}\mathcal{P}_i\mathcal{P}^*_j\sum_k G^{ij}_k(t)\gamma^{pp}_k(0)\left(\frac{M_X^2}{s_0}\right)^{\alpha_k(0)}$$

$$\alpha_p(t) = -0.35 + 0.99t$$
$$\alpha_{N^*}(t) = -0.73 + 0.95t$$
$$\alpha_\Delta(t) = 0.16 + 0.89t$$
$$\alpha_{\Delta^*}(t) = -0.56 + 0.80t$$



Reggeized propagator

$$\mathcal{P}_i(t) = \alpha'_i\xi_i(t)\Gamma(J_i - \alpha_i(t))(1 - x_F)^{-\alpha_i(t)}$$

Signature factor:

$$\xi_i(t) = \frac{1 + \tau_i \exp\{-i\pi(\alpha_i(t) - 0.5)\}}{2}$$

- Note that β should be real-valued function, so the phase of a Regge-pole contribution to A_N comes from the signature factor

Transverse single-spin asymmetry

Transverse single-spin asymmetry(TSSA)

- **TSSA**

$$A_N = \frac{d\Delta\sigma_\perp}{d\sigma} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

Spin-dependent cross section

$$d\Delta\sigma_\perp = \frac{1}{s}\sum_{i,j}\sum_{\lambda}\beta^i_{+\lambda}\beta^j_{-\lambda}2\mathrm{Im}\,\mathcal{P}_i\mathcal{P}_j^*\sum_k G_k^{ij}(t)\gamma_k^{pp}(0)\left(\frac{M_X^2}{s_0}\right)^{\alpha_k(0)}$$

Spin-averaged cross section

$$d\sigma = \frac{1}{s}\sum_{i,j}\sum_{\lambda}\beta^i_{+\lambda}\beta^j_{+\lambda}2\mathrm{Re}\,\mathcal{P}_i\mathcal{P}_j^*\sum_k G_k^{ij}(t)\gamma_k^{pp}(0)\left(\frac{M_X^2}{s_0}\right)^{\alpha_k(0)}$$

Parity invariance : $\beta^i_{\lambda_1\lambda_2} = \eta_1\eta_2\eta_i(-)^{\lambda_1-\lambda_2}\beta_{-\lambda_1,\lambda_2}$

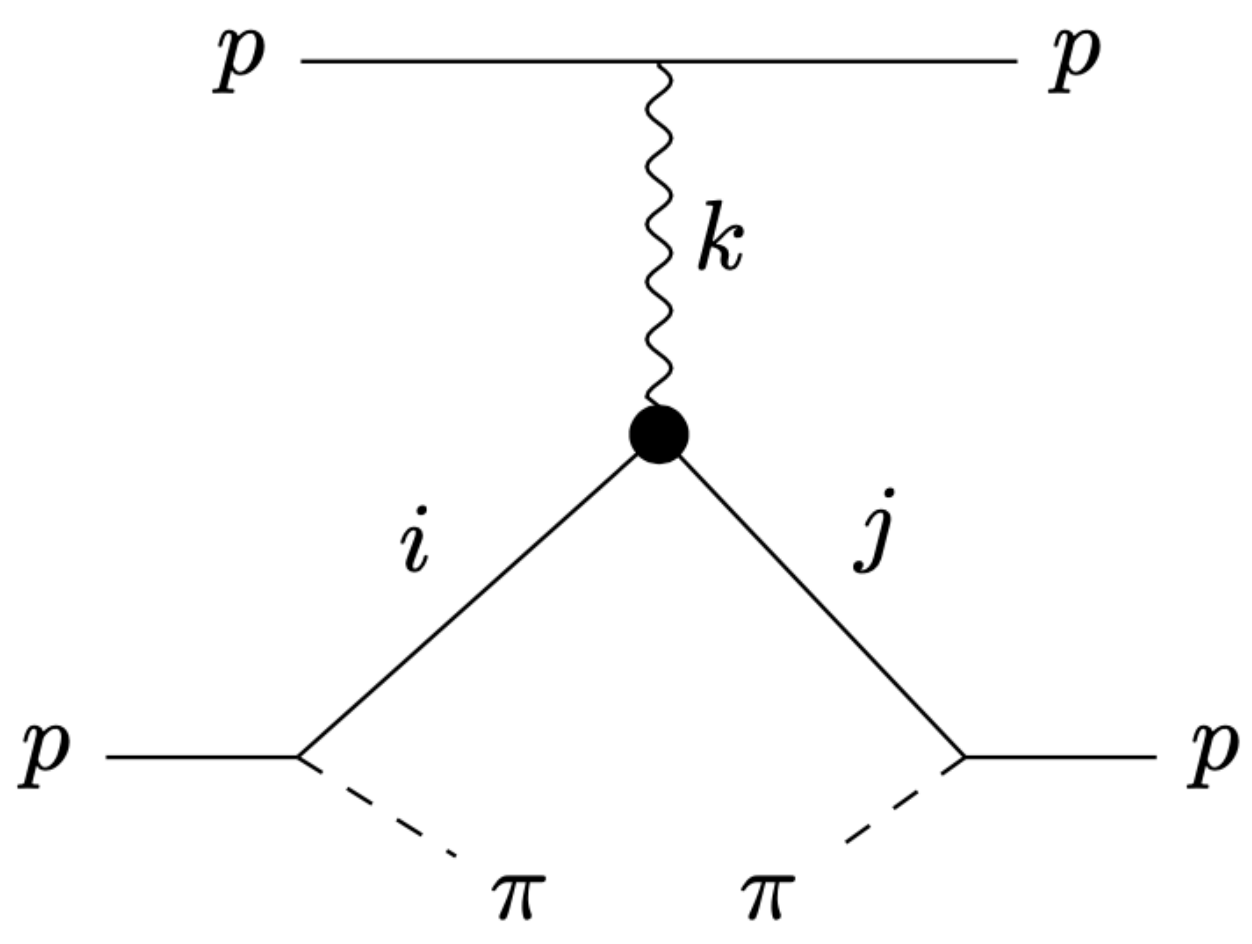
1. $d\sigma$ vanishes if *k* is an unnatural parity state.

$$\text{unnatural parity states} : \cancel{\pi,\ \omega,\ a_1, \dots}$$

$$\text{natural parity states} : \boxed{\text{Pomeron}},\ \rho,\ a_2, \dots$$

$$\alpha_{\mathbb{P}}(0) \simeq 1, \quad \alpha_\rho(0) \approx 0.5$$

2. $d\Delta\sigma_\perp$ vanishes when *i* and *j* have opposite naturalities.



Spin-dependent cross section

$$d\Delta\sigma_\perp = d\Delta\sigma^N_\perp + d\Delta\sigma^U_\perp$$

$$= \frac{1}{s}\sum_\lambda \left[\beta^N_{+\lambda}\beta^{N^*}_{-\lambda}\mathrm{Im}\,\mathcal{P}_N\mathcal{P}^*_{N^*}G^{NN^*}_{\mathbb{P}}(t) + \beta^\Delta_{+\lambda}\beta^{\Delta^*}_{-\lambda}\mathrm{Im}\,\mathcal{P}_\Delta\mathcal{P}^*_{\Delta^*}G^{\Delta\Delta^*}_{\mathbb{P}}(t)\right]\gamma^{pp}_{\mathbb{P}}(0)\left(\frac{M_X^2}{s_0}\right)^{\alpha_{\mathbb{P}}(0)}$$

Spin-averaged cross section

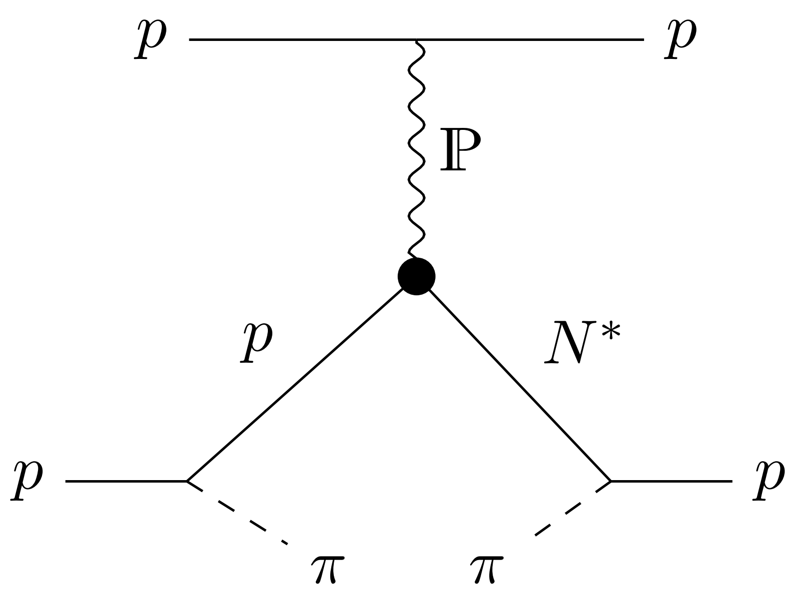
$$d\sigma = \frac{1}{s}\sum_\lambda\left[\sum_i 2(\beta^i_{+\lambda})^2|\mathcal{P}_i^2|G^{ii}_k(t) + \sum_{i\neq j}\beta^i_{+\lambda}\beta^j_{+\lambda}2\mathrm{Re}\,\mathcal{P}_i\mathcal{P}^*_jG^{ij}_{\mathbb{P}}(t)\right]\gamma^{pp}_{\mathbb{P}}(0)\left(\frac{M_X^2}{s_0}\right)^{\alpha_{\mathbb{P}}(0)}$$

$$A_N = \frac{\sum_\lambda \left[\beta^N_{+\lambda} \beta^{N^*}_{-\lambda} \mathrm{Im}\, \mathcal{P}_N \mathcal{P}^*_{N^*} (\sqrt{|t|}/m_\pi) g^{NN^*}_{\mathbb{P}} + \beta^\Delta_{+\lambda} \beta^{\Delta^*}_{-\lambda} \mathrm{Im}\, \mathcal{P}_\Delta \mathcal{P}^*_{\Delta^*} (\sqrt{|t|}/m_\pi) g^{\Delta\Delta^*}_{\mathbb{P}} e^{-b^{\Delta\Delta^*}_{\mathbb{P}} |t|} \right]}{\sum_\lambda \left[\sum_i (\beta^i_{+\lambda})^2 |\mathcal{P}^2_i| g^{ii}_{\mathbb{P}} e^{-b^{ii}_{\mathbb{P}} |t|} + \sum_{i \neq j} \beta^i_{+\lambda} \beta^j_{+\lambda} \mathrm{Re}\, \mathcal{P}_i \mathcal{P}^*_j (\sqrt{|t|}/m_\pi) g^{ij}_{\mathbb{P}} e^{-b^{ij}_{\mathbb{P}} |t|} \right]}$$

$$g^{ij}_{\mathbb{P}} \equiv G^{ij}_{\mathbb{P}}(0)/G^{NN}_{\mathbb{P}}(0), \quad b^{ij}_{\mathbb{P}} \equiv B^{ij}_{\mathbb{P}} - B^{NN}_{\mathbb{P}}$$

- Diagrammatic representation of the A_N

$A_N =$ [$-2\mathrm{Im}$ (



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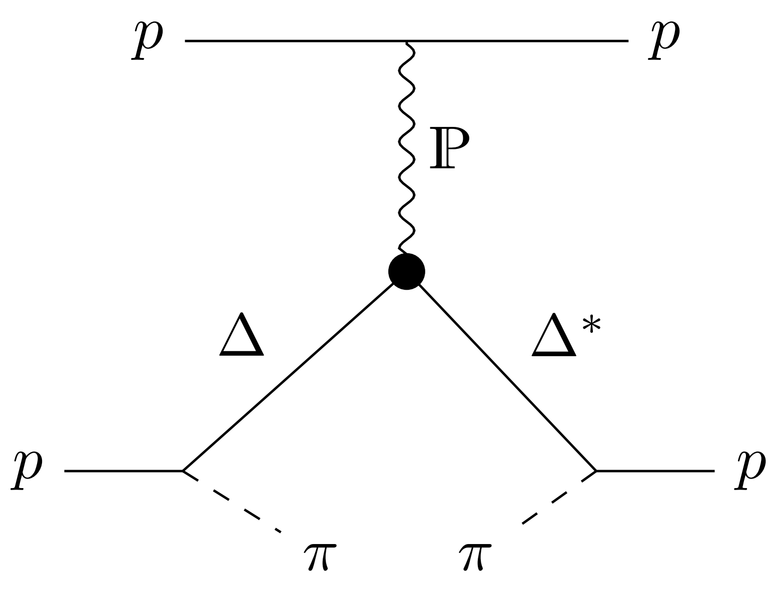

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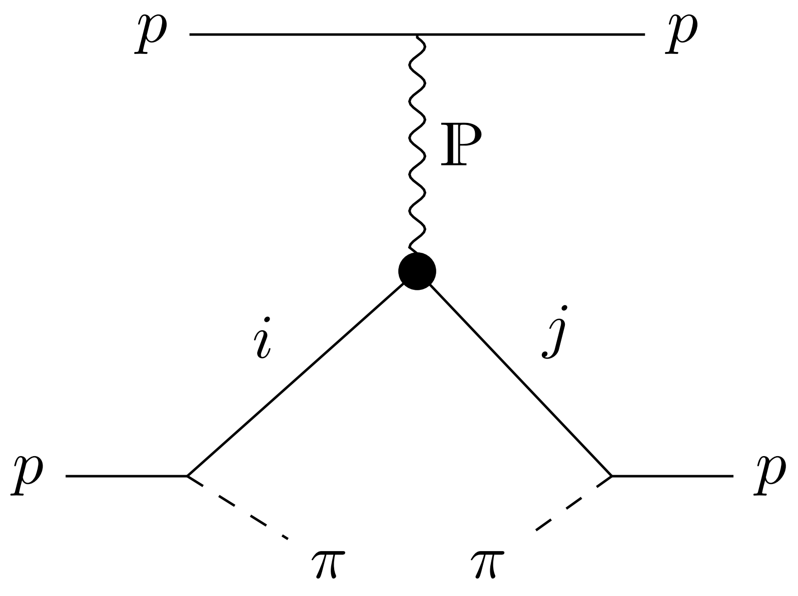

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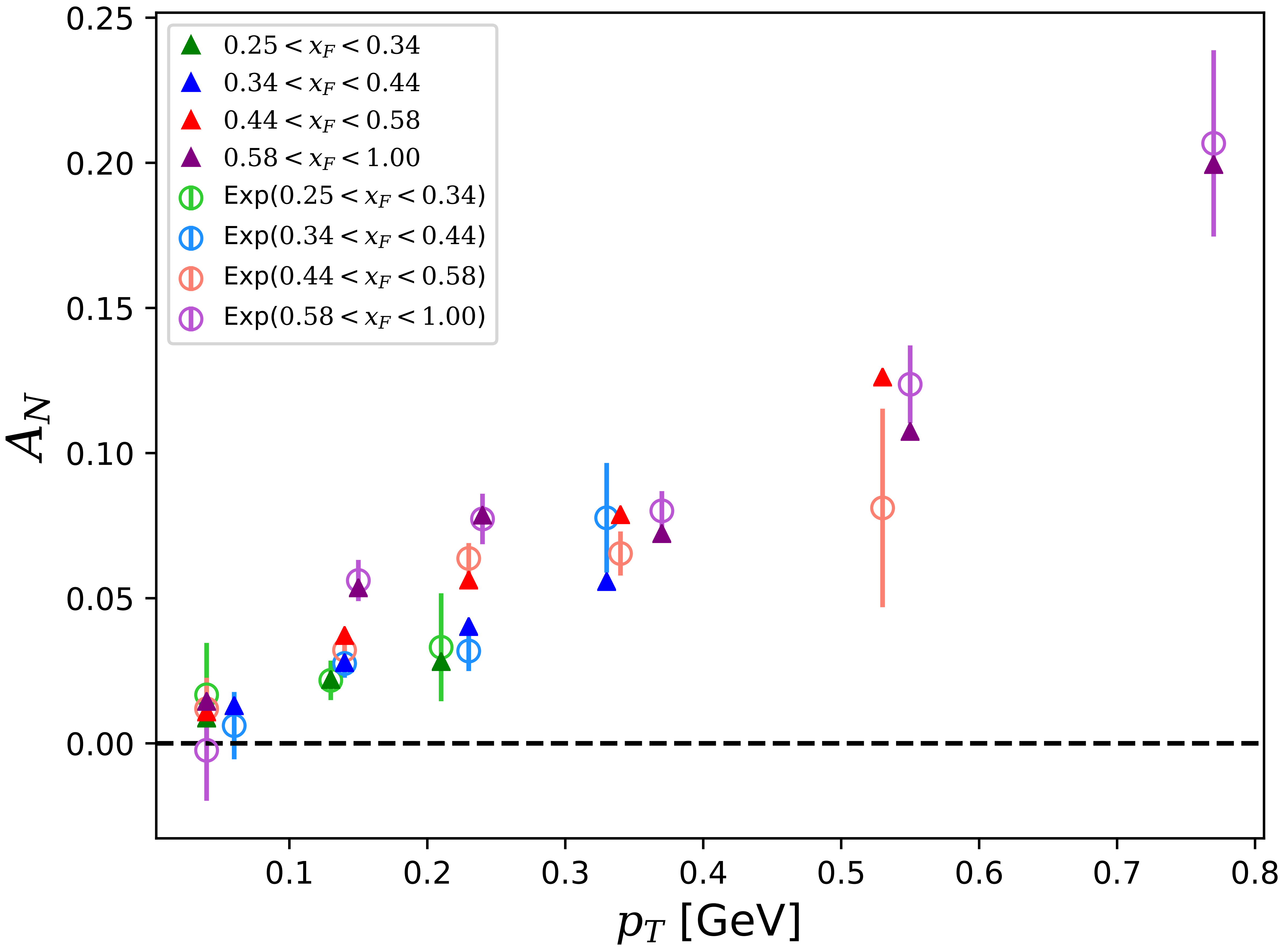
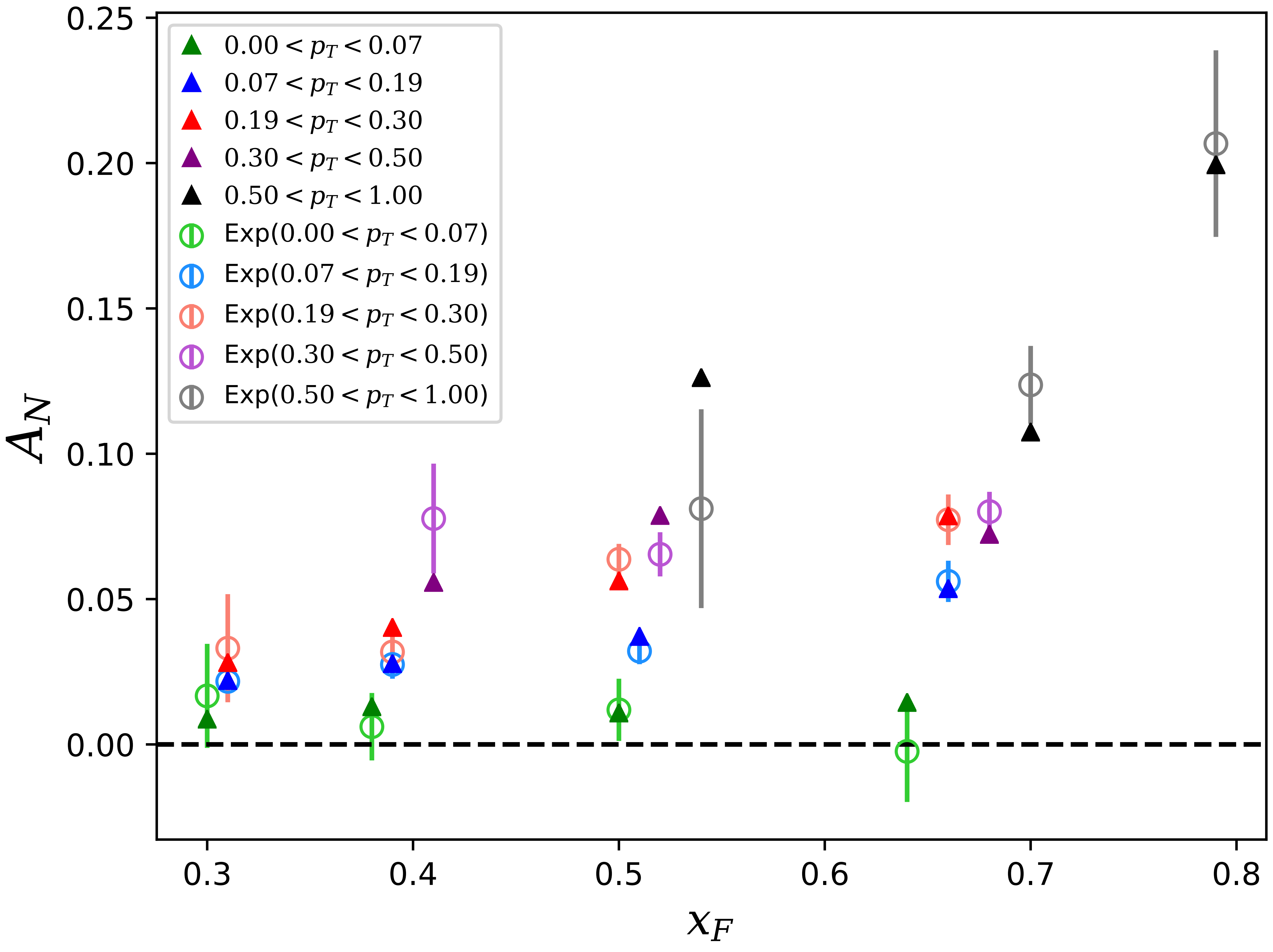
Results

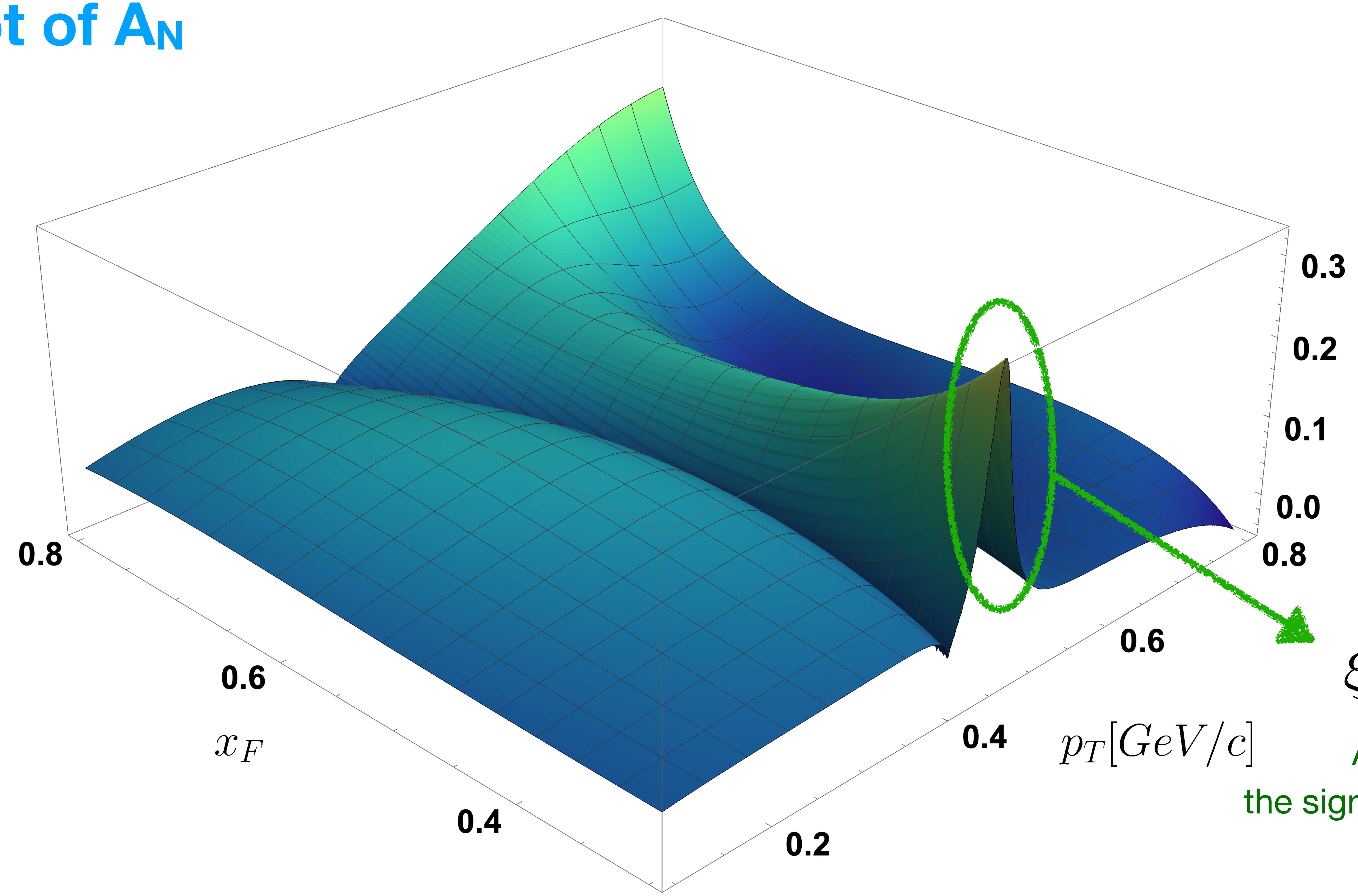
Results

	$g_{\mathbb{P}}^{ij}$	$b_{\mathbb{P}}^{ij}$ [GeV^{-2}]
NN^*	0.028	0.2
$\Delta\Delta^*$	−0.018	0
N^*N^*	0.10	0
$\Delta\Delta$	0.022	0
$\Delta^*\Delta^*$	0.079	0





3D Plot of A_N



$\xi_p(t) \approx 0$

A_N is sensitive to
the signature factor at small x_F

Summary

Summary

- We investigated the TSSA for very forward neutral pion through the Reggeon exchange processes.
- The differential cross-section for $pp^{\uparrow} \to \pi^0 X$ is approximated to the triple-Regge exchange process.
- Our results match the RHICf data of both transverse momentum and x_F distribution quite well.
- We found that diffractive reactions are a main source of the π^0 A_N in the very forward direction.
- $pp^{\uparrow} \to \pi^{\pm}X, \eta X, \Lambda X, \Delta X \ldots$

Thank you

Back up

Contribution from each interference

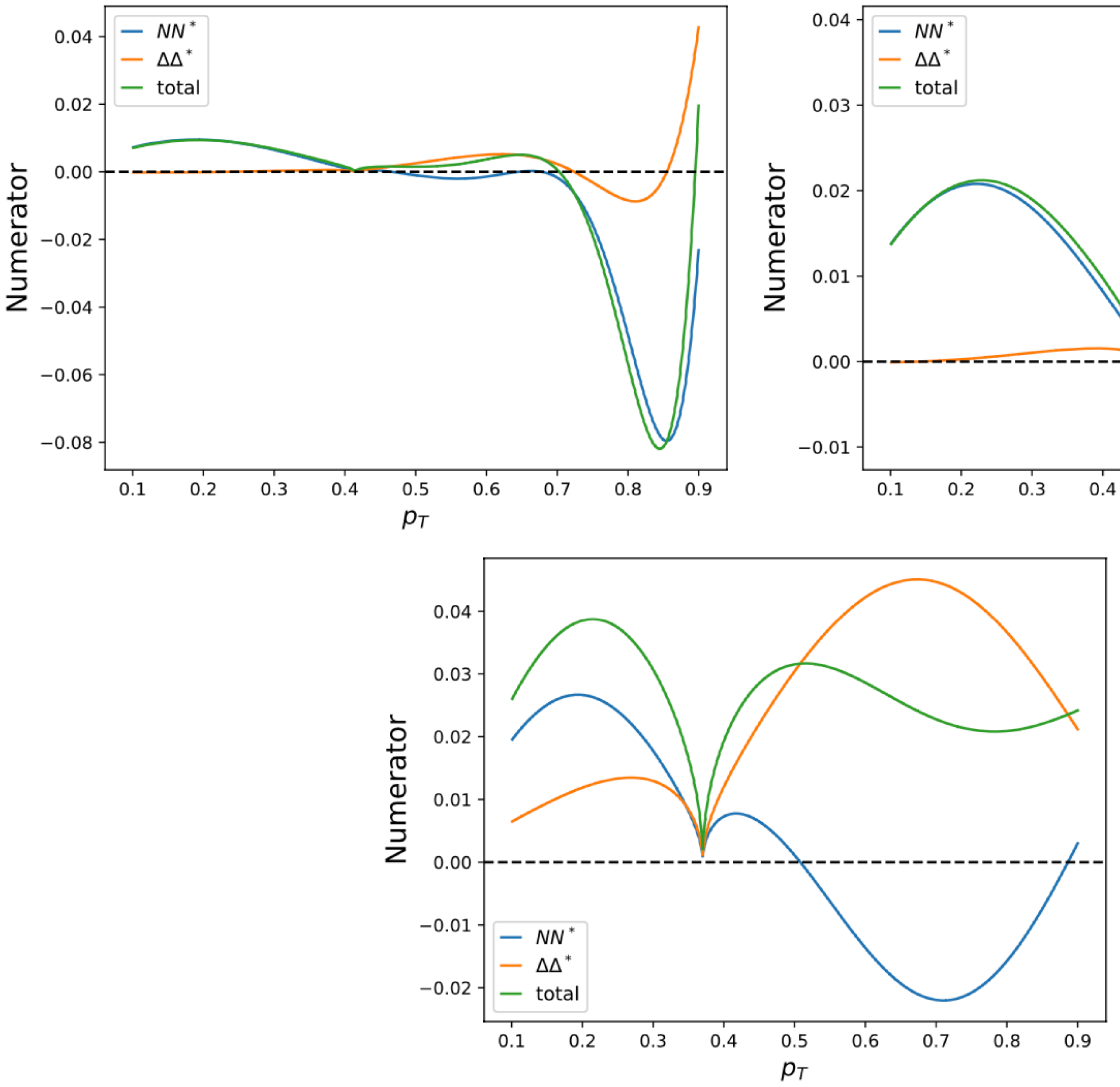


FIG. 7. Numerators when $x_F = 0.3, 0.5, 0.8$.

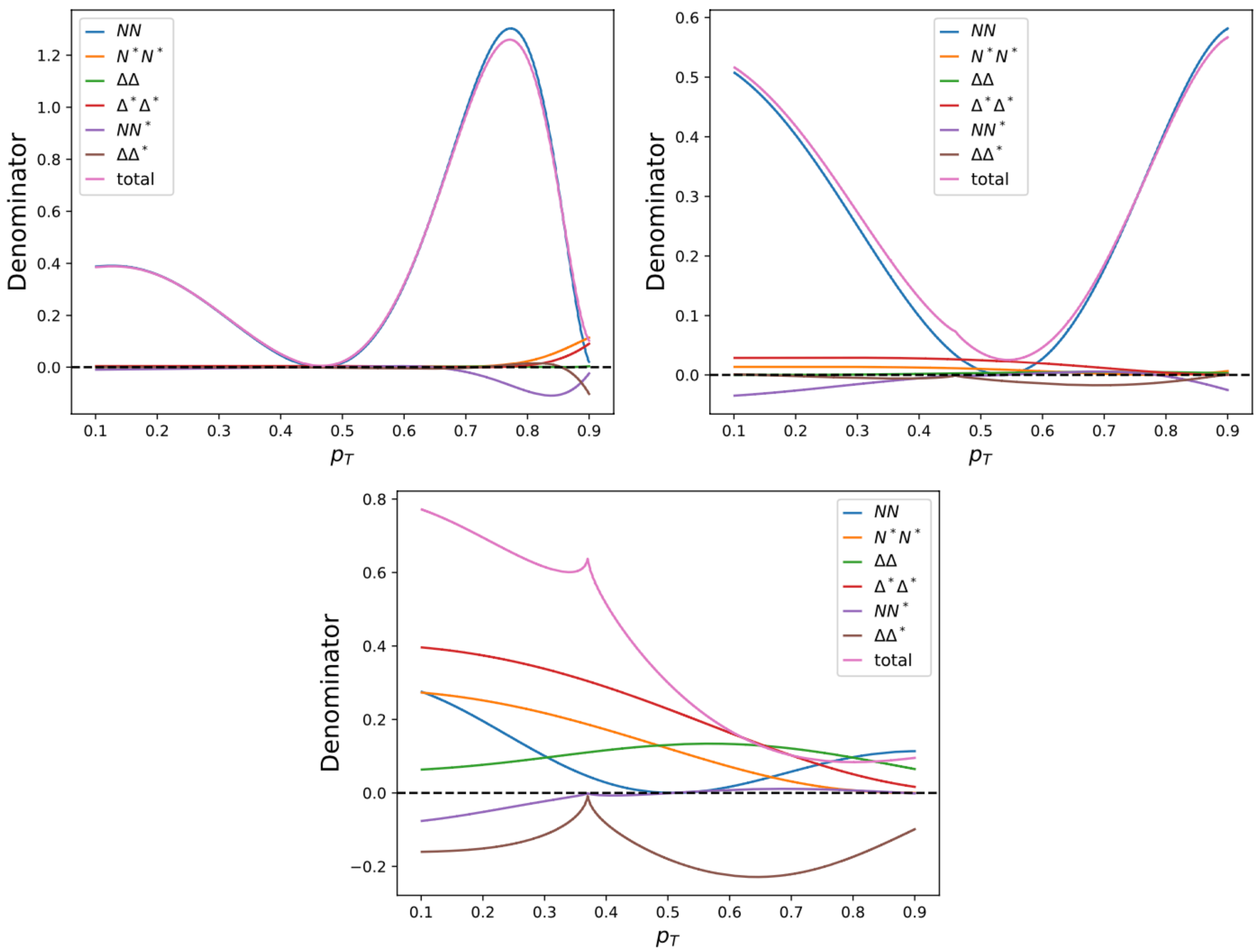


FIG. 8. Denominators when $x_F = 0.3, 0.5, 0.8$.

Effective Lagrangians

$$\mathcal{L}_{\pi NN} = -\frac{f_{\pi NN}}{m_\pi}\bar{\psi}\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\psi\partial^\mu\boldsymbol{\pi},$$

$$\mathcal{L}_{\pi NN^*} = -i\frac{f_{\pi NN^*}}{m_\pi}\bar{\psi}^\mu_{N^*}(g_{\mu\nu}+a\gamma_\mu\gamma_\nu)\gamma_5\boldsymbol{T}\cdot\psi\partial^\nu\boldsymbol{\pi},$$

$$\mathcal{L}_{\pi N\Delta} = -\frac{f_{\pi N\Delta}}{m_\pi}\bar{\psi}^\mu_{\Delta}(g_{\mu\nu}+a\gamma_\mu\gamma_\nu)\boldsymbol{T}\cdot\psi\partial^\nu\boldsymbol{\pi},$$

$$\mathcal{L}_{\pi N\Delta^*} = -\frac{f_{\pi N\Delta^*}}{m_\pi}\bar{\psi}^\mu_{\Delta^*}(g_{\mu\nu}+a\gamma_\mu\gamma_\nu)\boldsymbol{T}\cdot\psi\partial^\nu\boldsymbol{\pi},$$