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

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- 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, …)

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)

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(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].

- Since the produced particles have very large values of η and low p_T, the TSSA displays the *non-perturbative* and *diffractive* nature.

TSSA :

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

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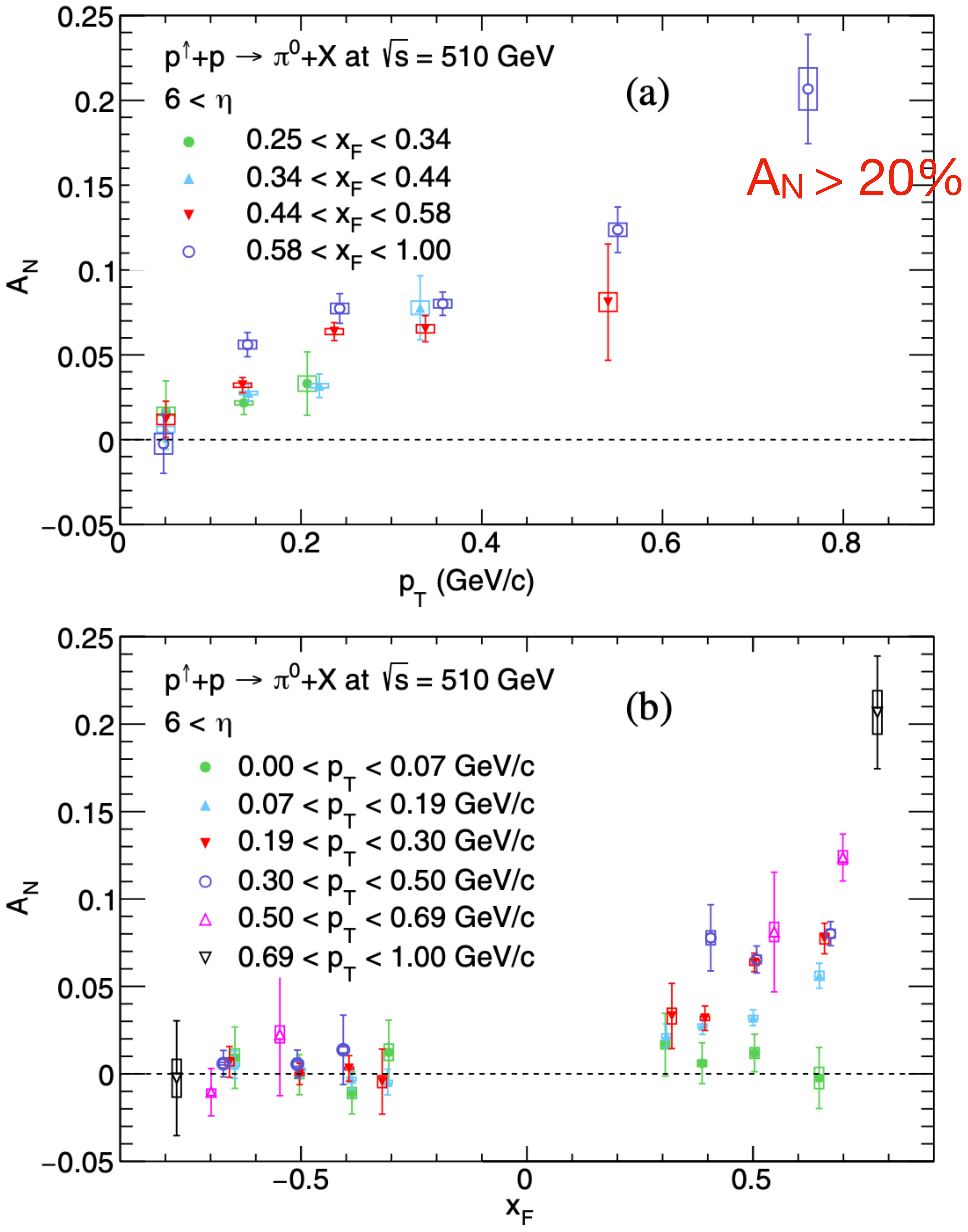
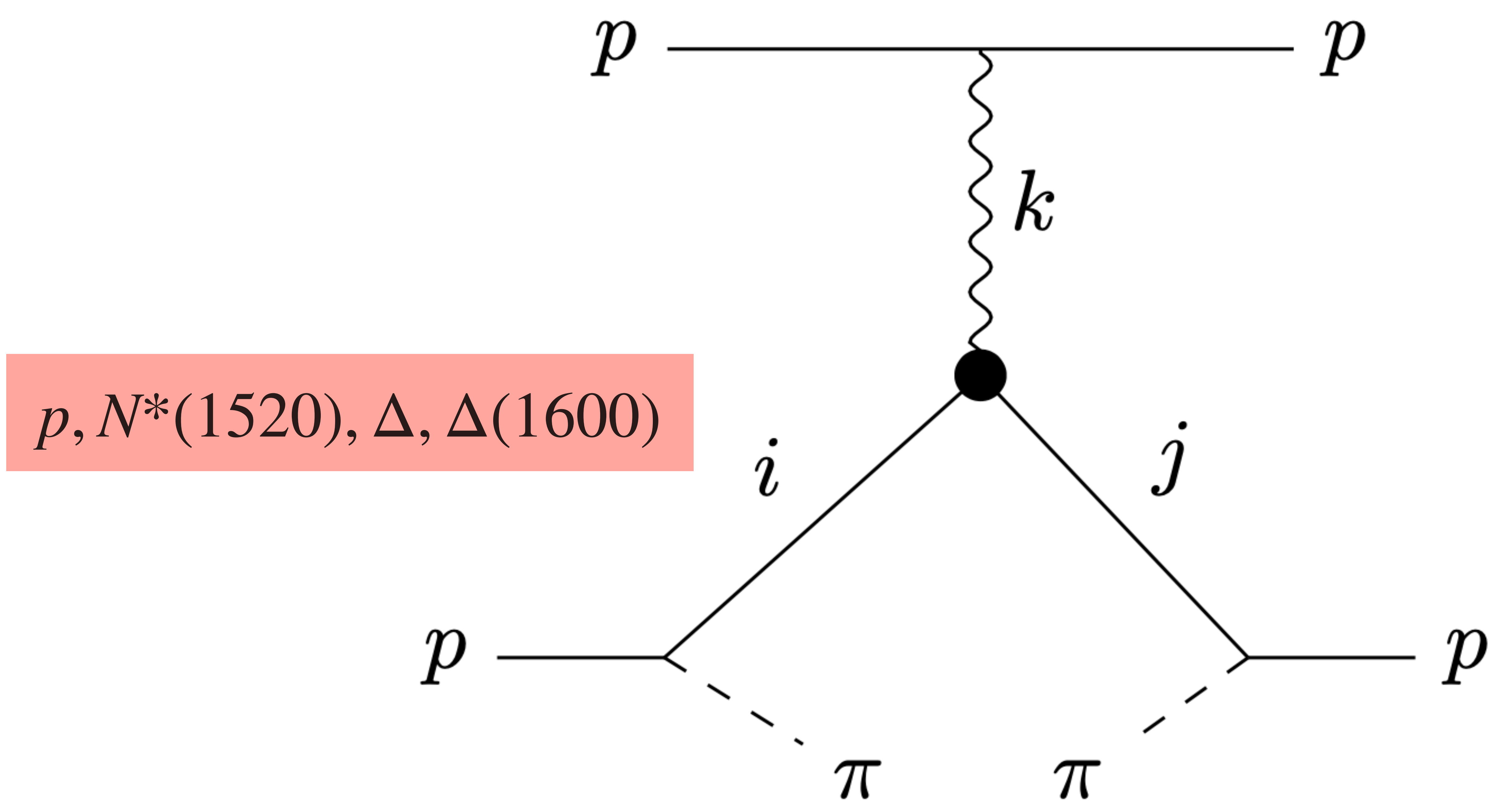
- Recently the TSSA of very forward neutral pion was measured in RHICf experiment [3].





- 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.

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

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

Kinematics

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

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

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

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

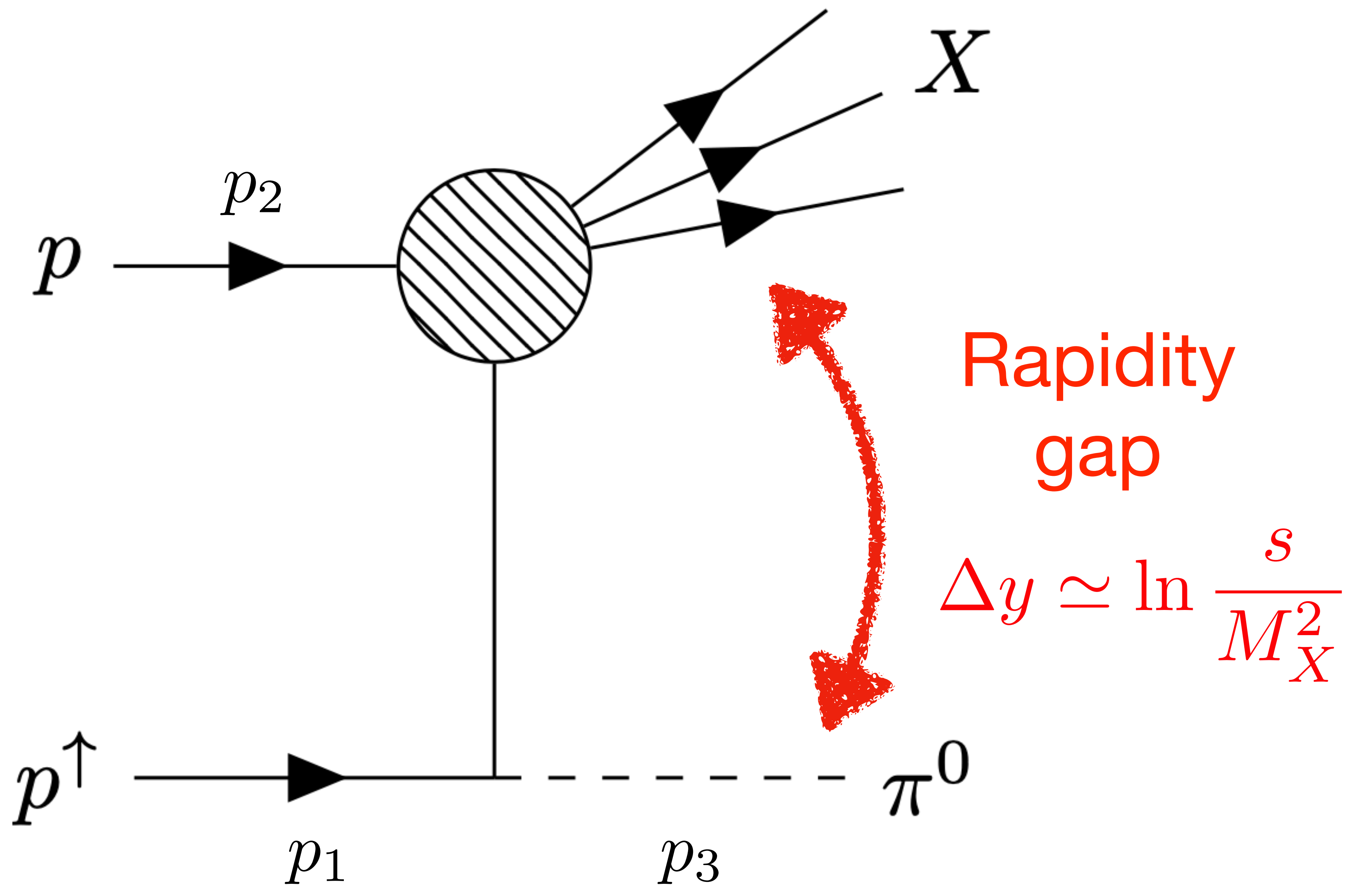
In high-energy hadron scattering the transverse momentum of the produced particle is quite small on average.

When $s, M_X^2 \gg m_i^2$ and $|p_T| < 1$ GeV/c, one can define

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

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

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

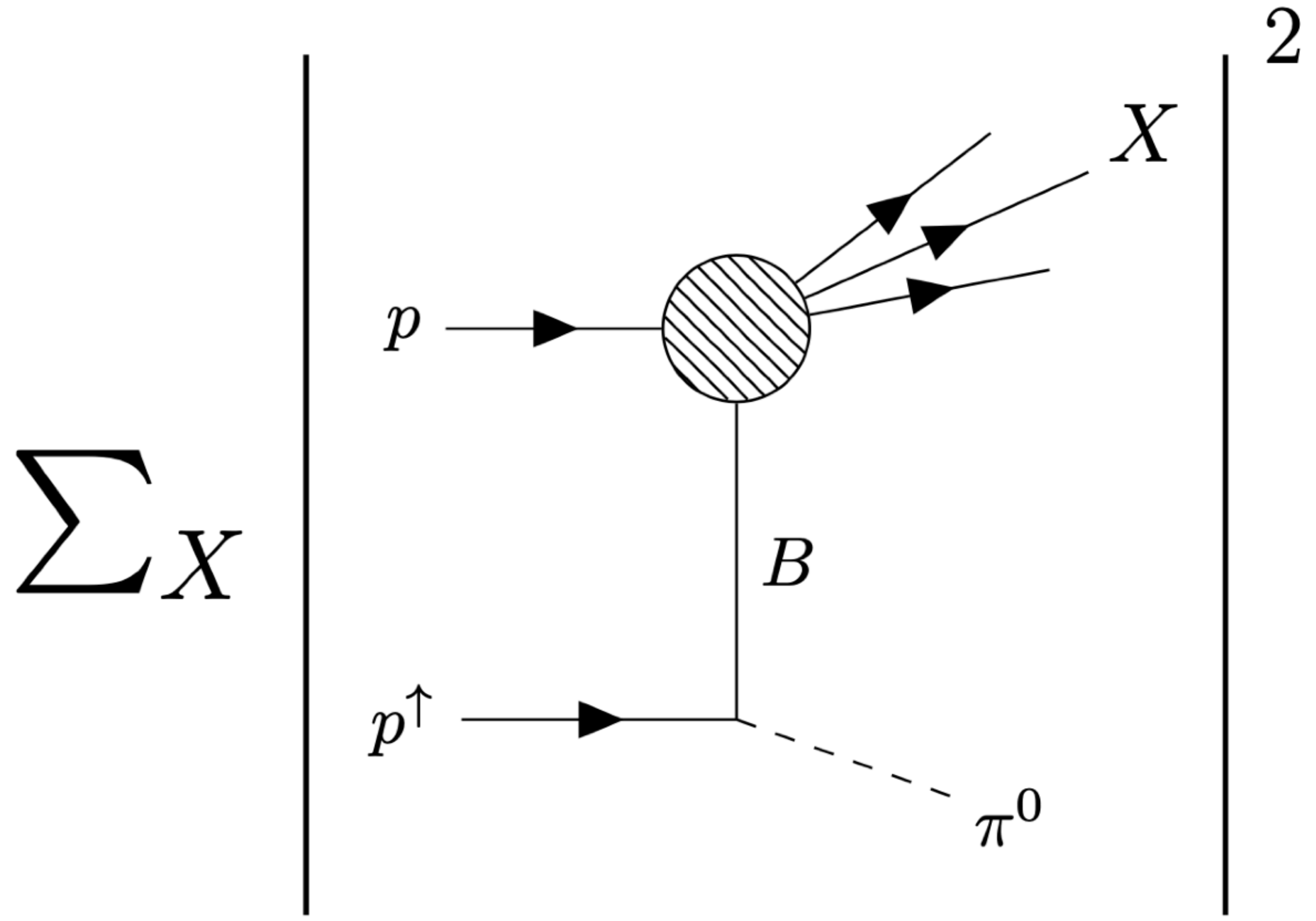


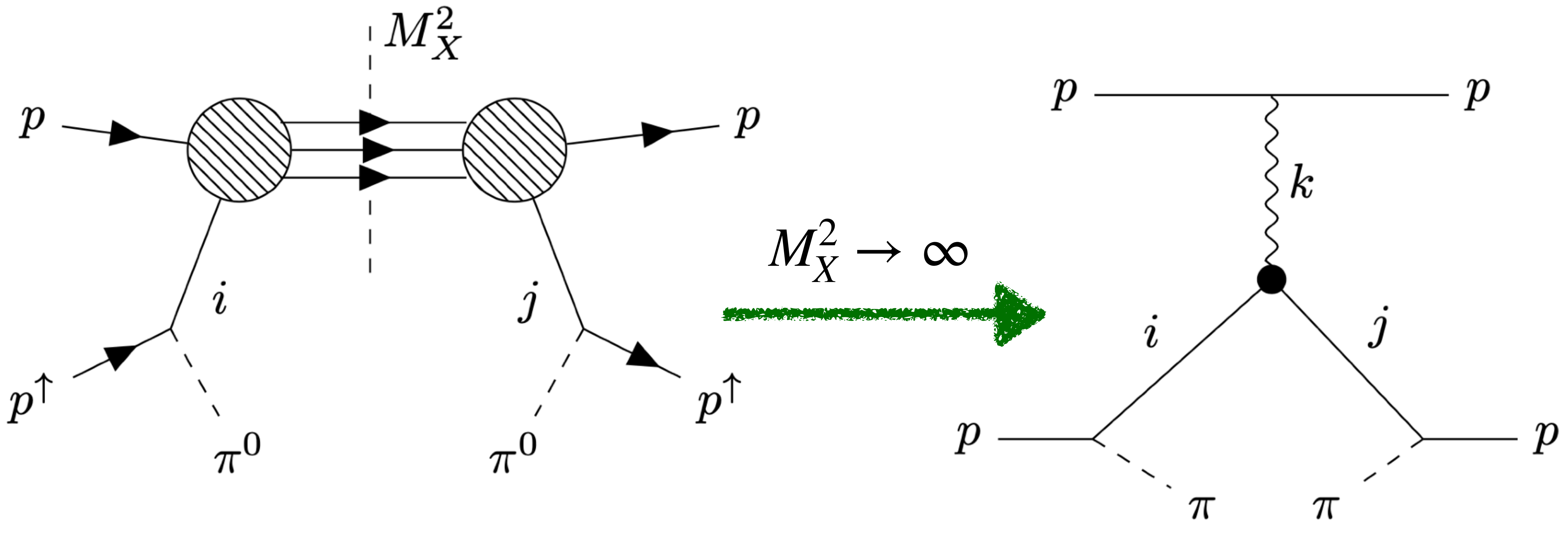
Invariant cross section in the triple-Regge limit

Invariant differential cross-section

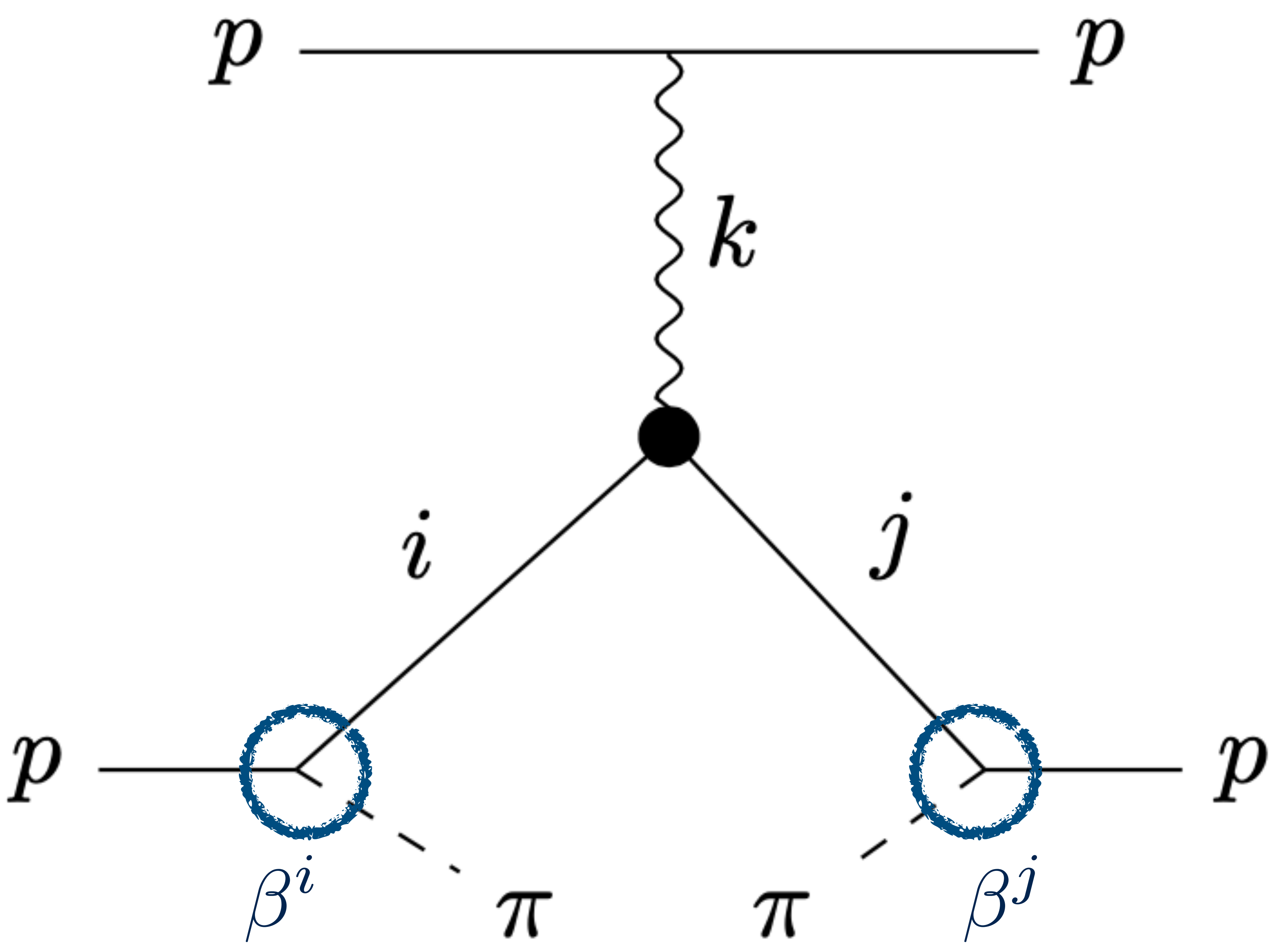
- The Lorentz-invariant differential cross section of π^0 :

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





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



Since the Regge approach does not provide the vertex structure, we need to employ the effective Lagrangians:

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

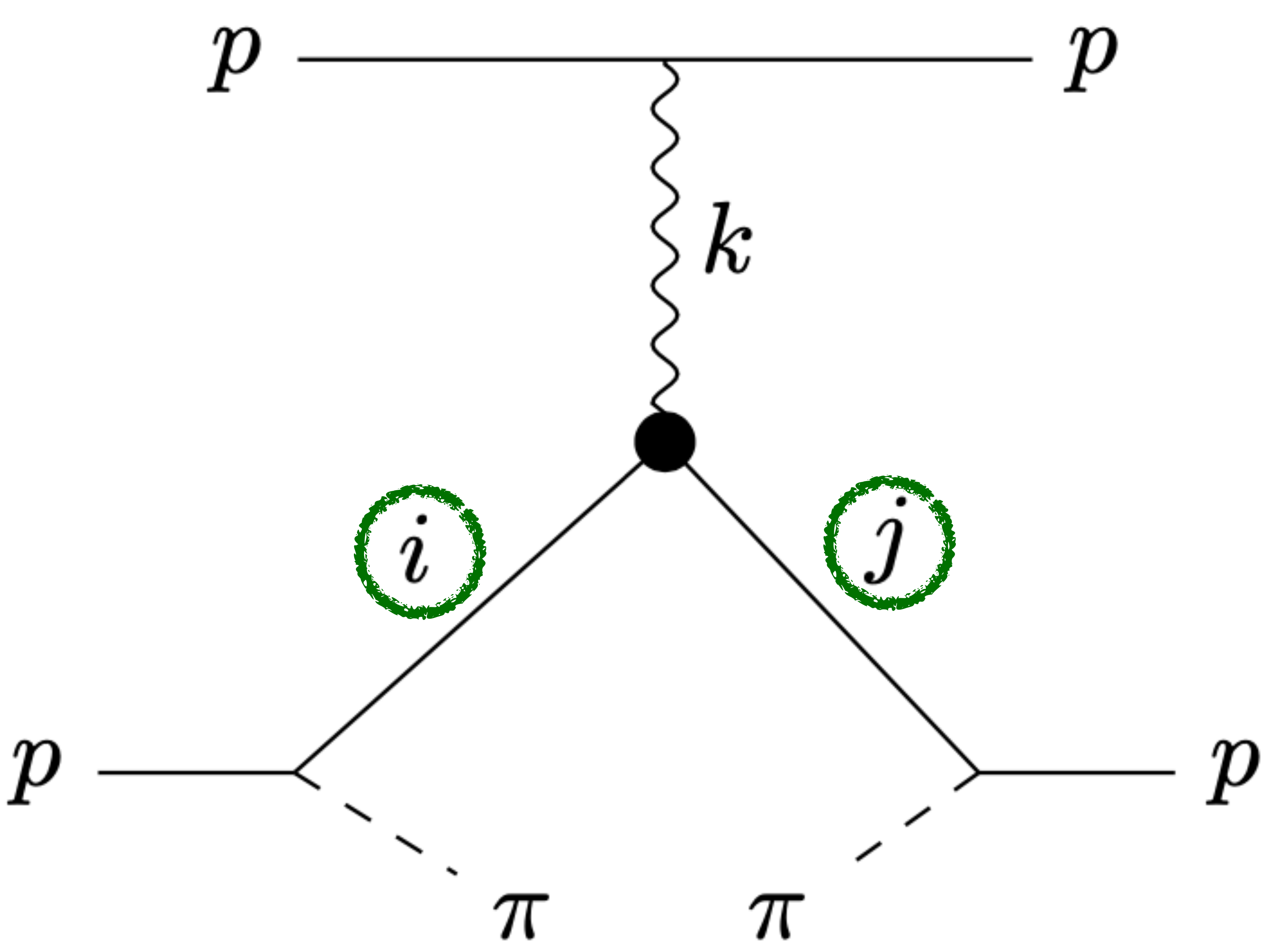
Residue functions with Born approximation

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

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

Regge trajectories:

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



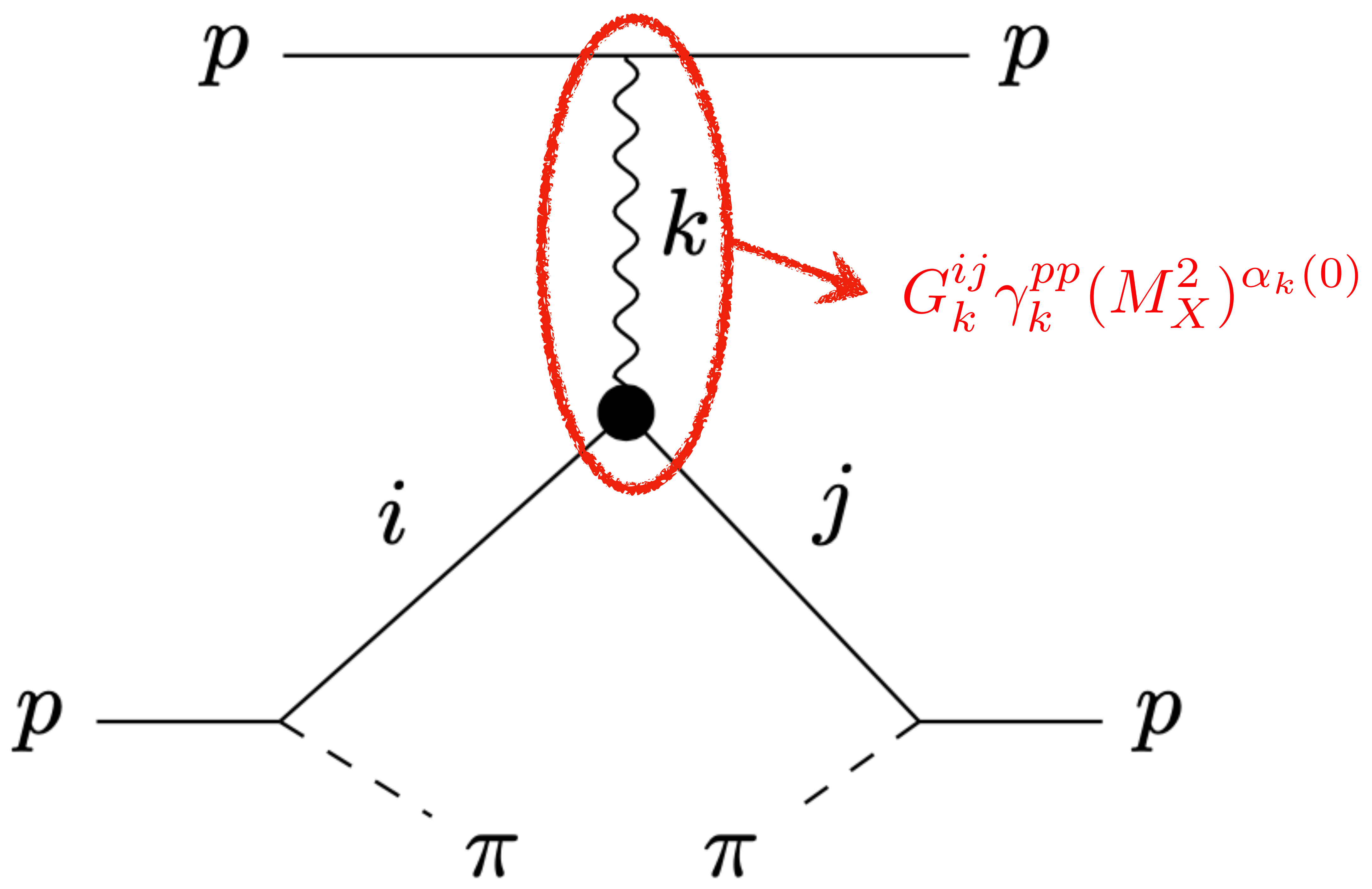
Reggeized propagator

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

Signature factor: $\xi_i(t) = \dfrac{1 + \tau_i \exp\{-i\pi(\alpha_i(t) - 0.5)\}}{2}$

- The residue functions β should be real-valued function, so the phase of a Regge-pole contribution to A_N comes from the *signature factor*

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



The triple-Regge coupling: $G^{ij}_k(t)$

The generalized optical theorem implies that

- No momentum transfer between unpolarized protons
- No spin flip by k-exchange

The *ppk* vertex function: $\gamma^{pp}_k(t_{pp}=0) = \sum_\lambda \beta^k_{\lambda\lambda}(0)$

k-reggeon propagator: $(M_X^2)^{\alpha_k(0)}$

Transverse single-spin asymmetry

Transverse single-spin asymmetry(TSSA)

- **TSSA**

TSSA is defined as a fraction of spin-dependent cross section and spin-averaged one:

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

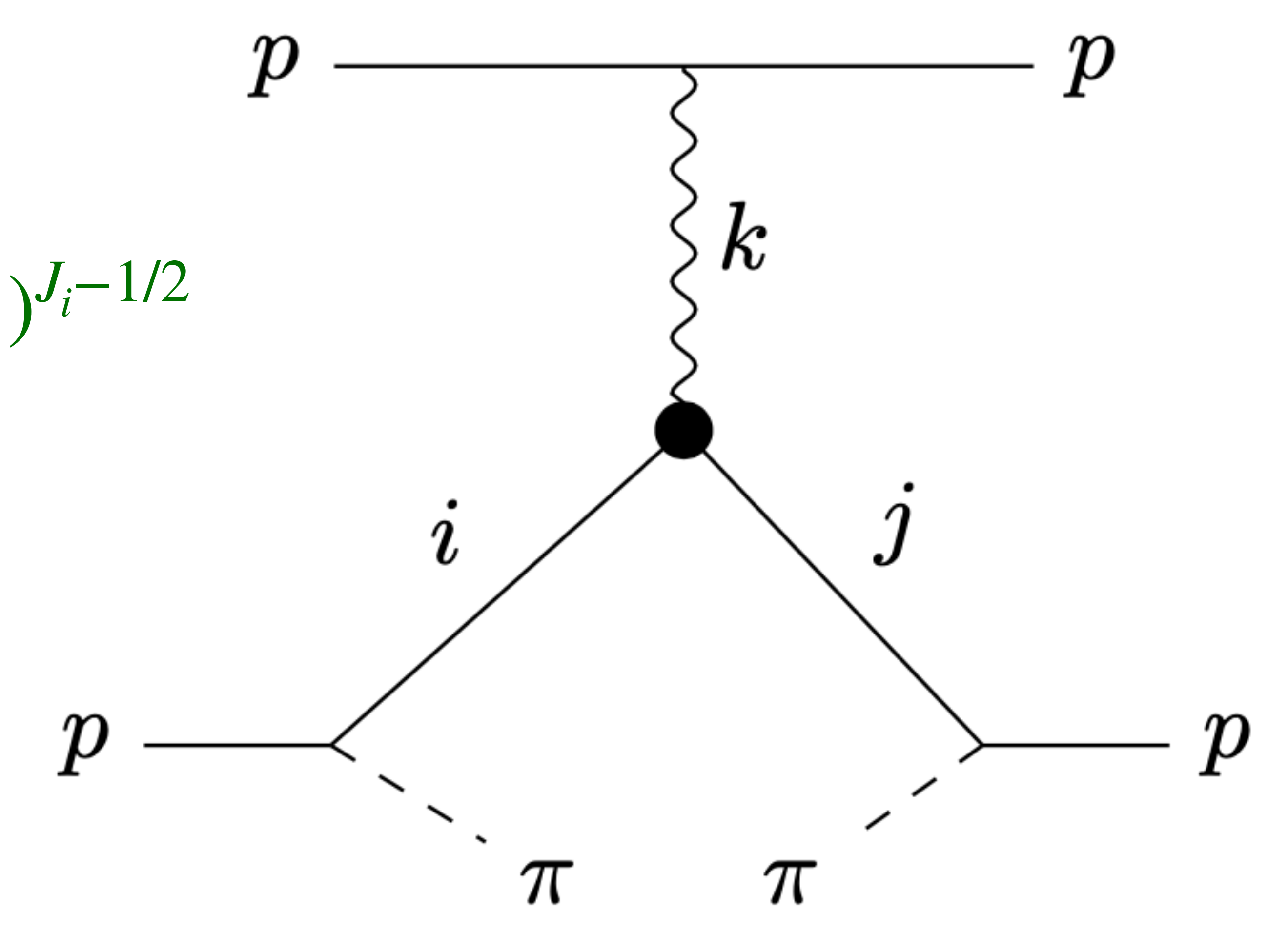
Spin-dependent differential cross section

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

Spin-averaged differential 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. $d\sigma^h$ vanishes if *k* is an unnatural parity state.

$$\text{unnatural parity states}: \pi,\ \eta,\ a_1, \ldots$$

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

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

Naturality : $\eta_i \equiv P_i\tau_i = P_i(-1)^{J_i-1/2}$

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

Spin-dependent cross section

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

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

natural: $N,\ N^*(1520)$ unnatural: $\Delta,\ \Delta(1600)$

Spin-averaged cross section

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

- Parameterization of the triple-Regge couplings

$$G_{\mathbb{P}}^{ij}(t) = \begin{cases} G_{\mathbb{P}}^{ij}(0)e^{-B_{\mathbb{P}}^{ij}|t|}, & \text{for } i = j \quad \text{(diagonal)} \\ G_{\mathbb{P}}^{ij}(0)\frac{\sqrt{|t|}}{m_\pi}e^{-B_{\mathbb{P}}^{ij}|t|}, & \text{for } i \neq j \quad \text{(non-diagonal)} \end{cases}$$

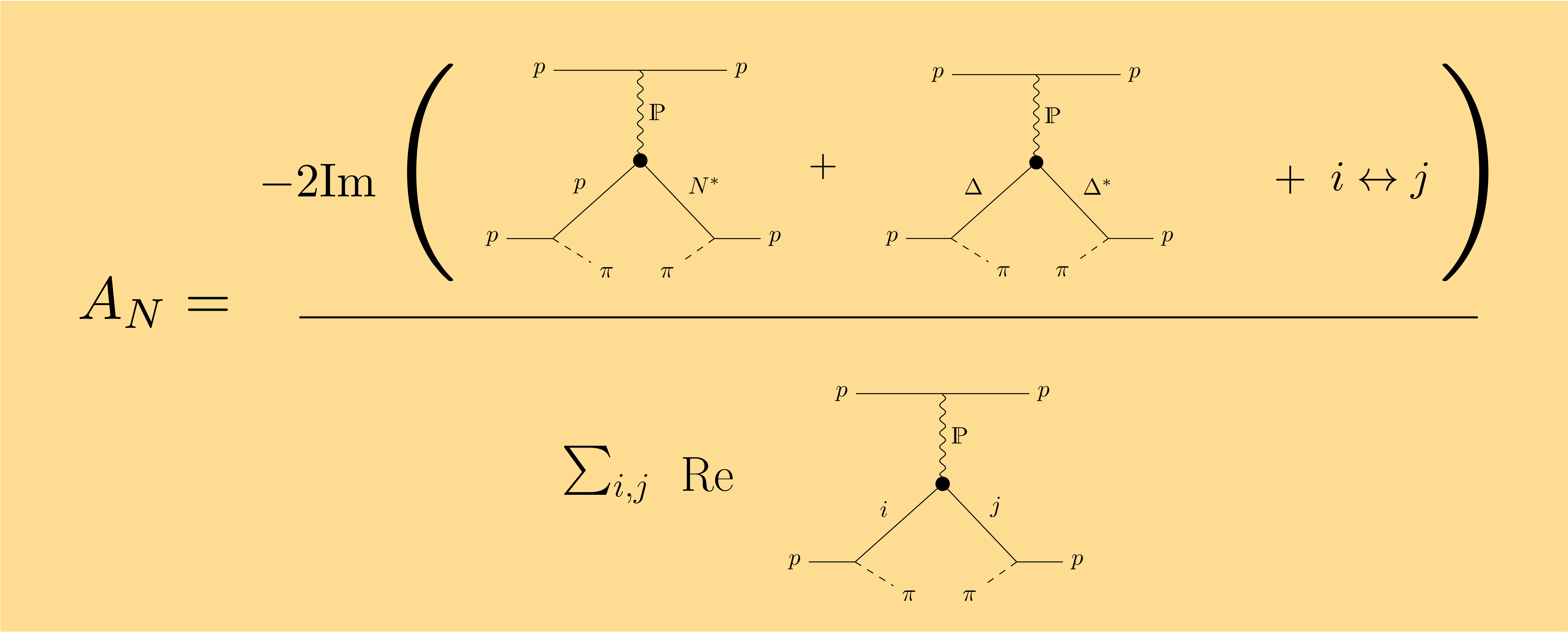
Redefine the parameters as

$$g_{\mathbb{P}}^{ij} \equiv G_{\mathbb{P}}^{ij}(0)/G_{\mathbb{P}}^{NN}(0), \quad b_{\mathbb{P}}^{ij} \equiv B_{\mathbb{P}}^{ij} - B_{\mathbb{P}}^{NN}$$

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

- Diagrammatic representation of the A_N

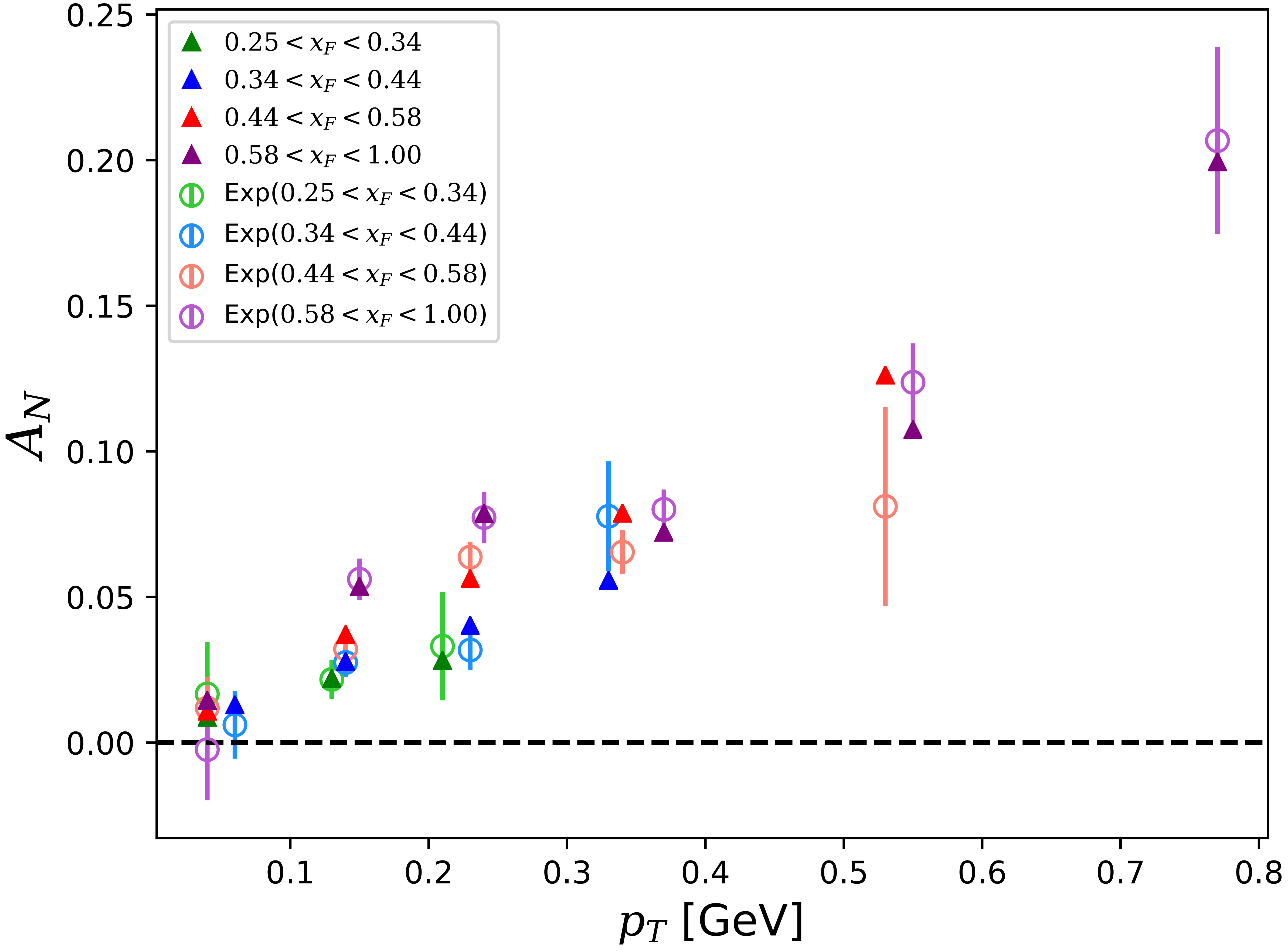
$$A_N = \frac{\sum_\lambda \left[\beta^{N}_{+\lambda}\beta^{N^*}_{-\lambda}\,\mathrm{Im}\,\mathcal{P}_N\mathcal{P}^*_{N^*}(\sqrt{|t|}/m_\pi)\,g_{\mathbb{P}}^{NN^*} + \beta^{\Delta}_{+\lambda}\beta^{\Delta^*}_{-\lambda}\,\mathrm{Im}\,\mathcal{P}_\Delta\mathcal{P}^*_{\Delta^*}(\sqrt{|t|}/m_\pi)\,g_{\mathbb{P}}^{\Delta\Delta^*}e^{-b_{\mathbb{P}}^{\Delta\Delta^*}|t|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

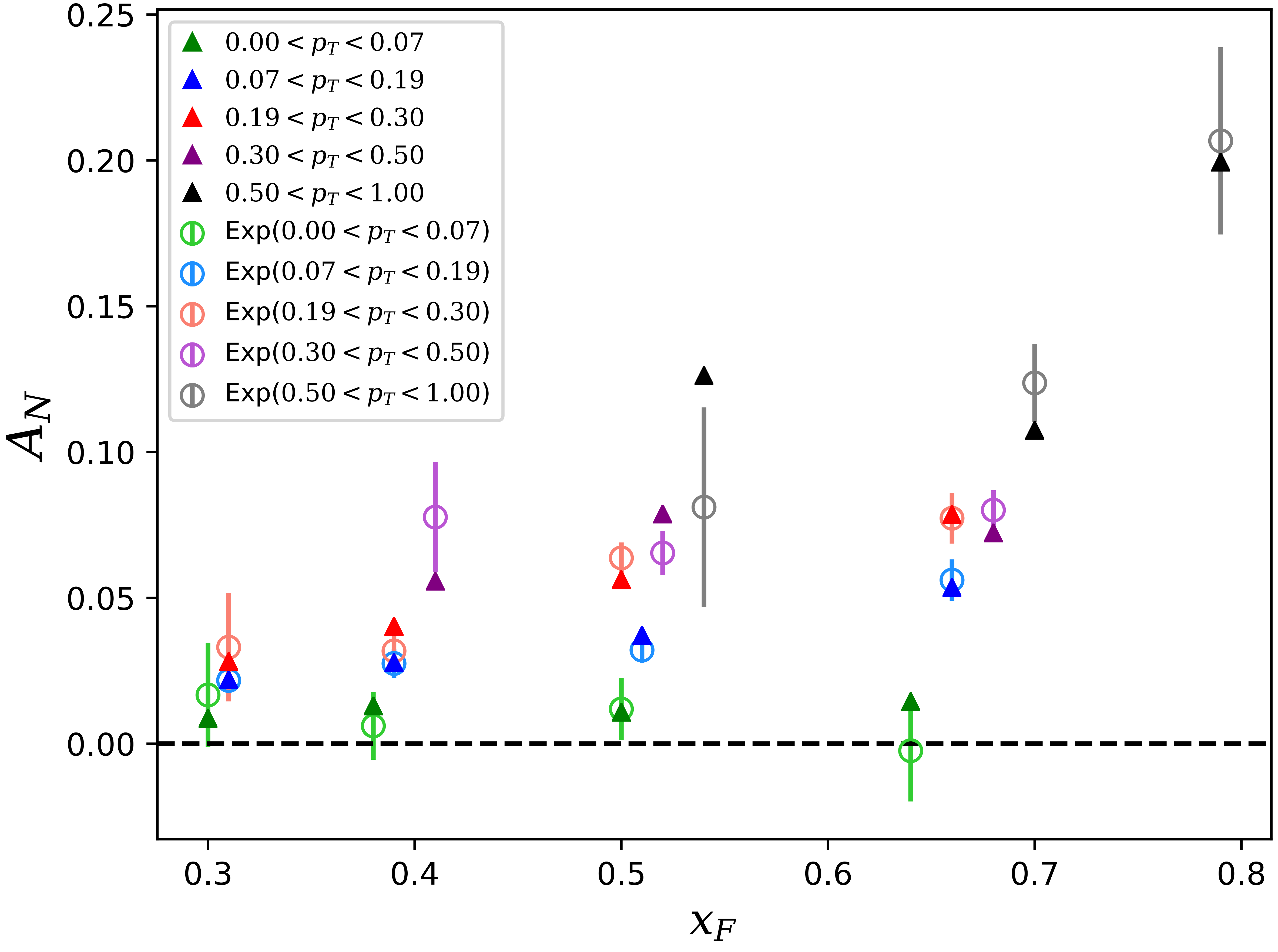


Results

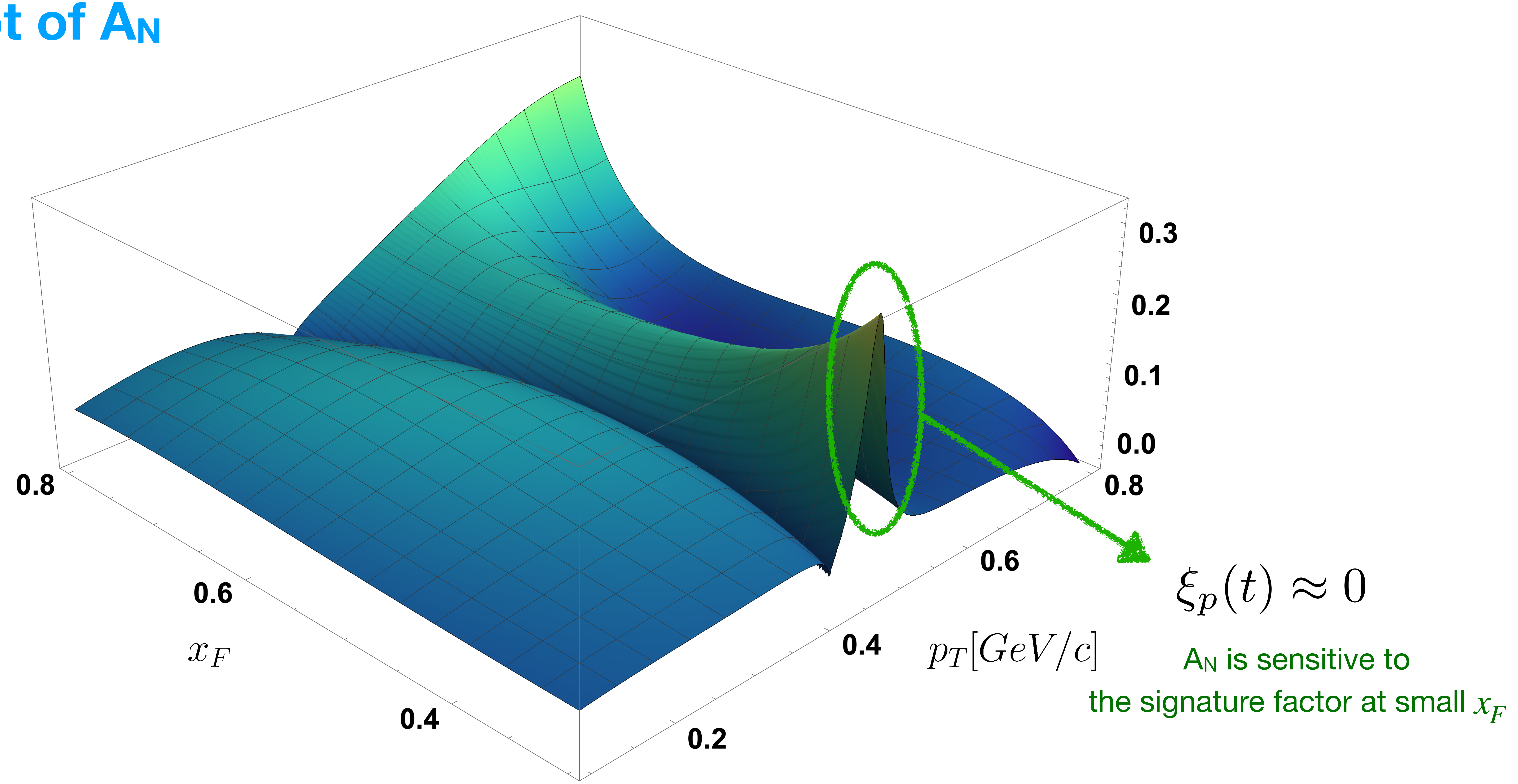
Results

	$g_{\mathbb{P}}^{ij}$	$b_{\mathbb{P}}^{ij}$ [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



0.3
0.2
0.1
0.0
0.8
0.6
0.4
x_F
0.8
0.6
0.4
0.2
$p_T[GeV/c]$
$\xi_p(t) \approx 0$
A_N is sensitive to
the signature factor at small x_F

Summary

Summary

- The TSSA for very forward neutral pion via the Reggeon exchange processes.
- The differential cross-section for $pp^{\uparrow} \rightarrow \pi^0 X$ is approximated to the triple-Regge exchange process.
- Good agreement with the RHICf data of both transverse momentum and x_F distribution quite well.
- We found that a large fraction of the π^0 A_N in the very forward direction is of diffractive nature.
- $pp^{\uparrow} \rightarrow \pi^{\pm}X, \eta X, \Lambda X, \Delta X \ldots$

Thank you

Back up

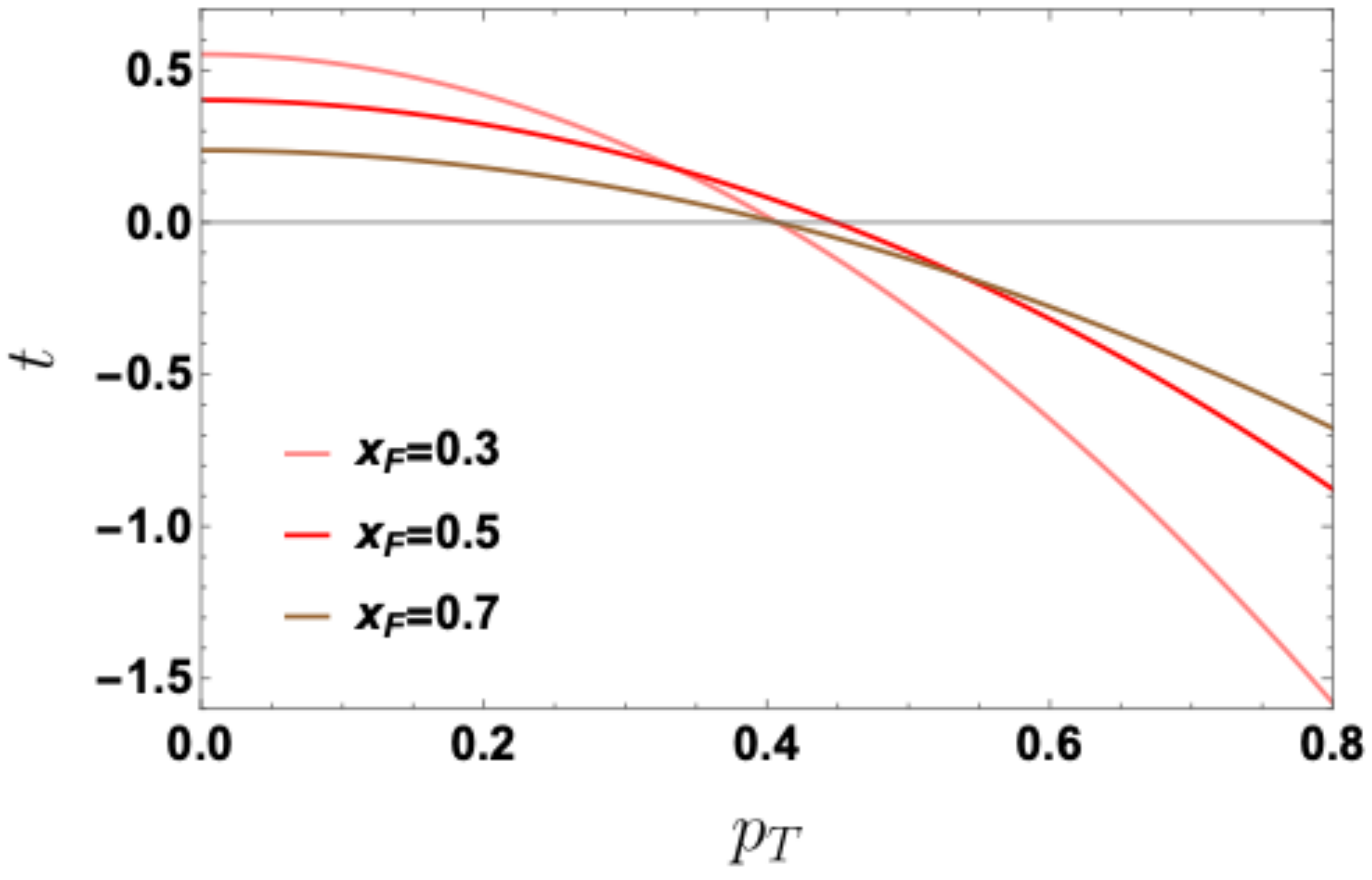
Kinematics

We are going to ignore the pion mass m_3 since it is negligible in the calculation. First, we expand the following variables up to $(m_N^2/s)^{1/2}$ order.

$$p_z = \sqrt{\frac{s}{4} - m_N^2} \approx \frac{\sqrt{s}}{2} - \frac{m_N^2}{\sqrt{s}}, \quad p_z' = p_z x_F \approx \frac{\sqrt{s}}{2} x_F - \frac{m_N^2}{\sqrt{s}} x_F,$$
$$E_3 = \sqrt{p_z'^2 + \boldsymbol{p}_T^2} \approx \frac{\sqrt{s}}{2} x_F - \frac{1}{x_F}\frac{m_N^2}{\sqrt{s}} + \frac{\boldsymbol{p}_T^2}{\sqrt{s}}. \tag{5}$$

The squared momentum transfer is then

$$\begin{aligned} t &= (p_1 - p_3)^2 \\ &= (E_1 - E_3)^2 - \boldsymbol{p}_T^2 - (p_z - p_z')^2 \\ &= \frac{s}{4}(1-x_F)^2 + (1-x_F)\left(m_N^2 x_F - \frac{\boldsymbol{p}_T^2}{x_F}\right) - \boldsymbol{p}_T^2 - \left[\frac{s}{4}(1-x_F)^2 - m_N^2(1-x_F)^2\right] \\ &= (1-x_F)m_N^2 - \frac{\boldsymbol{p}_T^2}{x_F}. \end{aligned}$$



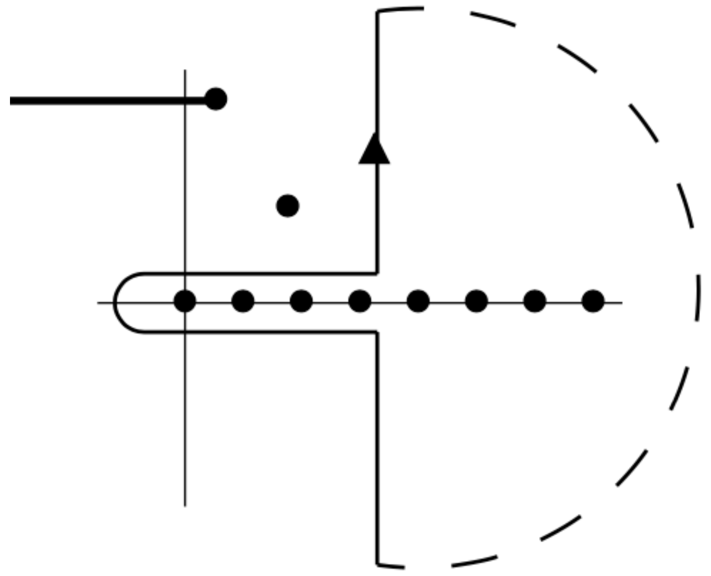
Regge poles

The t-channel partial-wave series for scattering amplitude: $A(s,t) = 16\pi \sum_{l=0}^{\infty} A_l(t) P_l(z_t)$

Ex) Equal-mass scattering: $z_t = 1 + \frac{2s}{t - 4m^2} \longrightarrow P_l(z_t) \sim s^l$

This series is a correct representation of scattering in the physical region of the t-channel, where $t > 4m^2, s < 0$, it is irrelevant for high-energy s-channel scattering.

- Analytic continuation to the complex ℓ*-plane*

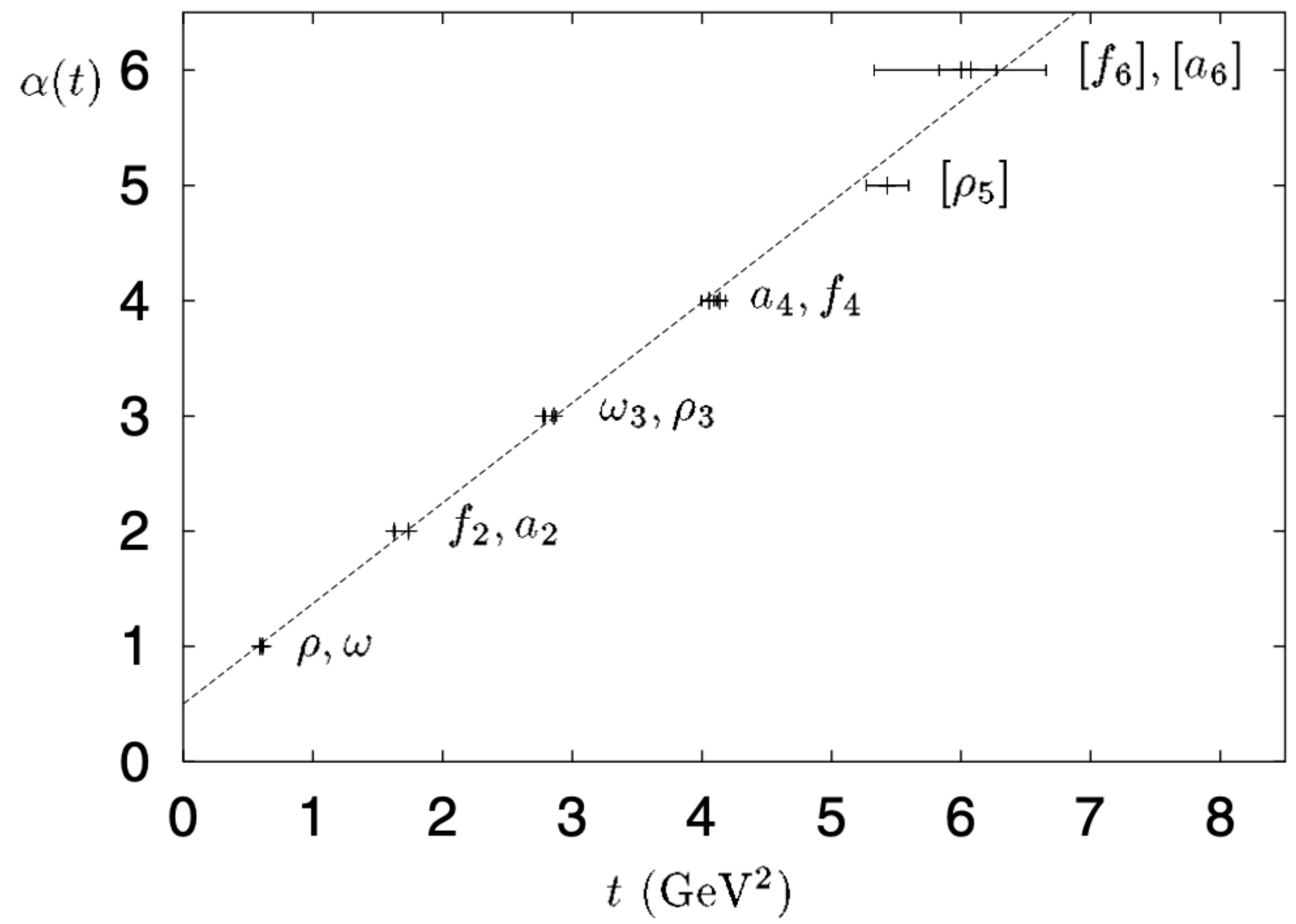


$$A(s,t) = 16\pi \sum_{l=0}^{\infty} A_l(t) P_l(z_t) \longrightarrow 8\pi i \int_C dl\, A(l,t) \frac{P_l(-z_t) + P_l(z_t)}{\sin \pi l}$$

The singularities of $A(l,t)$ are poles whose locations at $l = \alpha(t)$

$$A(s,t) \sim s^{\alpha(t)}$$

The functions $\alpha(t)$ are called Regge trajectories. The particles on the same trajectory give a collective energy dependence



interferences and pole contributions

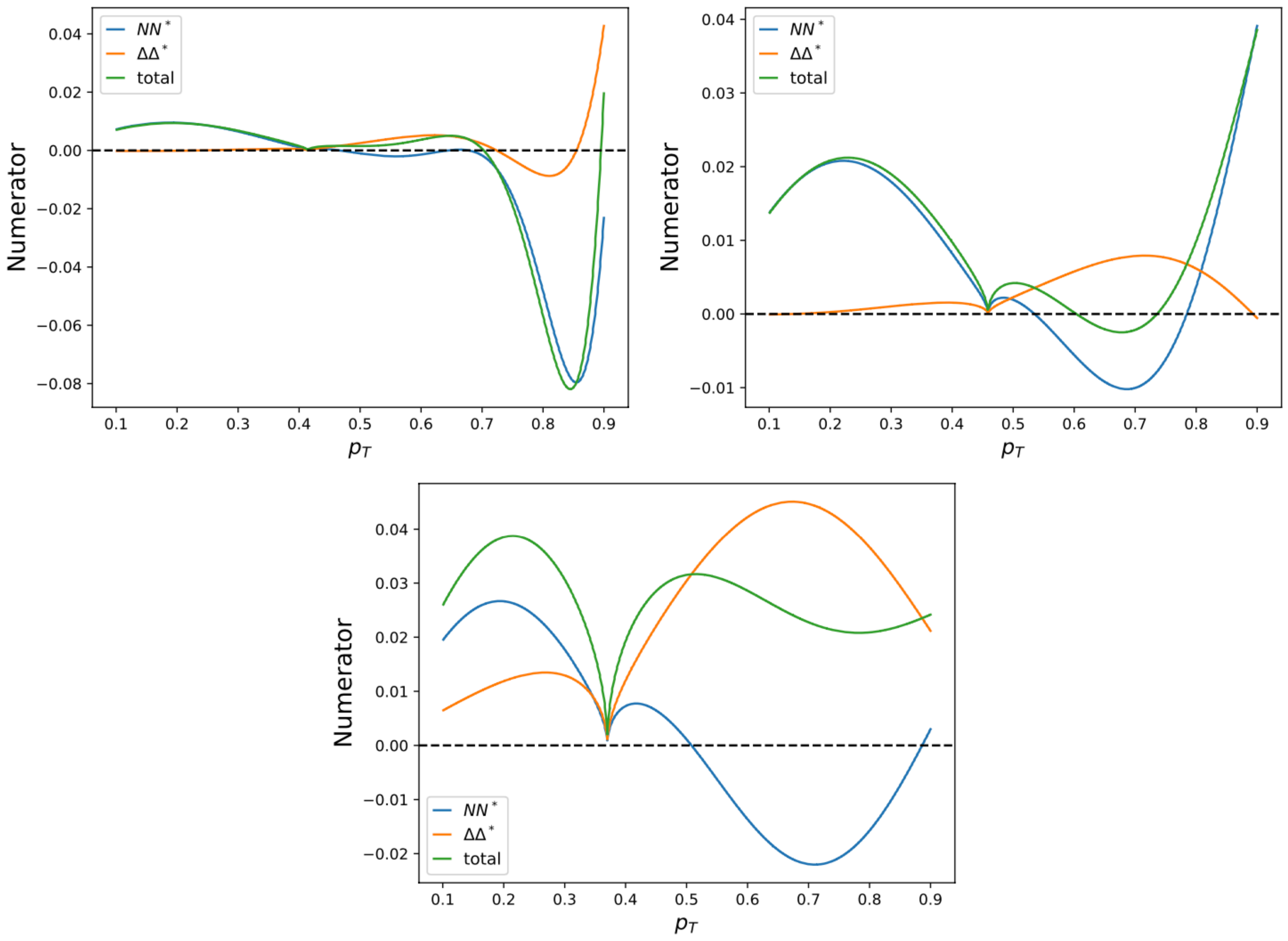


FIG. 7. Numerators when $x_F = 0.3, 0.5, 0.8$.

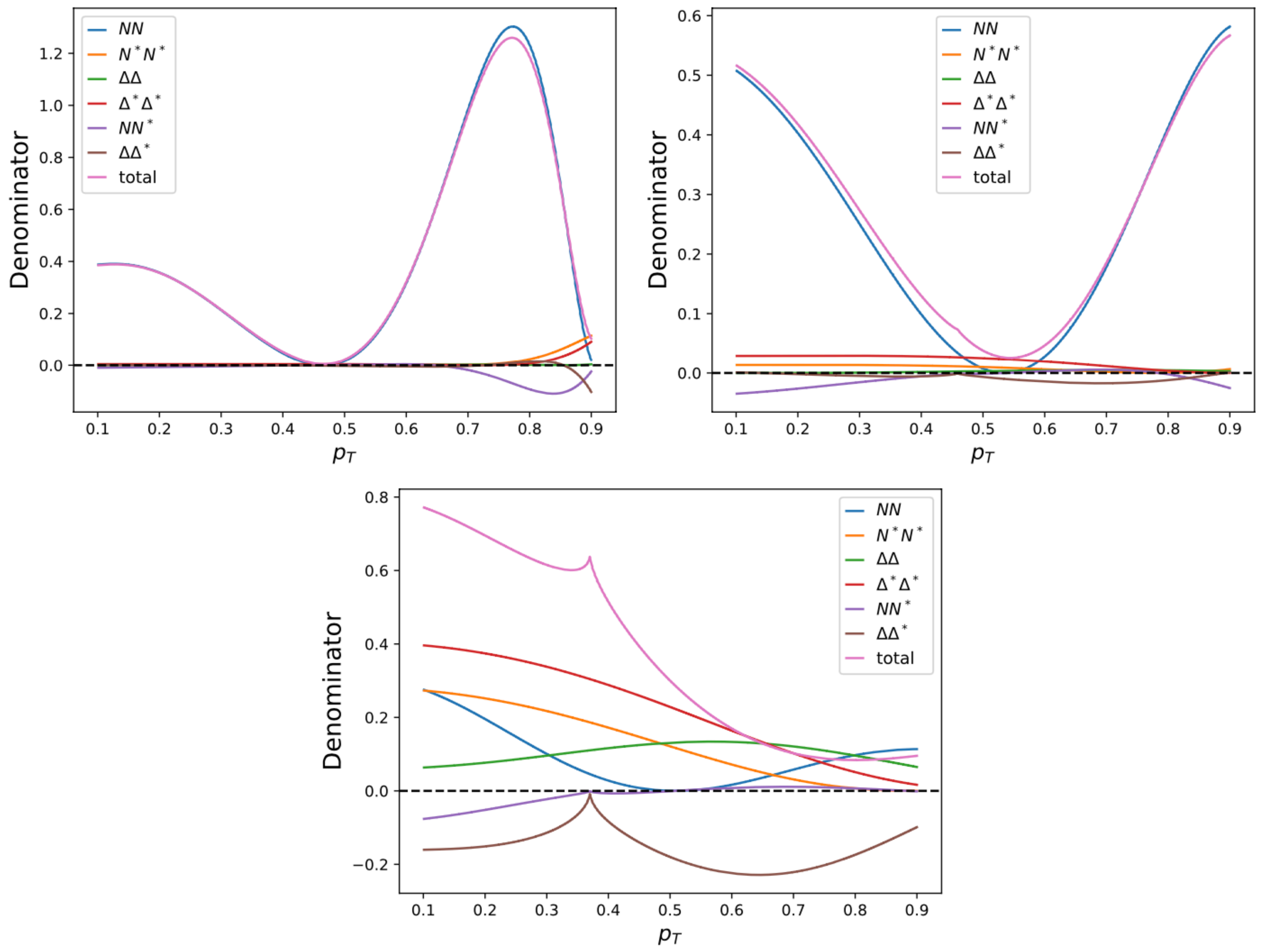


FIG. 8. Denominators when $x_F = 0.3, 0.5, 0.8$.