Diquark role in large-p_T baryon and exotic state production in pp- and dd- collisions at SPD NICA energies

Andrei V. Zelenov, Victor T. Kim
NRC «Kurchatov Institute» - PNPI, Gatchina

SPD first stage physics N10, 06.05.2025

Outline

- Large-p_T processes in QCD
- Diquark role in large-p_T hadron and symmetric hadron pairs production
- Diquark role in large-p_T multi-quark exotic state production
- Ulysses MC generator with Diquarks
- Summary

Introduction

The QCD parton model demonstrates a good description of mesons over a wide range of energies. But it can't describe an anomalously large yield of protons along with its strong scaling violation.

Taking into account the two-quark correlation (Diquark) allows us to describe the anomalous proton yield.

"Dynamical role of diquarks in processes of inclusive proton production" Laperashvili (Sov. J. Nucl. Phys. 35(3), 431-434,1982);

"Large-p_T protons from constituent diquark scattering" Ekelin et al (Physics Letters B, 149(6), 509-513, 1984);

"DIQUARKS AND DYNAMICS OF LARGE-P⊥ BARYON PRODUCTION" Kim (Modern Physics Letters A 03:09, 909-916,1988)

Being a higher-twist, the Diquark contribution can describe the strong scaling violation in deep inelastic scattering of nucleons observed in p/π^+ ratio.

"DIQUARKS AND DYNAMICS OF LARGE-P⊥ BARYON PRODUCTION" Kim (Modern Physics Letters A 03:09, 909-916,1988)

Types of multiparton dynamics

Multiparton processes are characterized by the participation of more than one parton in the hard subprocess for each colliding hadron. These subprocesses can be classified into three categories:

"Possible studies in the first stage of the NICA collider..." V.V. Abramov et al. (Phys. Part. Nucl. 2021)

a. when the subprocess consists of a single parton scattering event where more than one parton participates from one of the colliding hadrons, such as a two-quark correlation (higher twist) – diquark;

b. when the subprocess involves multiple simultaneous parallel parton scatterings;

c. when the subprocess involves at least several nucleons from one side, forming a multiquark state (fluctuon, few-nucleon short-range correlation) [*not considered in this work*].

Large-p_T processes in QCD

A key approach for studying parton dynamics at high energies is the investigation of hard processes, which are characterized by significant momentum transfer.

Colinear factorization: $$\frac{E\, d^3\sigma}{d^3p} = \int_{x_{min}}^{1} dx \int_{y_{min}}^{1} dy\; G_a^A(x, Q^2)\; G_b^B(y, Q^2)\; \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{ab} \frac{D_C^c(z, Q^2)}{\pi z}$$

According to the factorization theorem the inclusive cross-section for a hard process can be expressed as a convolution of contributions from interactions occurring at both large and small distance scales.

Large-p_T processes in QCD

Colinear factorization: $$\frac{E\, d^3\sigma}{d^3p} = \int_{x_{min}}^{1} dx \int_{y_{min}}^{1} dy\; G_a^A(x,Q^2)\; G_b^B(y,Q^2) \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{ab} \frac{D_C^c(z,Q^2)}{\pi z}$$

Small distances: $\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{ab}$ — can be described at the parton level using perturbative QCD

Large distances: $G_a^A(x,Q^2),\; G_b^B(y,Q^2),\; D_C^c(z,Q^2)$ — non-perturbative contribution

*Currently, it is not possible to compute these functions directly within the frame-work of non-perturbative QCD

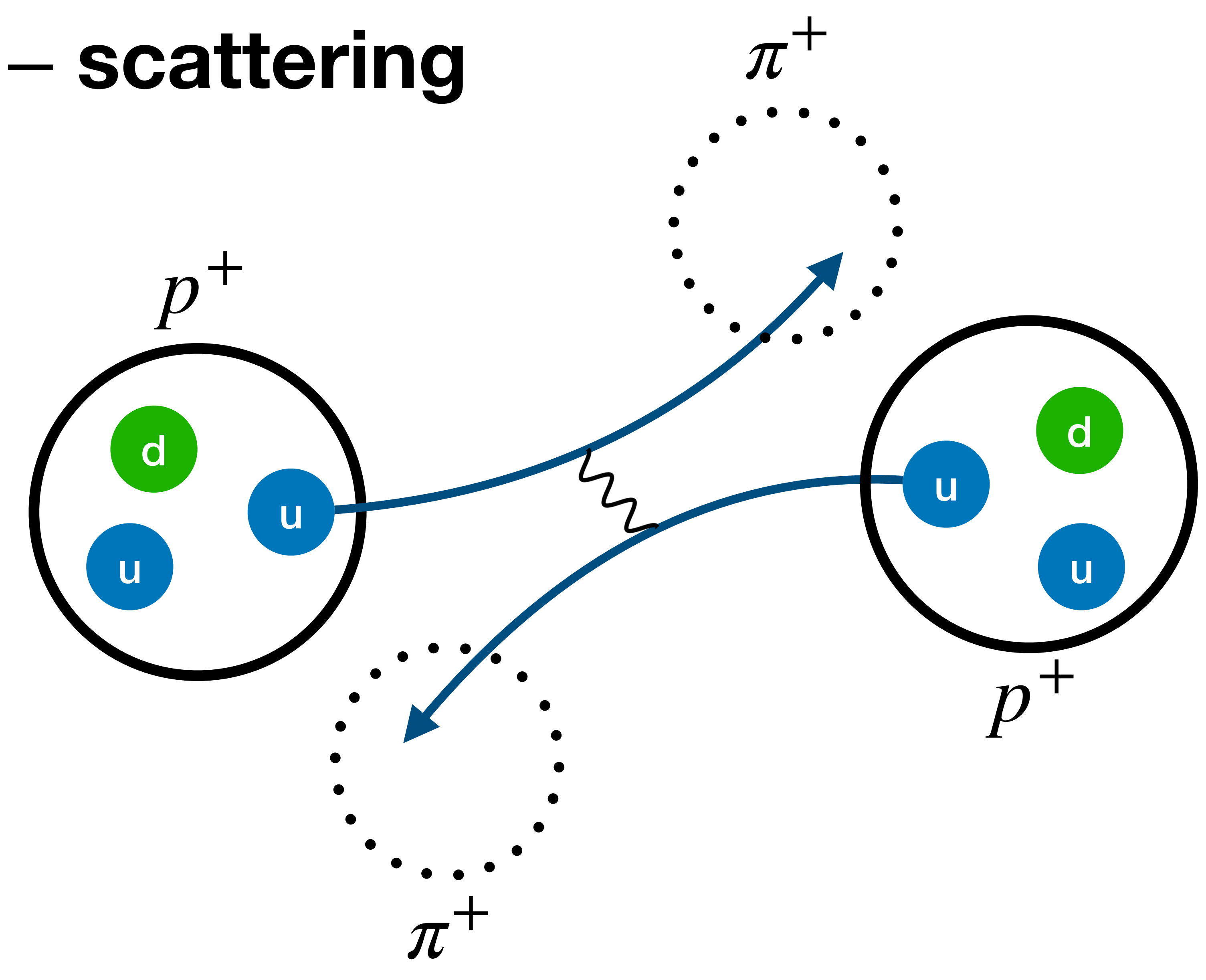
Colinear means $G_a^A(x,Q^2) = \int d^2k_T\, \tilde{G}_a^A(x,Q^2,k_T)$

Large-p_T processes in QCD

Colinear factorization: $$\frac{E\, d^3\sigma}{d^3p} = \int_{x_{min}}^{1} dx \int_{y_{min}}^{1} dy\ G_a^A(x, Q^2)\ G_b^B(y, Q^2)\ \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{ab}\ \frac{D_C^c(z, Q^2)}{\pi z}$$

Nowadays, the inclusive production of hadrons with large transverse momenta p_T is well-understood in scenarios where a hard subprocess involves one parton from each of the colliding hadrons.

qq – **scattering**



Parton-parton scattering is the main source of mesons with large p_T in pp collisions

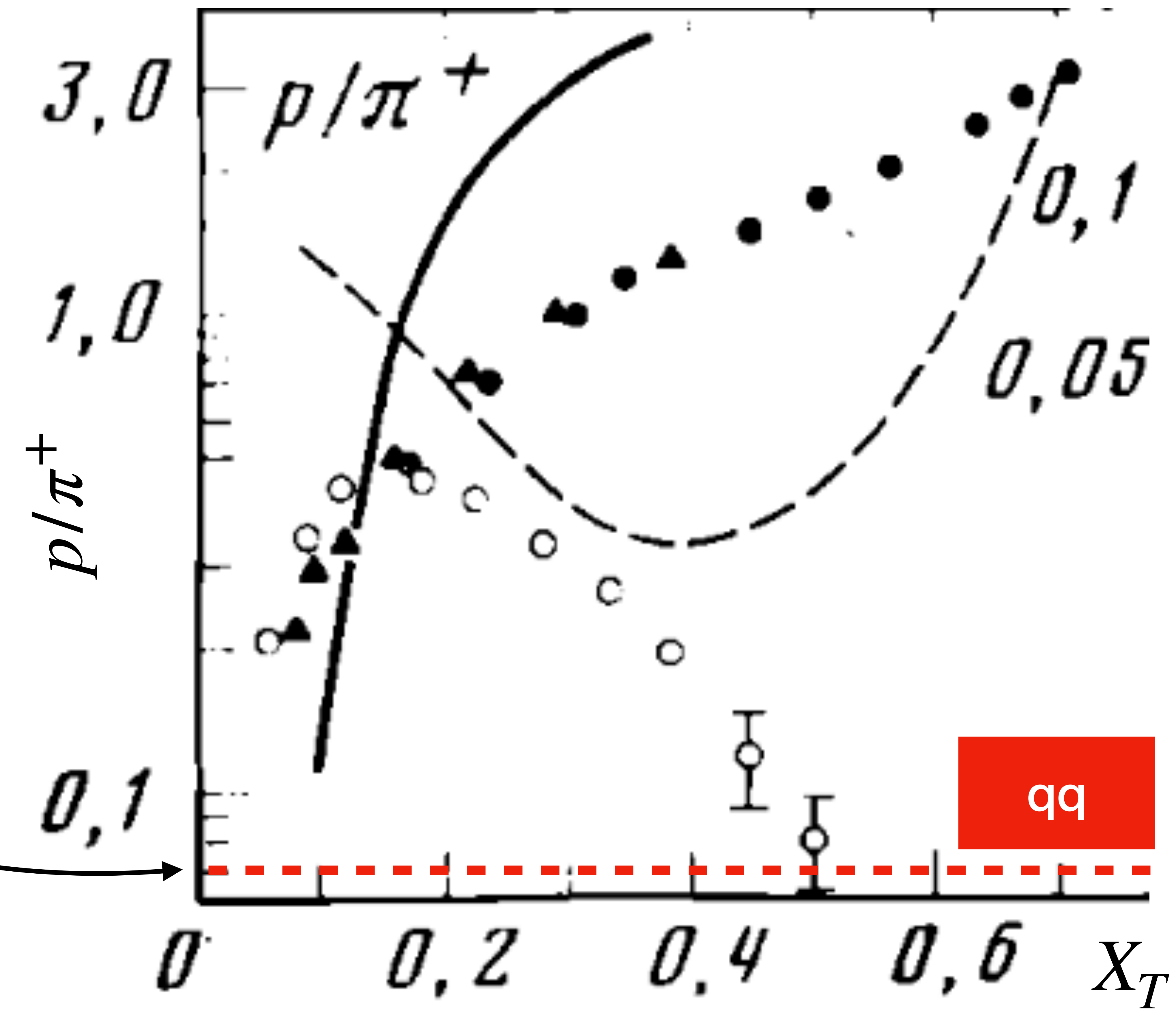
Large-p_T: strong scaling violation for protons

$$x_T = p_T/p_T^{max} = 2p_T/\sqrt{s}$$

$$\frac{E\, d^3\sigma}{d^3p} \sim \frac{c(x_T, \sqrt{s})}{p_T^4}$$

Weak dependence of $\sqrt{S}$ → scaling for pions

(▲, ●) **IHEP**, Serpukhov ,$\sqrt{s} = 11.5$ GeV
FODS, V.V. Abramov et al. (1985)
(O) **FNAL**, Batavia, $\sqrt{s} = 23.4$ GeV
D.Antreasyan et al. (1979)



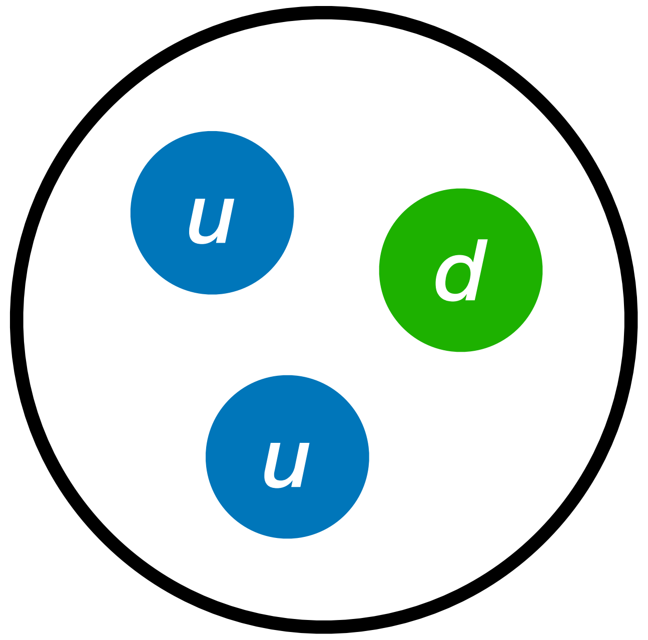
Parton-parton interactions fail to describe the anomalous yield of protons with large-p_T in pp collisions.

STRONG SCALING VIOLATION

Two-quark correlations: Diquarks

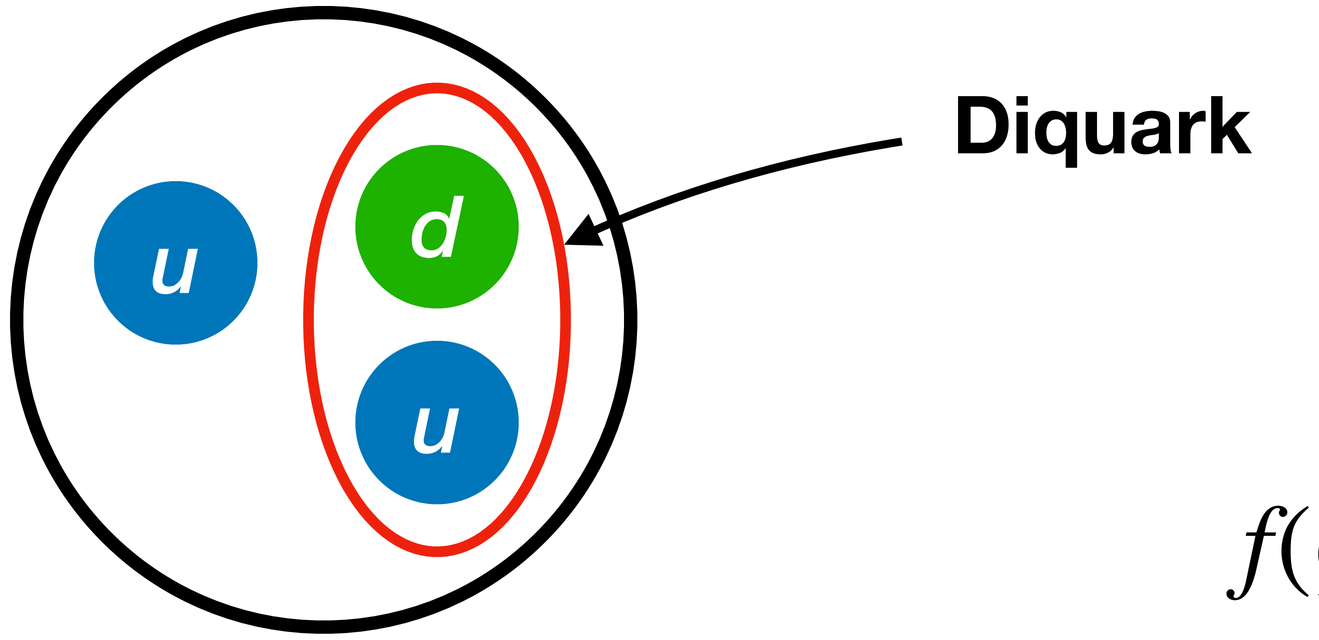
Diquark is a two-quark correlation in baryons.

$p\{uud\}$



Quark model of baryon

$p\{u(ud)\}$



Model of baryon with Diquark

Diquark is not a point-like object!

Higher-twists in deep inelastic scattering

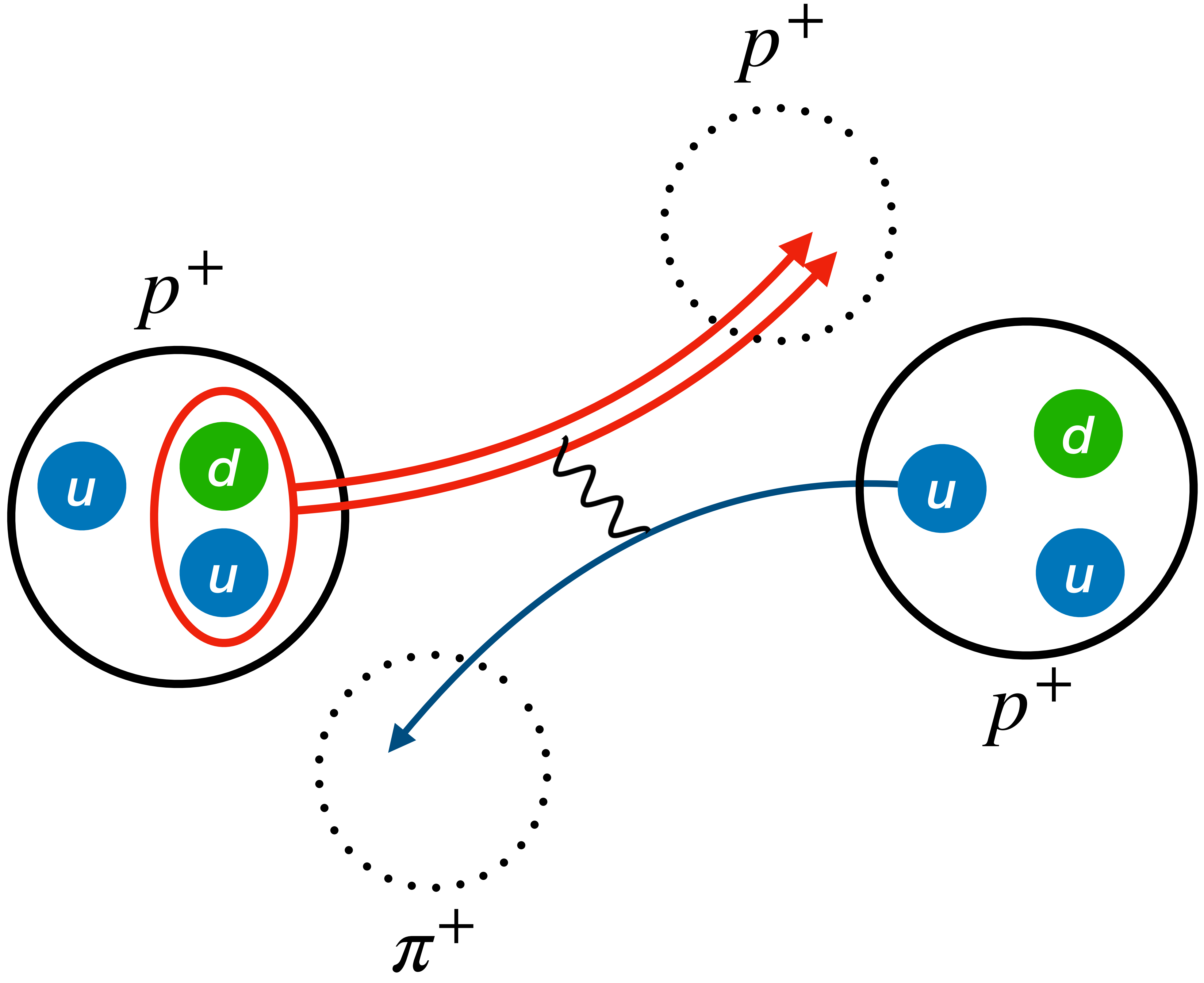
$$f(Q^2) = \frac{1}{1 + \frac{Q^2}{M^2}}$$ – **Diquark form-factor**

M^2 – **Diquark size parameter**

Baryon (proton) is in quark-Diquark state with probability W

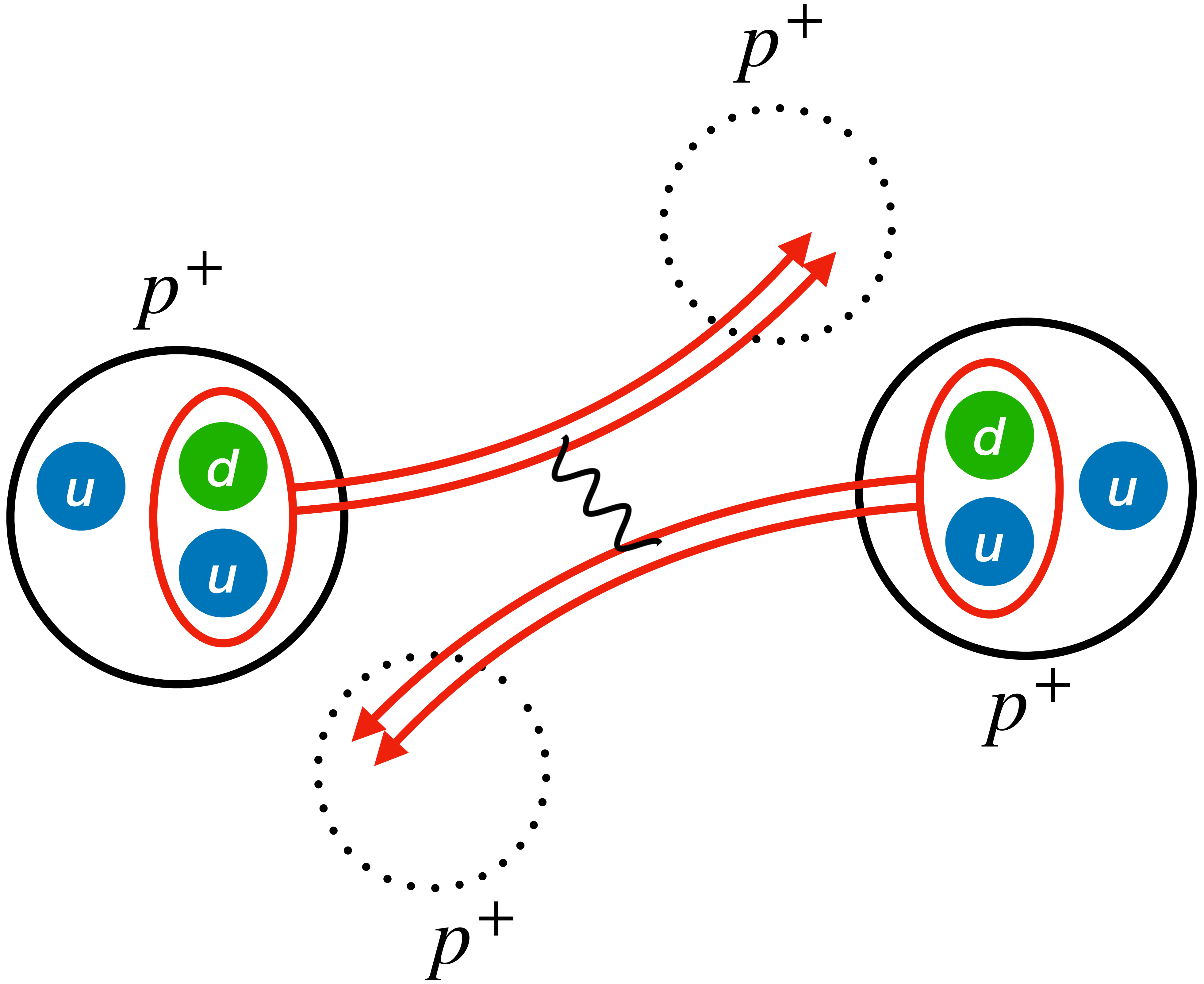
Two-quark correlations: Diquarks

(ud) Diquark scatters on u quark



$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qD} = \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qq} \cdot f^2(Q^2)$$

(ud) Diquark scatters on (ud) Diquark

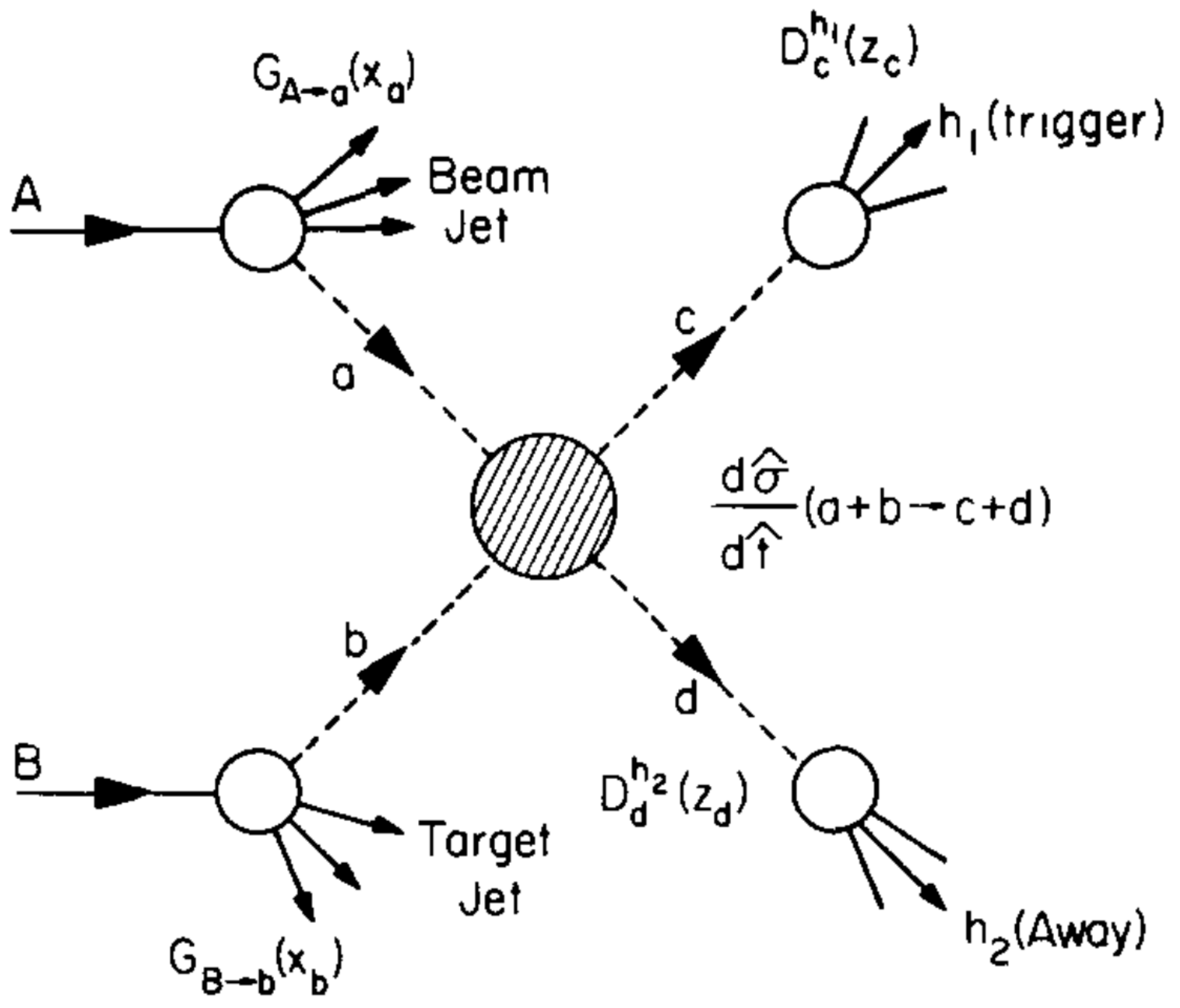


$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{DD} = \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qq} \cdot f^4(Q^2)$$

The main source of baryons with large p_T
in pp collisions at NICA energies

Feynman approach: collinear factorization improved by k_T dependence

R.P. Feynman, R.D. Field and G.C. Fox
Phys. Rev. **D** 18 (1978) 3320



$$Ed^3\sigma/d^3p(s,t,u;A+B\to h+X) =$$

$$\int d^2k_{T_a}\int d^2k_{T_b}\int d^2k_{T_c}\int dx_a\int dx_b\, \boxed{G_{A\to a}(x_a,k_{T_a},Q^2)\ G_{B\to b}(x_b,k_{T_b},Q^2)}$$

$$\times\ \boxed{D_c^h(z_c,k_{T_c},Q^2)}\frac{1}{z_c}\frac{1}{\pi}\boxed{\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s},\hat{t},\hat{u};q_a+q_b\to qc+q_d)}$$

Parton Distribution Function

Fragmentation Function

Subprocess cross section

$$F(x,y,k_T) = \hat{F}(x,y)\cdot\tilde{F}(k_T)$$

$$\tilde{F}(k_T) = J(k_T,Q^2) \sim e^{k_T^2/\sigma^2(Q^2)}\text{, where } \sigma^2 = \langle k_T^2\rangle$$

Feynman approach: collinear factorization improved by k_T dependence

Diquark impact: $Ed^3\sigma/d^3p(s,t,u;A+B\to h+X) =$

$$\int d^2k_{T_a}\int d^2k_{T_b}\int d^2k_{T_c}\int dx_a\int dx_b\ \boxed{G_{A\to a}(x_a,k_{T_a},Q^2)\ G_{B\to b}(x_b,k_{T_b},Q^2)}$$

$$\boxed{D_c^h(z_c,k_{T_c},Q^2)}\frac{1}{z_c}\frac{1}{\pi}\boxed{\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s},\hat{t},\hat{u};q_a+q_b\to qc+q_d)}$$

Fragmentation Function:

Diquark FF

Subprocess cross section:

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qD},\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{\bar{q}D},\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{gD},\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{DD}$$

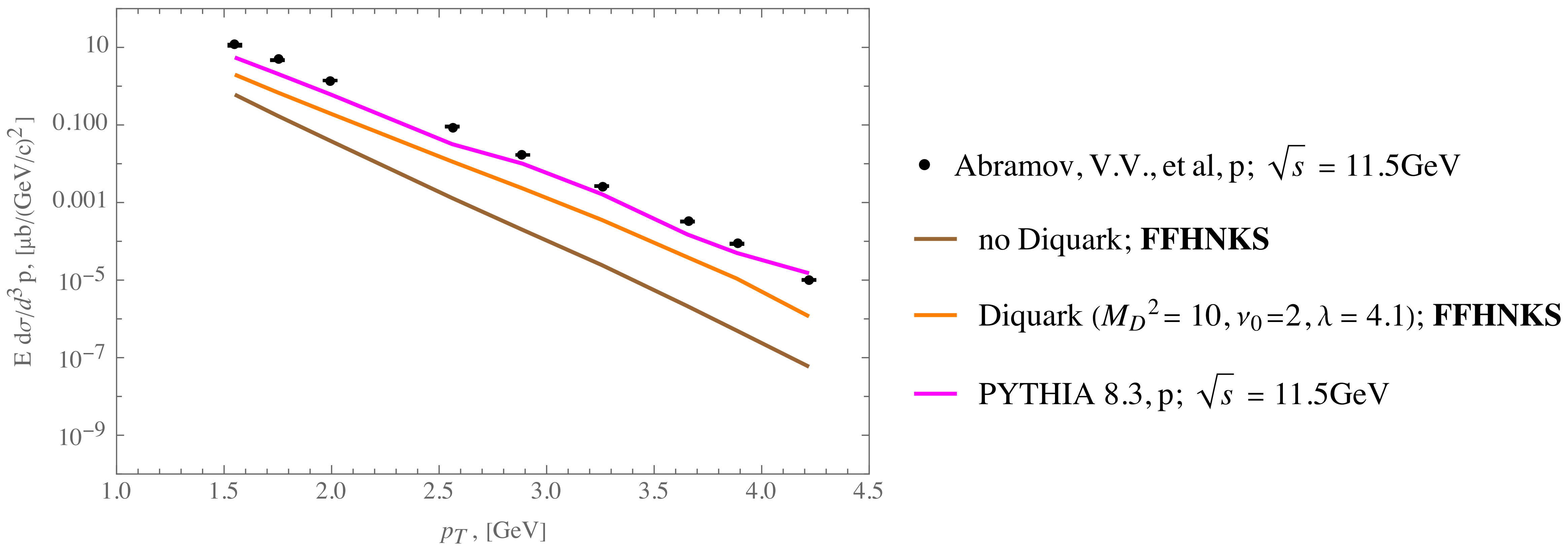
Parton Distribution Function:

Diquark PDF

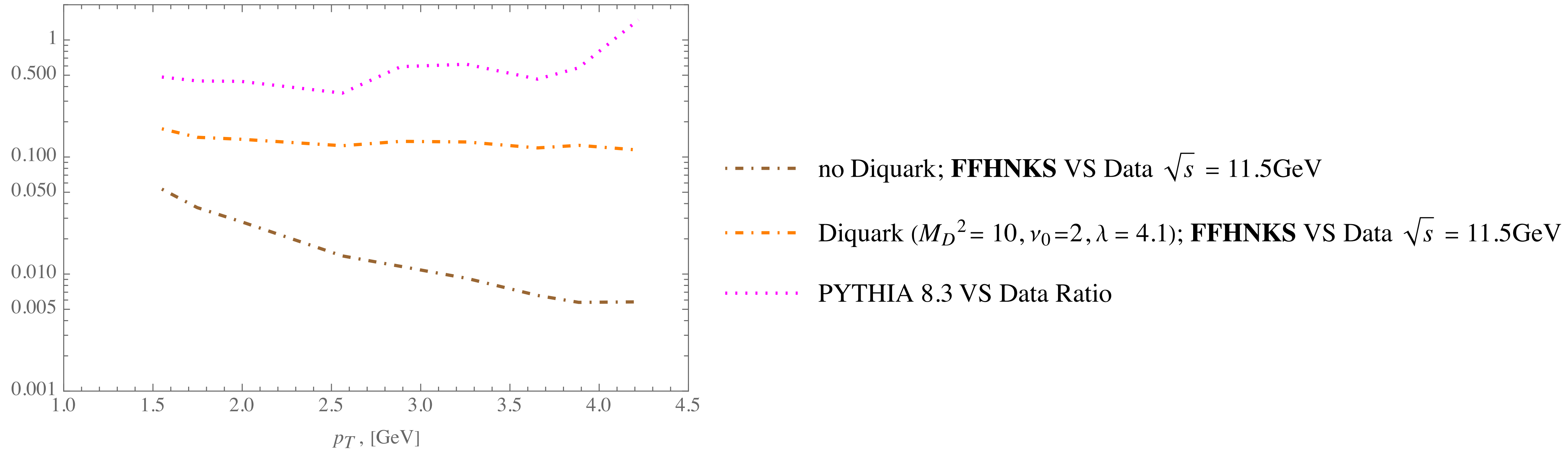
Large-p_T p production

“Diquarks for Large- Baryon Production at High-Energy Collisions” V.T. Kim, A.V. Zelenov (Phys. Part. Nucl. Lett., 2025, Vol. 22, No. 1, pp. 213–218)

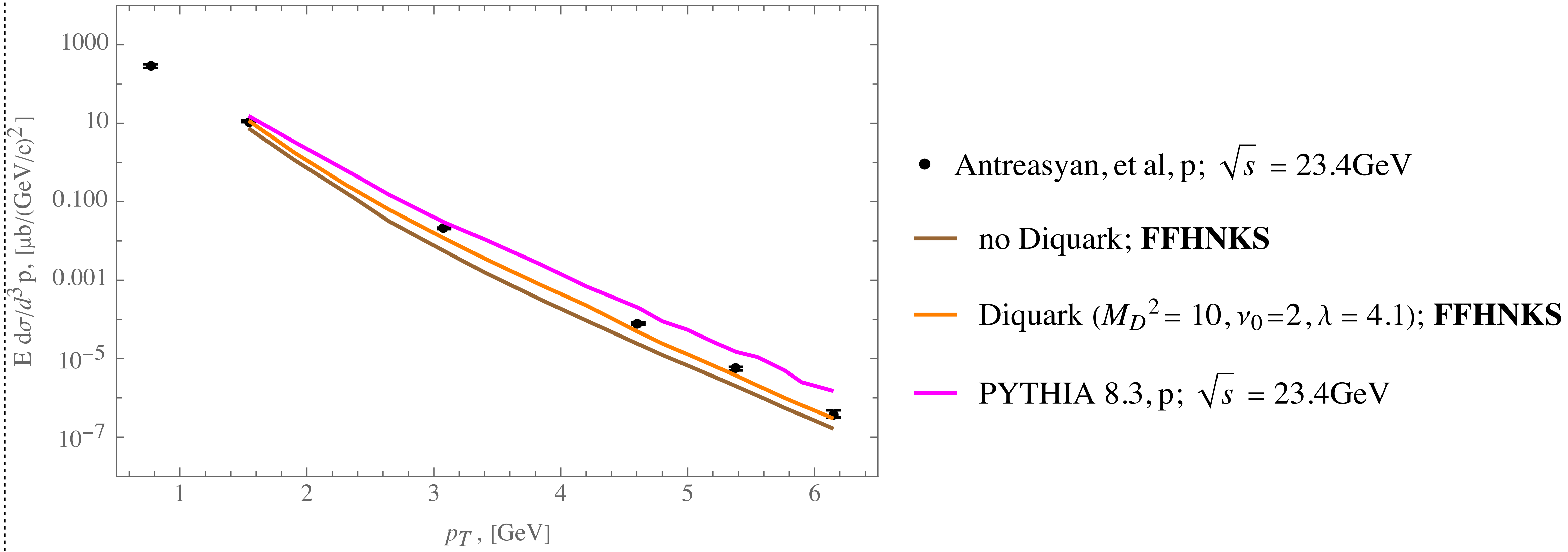
$\sqrt{s} = 11.5$ GeV



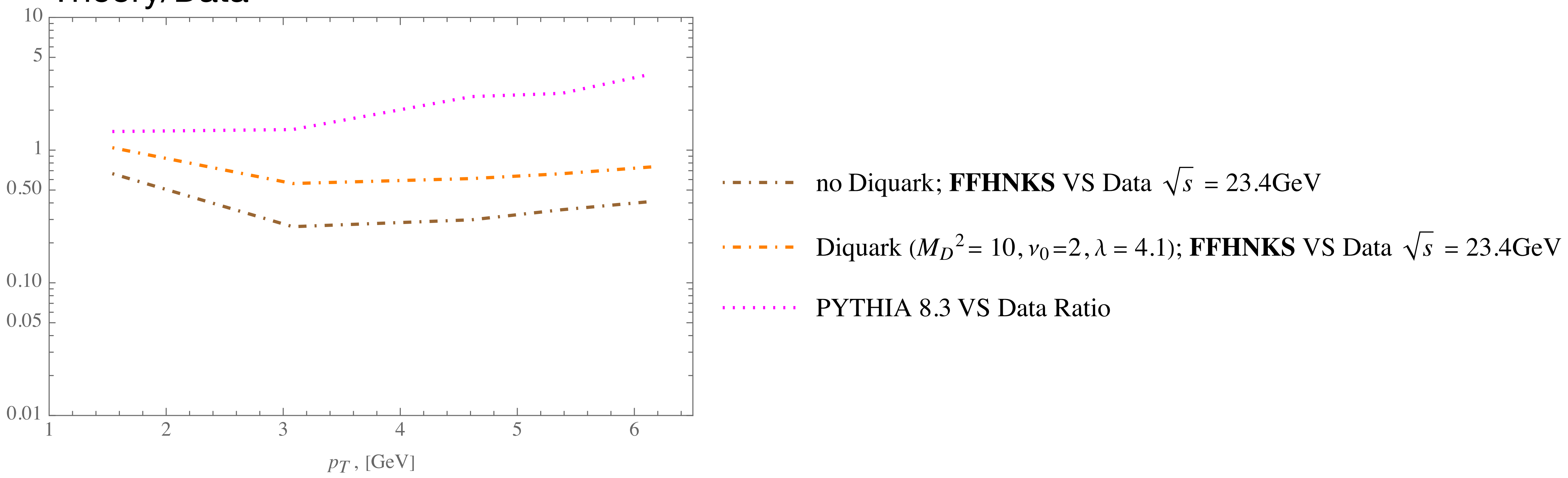
Theory/Data



$\sqrt{s} = 23.4$ GeV



Theory/Data

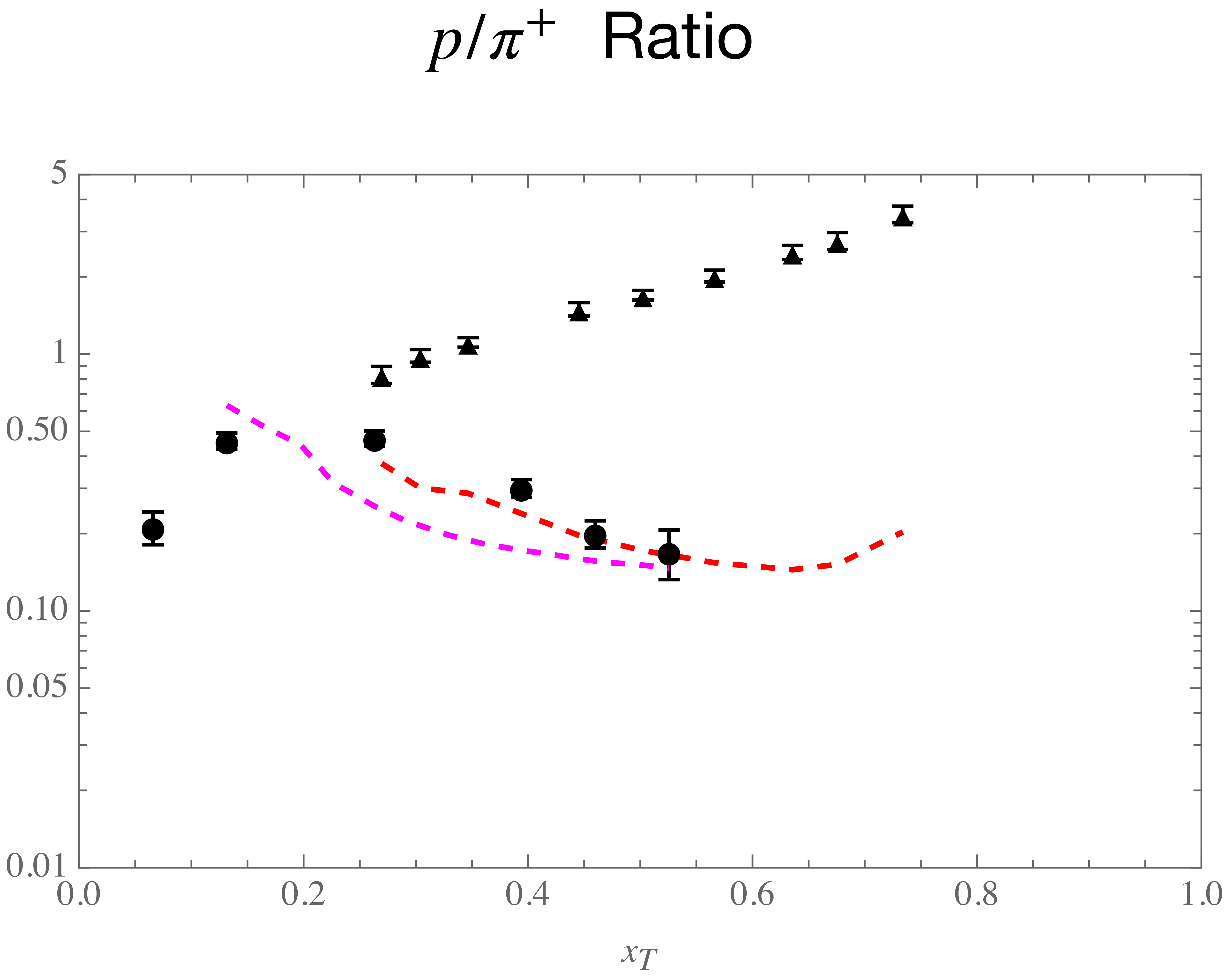


IHEP, Protvino, $\sqrt{s} = 11.5$ GeV
FODS, V.V. Abramov et al. (1985)

collinear factorization improved by k_T dependence was used for calculation R.P. Feynman, R.D. Field and G.C. Fox Phys. Rev. D 18 (1978) 3320

FNAL, Batavia, $\sqrt{s} = 23.4$ GeV
D.Antreasyan et al. (1979)

Scaling violation: p/π^+ ratio without Diquark



p/π^+ Ratio with $\theta_{\text{cms}} = 90^o$ in pp-collisions

(▲) **IHEP**, Protvino for $\sqrt{s} = 11.5$ GeV
FODS, V.V. Abramov et al. (1985)

(●) **FNAL**, Batavia for $\sqrt{s} = 23.4$ GeV
D.Antreasyan et al. (1979)

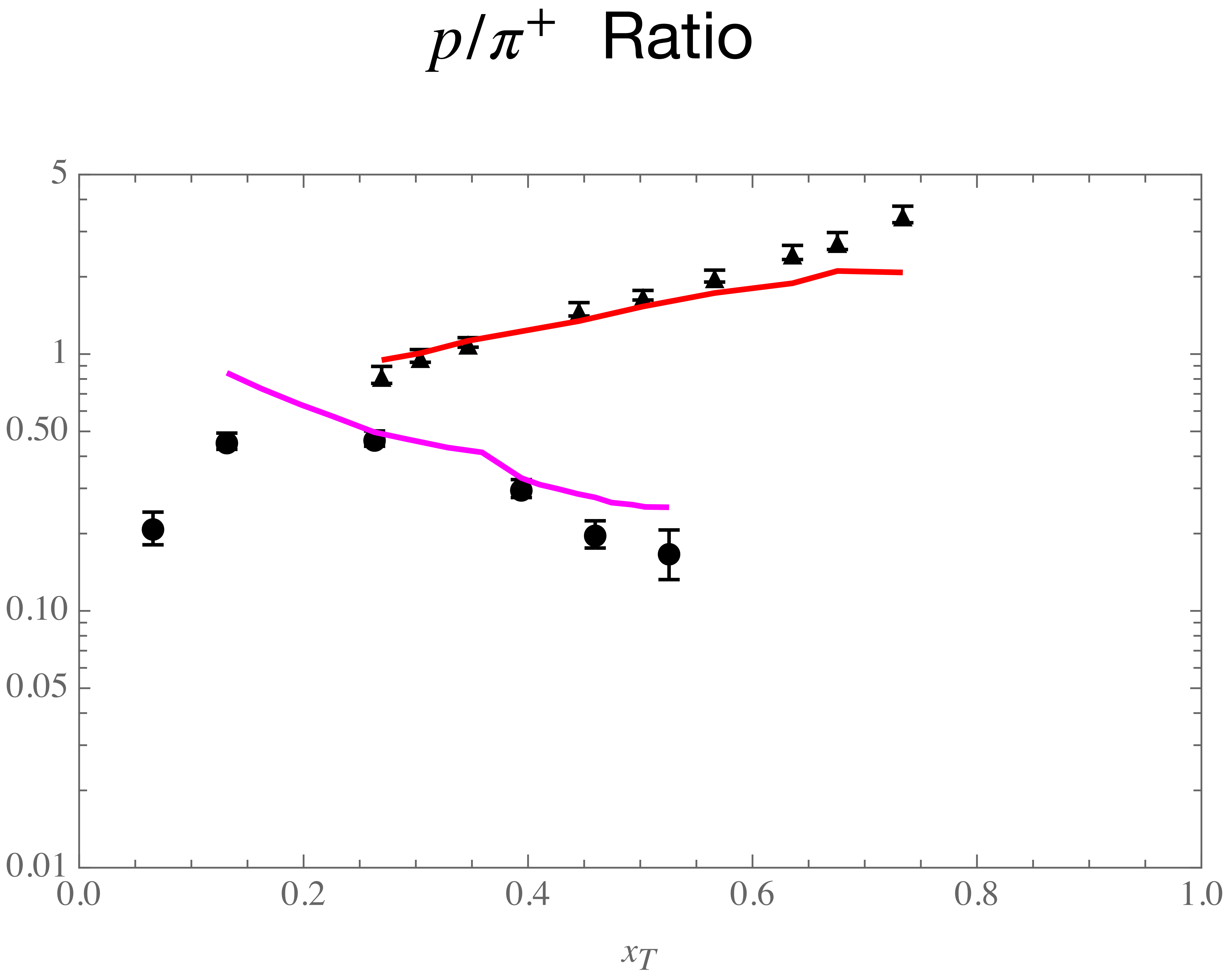
Calculation results**:**

Red dashed line $- \sqrt{s} = 11.5$ GeV,

Magenta dashed line $- \sqrt{s} = 23.4$ GeV

$x_T = 2p_T/\sqrt{s}$

Scaling violation: p/π^+ ratio with Diquark



p/π^+ Ratio with $\theta_{\text{cms}} = 90^o$ in pp-collisions

(▲) **IHEP**, Protvino for $\sqrt{s} = 11.5$ GeV
FODS, V.V. Abramov et al. (1985)

(●) **FNAL**, Batavia for $\sqrt{s} = 23.4$ GeV
D.Antreasyan et al. (1979)

Calculation results**:**

Red dashed line $- \sqrt{s} = 11.5$ GeV,

Magenta dashed line $- \sqrt{s} = 23.4$ GeV

$x_T = 2p_T/\sqrt{s}$

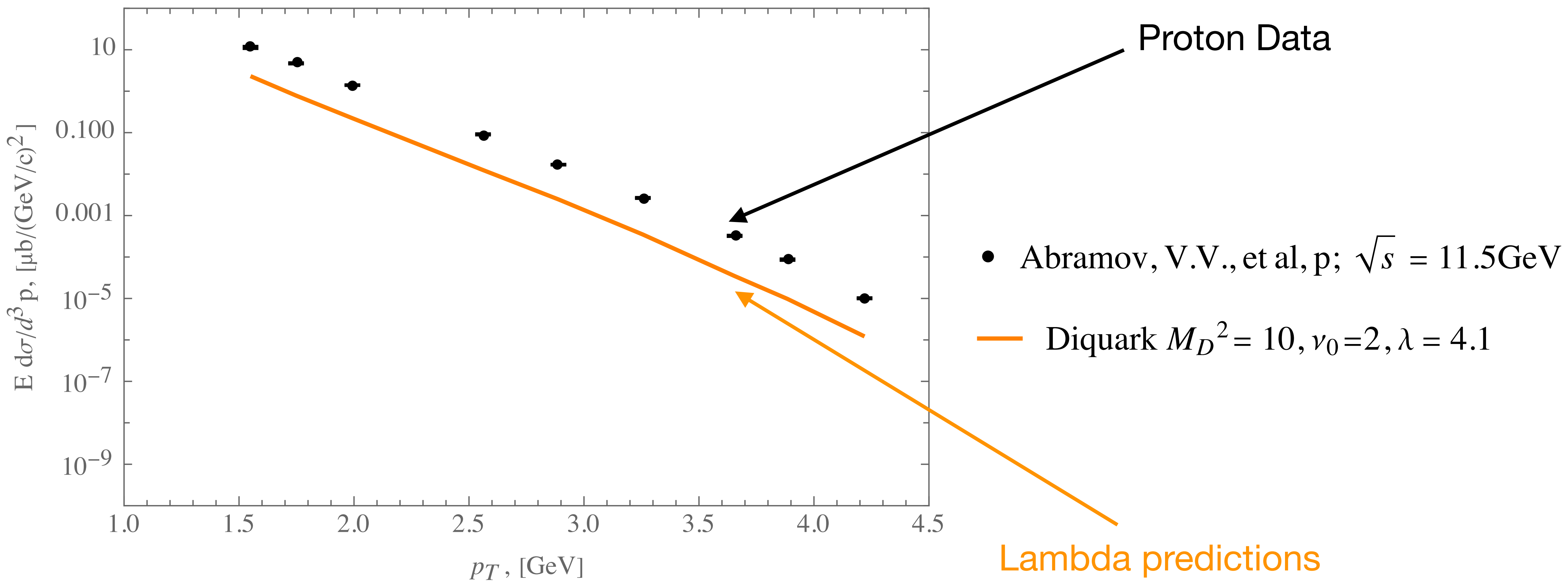
"Diquarks for Large- Baryon Production at High-Energy Collisions" V.T. Kim, A.V. Zelenov (Phys. Part. Nucl. Lett., 2025, Vol. 22, No. 1, pp. 213–218)

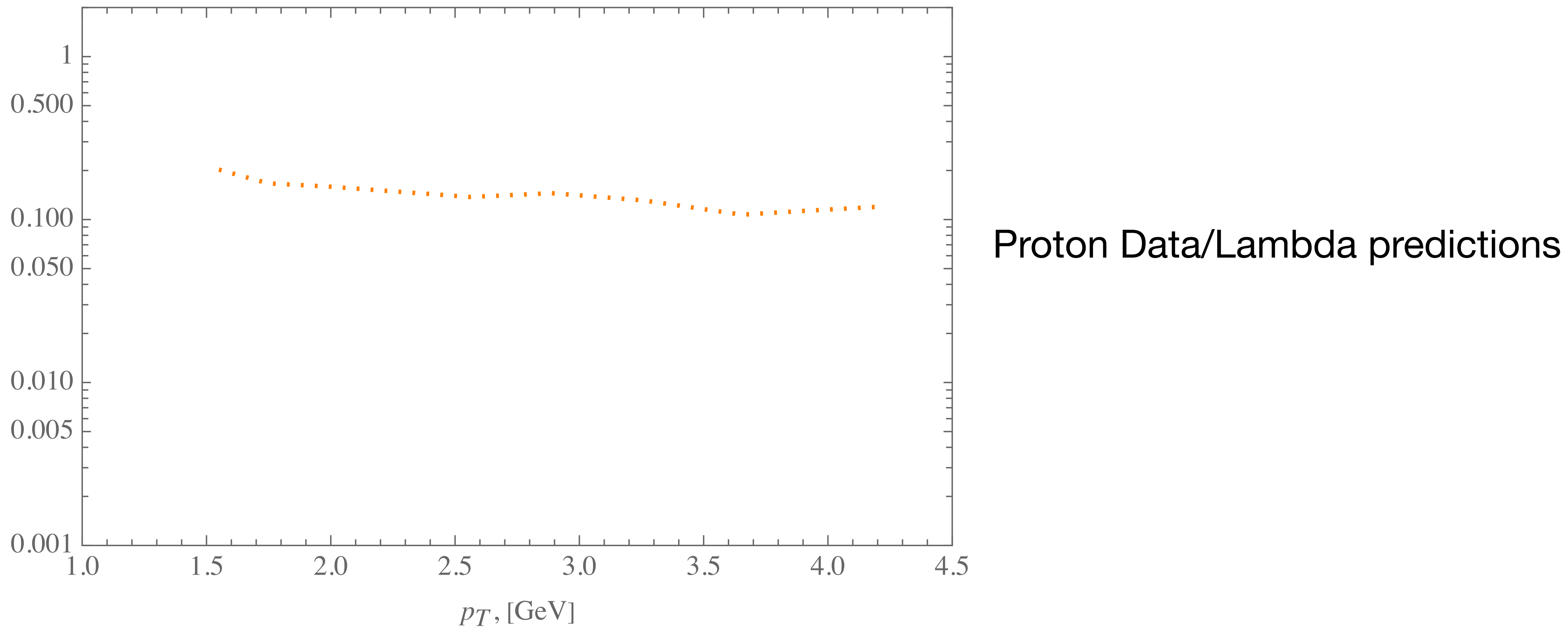
$\sqrt{s} = 8$ GeV : $x_T \sim 0.1 - 0.4 \rightarrow p_T \sim 0.2 - 1.6$ GeV

Large-p_T $\Lambda(uds)$ production

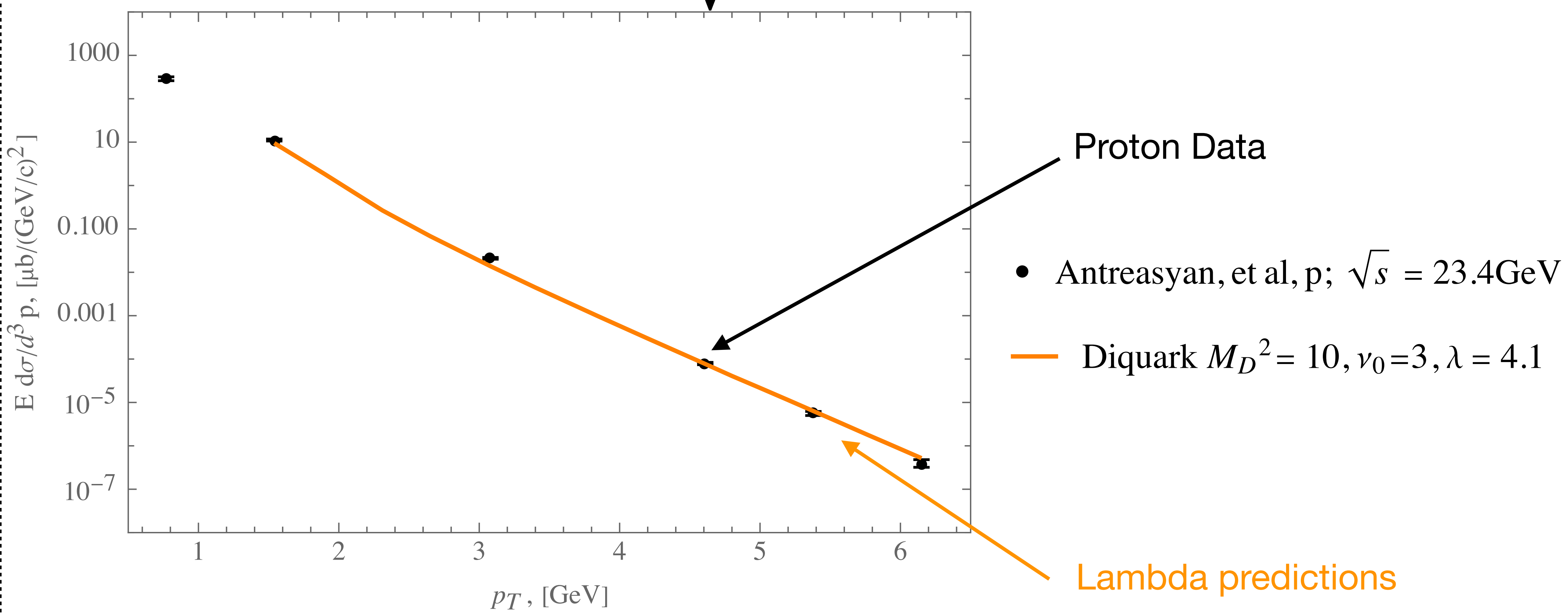
“Diquarks for Large- Baryon Production at High-Energy Collisions” V.T. Kim, A.V. Zelenov (Phys. Part. Nucl. Lett., 2025, Vol. 22, No. 1, pp. 213–218)

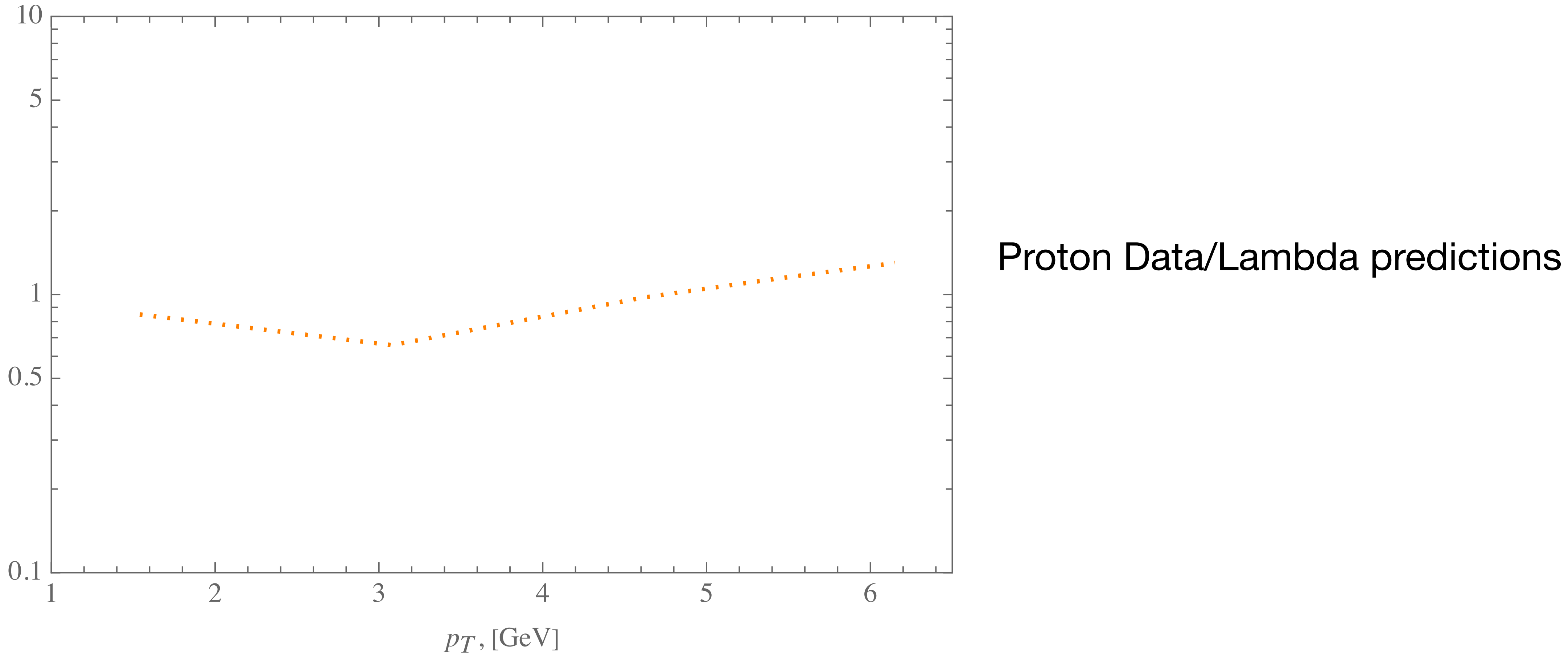
$\sqrt{s} = 11.5$ GeV





$\sqrt{s} = 23.4$ GeV





IHEP, Protvino, $\sqrt{s} = 11.5$ GeV
FODS, V.V. Abramov et al. (1985)

$\Lambda \to p\pi^-$

$L = 10^{31} cm^{-2} s^{-1};\ N = 10000 \quad t = \dfrac{N}{\sigma \cdot L \cdot Br \cdot \text{DetEff}} \simeq 1/2$ month

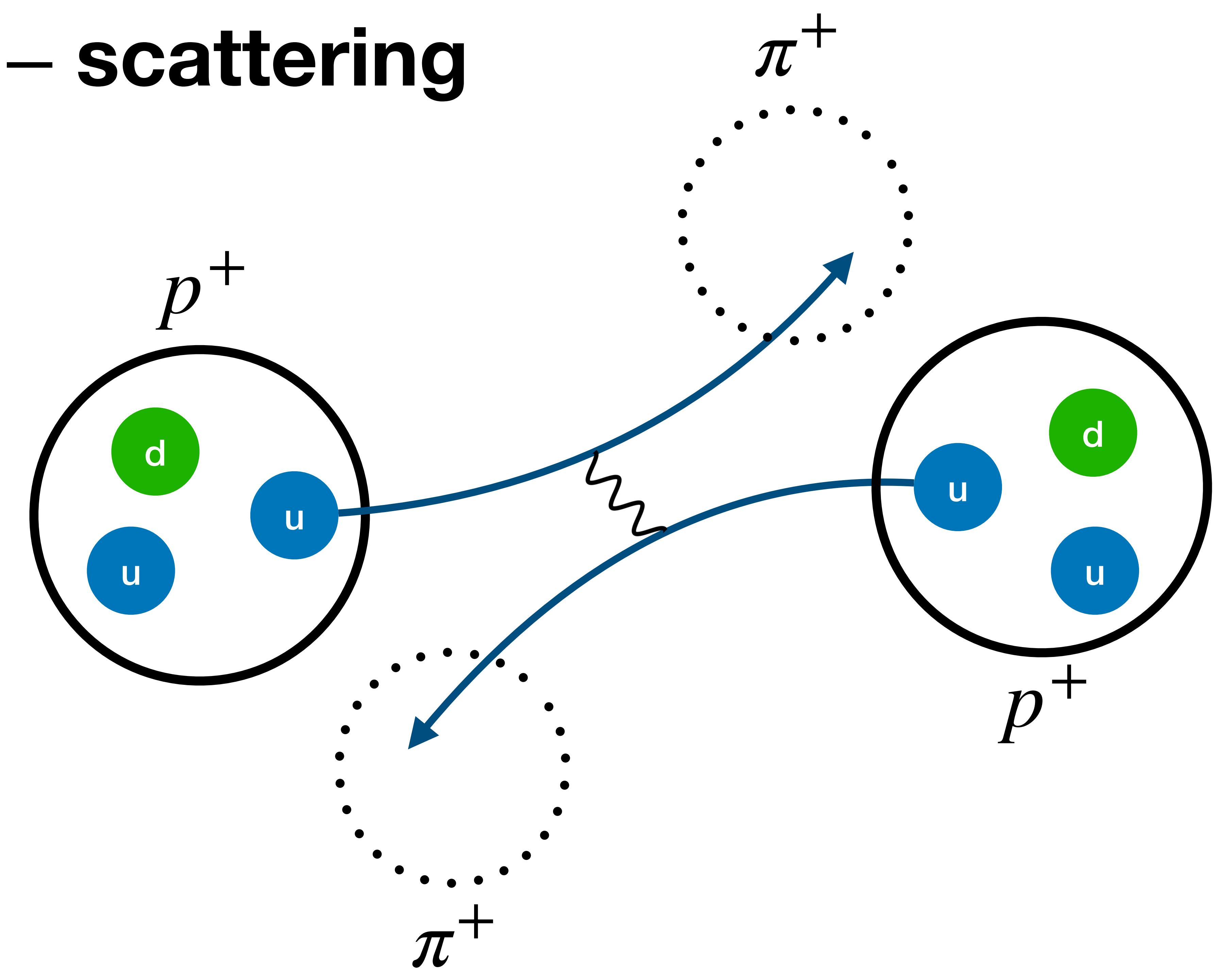
optimal data taking 3 months

FNAL, Batavia, $\sqrt{s} = 23.4$ GeV
D.Antreasyan et al. (1979)

Hadron symmetric pairs production

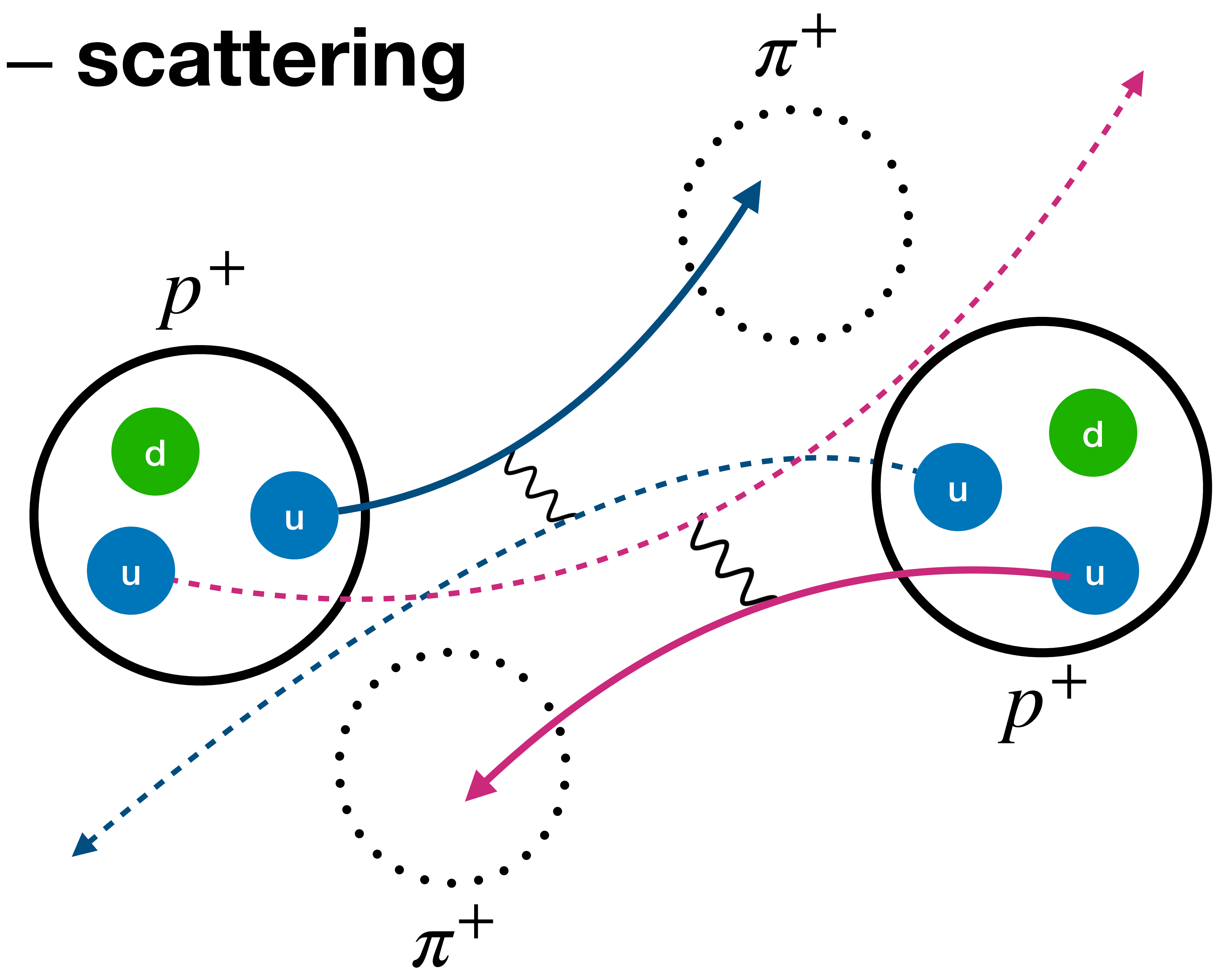
Non MPI

qq – **scattering**



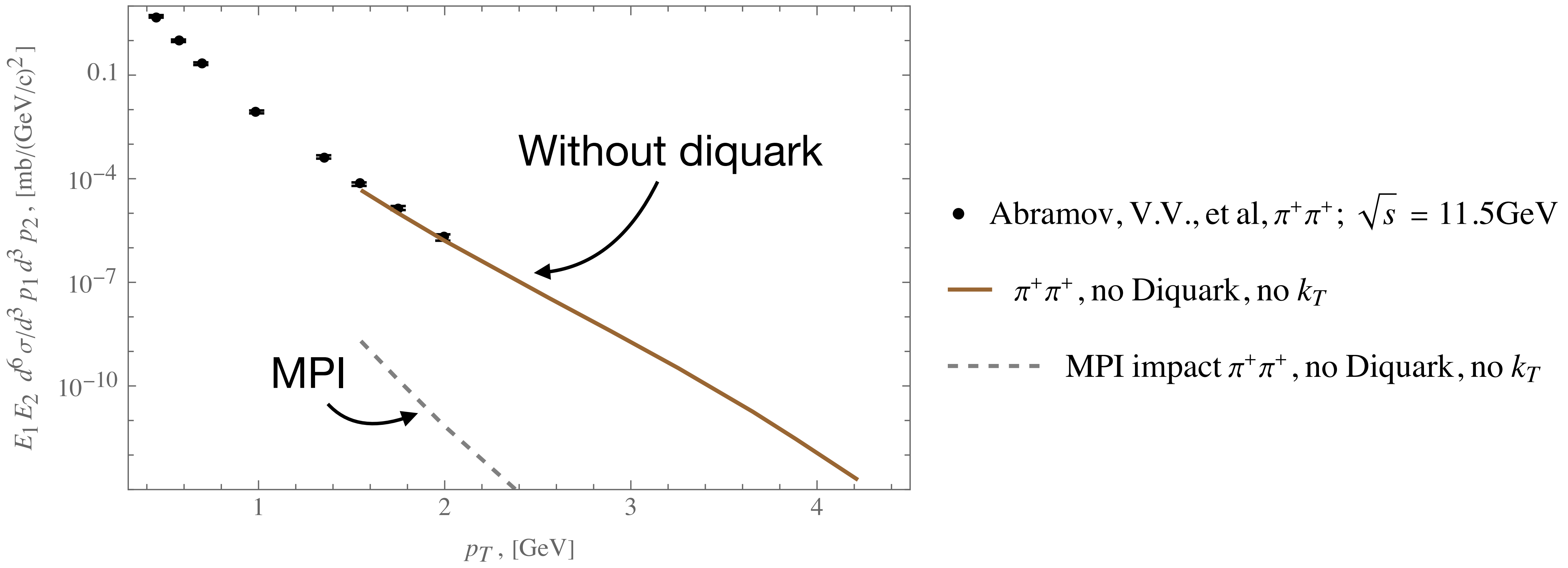
MPI

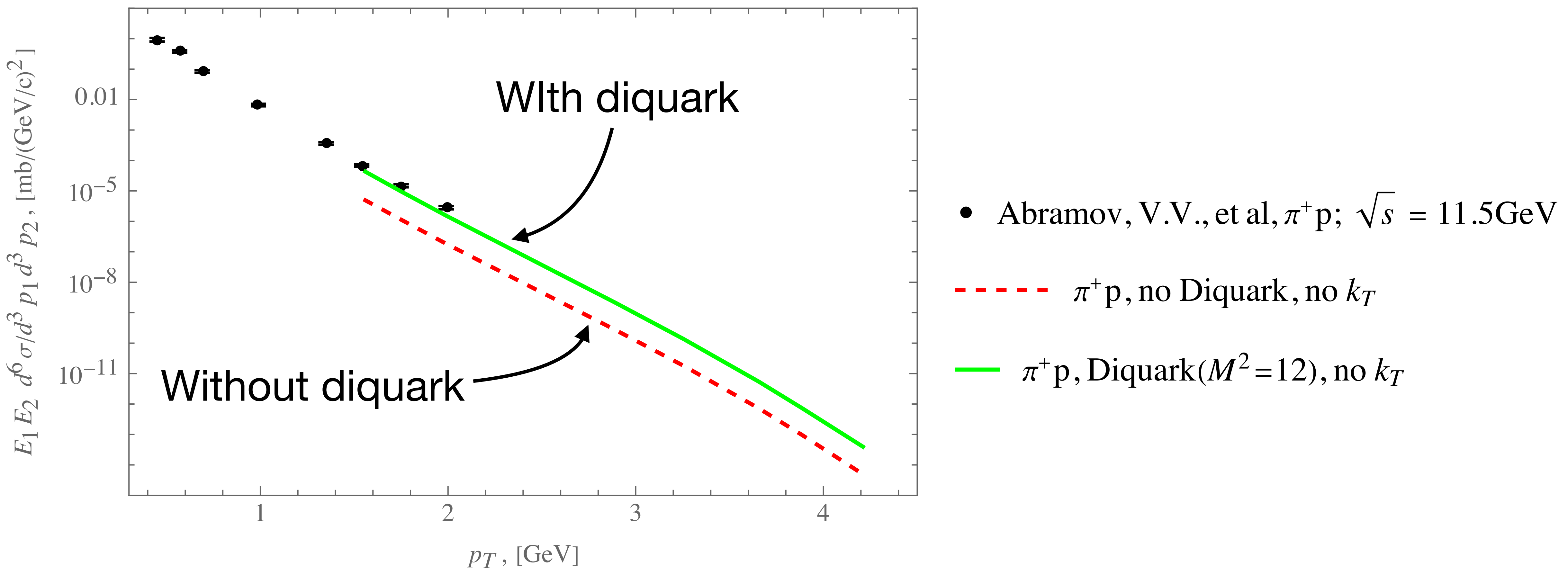
double
qq – **scattering**

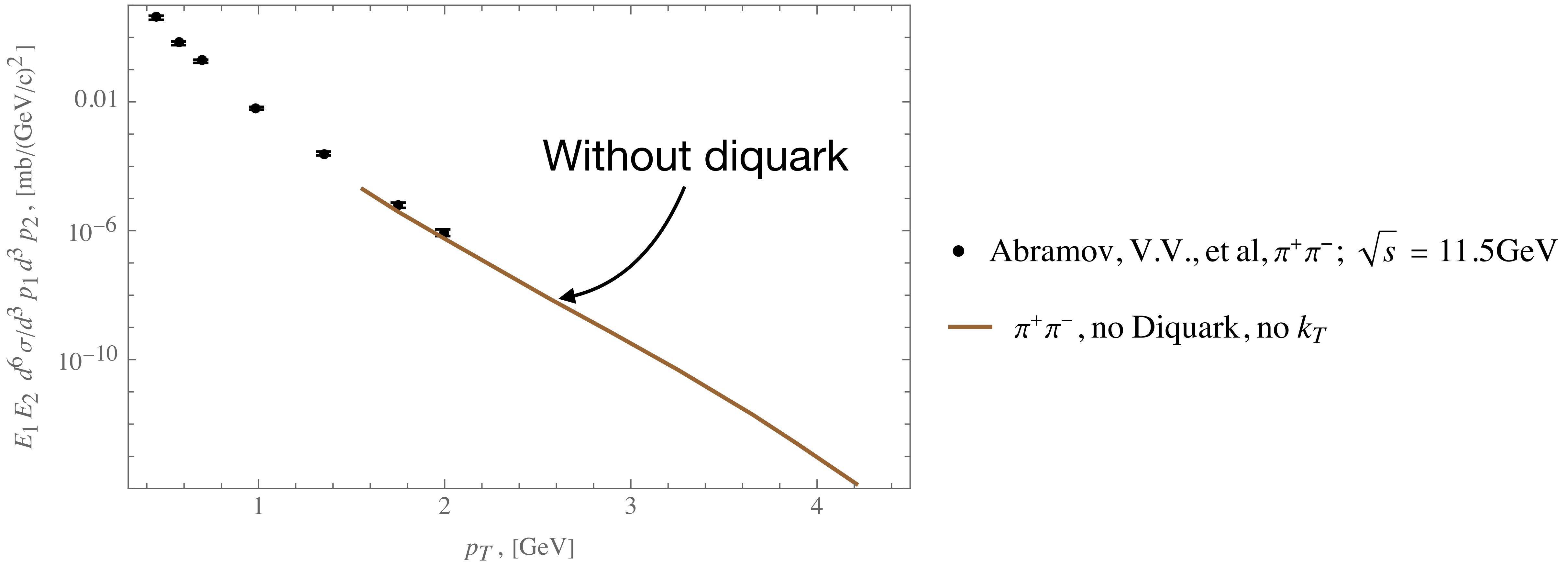


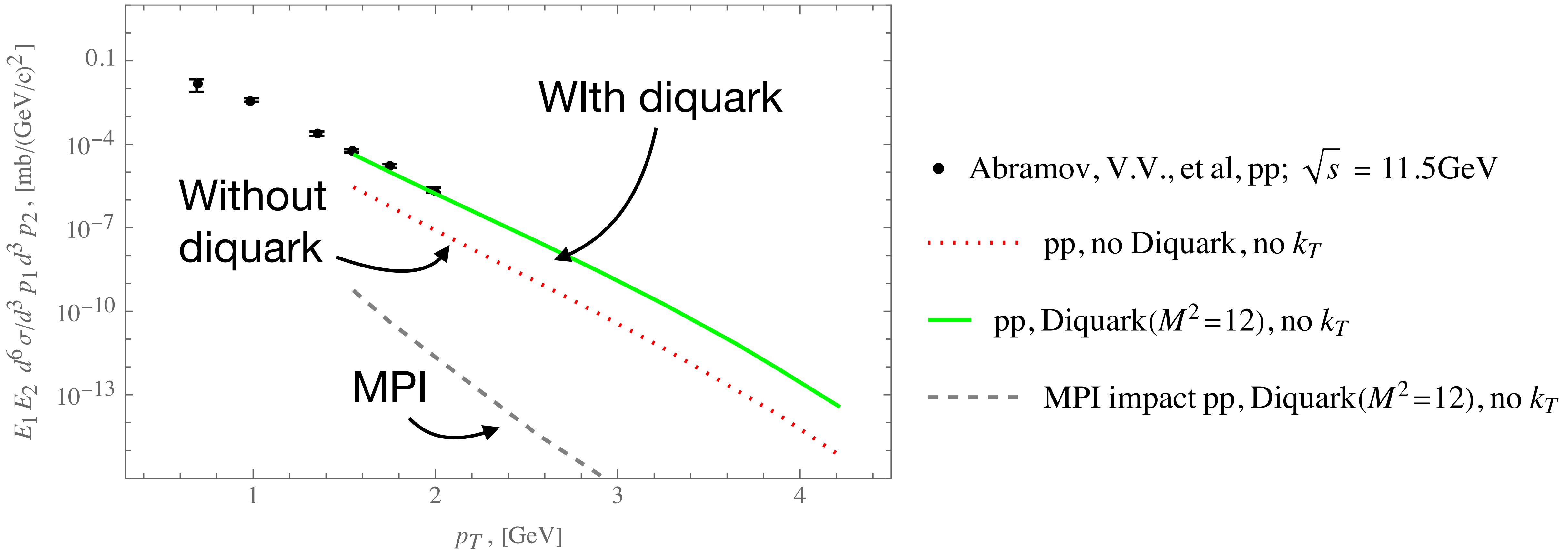
Hadron symmetric pairs production

$$p_{T_1} = p_{T_2}, \Delta\phi = (\phi_2 - \phi_1) = \pi; \theta_1 = \pi/2 \text{ and } \theta_2 = -\pi/2$$









IHEP, Protvino

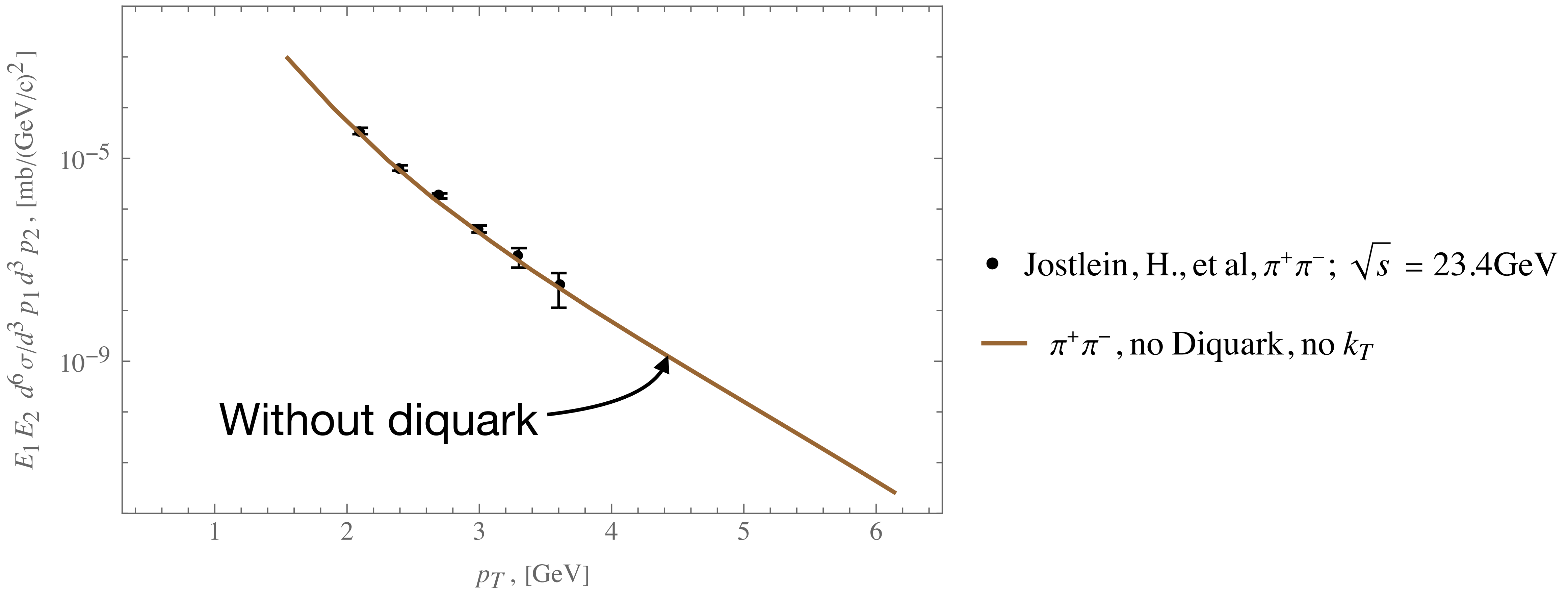
FODS, V.V. Abramov et al. (1985)

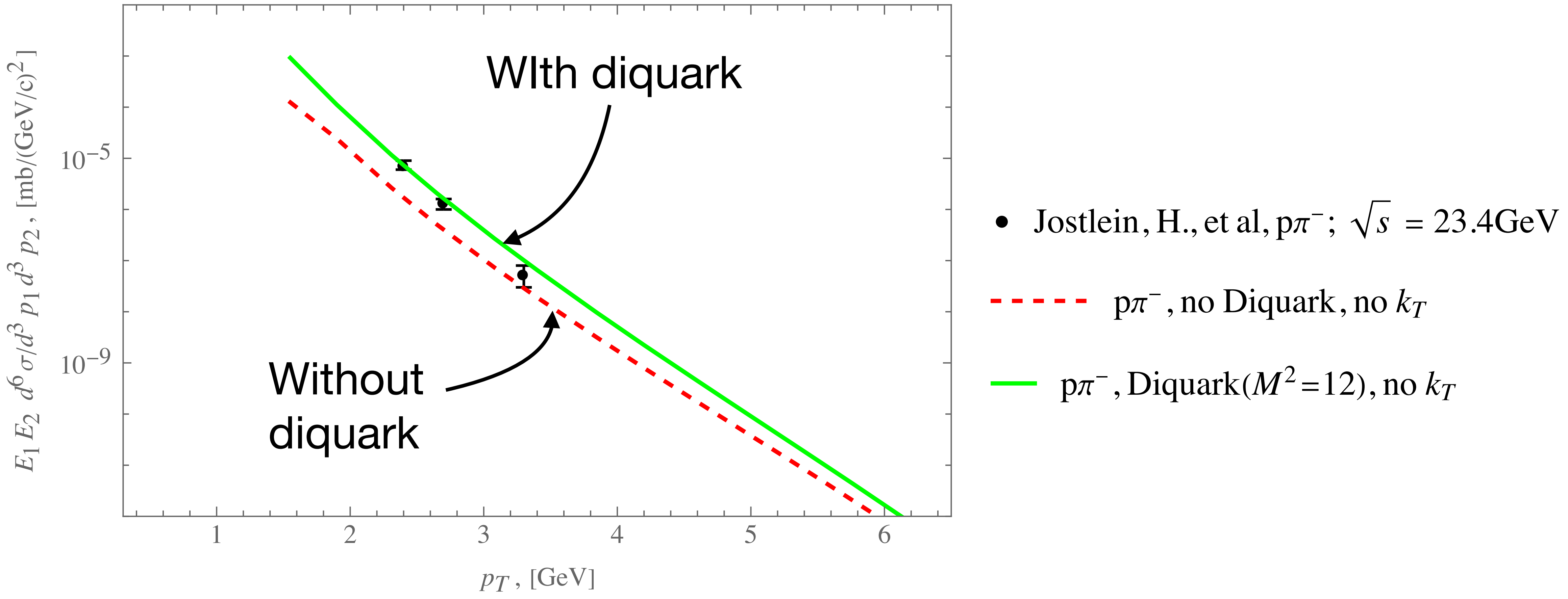
$$\sqrt{s} = 11.5 \text{ GeV}$$

Hadron symmetric pairs production

$$p_{T_1} = p_{T_2}, \Delta\phi = (\phi_2 - \phi_1) = \pi; \theta_1 = \pi/2 \text{ and } \theta_2 = -\pi/2$$

Red line — in standard approach (without diquarks), Green — with diquarks



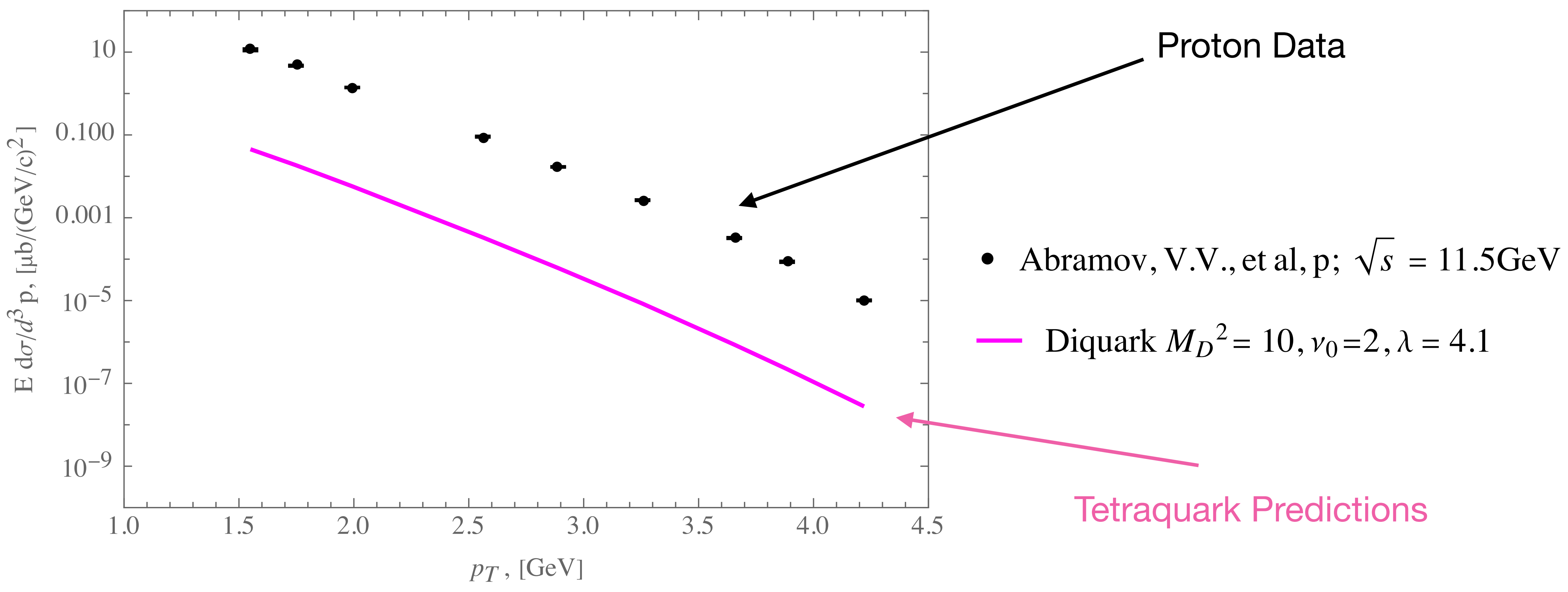


FNAL, Batavia
H.Jostlein et al. (1979)

$$\sqrt{s} = 23.4 \text{ GeV}$$

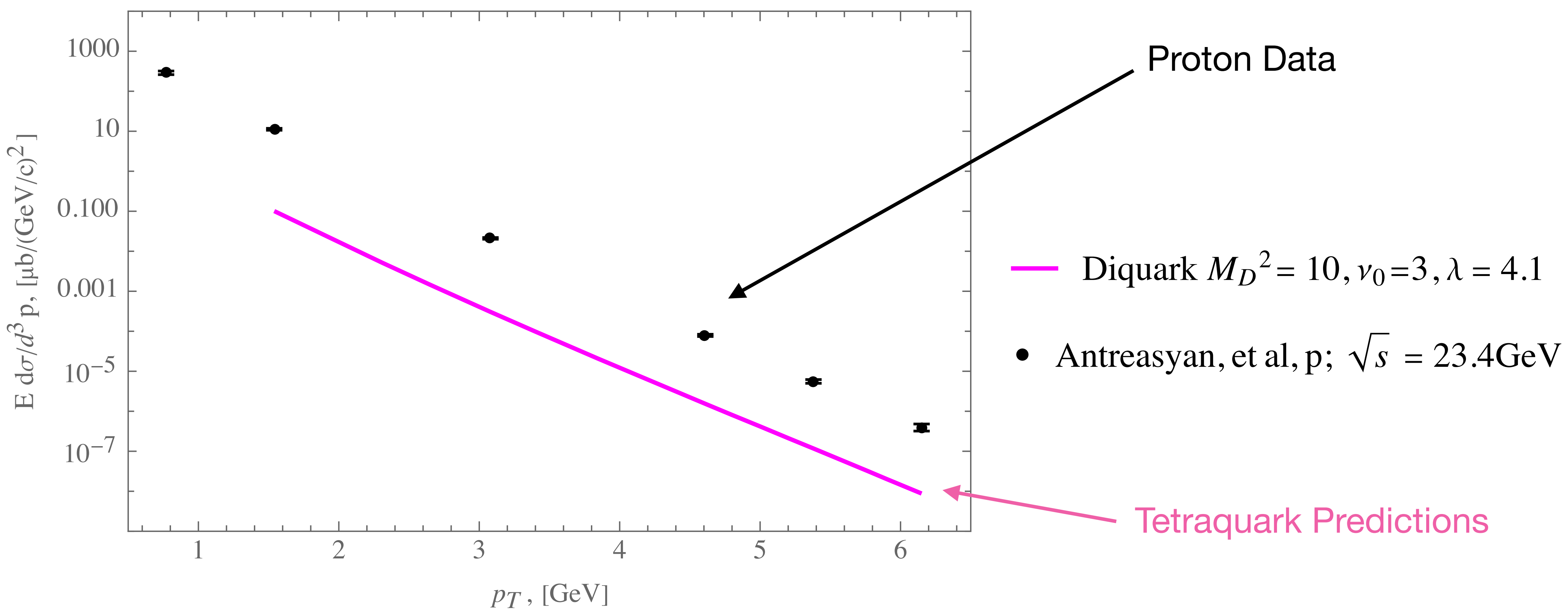
Exotic state production. Tetraquark $(qq\bar{q}\bar{q})$ $a_0(980)$: $\{(ud)\bar{u}\bar{d}\}$

$\sqrt{s} = 11.5$ GeV



IHEP, Protvino, $\sqrt{s} = 11.5$ GeV
FODS, V.V. Abramov et al. (1985)

$\sqrt{s} = 23.4$ GeV



FNAL, Batavia, $\sqrt{s} = 23.4$ GeV
D.Antreasyan et al. (1979)

$$a_0(980) \to K^0\bar{K}^0 \to \pi^+\pi^-\pi^+\pi^- \qquad p_T(\pi) \sim 1/4\ p_T(a_0)$$

$$L = 10^{31} cm^{-2} s^{-1};\ N = 1000 \qquad t = \frac{N}{\sigma \cdot L \cdot Br \cdot \text{DetEff}} \simeq 1 \text{ month}$$

optimal data taking 5 months

"Diquarks for Large- Baryon Production at High-Energy Collisions" V.T. Kim, A.V. Zelenov (Phys. Part. Nucl. Lett., 2025, Vol. 22, No. 1, pp. 213–218)

Assuming that Tetraquark consists at least 1 Diquark

R.L. Jaffe, Phys. Rev. D 15, 267 (1977);
R.L. Jaffe, Phys. Rev. D 15, 281 (1977);
R.L. Jaffe, Phys. Rep. 409, 1 (2005)

ULYSSES MC event generator

✓ Done:

- Implementation of scalar (ud) Diquark in hard hadronic processes:
  - Diquark structure function
  - Evolution of diquark structure function

✦ In Progress:

- Multiparton interactions with Diquarks
- Implementation of vector (uu) Diquark in hard hadronic processes
- Diquark parameters tuning for ULYSSES

Summary

- Two-quark correlations (Diquarks) can describe the strong scaling violation in large-p_T proton production in hard nucleon collisions at **SPD** energies.

- The **SPD** at **NICA** collider provides a unique opportunity to improve understanding of Diquark role for large-p_T baryon production in pp-collisions.

- The **SPD** at **NICA** collider provides a unique opportunity to study possible production of exotic multi quark states (tetra) in light quark sector

- The role of multiparton dynamics in the production of hadrons with large-p_T momenta and exotic hadronic states in high-energy pp collisions has been investigated. "Diquarks for Large-p_T Baryon Production at High-Energy pp Collisions" V.T. Kim, A.V. Zelenov (Phys. Part. Nucl. Lett., 2025, Vol. 22, No. 1, pp. 213–218)

- Exotic multiquark hadron state production is included to the physic program of **SPD** at **NICA**: "Possible studies in the first stage of the NICA collider..." V.V. Abramov et al. (Phys. Part. Nucl. 2021)