Diquark role in production of baryons and exotic hadrons for the SPD NICA energies

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Outline

- Large-p_T processes in QCD
- Diquark role in large-p_T hadron production
- Diquark role in large-p_T multi-quark exotic state production
- Ulysses
- Summary

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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. Laperashvili (1982), Ekelin et al (1984), Kim (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. Kim (1988)

Large-p_T processes in QCD

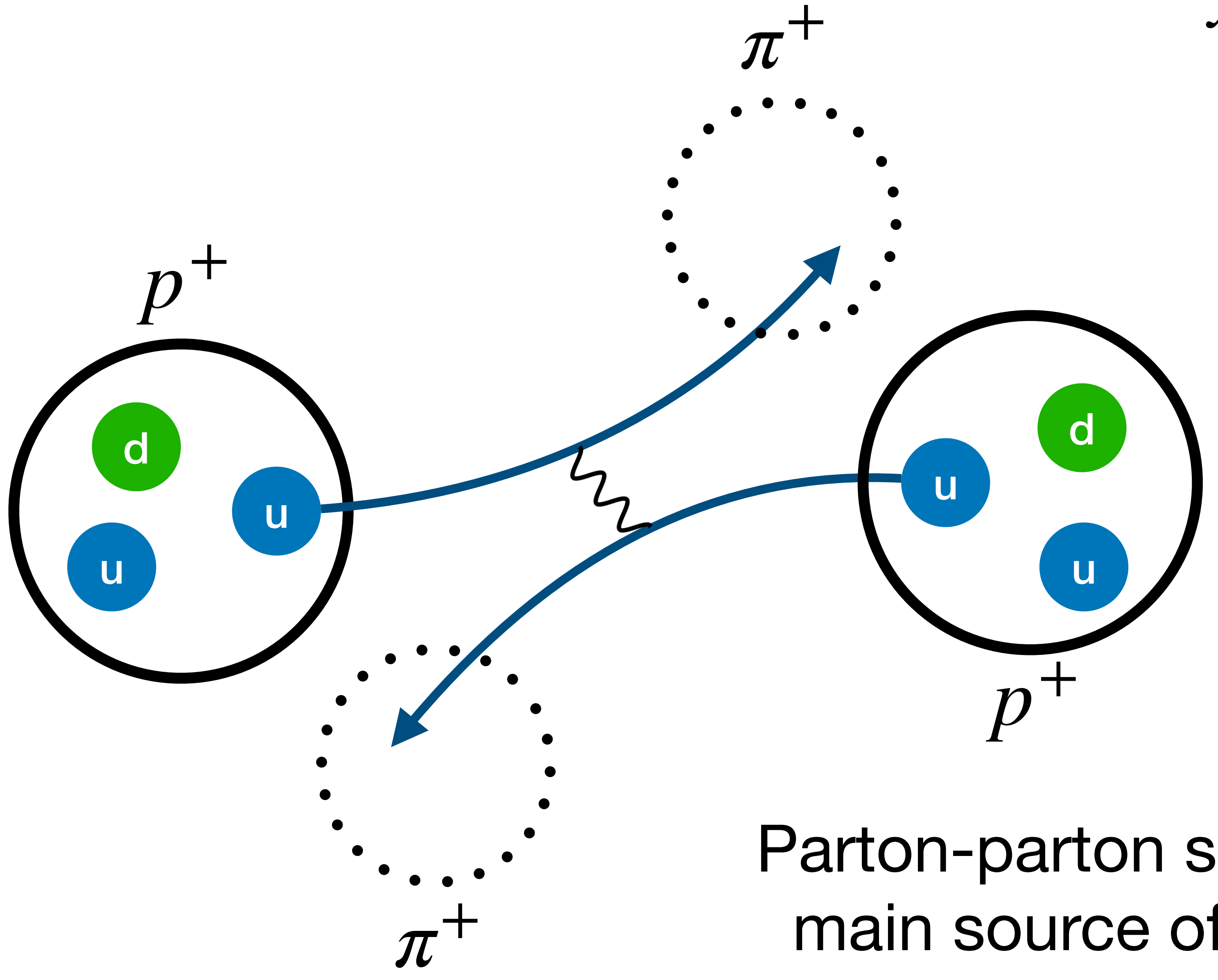
Colinear factorization

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

$G_a^A(x, Q^2),\ G_b^B(y, Q^2)\ \&\ D_C^c(z, Q^2)$ – **scaling functions**

qq – **scattering**

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

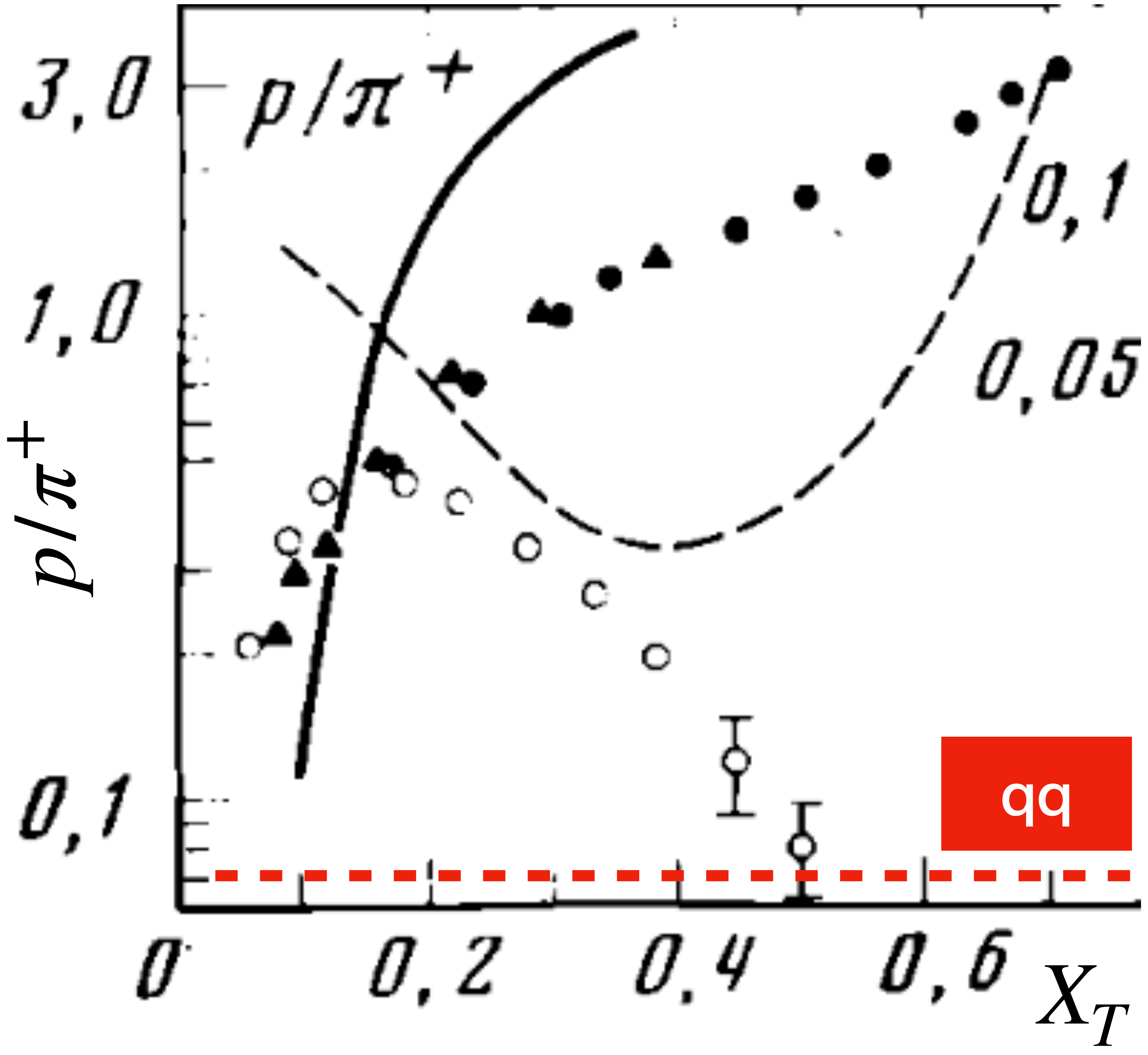


$$\frac{E\, d^3\sigma}{d^3p} \sim \frac{c(x_T, \sqrt{s})}{p_T^4}$$

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

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

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

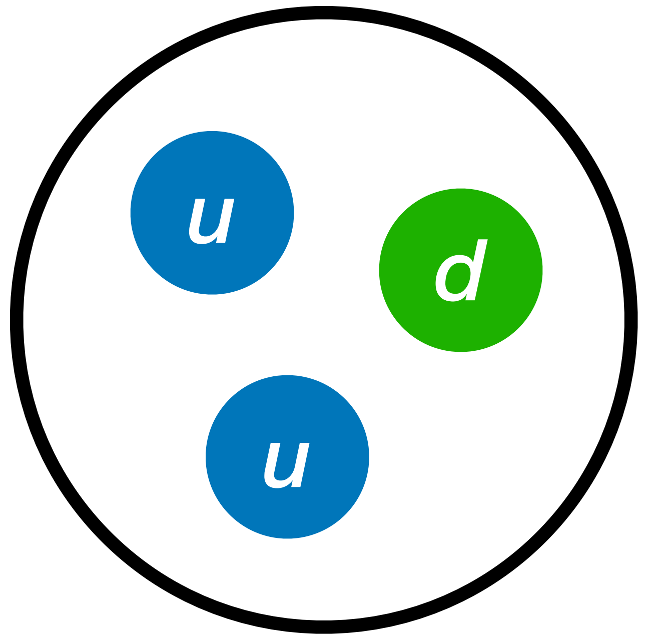


STRONG SCALING VIOLATION

Two-quark correlations: Diquarks

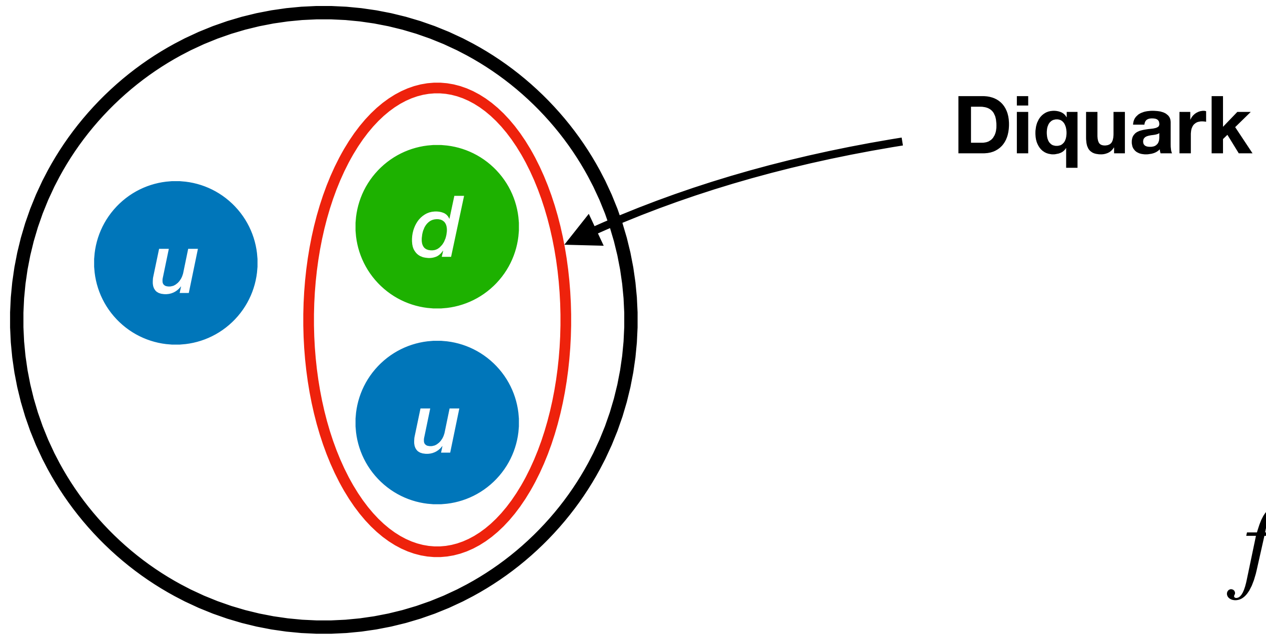
Diquark is a two-quark correlation in baryons.

$p\{uud\}$



Quark model of baryon

$p\{u(ud)\}$



Model of baryon with Diquark

Diquark is not a point-like object!

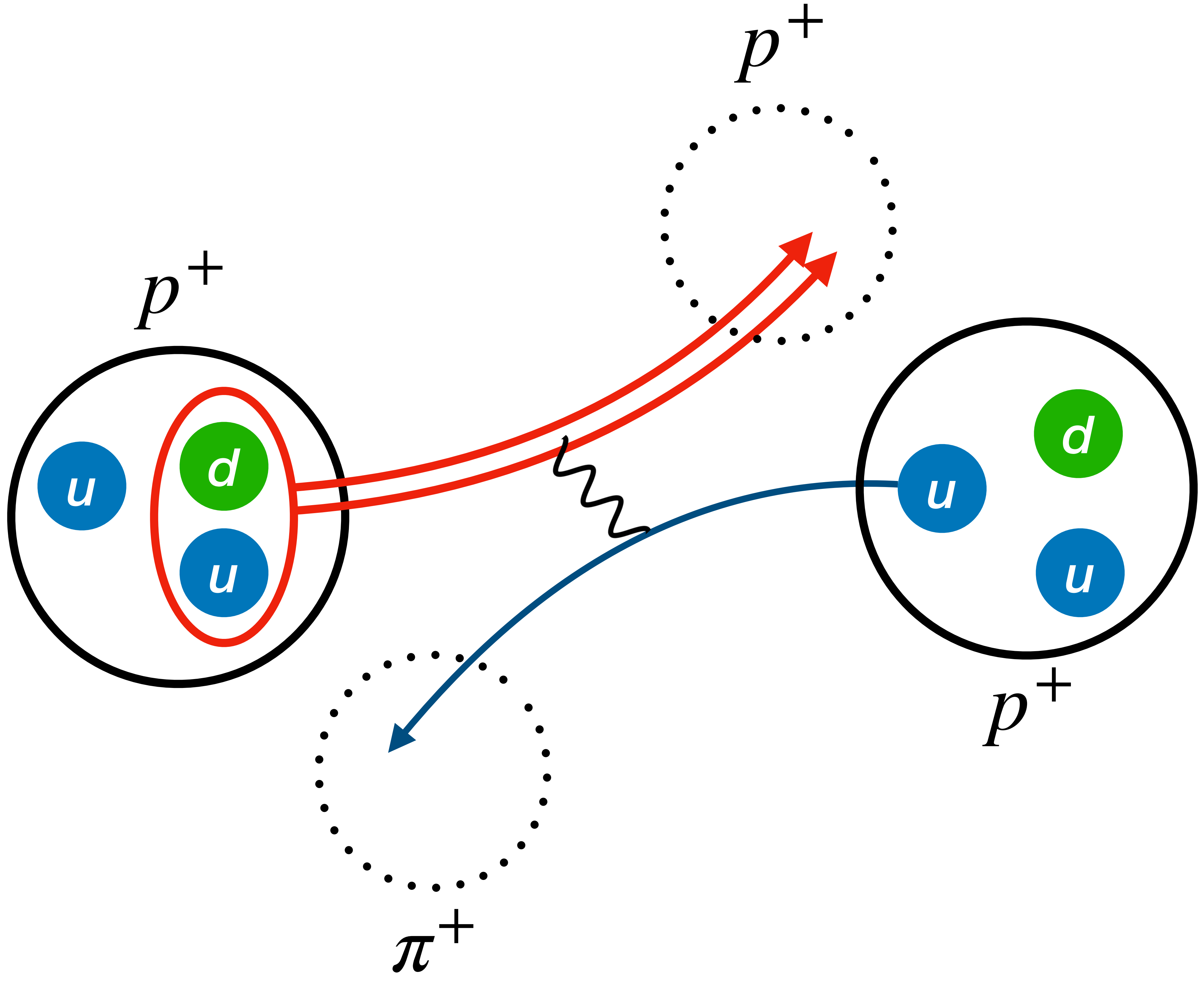
$$f(Q^2) = \frac{1}{1 + \frac{Q^2}{M^2}}$$ – **Diquark form-factor**

M^2 – **Diquark size parameter**

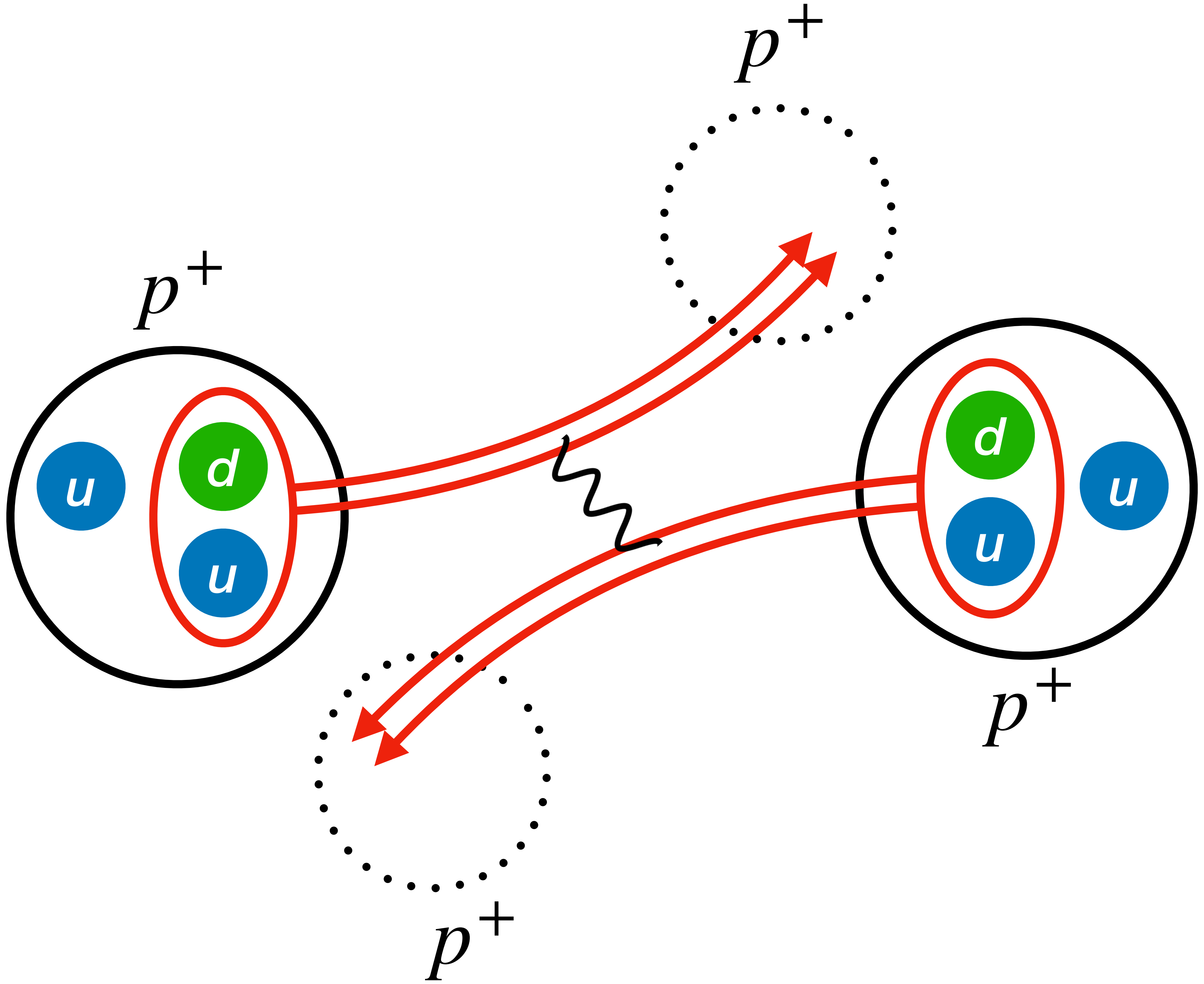
Baryon (proton) is in quark-Diquark state with probability W

Two-quark correlations: Diquarks

(ud) Diquark scatters on u quark



(ud) Diquark scatters on (ud) Diquark



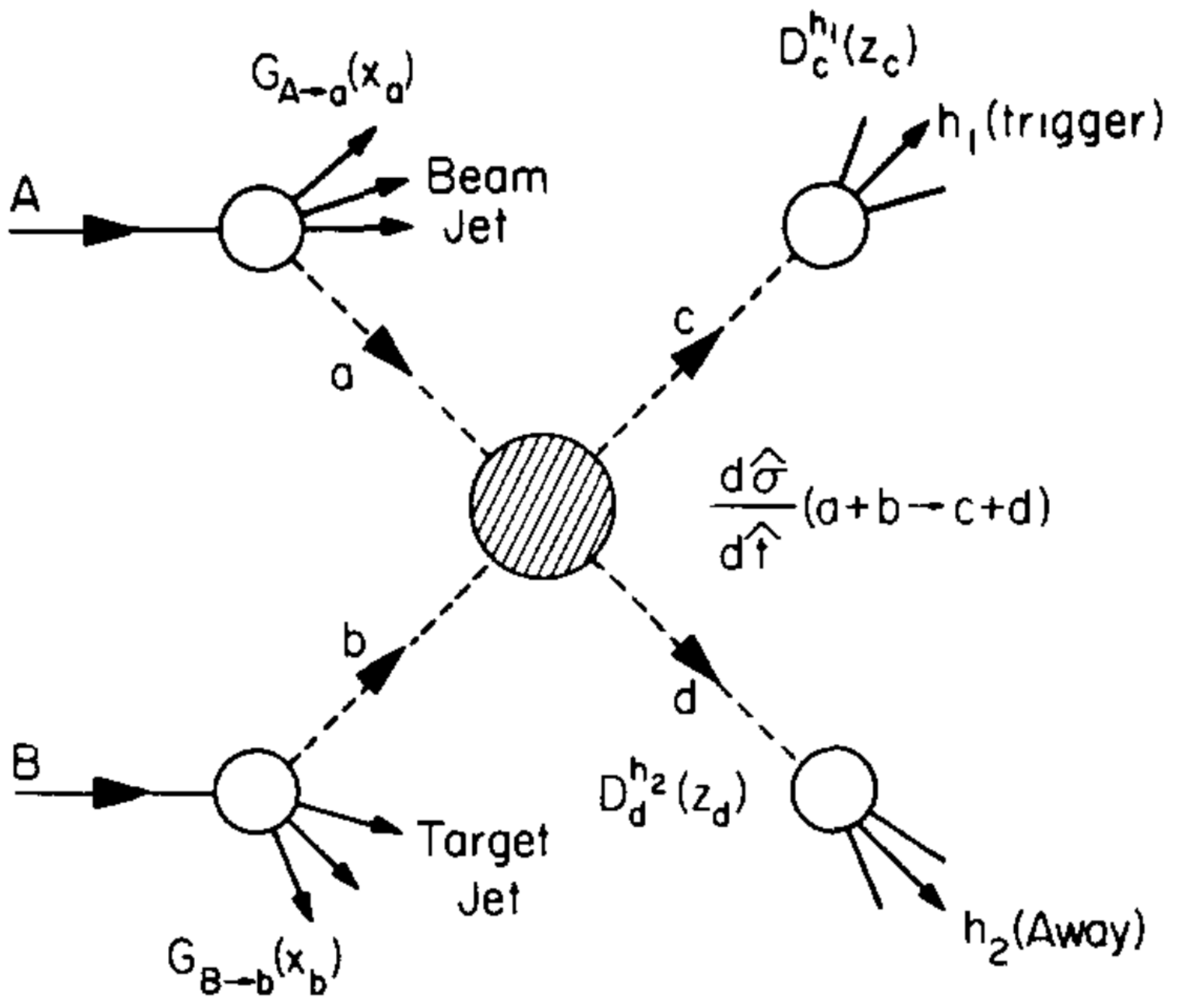
$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qD} = \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qq} \cdot f^2(Q^2)$$

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

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

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



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

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

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

Parton Distribution Functions

Fragmentation Function

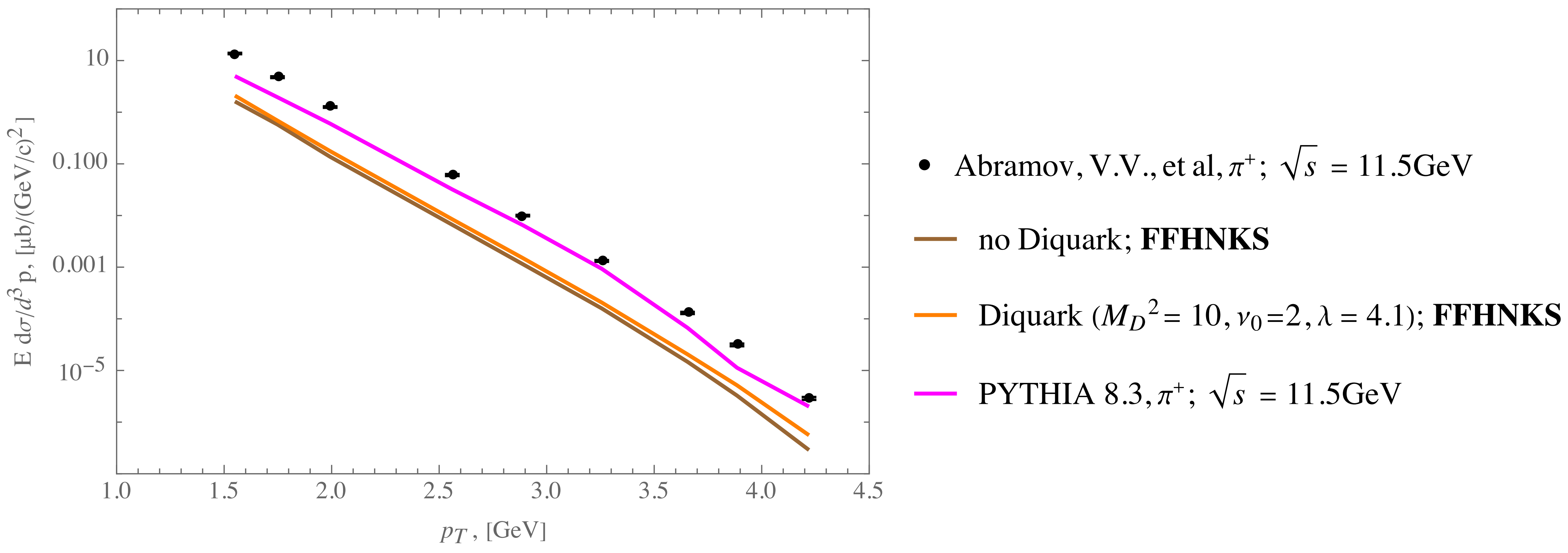
Subprocess cross section

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

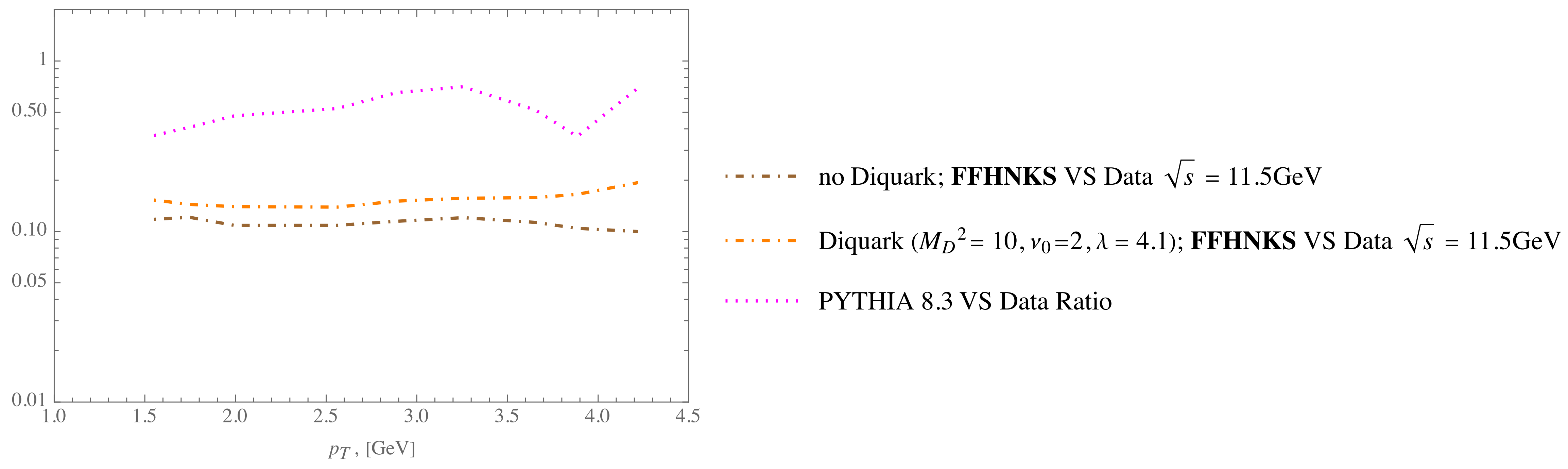
$$\tilde F(k_T) = J(k_T,Q^2)\sim e^{k_T^2/\sigma^2(Q^2)}, \text{where } \sigma^2 = \langle k_T^2\rangle$$

Large-p_T π^+ production

$\sqrt{s} = 11.5$ GeV

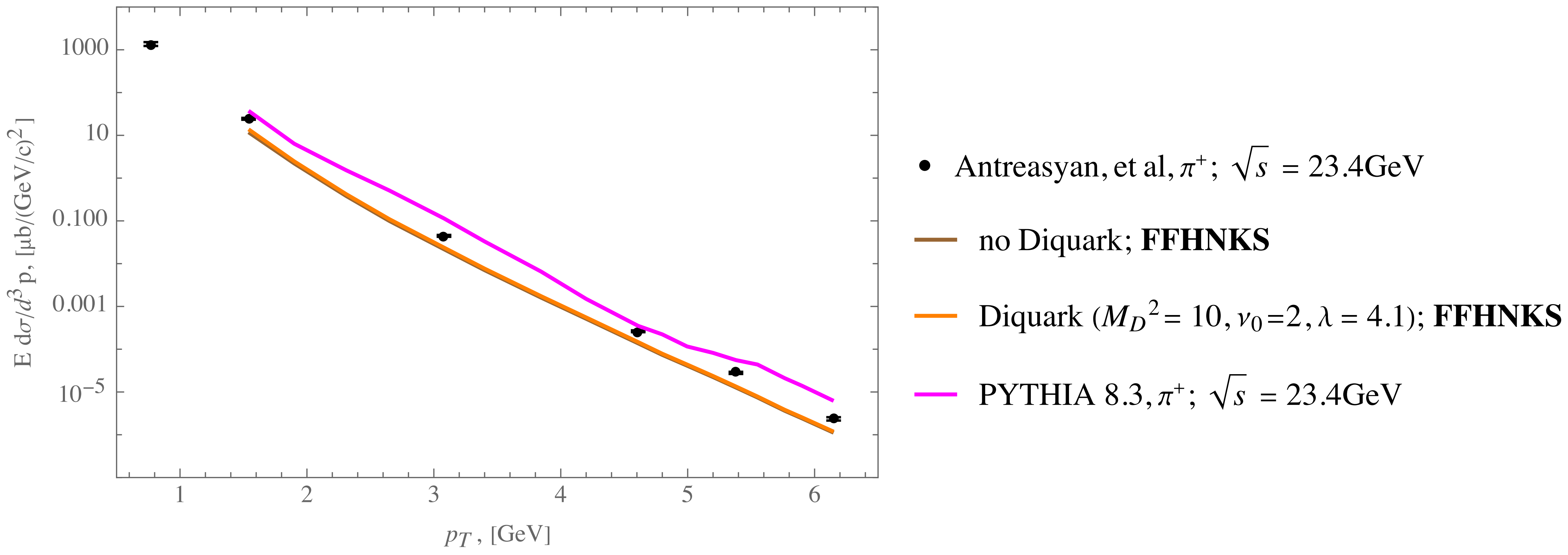


Theory/Data



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

$\sqrt{s} = 23.4$ GeV



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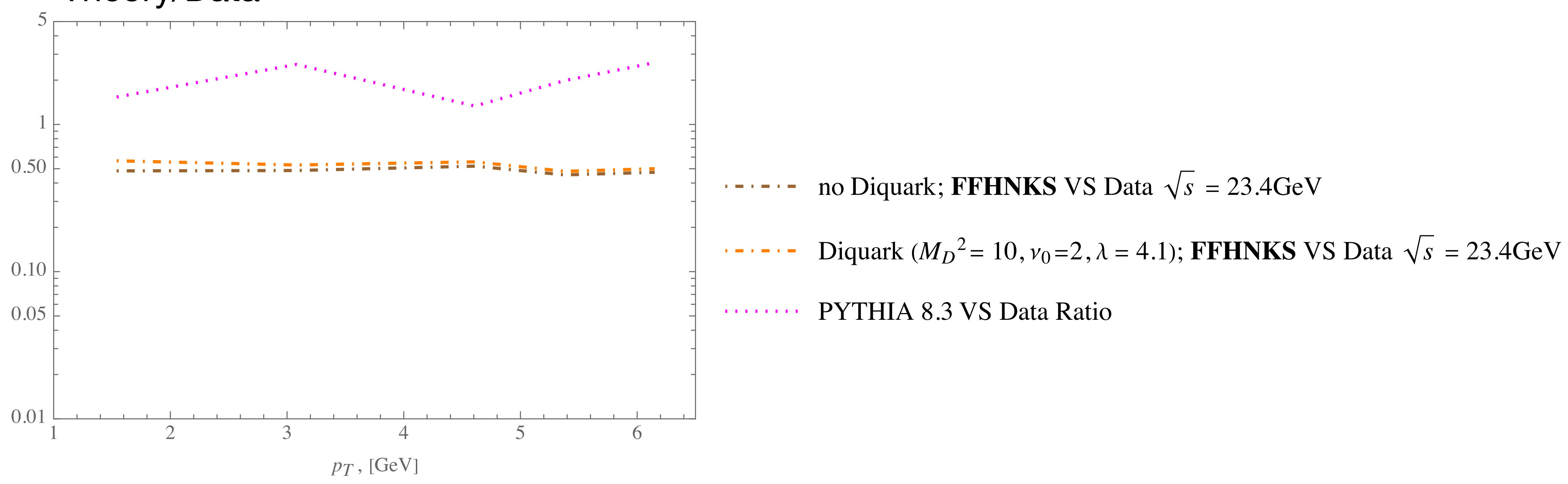
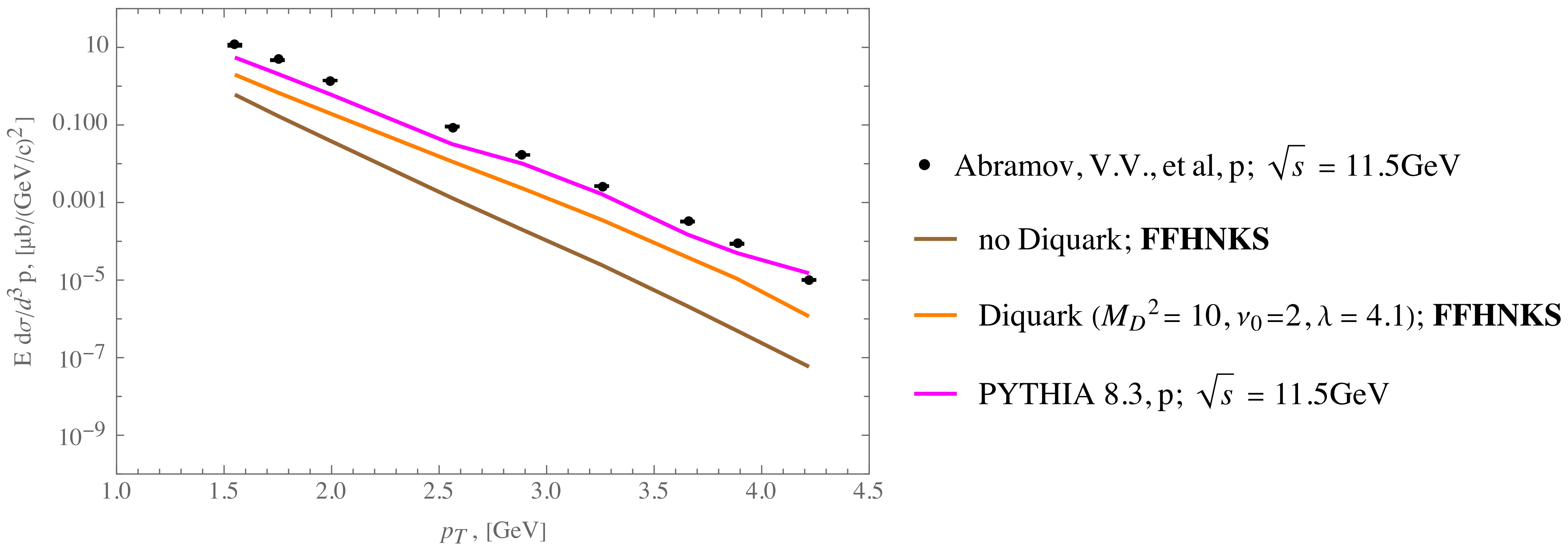


FNAL, Batavia, $\sqrt{s} = 23.4$ GeV
D.Antreasyan et al. (1979)

Large-p_T p production

$\sqrt{s} = 11.5$ GeV



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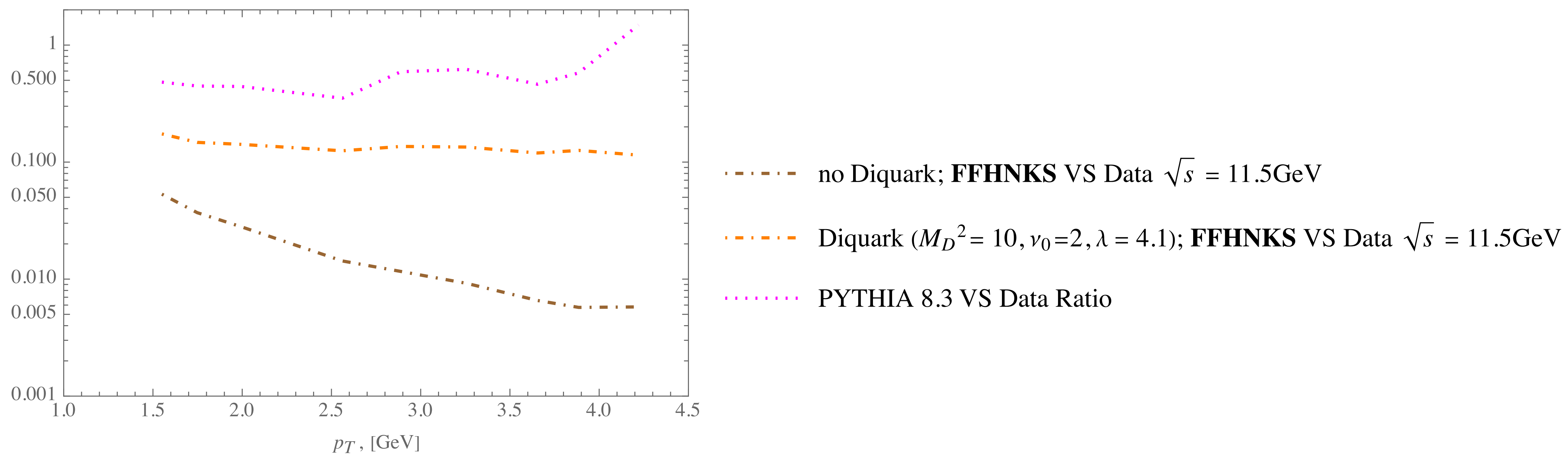

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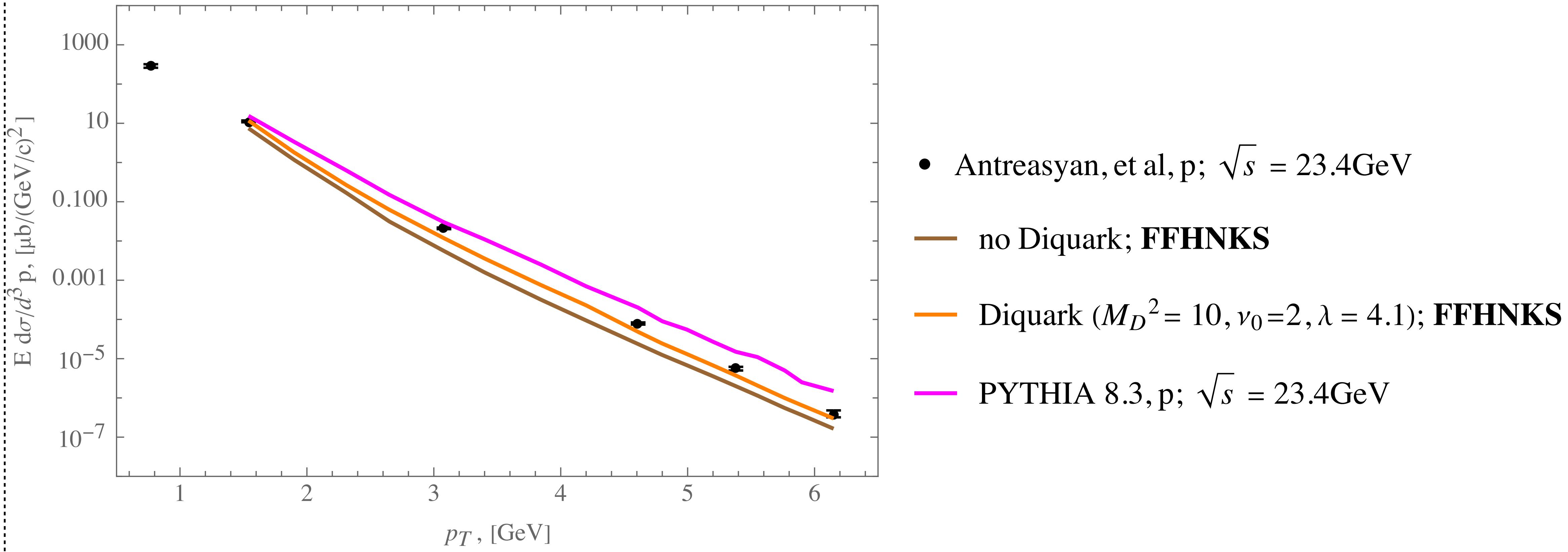

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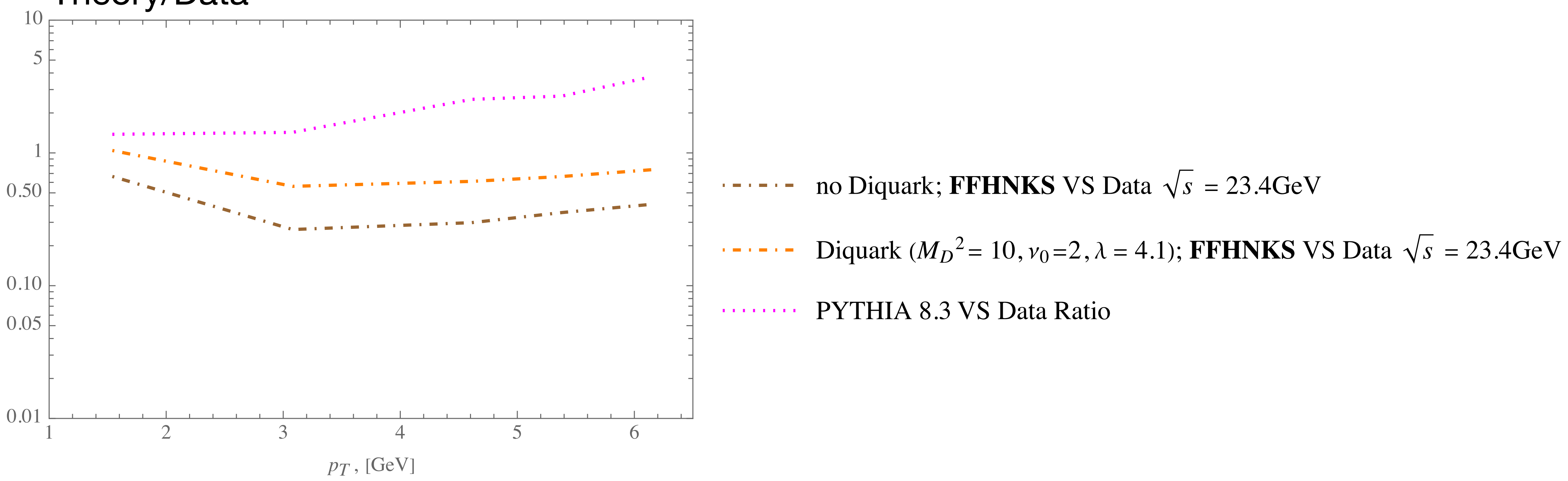
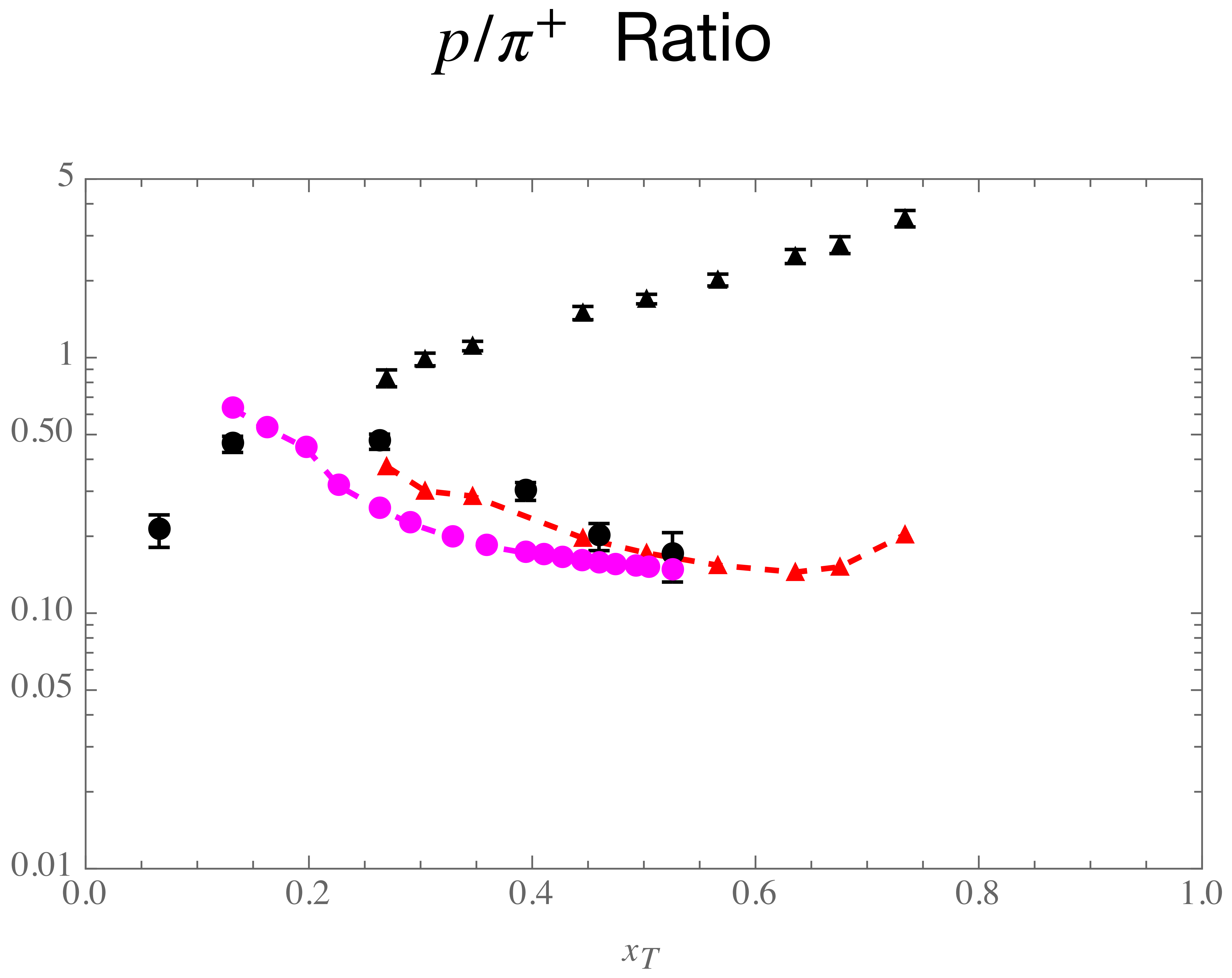


FNAL, Batavia, $\sqrt{s} = 23.4$ GeV

D.Antreasyan et al. (1979)

p/π^+ ratio without Diquark



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

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

FNAL, Batavia (•) для $\sqrt{s} = 23.4$ GeV
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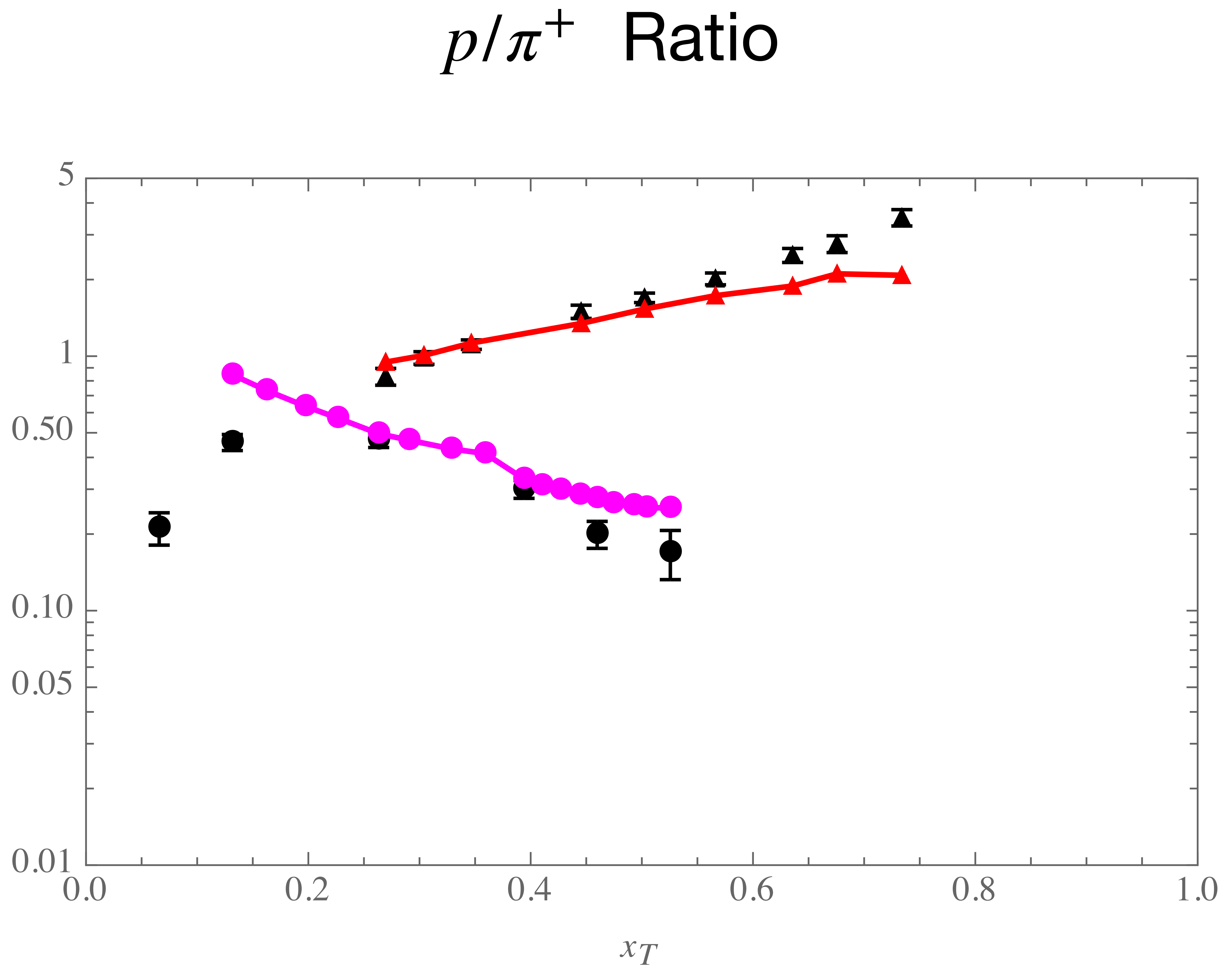
Calculation results**:**

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

Magenta $- \sqrt{s} = 23.4$ GeV,

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

p/π^+ ratio with Diquark



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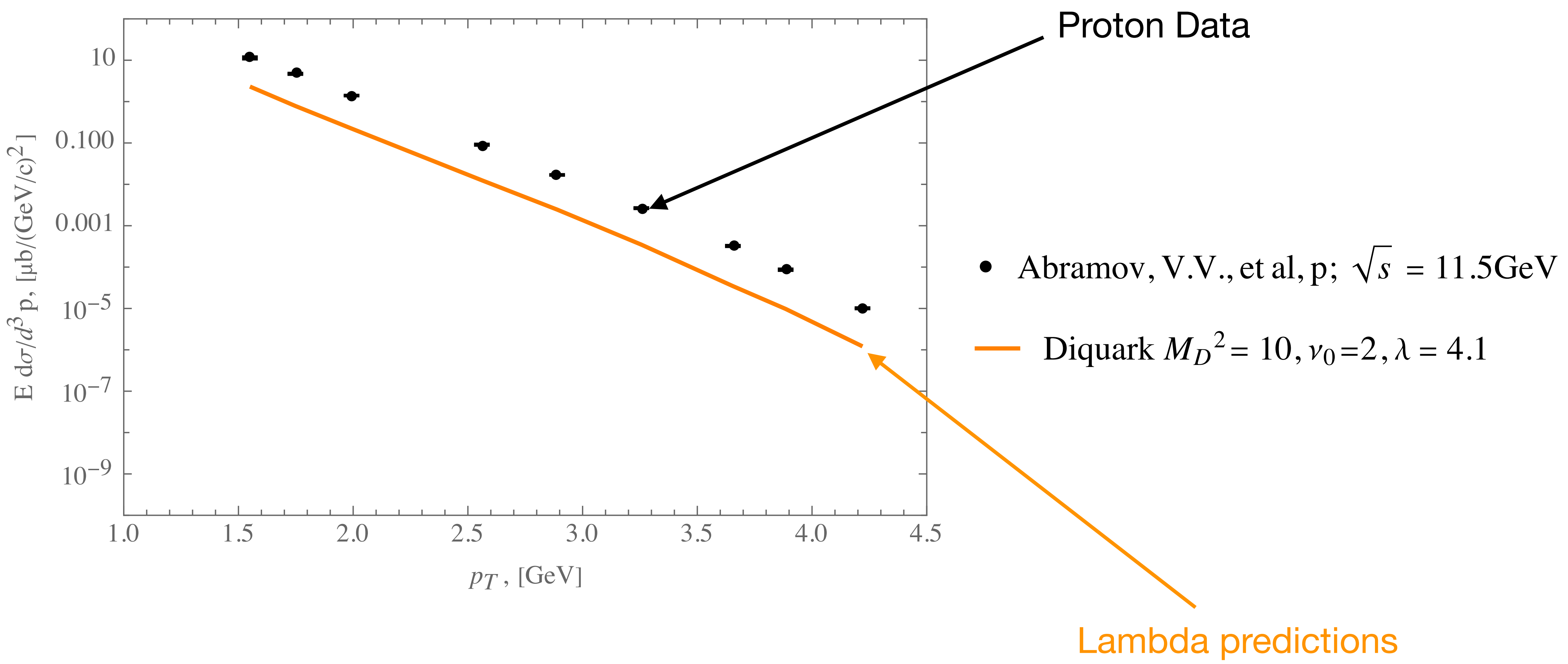
Large-p_T $\Lambda(uds)$ production

$\sqrt{s} = 11.5$ GeV



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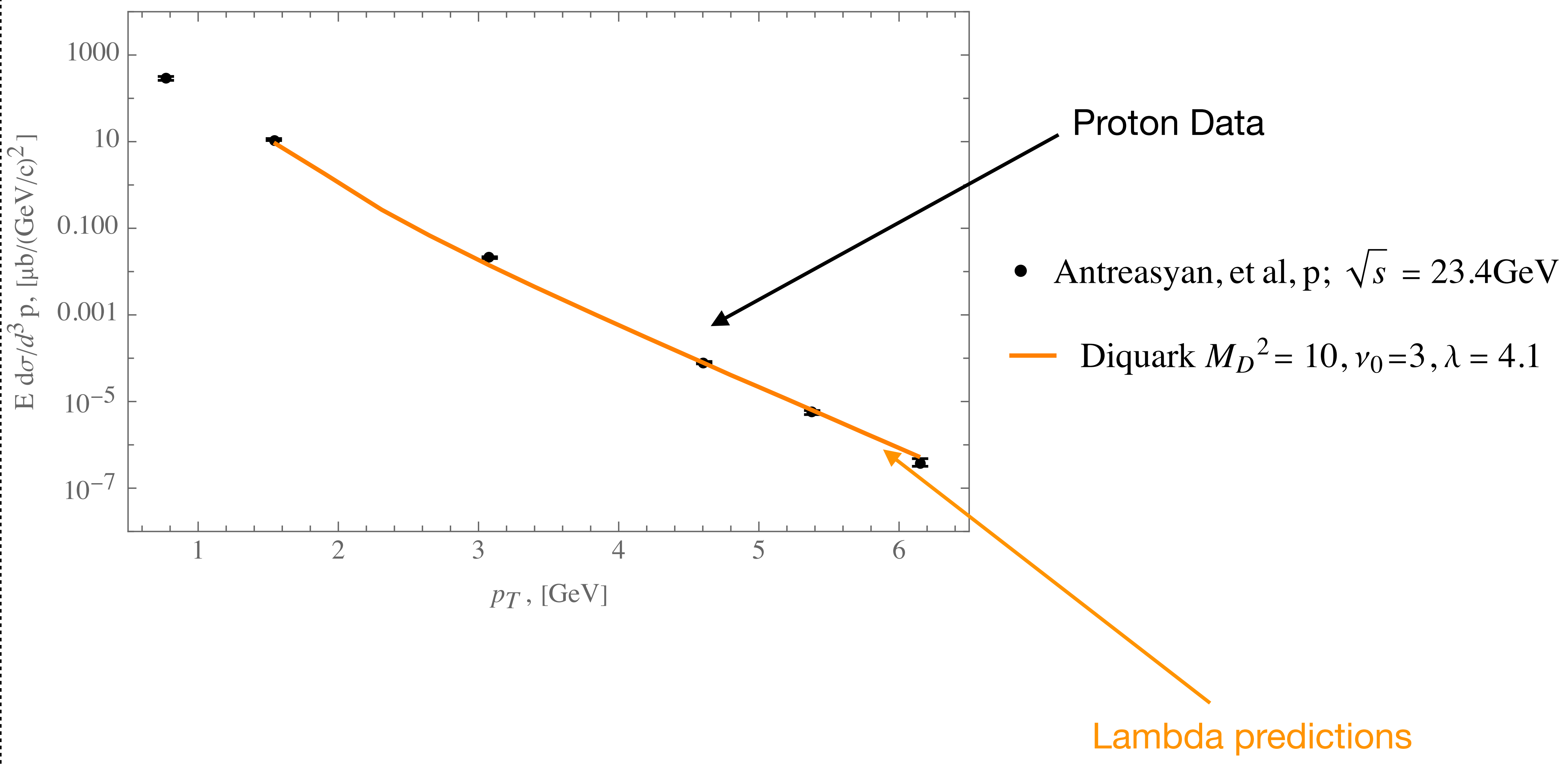
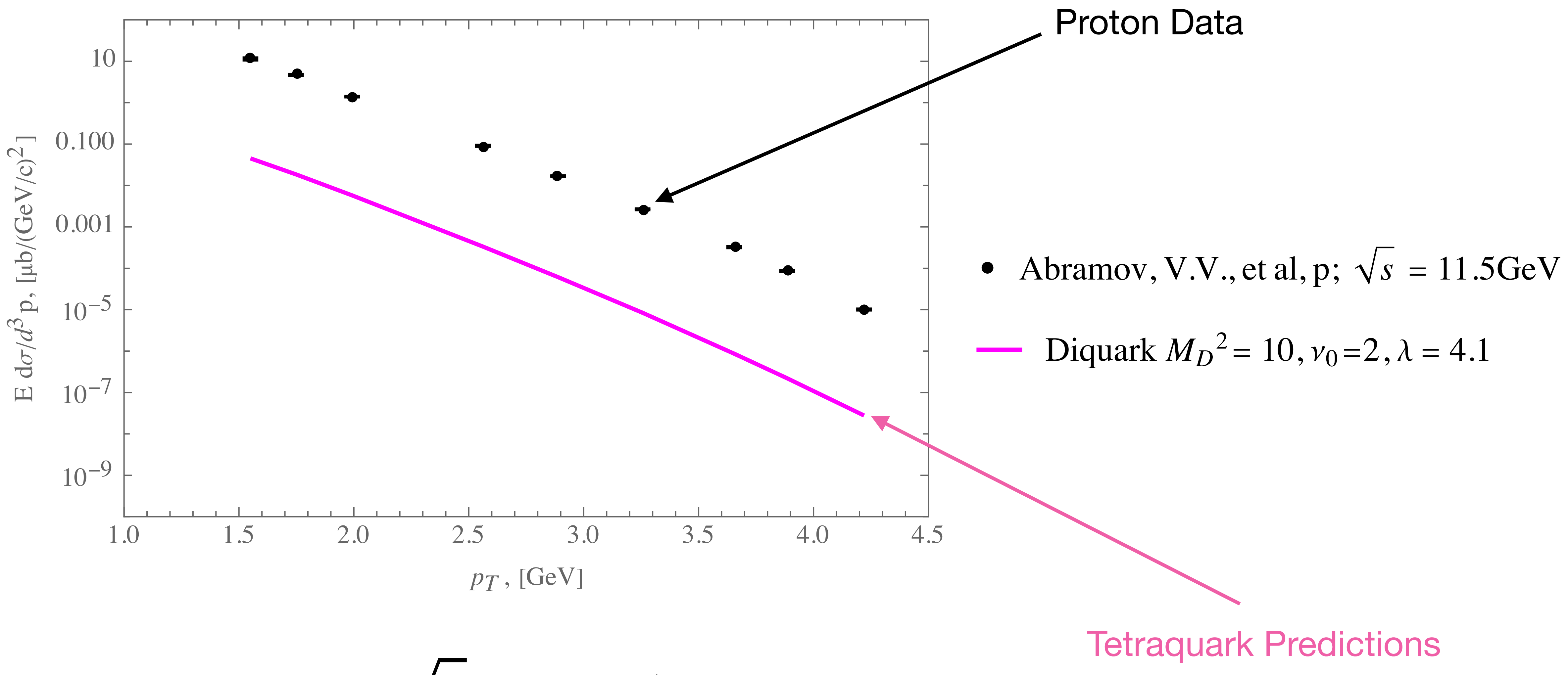
$\sqrt{s} = 23.4$ GeV

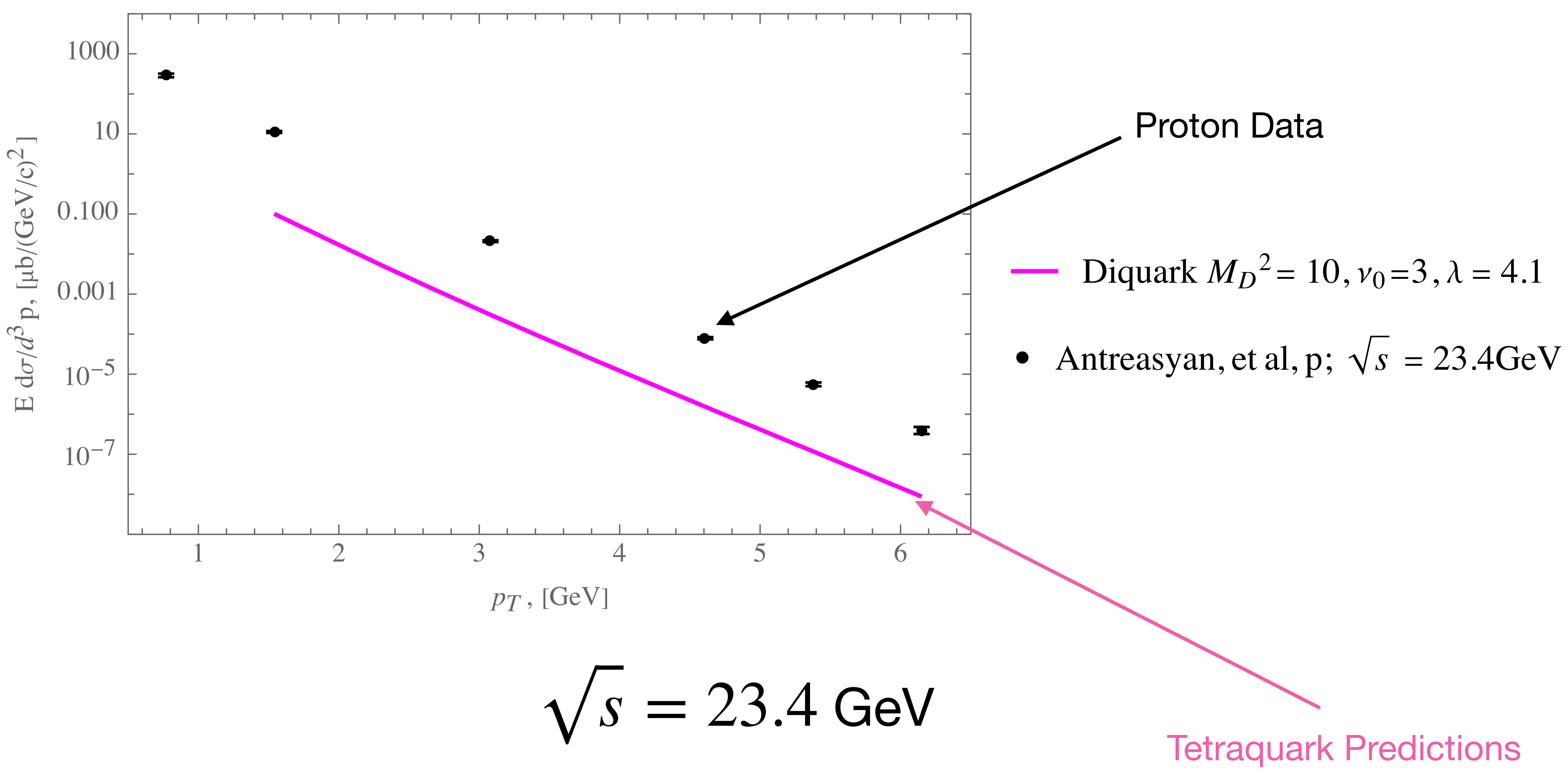


FNAL, Batavia, $\sqrt{s} = 23.4$ GeV
D.Antreasyan et al. (1979)

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



$\sqrt{s} = 11.5$ GeV



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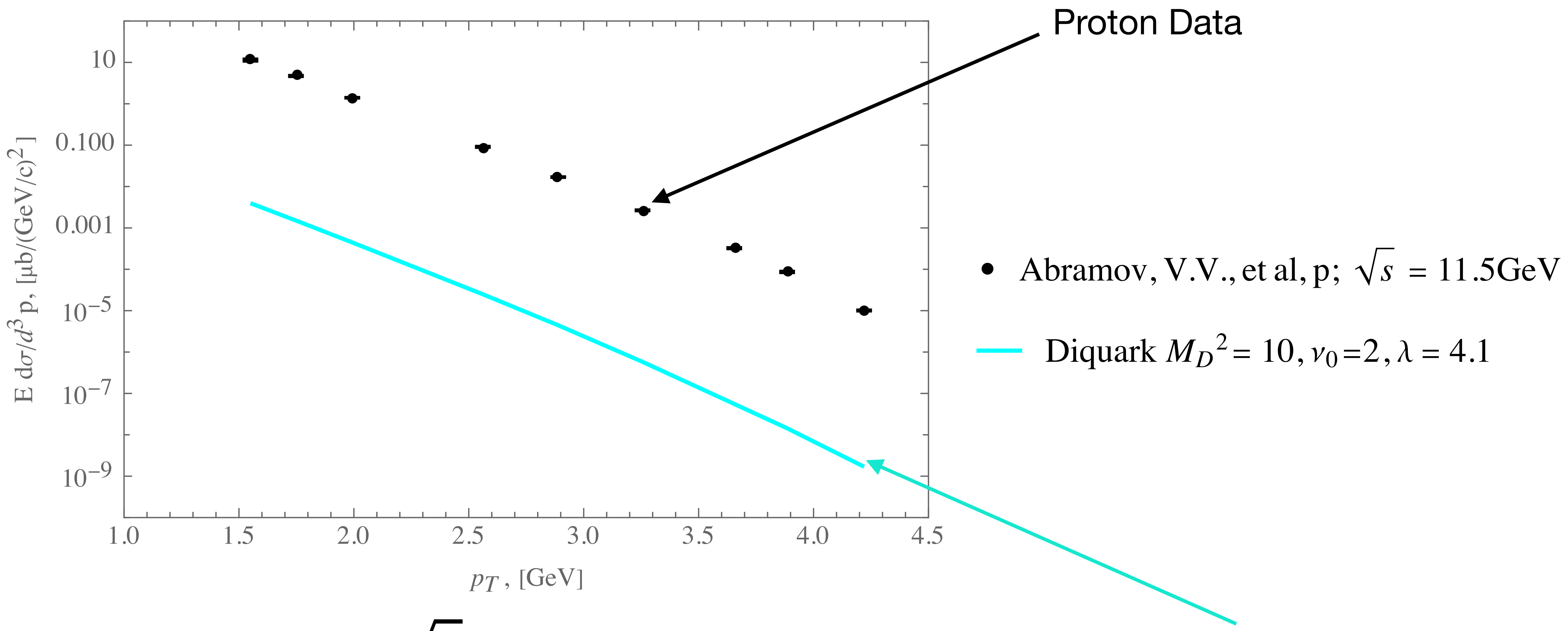
Exotic state production. Tetraquark $(qq\bar{q}\bar{q})\ X$: $\{(ud)\bar{s}\bar{s}\}$



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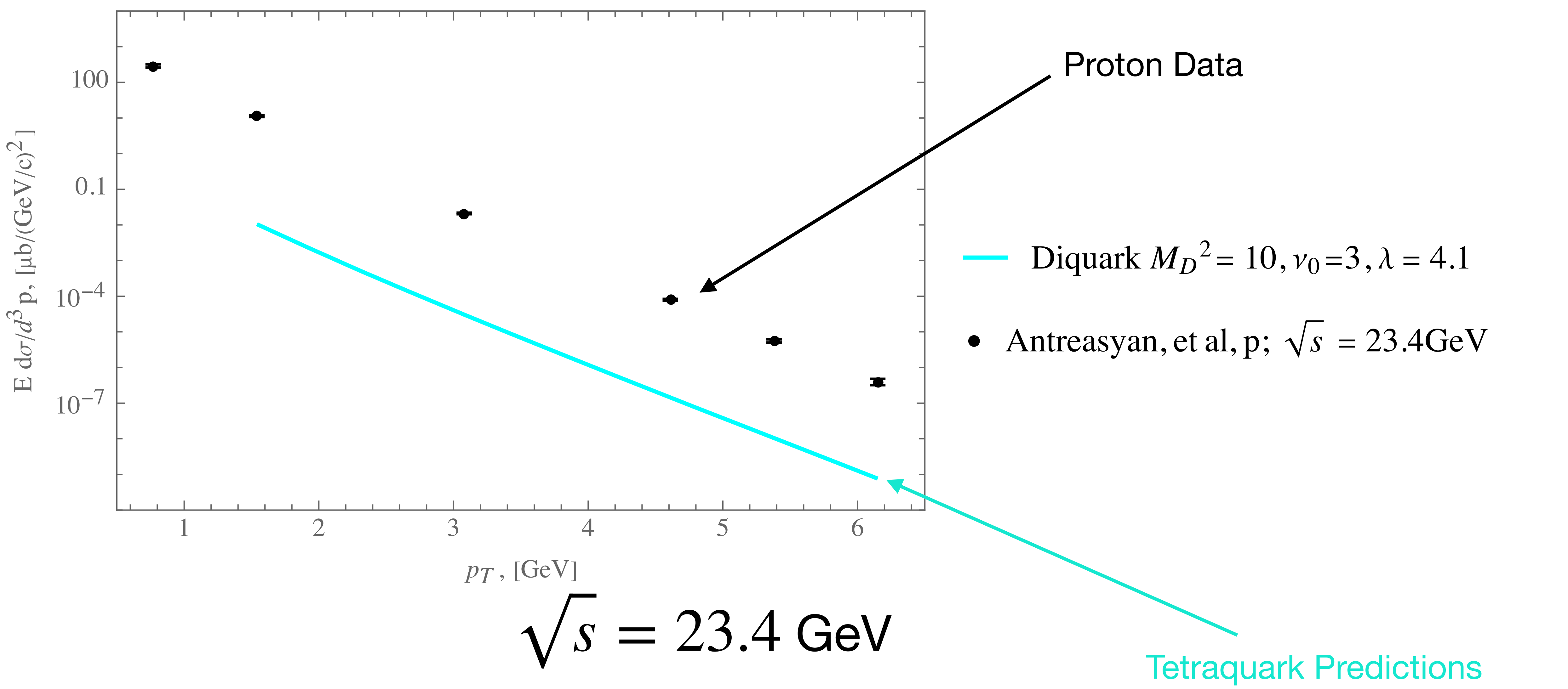

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ULYSSES MC event generator

✓ 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.

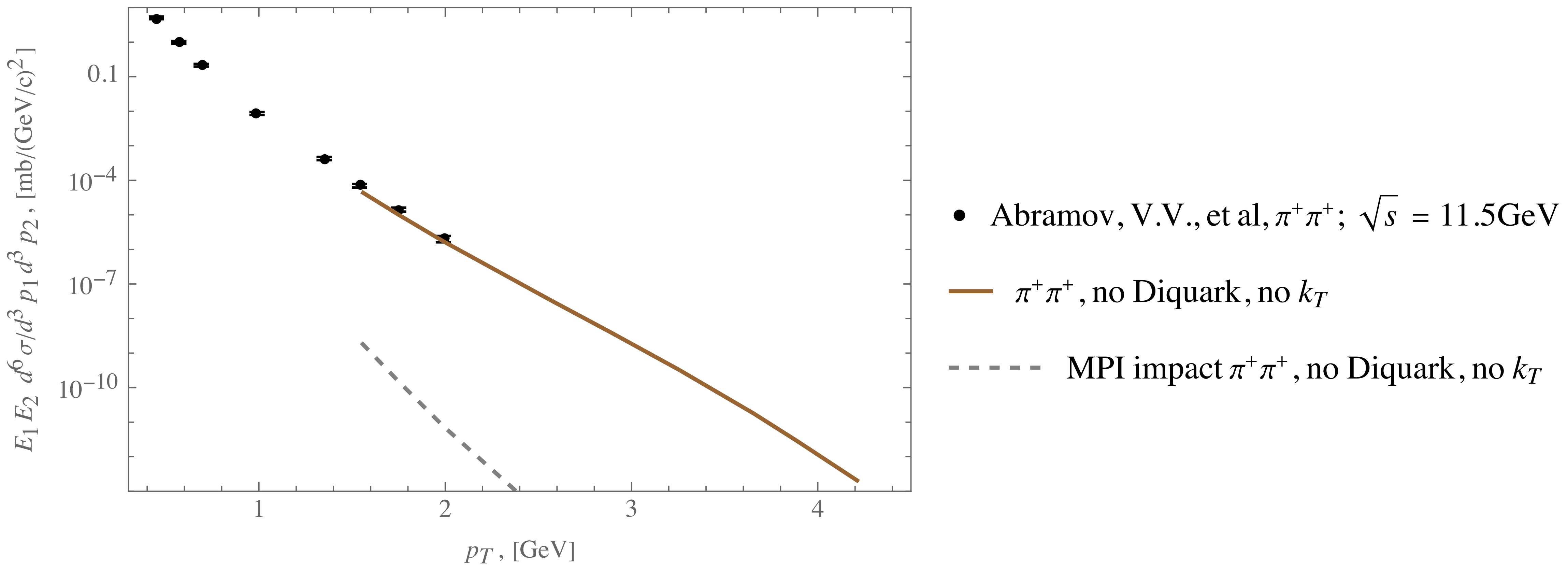
- On the basis of Diquark approach, estimations of the tetraquarks (exotic multiquark hadron states) production at the **SPD** energies have been made. To appear in Lett. Phys. Elem. Part. At. Nucl. (Jan. 2025)

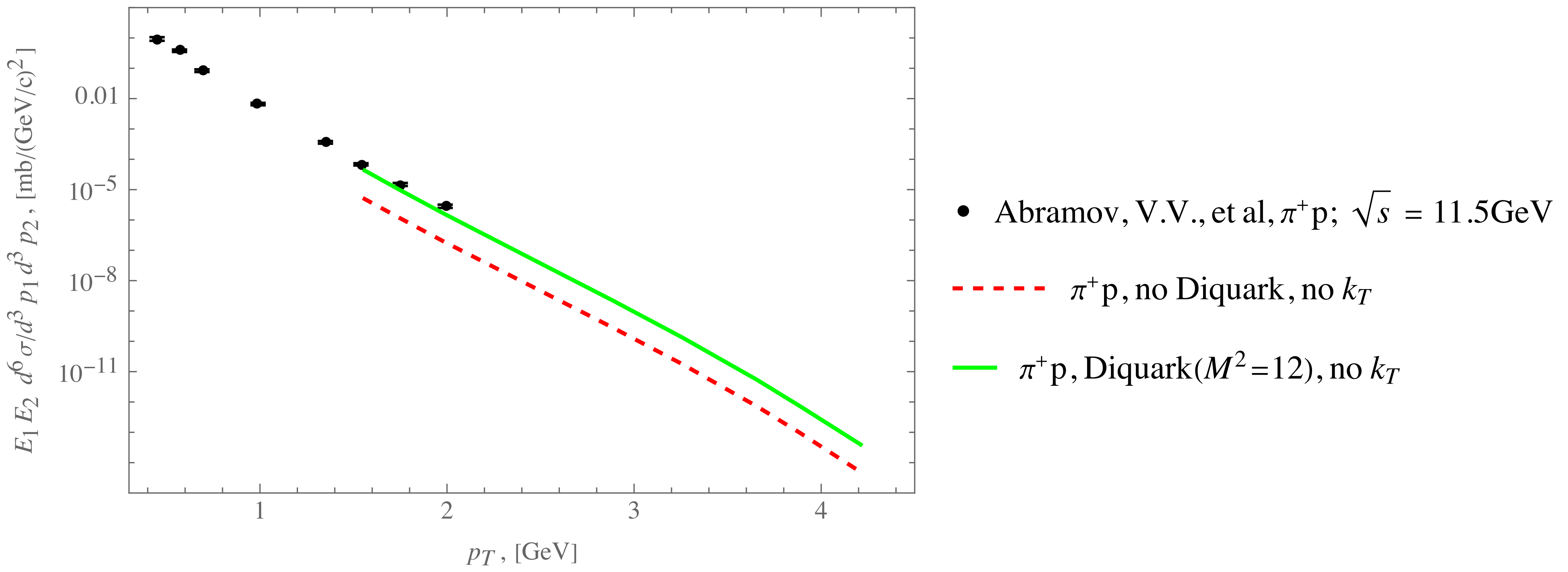
- These results will be used to tune the MC generator **ULYSSES** which is developing in NRC «Kurchatov Institute» - PNPI, Gatchina.

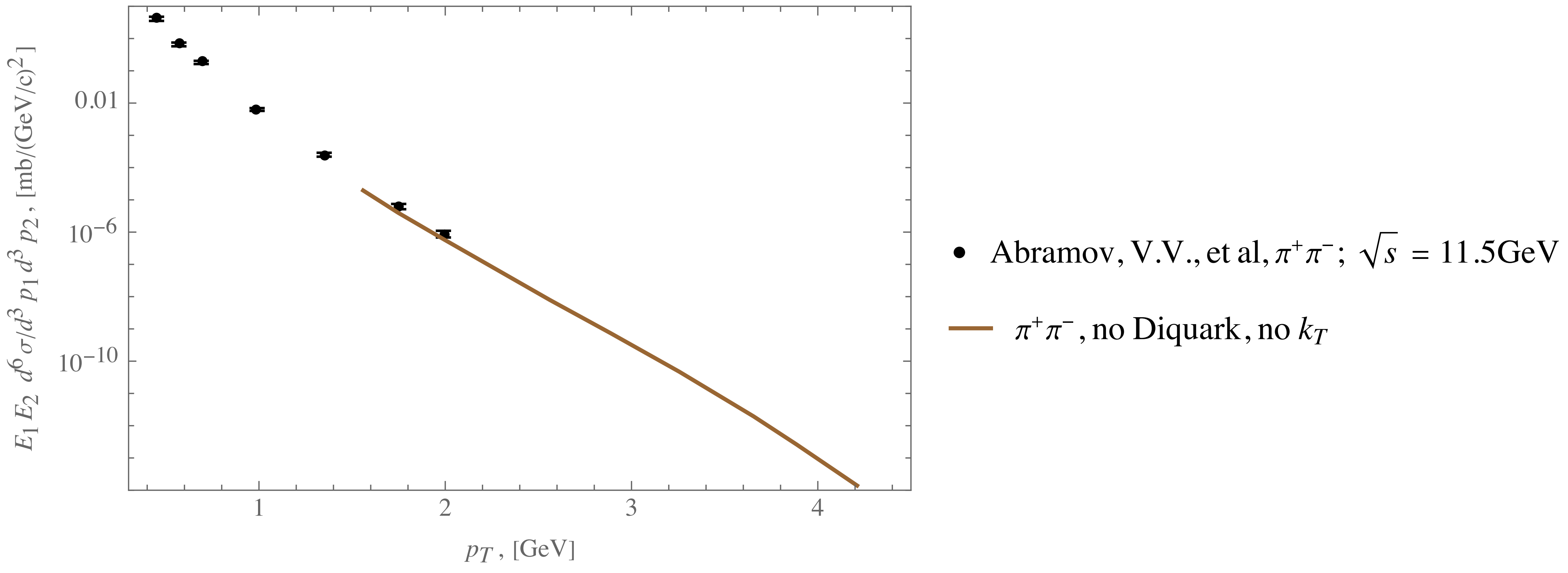
Hadron symmetric pairs production

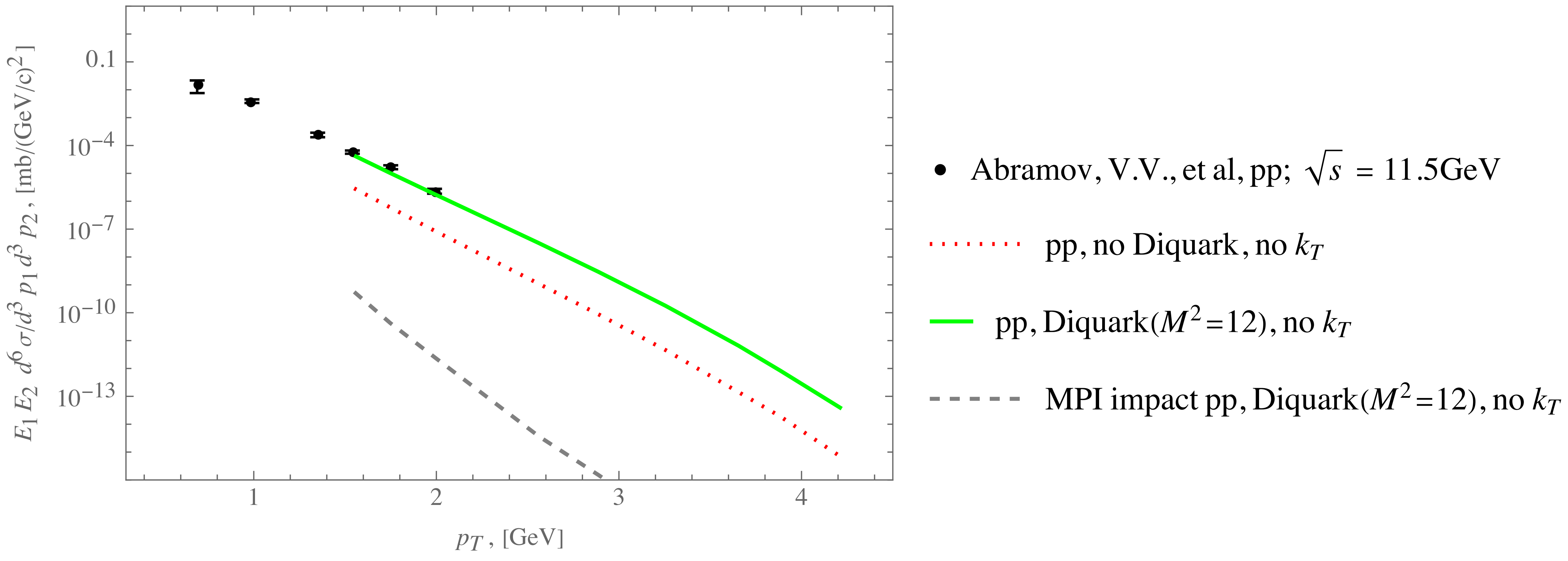
$$p_{T_1} = p_{T_2}, \Delta\phi = (\phi_2 - \phi_1) = \pi; \theta_1 = \pi/2 \text{ and } \theta_2 = -\pi/2$$

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









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

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

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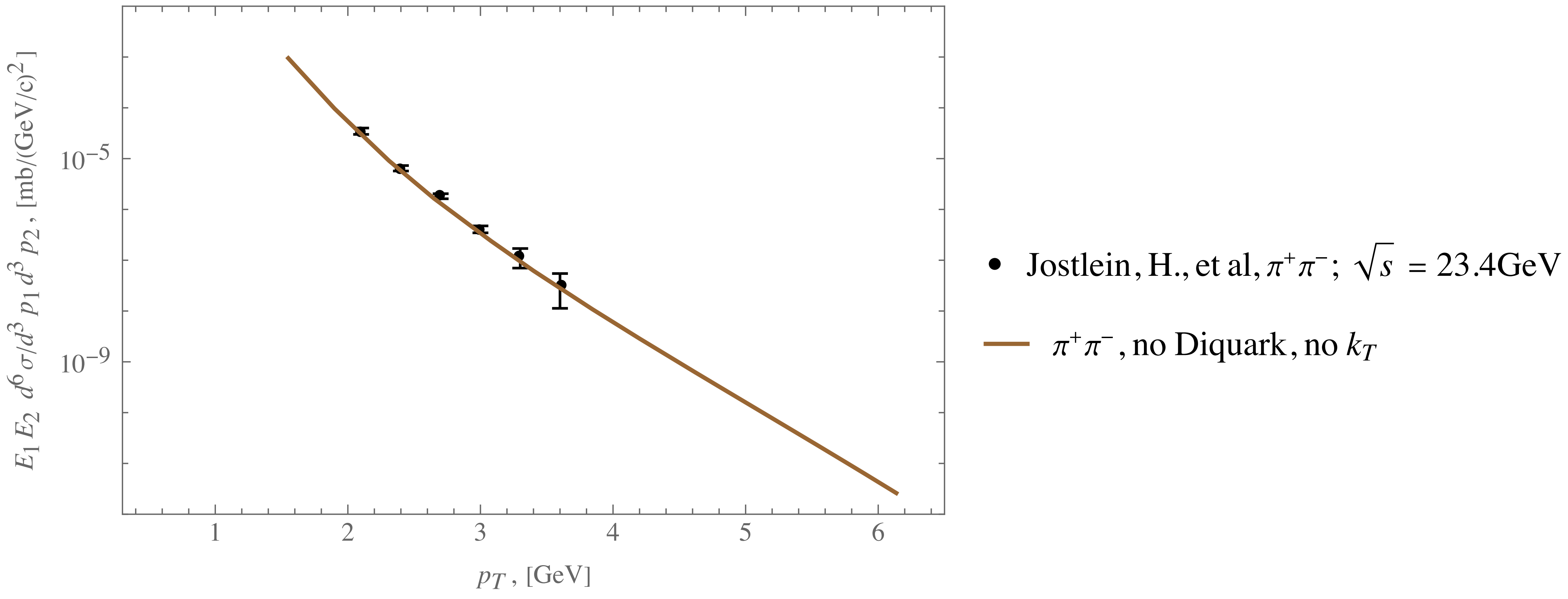

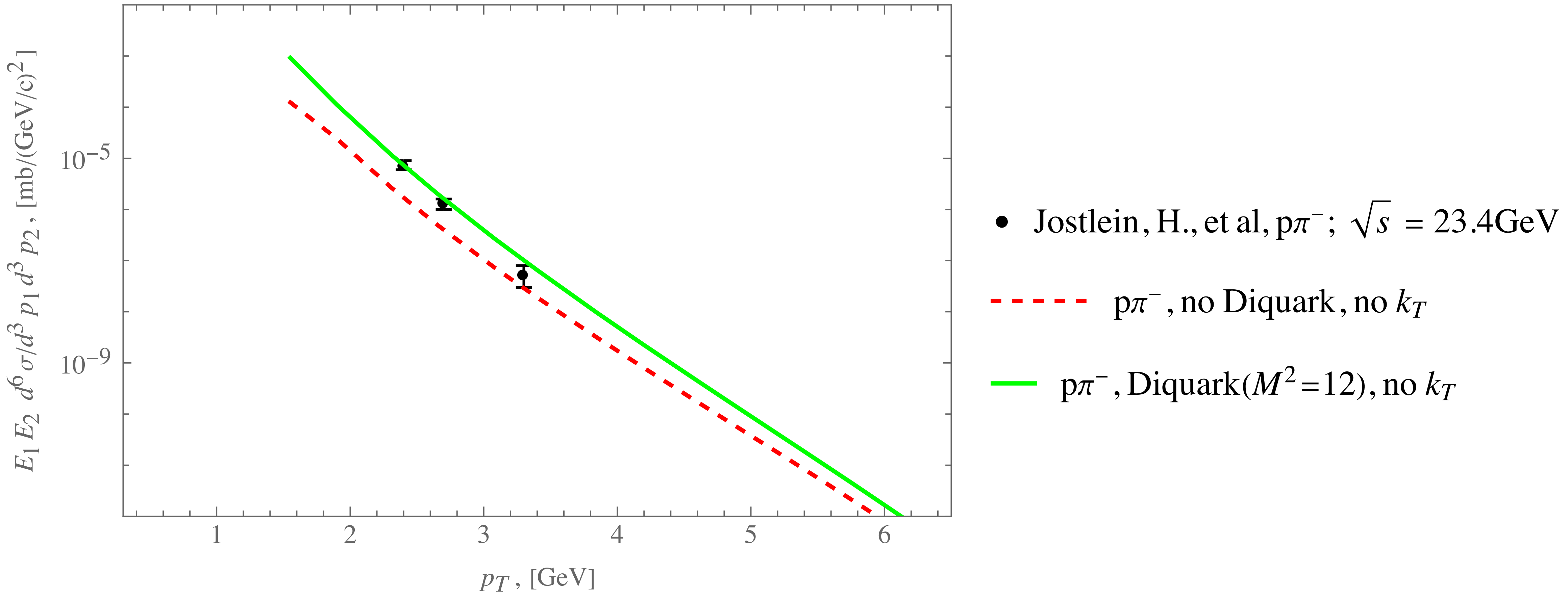

FNAL, Batavia
H.Jostlein et al. (1979)

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