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Diquark Role in Baryon and Exotic State Production with Large pT in pp- and dd- Collisions

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Outlooks

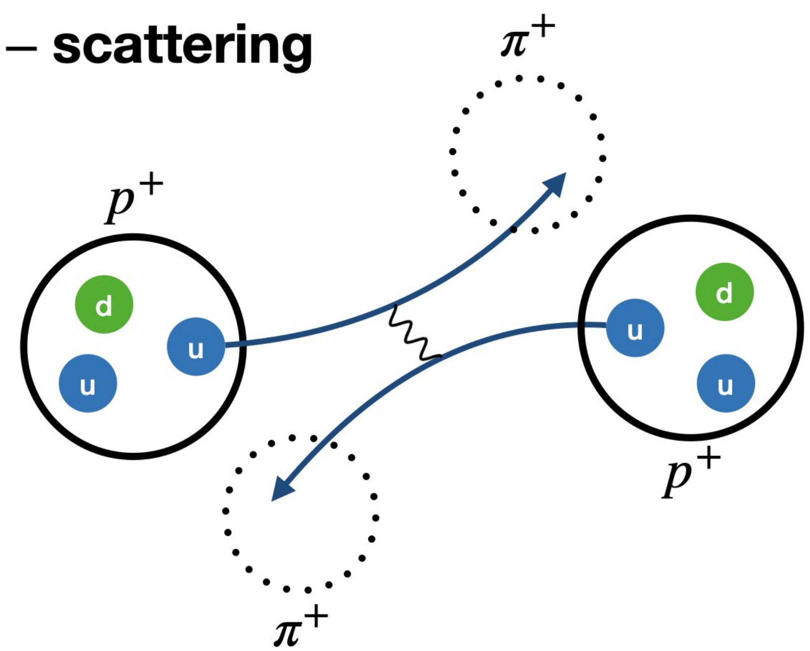
- Large-pT processes in QCD
- Diquark role in large- hadron and symmetric hadron pairs production
- Diquark role in large- multi-quark exotic state production
- Summary

Large-pT 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

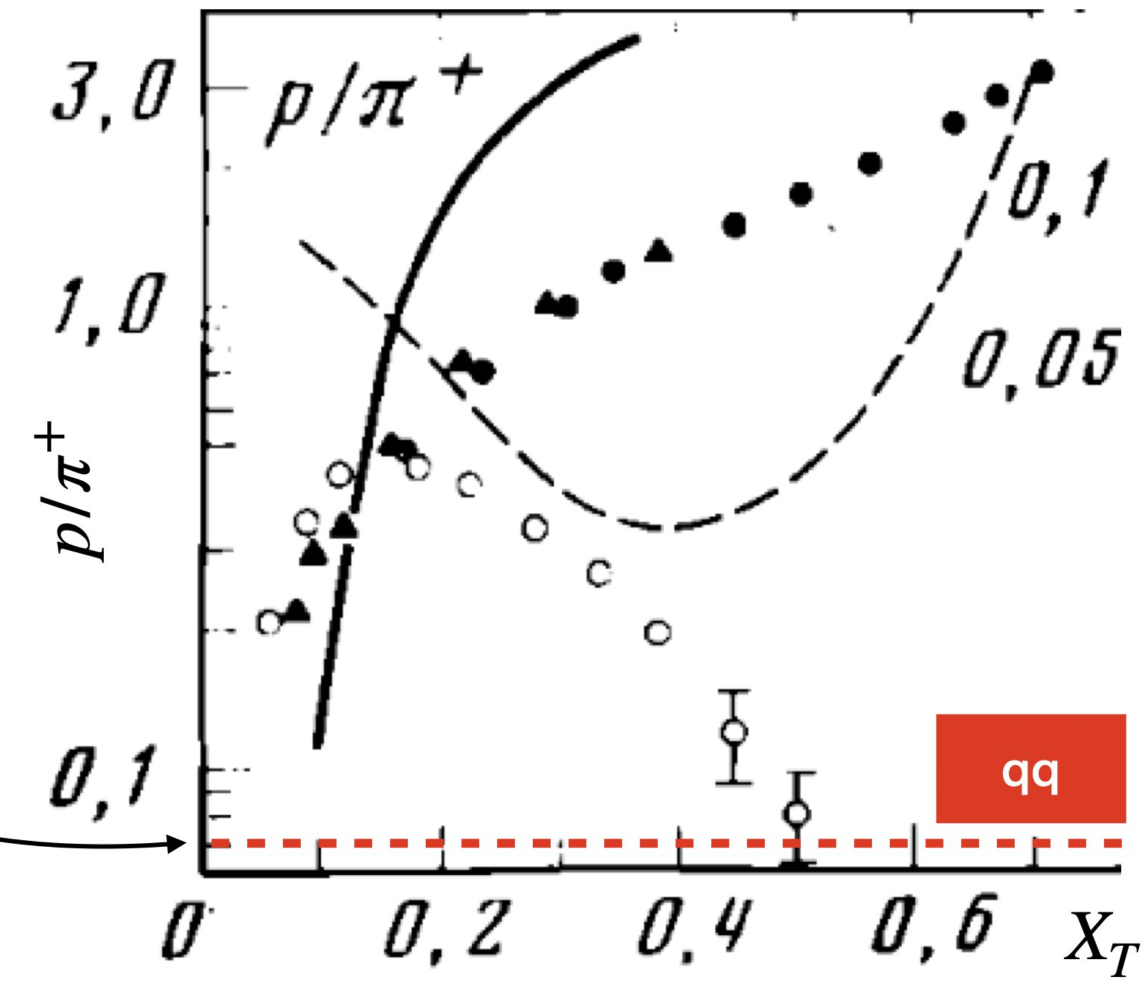
Large-pT hadron production: strong scaling violation for protons

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

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

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

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

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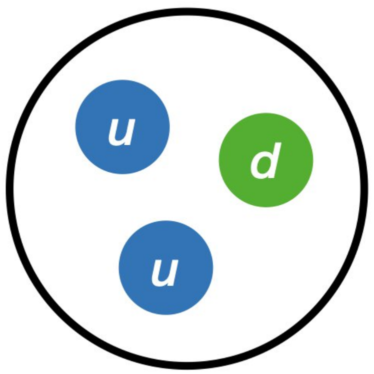
V.T. Kim, Mod. Phys. Lett. A3 (1988) 909

Two-quark correlations: Diquarks

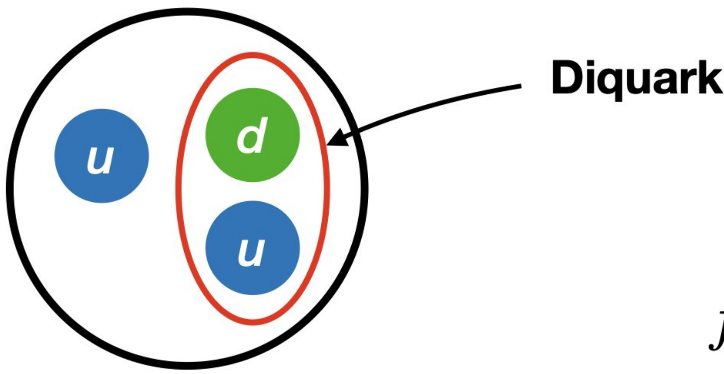
Diquark is a two-quark correlation in baryons.

$p\{uud\}$



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

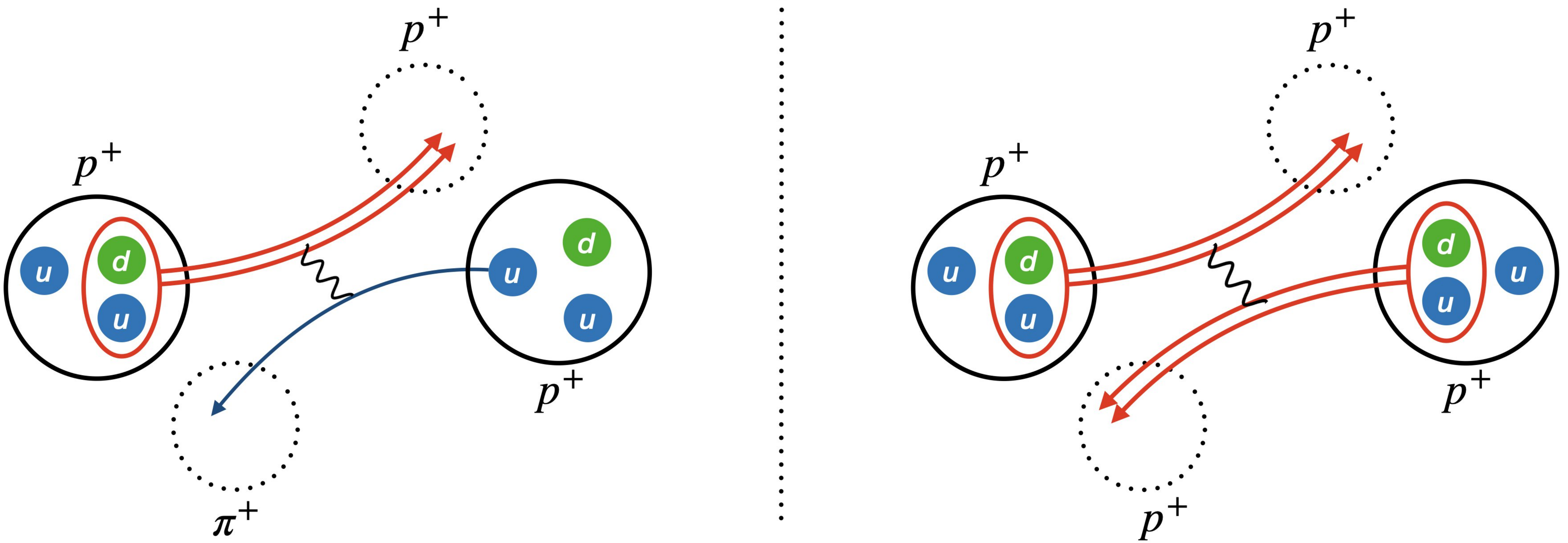
$$f(Q^2) = \frac{1}{1+\frac{Q^2}{M^2}}$$ – **Diquark form-factor**

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 | (ud) Diquark scatters on (ud) Diquark



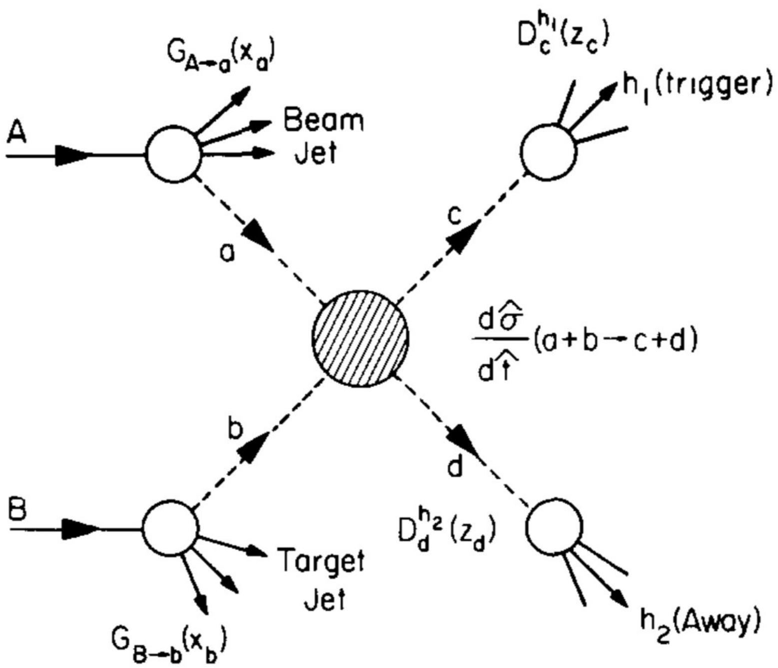
$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qD} = \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qq} \cdot f^2(Q^2)$$

The main source of baryons with large p_T in pp collisions

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

Feynman approach: collinear factorization improved by kT-dependence

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



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

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

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

Fragmentation Function

Subprocess cross section

Parton Distribution Function

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

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

Feynman approach: collinear factorization improved by kT-dependence

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

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

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

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:

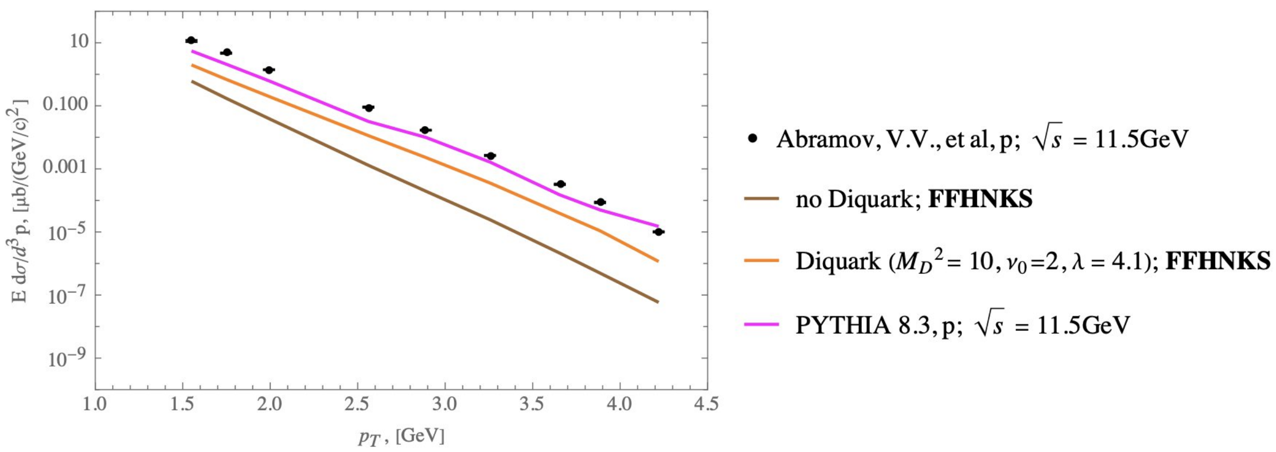
Diquark PDF

"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)

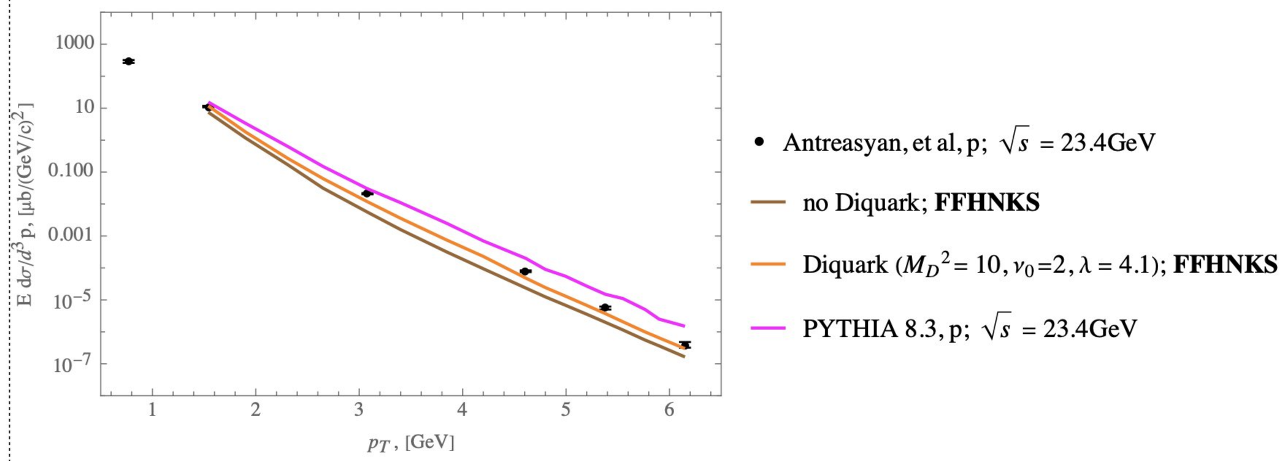
Large-pT proton production

“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)

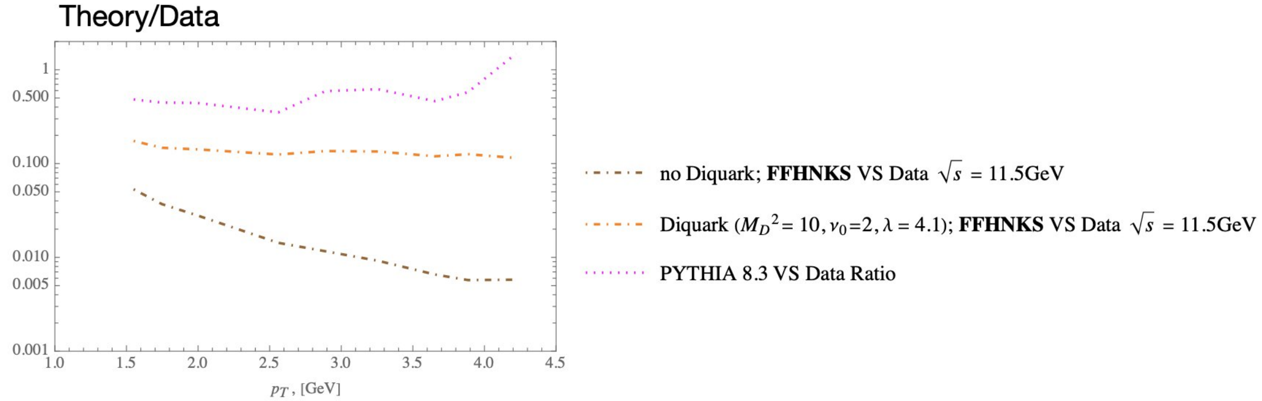
$\sqrt{s} = 11.5$ GeV



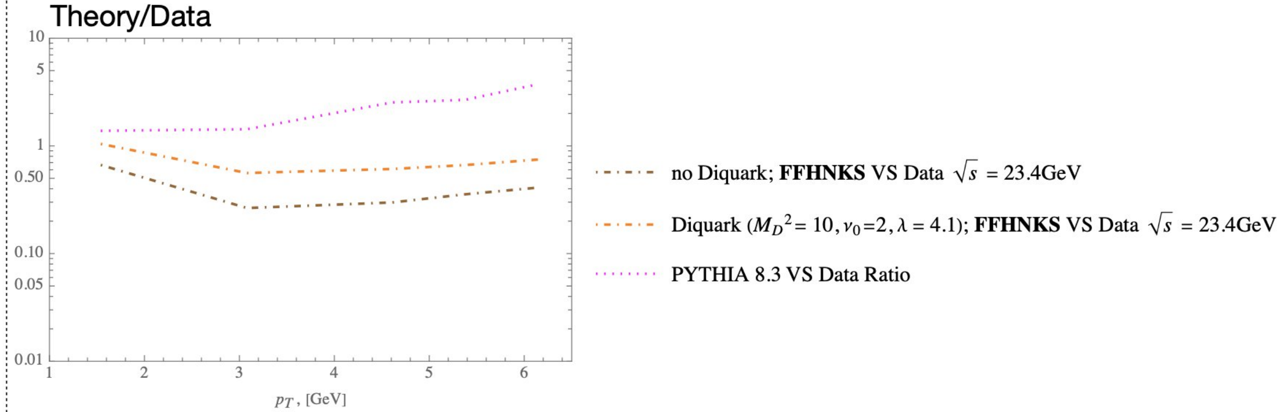
$\sqrt{s} = 23.4$ GeV



Theory/Data



Theory/Data



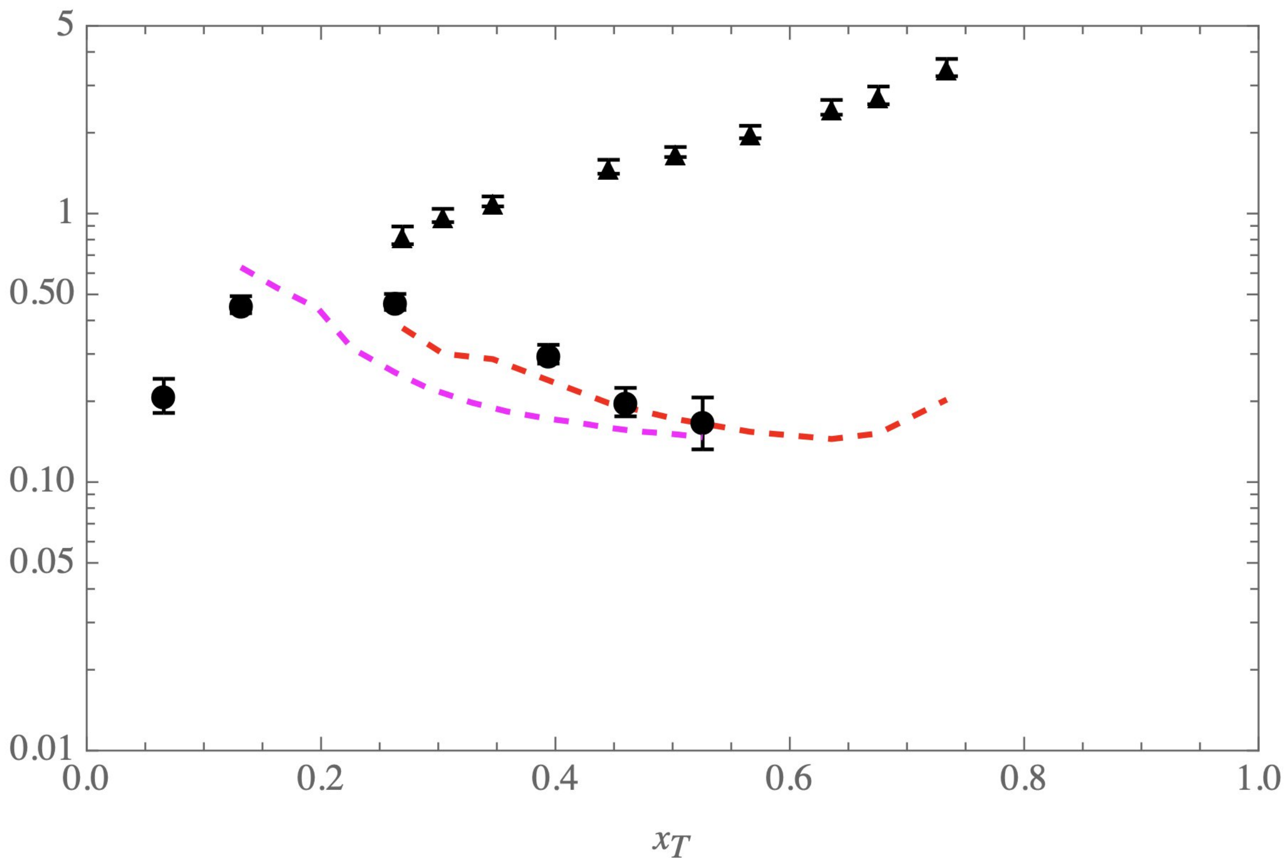
IHEP, Protvino, $\sqrt{s} = 11.5$ GeV
FODS, V.V. Abramov et al. (1985)

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/pi+ ratio without Diquark

p/π^+ Ratio



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

p/π^+ Ratio with $\theta_{cms} = 90^o$ 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

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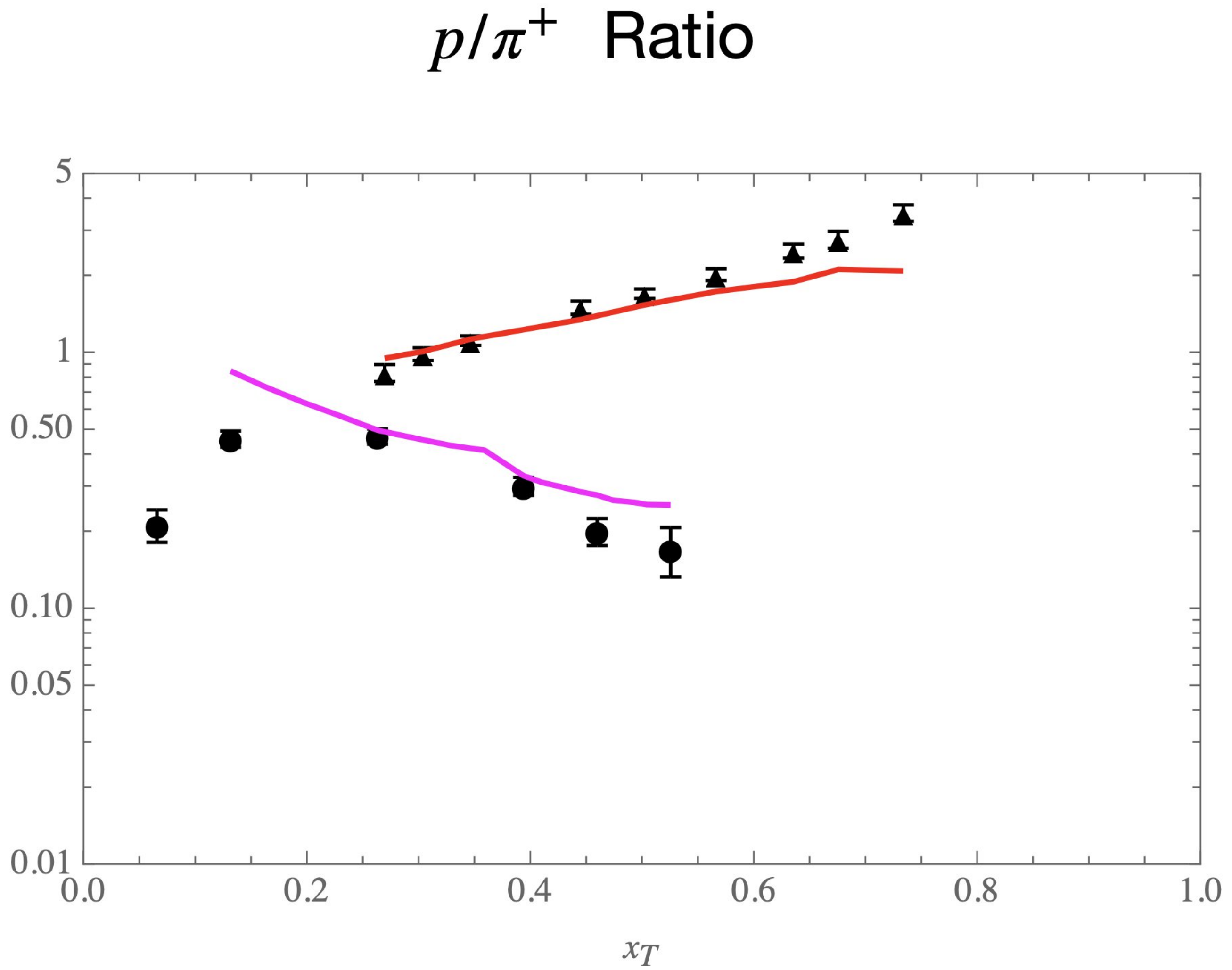
"Diquarks for Large- Baryon Production at High-Energy Collisions" V.T. Kim, A.V. Zelenov (Phys. Part. Nucl. Lett., 2025, Vol. 22, No. 1, pp. 213–218)

Scaling violation: p/pi+ ratio with Diquark



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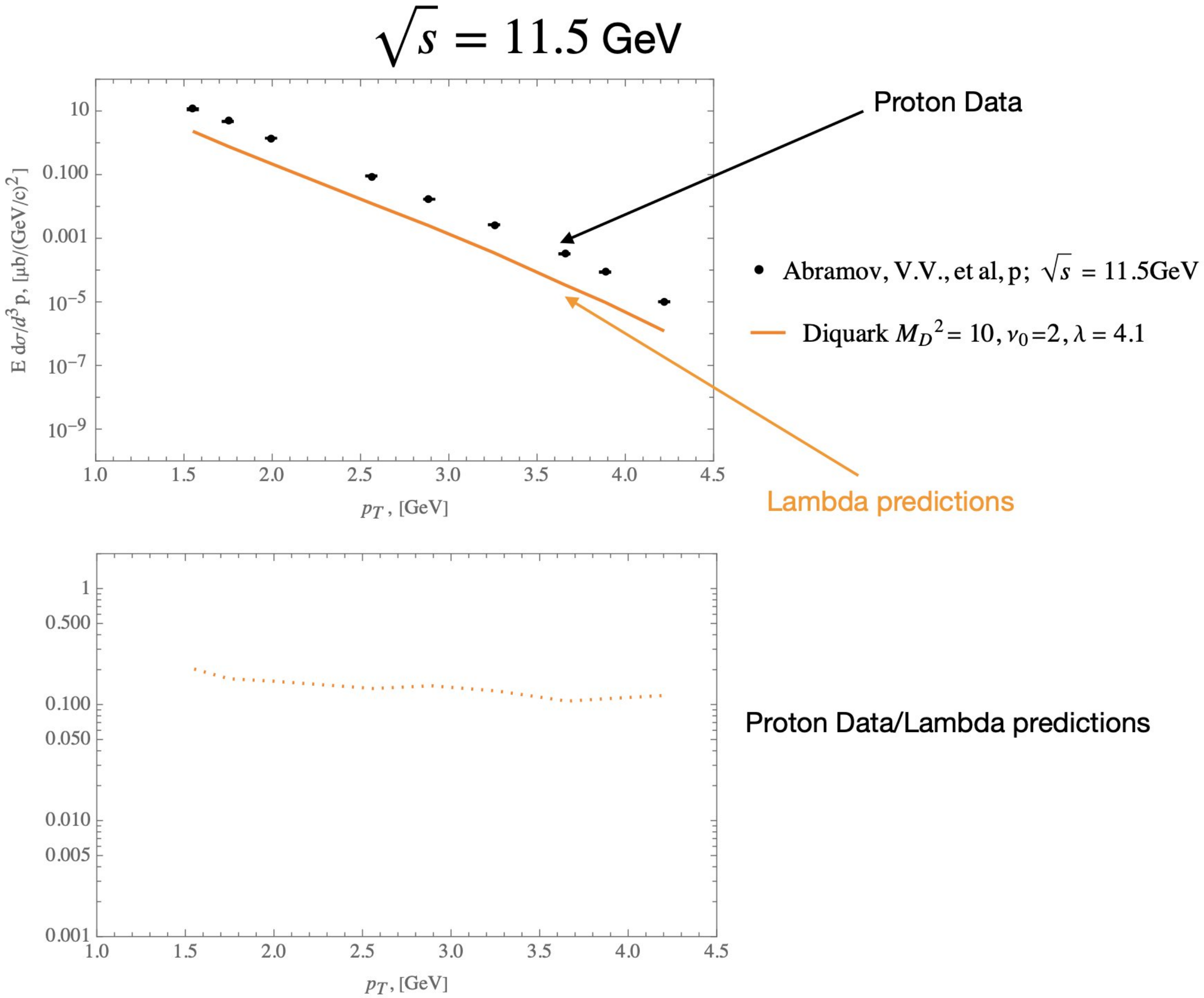
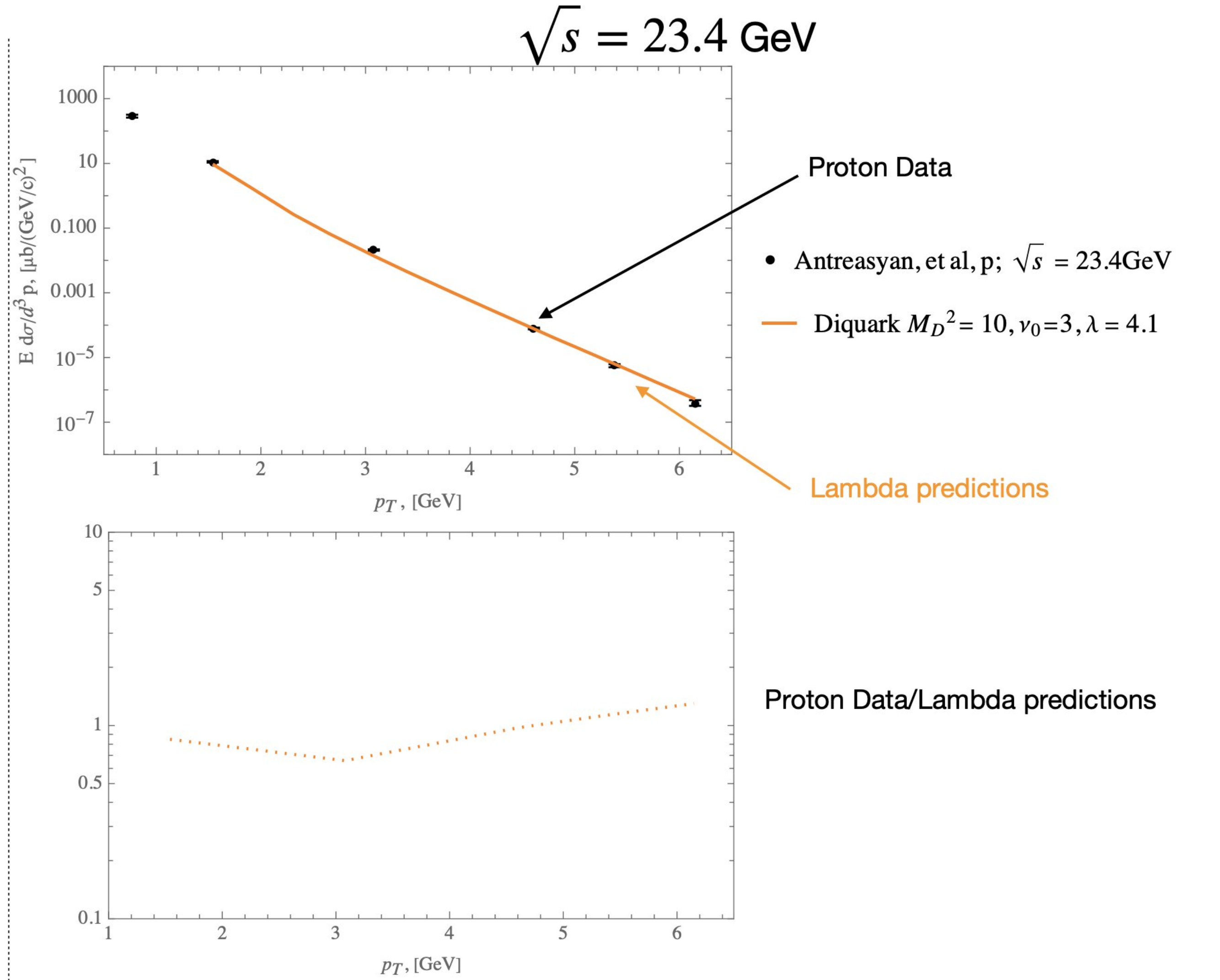
Large-pT Λ{(ud)s}-production





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

For **SPD@NICA:** $\Lambda \to p\pi^-$

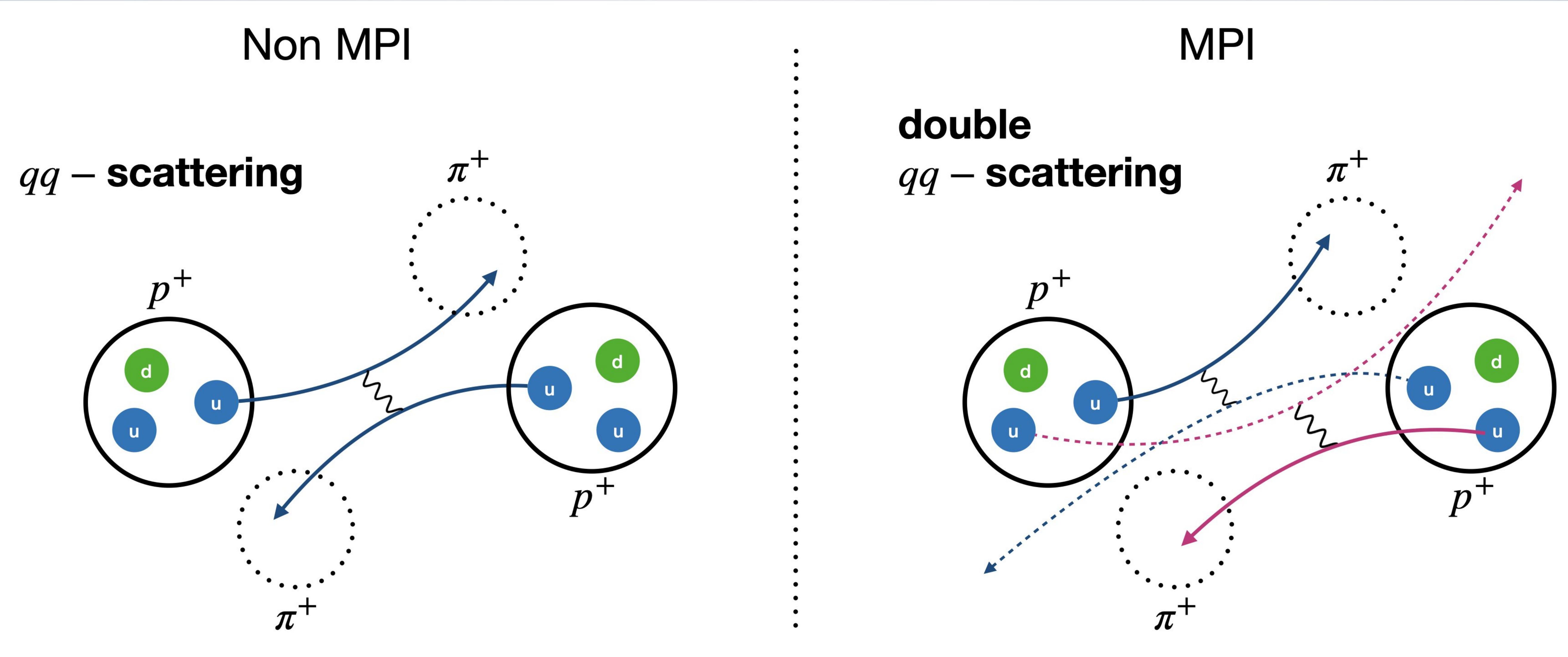
$$L = 10^{31} cm^{-2} s^{-1};\ N = 10000 \qquad t = \frac{N}{\sigma \cdot L \cdot Br \cdot \text{DetEff}} \simeq 1/2 \text{ month}$$

optimal data taking 3 months

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

“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)

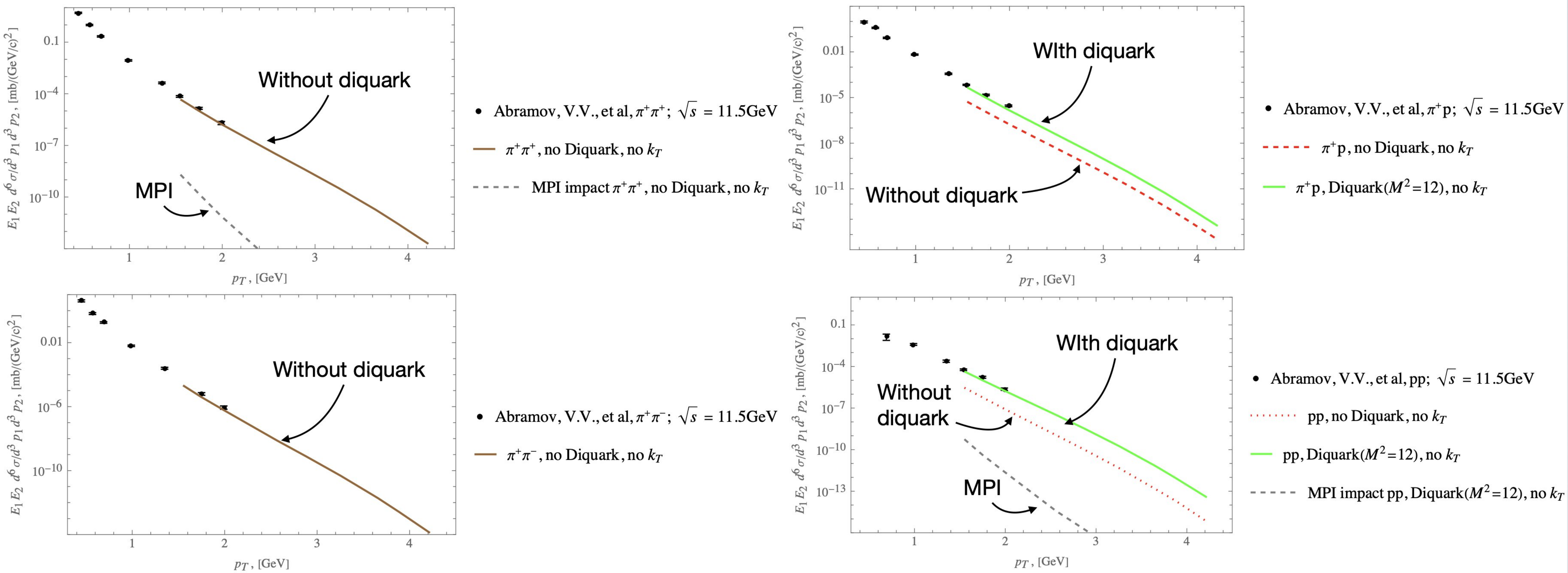
Hadron symmetric pairs production



Hadron symmetric pairs 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)

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



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

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

Hadron symmetric pairs productions

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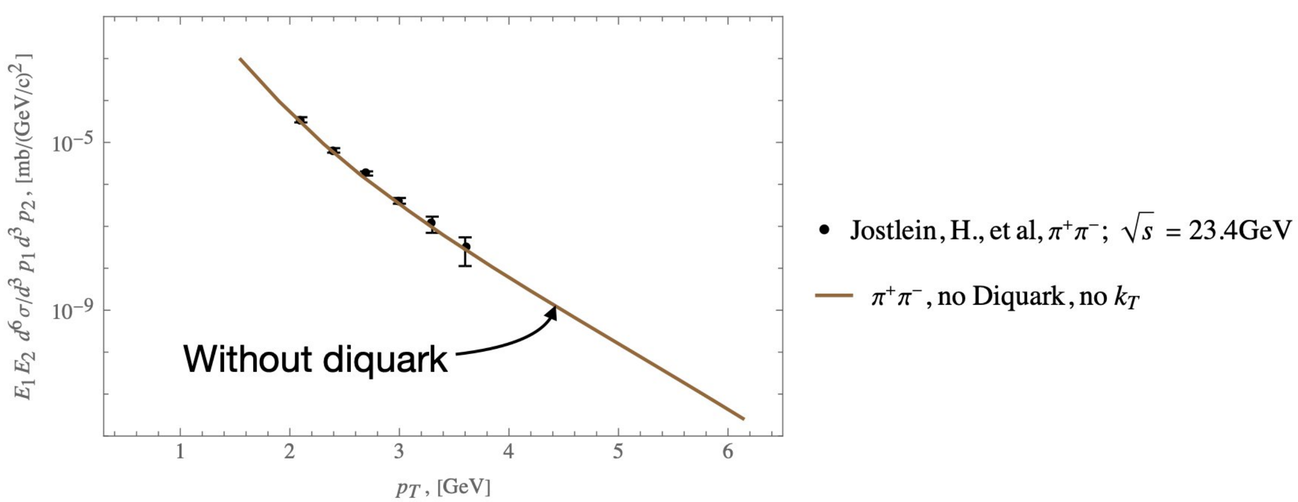
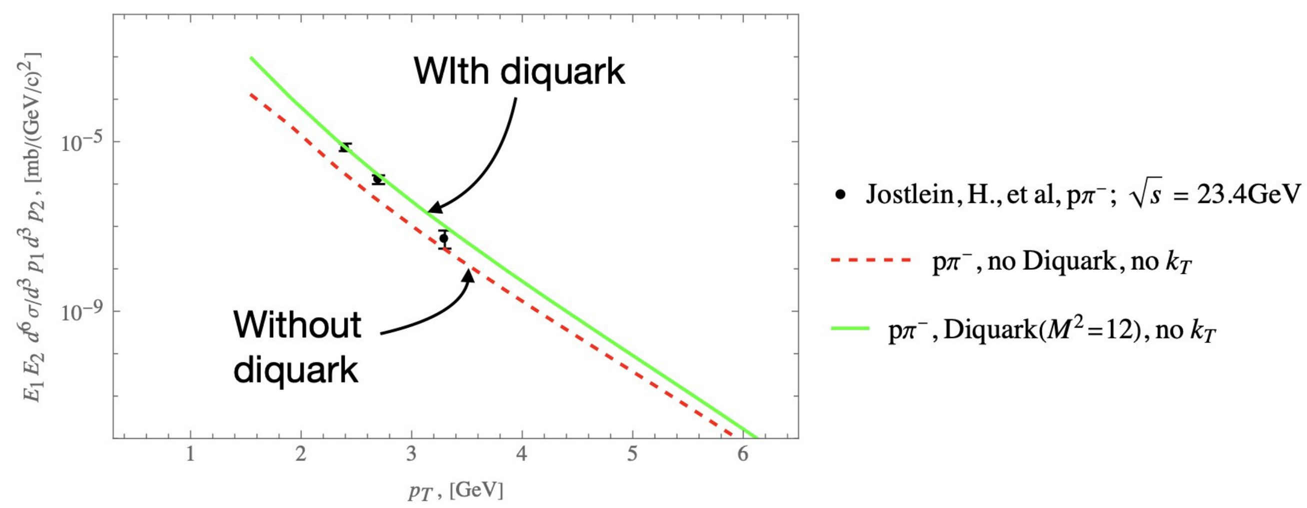
High-Energy Collisions” V.T. Kim, A.V. Zelenov
(Phys. Part. Nucl. Lett., 2025, Vol. 22, No. 1, pp. 213–218)

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

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



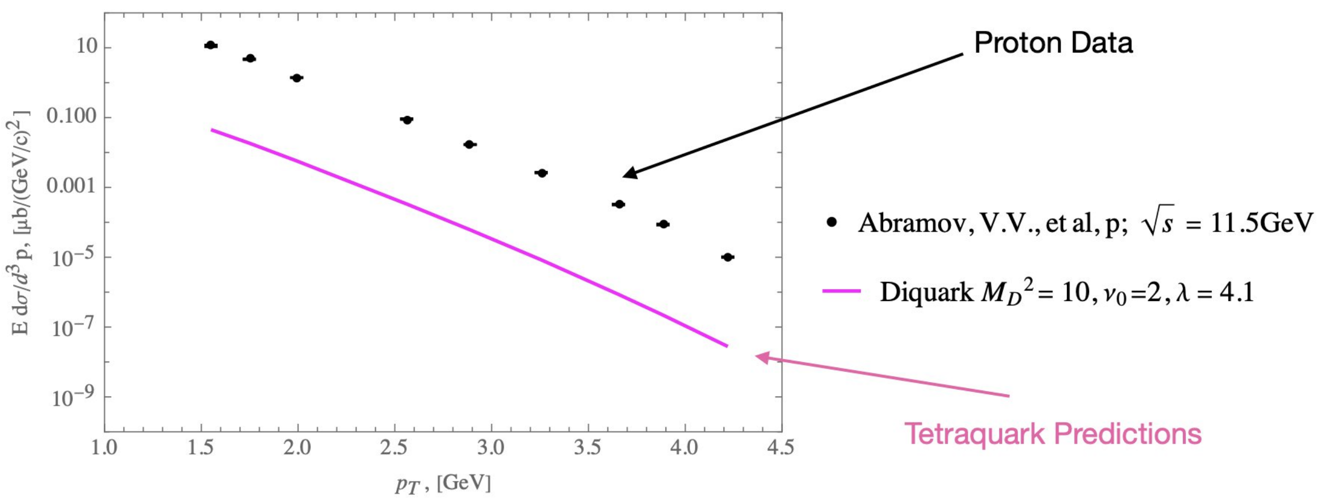


FNAL, Batavia
H.Jostlein et al. (1979)

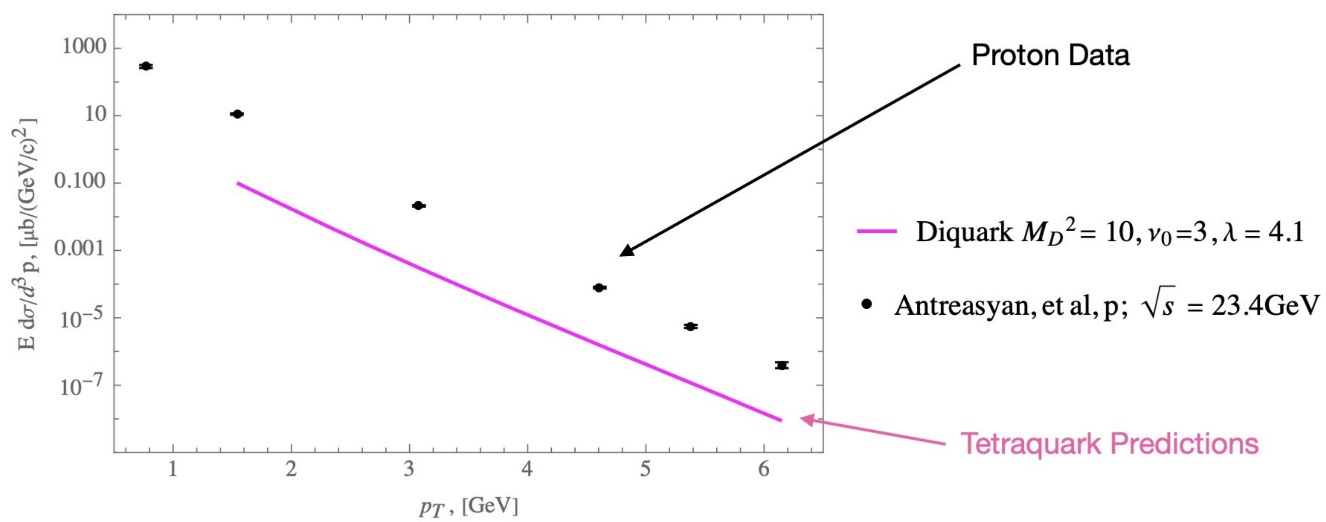
$$\sqrt{s} = 23.4 \text{ GeV}$$

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

$\sqrt{s} = 11.5$ GeV



$\sqrt{s} = 23.4$ GeV



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

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

For **SPD@NICA:** $a_0(980) \rightarrow K^0\bar{K}^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ $p_T(\pi) \sim 1/4\ p_T(a_0)$

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

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)

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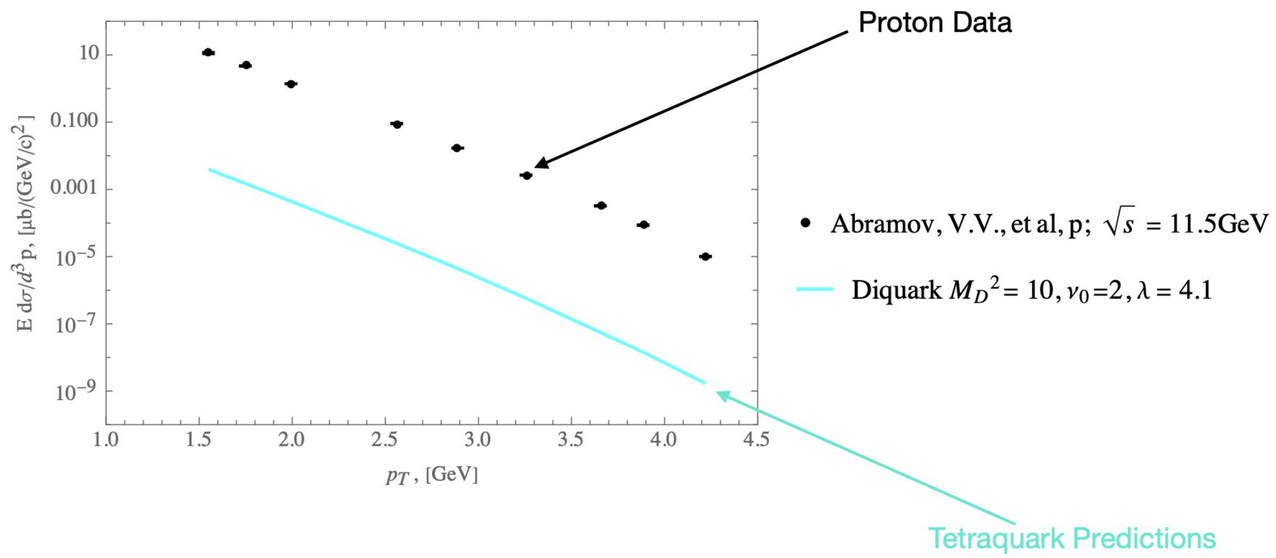
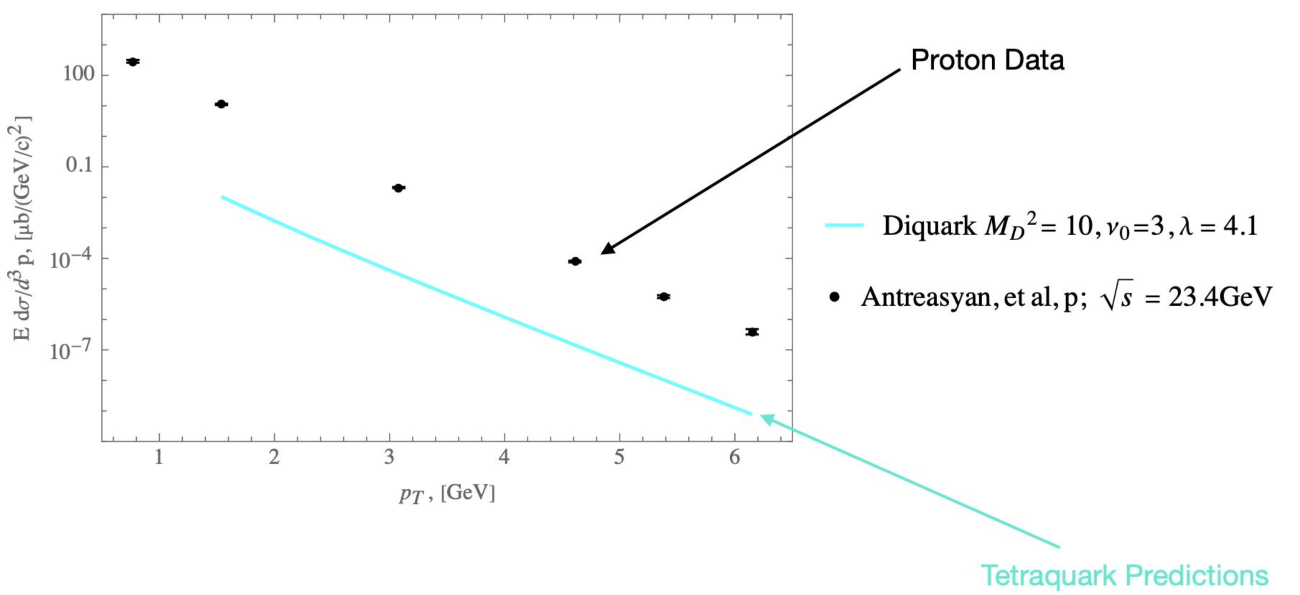
Exotic state production.
Tetraquark: $(qq\bar{q}\bar{q})$ $X:\{(ud)\bar{s}\bar{s}\}$

$\sqrt{s} = 11.5$ GeV



$\sqrt{s} = 23.4$ GeV



IHEP, Protvino, $\sqrt{s} = 11.5$ GeV
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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)

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Summary

- **Diquarks (2-quark correlations) can describe the strong scaling violation in large-pT proton production**

- **Large-pT hadron and symmetric hadron pairs production at SPD NICA provides a unique opportunity to improve understanding of Diquark role for production of baryons and the role of double-parton scattering**

- **Large-pT hadron and symmetric hadron pairs production at SPD NICA provides a unique opportunity to improve understanding of Diquark role for production of exotic multi-quark states - Tetraquarks**

"Diquarks for Large-pT 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)

"Possible Studies at the First Stage of the NICA Collider Operation with Polarized and Unpolarized Proton and Deuteron Beams..."
V.V. Abramov et al. (Phys. Part. Nucl. 2021, Vol. 52, No. 6, pp. 1044-1119)