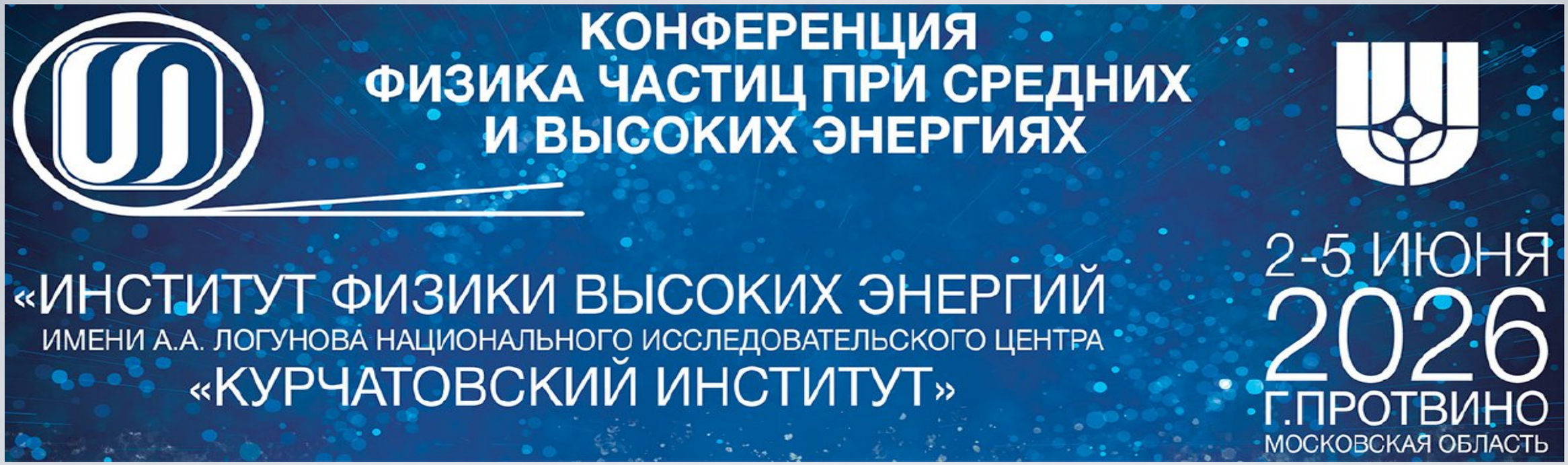


Diquark Role in Baryon and Exotic State Production with Large pT at high-energies

Victor T. Kim & Andrei V. Zelenov

Petersburg Nuclear Physics Institute
National Research Centre «Kurchatov Institute»

Outlooks

- Introduction
- Diquark role in large-pT baryon and symmetric back-to-back hadron pair production
- Diquark role in large-pT multi-quark exotic state production
- Summary

Diquarks in baryons

Diquarks in baryons

M. Ida, R. Kobayashi, Prog. Theor. Phys. (1966) 846

D. Lightenberg et al., Phys. Rev. 167 (1968) 1535
Phys. Rev. 174 (1968) 1681

V.V. Anisovich, P.E. Volkovizsky, V.I. Povzun ZhETP 70 (1976) 1613

M.I. Pavkovic, Phys. Rev. D13 (1976) 2128

Modern approaches to diquarks:
holographic QCD, meson-baryon “supersymmetry”, etc.

F. Gross et al., 50 Years of Quantum Chromodynamics,
Eur. Phys. J. C 83 (2023) 1125

Diquarks in nonperturbative QCD

QCD Sum Rules: M.A. Shifman, A.I. Vainshtein, V.I. Zakharov, V.A.Novikov
quark-gluons vacuum condensates (1978-1982)
quarks in hadrons directly interacts with vacuum

Instantons A.A. Belavin, A.M. Polyakov, A.S. Schwarts Yu.S. Tyupkin (1975)

quark interaction ‘t Hooft (1976)
E.V. Shuryak (1982)
D.I. Diakonov, V.Yu. Petrov (1984-1986)

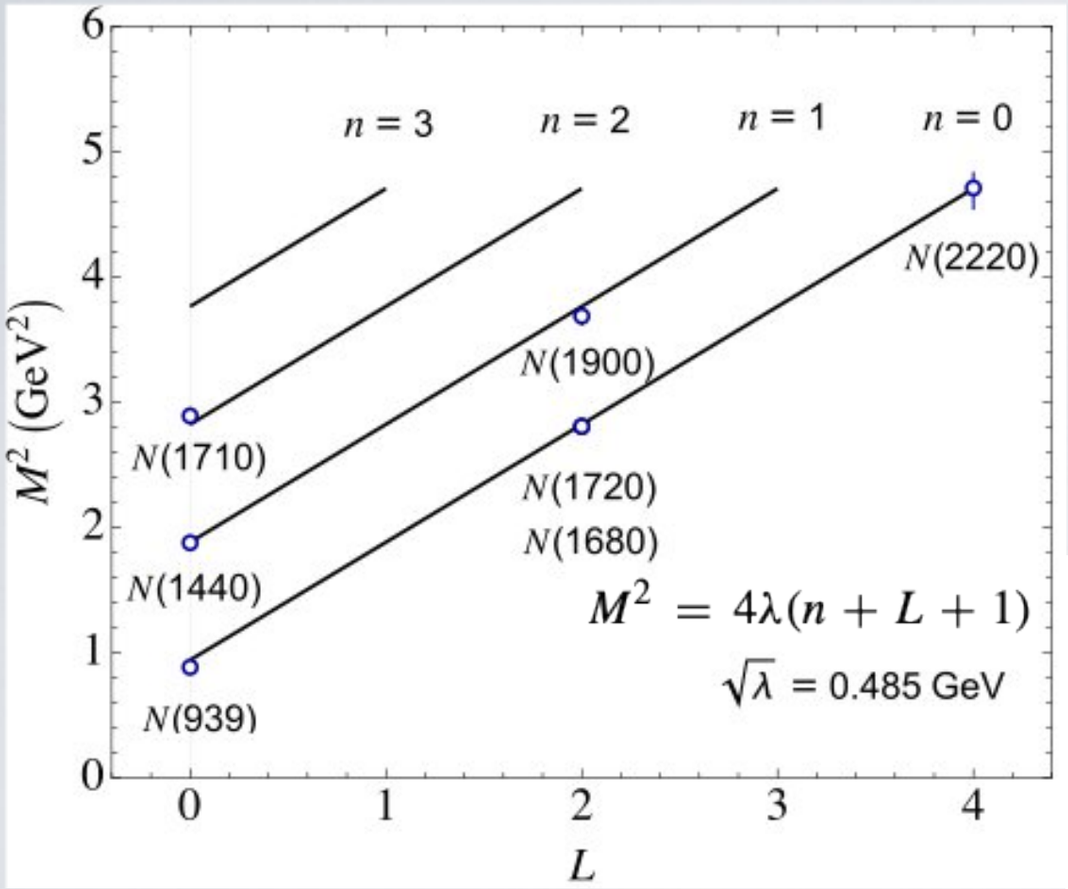
mass split of N(1/2) and Delta(3/2) baryons ~ 0.2 GeV
spin-spin interactions
pQCD -> ~10% MIT bag model

Instantons for hadron masses -> N.I. Kochelev
N.I. Kochelev, Yad. Fiz. 41 (1985) 456

Diquarks by Instantons -> favors scalar diquark
A.S. Dorokhov, N.I. Kochelev (1987-1994)

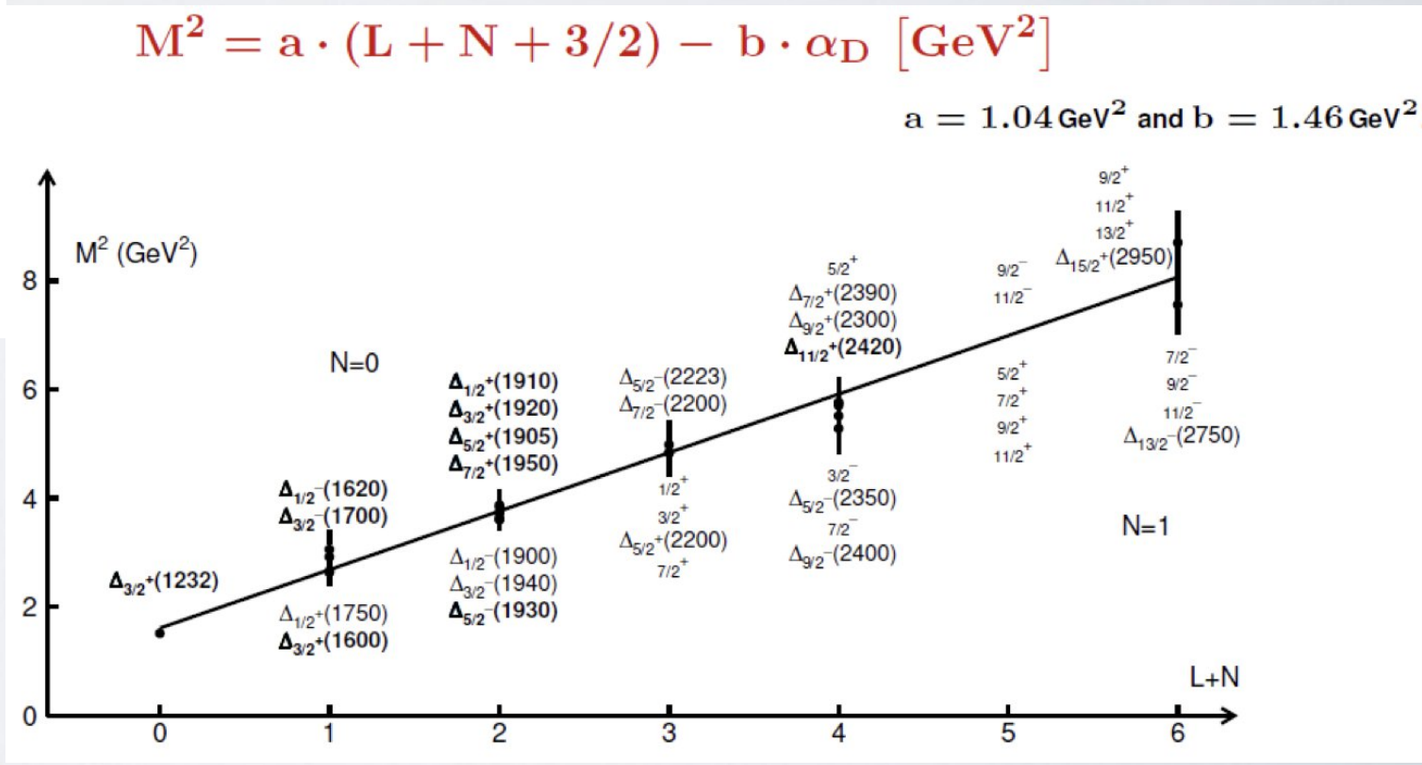
Diquarks in baryons

Regge-like spectrum of light baryons
F. Gross et al., "50 Years of QCD"
Eur. Phys. J. C 83 (2023) 1125



Lund String Model
Monter Carlo Event Generators
JETSET, PYTHIA, ...
A.V. Fredriksson et al.

For Delta baryons see, e.g.,
talk at this PPIHE-2026 conference
A.V. Sarantsev et al.

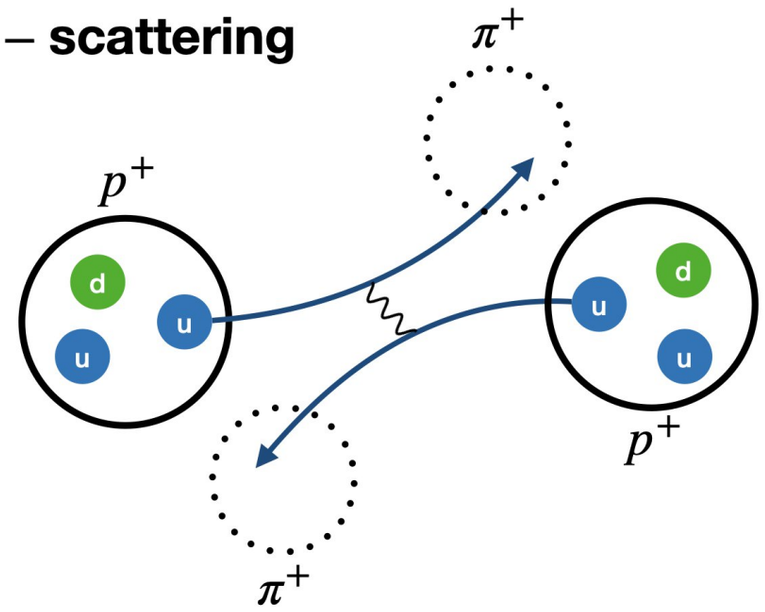


Large-pT processes in QCD

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**

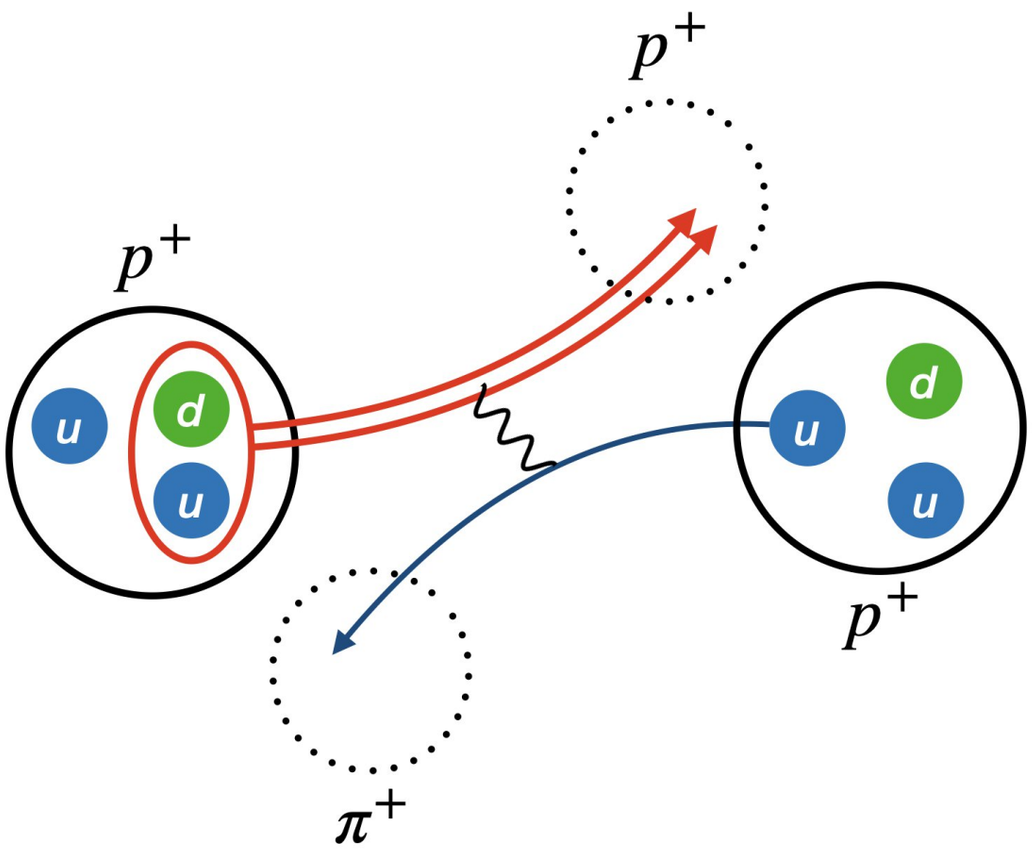


Parton-parton scattering is the main source of mesons with large p_T in pp collisions

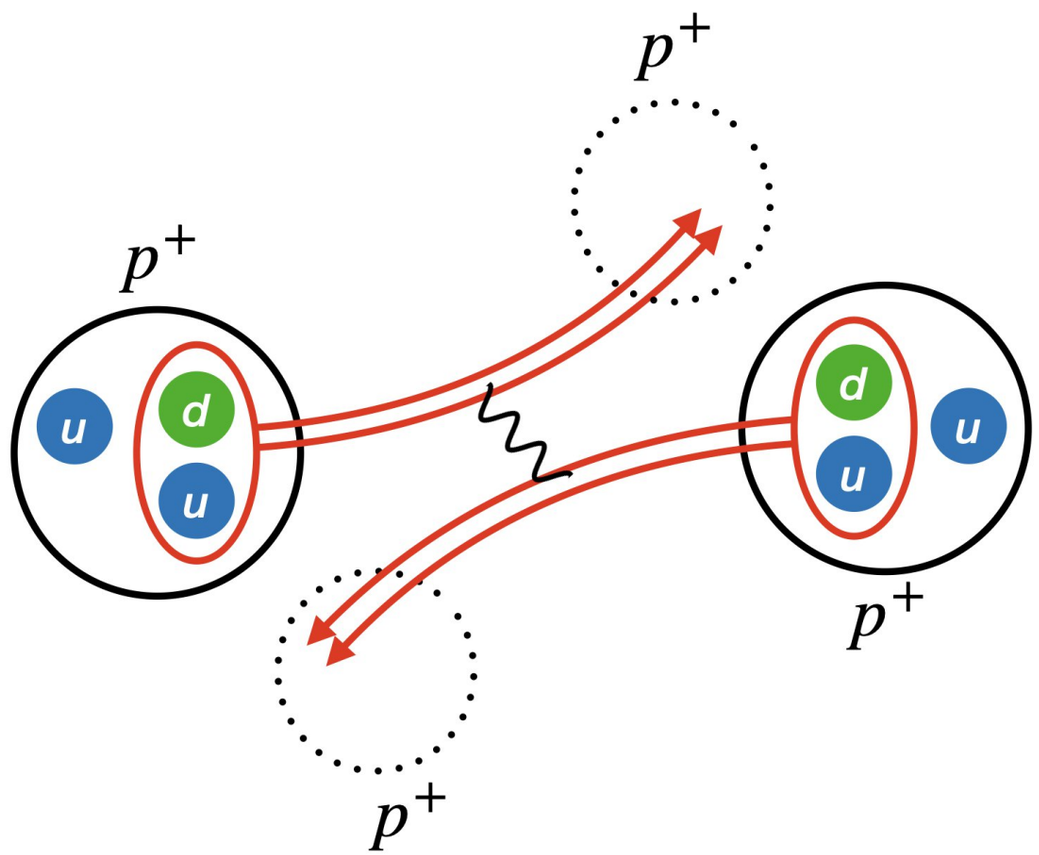
H. Minakata Shimizu, Lett. Nuovo Cim. 27 (1980) 241
L.V. Laperashvili, Yad. Fiz. 35 (1982) 732
T.I. Larsson, Phys. Rev. D29 (1984) 1013
S. Ekelin, S. Fredriksson, Phys. Lett. B149 (1984) 509
V.T. Kim, Mod. Phys. Lett. A3 (1988) 909

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

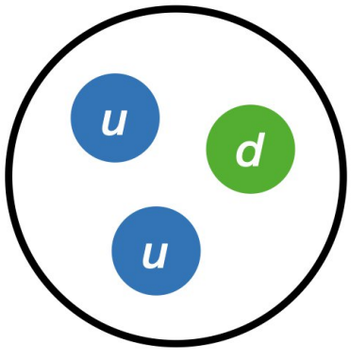
$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{DD} = \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qq} \cdot f^4(Q^2)$$

H. Minakata Shimizu, Lett. Nuovo Cim. 27 (1980) 241
L.V. Laperashvili, Yad. Fiz. 35 (1982) 732
T.I. Larsson, Phys. Rev. D29 (1984) 1013
S. Ekelin, S. Fredriksson, Phys. Lett. B149 (1984) 509
V.T. Kim, Mod. Phys. Lett. A3 (1988) 909, V.T. Kim, JINR E2-87-75 (1987)

Two-quark correlations: Diquarks

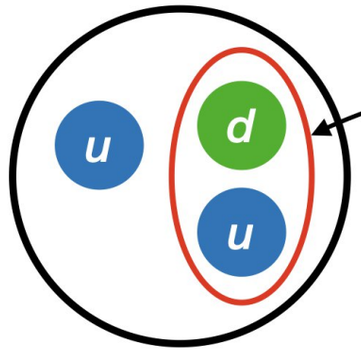
Diquark is a two-quark correlation in baryons.

$p\{uud\}$



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

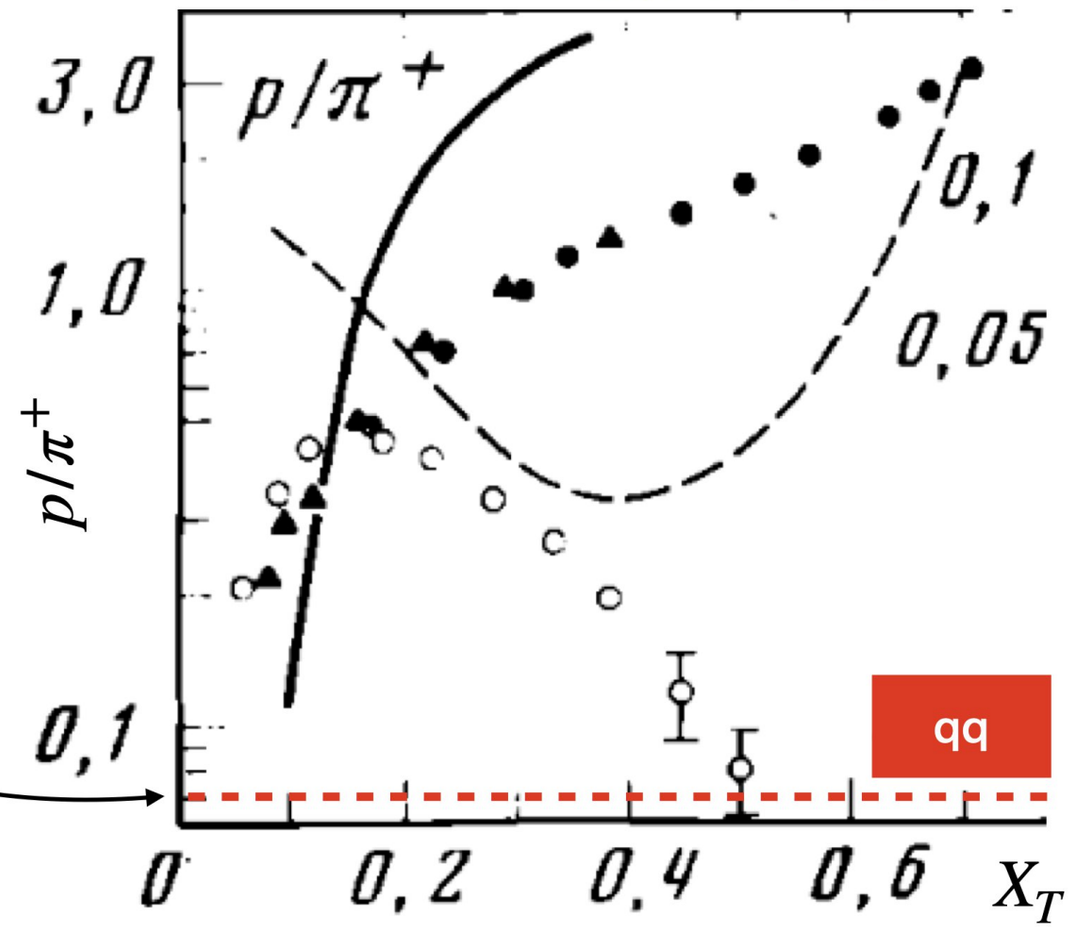
Large-pT hadron production: strong scaling violation for protons

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

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

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

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



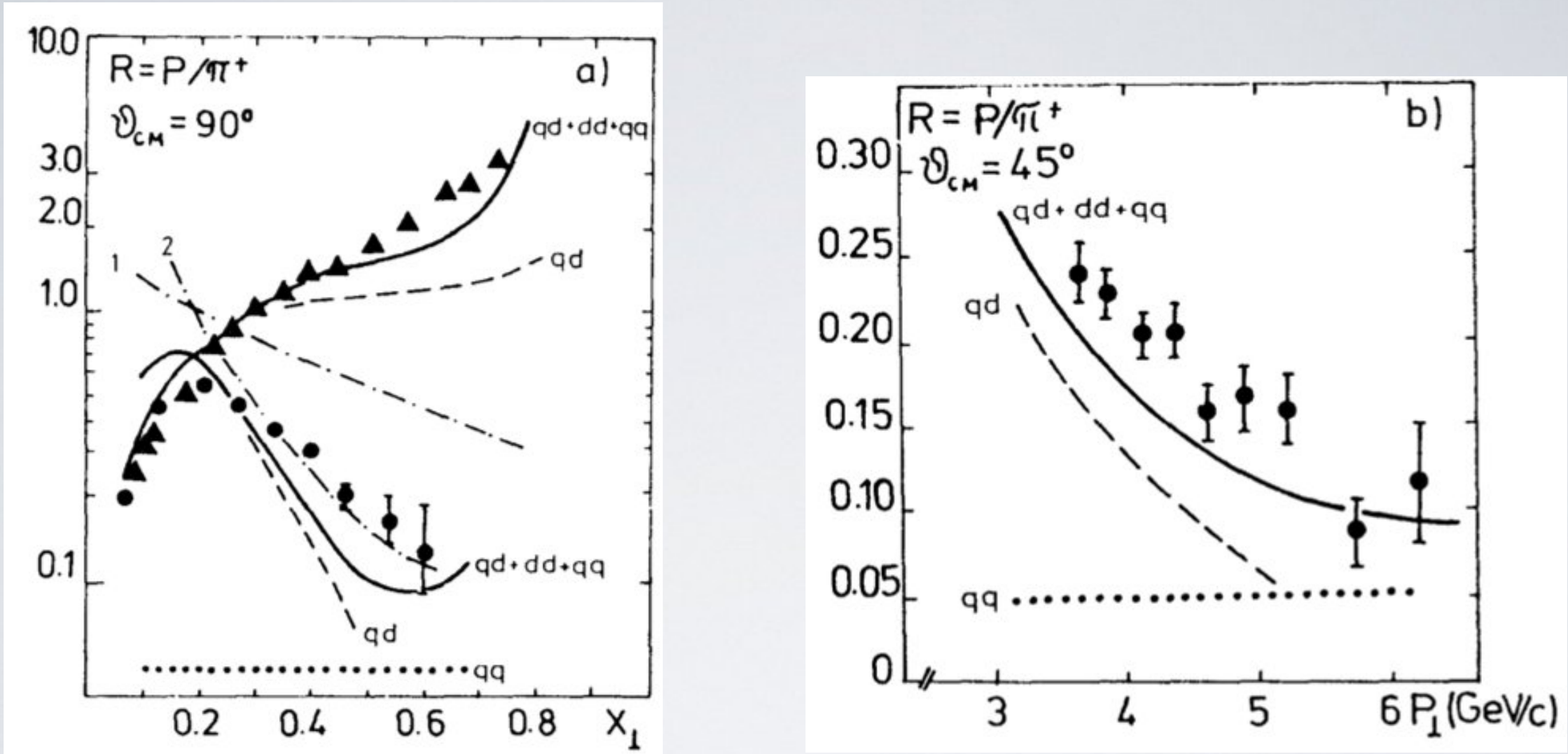
Parton-parton interactions fail to describe the anomalous yield of protons with large-p_T in pp collisions.

STRONG SCALING VIOLATION

proton/pion ratio: strong scaling violation
Protvino U70 FODS (√s=11.5 GeV), FNAL CP (√s=23.4 GeV)

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

Large-pT hadron production: strong scaling violation for protons



proton/pion ratio: strong scaling violation

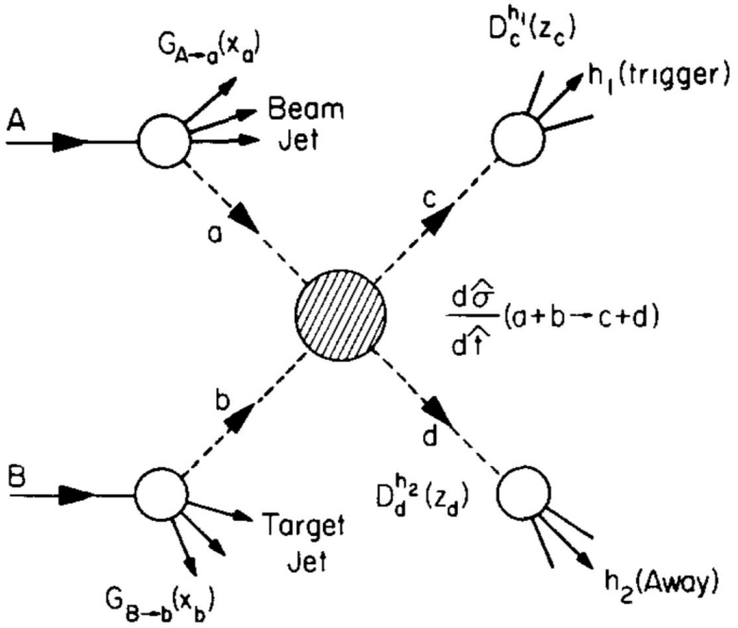
a) Protvino U70 FODS (√s=11.5 GeV), FNAL CP (√s=23.4 GeV),

b) CERN ISR ABCDHW (√s=62 GeV)

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

Feynman approach: collinear factorization improved by kT-dependence

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



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

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

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

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 kT-dependence

Diquark impact:

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

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

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

Parton Distribution Function:

Diquark PDF

Fragmentation Function:

Diquark FF

Subprocess cross section:

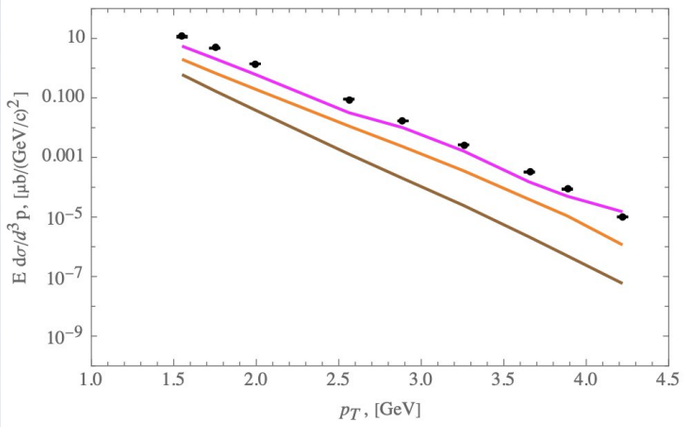
$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{qD},\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{\bar{q}D},\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{gD},\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{DD}$$

"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

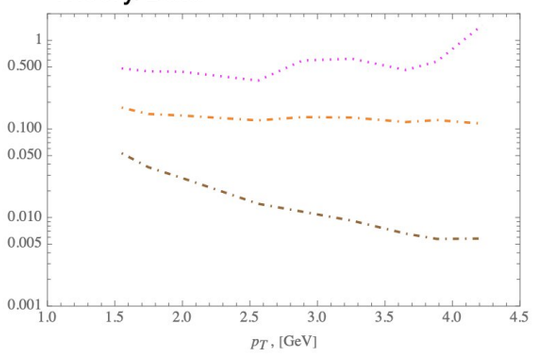
"Diquarks for Large- Baryon Production at High-Energy Collisions" V.T. Kim, A.V. Zelenov (Phys. Part. Nucl. Lett., 2025, Vol. 22, No. 1, pp. 213–218)

$\sqrt{s} = 11.5$ GeV



- Abramov, V.V., et al, p; $\sqrt{s}$ = 11.5GeV
- no Diquark; **FFHNKS**
- Diquark ($M_D{}^2$= 10, ν_0=2, λ = 4.1); **FFHNKS**
- PYTHIA 8.3, p; $\sqrt{s}$ = 11.5GeV

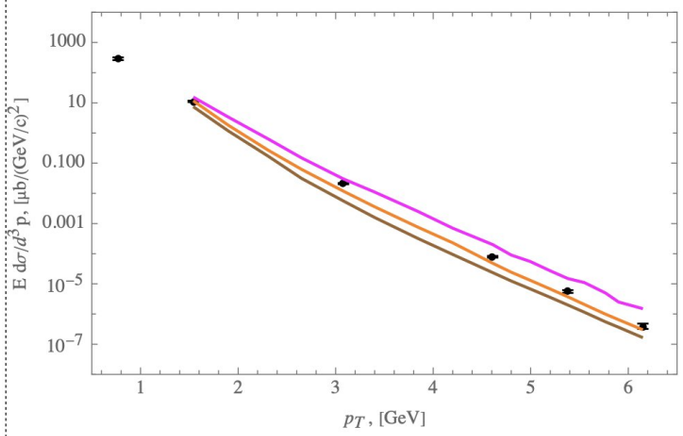
Theory/Data



- no Diquark; **FFHNKS** VS Data $\sqrt{s}$ = 11.5GeV
- Diquark ($M_D{}^2$= 10, ν_0=2, λ = 4.1); **FFHNKS** VS Data $\sqrt{s}$ = 11.5GeV
- PYTHIA 8.3 VS Data Ratio

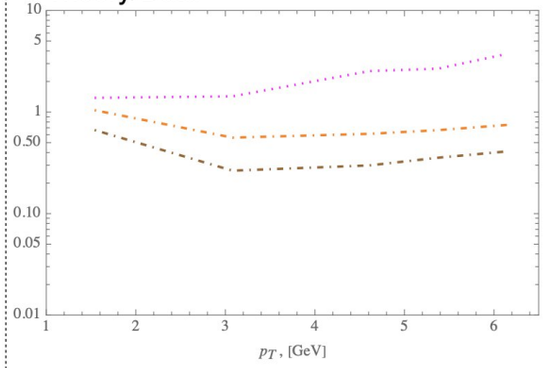
IHEP, Protvino, $\sqrt{s}$ = 11.5 GeV
FODS, V.V. Abramov et al. (1985)

$\sqrt{s} = 23.4$ GeV



- Antreasyan, et al, p; $\sqrt{s}$ = 23.4GeV
- no Diquark; **FFHNKS**
- Diquark ($M_D{}^2$= 10, ν_0=2, λ = 4.1); **FFHNKS**
- PYTHIA 8.3, p; $\sqrt{s}$ = 23.4GeV

Theory/Data



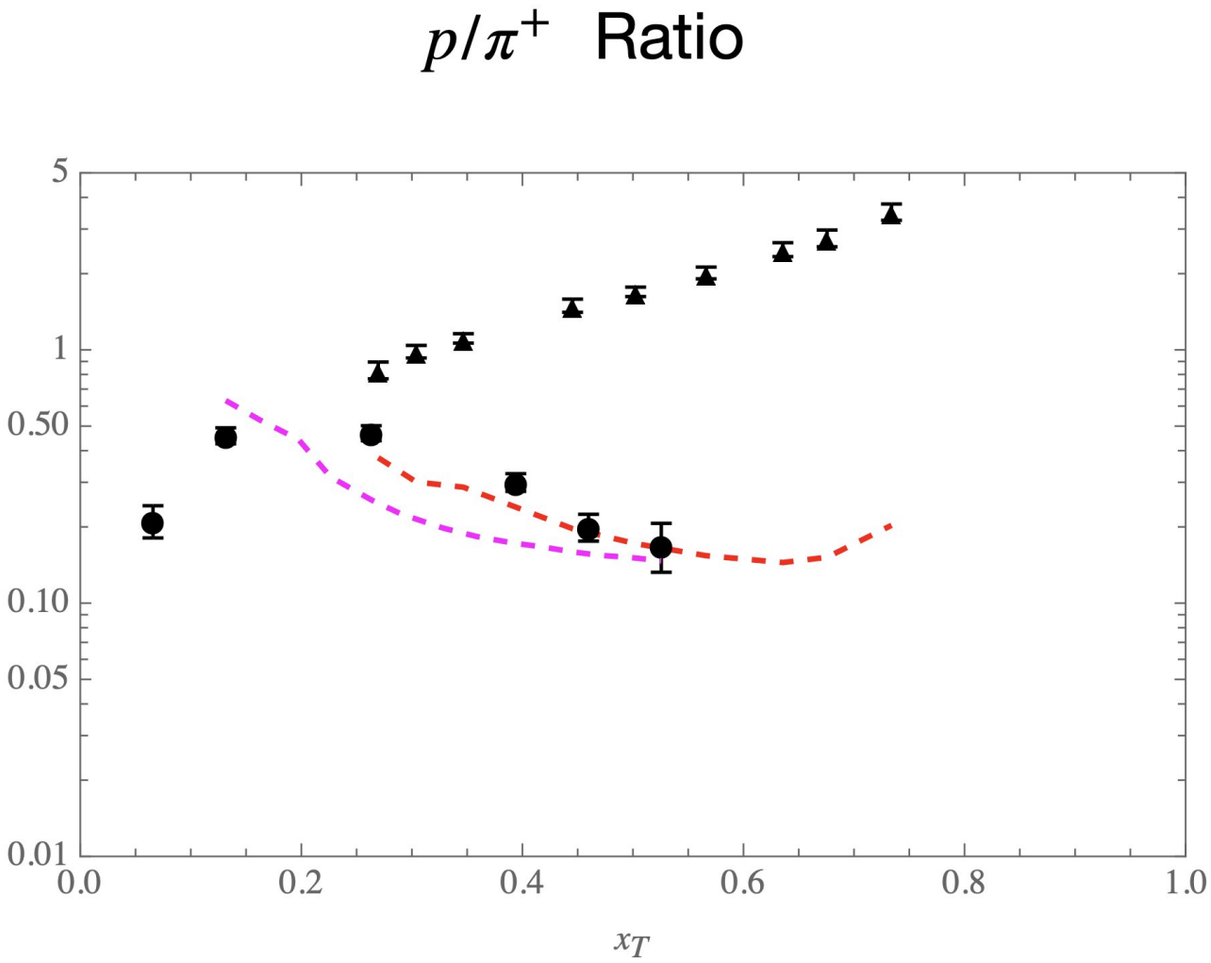
- no Diquark; **FFHNKS** VS Data $\sqrt{s}$ = 23.4GeV
- Diquark ($M_D{}^2$= 10, ν_0=2, λ = 4.1); **FFHNKS** VS Data $\sqrt{s}$ = 23.4GeV
- PYTHIA 8.3 VS Data Ratio

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)

1

Scaling violation: p/pi+ ratio without Diquark



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

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:

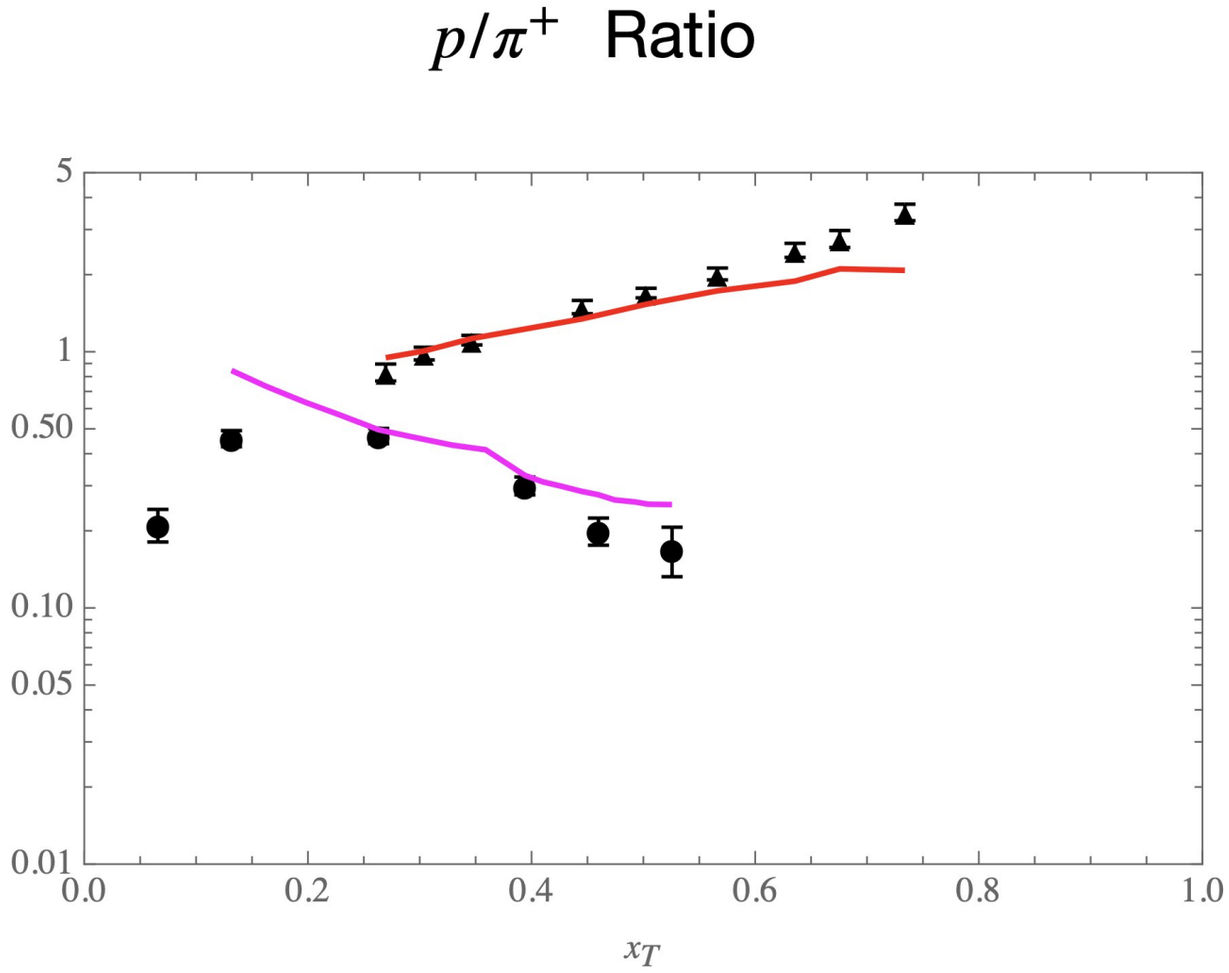
Red dashed line $-\sqrt{s} = 11.5$ GeV,

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

1

"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



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

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

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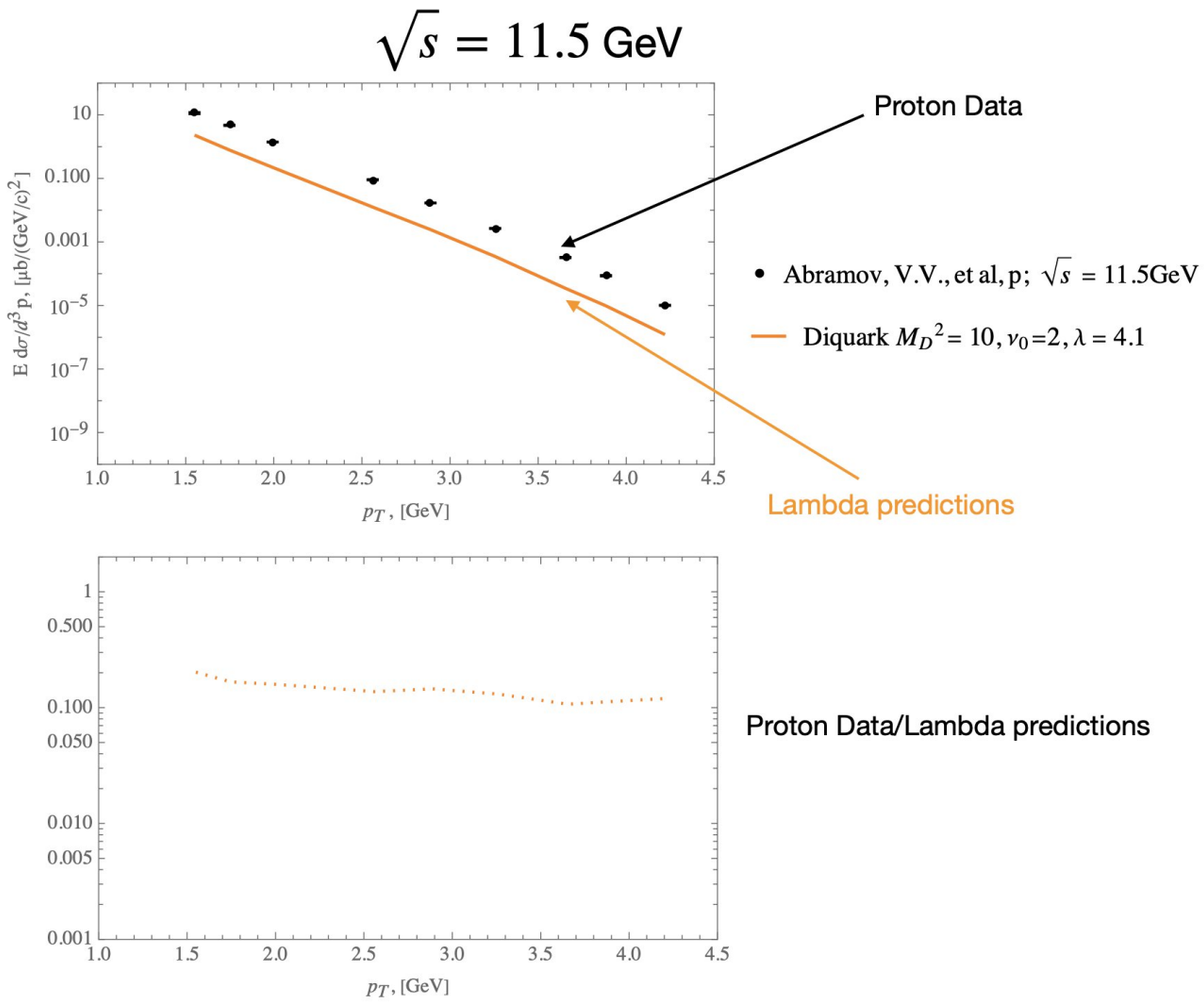
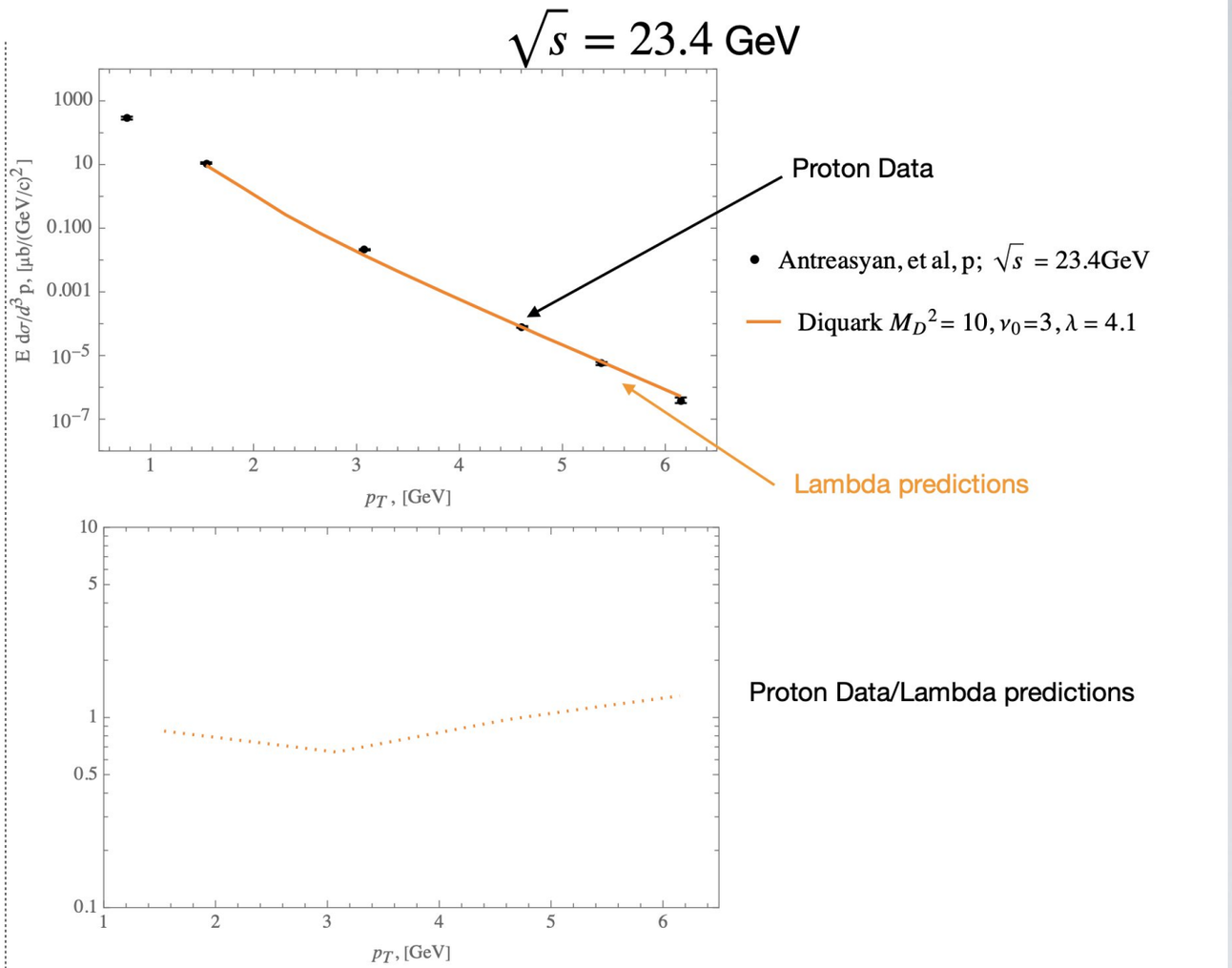
"Diquarks for Large- Baryon Production at High-Energy Collisions" V.T. Kim, A.V. Zelenov (Phys. Part. Nucl. Lett., 2025, Vol. 22, No. 1, pp. 213–218)

Large-pT Λ{(ud)s}-production



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



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

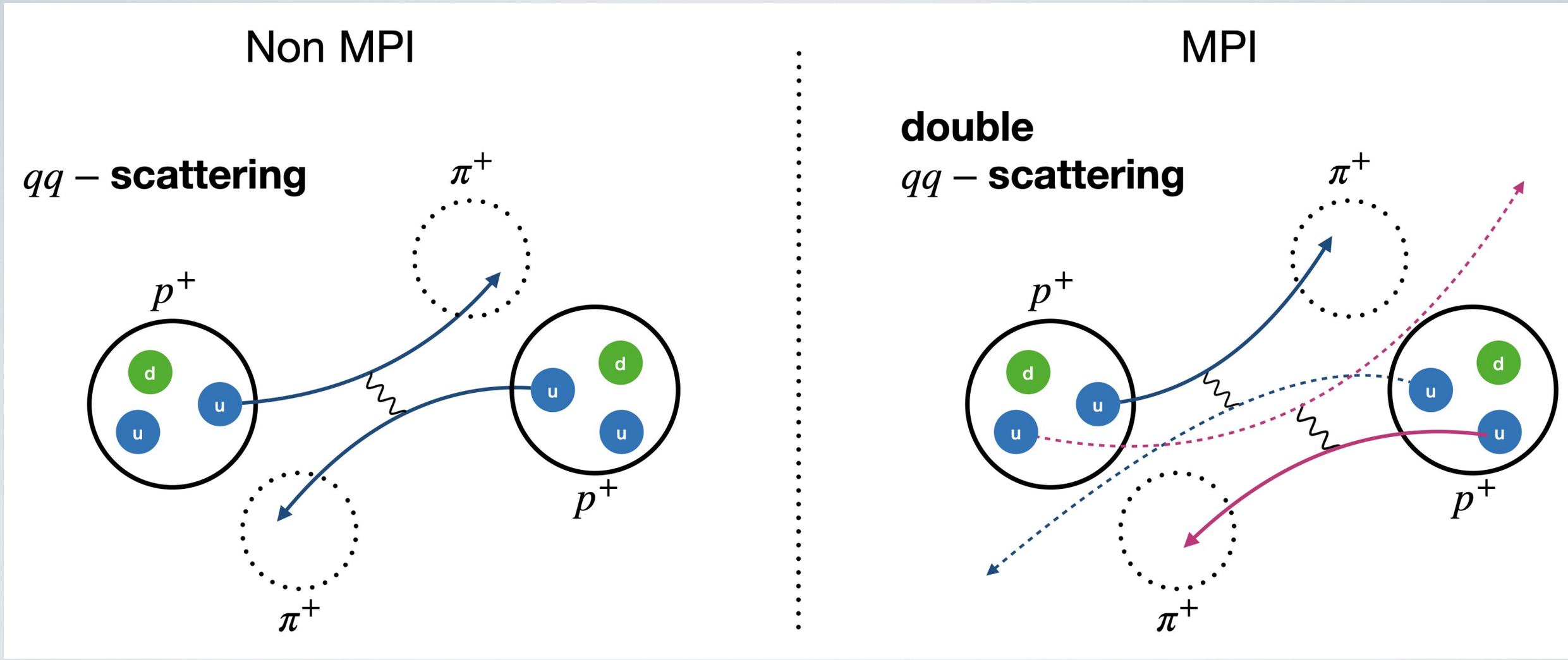
For **SPD@NICA:** $\Lambda \to p\pi^-$

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

optimal data taking 3 months

"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

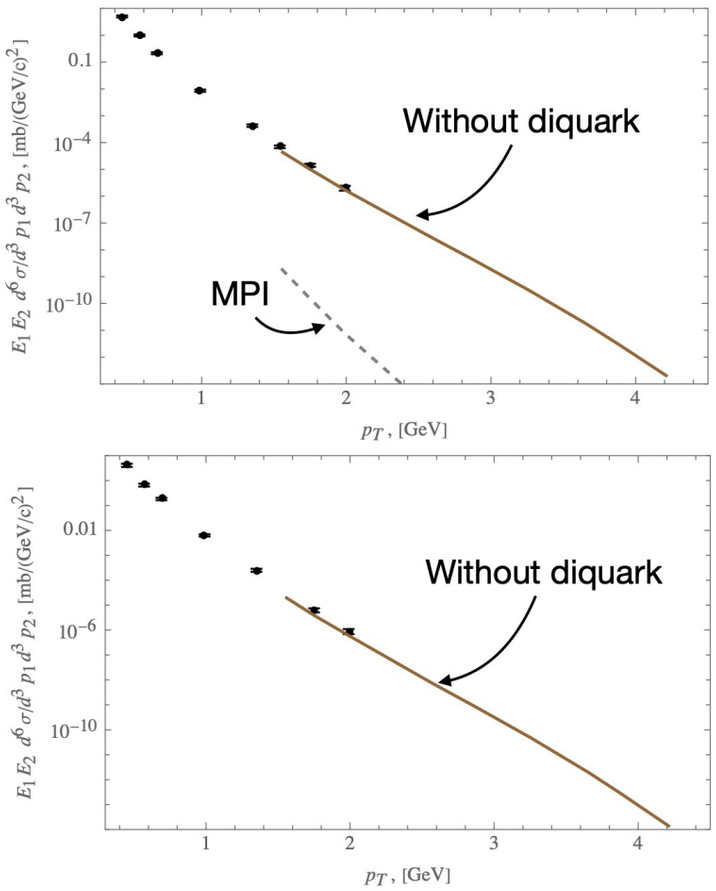


V.T. Kim, Mod. Phys. Lett. A3 (1988) 909, V.T. Kim, JINR E2-87-75 (1987)
V.T. Kim, A.V. Zelenov, Phys. Part. Nucl. Lett. 22 (2025) 213

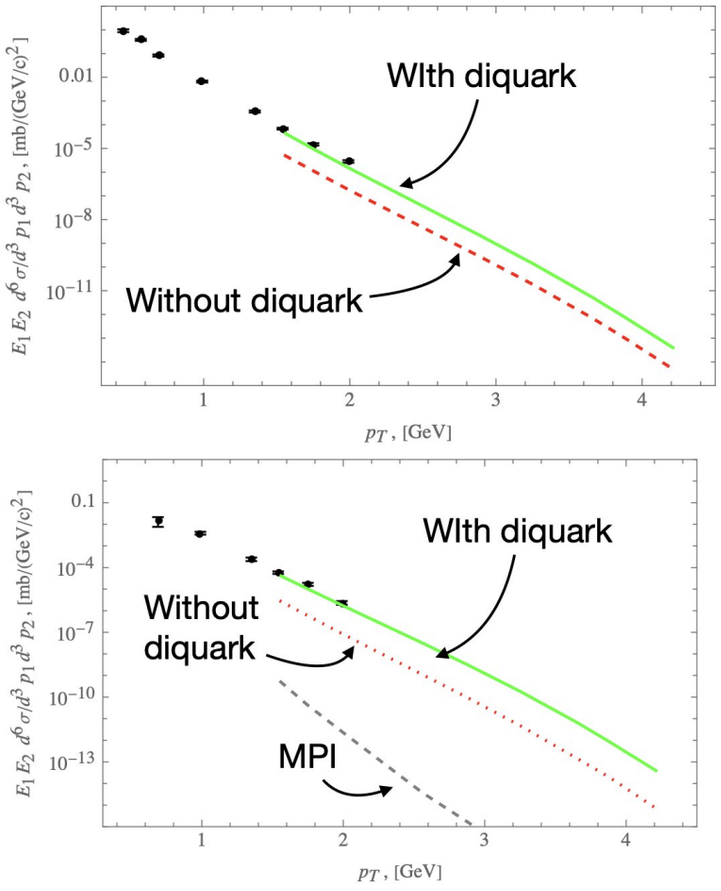
Hadron symmetric pair production

"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)

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



- Abramov, V.V., et al, $\pi^+\pi^+$; $\sqrt{s}$ = 11.5GeV
- $\pi^+\pi^+$, no Diquark, no k_T
- MPI impact $\pi^+\pi^+$, no Diquark, no k_T



- Abramov, V.V., et al, π^+p; $\sqrt{s}$ = 11.5GeV
- π^+p, no Diquark, no k_T
- π^+p, Diquark(M^2=12), no k_T

- Abramov, V.V., et al, $\pi^+\pi^-$; $\sqrt{s}$ = 11.5GeV
- $\pi^+\pi^-$, no Diquark, no k_T

- Abramov, V.V., et al, pp; $\sqrt{s}$ = 11.5GeV
- pp, no Diquark, no k_T
- pp, Diquark(M^2=12), no k_T
- MPI impact pp, Diquark(M^2=12), no k_T

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

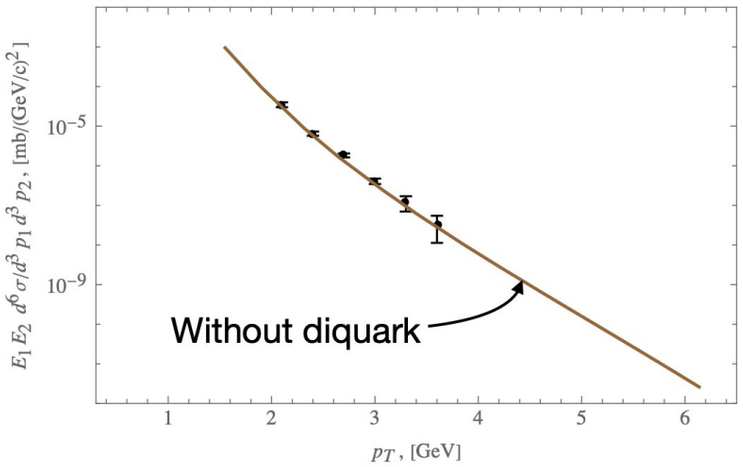
$$\sqrt{s} = 11.5 \text{ GeV}$$

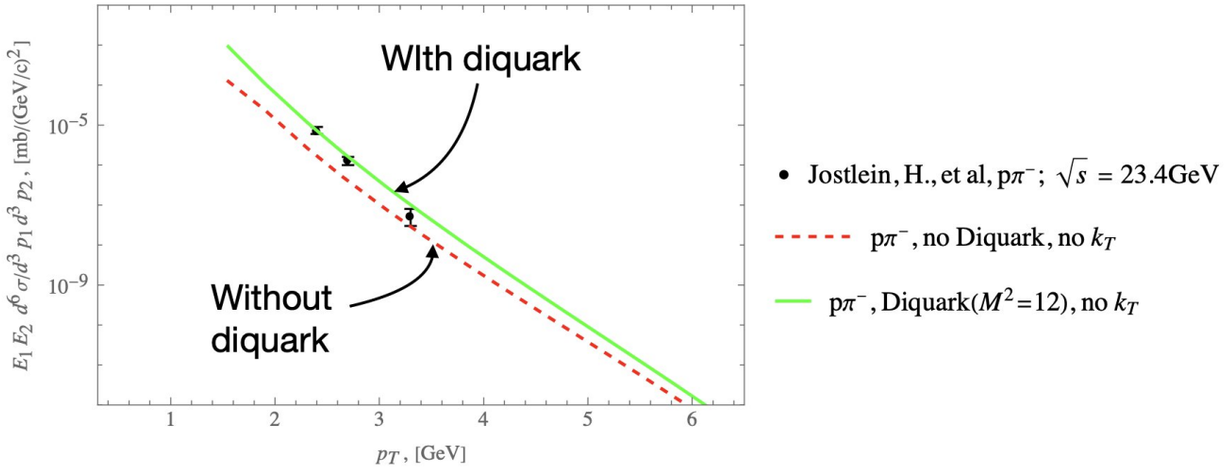
Hadron symmetric pairs productions

"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)

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

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



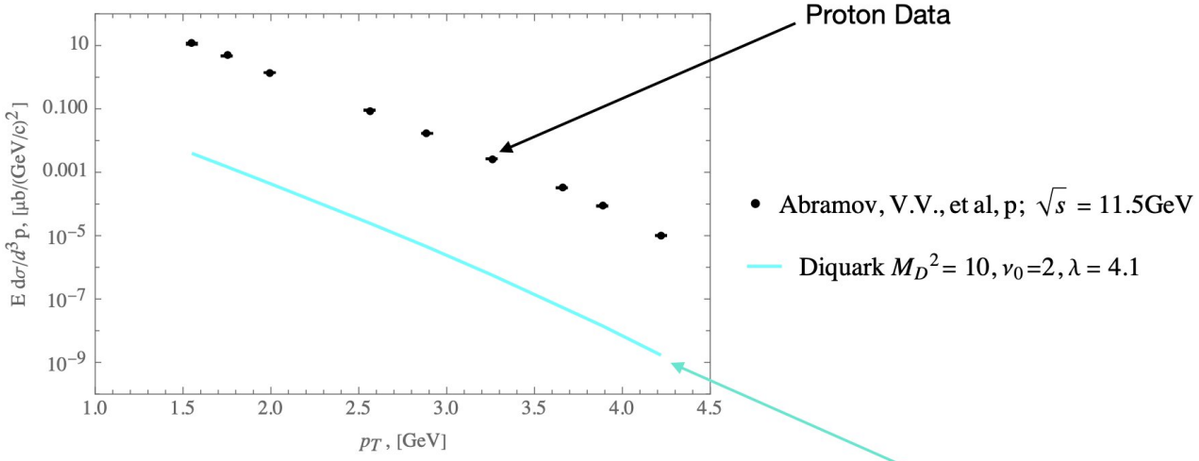


FNAL, Batavia
H.Jostlein et al. (1979)

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

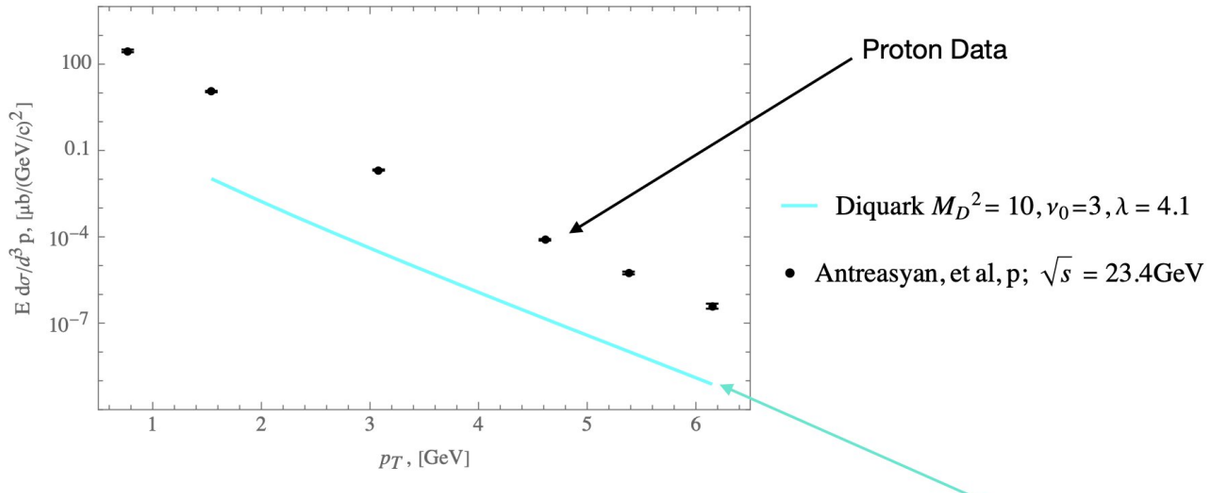
Exotic state production.
Tetraquark: (qq̄q̄q) X:{(ud)̄s̄s}

$\sqrt{s} = 11.5$ GeV



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

$\sqrt{s} = 23.4$ GeV



FNAL, Batavia, $\sqrt{s} = 23.4$ Ge
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)

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
V.T. Kim, A.V. Zelenov (2025)
A.V. Efremov, V.T. Kim (1987)

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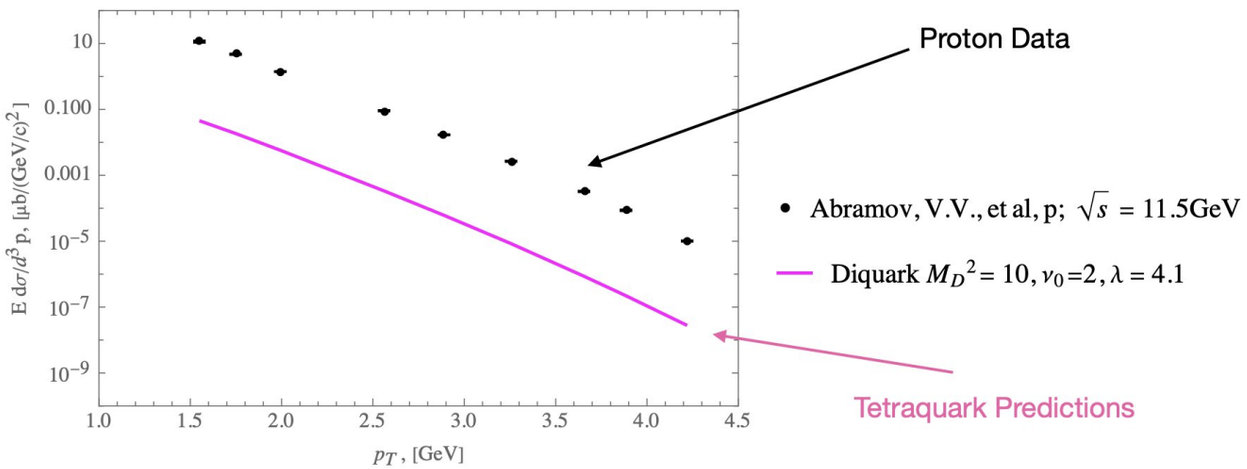
Exotic state production.
Tetraquark: $(qq\bar{q}\bar{q})$ a(980):{$(ud)\bar{q}\bar{q}$}

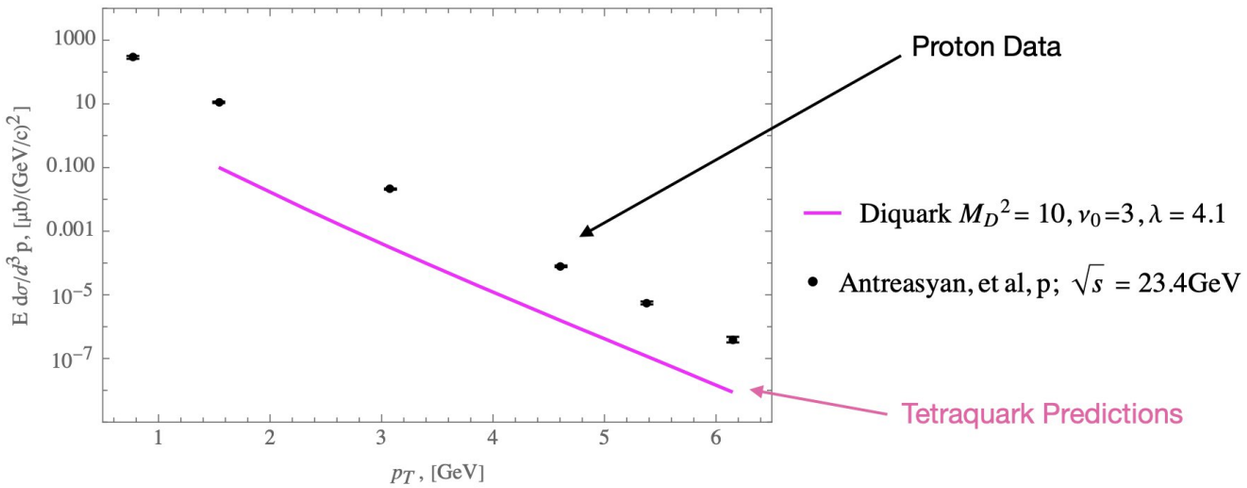
$\sqrt{s} = 11.5$ GeV



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)

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

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

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)

Summary

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

– **Large-pT hadron and symmetric hadron pair production at SPD NICA and U70/U1000 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 and U70/U1000 provides a unique opportunity to improve understanding of Diquark role for production of exotic multi-quark states - Tetraquarks and Pentaquarks**

“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)