The Gluon Exchange Model* for baryon stopping

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1. **Introduction ;**
2. **The Gluon Exchange Model ;**
3. **Results ;**
4. **Conclusions.**

*** GEM :-)**

APPB 51 (2020) 1207
PLB 816 (2021) 136200
EPJPlus 136 (2021) 971
APPB 52 (2021) 981
ArXiv: 2111.03401

This talk will be concerned with pp and pA collisions at $\sqrt{s} \sim 20$ GeV.

The implications touch all the high energy scale (LHC, cosmic), and heavy ion physics.

We introduce a new model, based on the exchange of **soft color octets** (gluons).

We find that the emergence of new **color configurations** of proton constituents provides a new, strong mechanism for baryon stopping.

a

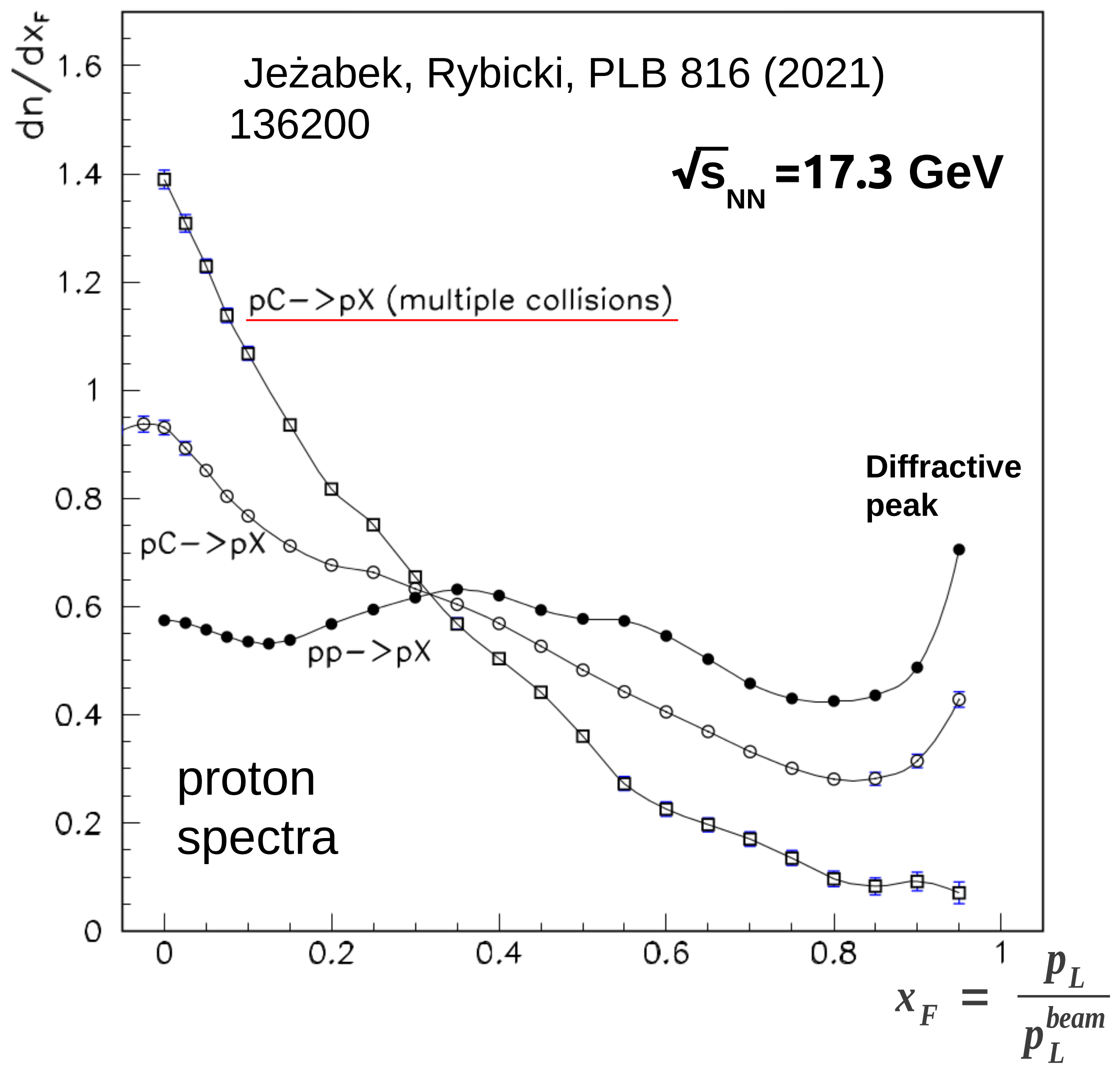
Proton-proton vs proton-nucleus collisions

$$\frac{dn}{dx_F}(pC_{\text{multiple collisions}} \rightarrow pX) = \frac{1}{1-P(1)}\left(\frac{dn}{dx_F}(pC \rightarrow pX) - P(1)\cdot\frac{dn}{dx_F}(pp \rightarrow pX)\right)$$

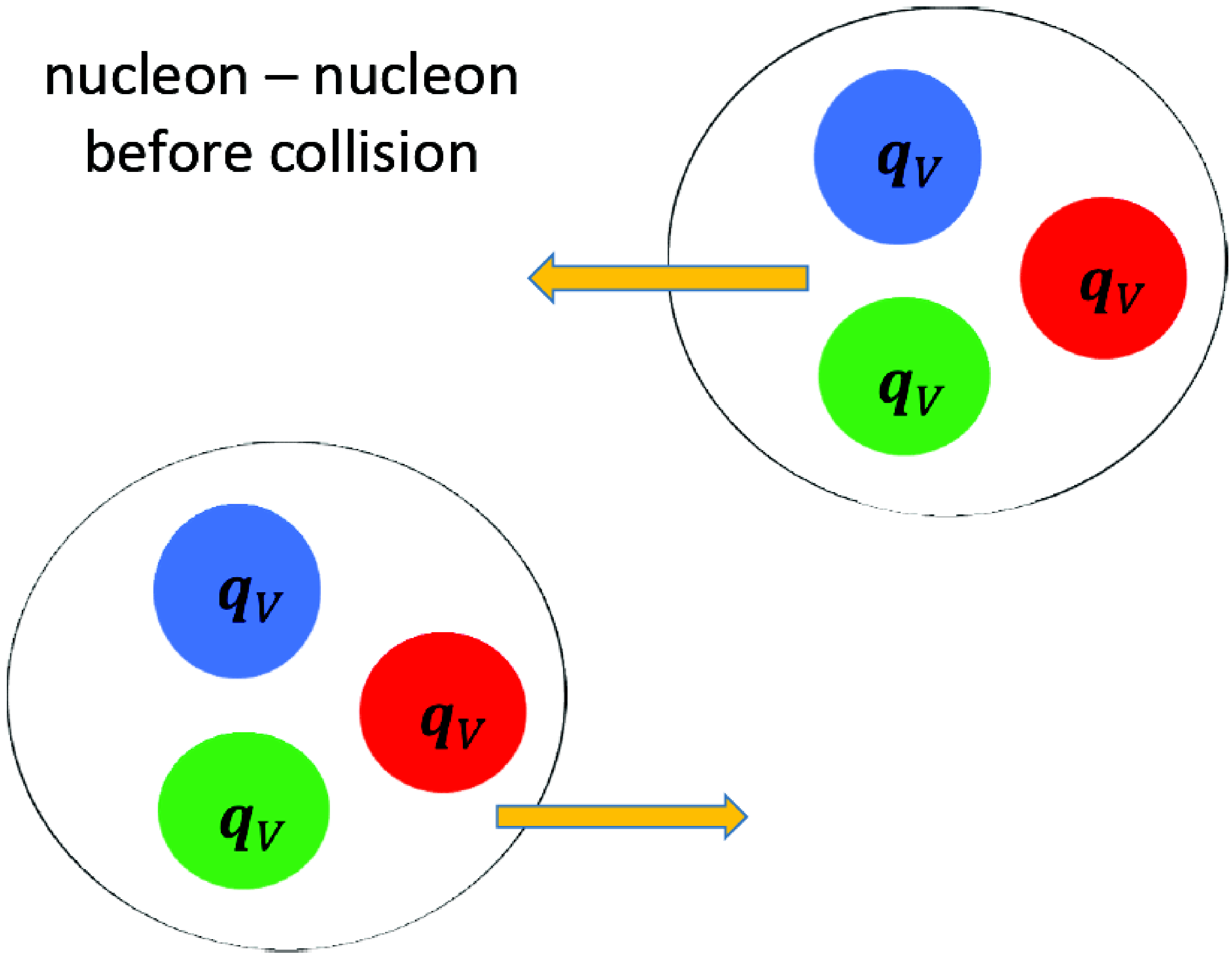
1. pp and pC data from the same NA49 experiment (Eur. Phys. J. **C65**, 9 (2010), Eur. Phys. J. **C73**, 2364 (2013)): protons, neutrons.

2. **P(1)** - probability of proton collision with one wounded nucleon.

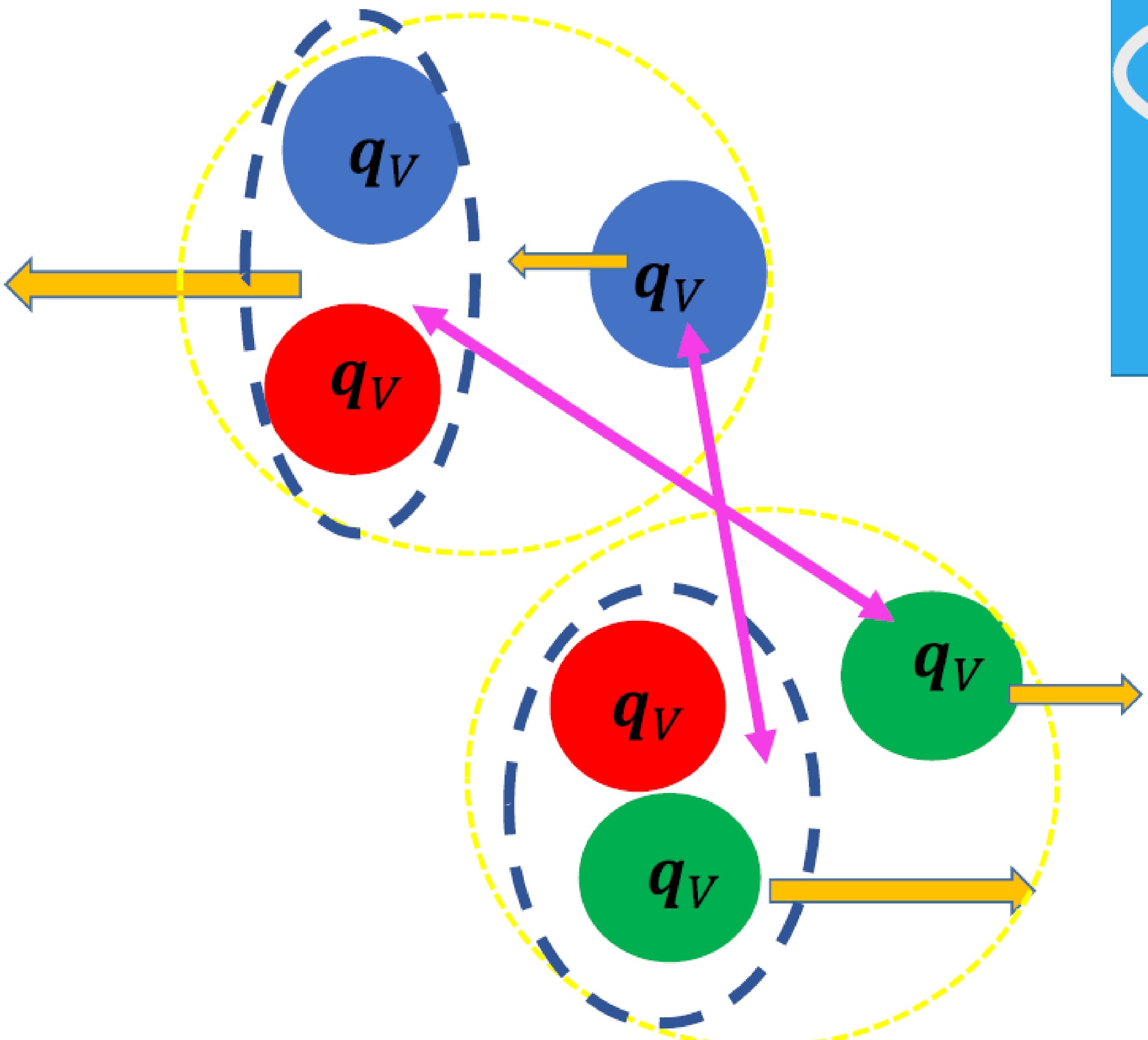
3. **Advantage**: we can extract pC collisions in which the proton collides with **multiple** (more than one) nucleons.

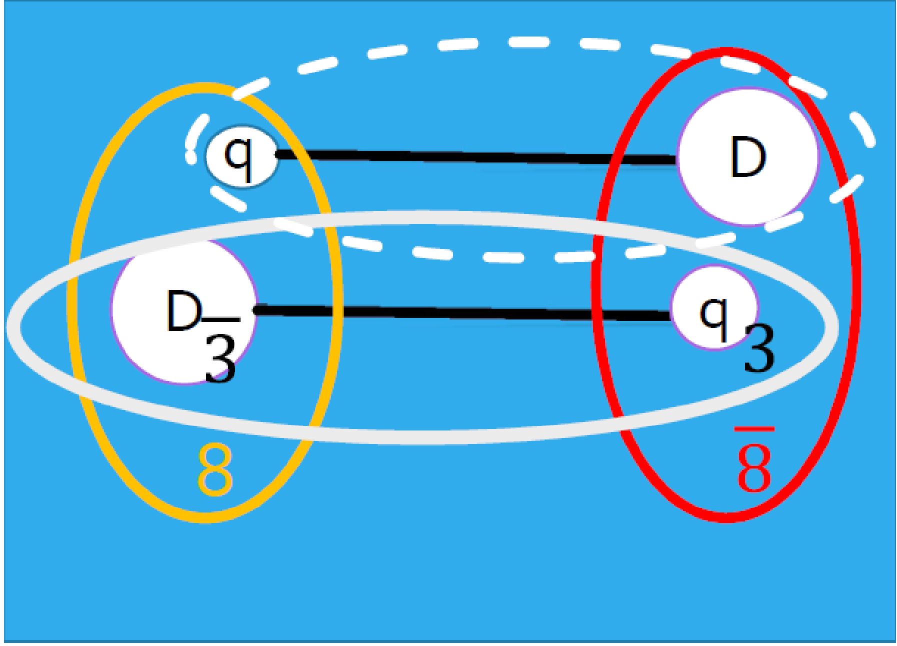


nucleon – nucleon
before collision



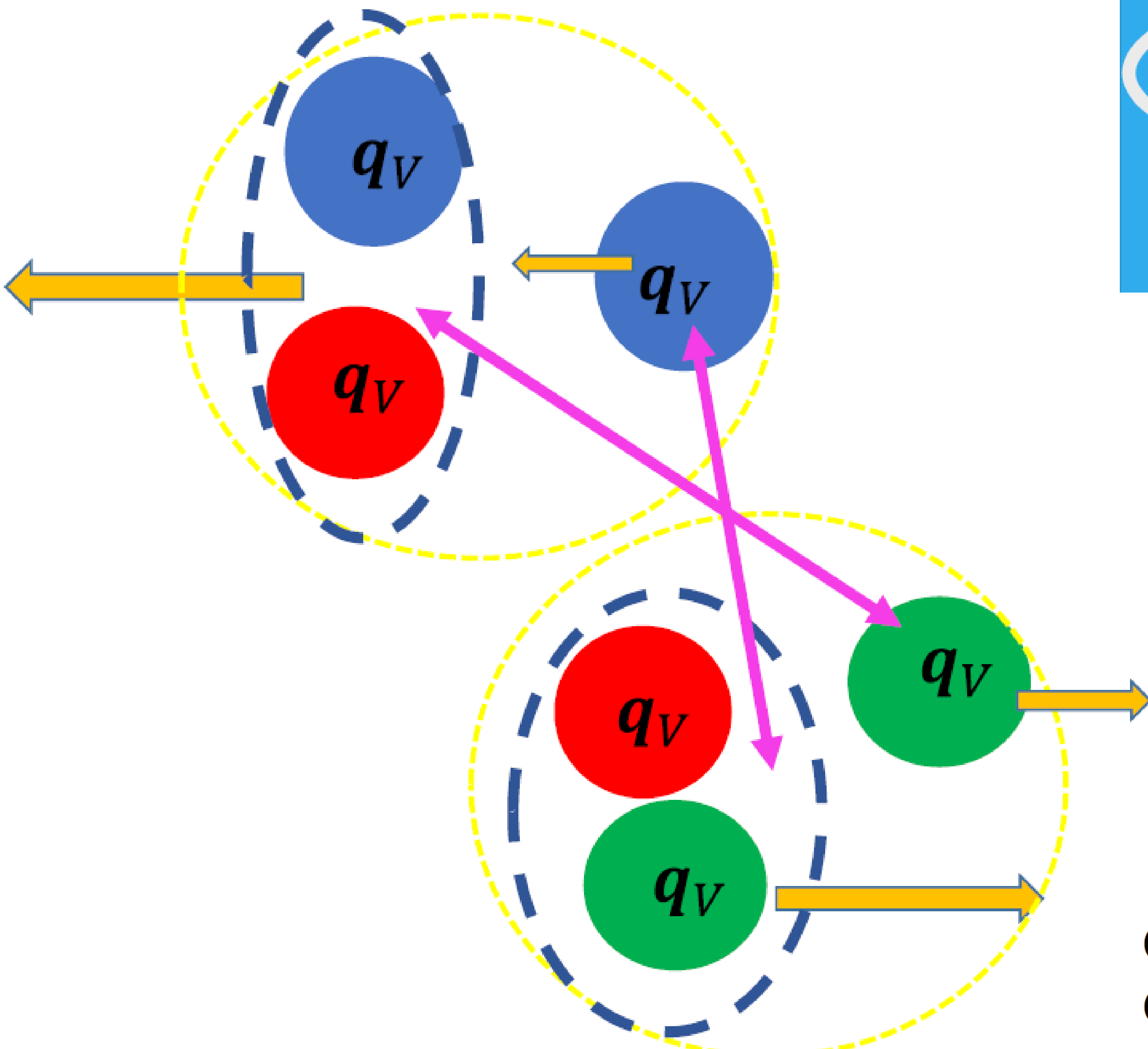
nucleon – nucleon
after collision

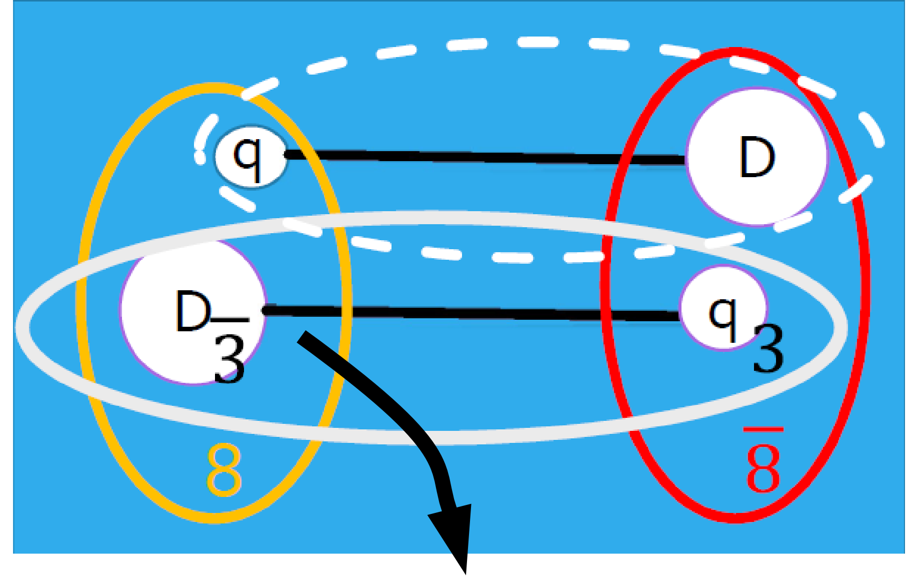




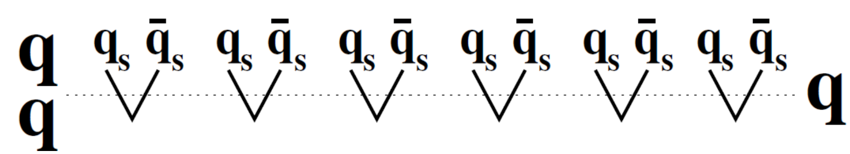
Note: this is like in the
Dual Parton Model.
A. Capella and J. Tran Thanh Van,
PLB **93**, 1980,
M.J., J.Karczmarczuk,
M.Różańska, ZPC **29**, 1985.

nucleon – nucleon
after collision

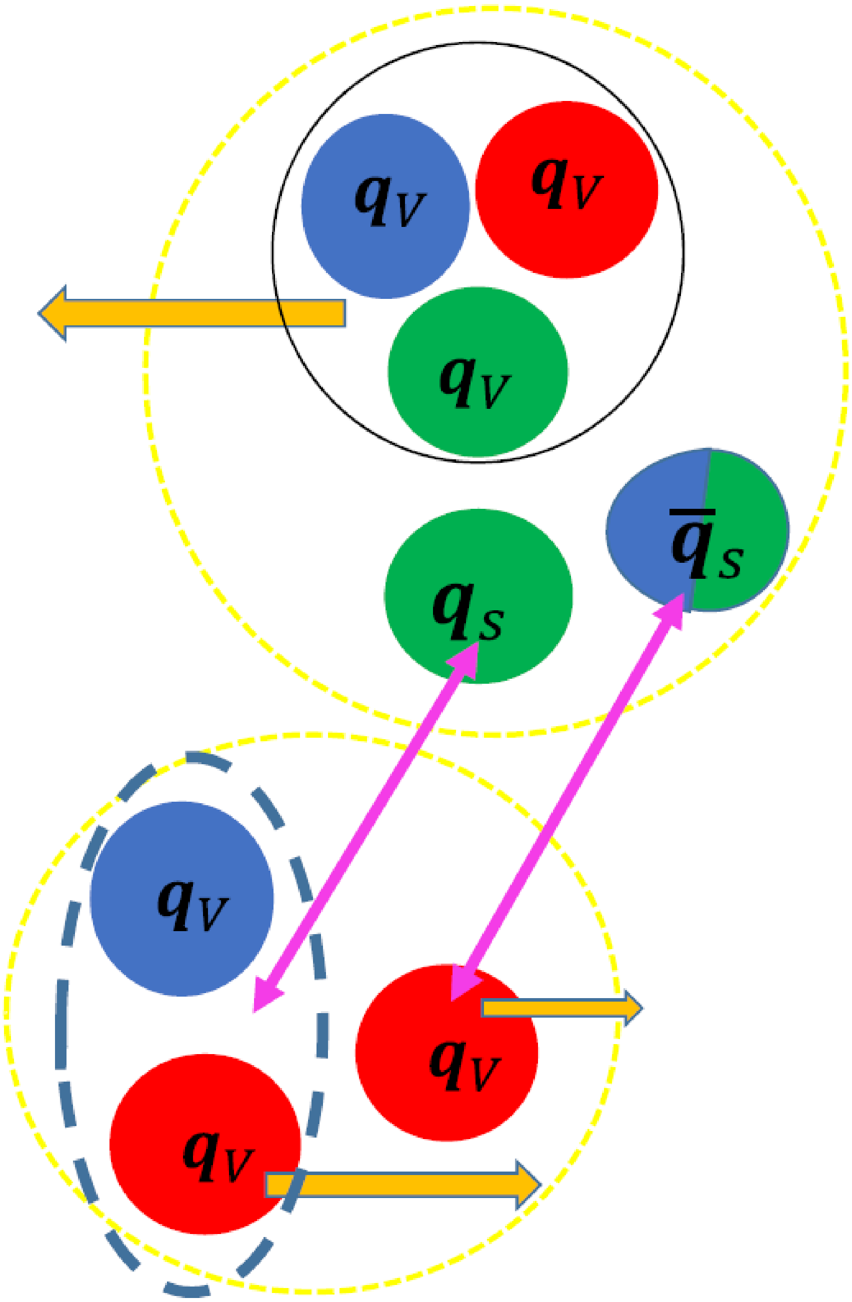




String fragmentation proceeds through q-$\bar{q}$ pairs thus it starts from the **Diquark.**



String fragmentation function into protons and neutrons: M.J., A.R., EPJPlus 136 (2021) 971



Gluon Exchange Model

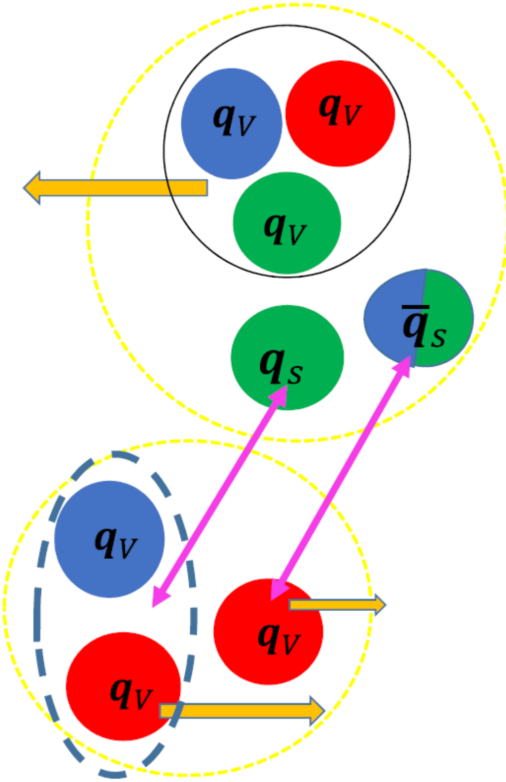
DPM + new contributions

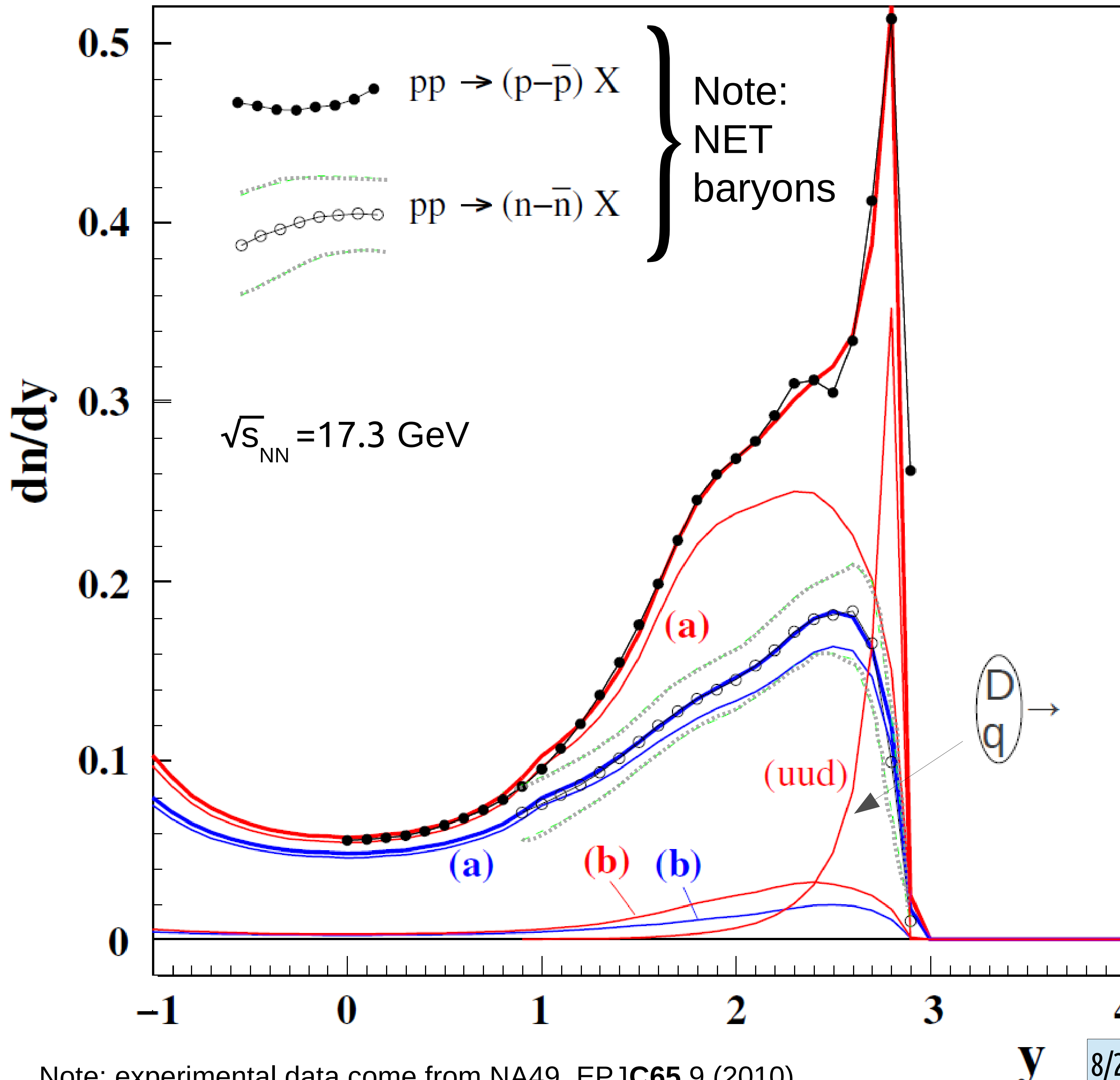
nucleon – nucleon:

inelastic diffraction

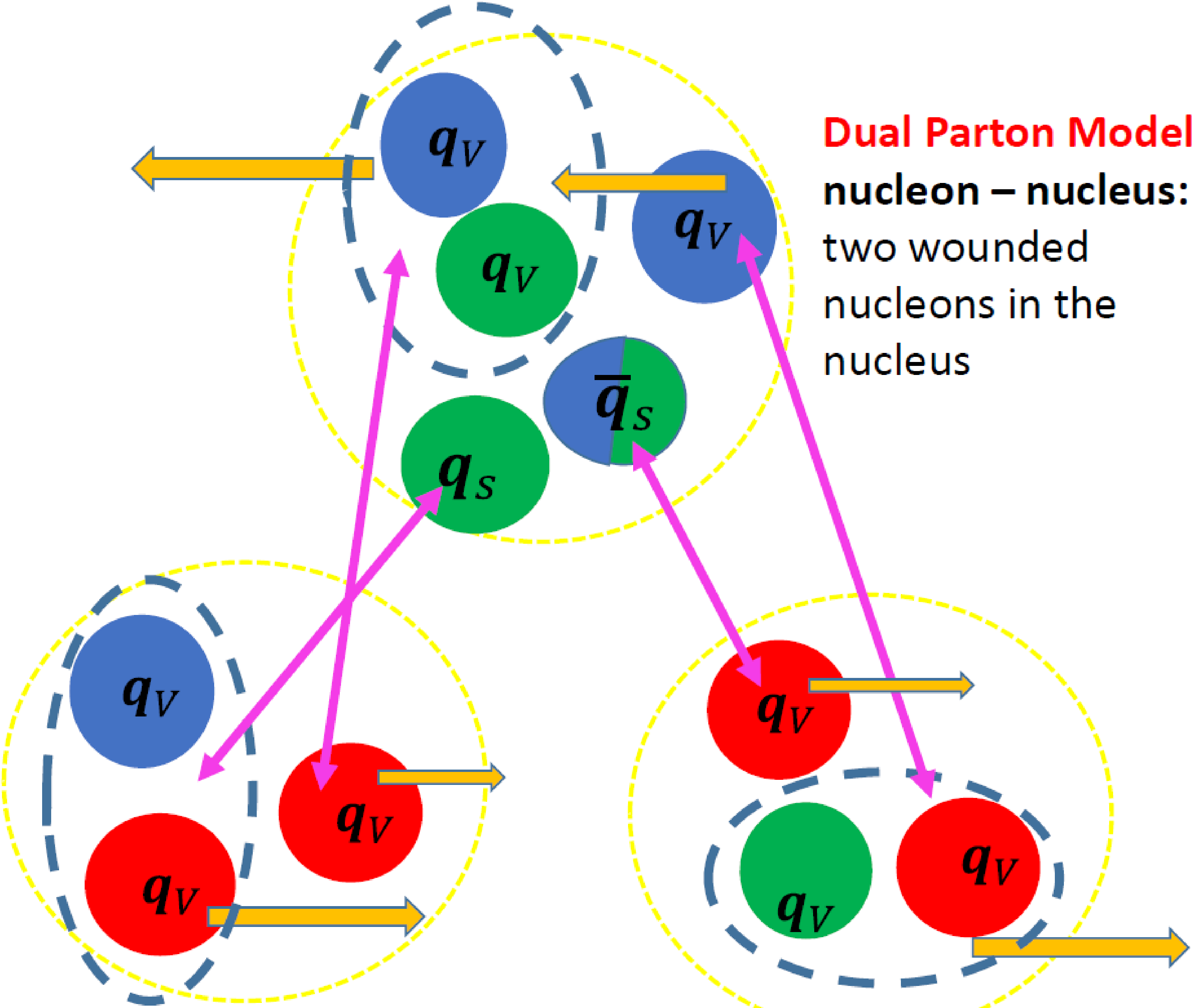
GEM in pp collisions

PLB 816 (2021) 136200





Note: experimental data come from NA49, EPJ**C65** 9 (2010).



Dual Parton Model

nucleon – nucleus:

two wounded nucleons in the nucleus

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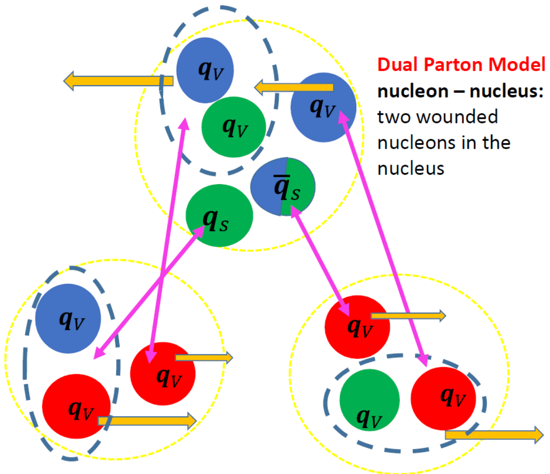
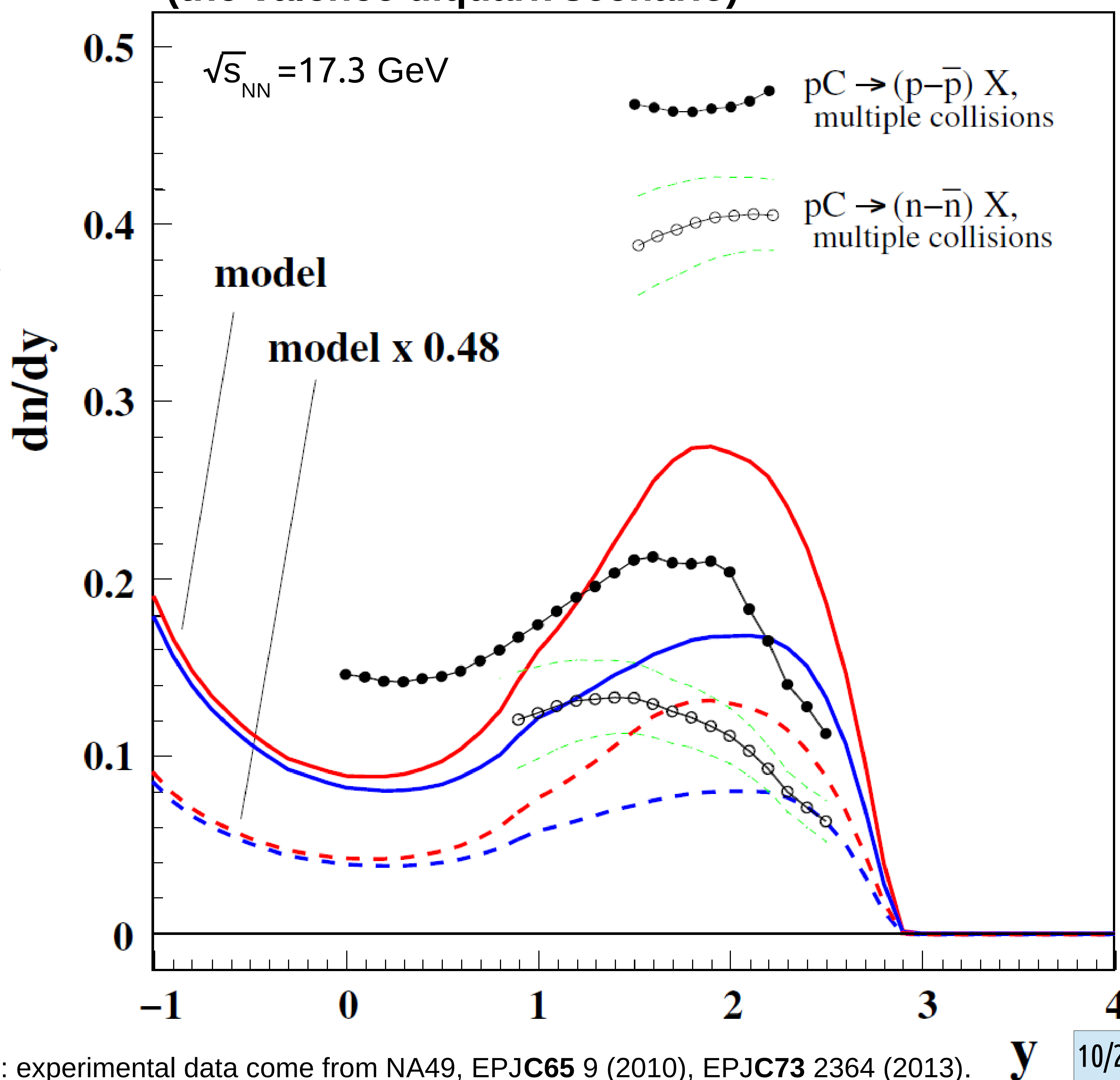
pA collisions (the valence diquark scenario)



- Exp. data: this diagram cannot be responsible for 100% of baryon stopping ;
- Upper limit for this contribution : 48% .

we need to go beyond valence diquarks



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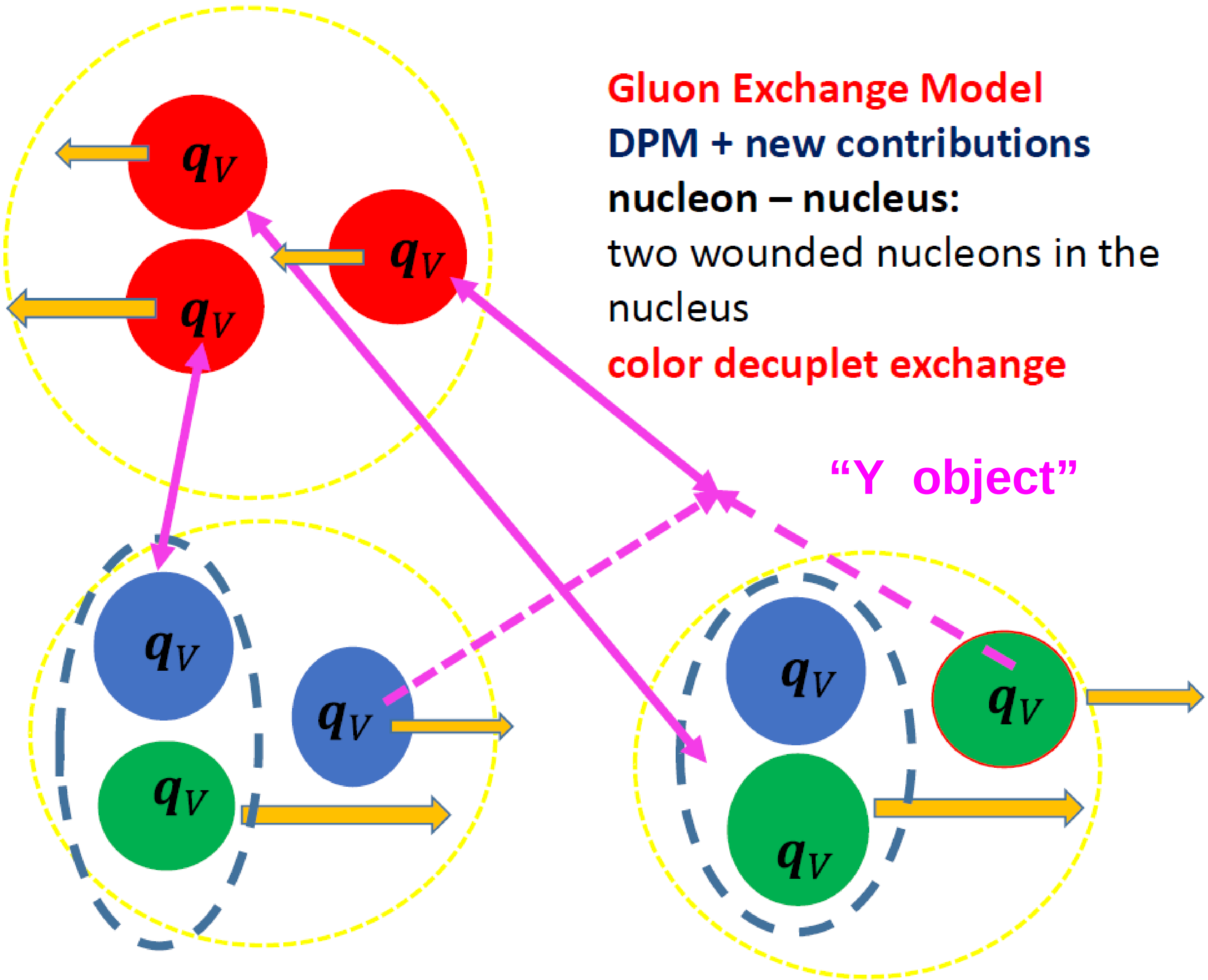
Note: experimental data come from NA49, EPJ**C65** 9 (2010), EPJ**C73** 2364 (2013).

M.J., A.R., EPJPlus 136 (2021) 971



Gluon Exchange Model

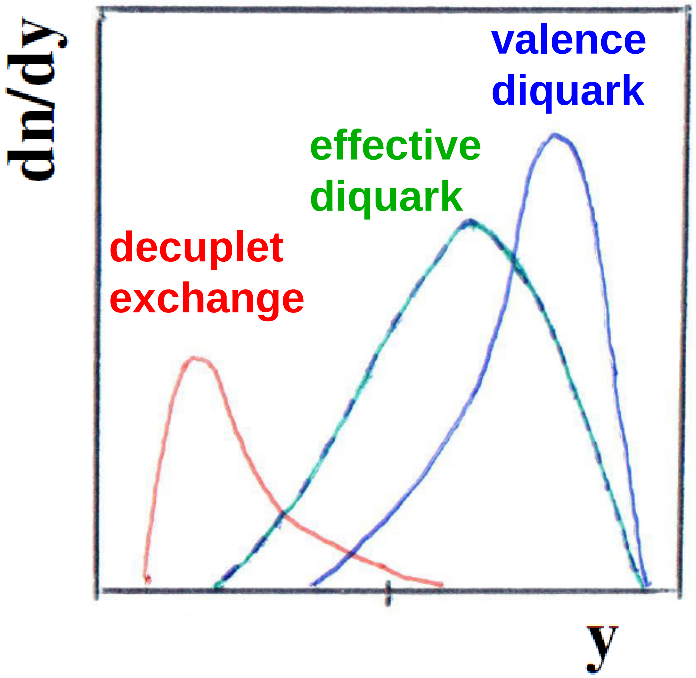
DPM + new contributions

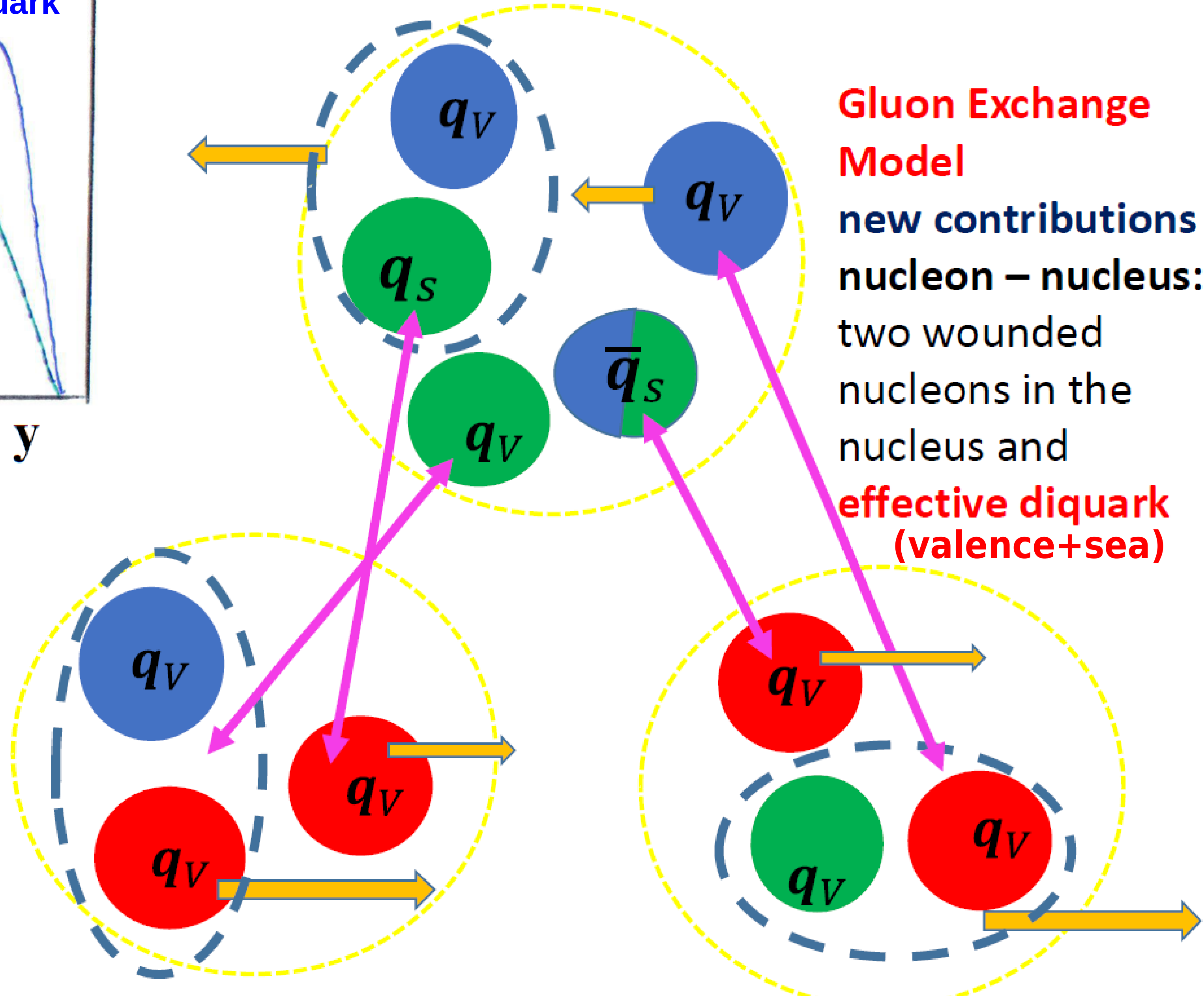
nucleon – nucleus:

two wounded nucleons in the nucleus

color decuplet exchange

M.J., A.R.,
EPJPlus 136 (2021) 971





Gluon Exchange Model

new contributions

nucleon – nucleus:

two wounded nucleons in the nucleus and

effective diquark (valence+sea)

Summary (1)

Five classes of events in the projectile hemisphere of pp/pA reactions:

1. “inelastic diffraction" (→ very fast proton).

2. diquark made by two valence quarks (→ like in DPM).

3. effective diquark, made from one valence quark and one sea quark (→ softer baryon, specific to multiple collisions).

4. effective diquark, made from two sea quarks (→ still softer baryon, specific to multiple collisions).

5. decuplet exchange (→ with large probability, no baryon in the projectile hemisphere, specific to multiple collisions).

M.J., A.R.,
ArXiv: 2111.03401

Statistical scheme for color representations of quarks in the proton, resulting from multiple gluon exchange.

1. Two options:

(a) **one gluon** brings the projectile valence quarks into the **color octet** state.
N-1 gluons couple to sea quark-antiquark pairs ;

Color representation for valence and sea quarks: $R_8^{N-1} = \underset{\sim}{8} \otimes \underset{\sim}{3}^{N-1},$

Effective diquarks: valence-valence, valence-sea, sea-sea .

(b) **two gluons** bring the projectile valence quarks into the **symmetric color decuplet** state. ***N-2*** gluons couple to sea quark-antiquark pairs ;

Color representation: $R_{10}^{N-2} = \underset{\sim}{10} \otimes \underset{\sim}{3}^{N-2},$

No-diquark, or effective diquarks: valence-sea, sea-sea .

2. We reduce R into **irreducible representations.**

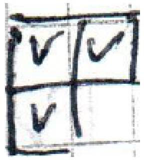
3. For a given irreducible representation, we assume that the **probabilities to form an effective diquark are equal for all allowed quark pairs.**

Color representations for *N = 1, 2, 3* gluons

ArXiv: 2111.03401

N=1 : ***octet :***

$$R_8^0 = \underset{\sim}{8} = (2,1,0)$$

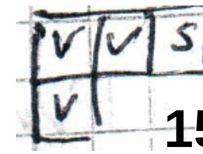


Dimension = 8

$$P_{vv} = 1$$

N=2 : ***octet :***

$$R_8^1 = \underset{\sim}{8} \otimes \underset{\sim}{3} = (3,1,0) \oplus (2,2,0) \oplus (2,1,1)$$



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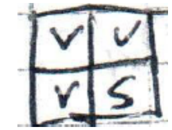
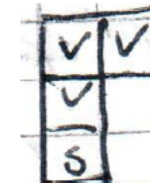


6*

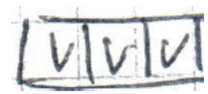


3

decuplet :

$$R_{10}^0 = \underset{\sim}{10} = (3,0,0)$$

$$P_0 = 1$$

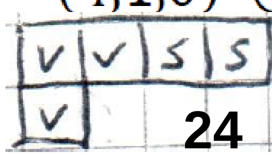


10

no diquark

N=3 : ***octet :***

$$R_8^2 = \underset{\sim}{8} \otimes \underset{\sim}{3}^2 = (4,1,0) \oplus 2\cdot(3,2,0) \oplus 2\cdot(3,1,1) \oplus 2\cdot(2,2,1)$$



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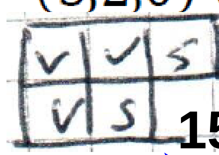
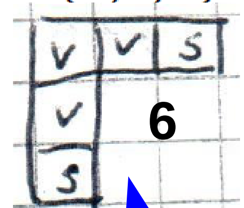


15*



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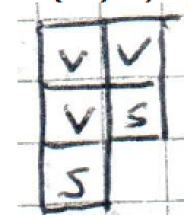
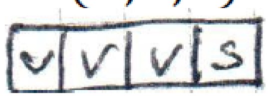


3*

decuplet :

$$R_{10}^1 = \underset{\sim}{10} \otimes \underset{\sim}{3} = (4,0,0) \oplus (3,1,0)$$



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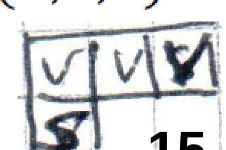


15

ss diquark!

color octet representations up to 9 gluons

$$R_8^0 = \underset{\sim}{8} = (2,1,0)$$

$$R_8^1 = \underset{\sim}{8} \otimes \underset{\sim}{3} = (3,1,0) \oplus (2,2,0) \oplus (2,1,1)$$

$$R_8^2 = \underset{\sim}{8} \otimes \underset{\sim}{3}^2 = (4,1,0) \oplus 2\cdot(3,2,0) \oplus 2\cdot(3,1,1) \oplus 2\cdot(2,2,1)$$

$$R_8^3 = (5,1,0) \oplus 3\cdot(4,2,0) \oplus 3\cdot(4,1,1) \oplus 2\cdot(3,3,0) \oplus 6\cdot(3,2,1) \oplus 2\cdot(2,2,2)$$

$$R_8^4 = (6,1,0) \oplus 4\cdot(5,2,0) \oplus 4\cdot(5,1,1) \oplus 5\cdot(4,3,0) \oplus 12\cdot(4,2,1) \oplus 8\cdot(3,3,1) \oplus 8\cdot(3,2,2)$$

$$R_8^5 = (7,1,0) \oplus 5\cdot(6,2,0) \oplus 5\cdot(6,1,1) \oplus 9\cdot(5,3,0) \oplus 20\cdot(5,2,1) \oplus 5\cdot(4,4,0) \oplus 25\cdot(4,3,1) \oplus 20\cdot(4,2,2) \oplus 16\cdot(3,3,2)$$

$$R_8^6 = (8,1,0) \oplus 6\cdot(7,2,0) \oplus 6\cdot(7,1,1) \oplus 14\cdot(6,3,0) \oplus 30\cdot(6,2,1) \oplus 14\cdot(5,4,0) \oplus 54\cdot(5,3,1) \oplus 40\cdot(5,2,2) \oplus 30\cdot(4,4,1) \oplus 61\cdot(4,3,2) \oplus 16\cdot(3,3,3)$$

$$R_8^7 = (9,1,0) \oplus 7\cdot(8,2,0) \oplus 7\cdot(8,1,1) \oplus 20\cdot(7,3,0) \oplus 42\cdot(7,2,1) \oplus 28\cdot(6,4,0) \oplus 98\cdot(6,3,1) \oplus 70\cdot(6,2,2) \oplus 14\cdot(5,5,0) \oplus 98\cdot(5,4,1) \oplus 155\cdot(5,3,2) \oplus 91\cdot(4,4,2) \oplus 77\cdot(4,3,3)$$

$$R_8^8 = (10,1,0) \oplus 8\cdot(9,2,0) \oplus 8\cdot(9,1,1) \oplus 27\cdot(8,3,0) \oplus 56\cdot(8,2,1) \oplus 48\cdot(7,4,0) \oplus 160\cdot(7,3,1) \oplus 112\cdot(7,2,2) \oplus 42\cdot(6,5,0) \oplus 224\cdot(6,4,1) \oplus 323\cdot(6,3,2) \oplus 112\cdot(5,5,1) \oplus 344\cdot(5,4,2) \oplus 232\cdot(5,3,3) \oplus 168\cdot(4,4,3)$$

color decuplet representations up to 9 gluons

$$R_{10}^{0} = \underset{\sim}{10} = (3,0,0)$$

$$R_{10}^{1} = \underset{\sim}{10} \otimes \underset{\sim}{3} = (4,0,0) \oplus (3,1,0)$$

$$R_{10}^{2} = \underset{\sim}{10} \otimes \underset{\sim}{3}^{2} = (5,0,0) \oplus 2\cdot(4,1,0) \oplus (3,2,0) \oplus (3,1,1)$$

$$R_{10}^{3} = (6,0,0) \oplus 3\cdot(5,1,0) \oplus 3\cdot(4,2,0) \oplus 3\cdot(4,1,1) \oplus (3,3,0) \oplus 2\cdot(3,2,1)$$

$$R_{10}^{4} = (7,0,0) \oplus 4\cdot(6,1,0) \oplus 6\cdot(5,2,0) \oplus 6\cdot(5,1,1) \oplus 4\cdot(4,3,0) \oplus 8\cdot(4,2,1) \oplus 3\cdot(3,3,1) \oplus 2\cdot(3,2,2)$$

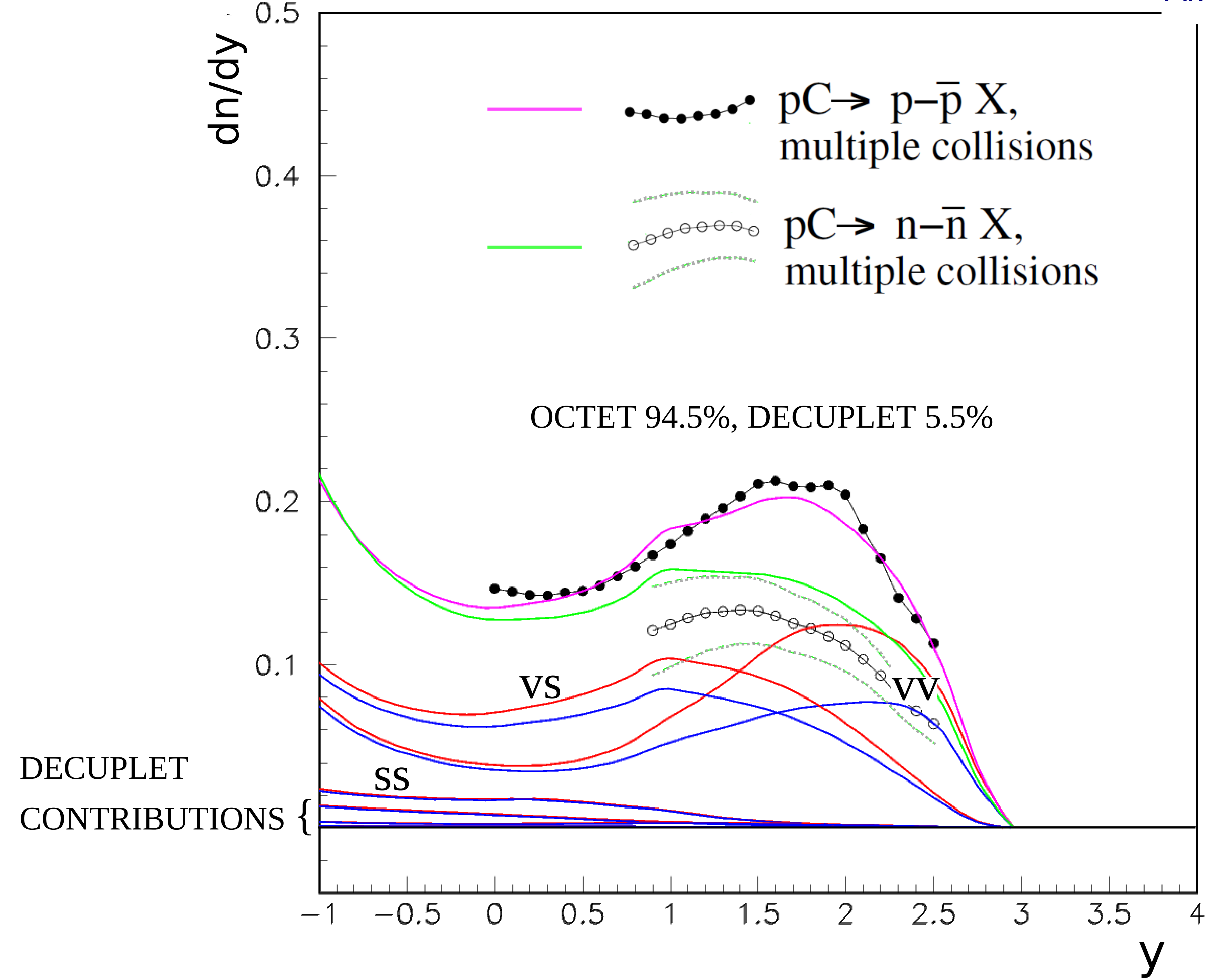
$$R_{10}^{5} = (8,0,0) \oplus 5\cdot(7,1,0) \oplus 10\cdot(6,2,0) \oplus 10\cdot(6,1,1) \oplus 10\cdot(5,3,0) \oplus 20\cdot(5,2,1) \oplus 4\cdot(4,4,0) \oplus 15\cdot(4,3,1) \oplus 10\cdot(4,2,2) \oplus 5\cdot(3,3,2)$$

$$R_{10}^{6} = (9,0,0) \oplus 6\cdot(8,1,0) \oplus 15\cdot(7,2,0) \oplus 15\cdot(7,1,1) \oplus 20\cdot(6,3,0) \oplus 40\cdot(6,2,1) \oplus 14\cdot(5,4,0) \oplus 45\cdot(5,3,1) \oplus 30\cdot(5,2,2) \oplus 19\cdot(4,4,1) \oplus 30\cdot(4,3,2) \oplus 5\cdot(3,3,3)$$

$$R_{10}^{7} = (10,0,0) \oplus 7\cdot(9,1,0) \oplus 21\cdot(8,2,0) \oplus 21\cdot(8,1,1) \oplus 35\cdot(7,3,0) \oplus 70\cdot(7,2,1) \oplus 34\cdot(6,4,0) \oplus 105\cdot(6,3,1) \oplus 70\cdot(6,2,2) \oplus 14\cdot(5,5,0) \oplus 78\cdot(5,4,1) \oplus 105\cdot(5,3,2) \oplus 49\cdot(4,4,2) \oplus 35\cdot(4,3,3)$$

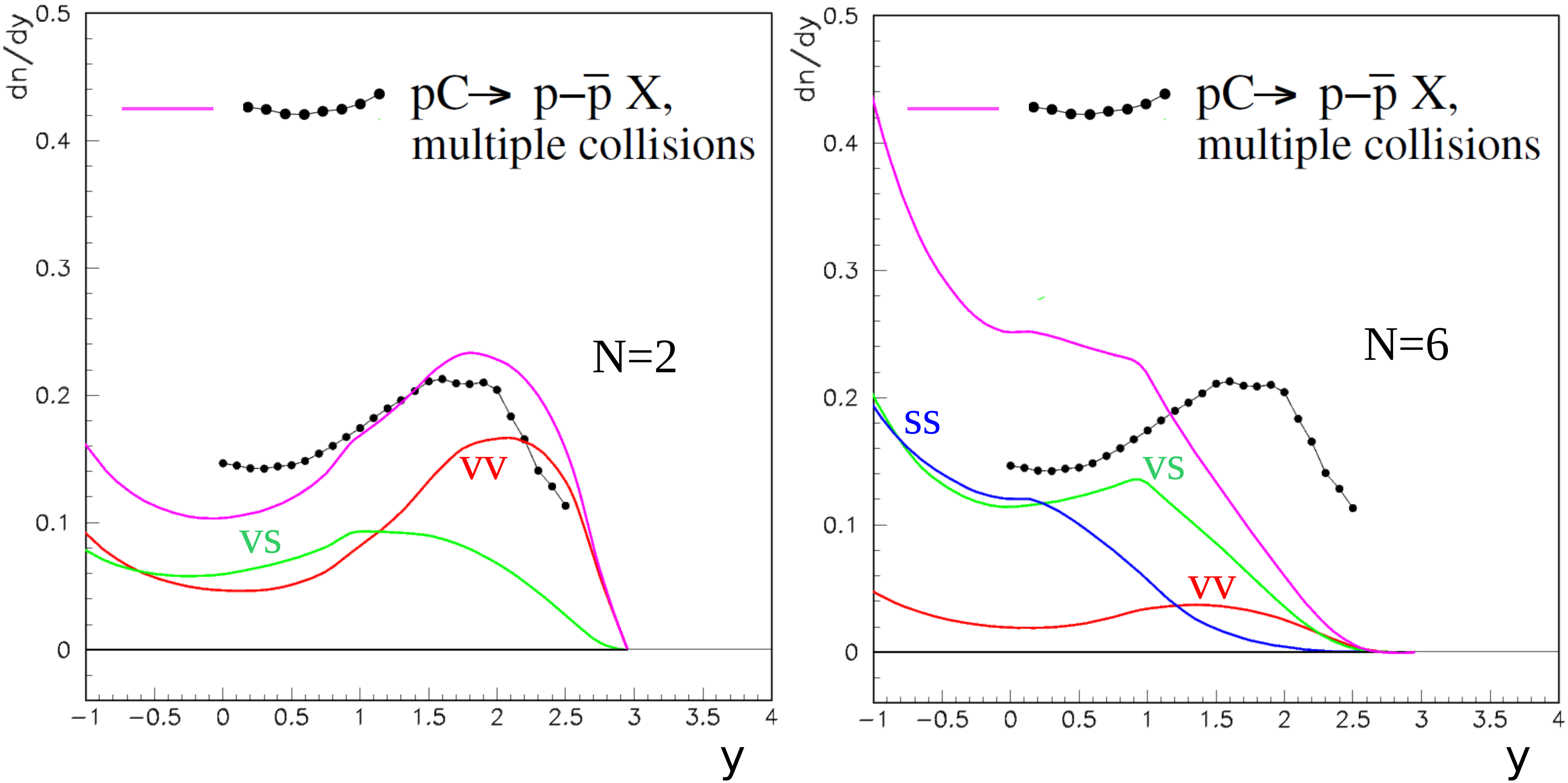
no diquark

	Octet			Decuplet		
	$\underline{8} \otimes \underline{3^{N-1}}$			$\underline{10} \otimes \underline{3^{N-2}}$		
N	V V	V S	S S	0	V S	S S
1	1	-	-	-	-	-
2	0.5917	0.4083	-	1	-	-
3	0.3740	0.5223	0.1037	0.5	0.5	-
4	0.2520	0.5407	0.2073	0.2333	0.6238	0.1429
5	0.1784	0.5213	0.3002	0.1037	0.6179	0.2784
6	0.1319	0.4908	0.3773	0.0444	0.5733	0.3823
7	0.1010	0.4582	0.4408	0.0185	0.5234	0.4581
8	0.0797	0.4272	0.4931	0.0075	0.4770	0.5155
9	0.0644	0.3989	0.5367	0.0030	0.4366	0.5604



Note: experimental data come from
NA49, EPJ**C65** 9 (2010), EPJ**C73** 2364 (2013).

ArXiv: 2111.03401



Baryon stopping ≈

emergence of new **color configurations** of constituents of the baryon (valence-valence, valence-sea, and sea-sea diquarks), as a function of the **number of collisions**.

Note: experimental data come from NA49, EPJ**C65** 9 (2010), EPJ**C73** 2364 (2013).
Note (2): this calculation is made in 100% color octet approximation.

Conclusions

1. Spectra of baryons are governed by **color configurations** of constituent quarks (valence + sea);

2. These configurations depend on the **number of exchanged gluons** and are *richer* in the multiple collision process, which results in **stronger baryon stopping** as a function of the number of collisions.

3. We found **five classes of events** in the projectile hemisphere of pp/pA collisions:

inelastic diffraction
valence diquark
} present already in pp reactions ;

effective diquark (valence+sea)
effective diquark (sea+sea)
color decuplet exchange
} specific to multiple collisions, leading to stronger stopping.

… thank you !

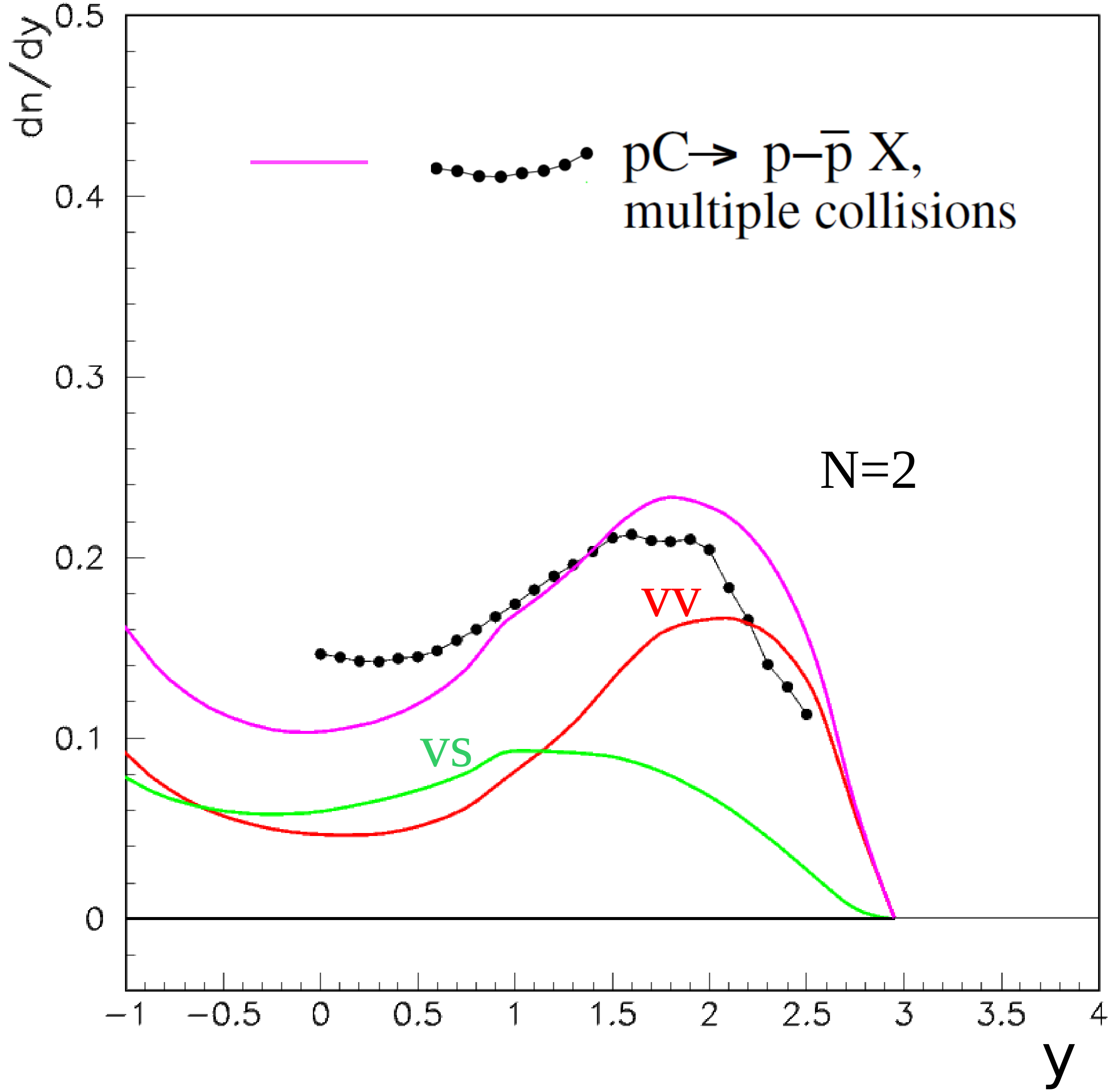
Extra slides

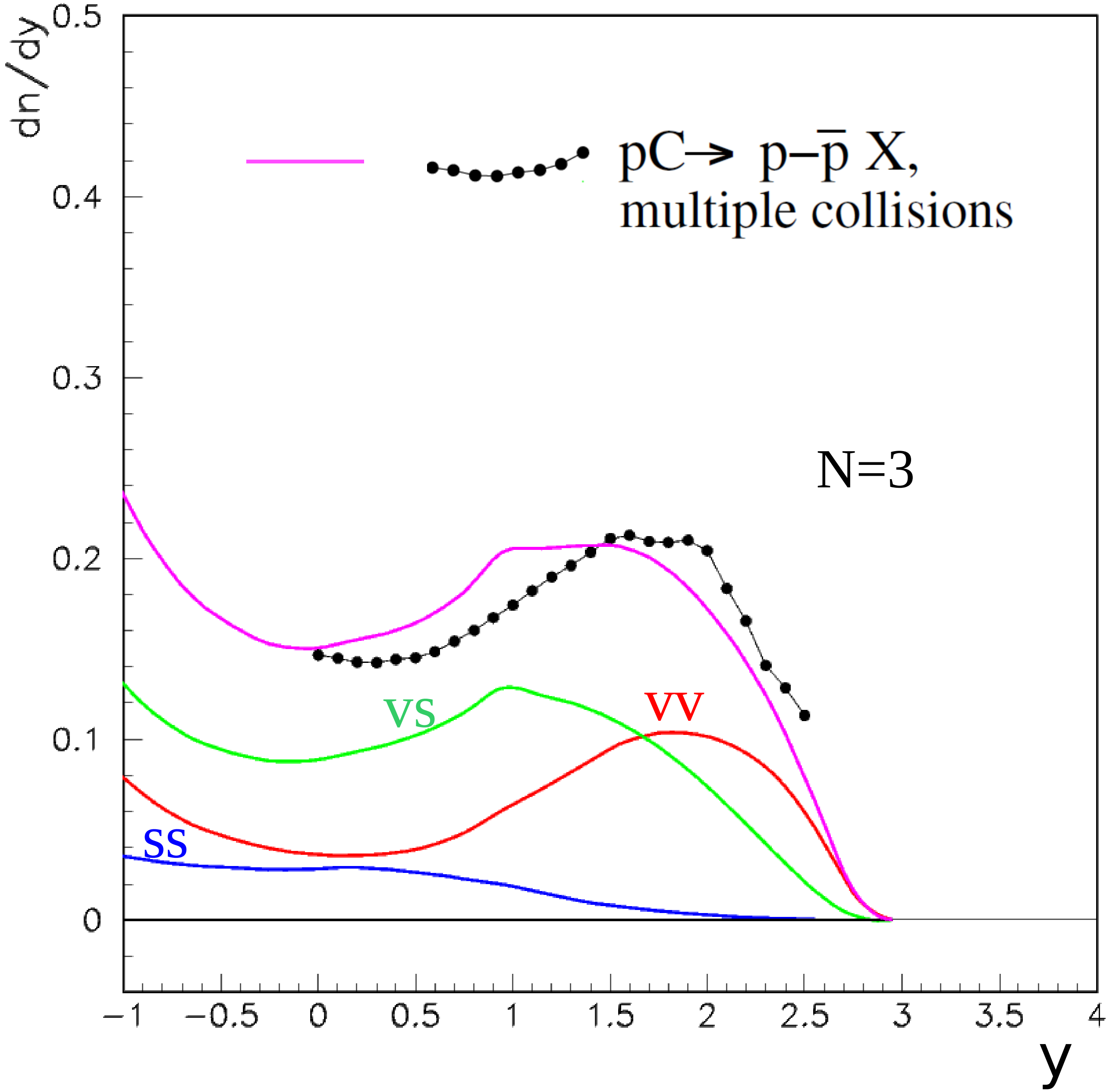
Constituent distribution

(x_{q_i}, x_i - momentum fractions, μ-sea quark mass):

$$\rho_m(x_{q_1}, x_{q_2}, x_{q_3}, x_1, ..., x_{2m}) =$$

$$C_m(x_{q_1} + x_{q_2})^{1/2} x_{q_3}^{-1/2} \prod_{i=1}^{2m} (x_i^2 + 4\mu^2/s)^{-1/2} \cdot \delta\left(1 - x_{q_1} - x_{q_2} - x_{q_3} - \sum_{i=1}^{2m} x_i\right)$$


dn/dy
0.5
0.4
0.3
0.2
0.1
0
pC→ p−p̄ X,
multiple collisions
N=2
VV
VS
−1
−0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
y


dn/dy
0.5
0.4
0.3
0.2
0.1
0
pC→ p−p̄ X,
multiple collisions
N=3
VS
VV
SS
−1
−0.5
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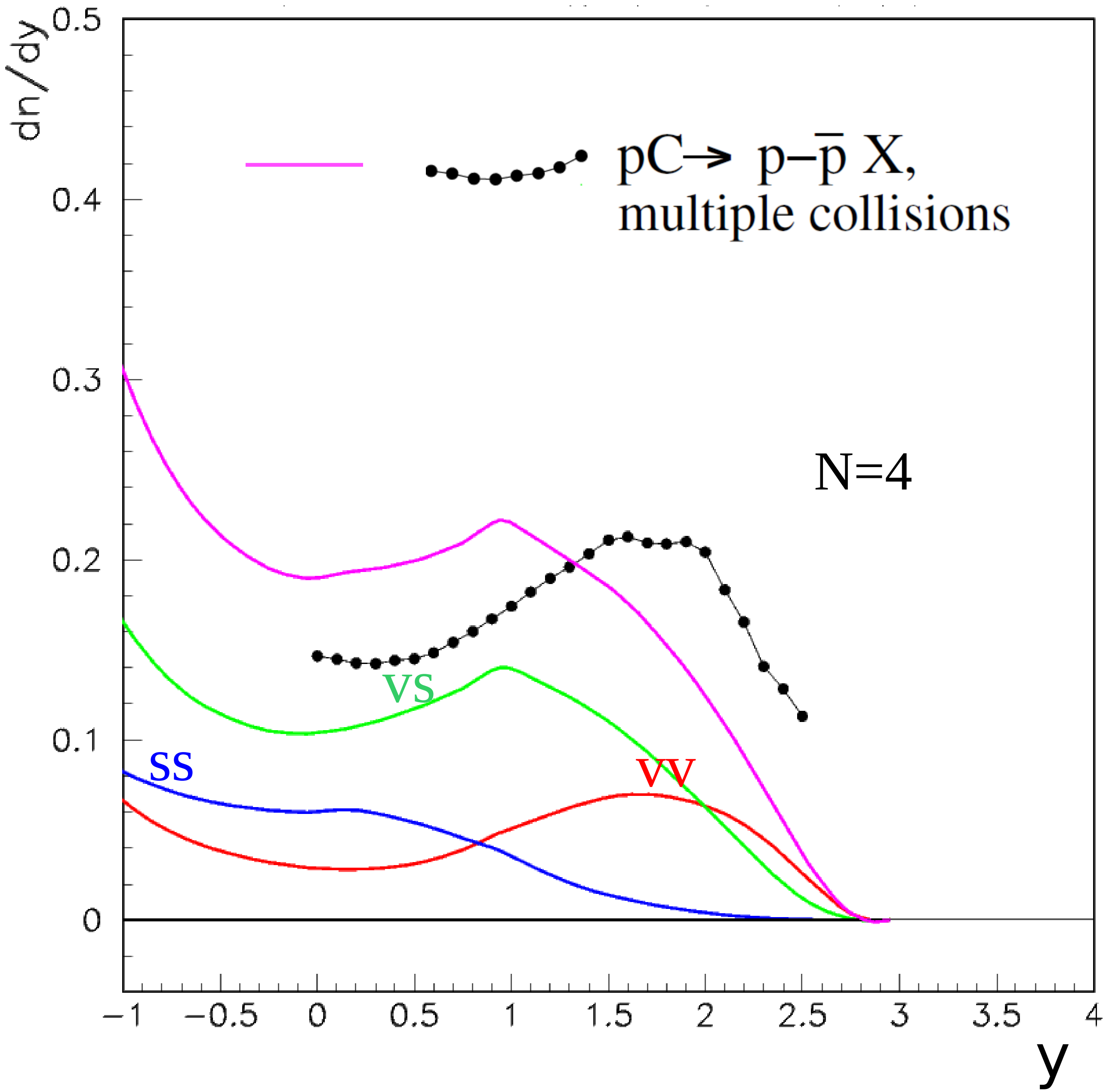
0.5
1
1.5
2
2.5
3
3.5
4
y


dn/dy
0.5
0.4
0.3
0.2
0.1
0
pC→ p−p̄ X,
multiple collisions
N=4
VS
SS
VV
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−0.5
0
0.5
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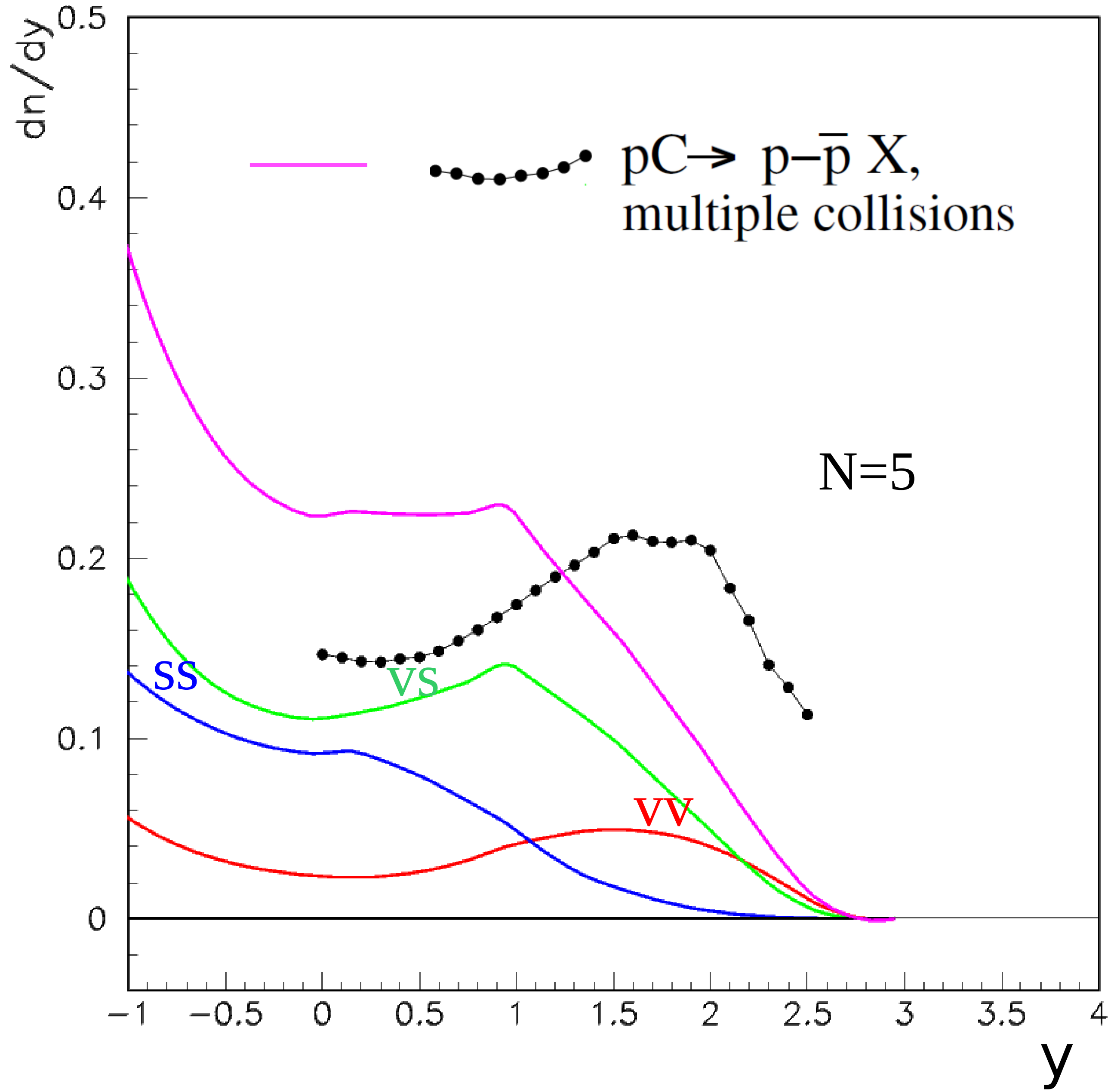
1.5
2
2.5
3
3.5
4
y


dn/dy
0.5
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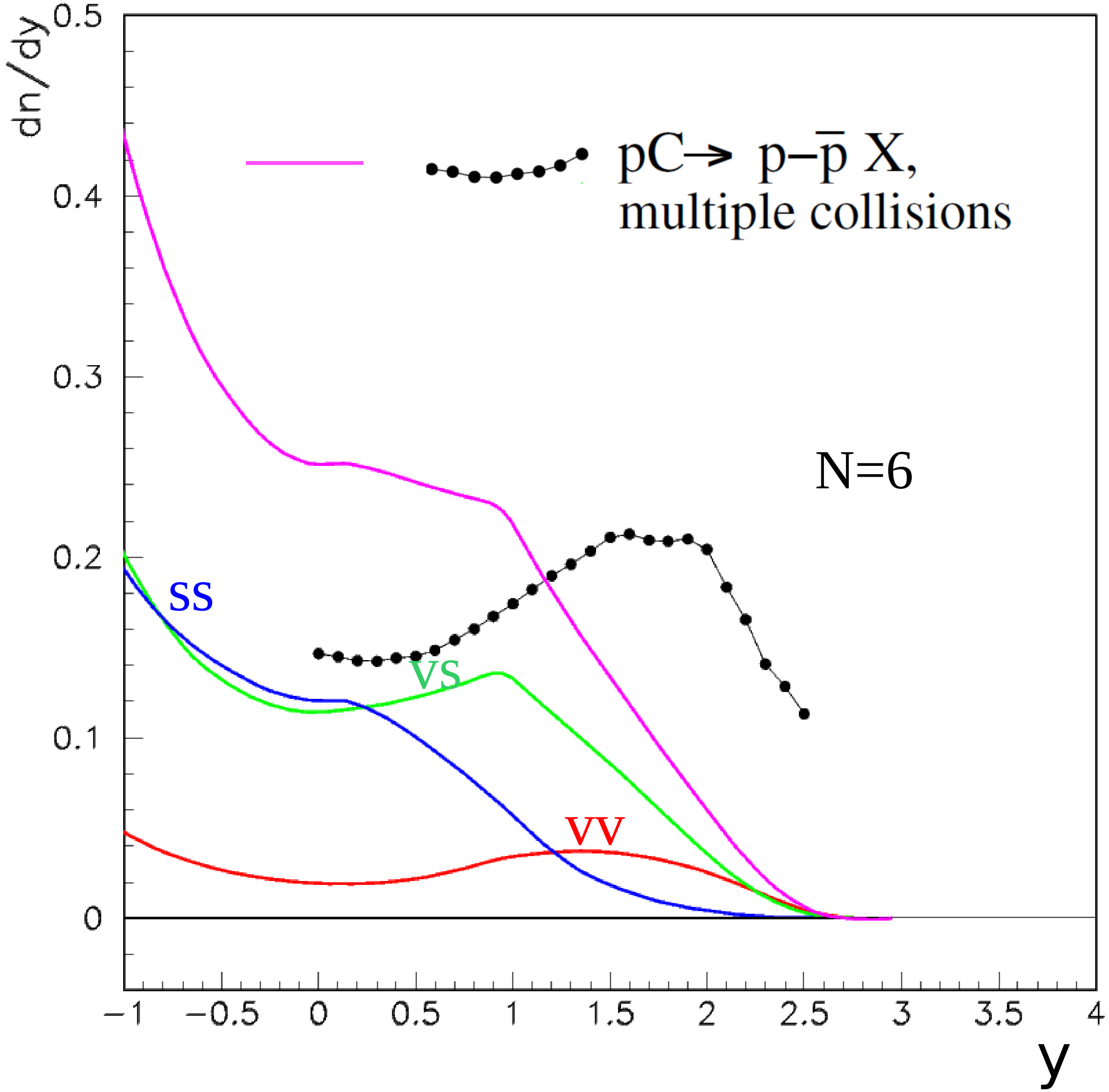
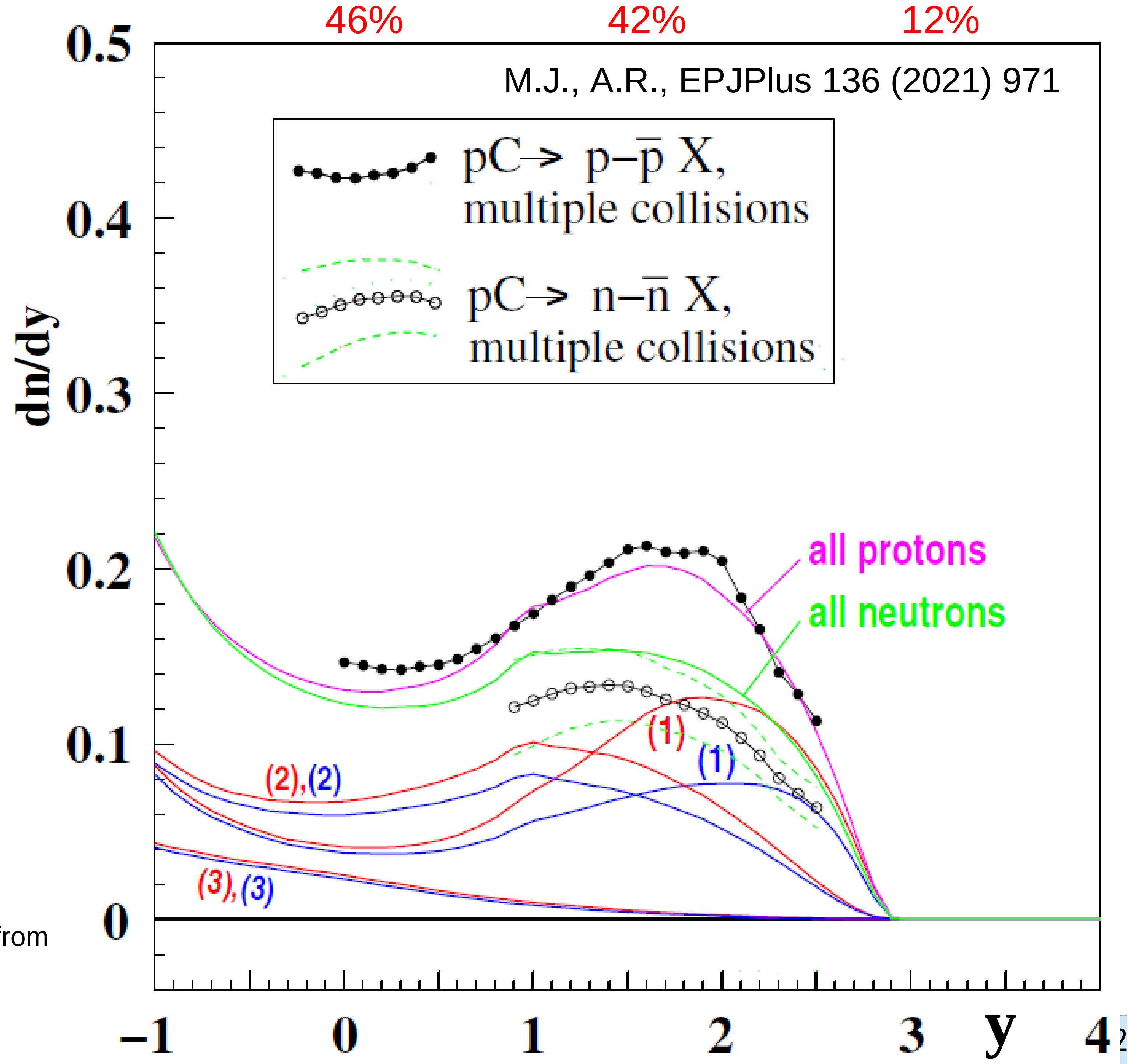
0
pC→ p−p̄ X,
multiple collisions
N=5
SS
VS
VV
−1
−0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
y


dn/dy
0.5
0.4
0.3
0.2
0.1
0
pC→ p−p̄ X,
multiple collisions
N=6
SS
VS
VV
−1
−0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
y

Empirical fit to pA collisions
(1) valence diquark, (2) effective diquark, (3) decuplet.

Prior to establishing the statistical scheme for color exchange, we attemped an empirical fit to the exp. data.

→ M.J., A.R., EPJPlus 136 (2021) 971



The result was essentially consistent with what was later obtained from the statistical scheme, see slide 20 for comparison.

Note: experimental data come from NA49, EPJ**C65** 9 (2010), EPJ**C73** 2364 (2013).