The Gluon Exchange Model: solving the puzzle of nuclear stopping power

Marek Jeżabek and Andrzej Rybicki

Institute of Nuclear Physics, Polish Academy of Sciences

Cracow, Poland

1. **Motivation ;**
2. **The Gluon Exchange Model ;**
3. **Summary ;**
4. **Outlook.**

Based on:

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

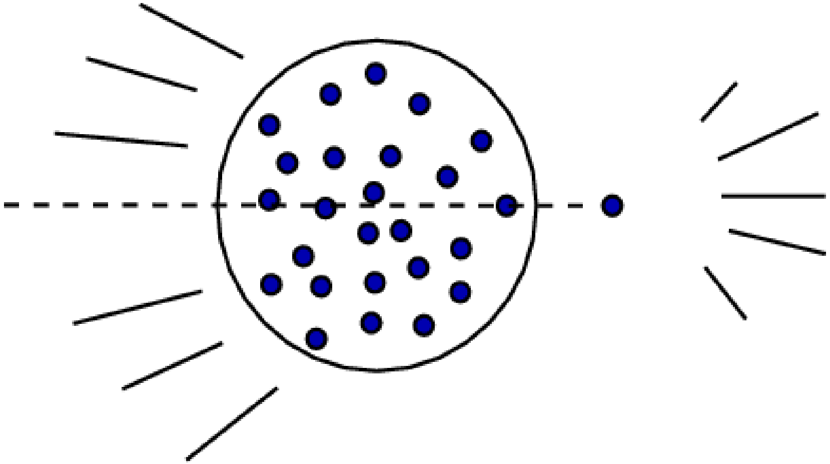
1)
Motivation

This talk will be concerned with **proton-proton** and **proton-nucleus** collisions at $\sqrt{s_{NN}} \sim$ **20 GeV.**

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

We are interested in the emission of secondary **baryons (protons, neutrons)** in these collisions.

Despite ~50 years of study these **“soft”** processes ($p_T < 1$ GeV/*c*) are relatively **poorly understood**, and phenomenological research remains **data-driven**. This is because perturbative Quantum Chromodynamics **does not apply here**.



At the beginning of the last decade **new experimental data** appeared.

The exploitation of these data allows for a more precise, **better understanding** of soft baryon emission processes.

(Note! All kinematical variables are in the **nucleon-nucleon c.m.s.**)

New experimental data

[1] T. Anticic *et al.* [NA49 Collab.], Eur. Phys. J. **C65**, 9 (2010),
[2] B. Baatar *et al.* [NA49 Collab.], Eur. Phys. J. **C73**, 2364 (2013).

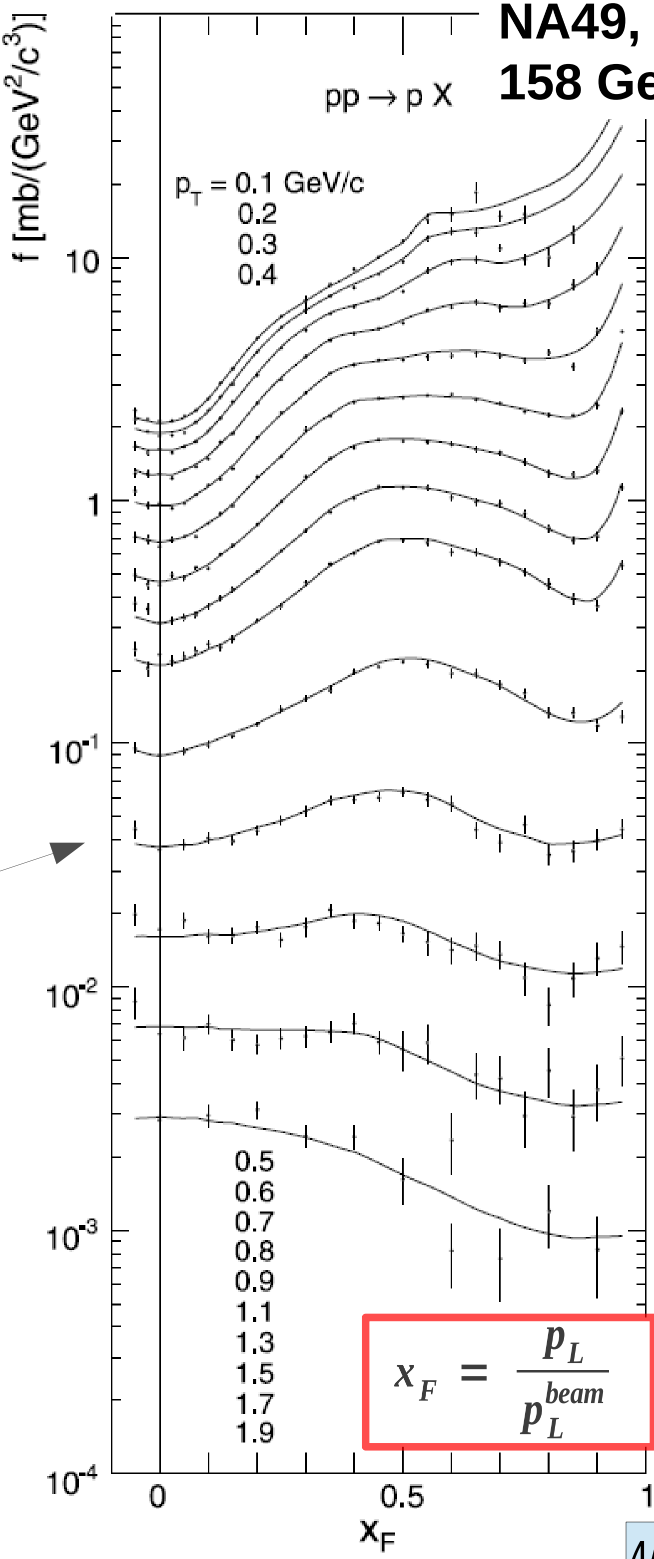
IFJ PAN participated in the NA49 experiment at CERN (presently NA61/SHINE).

1. No need to use protons as a **(wrong!) proxy** for **all the baryons** ;

2. Hermeticity (full projectile hemisphere, no p_T-cutoff) ;

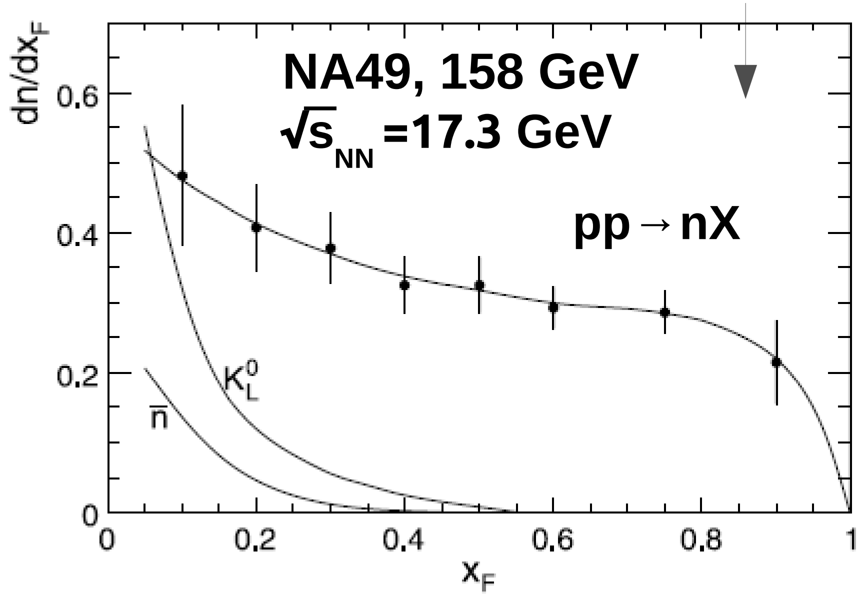
3. Both **pp and pC data sets** were provided by the same experiment.

NA49, 158 GeV



$$x_F = \frac{p_L}{p_L^{beam}}$$

[1]



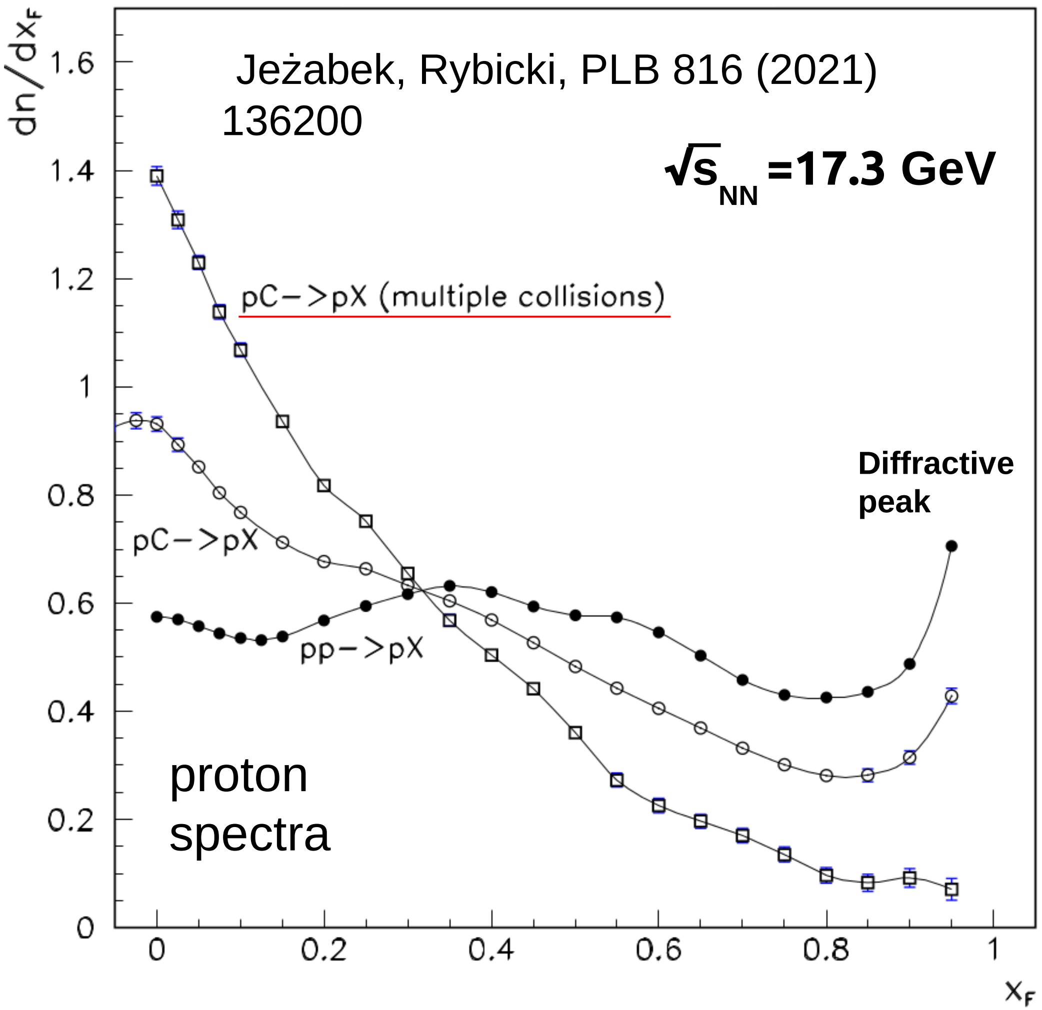
Our personal baryon number test: 0.96 (96/100) [excellent!!!]

a

Proton-proton vs proton-nucleus collisions

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

1. pp and pC data from the same NA49 experiment.
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.



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Qualitative difference between single and multiple proton-nucleon collisions!

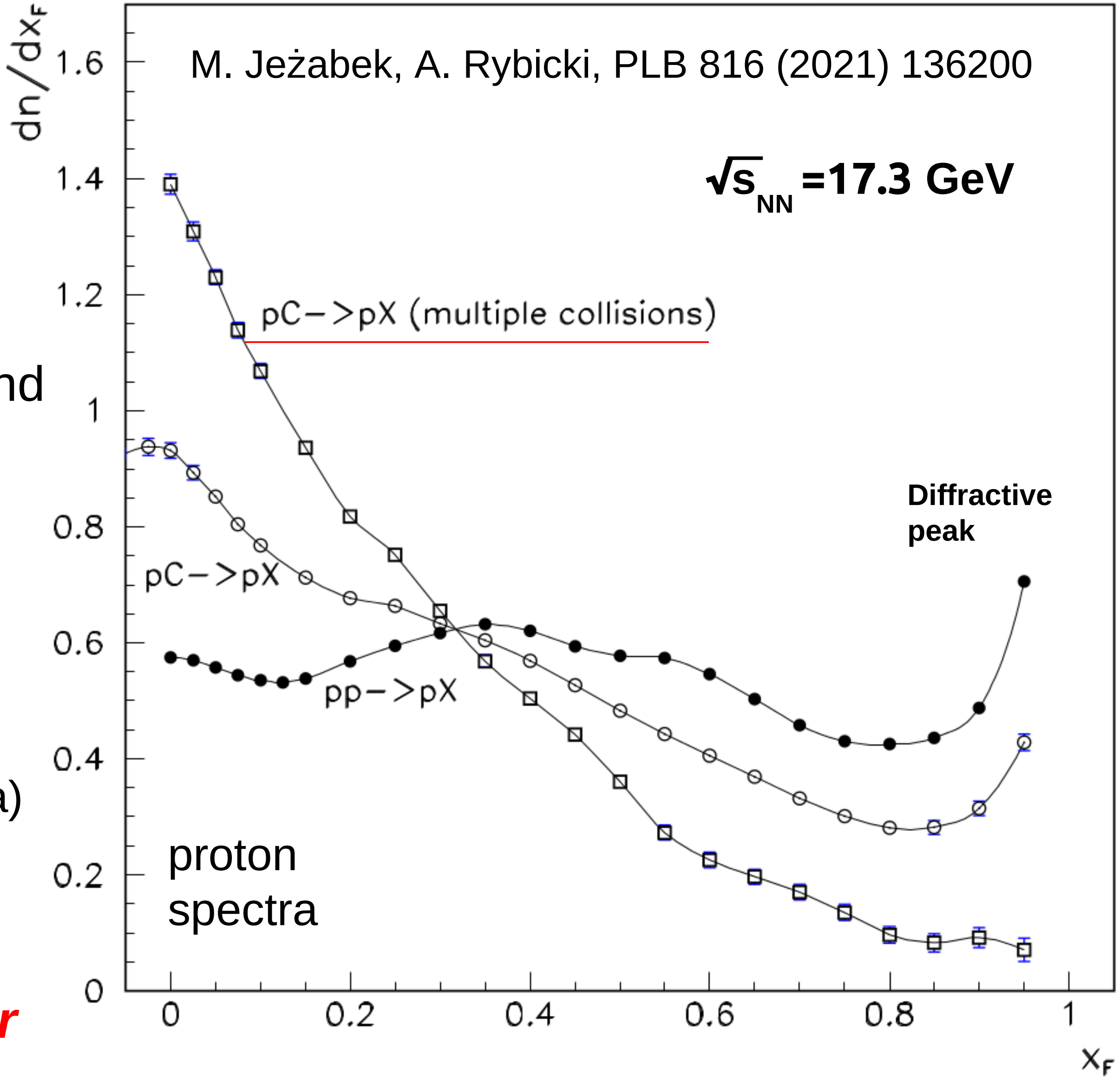
→ multiple collisions: **vanishing of diffractive peak** ;

→ multiple collisions: **very strong nuclear stopping power !**

→ it seems **hopeless** to understand this process w/o involving the **internal structure** of the proton...

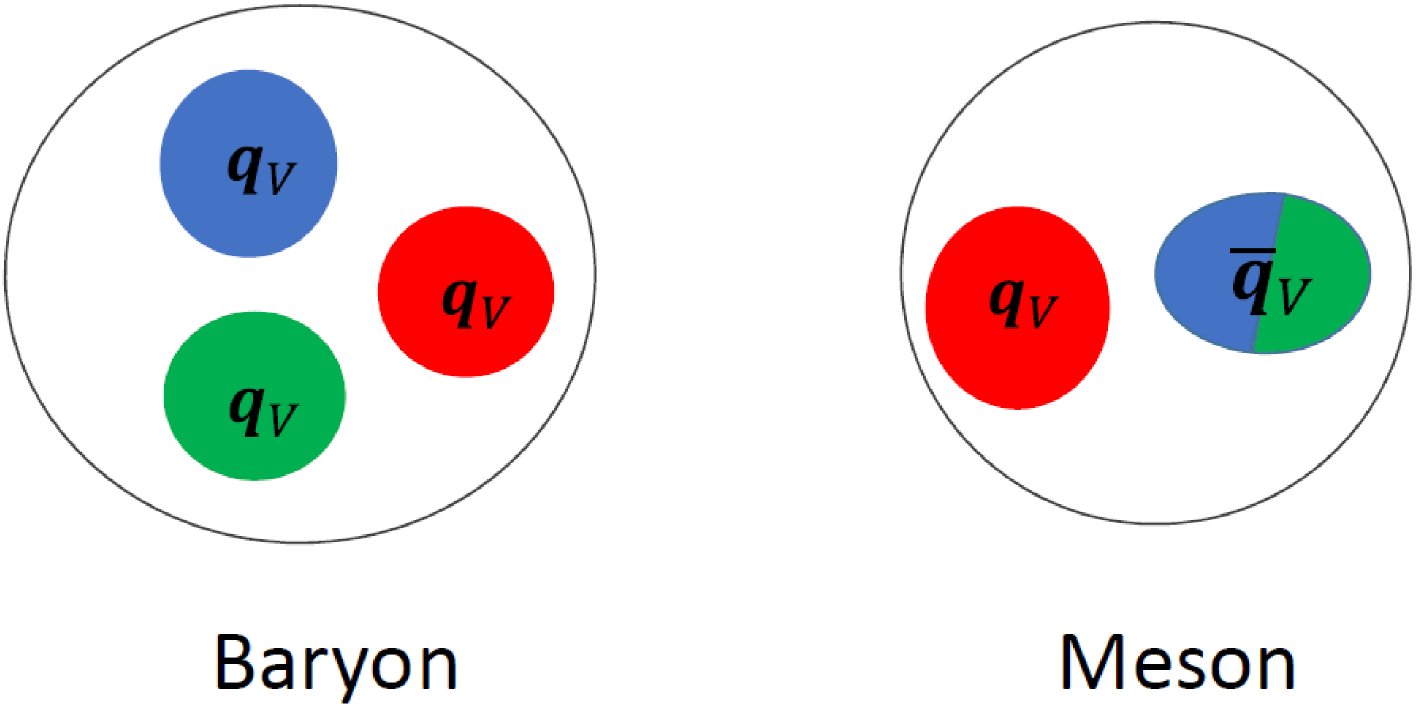
→ … but even models which did (Capella and Tran Thanh Van, Jeżabek, Karczmarczuk, Różańska) **failed** to describe the **strength** of this effect.

“The puzzle of nuclear stopping power”



2)
the Gluon Exchange Model
(GEM)

How do we imagine a proton in “soft” processes ?



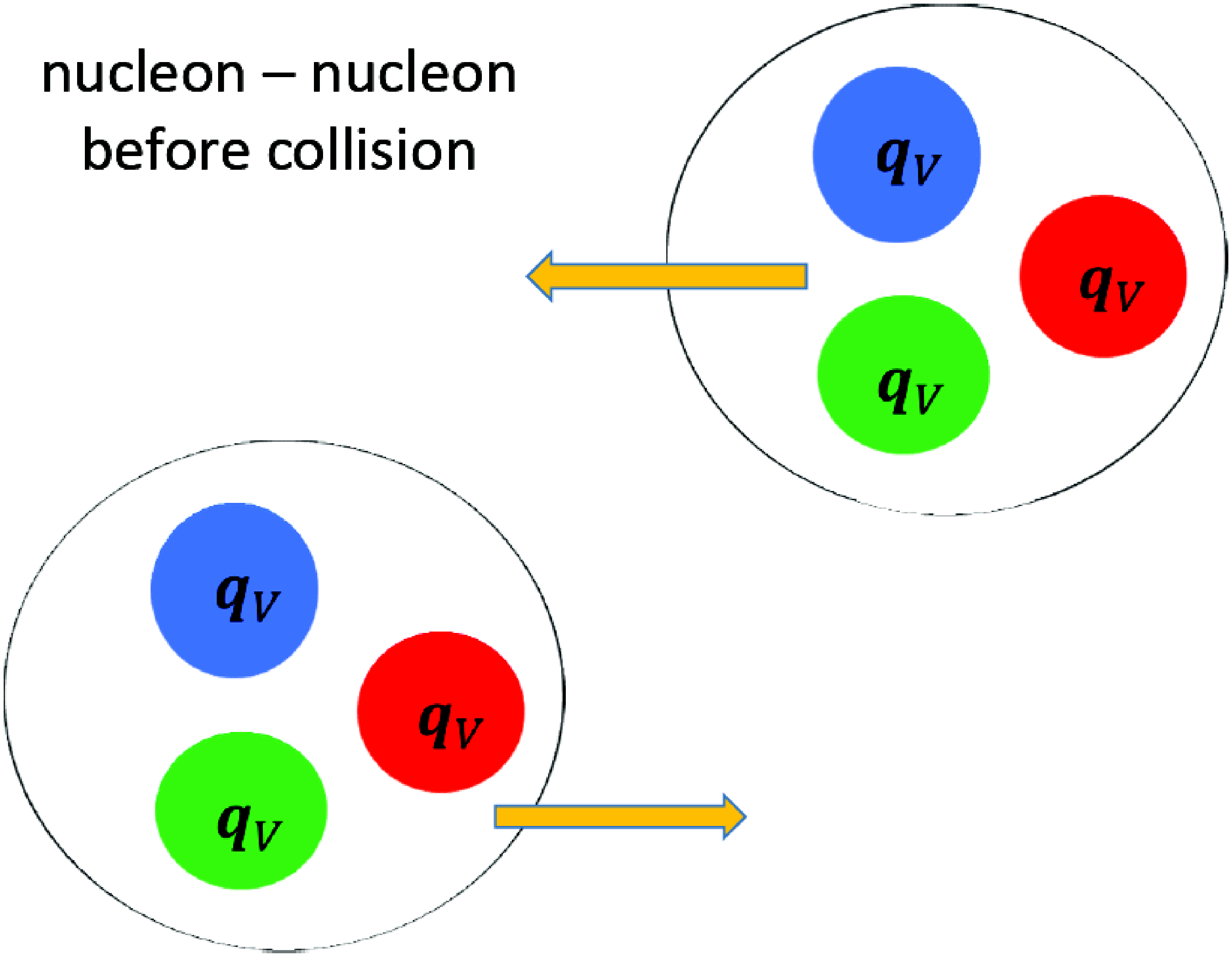
→ Quarks and gluons carry a special quantum number: **color** ;

→ quarks are **color triplets** ; → antiquarks carry anti-color ;

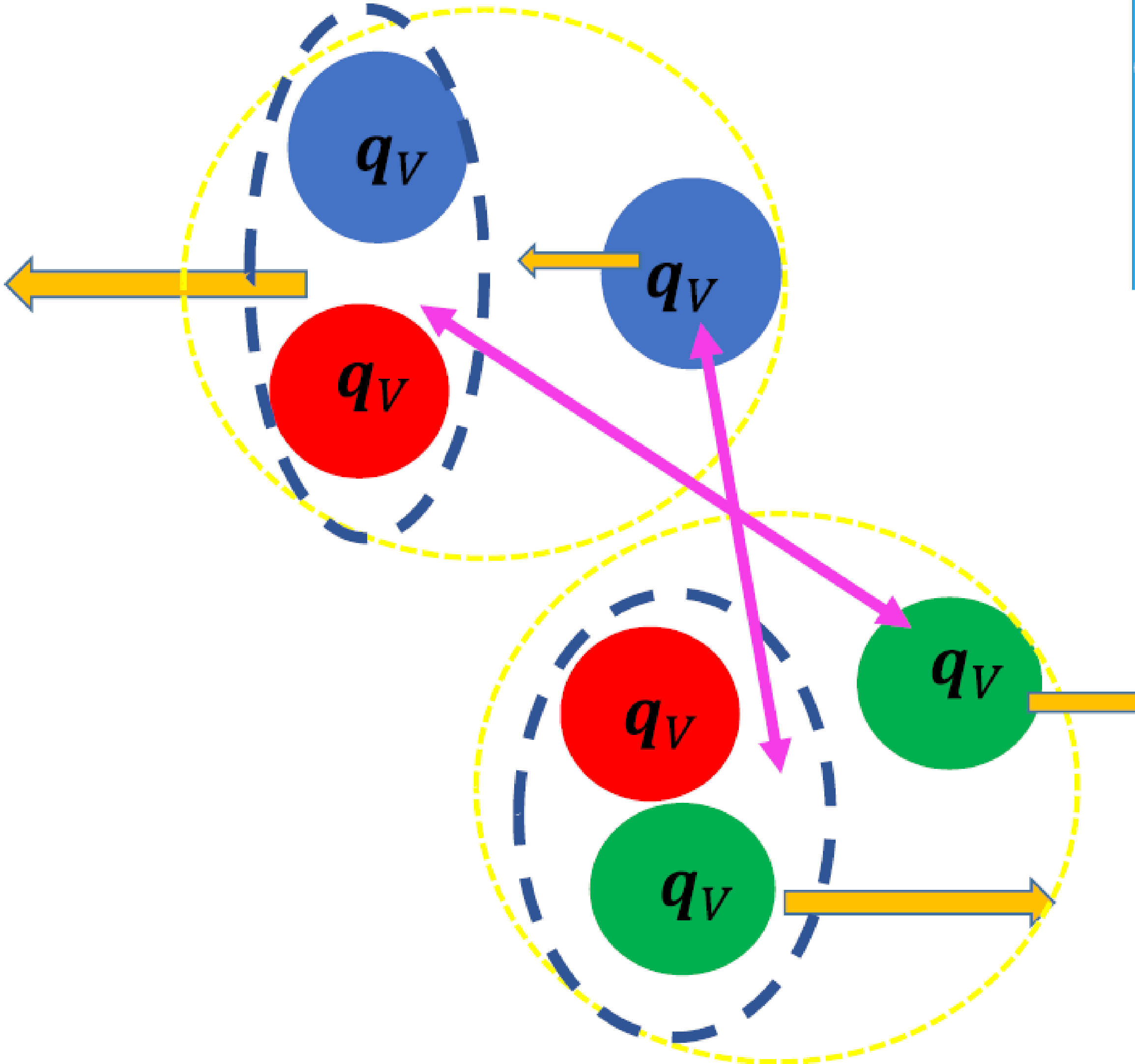
→ gluons are **color octets** ; → gluon exchange = **exchange of color !**

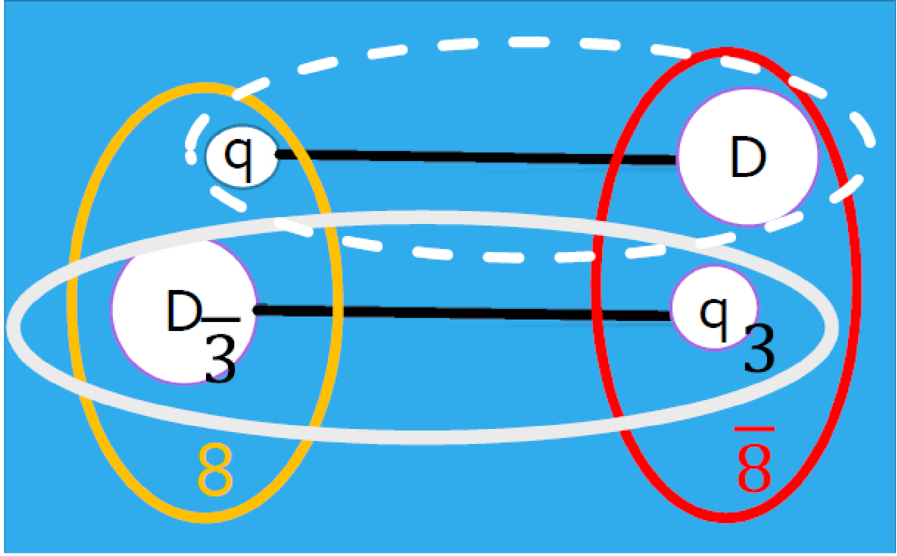
→ **all hadrons** (protons, neutrons, mesons etc.) are **color-neutral .**

nucleon – nucleon
before collision



nucleon – nucleon
after collision



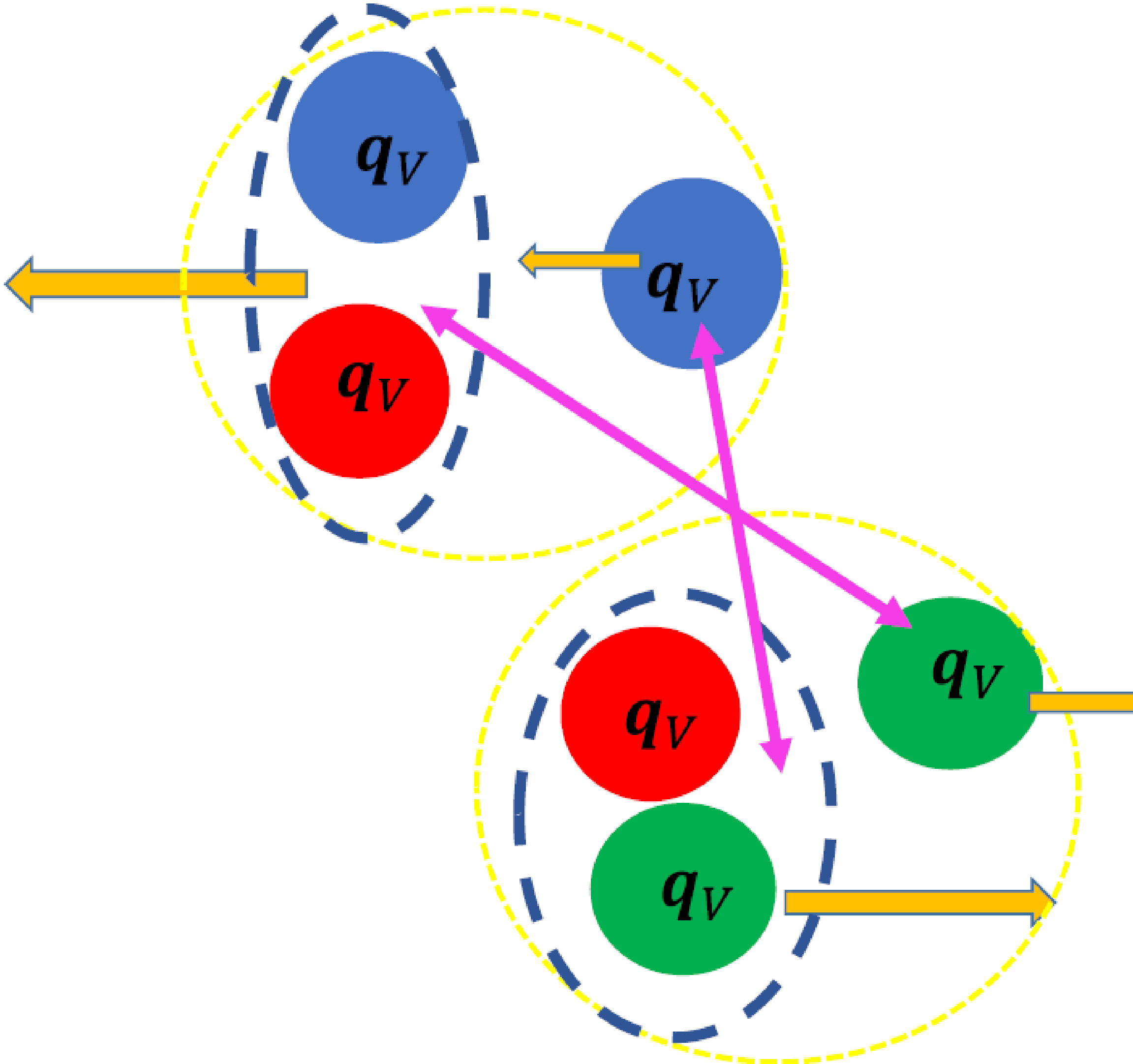


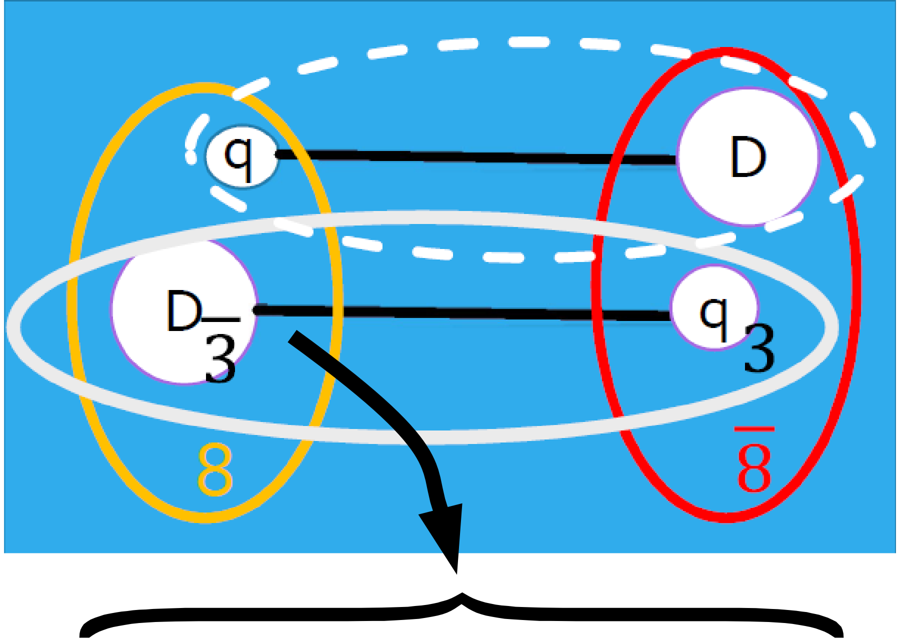
Note: this is like in the Dual Parton Model (DPM).

A. Capella and J. Tran Thanh Van, PLB **93**, 1980,
MJ, J. Karczmarczuk, M. Różańska, ZPC **29**, 1985.

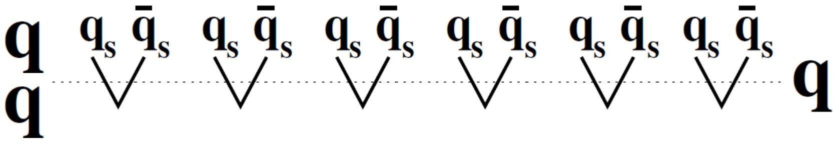
(*) **Diquark** = two quarks
in **color antitriplet state ($\bar{3}$).**

nucleon – nucleon
after collision





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

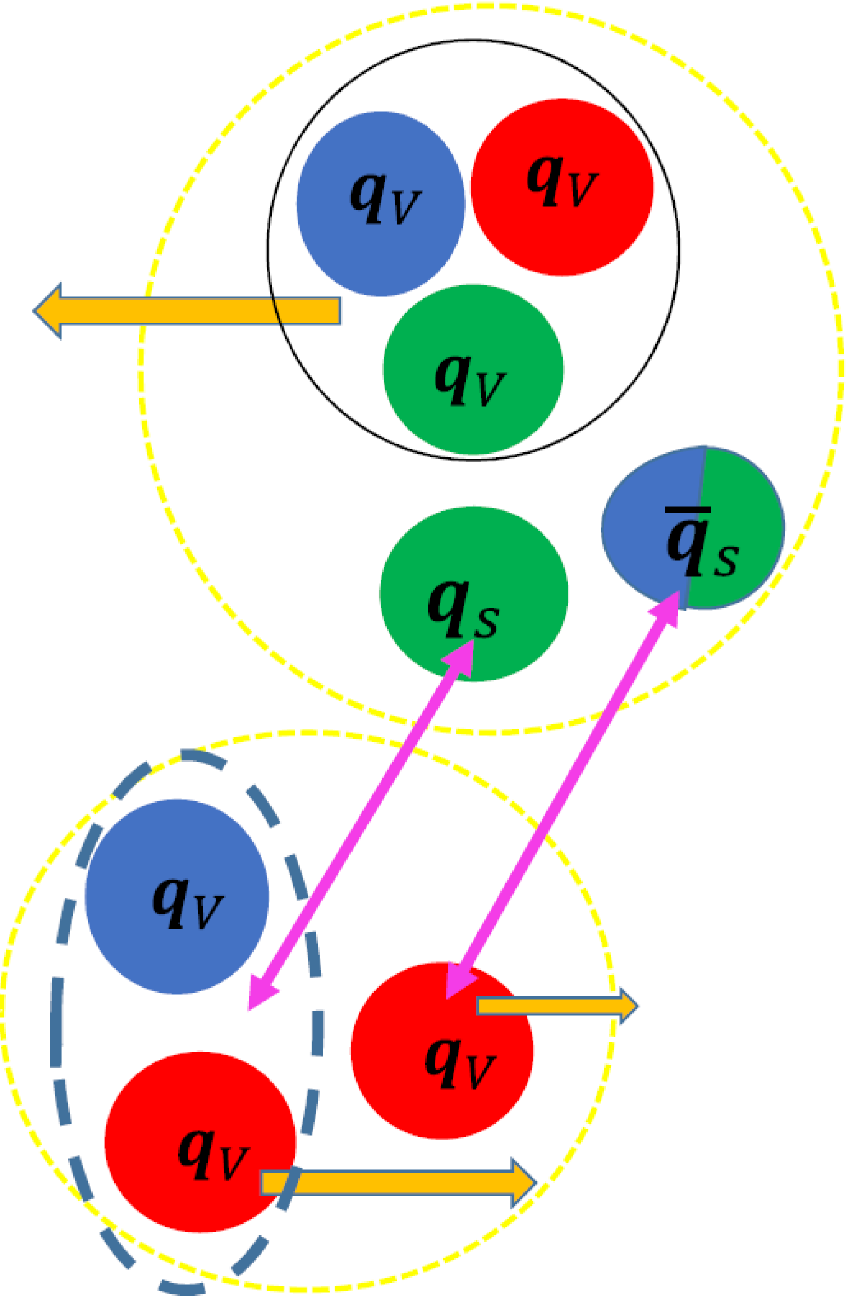


Note: Diquarks are essential for the emission of baryons !

- **Question:**

  will three valence quarks in the proton be sufficient to describe the emission of secondary baryons?

- **in proton-proton collisions →M.J., A.R., PLB 816 (2021) 136200 ;**
- **in proton-nucleus collisions → M.J., A.R., EPJPlus 136 (2021) 971 .**



Gluon Exchange Model

DPM + new contributions

nucleon – nucleon:
inelastic diffraction

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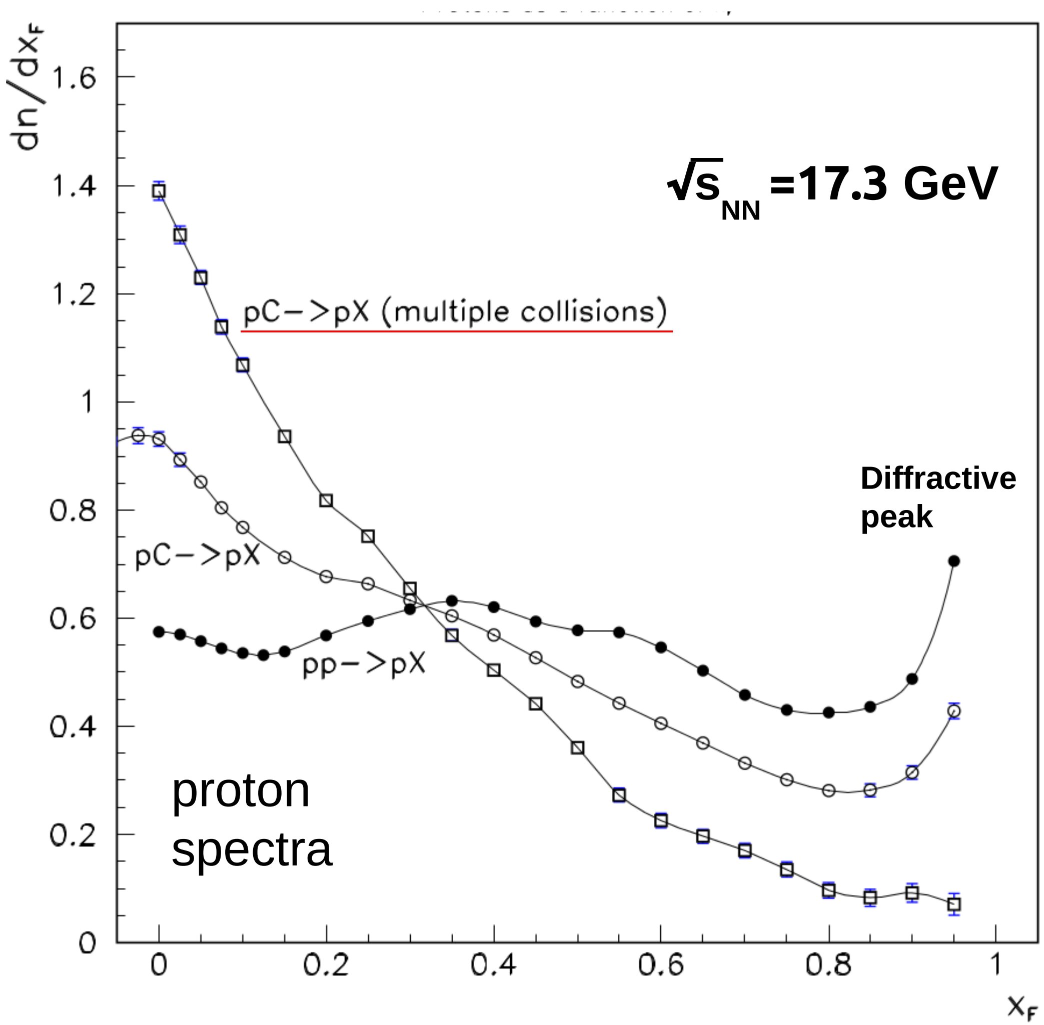

- **Note!**
- **Below we will discuss NET baryon spectra as a function of rapidity :**

$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

- **Baryon-antibaryon pair production has been subtracted from all the distributions !**
- **Unlike at the LHC, at the SPS the $\bar{\text{p}}$/p ratio is ~0.25 at $\boldsymbol{y_{(c.m.s.)}} = 0$.**

GEM in pp collisions

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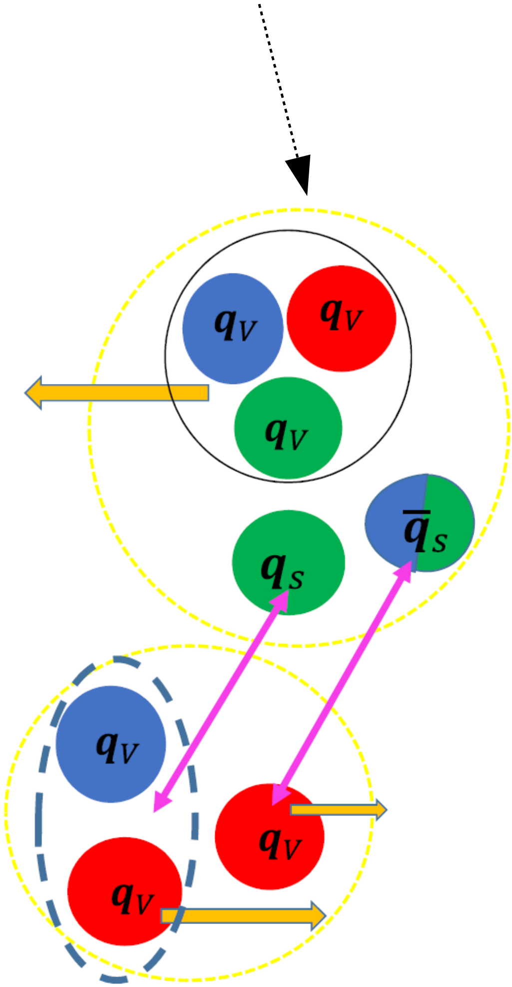
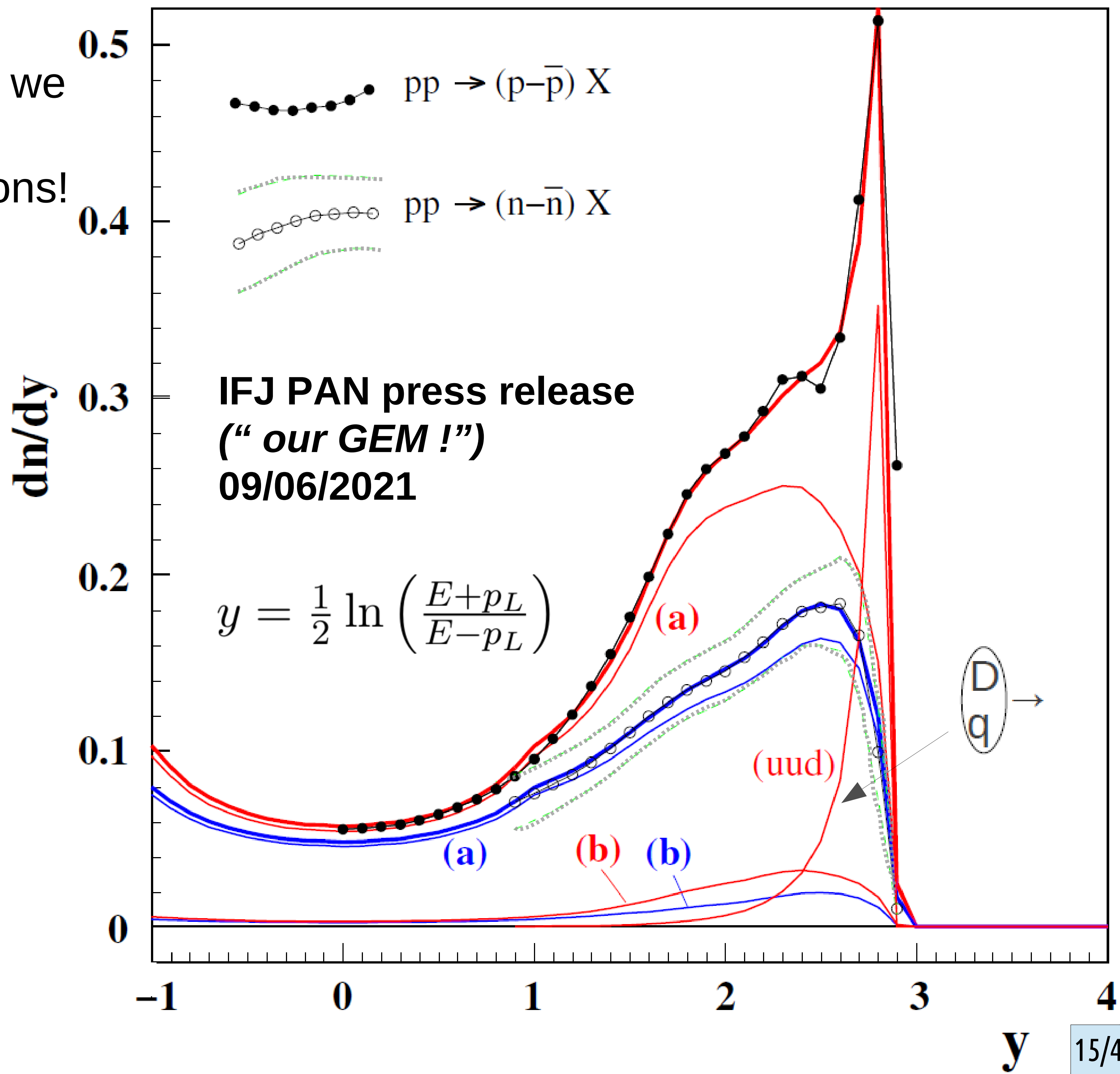
Note:
this is the **structure of the proton** which we need to understand proton-proton collisions!



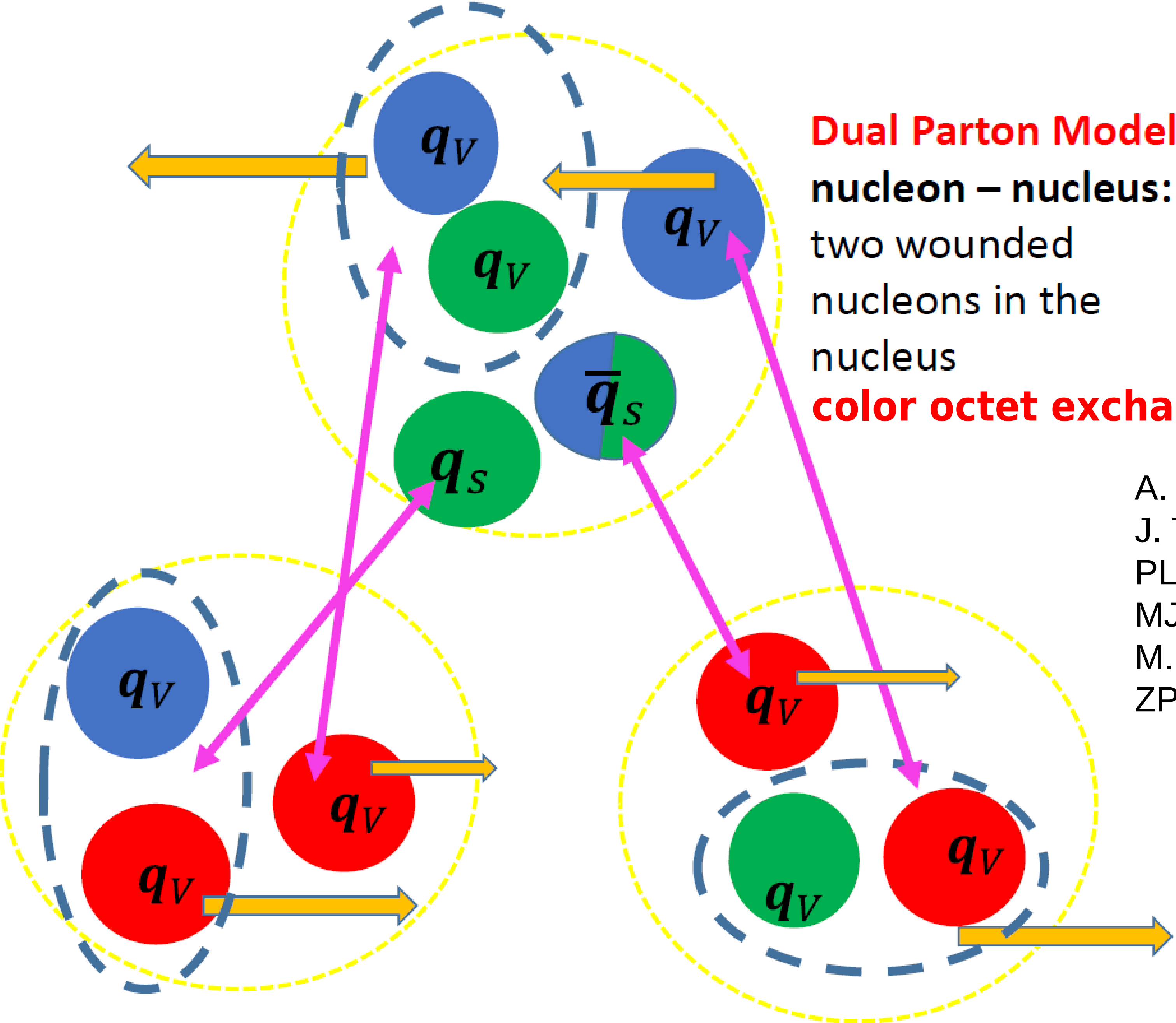


IFJ PAN press release
(" our GEM !")
09/06/2021

$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

Baryon stopping in proton-nucleus collisions

Proton-carbon (pC) data from the NA49 experiment,
Eur. Phys. J. **C73**, 2364 (2013) .



Dual Parton Model (1980)

nucleon – nucleus:

two wounded nucleons in the nucleus

color octet exchange

A. Capella and
J. Tran Thanh Van,
PLB **93**, 1980,
MJ, J. Karczmarczuk,
M. Różańska,
ZPC **29**, 1985.

Sea quark/antiquark degrees of freedom for multiple collision processes: **DPM.**
Still, **secondary baryons** are created from **valence diquarks.**

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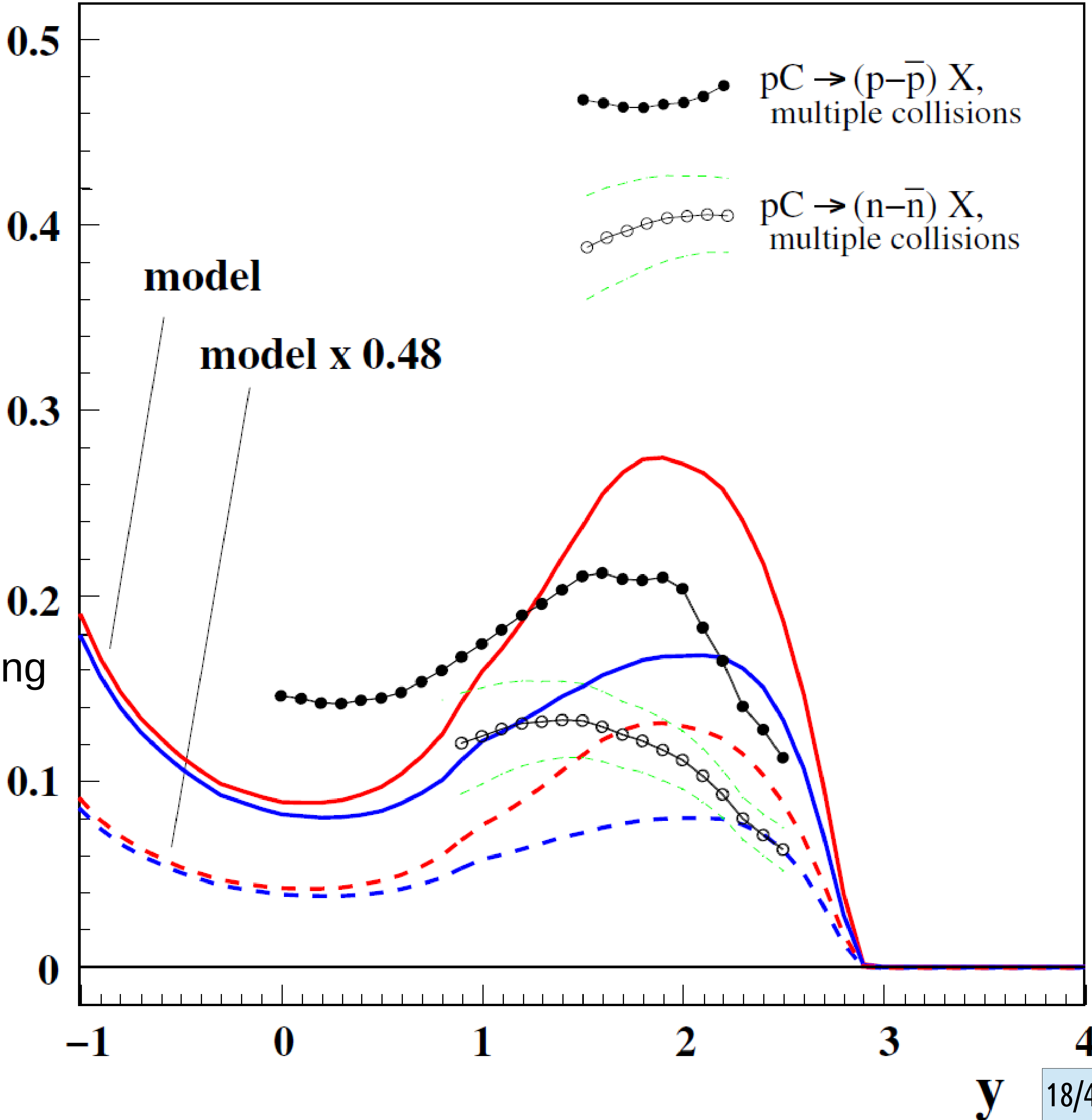
GEM in pA collisions (the diquark-preserving scenario)

Note:
this is (again) the
puzzle of nuclear stopping power.

(*) see also
M.J., M. Różańska,
PLB 175 (1986) 206.



- Exp. data: diquark-preserving diagrams cannot be responsible for 100% of baryon “stopping” ;
- Upper limit for this contribution : 48% .

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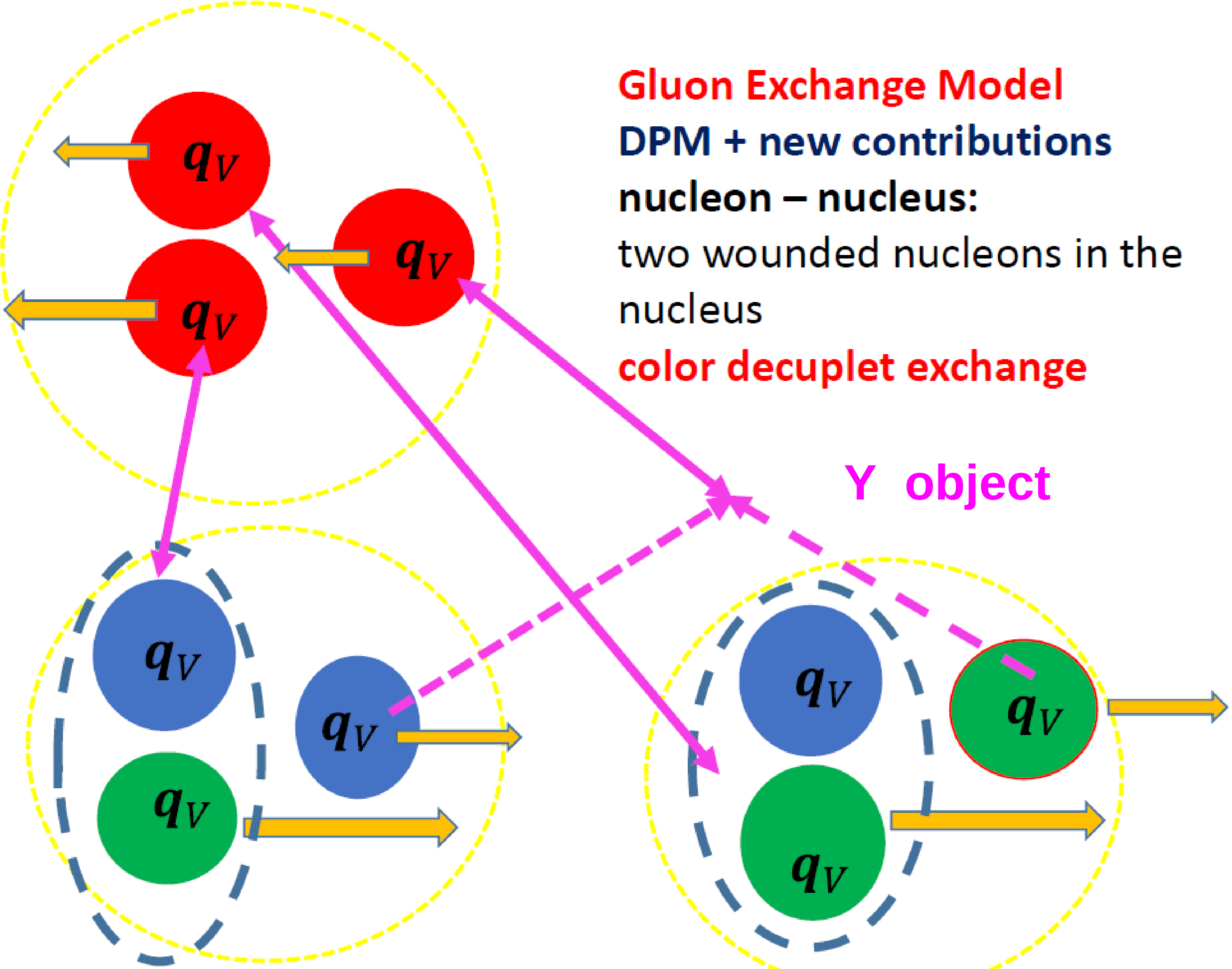

Gluon Exchange Model

DPM + new contributions

nucleon – nucleus:

two wounded nucleons in the nucleus

color decuplet exchange

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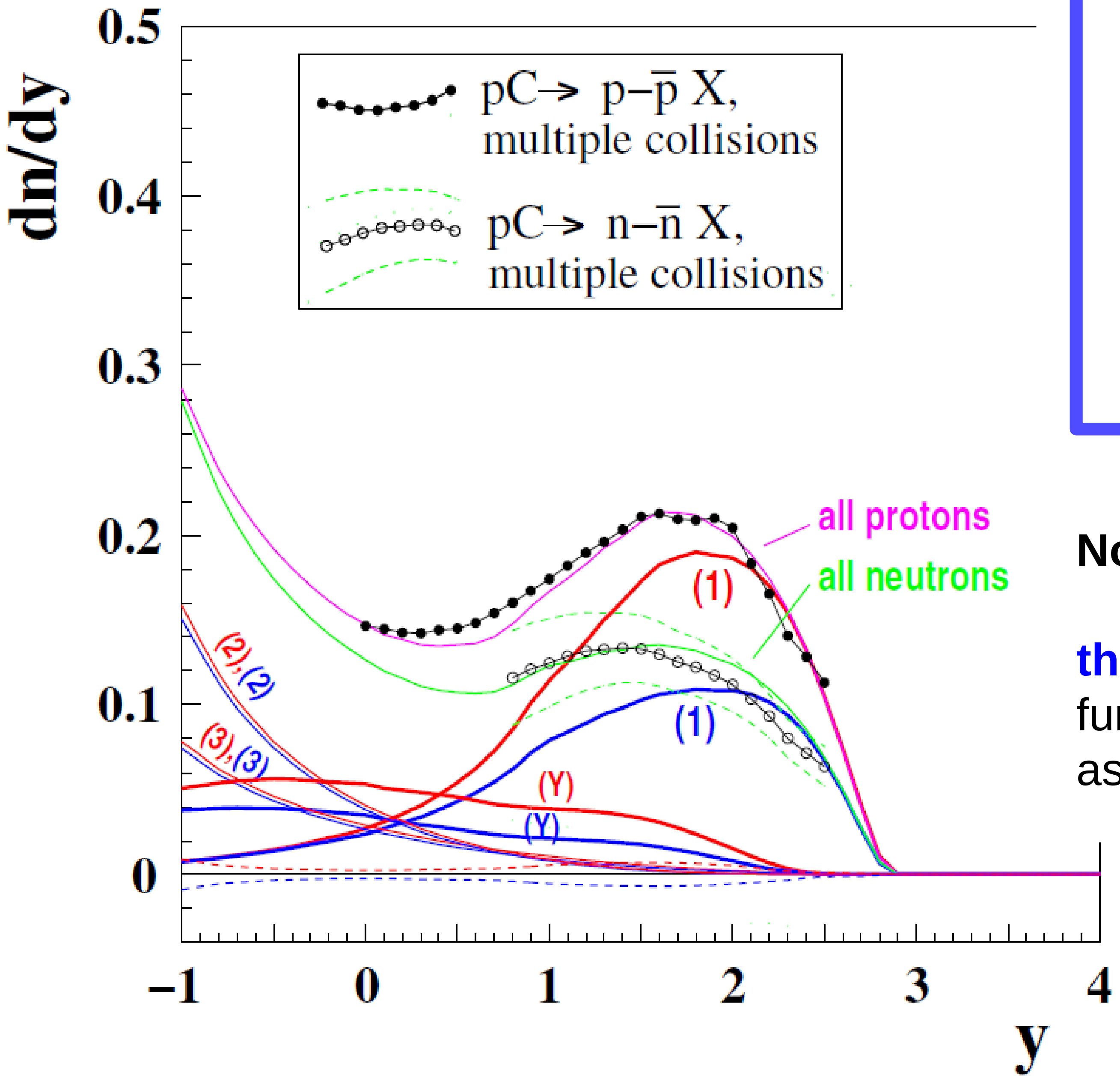
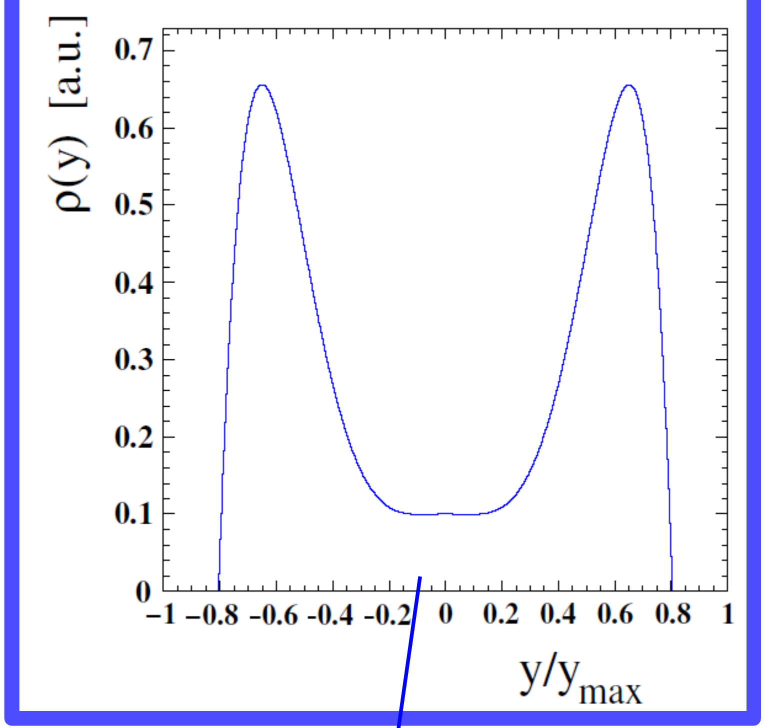
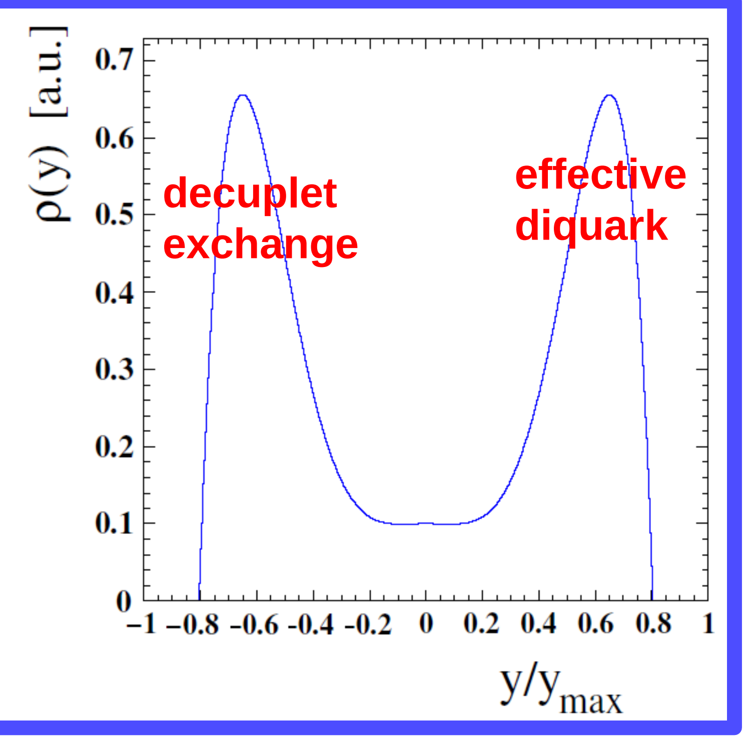




Note!

this is the fragmentation function which we had to assume for the “Y object”.



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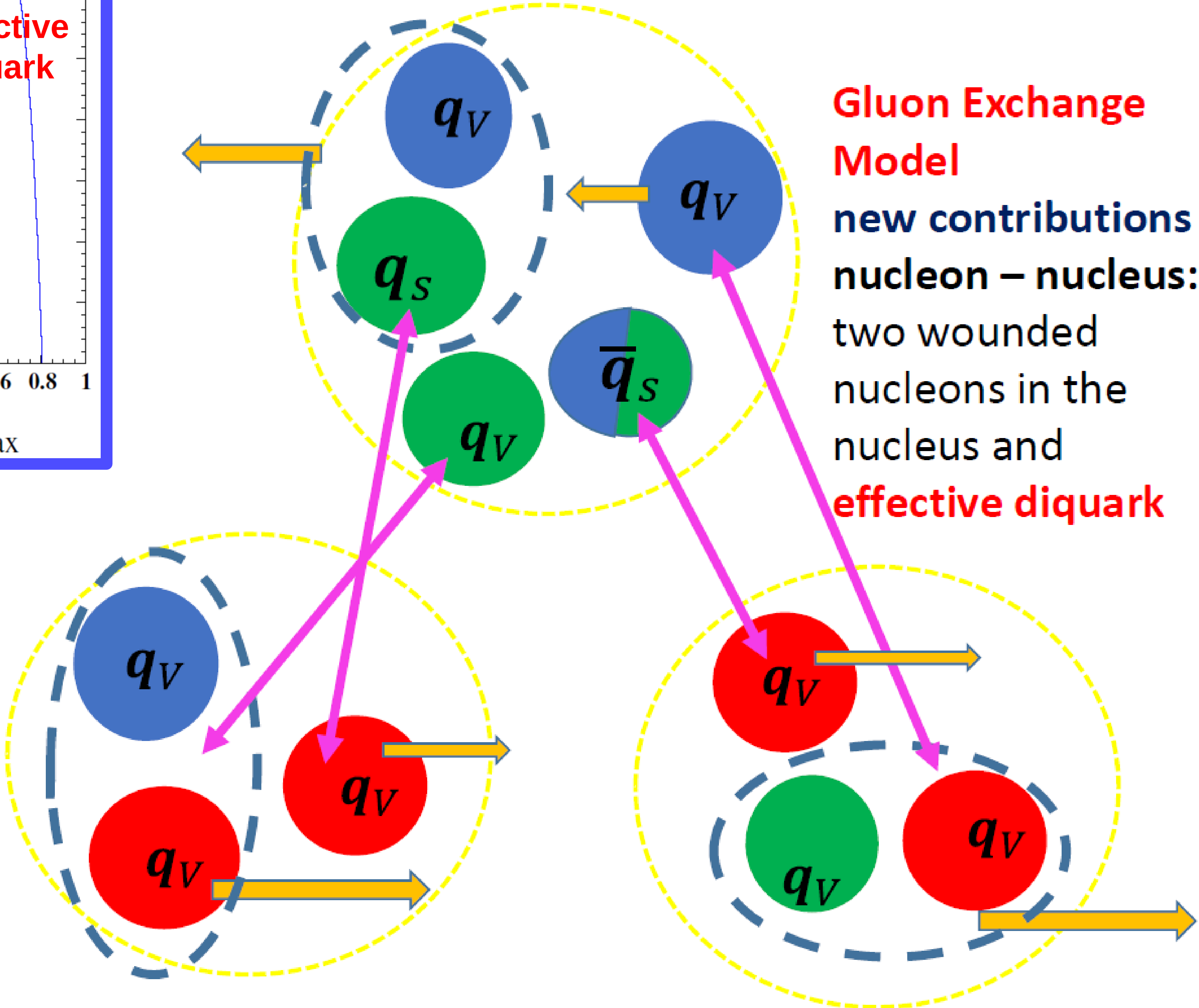


Gluon Exchange Model

new contributions nucleon – nucleus:

two wounded nucleons in the nucleus and **effective diquark**

we need to go beyond valence diquarks

Summary (1)

1. For pp collisions, we found that it is necessary to go beyond the **valence quark degrees of freedom (inelastic diffraction) ;**

2. The importance of **sea quarks and antiquarks** in the multiple collision process was known already in the Dual Parton Model. Still, **secondary baryons** were produced only from **valence diquarks** ;

3. Relying uniquely on **valence quarks** in the proton brought us to two configurations: **color octet** and **color decuplet** ;

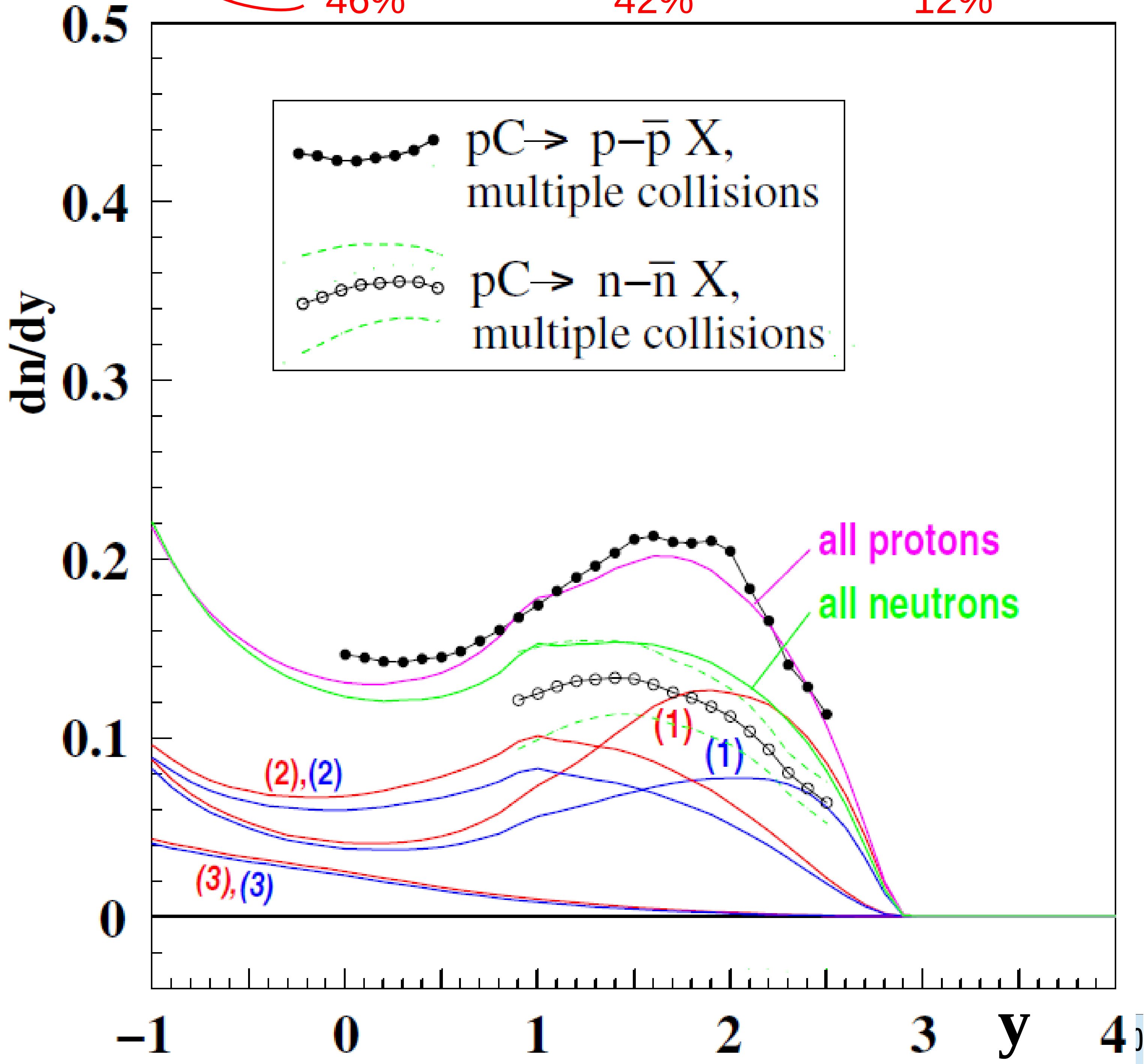
4. This brought us to a **non-intuitive** fragmentation function for the “Y” object ;

5. In order to preserve an intuitive fragmentation scheme, the exp. data **forced us** to introduce **effective diquarks (valence + sea quark).**

GEM in pA collisions
(1) octet, (2) effective diquark, (3) decuplet.

46% 42% 12%

In order to understand these numbers, we will now introduce a **statistical postulate.**



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

Statistical scheme for color exchange in p-nucleus collisions:

M.J., A.R.,
ArXiv: 2111.03401,
submitted to PLB.

1. *N* gluons are exchanged.

2. We consider two options:

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

Valence and sea quarks are in the **color representation** $R_8^{N-1} = \underset{\sim}{8} \otimes \underset{\sim}{3}^{N-1},$

Effective diquarks can be of type: **valence-valence, valence-sea, sea-sea .**

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

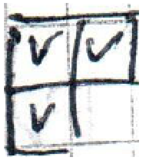
Valence and sea quarks are in the **color representation** $R_{10}^{N-2} = \underset{\sim}{10} \otimes \underset{\sim}{3}^{N-2},$

Effective diquarks can be of type: **no-diquark, valence-sea, sea-sea .**

3. The **probability** of obtaining an **effective diquark of a given type** can be obtained by decomposition into **irreducible representations,** and assuming that probabilities to form a diquark are **equal** for all the allowed pairs of quarks.

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

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

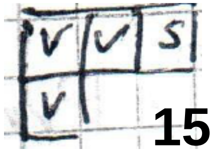


Dimension = 8

$$P_{vv} = 1$$

For 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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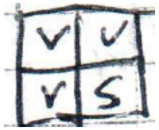

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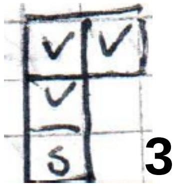


3

decuplet :

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

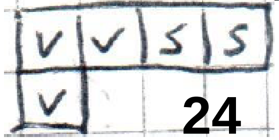
$$P_0 = 1$$

10

The experimental qualitative difference between *N=1* and *N⩾2* (slide 6) becomes evident here.

For 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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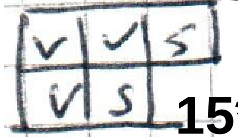
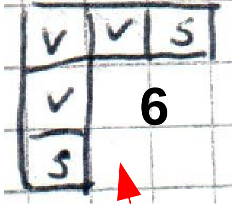


15*



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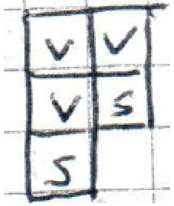
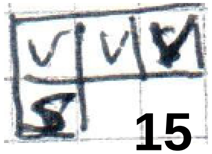


3*

decuplet :

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

15



15

ss diquark!

M.J., A.R.,
ArXiv: 2111.03401,
submitted to PLB.

color octet representations up to 9 gluons

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

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

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

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

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

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

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

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

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

M.J., A.R.,
ArXiv: 2111.03401,
submitted to PLB.

color decuplet representations up to 9 gluons

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

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

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

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

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

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

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

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

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	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

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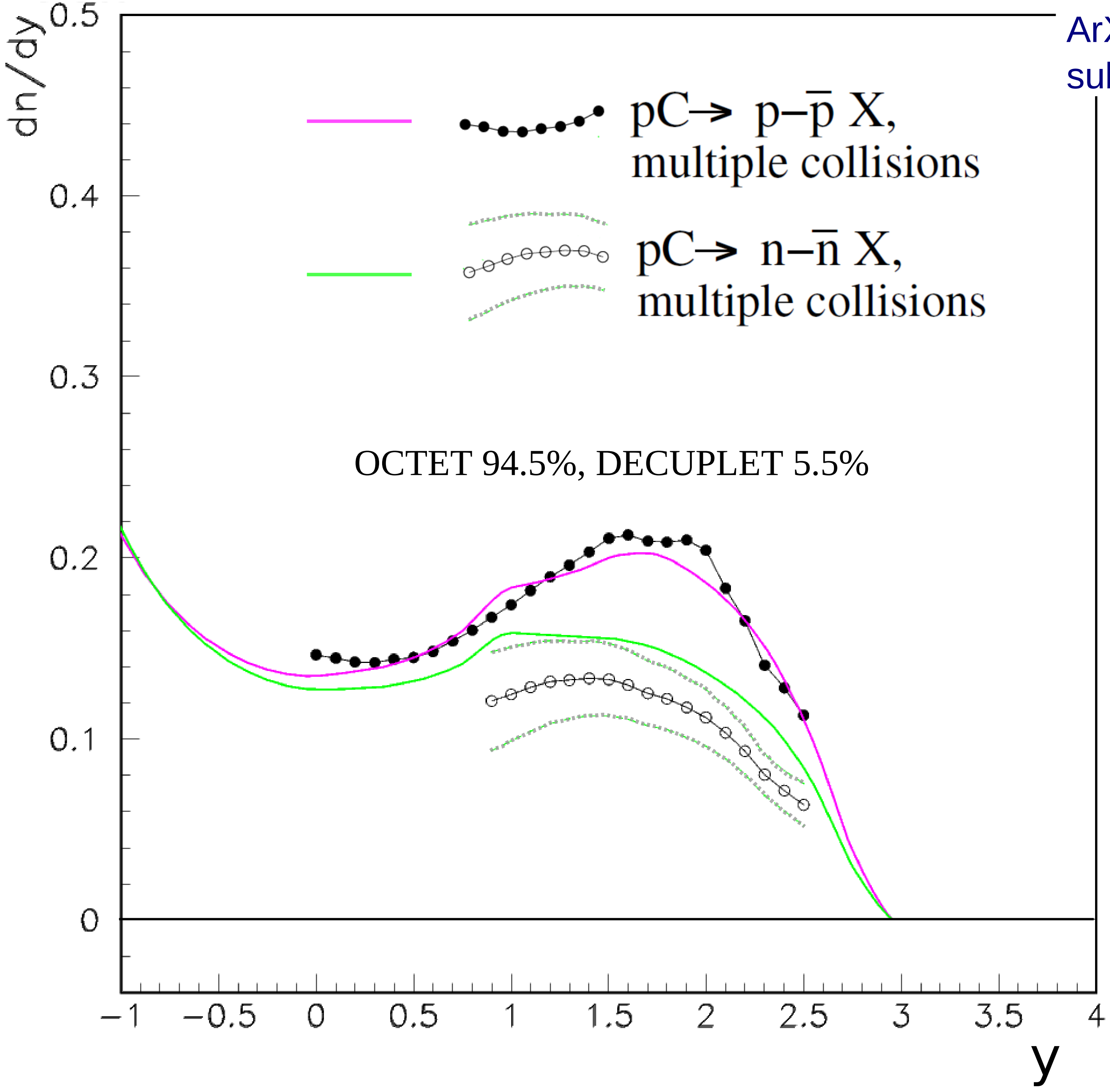

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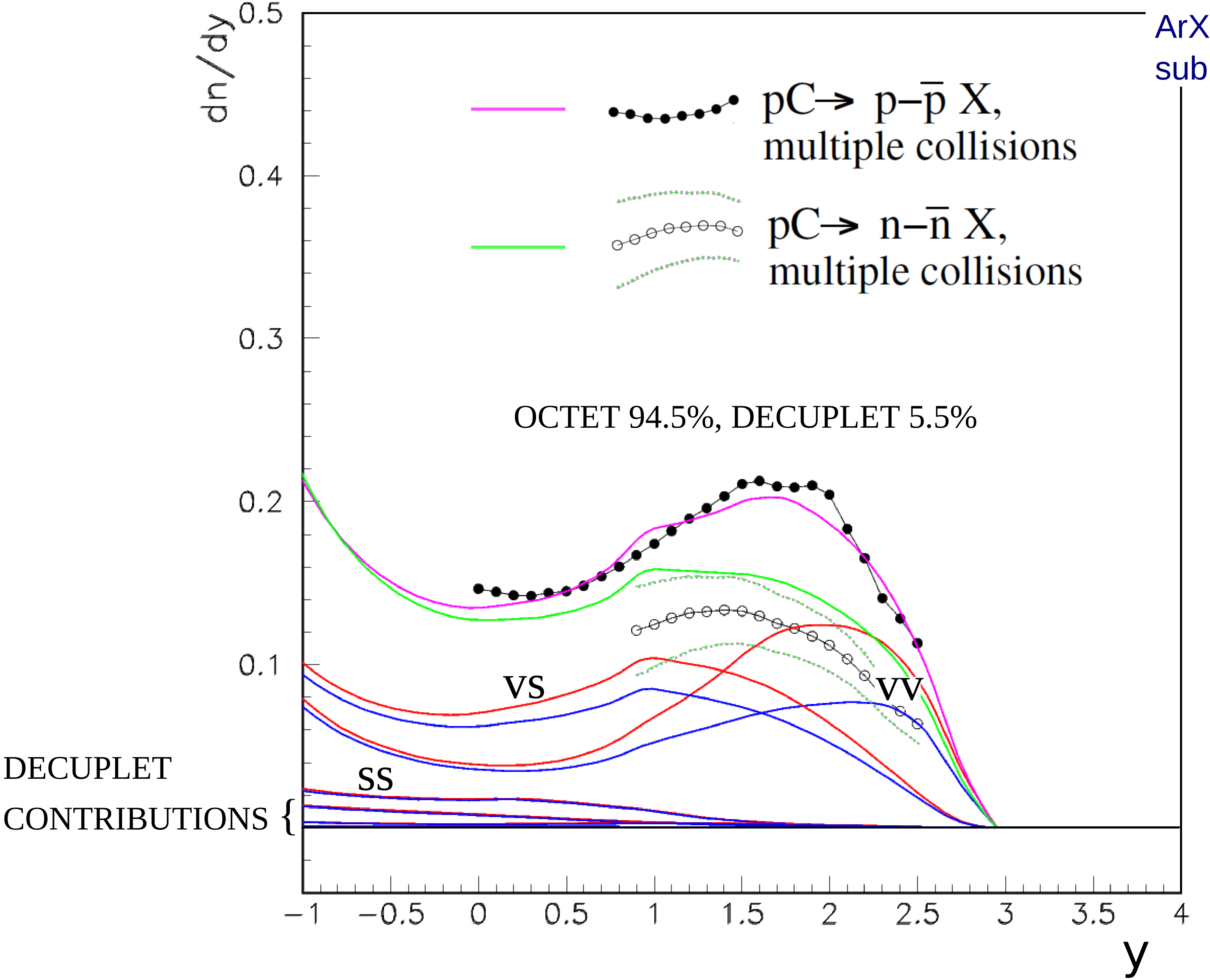

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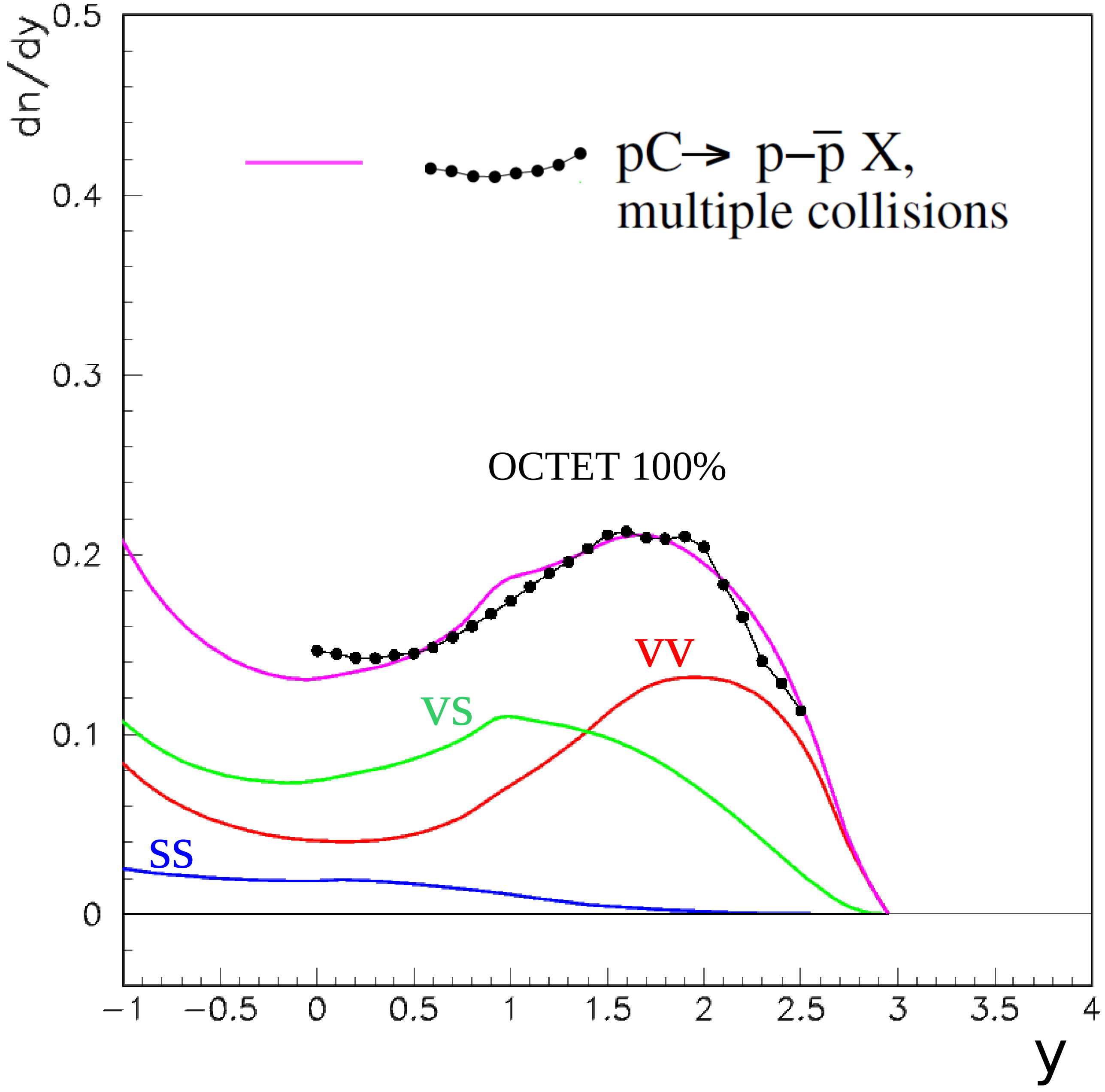

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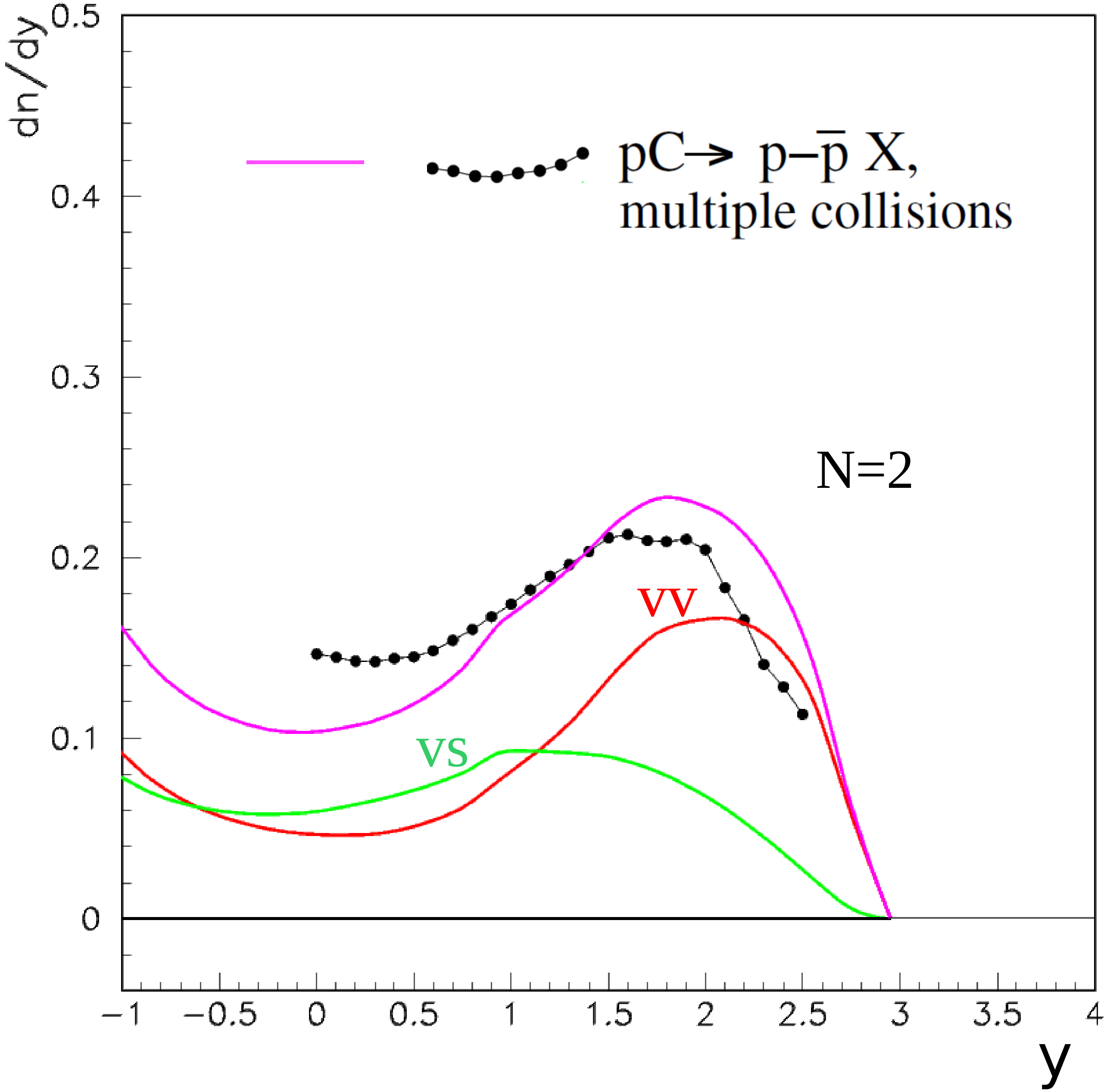

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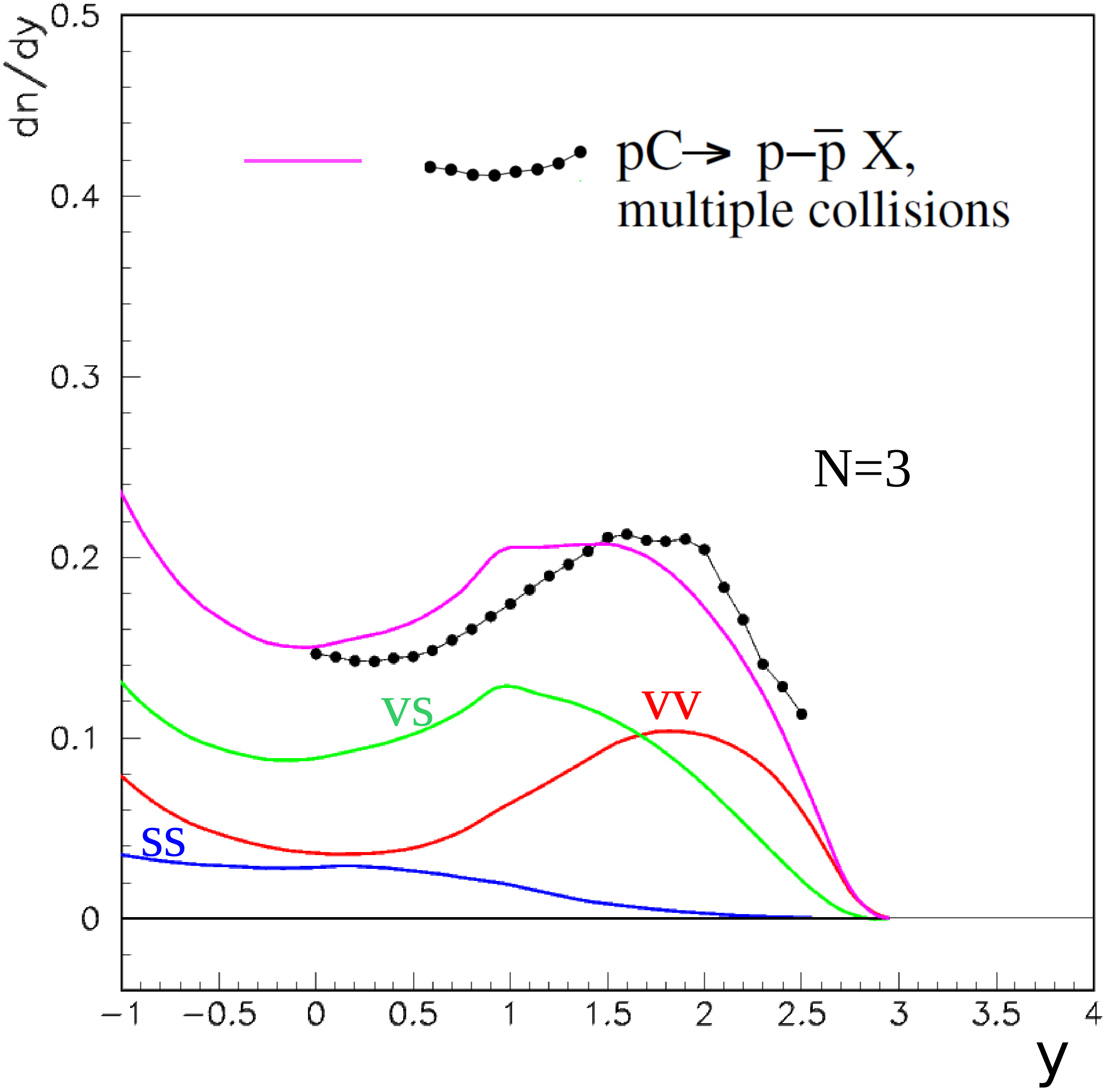

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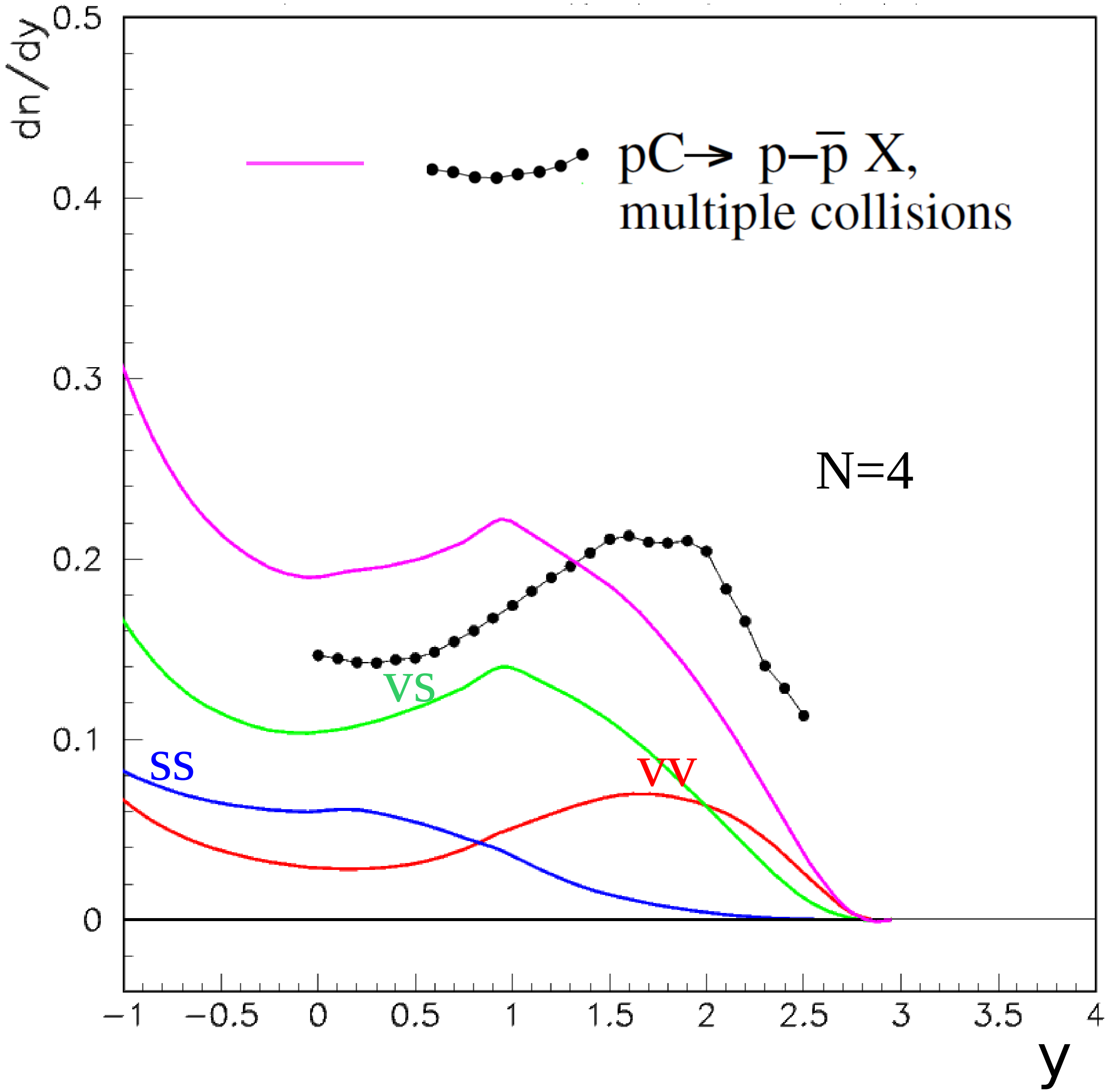

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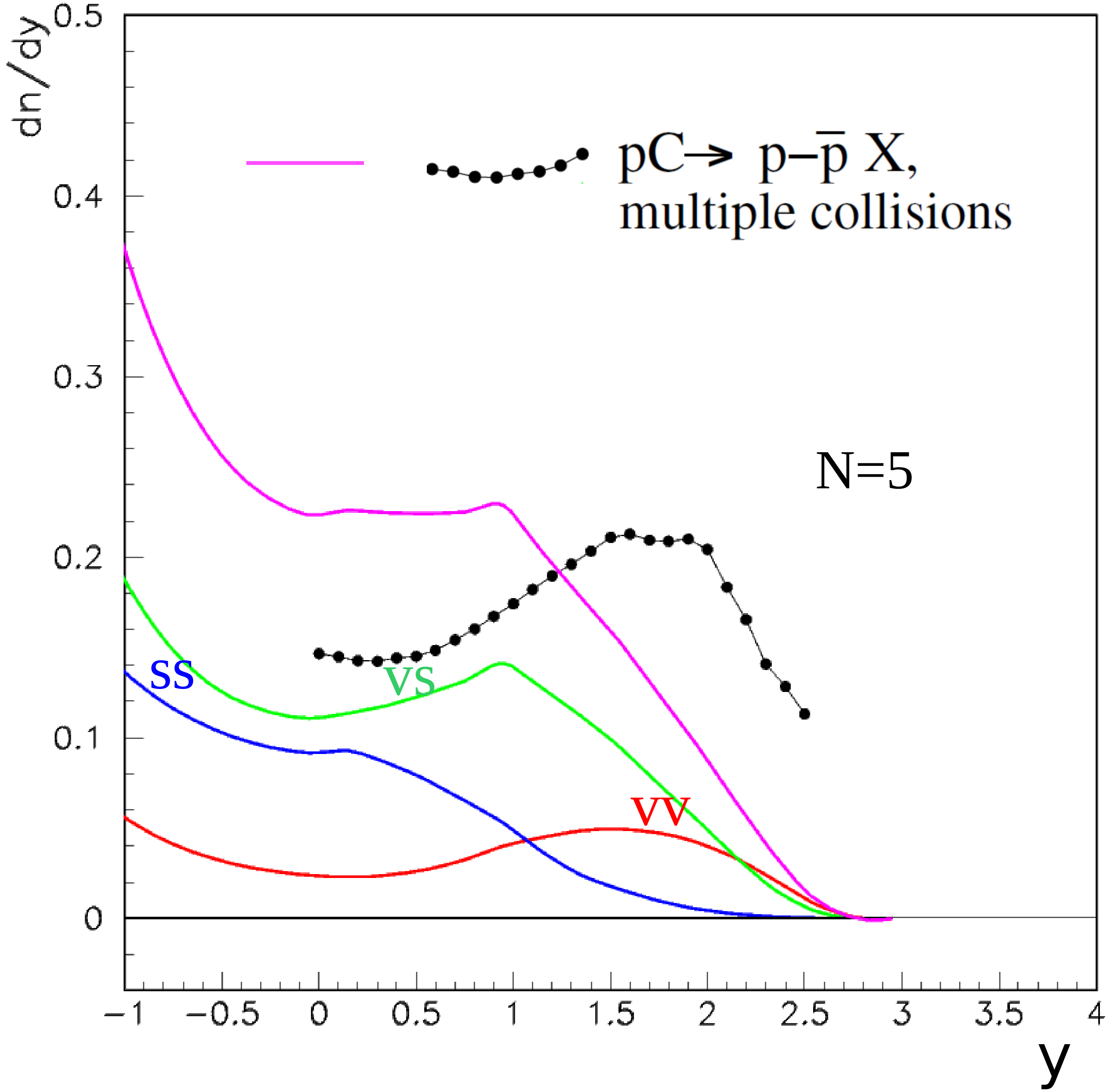

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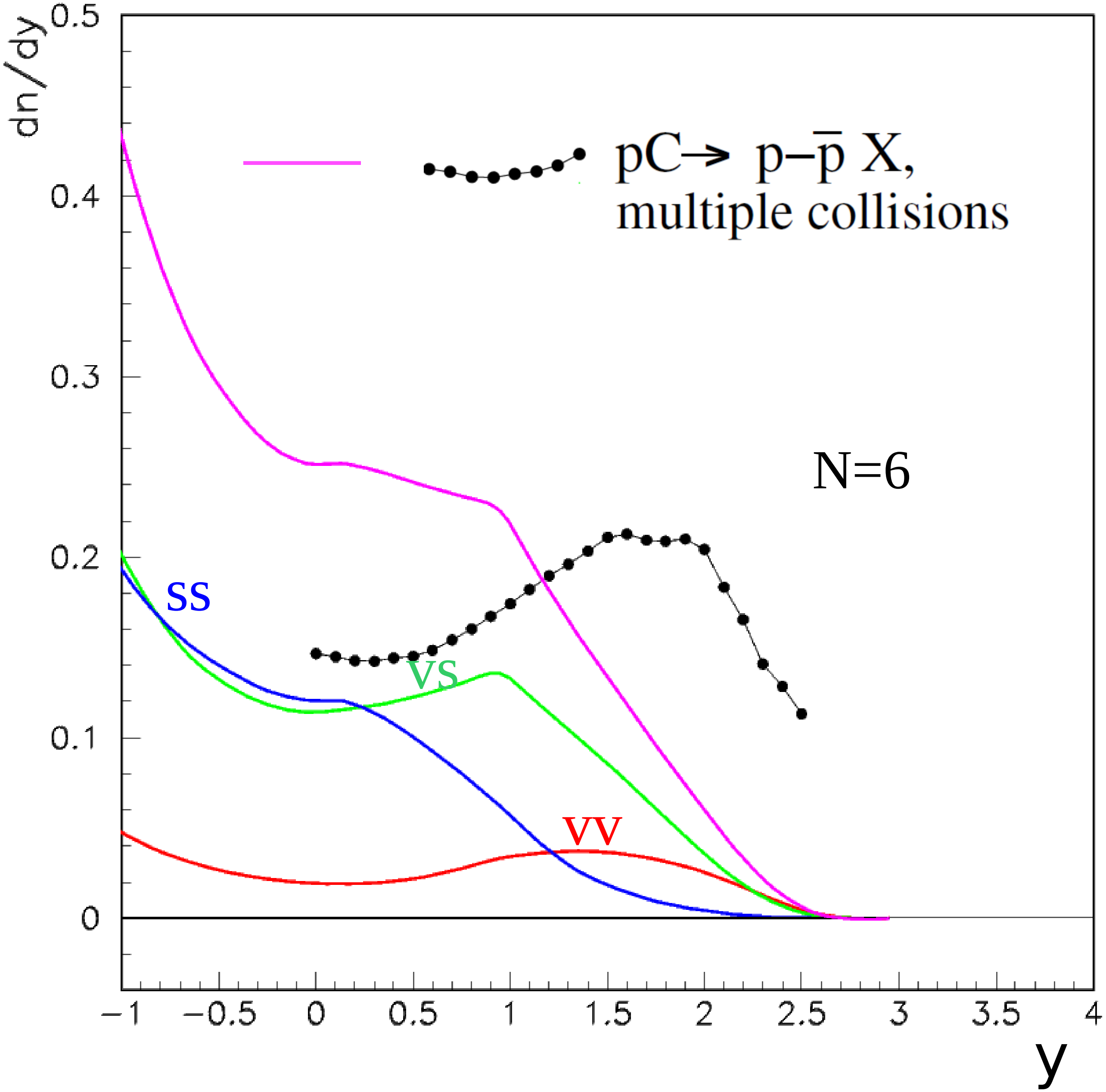

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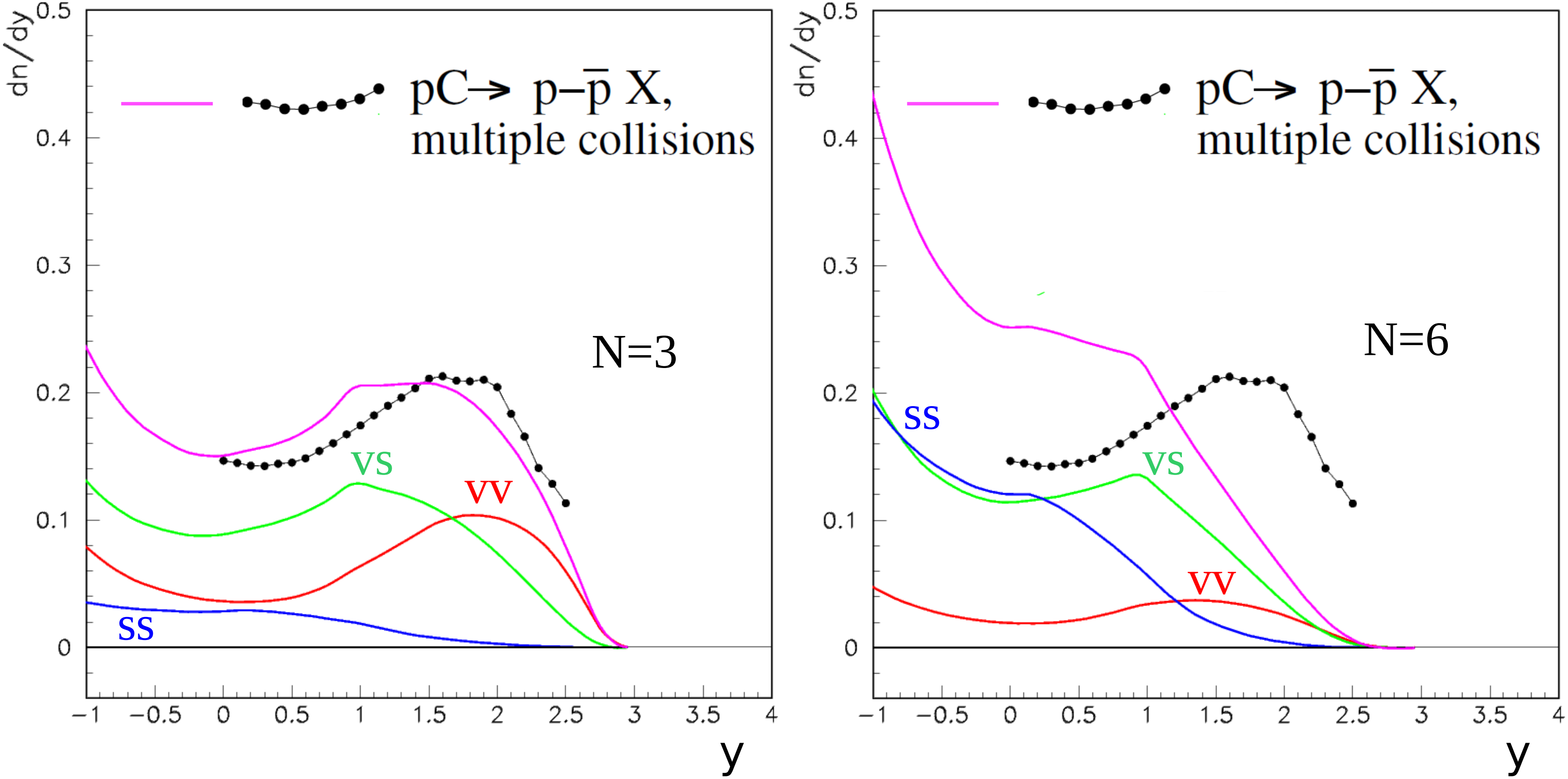


The process of baryon stopping is governed by the different **color configurations** of constituents of the proton (valence-valence, valence-sea, sea-sea), which **emerge** as a function of the **number of collisions**.

→ should be verified with experimental data on **p-Pb reactions.**

3) Summary

1. The process of emission of **secondary baryons** plays an important role in understanding of high energy proton-proton, proton-nucleus and heavy ion collisions (including **particle production**, **quark-gluon plasma** formation).

2. We attempted to describe new, precise **experimental data** on **pp** and **pC collisions** by proposing a **new model**, starting from the picture of the proton composed of **three valence quarks**.

3. An essential role is played by the **color configurations** of **constituents of the proton** in multiple scattering processes.

4. The inclusion of **valence degrees of freedom** alone is **not sufficient** to describe the experimental data.

5. Our work indicates that there are **four classes of contributions** to the spectra of secondary baryons, corresponding to **three types of diquarks** (**valence-valence, valence-sea, sea-sea**), and to **no diquark** in the forward hemisphere.

4) Outlook

1. Scattering of **antiprotons** on **protons** and **nuclei** is even more interesting, and may reveal **new phenomena** which will provide a deeper understanding of the **nature of annihilation** ;

2. **Work in progress** ;

3. **Ideal task for NA61/SHINE.**

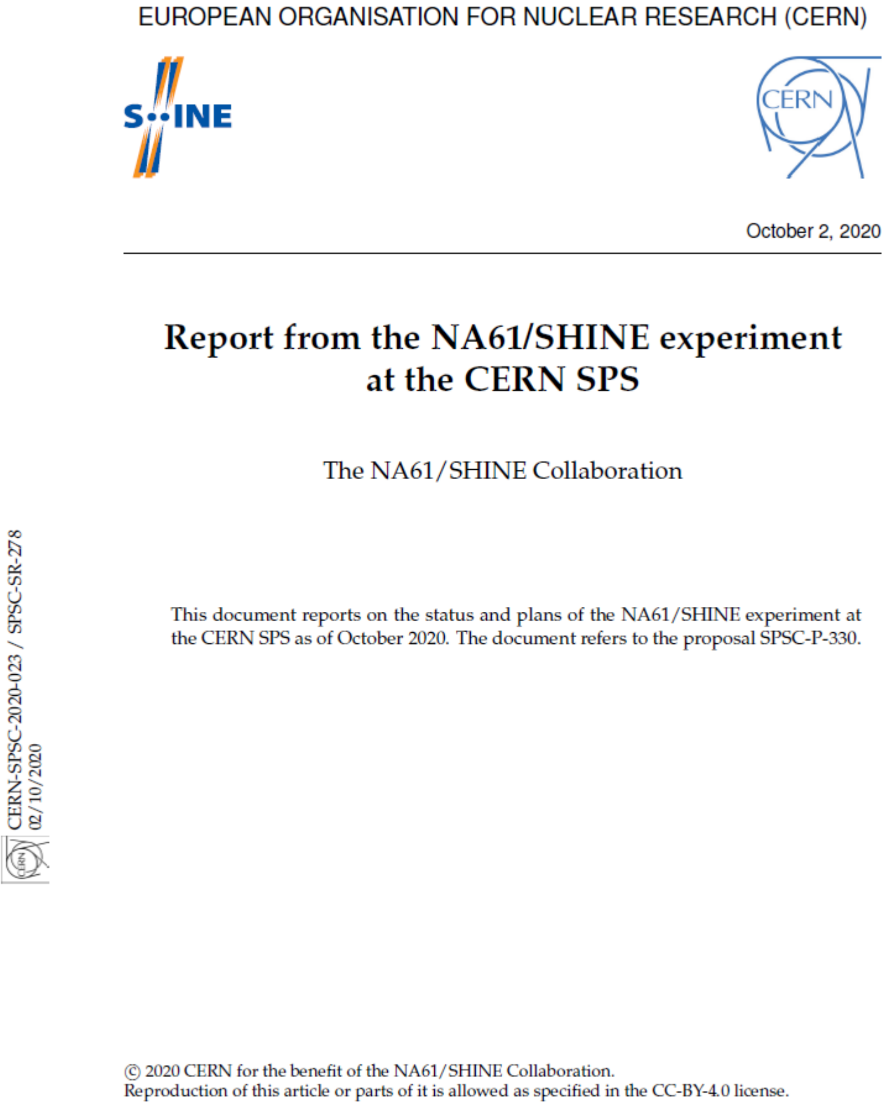
Acknowledgments

M.J. gratefully acknowledges the many years long collaboration with Maria Różańska; this collaboration contributed in an essential way to the phenomenology and ideas presented in this paper.

Also A.R. warmly thanks M. Różańska for very instructive discussions on the physics of soft baryon emission.

… thank you !

Extra slides



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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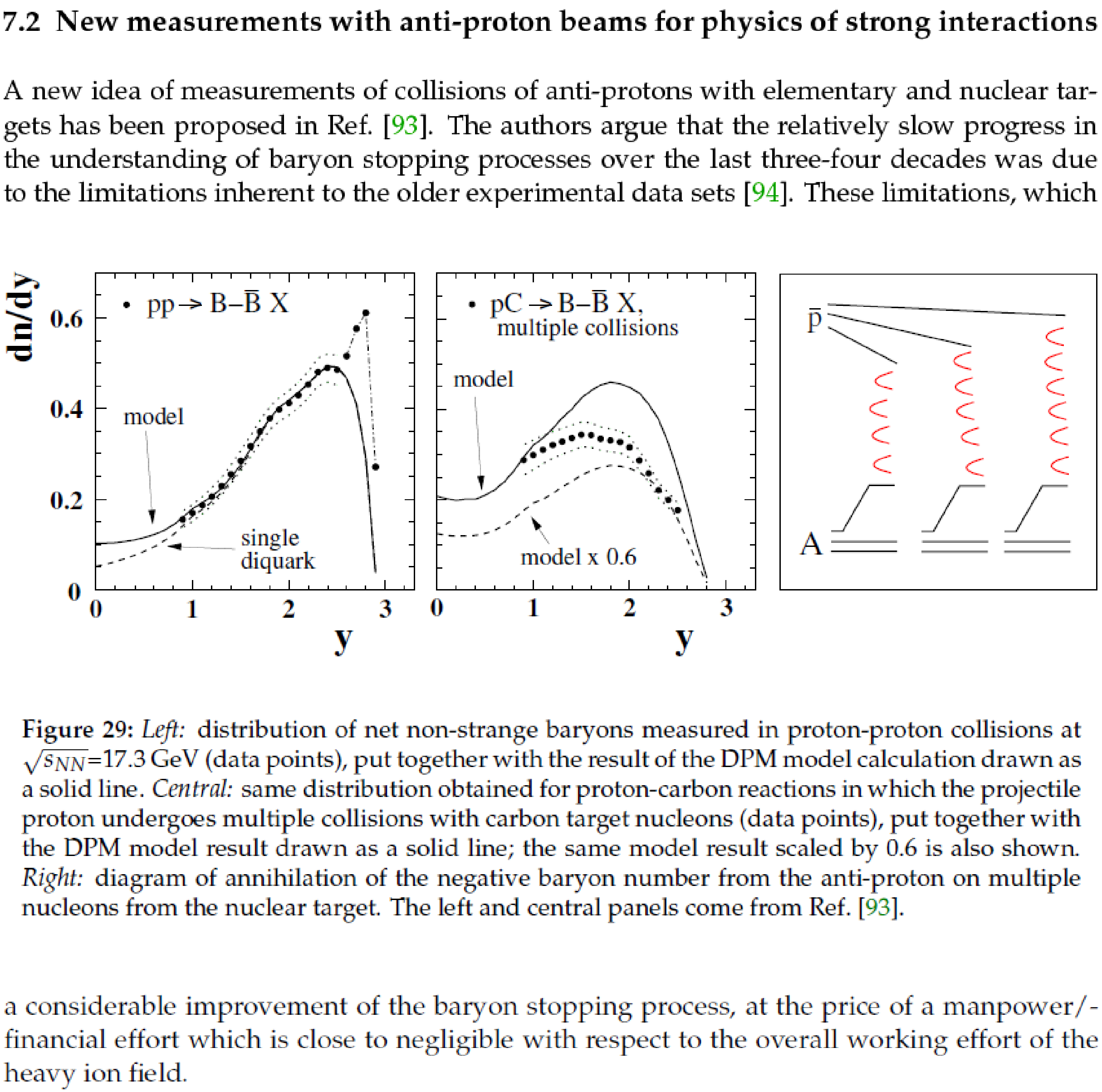
02/10/2020

Report from the NA61/SHINE experiment at the CERN SPS

The NA61/SHINE Collaboration

This document reports on the status and plans of the NA61/SHINE experiment at the CERN SPS as of October 2020. The document refers to the proposal SPSC-P-330.



7.2 New measurements with anti-proton beams for physics of strong interactions

A new idea of measurements of collisions of anti-protons with elementary and nuclear targets has been proposed in Ref. [93]. The authors argue that the relatively slow progress in the understanding of baryon stopping processes over the last three-four decades was due to the limitations inherent to the older experimental data sets [94]. These limitations, which

Figure 29: *Left:* distribution of net non-strange baryons measured in proton-proton collisions at $\sqrt{s_{NN}}$=17.3 GeV (data points), put together with the result of the DPM model calculation drawn as a solid line. *Central:* same distribution obtained for proton-carbon reactions in which the projectile proton undergoes multiple collisions with carbon target nucleons (data points), put together with the DPM model result drawn as a solid line; the same model result scaled by 0.6 is also shown. *Right:* diagram of annihilation of the negative baryon number from the anti-proton on multiple nucleons from the nuclear target. The left and central panels come from Ref. [93].

a considerable improvement of the baryon stopping process, at the price of a manpower/-financial effort which is close to negligible with respect to the overall working effort of the heavy ion field.