CERN-TH colloquium, May 29, 2024

Non-perturbative and topological aspects of QCD, CERN, May 29-30, 2024

Can gluons carry baryon number?

ImageFX
Google AI
+ DK

Dmitri Kharzeev

U.S. DEPARTMENT OF ENERGY
Office of Science

Center for Nuclear Theory
Stony Brook University

C2QA Co-design Center for Quantum Advantage

Brookhaven National Laboratory

carry 1 of 2 verb

car·ry 'ker-ē 'ka-rē

carried; carrying; carries

Synonyms of *carry* >

transitive verb

1 : to move while supporting : **TRANSPORT**

> her legs refused to *carry* her further
> – Ellen Glasgow

6 : to transfer from one place (such as a column) to another

> *carry* a number in adding

Merriam-Webster
Est. 1828

Based on:

D. Frenklakh, DK, G. Rossi, G. Veneziano

“Baryon-number – flavor separation in topological expansion of QCD”

arXiv:2405.04569



D. Frenklakh, DK, W. Li, Phys. Lett. B 853 (2024) 138680

DK, “Can gluons trace baryon number?” Phys. Lett. B 378 (1996) 238

Baryon number in the Standard Model

Noether theorem:

For every symmetry
of the action there is a
conservation law

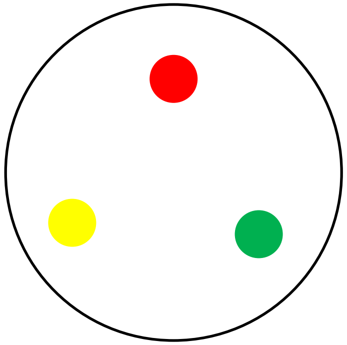
Baryon number conservation:

$U_V(1)$ global symmetry
of QCD Lagrangian results
in conserved baryon current

Baryon number in the Standard Model

The conserved baryon current is local, $J^\mu(x) \sim \bar{q}(x)\gamma^\mu q(x)$

However, a baryon has a finite size, with the three quarks located at different positions: $q(x_1)\ q(x_2)\ q(x_3)$



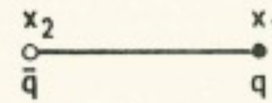
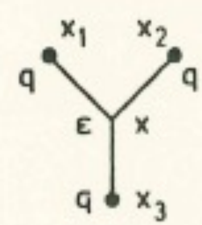
This wave function is not gauge-invariant!

How to construct a gauge-invariant wave function of a baryon?

G. Rossi, G. Veneziano 1977

Table IIa

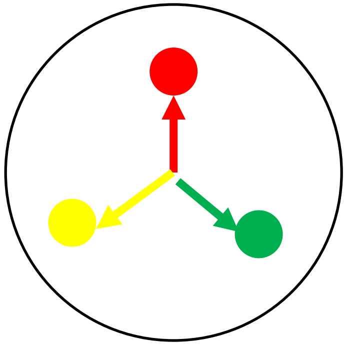
Simplest mesons and baryons : colour structure and string picture

HADRON	GAUGE INVARIANT OPERATOR	STRING PICTURE
$M_2 = q\bar{q}$ meson	$\bar{q}^{j_2}(x_2)\left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu\, dx^\mu\right)\right]_{j_2}^{j_1} q_{j_1}(x_1)$	
M_0 = quarkless meson	$\mathrm{Tr}\left[P\exp\left(ig\oint A_\mu\, dx^\mu\right)\right]$	
$B_3 = qqq$ baryon	$\epsilon^{j_1 j_2 j_3}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu\, dx^\mu\right) q(x_1)\right]_{j_1}$ $\left[P\exp\left(ig\int_{x_2}^{x} A_\mu\, dx^\mu\right) q(x_2)\right]_{j_2}\left[P\exp\left(ig\int_{x_3}^{x} A_\mu\, dx^\mu\right) q(x_3)\right]_{j_3}$	

Baryon junction

The gauge-invariant baryon wave function must possess the baryon junction that at strong coupling becomes a new constituent of the baryon:

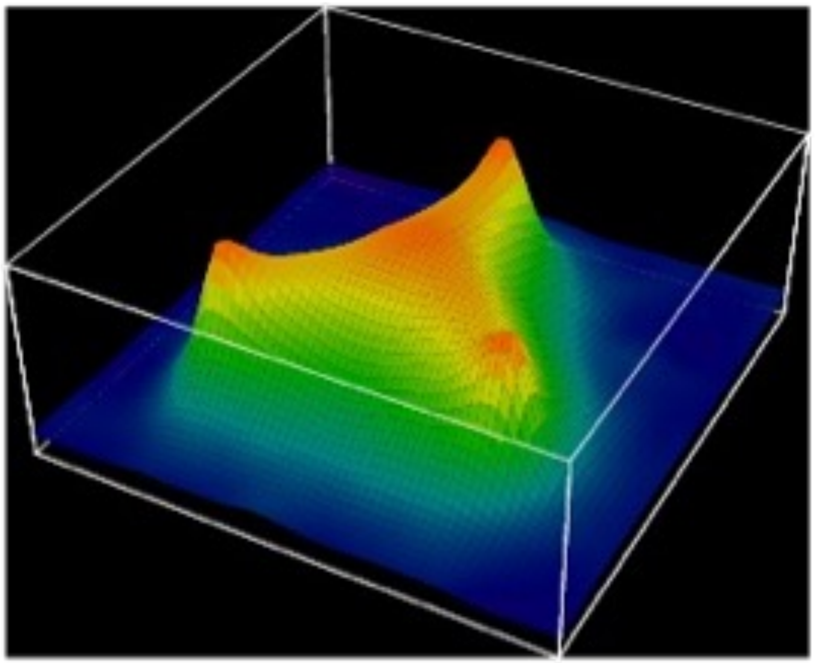
$$U(\mathcal{C}(x_1, x_2)) \equiv P \exp\left(ig \int_{\mathcal{C}(x_1,x_2)} A_\mu(x) dx^\mu \right)$$

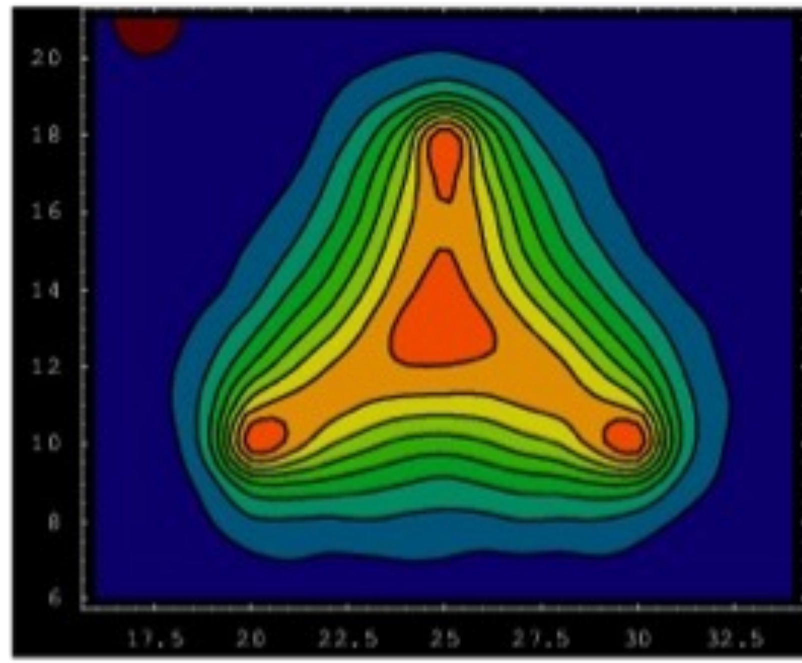


$$A_\mu \equiv t^a A^a_\mu$$

$$B(\mathcal{C}_1, \mathcal{C}_2, \mathcal{C}_3) = \epsilon^{ijk} \left[U(\mathcal{C}_1(x, x_1))q(x_1)\right]_i \left[U(\mathcal{C}_2(x, x_2))q(x_2)\right]_j \left[U(\mathcal{C}_3(x, x_3))q(x_3)\right]_k$$

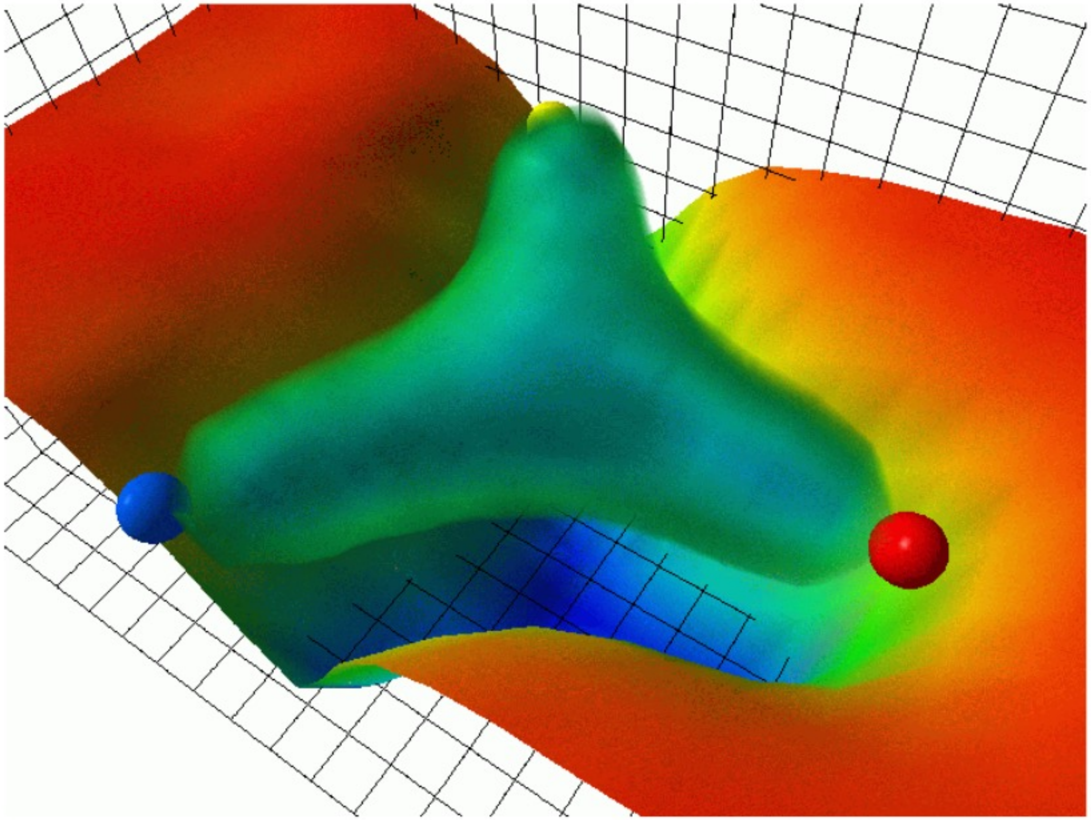
Baryon junctions





H. Suganuma, H. Ichie, T. Takahashi 2004

Baryon junctions

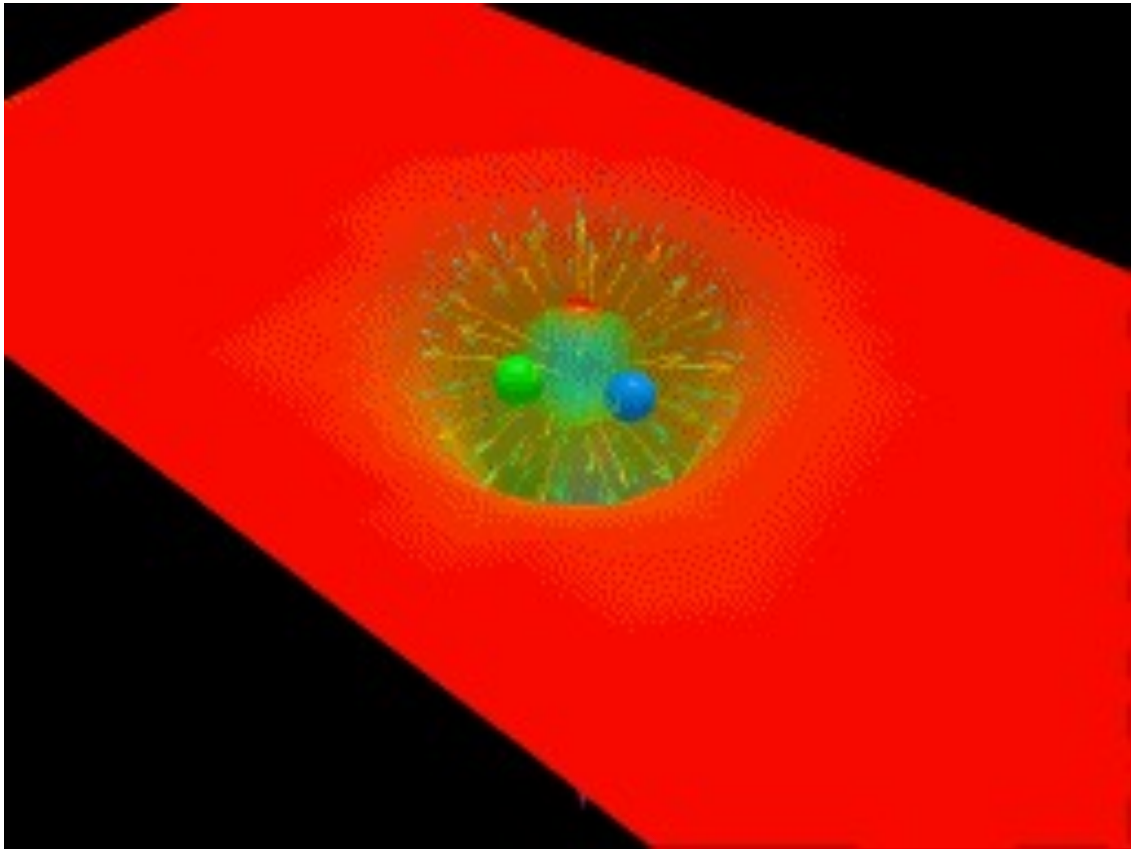


Gluon field distribution in baryons

Nuclear Physics B (Proc. Suppl.) 141 (2005) 22–25

F. Bissey[a], F-G. Cao[a], A. Kitson[a], B. G. Lasscock[b], D. B. Leinweber[b], A. I. Signal[a], A. G. Williams[b] and J. M. Zanotti[bc]

Baryon junctions



D. Leinweber

Baryon-number – flavor separation in high energy collisions

Physics Letters B 378 (1996) 238–246

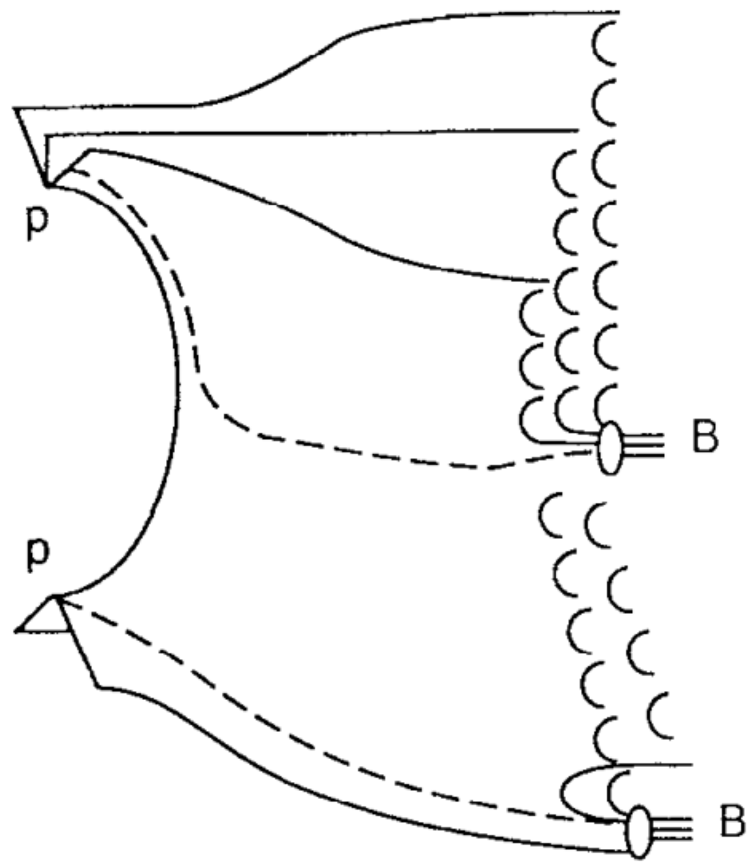
Can gluons trace baryon number?

D. Kharzeev
Theory Division, CERN, CH-1211 Geneva, Switzerland
and Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany

Received 15 March 1996
Editor: R. Gatto

$$E_B \frac{d^3\sigma^{(1)}}{d^3p_B} = 8\pi G_p^M(0) G_p^P(0)\; f_B^{MP}(m_t^2)\; \left(\frac{\sqrt{s}\; m_t}{s_0}\right)^{\alpha_0^J(0)+\alpha_P(0)-2}$$

$$\times \left(exp[y^*(\alpha_P(0) - \alpha_0^J(0))] + exp[-y^*(\alpha_P(0) - \alpha_0^J(0))] \right).$$



Basing on the junction intercept ½ predicted by G.Rossi and G.Veneziano, one expects significant baryon-antibaryon asymmetry even at RHIC and LHC energies.

What does experiment say?

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

CERN-PH-EP-2013-080
May 03, 2013

Mid-rapidity anti-baryon to baryon ratios in pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV measured by ALICE

ALICE Collaboration*

Eur.Phys.J C73 (2013) 2496

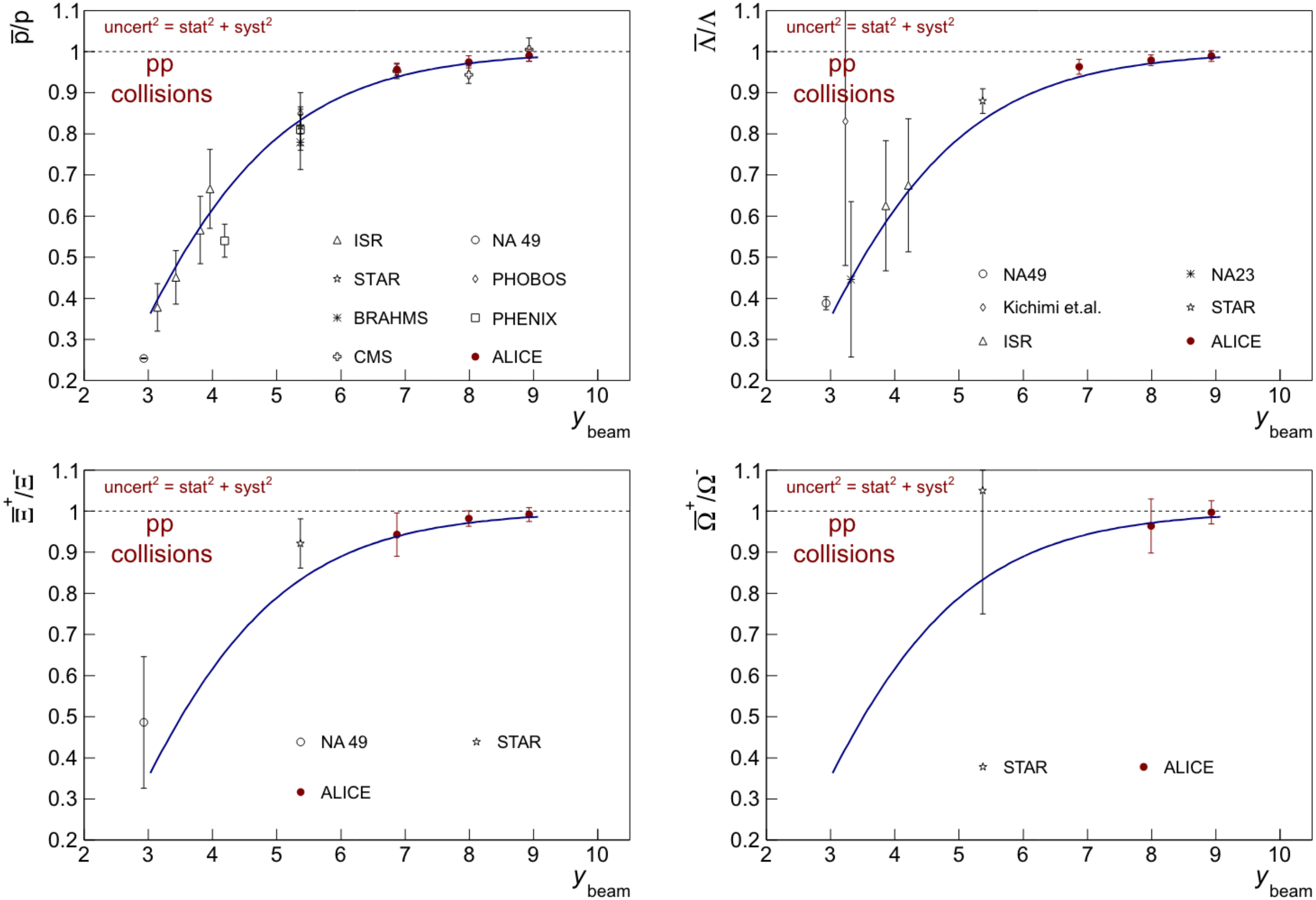
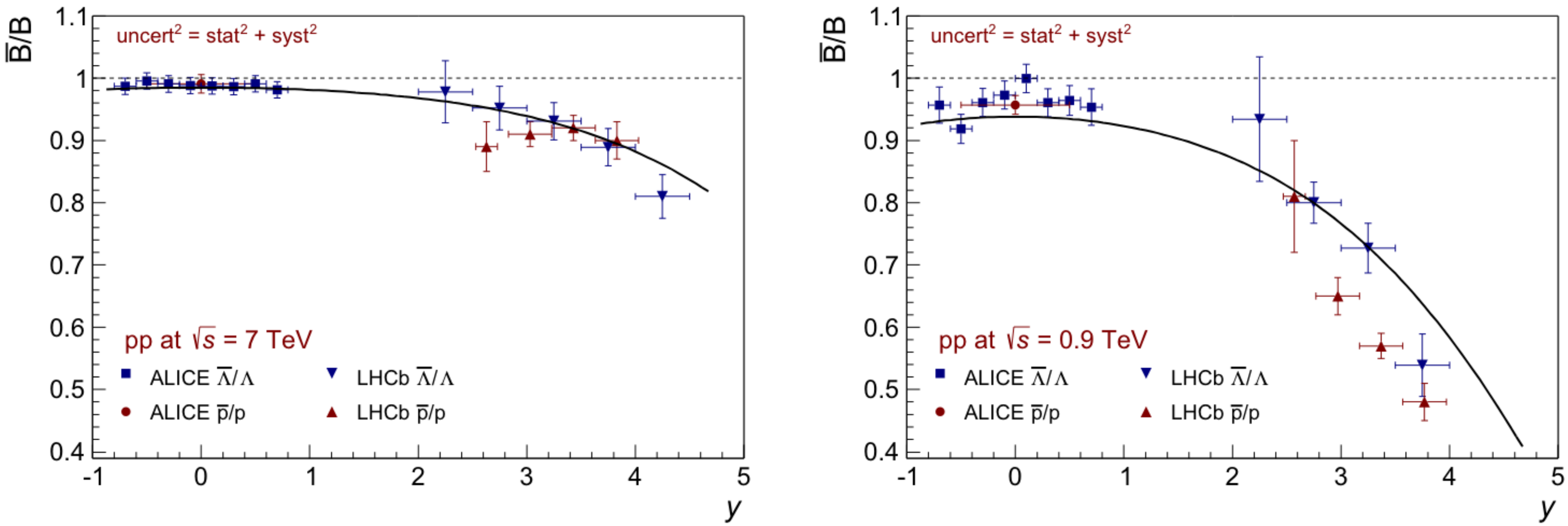


Fig. 16: (Colour online) Anti-baryon to baryon yields ratios as a function of beam rapidity for various baryons separately. The parametrisation with Eq. (4) (blue line) is shown. The red points show the ALICE measurements.



$\overline{B}/B$
uncert^2 = stat^2 + syst^2
pp at $\sqrt{s}$ = 7 TeV
ALICE $\overline{\Lambda}/\Lambda$
LHCb $\overline{\Lambda}/\Lambda$
ALICE $\overline{p}/p$
LHCb $\overline{p}/p$
y
$\overline{B}/B$
uncert^2 = stat^2 + syst^2
pp at $\sqrt{s}$ = 0.9 TeV
ALICE $\overline{\Lambda}/\Lambda$
LHCb $\overline{\Lambda}/\Lambda$
ALICE $\overline{p}/p$
LHCb $\overline{p}/p$
y

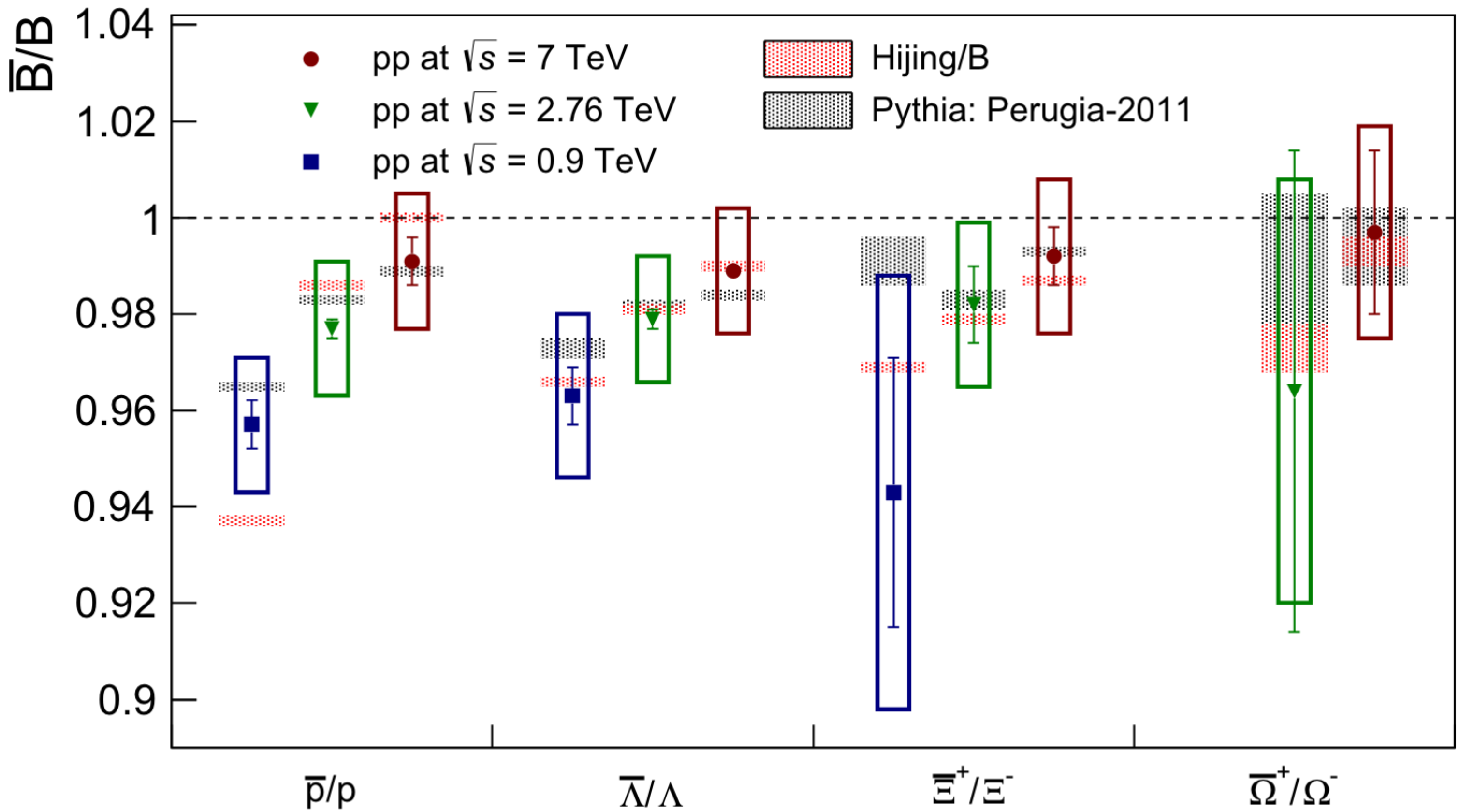


Fig. 15: The mid-rapidity yields ratio integrated over $|y| < 0.5$ for $\overline{p}/p$ and $|y| < 0.8$ for $\overline{\Lambda}/\Lambda$, $\overline{\Xi}^{+}/\Xi^{-}$ and $\overline{\Omega}^{+}/\Omega^{-}$. Squares, triangles and circles are for the data from pp at $\sqrt{s} = 0.9$, 2.76 and 7 TeV, respectively. The strangeness content increases along the abscissa.

UNIVERSITY

SEARCH FOR BARYON JUNCTIONS IN PHOTONUCLEAR PROCESSES AND HEAVY-ION COLLISIONS AT STAR

Nicole Lewis, for the STAR Collaboration

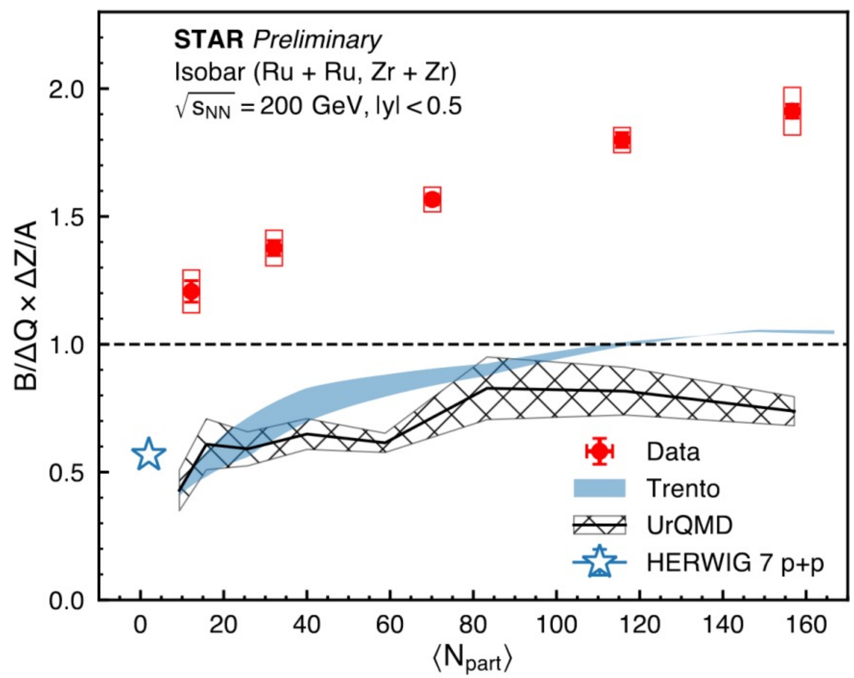
Isobar run at RHIC:

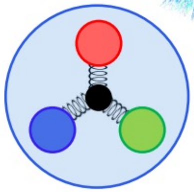
baryon number is stopped, but the electric charge is not!

Talk by Prithwish Tribedy tomorrow

Charge Stopping vs Baryon Stopping

STAR





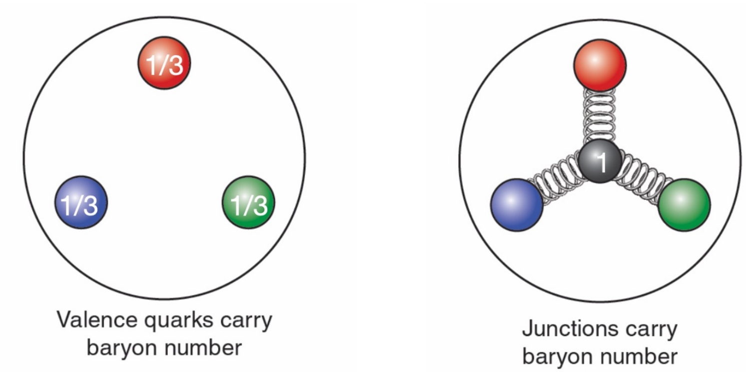
- Data:
  $$\frac{B}{\Delta Q} \times \frac{\Delta Z}{A} > 1$$
- This is consistent with baryon junction prediction
  - Junctions carry a much smaller momentum fraction compared to valence quarks
  - Larger reaction cross section, more baryon stopping
- Ratio decreases with decreasing multiplicity due to effects from the neutron skin

New precise data from RHIC and LHC support the existence of the baryon junction.

Motivation to revisit the problem of baryon stopping, and to derive a more precise result for the intercept.

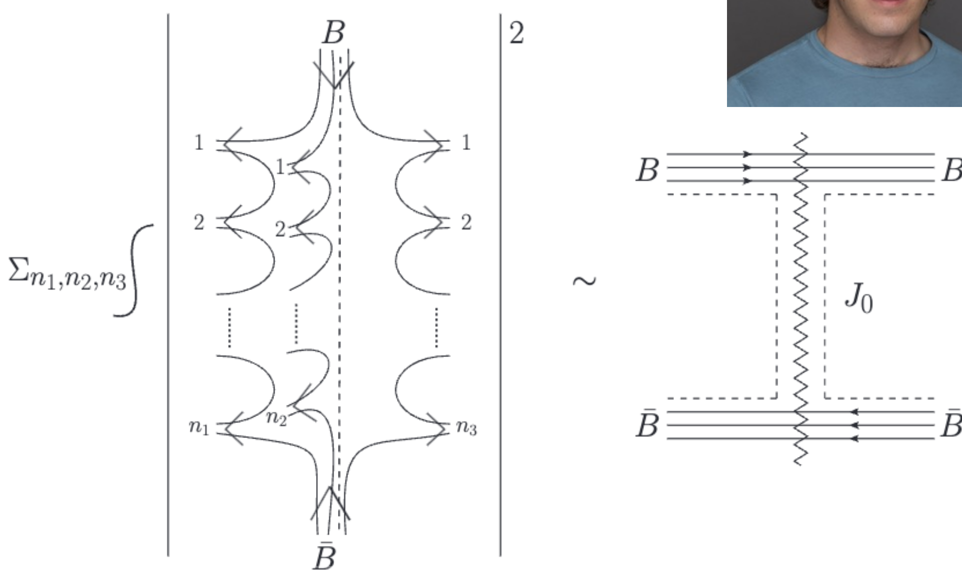
1st Workshop on Baryon Dynamics

Jan 22 – 24, 2024
CFNS
America/New_York timezone



Baryon-number – flavor separation from the topological expansion of QCD

D. Frenklakh, DK, G. Rossi, G. Veneziano, arXiv:2405.04569



Three ingredients:

Duality

Topological expansion

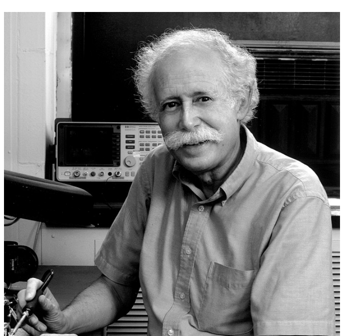
Feynman-Wilson gas

Duality

Construction of a Crossing-Simmetric, Regge-Behaved Amplitude for Linearly Rising Trajectories.

G. VENEZIANO (*)
CERN - Geneva

(ricevuto il 29 Luglio 1968)



GRAPHICAL FORM OF DUALITY*

Jonathan L. Rosner†
Physics Department, Tel-Aviv University, Ramat A
(Received 3 February 1969)

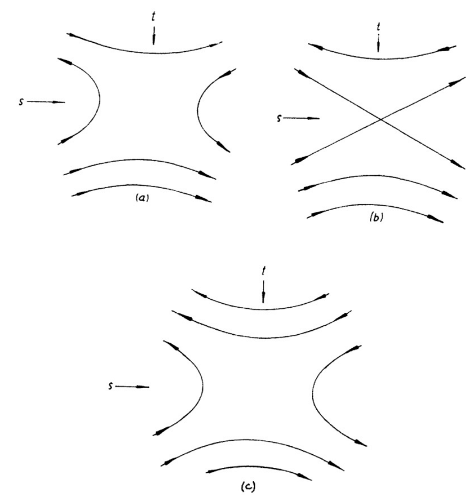


FIG. 1. Connected graphs for four-point functions. (a) Graph with an imaginary part at high s. (b) Graph with no imaginary part at high s. (c) Graph for baryon-antibaryon scattering with an imaginary part at high s.

Planar duality

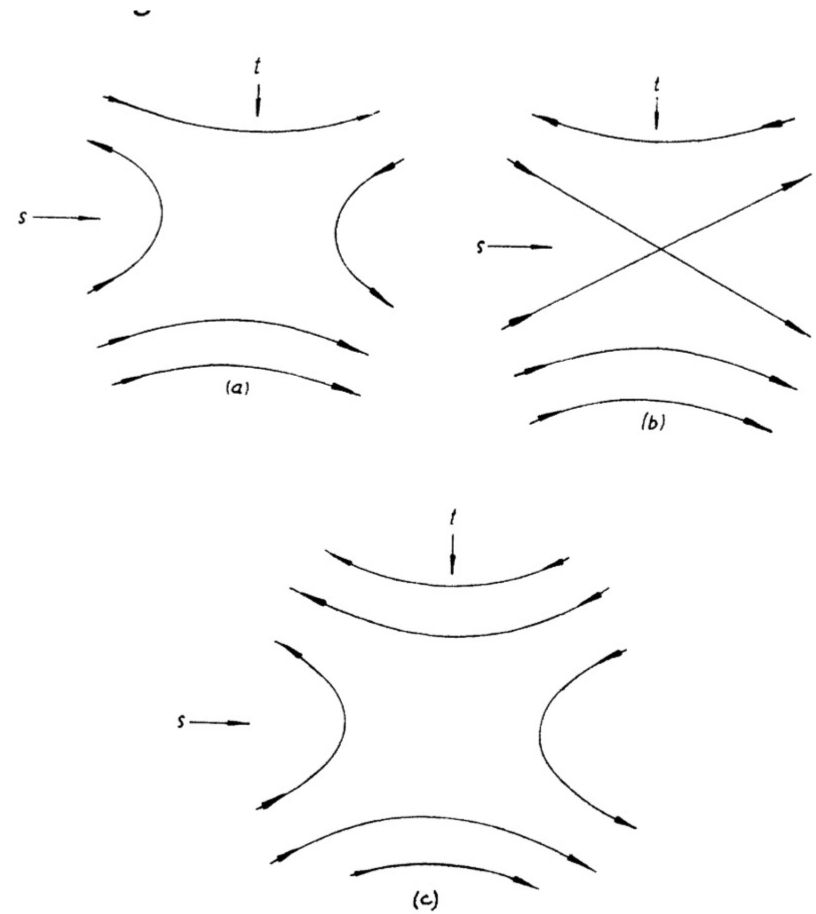
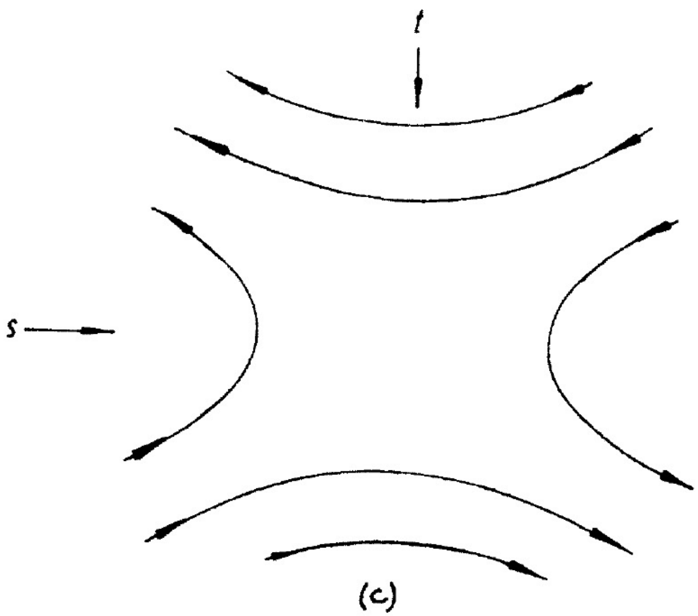


FIG. 1. Connected graphs for four-point functions. (a) Graph with an imaginary part at high s. (b) Graph with no imaginary part at high s. (c) Graph for baryon-antibaryon scattering with an imaginary part at high s.

In this note we show this to be so; adding duality to the usual Regge model suggests the following simple rule for seeing many of these constraints: (1) Represent mesons by $q\bar{q}$ and baryons by qqq. (2) Write all "connected" graphs as in Fig. 1. (3) A given graph will then exhibit duality among the channels in which it can be written in "planar" form, i.e., without quark lines crossing one another.

Difficulty with baryons



Consider Baryon-Antibaryon scattering.

Two problems:

1. t-channel meson exchange is dual to $qq\bar{q}\bar{q}$ exotic s-channel states (tetra-quarks!)

2. It is not clear when this diagram describes baryon annihilation

Baryons junctions and duality

A POSSIBLE DESCRIPTION OF BARYON DYNAMICS IN DUAL AND GAUGE THEORIES

G.C. Rossi*)

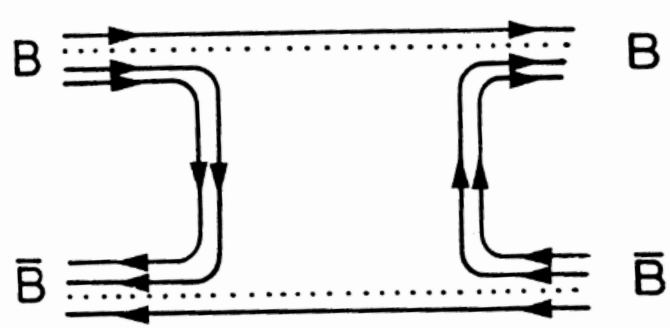
and

G. Veneziano**)

CERN - Geneva

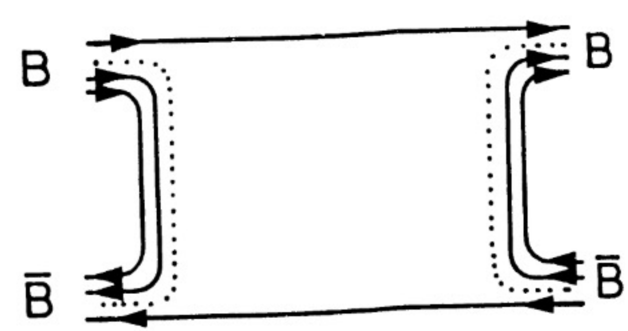
1977

No annihilation:



(b)

Annihilation:

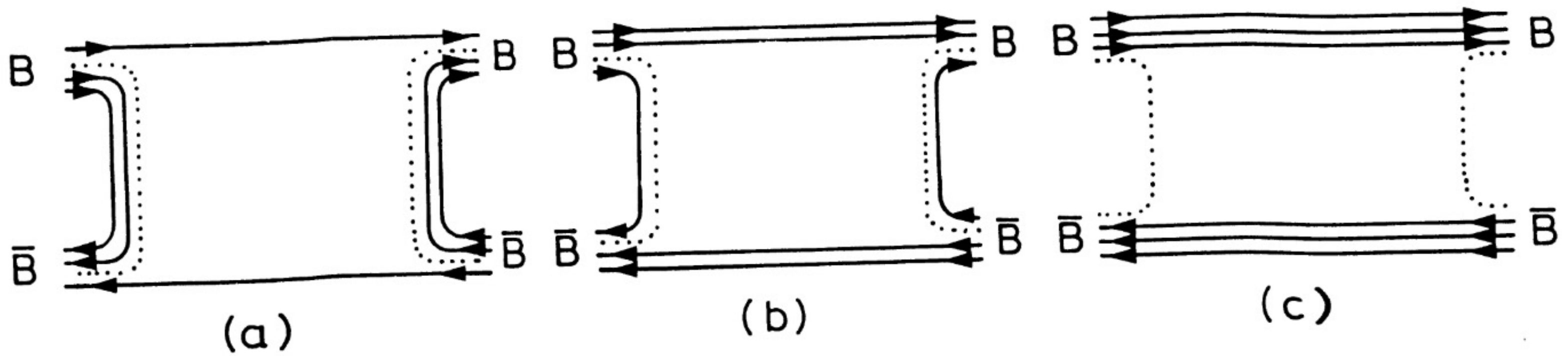


(a)

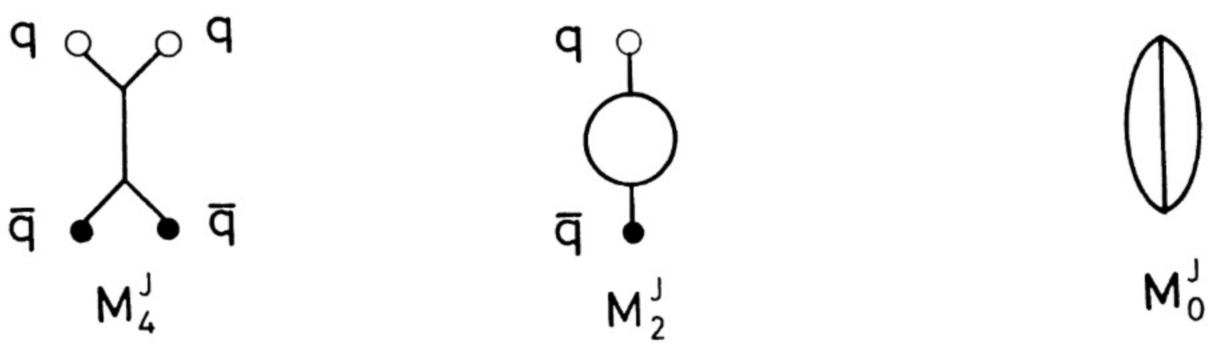
Baryons junctions and duality

G.Rossi, G. Veneziano 1977

Baryon annihilation diagrams:



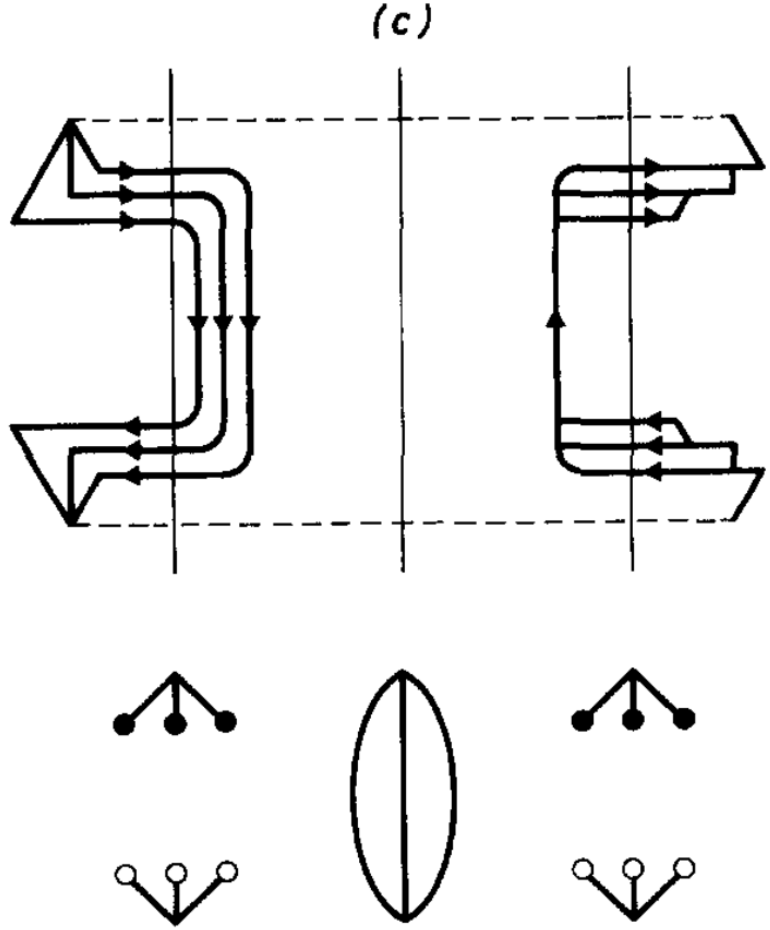
States exchanged in the t-channel:



Glueball
with
a hidden
baryon
number!

Baryons junctions and duality

The glueball with a hidden baryon number can also be produced in the s-channel (no annihilation):

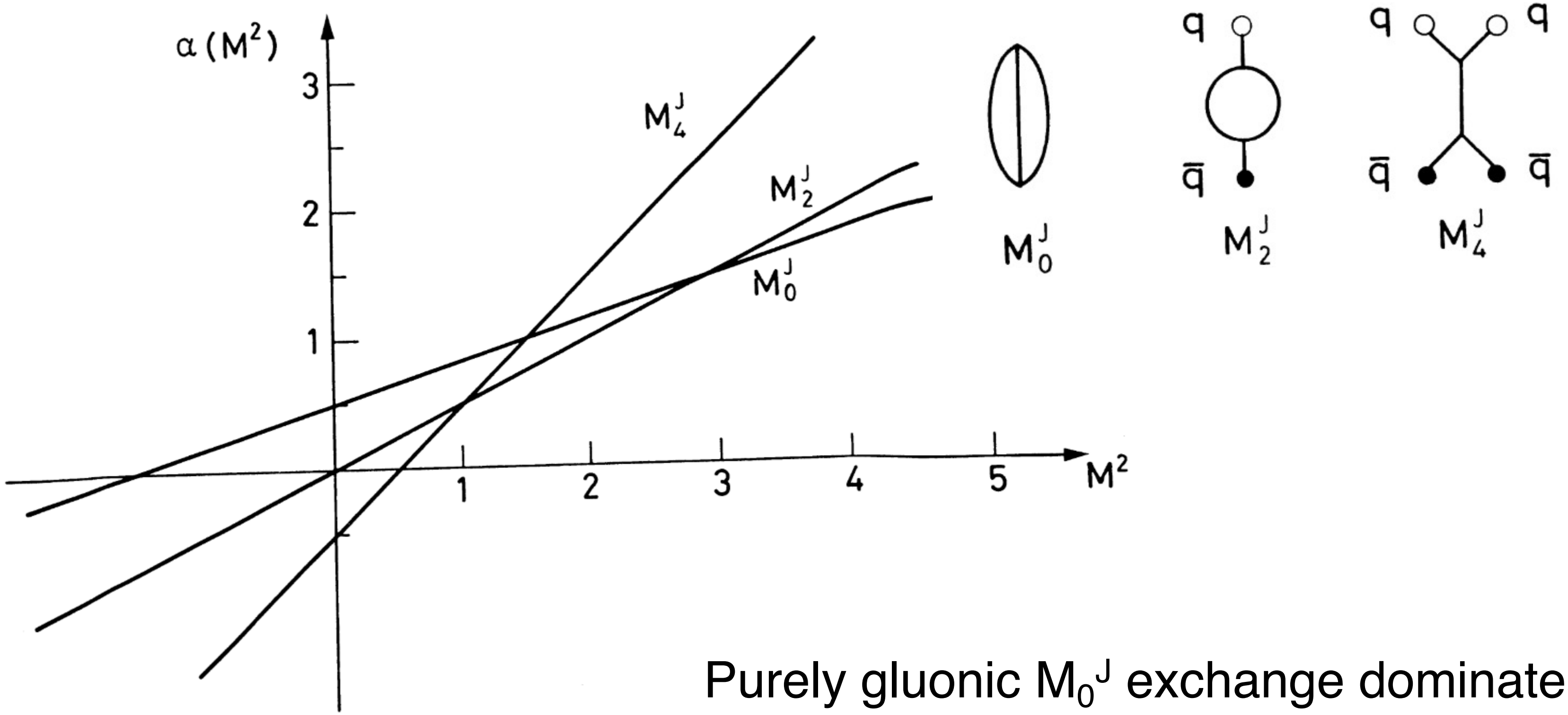


G.Rossi, G. Veneziano 1977

Baryons junctions and duality

G.Rossi, G. Veneziano 1977

Estimated Regge trajectories:



Purely gluonic M_0^J exchange dominates at high energies!

Large N expansion

A PLANAR DIAGRAM THEORY FOR STRONG INTERACTIONS

G. 't HOOFT
CERN, Geneva

Received 21 December 1973

Abstract: A gauge theory with colour gauge group $U(N)$ and quarks having a colour index running from one to N is considered in the limit $N \to \infty$, g^2N fixed. It is shown that only planar diagrams with the quarks at the edges dominate; the topological structure of the perturbation series in $1/N$ is identical to that of the dual models, such that the number $1/N$ corresponds to the dual coupling constant. For hadrons N is probably equal to three. A mathematical framework is proposed to link these concepts of planar diagrams with the functional integrals of Gervais, Sakita and Mandelstam for the dual string.

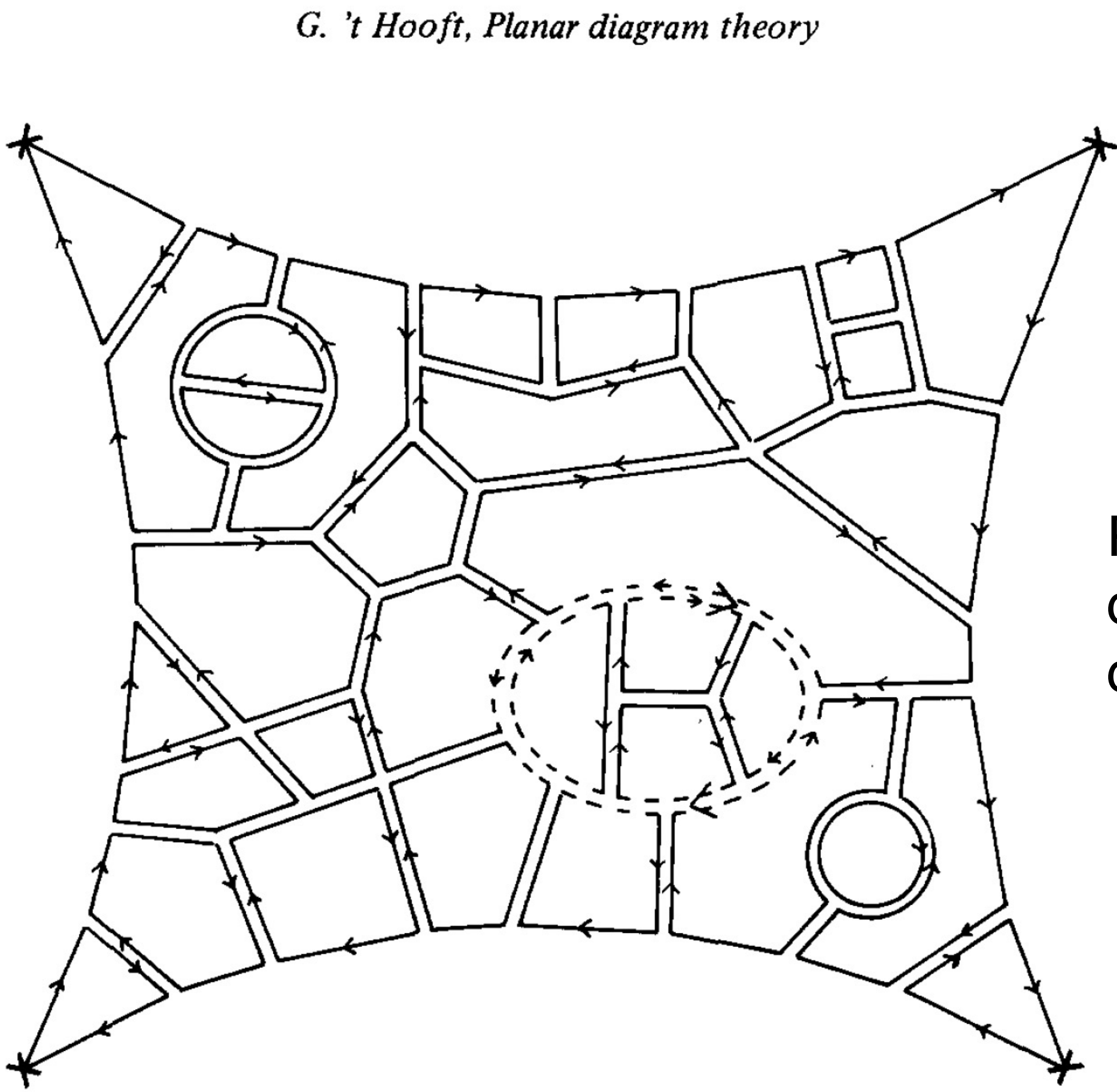


Fig. 3. One of the leading diagrams for the four-point function.

Planar diagrams dominate

Large N expansion

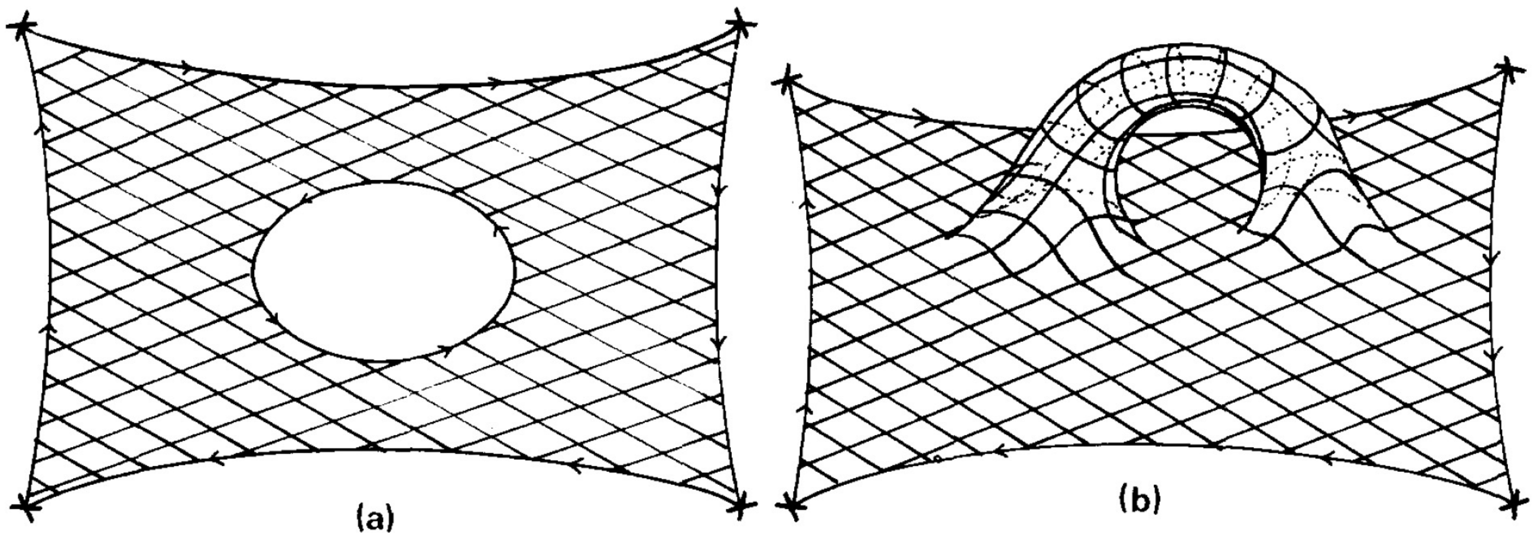


Fig. 4. Two diagrams of higher order in $1/N$: (a) obtain a factor $1/N$, (b) obtain a factor $1/N^2$, as compared with the lowest-order graphs of the previous figure.

The diagrams with string breaking due to quark-antiquark pair production are suppressed in 1/N.

But in the real world, the strings always break!

Large N expansion

A PLANAR DIAGRAM THEORY FOR STRONG INTERACTIONS

G. 't HOOFT
CERN, Geneva

Received 21 December 1973

As for baryons, the situation is even more complicated. The Han-Nambu theory clearly suggests $N = 3$. In that case we can raise or lower indices in the following way:

$$\lambda_i \rightarrow \lambda^{ij} = \epsilon^{ijk} \lambda_k = -\lambda^{ji}. \tag{7.1}$$

Taking p_i, n_i and λ^{ij} as our elementary fermions we can again consider the $N \rightarrow \infty$ limit. The λ quark will then sit in the middle of a string with p and/or n quarks at its ends: we have a string with Σ or Λ baryons! Similarly protons, neutrons and all other baryons can be constructed.

It will be clear that in the case of baryons the $1/N$ expansion is extremely delicate.

Large N expansion

A hint towards the role of topology in baryon structure:

Baryon mass at large N is

$$M_B \sim N$$

but g^2N is fixed, so

$$M_B \sim \frac{1}{g^2}$$

Baryon as a topological soliton?

Baryon as a soliton

A non-linear field theory

BY T. H. R. SKYRME

Atomic Energy Research Establishment, Harwell

(*Communicated by Sir Basil Schonland, F.R.S.—Received* 5 *September* 1960)

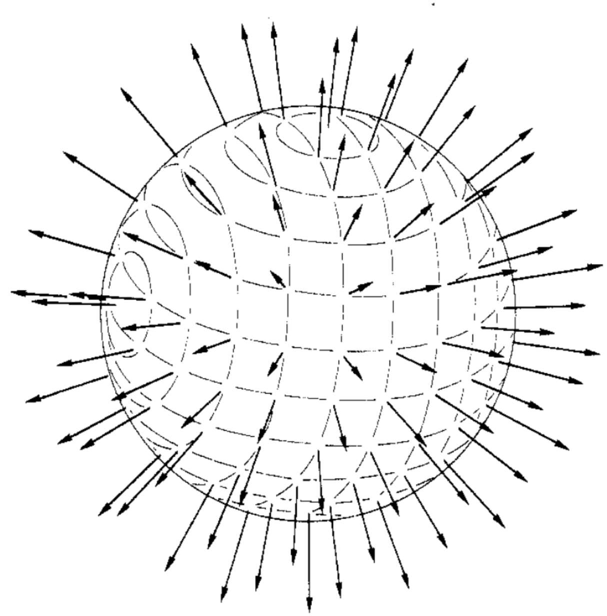


Figure 2. Hedgehog configuration. Arrows indicate the directions of the isovector field φ at different points in coordinate space.

Image:
G. Holzwarth,
B. Schwesinger 1986

Topological expansion

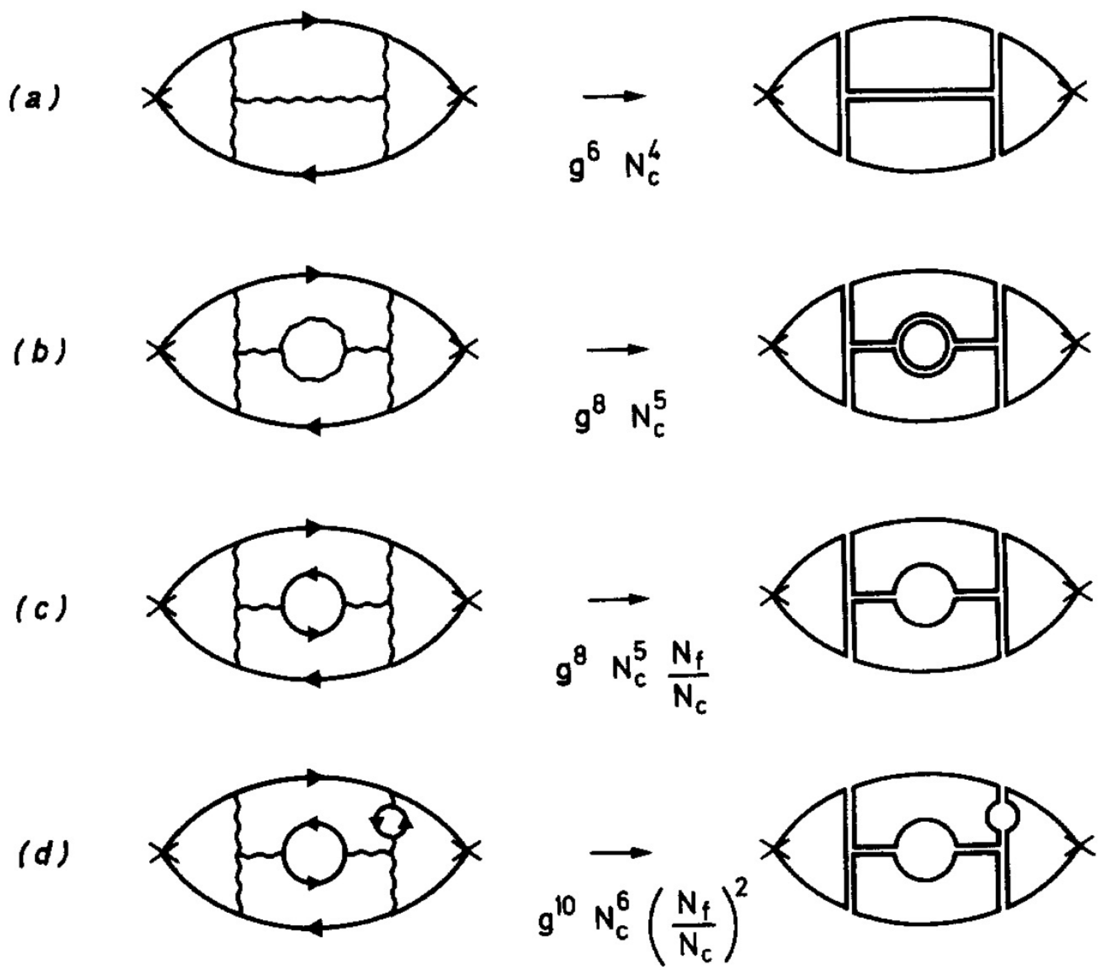
LARGE N EXPANSION IN DUAL MODELS *)

G. Veneziano
CERN - Geneva
and
Weizmann Institute of Science,
Rehovot, Israel

ABSTRACT

A "topological" expansion, recently proposed for unitarization of planar dual models, is reformulated as a 1/N expansion. The possible connection of this expansion to those used for multiparticle production at high energy is pointed out.

Topological expansion



String breaking is allowed – duality, Regge theory, …

LARGE N EXPANSION IN DUAL MODELS *)

G. Veneziano
CERN – Geneva
and
Weizmann Institute of Science,
Rehovot, Israel

ABSTRACT

A "topological" expansion, recently proposed for unitarization of planar dual models, is reformulated as a 1/N expansion. The possible connection of this expansion to those used for multiparticle production at high energy is pointed out.

$g^2 N_c$ fixed,

N_f / N_c fixed,

$N_c \to \infty$

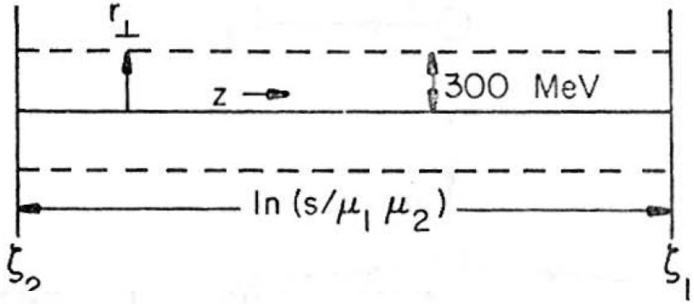
Feynman-Wilson gas

Some Experiments on Multiple Production*

Kenneth G. Wilson

Laboratory of Nuclear Studies, Cornell University,

Ithaca, New York 14850



scaling laws.[10] The best way to introduce these scaling laws is, I think, to use an analogy invented by Feynman.[11] This analogy links multiparticle production cross sections to the multiparticle distribution functions of a classical gas, with the total cross section becoming the partition function of a gas. This analogy is very much on Feynman's mind when he discusses his parton model of high energy collisions, although it is not discussed in his papers.

11. R. P. Feynman, private communication.

Feynman-Wilson gas

(1+1)d gas	High energy interactions
Volume	Total rapidity
Particle’s coordinate	Rapidity of the produced hadron
Short-range particle correlations	Short-range rapidity correlations
Partition function	Generating function for cross sections
Fugacity	Parameter of the generating function

Short-range rapidity correlations – “multiperipheral” mechanism of high energy interactions

Theory of High-Energy Scattering and Multiple Production.

D. AMATI and A. STANGHELLINI

CERN - Geneva

S. FUBINI

Istituto di Fisica dell'Università - Torino
CERN - Geneva

(ricevuto il 4 Luglio 1962)

Summary. — In this paper we propose a theoretical model for high-energy interaction, the basic idea of which is that the high-energy processes are reducible to the low-energy ones, through a peripheral mechanism. The asymptotic properties of this model are studied by means

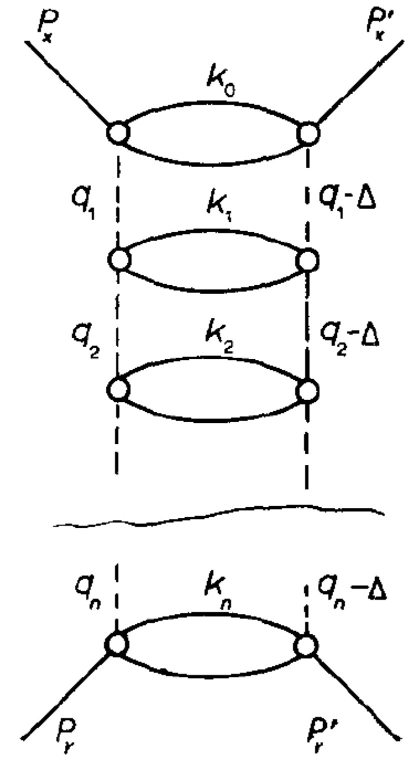


Fig. 3.

Feynman-Wilson gas

Generating functional of exclusive cross sections is given by:

$$\Sigma[z(x)] = \sum_n \int \prod_{j=1}^{n} (dx^j z(x^j)) \frac{1}{\sigma_t} \frac{d\sigma(a+b \to x^1, x^2 \ldots x^n)}{dx^1 dx^2 \ldots dx^n}$$

x_j are "coordinates of the final-state particles (rapidity, p_t, …)

$$\Sigma[z(x) = 1] = 1.$$

Exclusive differential cross sections can be obtained by taking partial functional derivatives at z=0.

Feynman-Wilson gas

m-particle inclusive cross sections

$$\rho_m(x^1, x^2 \dots x^m) = \frac{1}{\sigma_t} \sum_X \frac{d\sigma(a + b \to x^1, x^2 \dots x^m + X)}{dx^1 dx^2 \dots dx^m}$$

are obtained by m-order partial derivatives at $z(x^j)=1$.

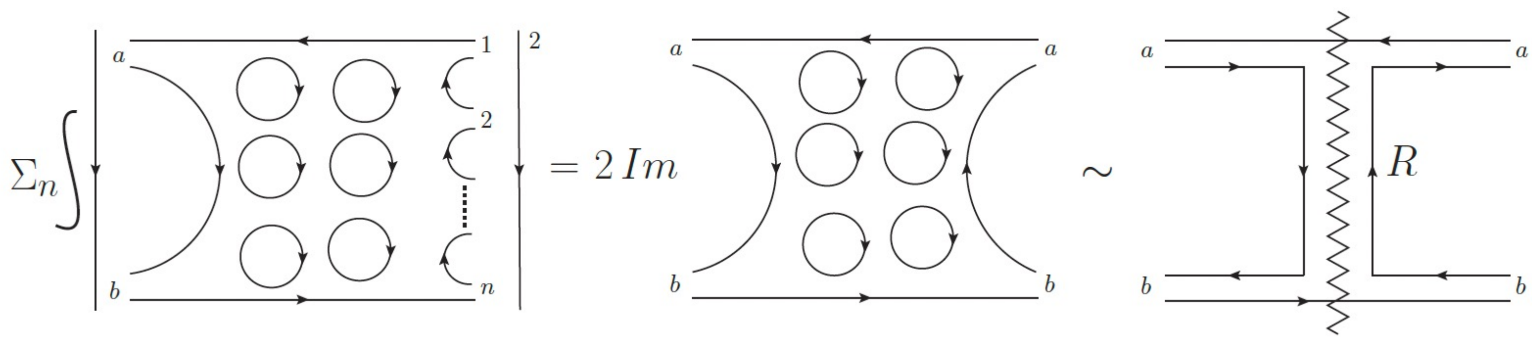
Now we can use the cluster decomposition to express these inclusive cross sections in terms of connected correlators defined through (at z(x)=1):

$$\log \Sigma[z(x)] = \sum_m \frac{1}{m!} \int \prod_{j=1}^{m} [dx^j (z(x^j) - 1)] c_m(x^1, x^2 \dots x^m) \equiv p[z(x)]V$$

"grand canonical partition function" $\log \Sigma = \frac{PV}{k_B T}$ "pressure"

Feynman-Wilson gas: planar bootstrap and Regge theory

At high energies, hadron cross sections are described by Regge theory:



The energy dependence of cross sections is determined by the Reggeon intercept

Total

$$\sigma_t^{pl} \sim s^{\alpha_{\mathbb{R}}-1}$$

Exclusive 2->2

$$\sigma_{excl}^{pl} \sim s^{2\alpha_{\mathbb{R}}-2}$$

Baron Munchausen pulls himself and his horse out of a swamp by his pigtail.

Bootstrap

Feynman-Wilson gas: planar bootstrap and Regge theory

Therefore, the pressure of the planar Feynman-Wilson gas yields the leading Reggeon intercept:

$$\sigma_t^{pl} \sim s^{\alpha_{\mathbb{R}}-1} \qquad \sigma_{excl}^{pl} \sim s^{2\alpha_{\mathbb{R}}-2}$$

$$\log \Sigma = \frac{PV}{k_B T}$$

$$\Sigma_{pl}(z) \to \frac{\sigma_{excl}^{pl}}{\sigma_t^{pl}} \sim s^{\alpha_{\mathbb{R}}-1} \Rightarrow -p(0) = 1 - \alpha_{\mathbb{R}}(0)$$

Feynman-Wilson gas: planar bootstrap and Regge theory

Use the Feynman-Wilson gas analogy to compute the Reggeon intercept using the cluster decomposition!

$$\Sigma_{pl}(z) \equiv \exp\left(Y p(z)\right) = \exp\left(Y \sum_{m\geq 1} c_m \frac{(z-1)^m}{m!}\right) \ ;$$

$$p(1) = 0 \ , \ p'(1)Y = c_1 Y = \langle n \rangle \ , \ p''(1)Y = c_2 Y = \langle n(n-1) \rangle - \langle n \rangle^2 \ ,$$

$$p'''(1)Y = c_3 Y = \langle n(n-1)(n-2) \rangle - \langle n \rangle^3 - 3c_1 c_2 Y^2 \ ,$$

⬇

$$-p(0) = 1 - \alpha_{\mathbb{R}}(0) = \sum_m c_m \frac{(-1)^{m+1}}{m!} = \frac{\langle n \rangle}{Y} - \frac{c_2}{2} + \ldots$$

Reggeon intercept ⟷ Multi-hadron correlations

Feynman-Wilson gas: planar bootstrap and Regge theory

For vanishing correlations (Poisson distributions), we get

$$-p(0) = 1 - \alpha_{\mathbb{R}}(0) = \sum_m c_m \frac{(-1)^{m+1}}{m!} = \frac{\langle n \rangle}{Y} - \frac{c_2}{2} + \dots$$

⬇

$$\alpha_{\mathbb{R}}(0) = 1 - \frac{\langle n \rangle}{Y}$$

This result agrees with

Multiperipheral Bootstrap Model*

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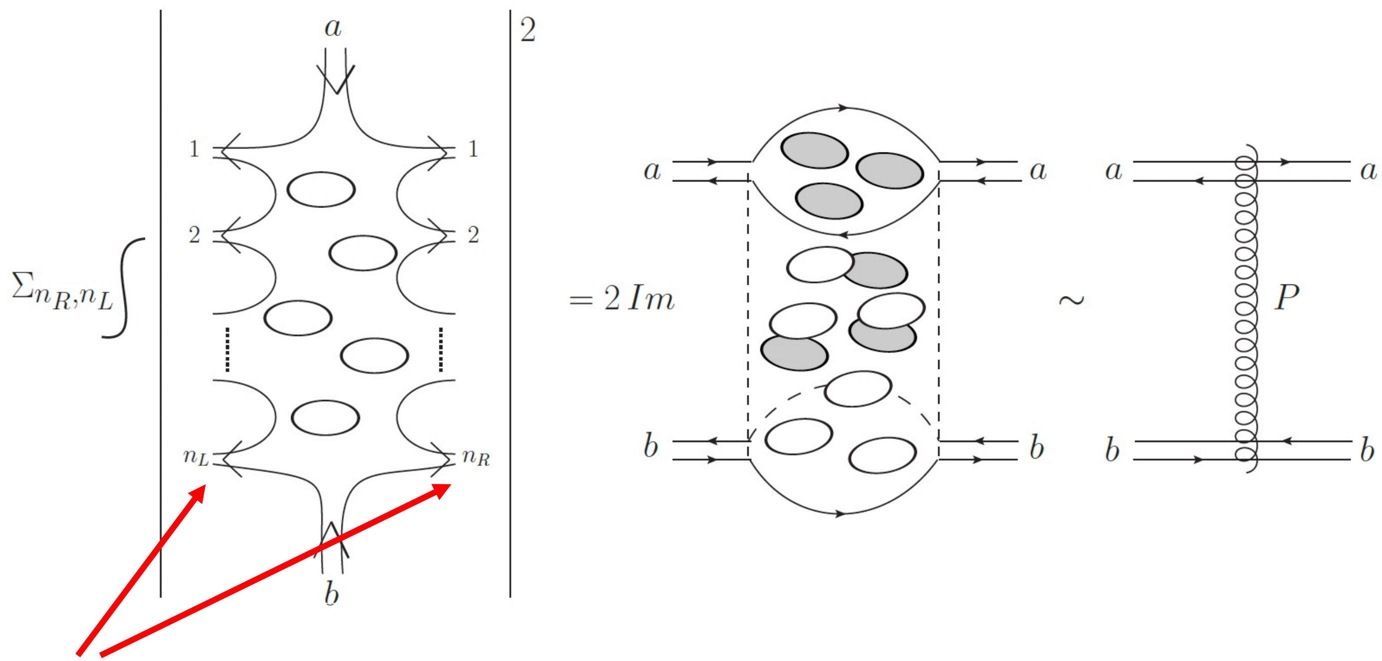
Lawrence Radiation Laboratory, University of California, Berkeley, California 94704

(Received 3 July 1968)

What about the Pomeron?

Here, we have to reconcile the Feynman-Wilson gas with the topological expansion (TE) of QCD.

In TE, the Pomeron has topology of a cylinder:



Two copies of Feynman-Wilson gas!

Cylinder topology of the perturbative BFKL Pomeron

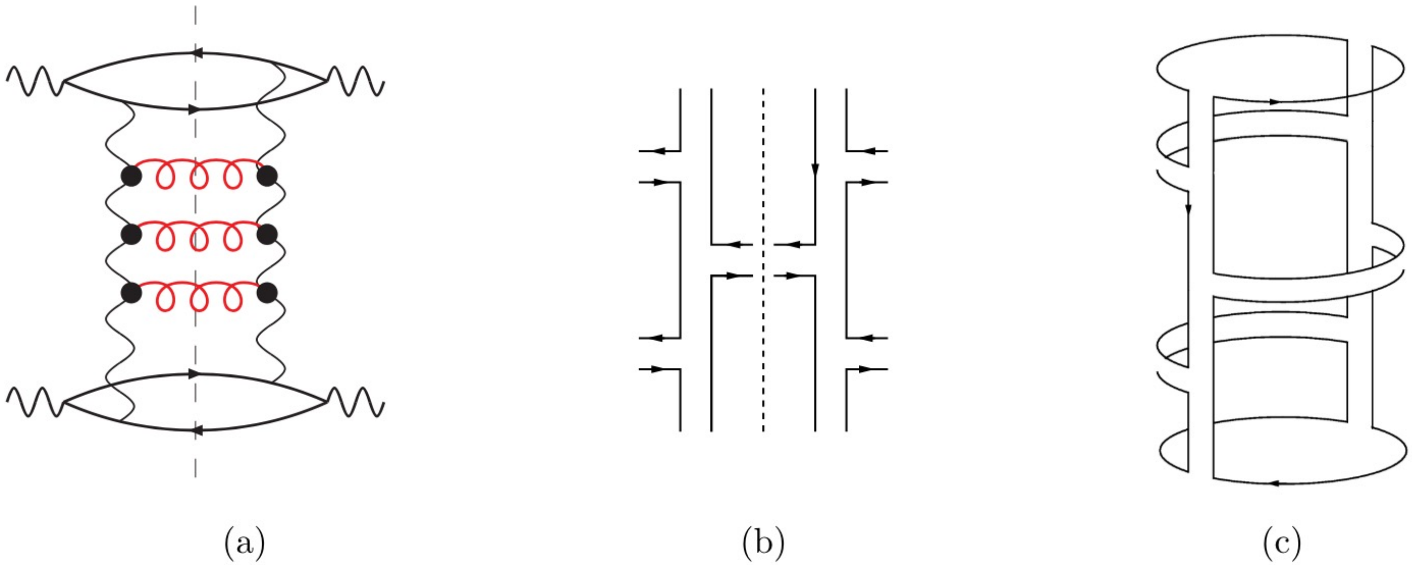


Figure 8: Multi-gluon emission within the MRK. (a) The cut Feynman diagram (b) Combination of relevant color diagrams of the production vertex. (c) The combination of (b) on the cylinder.

From: J.Bartels and M.Hentschinski, JHEP 08 (2009) 103

The Pomeron

The partition function of two-species Feynman-Wilson gas:

$$\Sigma_{cyl}(z_R, z_L) = \frac{1}{\sigma_t^{cyl}} \sum_{n_R+n_L\geq 2} z_R^{n_R} z_L^{n_L} \sigma^{cyl}(n_R, n_L) \Rightarrow \Sigma_{cyl}(1,1) = 1$$

The cluster expansion

$$\Sigma_{cyl}(z_R, z_L) \equiv \exp\left(Y p(z_R, z_L)\right) = \exp\left(Y \sum\nolimits_{m_R+m_L\geq 1} c(m_R, m_L) \frac{(z_R-1)^{m_R}(z_L-1)^{m_L}}{m_R! m_L!}\right)$$

$$c(1,0)Y = \langle n_R \rangle \ , \ c(0,1)Y = \langle n_L \rangle \ , \ c(1,1)Y = \langle n_R n_L \rangle - \langle n_R \rangle \langle n_L \rangle \ , \ \ldots$$

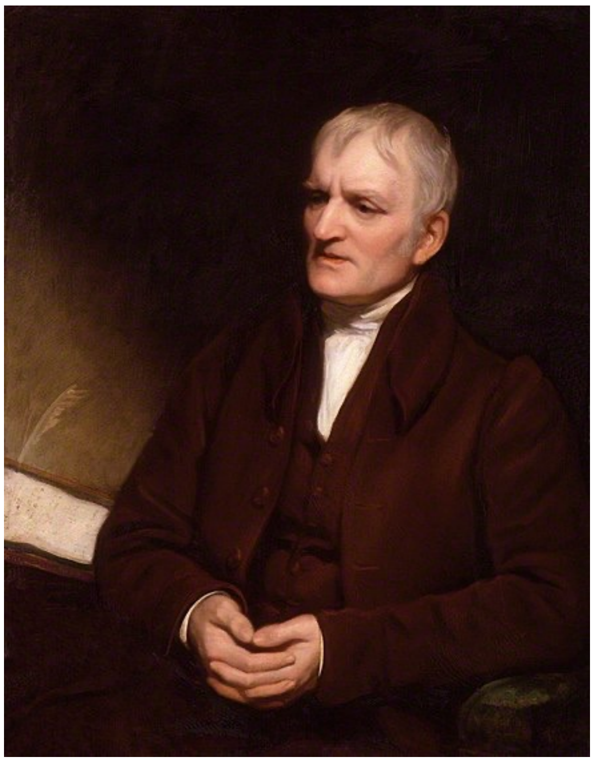
yields the Pomeron intercept:

$$\alpha_{\mathbb{P}} = \ 1 + \sum\nolimits_{m_R, m_L \geq 1} \frac{c(m_R, m_L)}{m_R! m_L!} (-1)^{m_R+m_L} = 1 + \frac{\langle n_R n_L \rangle - \langle n_R \rangle \langle n_L \rangle}{Y} + \ldots$$

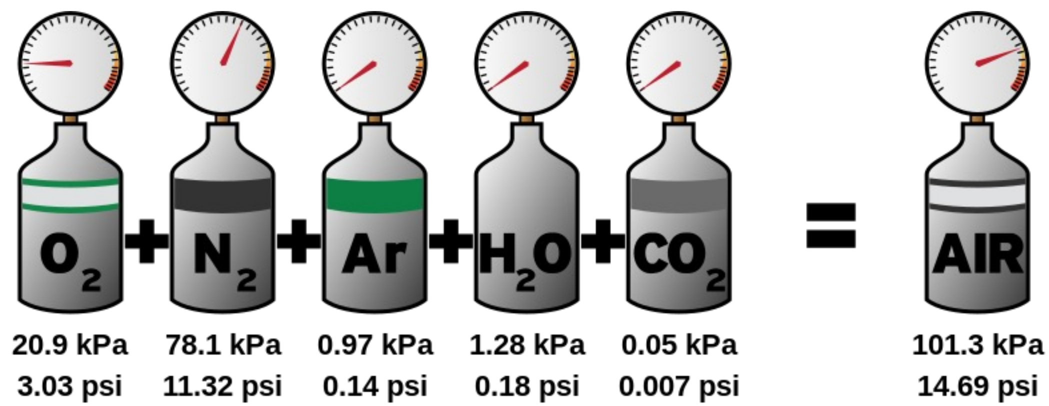
If correlations are neglected, the intercept is 1

The Pomeron

The absence of correlations (leading to intercept=1) is the analog of Dalton's law in Feynman-Wilson gas.



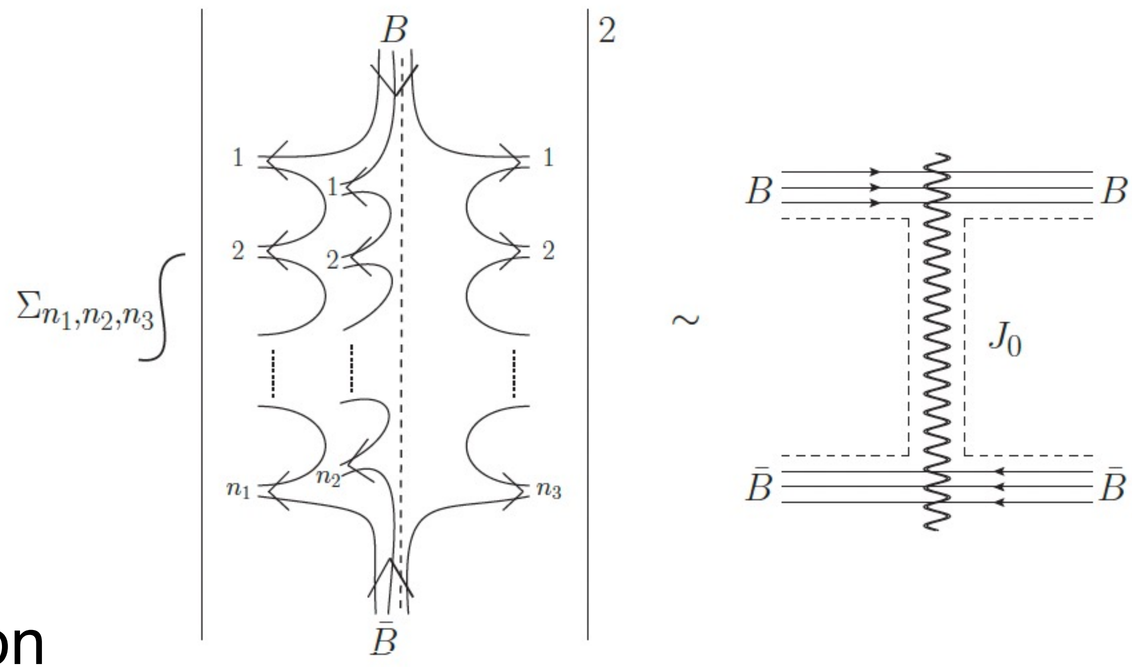
John Dalton 1766-1844



Also: Daltonism – color blindness

Feynman-Wilson gas with baryons

Consider baryon-antibaryon annihilation through the junction:



The cluster expansion

$$\Sigma_{ann}(z_1, z_2, z_3) \equiv e^{Y p(z_1,z_2,z_3)} =$$

$$= \exp\left(Y \sum_{m_1+m_2+m_3 \geq 1} c(m_1, m_2, m_3) \frac{(z_1-1)^{m_1}(z_2-1)^{m_2}(z_3-1)^{m_3}}{m_1! m_2! m_3!} \right)$$

Feynman-Wilson gas with baryons

The corresponding intercepts:

$$\alpha_{\mathbb{J}_4} = (2\alpha_{\mathbb{B}} - 1) + 2(1 - \alpha_{\mathbb{P}}) + (1 - \alpha_{\mathbb{R}}) - C_3 \sim -0.5 - 2C_{RL} - C_3$$
$$\alpha_{\mathbb{J}_2} = (2\alpha_{\mathbb{B}} - 1) + 3(1 - \alpha_{\mathbb{P}}) + 2(1 - \alpha_{\mathbb{R}}) - C_3 \sim 0 - 3C_{RL} - C_3$$
$$\alpha_{\mathbb{J}_0} = (2\alpha_{\mathbb{B}} - 1) + 3(1 - \alpha_{\mathbb{P}}) + 3(1 - \alpha_{\mathbb{R}}) - C_3 \sim 0.5 - 3C_{RL} - C_3$$

three-species correlations should be weaker and may be neglected;

C_{RL} is given by the Pomeron intercept.

All of the intercepts are thus fixed.

The junction-anti-junction intercept

$$\alpha_{\mathbb{P}} = 1 + C_{RL}$$

$$\alpha_{\mathbb{J}_0} = (2\alpha_{\mathbb{B}} - 1) + 3(1 - \alpha_{\mathbb{P}}) + 3(1 - \alpha_{\mathbb{R}}) - C_3 \sim 0.5 - 3C_{RL} - C_3$$

↓

$$\alpha_{\mathbb{J}_0} \simeq 0.26$$

↓

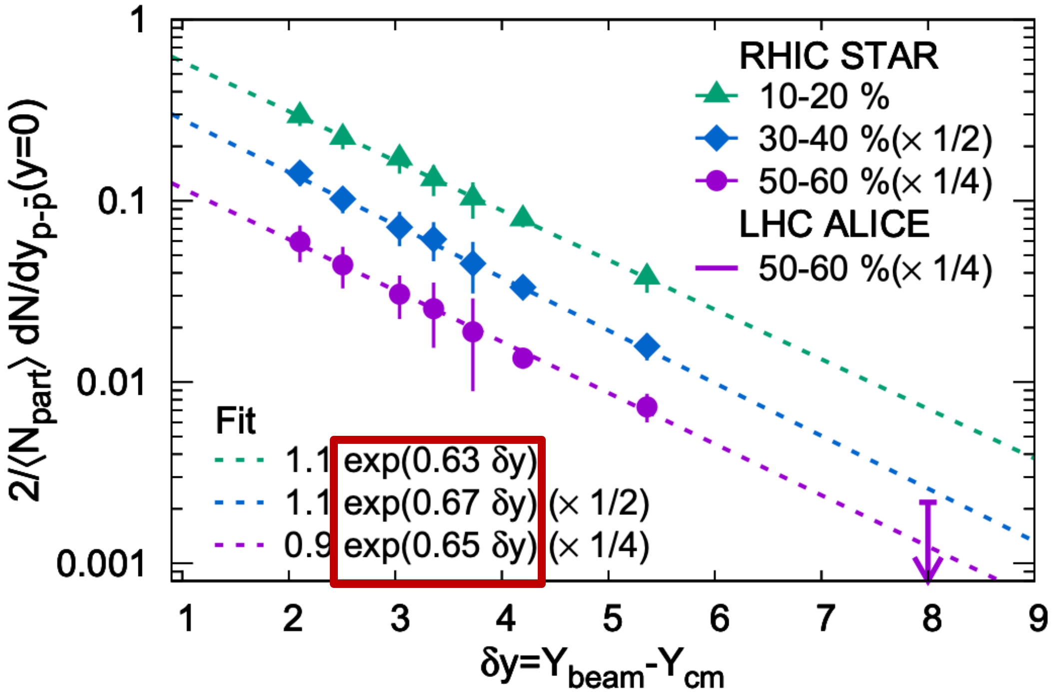
$$\text{beam rapidity dependence } e^{(\alpha_{\mathbb{J}_0} + \alpha_{\mathbb{P}} - 2)Y/2} = e^{-0.66\ Y/2}$$

D. Frenklakh, DK, G. Rossi, G. Veneziano, arXiv:2405.04569

Feynman-Wilson gas + topological expansion of QCD

beam rapidity dependence $e^{(\alpha_{\mathbb{J}_0}+\alpha_{\mathbb{P}}-2)Y/2} = e^{-0.66\ Y/2}$

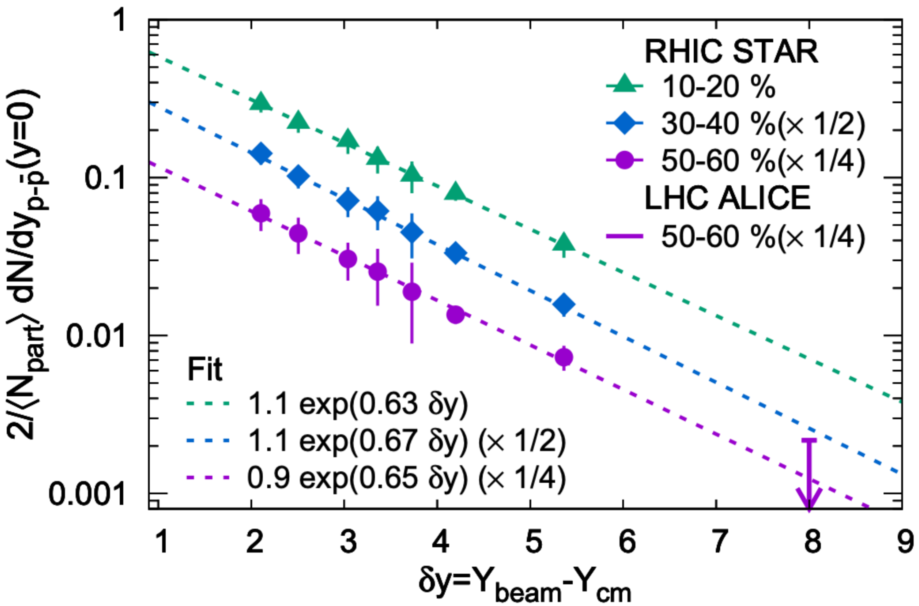
D. Frenklakh, DK, G. Rossi, G. Veneziano, arXiv:2405.04569

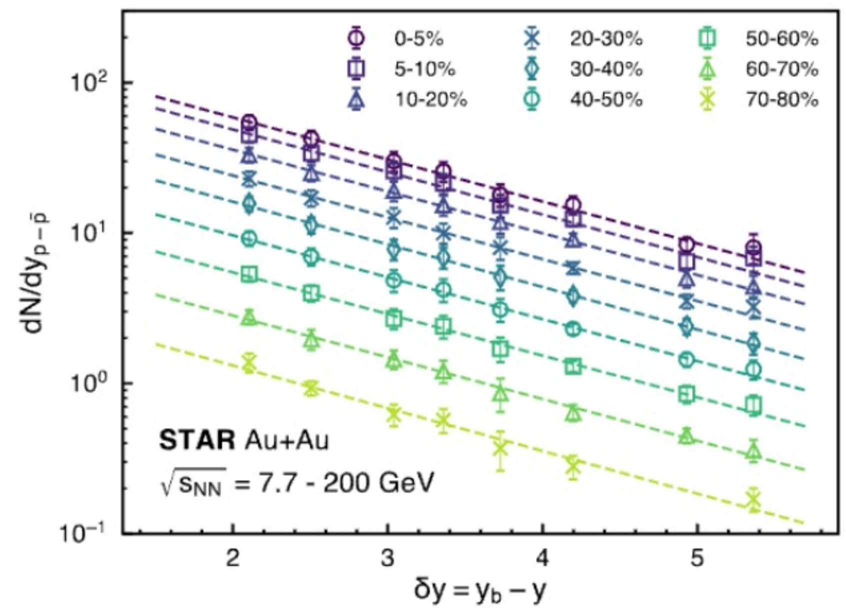


Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

James Daniel Brandenburg,[1] Nicole Lewis,[1,] Prithwish Tribedy,[1] and Zhangbu Xu[1]*
[1] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
(Dated: August 25, 2022)

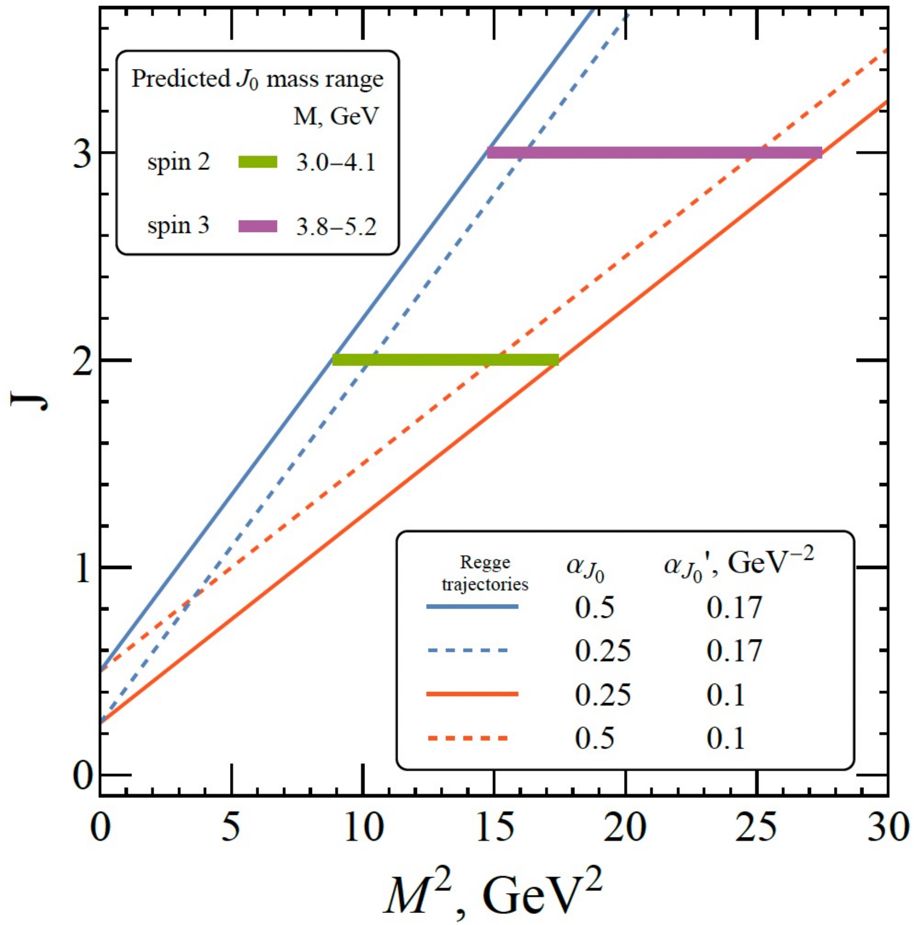
Talk by Prithwish Tribedy tomorrow





The slope of rapidity distribution does not change with centrality –
the baryon stopping is not a result of multiple rescattering inside the nuclei!

Regge trajectory and spectroscopy of $J\bar{J}$ glueballs

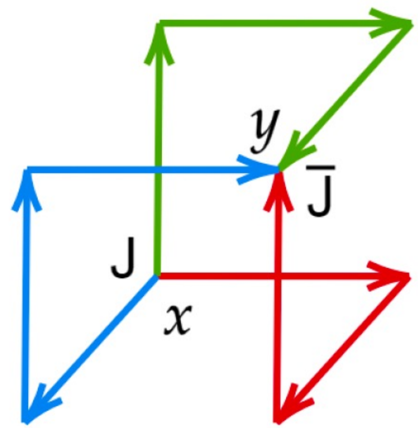


D. Frenklakh, DK, G. Rossi, G. Veneziano, arXiv:2405.04569

Regge trajectory and spectroscopy of $J\bar{J}$ glueballs

Current lattice QCD results on glueballs may not be sensitive to JJ glueballs due to the JOZI rule (suppression of JJ annihilation).

Perform lattice QCD calculation with the following glueball lattice JJ operator:



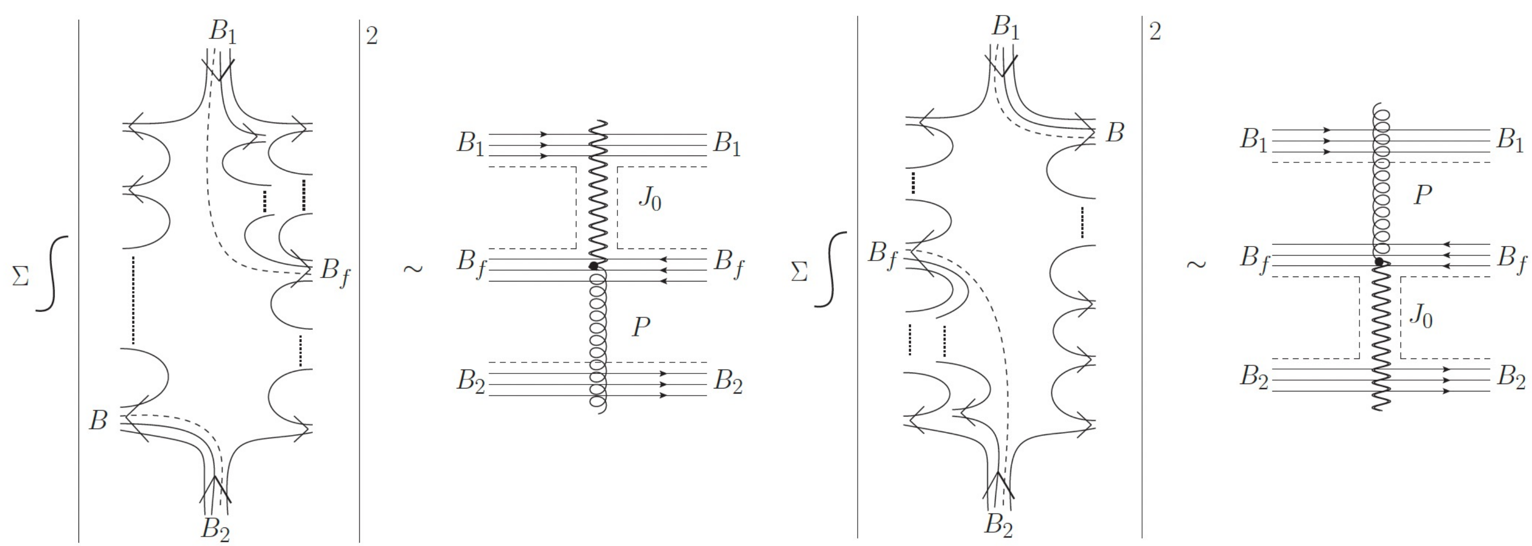
D. Frenklakh, DK, G. Rossi, G. Veneziano, arXiv:2405.04569

Future tests at RHIC and LHC

Baryon number distribution

$$\frac{dN}{dy_f} \propto e^{(\alpha_{\mathbb{J}_0}+\alpha_{\mathbb{P}}-2)Y/2}\left[e^{(\alpha_{\mathbb{P}}-\alpha_{\mathbb{J}_0})y_f}+e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{P}})y_f}\right],$$

DK, 1996

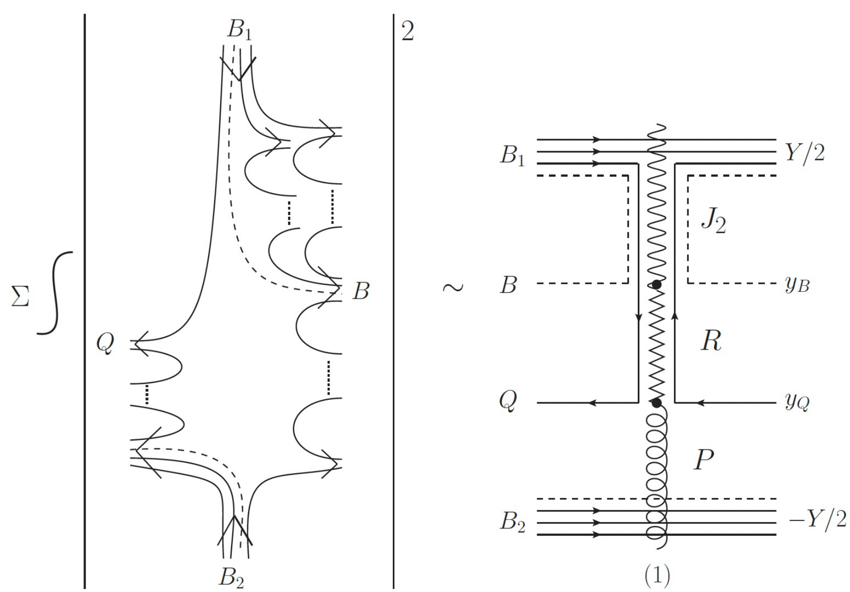


Future tests at RHIC and LHC

Measure combined Baryon-number-charge distribution:

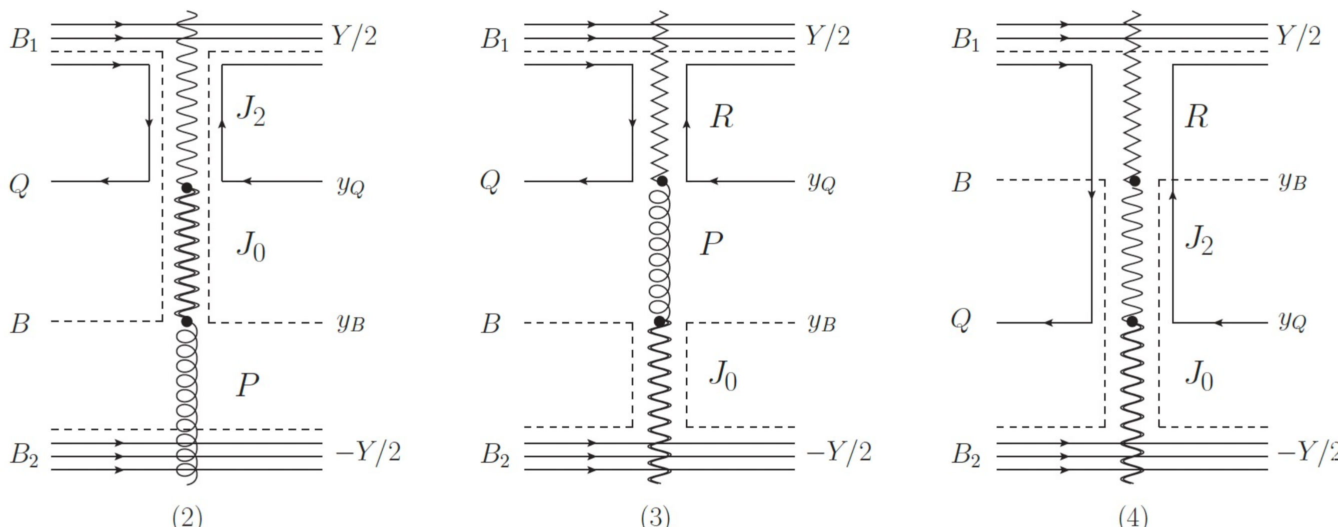
$$\frac{d^2\sigma_{(B,Q)}}{dy_B dy_Q} \equiv F_{(B,Q)}(Y, y_B, y_Q)$$

A direct test of baryon-number-flavor separation.



Future tests at RHIC and LHC

Combined Baryon-number-charge distribution:



For different rapidity orderings

$$F^{(1)}_{(B,Q)} \propto e^{(\alpha_{\mathbb{P}}+\alpha_{\mathbb{J}_2}-2)\frac{Y}{2}}\ e^{(\alpha_R-\alpha_{\mathbb{J}_2})y_B}\ e^{(\alpha_{\mathbb{P}}-\alpha_R)y_Q}\ ,$$

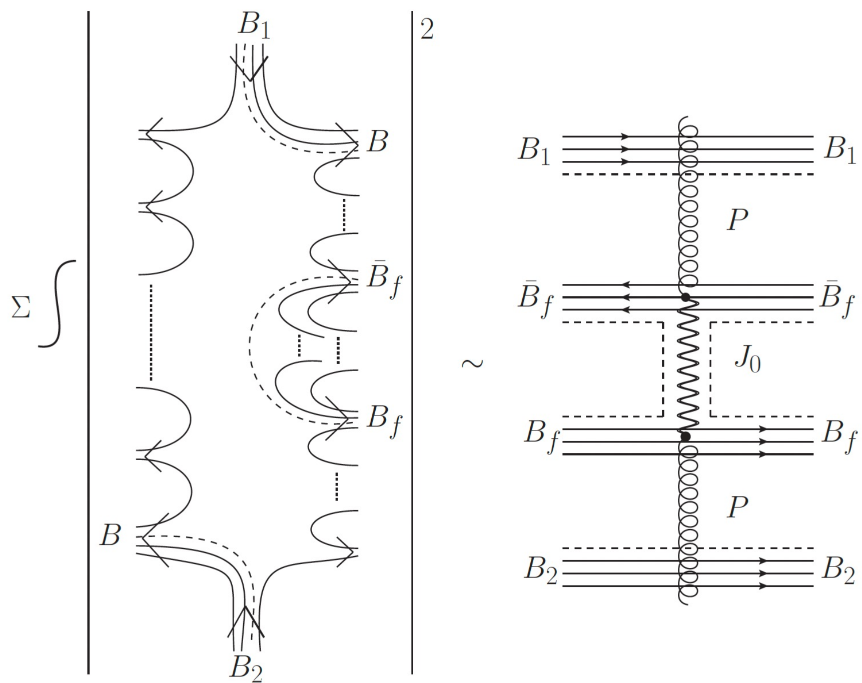
$$F^{(2)}_{(B,Q)} \propto e^{(\alpha_{\mathbb{P}}+\alpha_{\mathbb{J}_2}-2)\frac{Y}{2}}\ e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{J}_2})y_Q}\ e^{(\alpha_{\mathbb{P}}-\alpha_{\mathbb{J}_0})y_B}\ ,$$

$$F^{(3)}_{(B,Q)} \propto e^{(\alpha_R+\alpha_{\mathbb{J}_0}-2)\frac{Y}{2}}\ e^{(\alpha_{\mathbb{P}}-\alpha_R)y_Q}\ e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{P}})y_B}\ ,$$

$$F^{(4)}_{(B,Q)} \propto e^{(\alpha_R+\alpha_{\mathbb{J}_0}-2)\frac{Y}{2}}\ e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{J}_2})y_Q}\ e^{(\alpha_{\mathbb{J}_2}-\alpha_R)y_B}\ .$$

Future tests at RHIC and LHC

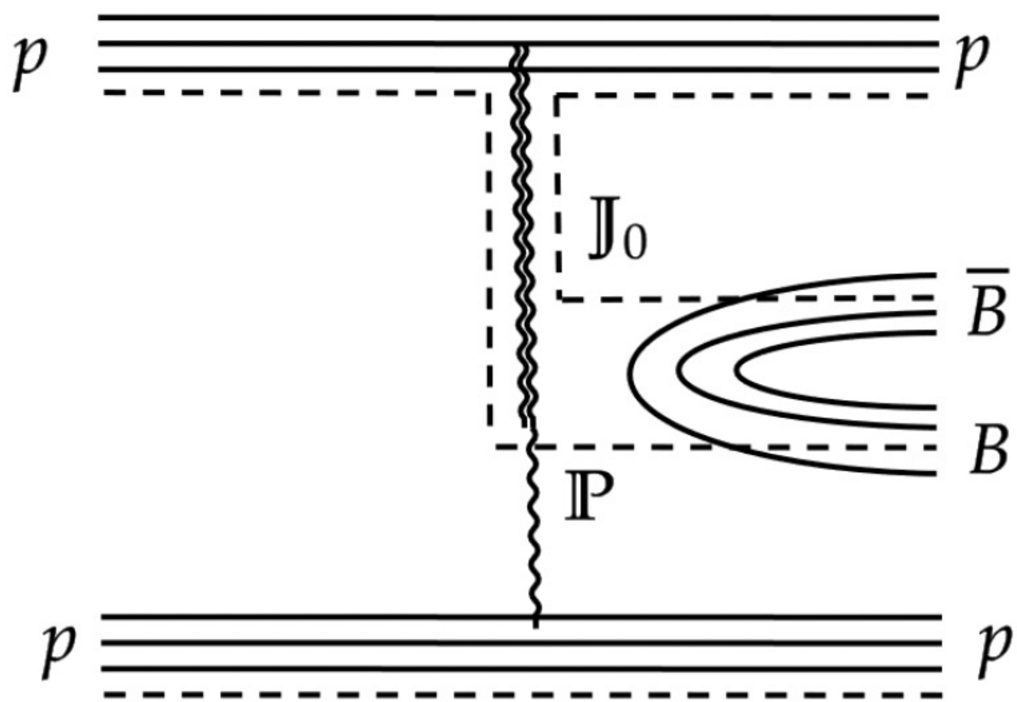
Baryon-antibaryon correlations in rapidity:



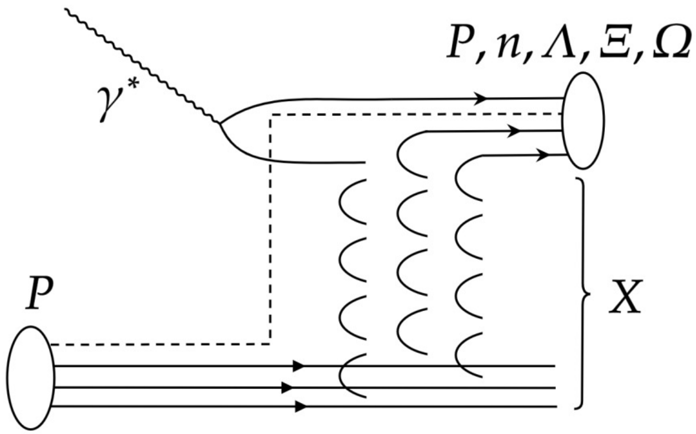
$$\rho_{B,\bar{B}}(\Delta y) \sim e^{-|\Delta y|(\alpha_{\mathbb{P}} - \alpha_{\mathbb{J}_0})}$$

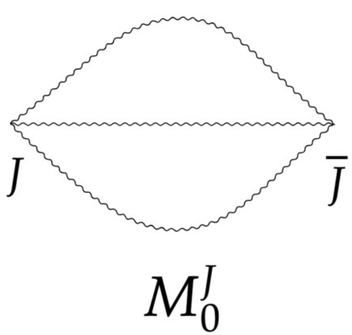
Future tests at RHIC and LHC

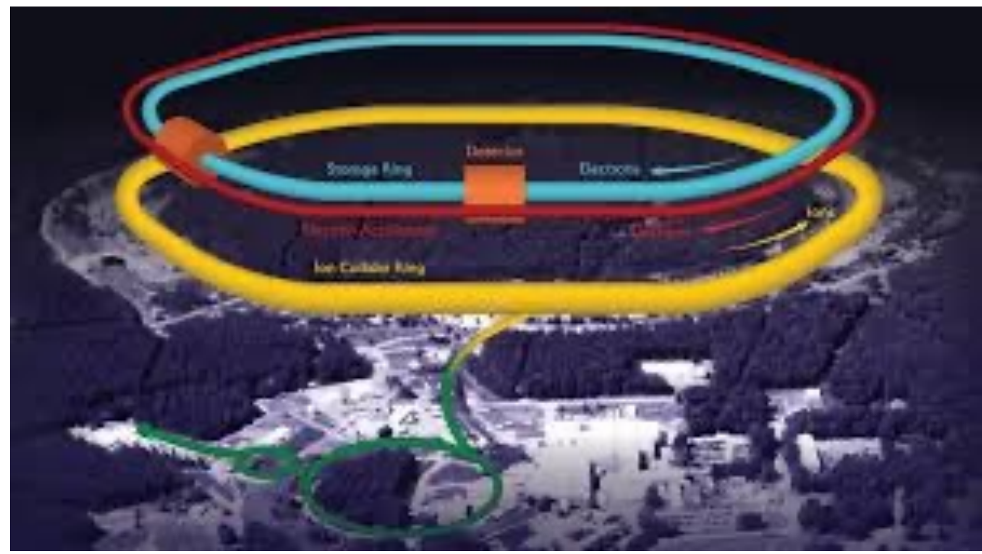
Extract the <u>slope</u> of J_0 trajectory in diffractive production of baryon-antibaryon pairs (or tetraquarks):



Baryon junctions at EIC







D. Frenklakh, DK, W. Li, arXiv:2312.15039 (PLB 2024)

Some other recent theory work

Baryons And Branes In Anti de Sitter Space

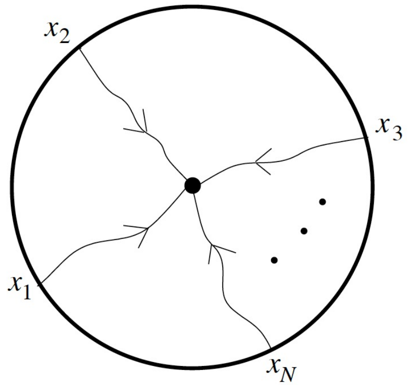


Fig. 1. N elementary strings attached to points $x_1, x_2, \ldots, x_N$ on the boundary of AdS space and joining at a baryon vertex in the interior.

Edward Witten

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Chirality distributions inside baryons in QCD_2

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[2]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*

The Baryon Junction and String Interactions

Zohar Komargodski* and Siwei Zhong†
Simons Center for Geometry and Physics, SUNY, Stony Brook, NY 11794, USA and
C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794, USA

(Dated: May 21, 2024)

Summary

- **The baryon number in high energy interactions is transported by gluons.**

- Topological expansion of QCD, and the Feynman-Wilson analogy, provide a framework for a quantitative description of this phenomenon.

- Many novel phenomena to be explored at the current and future experimental facilities (RHIC, JLab, LHC, EIC).