NREC 2026 Workshop

CFNS, Stony Brook, April 13-17, 2026

J/ψ photoproduction and quark, gluon and baryon number spatial distributions inside the nucleon

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C2QA
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Quantum anomalies and topology in the structure of the nucleon

Outline

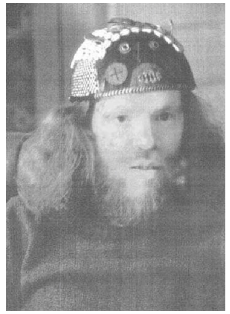
1. Gluon, quark spatial distributions and
   the scale anomaly

2. Baryon number distribution inside the nucleon

3. Measurements at the EIC and JLab that can
   advance our knowledge

Based on:

1. Spatial distributions and the scale anomaly:



DK, nucl-th/9601029 (Enrico Fermi School)

DK, H.Satz, A.Syamtomov, G.Zinovjev,
EPJC9(1999)459

H. Fujii, DK, Phys. Rev. D60, 114039 (1999)

J. Ellis, H. Fujii, DK, hep-ph/9909322

DK, E. Levin, K. Tuchin, Phys. Rev. D70 (2004) 054005;
JHEP 06 (2009) 055

DK, Phys. Rev. D104 (2021) 054015

Based on:

2. Baryon number distribution inside the nucleon:

DK, Phys. Lett.B 378 (1996) 238;

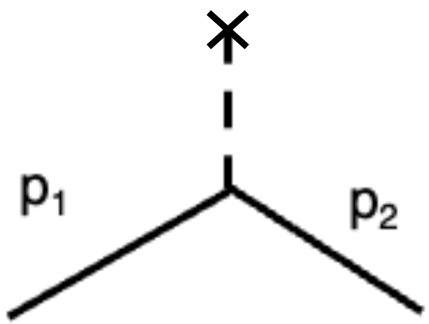
A.Florio, D.Frenklakh, DK, Phys.Rev. D106 (2022) 096025;

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

D. Frenklakh, DK, G. Rossi, G. Veneziano, JHEP 07 (2024) 262.

How to define the gluon and quark radii?

We need to measure a spatial distribution (formfactor) of a local gauge-invariant operator made of gluon or quark fields:



Let us begin with a scalar gluon operator $\beta(g)/2g\ G^2$

Lowest dimension gauge-invariant operator $J^{PC}=0^{++}$

It plays a fundamental role in QCD due to the scale anomaly:

$$T^{\mu}_{\mu} = \frac{\beta(g)}{2g}\, G^{\mu\nu a} G^{a}_{\mu\nu} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l + \sum_{h=c,b,t} m_h (1+\gamma_{m_h}) \bar{Q}_h Q_h$$

Trace of $T^{\mu\nu}$ plays a fundamental role: link to scale invariance

Scale transformations (dilatations) are defined by

$$x \to e^{\lambda}\ x$$

the corresponding dilatational current is

$$s^{\mu} = x_{\nu} T^{\mu\nu}$$

Hermann Weyl
(1885-1955)

It is conserved
(a theory is scale-invariant)
if the energy-momentum is traceless:

$$\partial_{\mu} s^{\mu} = T^{\mu}_{\mu} \equiv T$$

Scale invariance in QCD

The trace of the energy-momentum tensor in QCD (computed in classical field theory) is

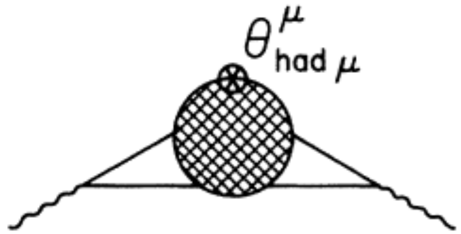
$$T^{\mu}_{\mu} = \sum_{l=u,d,s} m_l \; \bar{q}_l q_l + \sum_{h=c,b,t} m_h \; \bar{Q}_h Q_h$$

Two problems:

1. Potentially large contribution from heavy quarks to the masses of light hadrons

2. If we forget about heavy quarks, all hadron masses must be equal to zero in the chiral limit

Scale anomaly in QCD



The quantum effects (loop diagrams) modify
the expression for the trace of the energy-momentum tensor:

$$T^{\mu}_{\mu} = \frac{\beta(g)}{2g}\, G^{\mu\nu a} G^{a}_{\mu\nu} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l + \sum_{h=c,b,t} m_h (1+\gamma_{m_h}) \bar{Q}_h Q_h$$

Running coupling -> dimensional transmutation -> mass scale

Gross, Wilczek;
Politzer

$$\beta(g) = -b\frac{g^3}{16\pi^2} + \ldots,\;\; b = 9 - \frac{2}{3} n_h,$$

Ellis, Chanowitz;
Crewther;
Collins, Duncan,
Joglecar; …

At small momentum transfer, heavy quarks decouple:

$$\sum_h m_h \bar{Q}_h Q_h \to -\frac{2}{3}\, n_h\, \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \ldots$$

so only light quarks enter the final expression

Shifman,
Vainshtein
Zakharov ’78

$$T^{\mu}_{\mu} = \frac{\tilde{\beta}(g)}{2g}\, G^{\mu\nu a} G^{a}_{\mu\nu} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l,$$

0

The proton mass

At zero momentum transfer, the matrix element of the trace of the energy-momentum tensor defines the mass of the proton:

$$\langle \mathbf{p}=0|T|\mathbf{p}=0\rangle = \langle \mathbf{p}=0|T_{00}|\mathbf{p}=0\rangle = M,$$

$$T^{\mu}_{\mu} = \frac{\tilde{\beta}(g)}{2g}\, G^{\mu\nu a}G^{a}_{\mu\nu} + \sum_{l=u,d,s} m_l(1+\gamma_{m_l})\bar{q}_l q_l,$$

In the chiral limit, the only contribution is from gluons!

Demonstration of the hadron mass origin from the QCD trace anomaly

Fangcheng He,[1,*] Peng Sun,[2,†] and Yi-Bo Yang[1,3,4,5,‡]

(χQCD Collaboration)

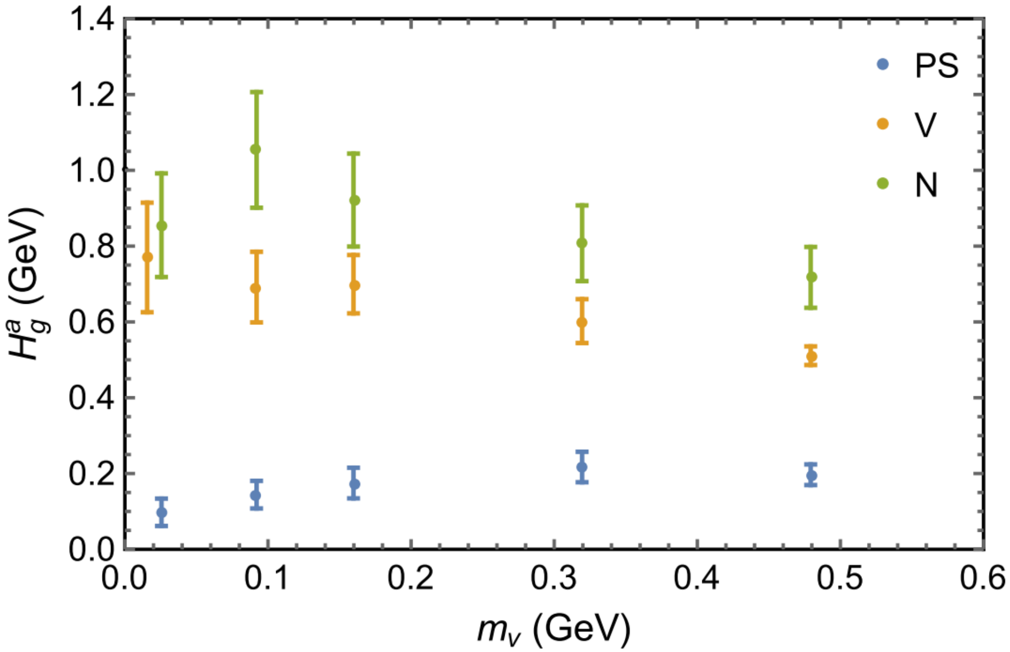


FIG. 3. The gluon trace anomaly contribution to the hadron mass. For five different quark masses, the corresponding pion masses are 0.340, 0.647, 0.864, 1.277, and 1.640 GeV. We can see that it is always small for the PS meson, while it approaches ~800 MeV for the nucleon and vector mesons in the chiral limit $m_v \to 0$.

Confinement due to scale anomaly?

$$T^{\mu}_{\mu} = \frac{\tilde{\beta}(g)}{2g} G^{\mu\nu a} G^a_{\mu\nu} + \sum_{l=u,d,s} m_l (1 + \gamma_{m_l}) \bar{q}_l q_l,$$

In quantum theory, scale anomaly induces conformally flat deformation of space-time.
Can this be used to describe confinement?

QCD in curved space-time: A conformal bag model Also: JHEP06(2009)055

Dmitri Kharzeev, Eugene Levin, and Kirill Tuchin
Phys. Rev. D **70**, 054005 – Published 3 September 2004

$$g_{\mu\nu}(x) = e^{h(x)} \delta_{\mu\nu}$$

$$S = \int d^4x \left(\frac{4|\epsilon_v|}{m^2} e^h (\partial_\mu h)^2 - \frac{1}{4} (F^a_{\mu\nu})^2 + |\epsilon_v| e^{2h} - \frac{1}{4} e^{2h} \left[-\frac{b g^2}{32\pi^2} (F^a_{\mu\nu})^2 \right] \right)$$

This model belongs to the class of confining models proposed in
't Hooft hep-th/0207179: It describes gluons in the dilaton background:

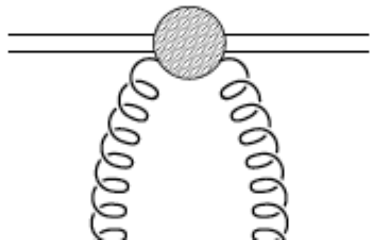
$$\mathcal{L} = -V(\chi) - Z(\chi) \frac{1}{4} (F^a_{\mu\nu})^2 \qquad Z(\chi) = -e^{\chi} (1-\chi) c + 1, \quad V(\chi) = -|\epsilon_v| e^{\chi} (1-\chi)$$

How to measure the scalar gluon radius (mass radius)?

No dilatons available…
next best thing: a heavy quarkonium

QCD multipole expansion:

Voloshin ‘78; Appelquist, Fischler ‘78; Gottfried ‘78; Peskin ‘79; Novikov, Shifman ‘81; Leutwyler ‘81, Luke, Manohar, Savage ‘92, …



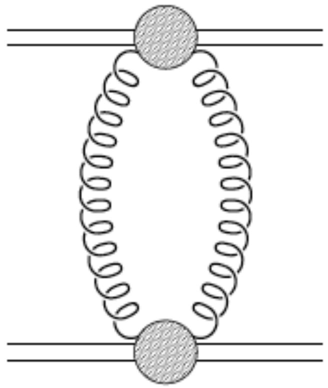
M.B. Voloshin
1953-2020

$$g^2\mathbf{E}^{a2} = \frac{g^2}{2}(\mathbf{E}^{a2} - \mathbf{B}^{a2}) + \frac{g^2}{2}(\mathbf{E}^{a2} + \mathbf{B}^{a2})$$

$$= -\frac{1}{4}g^2 G^a_{\alpha\beta}G^{a\alpha\beta} + g^2(-G^a_{0\alpha}G^{a\alpha}_0 + \frac{1}{4}g_{00}G^a_{\alpha\beta}G^{a\alpha\beta}) = \frac{8\pi^2}{b}\theta^\mu_\mu + g^2\theta^{(G)}_{00}$$

$$\theta^\mu_\mu \equiv \frac{\beta(g)}{2g}G^{a\alpha\beta}G^a_{\alpha\beta} = -\frac{bg^2}{32\pi^2}G^{a\alpha\beta}G^a_{\alpha\beta}\ , \quad \theta^{(G)}_{\mu\nu} \equiv -G^a_{\mu\alpha}G^{a\alpha}_\nu + \frac{1}{4}g_{\mu\nu}G^a_{\alpha\beta}G^{a\alpha\beta}$$

Quarkonium interactions at low energy



Perturbation theory:

at large distances,
the Casimir-Polder
interaction (retardation)

Bhanot, Peskin '78

$$V^{\rm pt}(R) = -g^4 \left(\bar{d}_2 \frac{a_0^2}{\epsilon_0} \right)^2 \frac{23}{8\pi^3} \frac{1}{R^7}$$

Fujii, DK '99

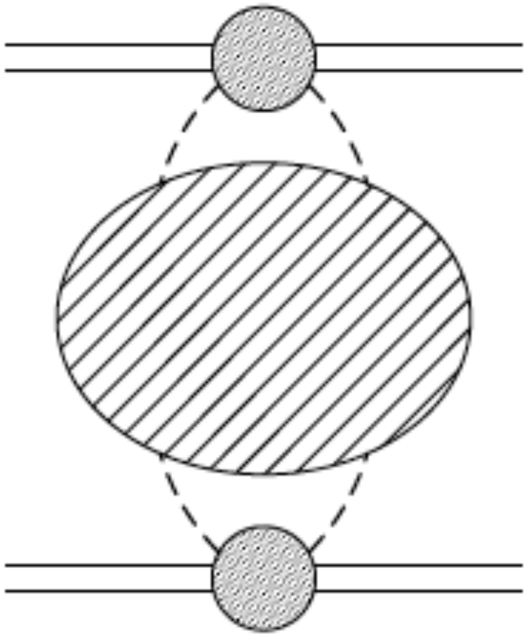
23 = 15 + 8

scalar 0^{++} tensor 2^{++}

Beyond perturbation theory, scalar is strongly enhanced due to scale anomaly

Quarkonium interactions at low energy and the scale anomaly

But, at very large distances, the interaction must be dominated by the lightest physical states - pions



conversion of gluons to pions is a (hopeless?) non-perturbative problem

...but, can use scale anomaly matching!

Voloshin, Zakharov ’80
Novikov, Shifman ‘82

Quarkonium interactions at low energy and the scale anomaly

Use RG invariance to match the EMT computed in QCD and in the chiral theory:

$$\theta^\mu_\mu = -2\,\frac{f_\pi^2}{4}\,\mathrm{tr}\,\partial_\mu U \partial^\mu U^\dagger \;-\; m_\pi^2 f_\pi^2\,\mathrm{tr}\left(U + U^\dagger\right)$$

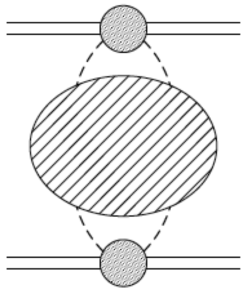
to lowest order in the pion field

$$\theta^\mu_\mu = -\partial_\mu \pi^a \partial^\mu \pi^a + 2 m_\pi^2 \pi^a \pi^a + \cdots$$

In the chiral limit scale anomaly yields:

$$\langle \pi^+ \pi^- | \theta^\mu_\mu | 0 \rangle = q^2$$

Quarkonium interactions at low energy and the scale anomaly

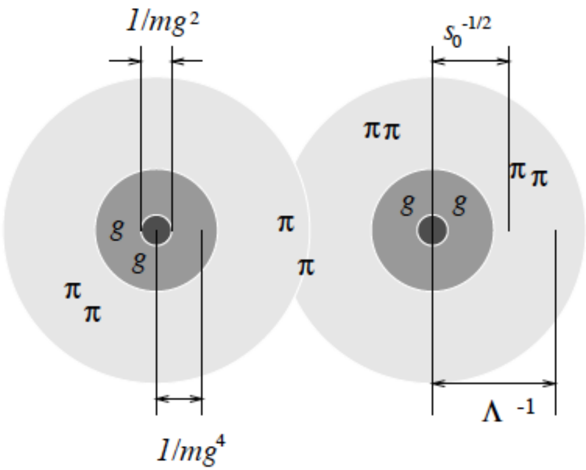


The result (long distances):

$$V^{\pi\pi}(R) \to -\left(\bar{d}_2 \frac{a_0^2}{\epsilon_0}\right)^2 \left(\frac{4\pi^2}{b}\right)^2 \frac{3}{2}(2m_\pi)^4 \, \frac{m_\pi^{1/2}}{(4\pi R)^{5/2}} \, e^{-2m_\pi R}.$$

Fujii, DK, PRD (1999)

See also A.Belitsky and X.Ji, PLB (2002)



1. Not a Yukawa potential (retardation)
2. The QCD coupling has disappeared at large distance (but not b from the beta-function)
3. Entirely due to scalar 0^{++} exchange

This two-pion tail in quarkonium interactions has just been clearly observed on the lattice:

arXiv:2205.10544

Attractive N-ϕ Interaction and Two-Pion Tail from Lattice QCD near Physical Point

Yan Lyu,[1,2,*] Takumi Doi,[2,†] Tetsuo Hatsuda,[2,‡] Yoichi Ikeda,[3,§]
Jie Meng,[1,4,¶] Kenji Sasaki,[3,**] and Takuya Sugiura[2,††]

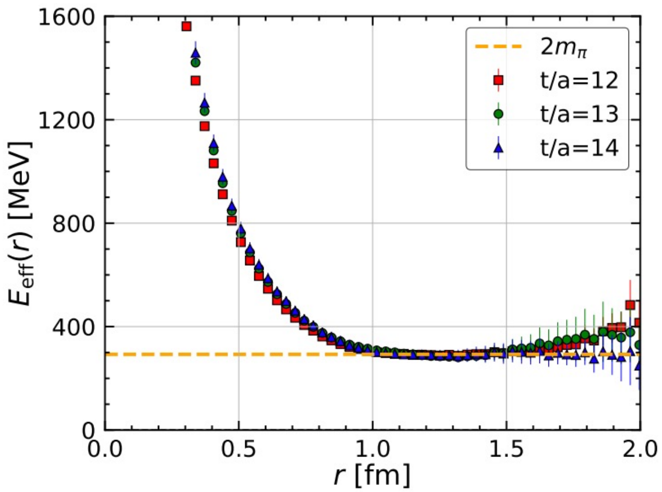
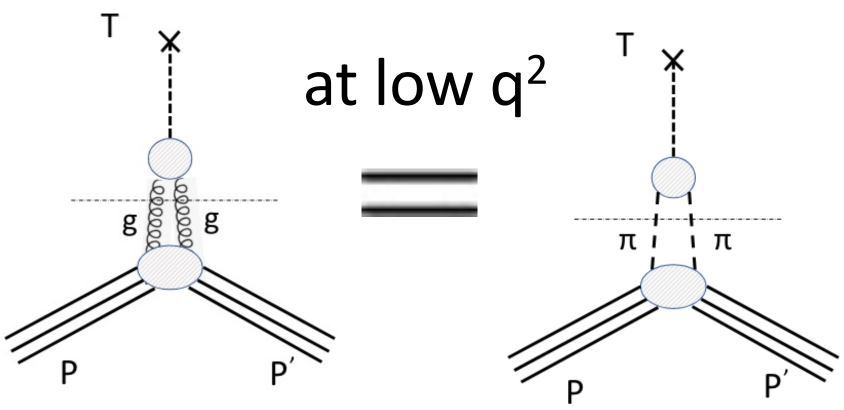


FIG. 2. (Color online). The spatial effective energy $E_{\rm eff}(r)$ as a function of separation r at Euclidean time $t/a = 12$ (red squares), 13 (green circles) and 14 (blue triangles). The orange dashed line corresponds to $2m_\pi$ with lattice pion mass $m_\pi = 146.4$ MeV.

Why the (scalar) gluon (=mass) radius of the nucleon should be smaller than the (scalar) quark radius?

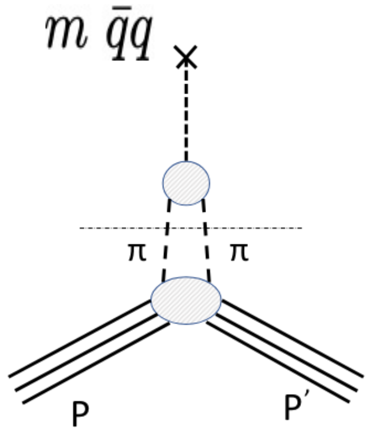
gluon radius



$$\langle 0|T|\pi^+\pi^-\rangle = q^2$$

suppression at low q^2 –
smaller radius

quark radius



PCAC: $m\,\bar{q}q \sim M_\pi^2\,\pi^2$

no suppression at low q^2 –
larger radius

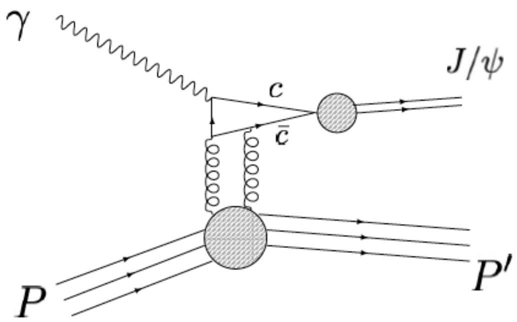
DK, arXiv:2102.00110

Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton

The amplitude:

$$\mathcal{M}_{\gamma P \to \psi P}(t) = -Qe\ c_2\ 2M\ \langle P'|g^2 \mathbf{E}^{a2}|P\rangle,$$

$$Qe = 2e/3$$



$$\mathcal{M}_{\gamma P \to \psi P}(t) = -Qe\ c_2\ \frac{16\pi^2 M}{b}\ \langle P'|T|P\rangle$$

Differential cross section:

$$\frac{d\sigma_{\gamma P \to \psi P}}{dt} = \frac{1}{64\pi s}\ \frac{1}{|\mathbf{p}_{\gamma cm}|^2}\ |\mathcal{M}_{\gamma P \to \psi P}(t)|^2$$

DK, PRD'21

$$\sigma_{\gamma P \to \psi P}(s) = \int_{t_{min}}^{t_{max}} dt\ \frac{d\sigma_{\gamma P \to \psi P}}{dt},$$

Probing the proton mass

The quarkonium-proton scattering amplitude

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} d_n \langle h | \frac{1}{2} G_{0i}^a (D^0)^{n-2} G_{0i}^a | h \rangle$$

Wilson coefficients

$$d_n^{(1S)} = \left(\frac{32}{N}\right)^2 \sqrt{\pi}\, \frac{\Gamma(n+\frac{5}{2})}{\Gamma(n+5)}$$

M.Peskin ‘78

$$d_n^{(2S)} = \left(\frac{32}{N}\right)^2 4^n \sqrt{\pi}\, \frac{\Gamma(n+\frac{5}{2})}{\Gamma(n+7)} (16n^2 + 56n + 75)$$

$$d_n^{(2P)} = \left(\frac{15}{N}\right)^2 4^n 2\sqrt{\pi}\, \frac{\Gamma(n+\frac{7}{2})}{\Gamma(n+6)}$$

DK, ‘96
nucl-th/9601029

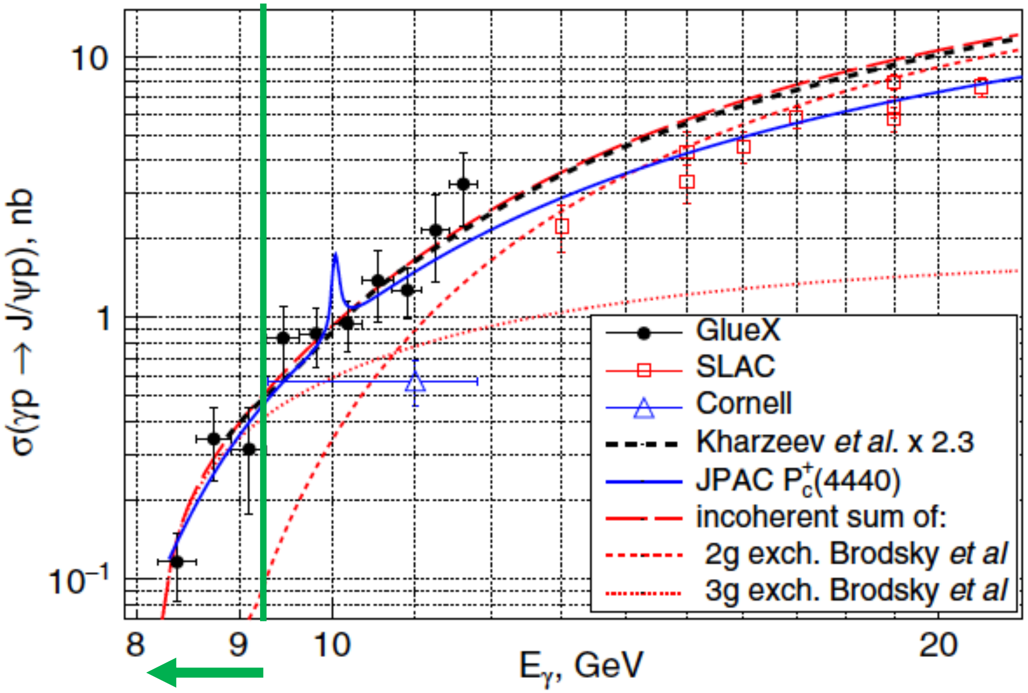
PHYSICAL REVIEW LETTERS **123,** 072001 (2019)

Editors' Suggestion

First Measurement of Near-Threshold J/ψ Exclusive Photoproduction off the Proton

A. Ali,[10] M. Amaryan,[22] E. G. Anassontzis,[2] A. Austregesilo,[3] M. Baalouch,[22] F. Barbosa,[14] J. Barlow,[7] A. Barnes,[3] E. Barriga,[7] T. D. Beattie,[23] V. V. Berdnikov,[17] T. Black,[20] W. Boeglin,[6] M. Boer,[4] W. J. Briscoe,[8] T. Britton,[14] W. K. Brooks,[24] B. E. Cannon,[7] N. Cao,[11] E. Chudakov,[14] S. Cole,[1] O. Cortes,[8] V. Crede,[7] M. M. Dalton,[14] T. Daniels,[20] A. Deur,[14] S. Dobbs,[7] A. Dolgolenko,[13] R. Dotel,[6] M. Dugger,[1] R. Dzhygadlo,[10] H. Egiyan,[14] A. Ernst,[7] P. Eugenio,[7] C. Fanelli,[16] S. Fegan,[8] A. M. Foda,[23] J. Foote,[12] J. Frye,[12] S. Furletov,[14] L. Gan,[20] A. Gasparian,[19] V. Gauzshtein,[25,26] N. Gevorgyan,[27] C. Gleason,[12] K. Goetzen,[10] A. Goncalves,[7] V. S. Goryachev,[13] L. Guo,[6] H. Hakobyan,[24] A. Hamdi,[10] S. Han,[29] J. Hardin,[16] G. M. Huber,[23] A. Hurley,[28] D. G. Ireland,[9] M. M. Ito,[14] N. S. Jarvis,[3] R. T. Jones,[5] V. Kakoyan,[27] G. Kalicy,[4] M. Kamel,[6] C. Kourkoumelis,[2] S. Kuleshov,[24] I. Kuznetsov,[25,26] I. Larin,[15] D. Lawrence,[14] D. I. Lersch,[7] H. Li,[3] W. Li,[28] B. Liu,[11] K. Livingston,[9] G. J. Lolos,[23] V. Lyubovitskij,[25,26] D. Mack,[14] H. Marukyan,[27] V. Matveev,[13] M. McCaughan,[14] M. McCracken,[3] W. McGinley,[3] J. McIntyre,[5] C. A. Meyer,[3] R. Miskimen,[15] R. E. Mitchell,[12] F. Mokaya,[5] F. Nerling,[10] L. Ng,[7] A. I. Ostrovidov,[7] Z. Papandreou,[23] M. Patsyuk,[16] P. Pauli,[9] R. Pedroni,[19] L. Pentchev,[14,*] K. J. Peters,[10] W. Phelps,[8] E. Pooser,[14] N. Qin,[21] J. Reinhold,[6] B. G. Ritchie,[1] L. Robison,[21] D. Romanov,[17] C. Romero,[24] C. Salgado,[18] A. M. Schertz,[28] R. A. Schumacher,[3] J. Schwiening,[10] K. K. Seth,[21] X. Shen,[11] M. R. Shepherd,[12] E. S. Smith,[14] D. I. Sober,[4] A. Somov,[14] S. Somov,[17] O. Soto,[24] J. R. Stevens,[28] I. I. Strakovsky,[8] K. Suresh,[23] V. Tarasov,[13] S. Taylor,[14] A. Teymurazyan,[23] A. Thiel,[9] G. Vasileiadis,[2] D. Werthmüller,[9] T. Whitlatch,[14] N. Wickramaarachchi,[22] M. Williams,[16] T. Xiao,[21] Y. Yang,[16] J. Zarling,[12] Z. Zhang,[29] G. Zhao,[11] Q. Zhou,[11] X. Zhou,[29] and B. Zihlmann[14]

(GlueX Collaboration)

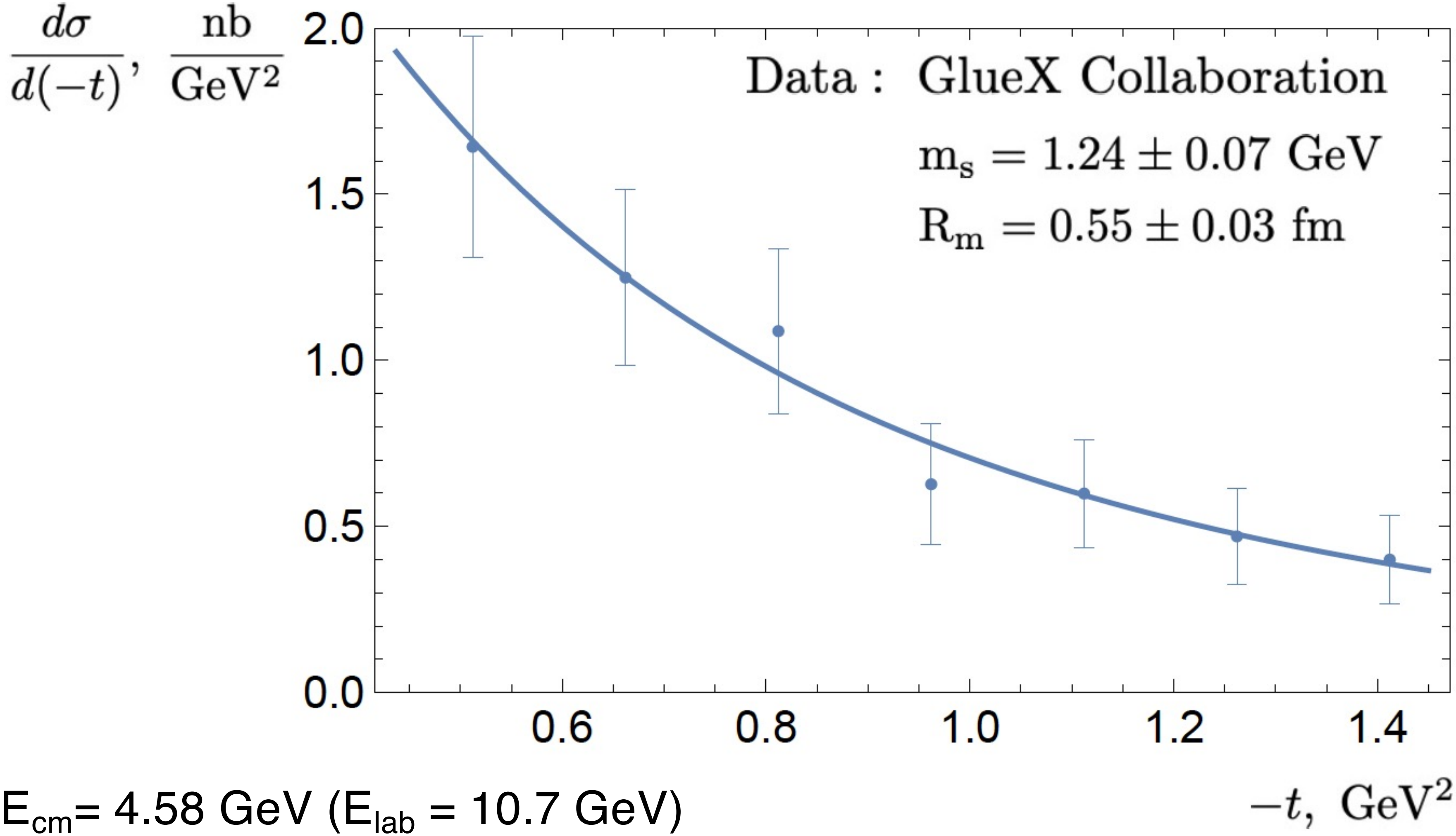


Need to focus on
the threshold region!

$E_{cm} < 4.25$ GeV
$E_\gamma < 9.2$ GeV

Differential cross section

DK, arXiv:2102.00110, PRD(2021)



E_{cm}= 4.58 GeV (E_{lab} = 10.7 GeV)

$$|c_2|^2 = 0.043 \pm 0.006 \text{ fm}^4$$

Lattice QCD, P. Shanahan, W. Detmold PRD'19:

$$m_s = 1.13 \pm 0.06 \text{ GeV}$$ (Traceless gluon operator)

$$c_2 \sim \pi r_{c\bar{c}}^2 \qquad r_{c\bar{c}} \simeq 0.1 \text{ fm}$$

The proton mass radius

The r.m.s. "proton mass radius" from GlueX data:

$$R_{\mathrm{m}} \equiv \sqrt{\langle R_{\mathrm{m}}^2 \rangle} = 0.55 \pm 0.03 \text{ fm}$$

DK, arXiv:2102.00110, PRD(2021)

Compare to the proton charge radius:

$$\bar{\mathrm{R}}_{\mathrm{c}} \equiv \sqrt{R_c^2} = 0.8409 \pm 0.0004 \quad \mathrm{fm}$$

See J.Bernauer, EPJ 234 (2020) for review

A more compact mass distribution? Need more data!

VALUE (fm)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.8409 ± 0.0004	**OUR AVERAGE**			
0.833 ±0.010	[1] BEZGINOV	2019	LASR	2S-2P transition in H
0.831 ±0.007 ±0.012	[2] XIONG	2019	SPEC	$e\,p \to ep$ form factor
0.84087 ±0.00026 ±0.00029	ANTOGNINI	2013	LASR	μp -atom Lamb shift
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.877 ±0.013	[3] FLEURBAEY	2018	LASR	1S-3S transition in H
0.8335 ±0.0095	[4] BEYER	2017	LASR	2S-4P transition in H
0.8751 ±0.0061	MOHR	2016	RVUE	2014 CODATA value
0.895 ±0.014 ±0.014	[5] LEE	2015	SPEC	Just 2010 Mainz data
0.916 ±0.024	LEE	2015	SPEC	World data, no Mainz
0.8775 ±0.0051	MOHR	2012	RVUE	2010 CODATA, ep data
0.875 ±0.008 ±0.006	ZHAN	2011	SPEC	Recoil polarimetry
0.879 ±0.005 ±0.006	BERNAUER	2010	SPEC	$e\,p \to ep$ form factor

2020 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

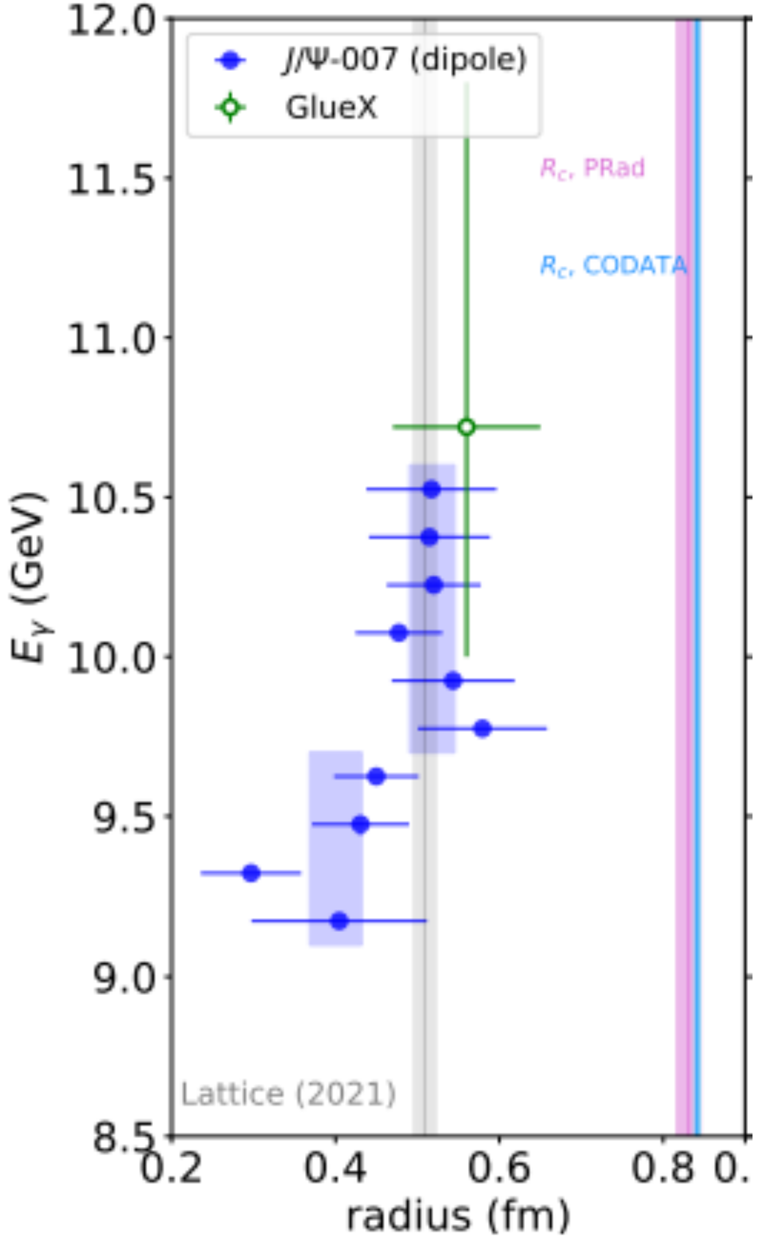
Some day:
p MASS RADIUS in PDG?

When Color meets Gravity; Near-Threshold Exclusive J/ψ Photoproduction on the Proton

B. Duran[3,1], Z.-E. Meziani[1,3**], S. Joosten[1], M. K. Jones[2], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[3], E. Chudakov[2], H. Bhatt[5], D. Bhetuwal[5], M. Boer[11], A. Camsonne[2], J.-P. Chen[2], M. Dalton[2], N. Deokar[3], M. Diefenthaler[2], J. Dunne[5], L. El Fassi[5], E. Fuchey[9], H. Gao[4], D. Gaskell[2], O. Hansen[2], F. Hauenstein[6], D. Higinbotham[2], S. Jia[3], A. Karki[5], C. Keppel[2], P. King[6], H.S. Ko[10], X. Li[4], R. Li[3], D. Mack[2], S. Malace[2], M. McCaughan[2], R. E. McClellan[8], R. Michaels[2], D. Meekins[2], L. Pentchev[2], E. Pooser[2], A. Puckett[9], R. Radloff[5], M. Rehfuss[3], P. E. Reimer[1], S. Riordan[1], B. Sawatzky[2], A. Smith[4], N. Sparveris[3], H. Szumila-Vance[2], S. Wood[2], J. Xie[1], Z. Ye[1], C. Yero[6], and Z. Zhao[4]

J/ψ 007 Coll.

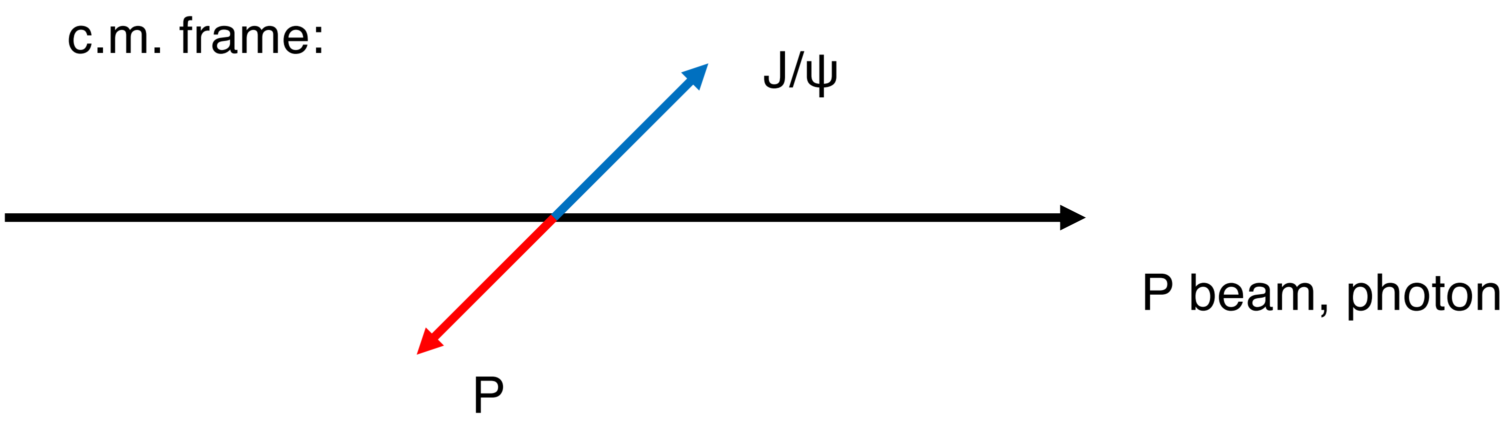
arXiv:2207.05212



below 9.7 GeV. The radius determined in the energy independent region averages to $\sqrt{\langle r_m^2 \rangle} = 0.52 \pm 0.03$fm. This result

Future measurements

- GlueX has 10 times more data
- Future: SoLID@Jlab (~ 2028), EIC (including Υ !)
- Polarization? (scalar vs tensor)
- Also: ultra-peripheral collisions at RHIC?



For a fixed invariant mass (cms energy), measure the angular distribution – differential cross section of photoproduction

What is the radius of baryon number distribution inside the nucleon?

To answer this question, we need to know what carries the baryon number
(what gauge-invariant operator to use,
and what is the spectrum of corresponding states)

Baryon number in the Standard Model

Noether theorem:

For every symmetry
of the action there is a
conservation law

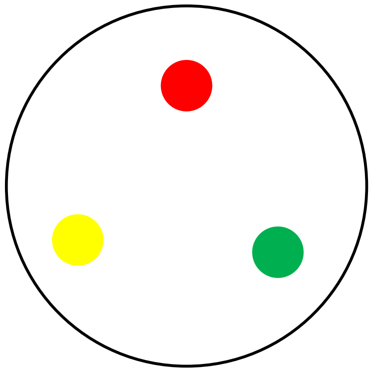
Baryon number conservation:

$U_V(1)$ 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: $q(x_1)\ q(x_2)\ q(x_3)$



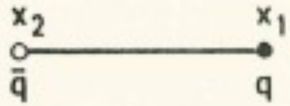
This wave function is not gauge-invariant!

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

G. Rossi, G. Veneziano 1977

Table IIa

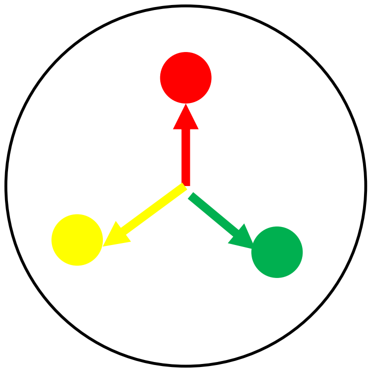
Simplest mesons and baryons : colour structure and string picture

HADRON	GAUGE INVARIANT OPERATOR	STRING PICTURE
$M_2 = q\bar{q}$ meson	$\bar{q}^{j_2}(x_2)\left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu\, dx^\mu\right)\right]^{j_1}_{j_2} q_{j_1}(x_1)$	
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:

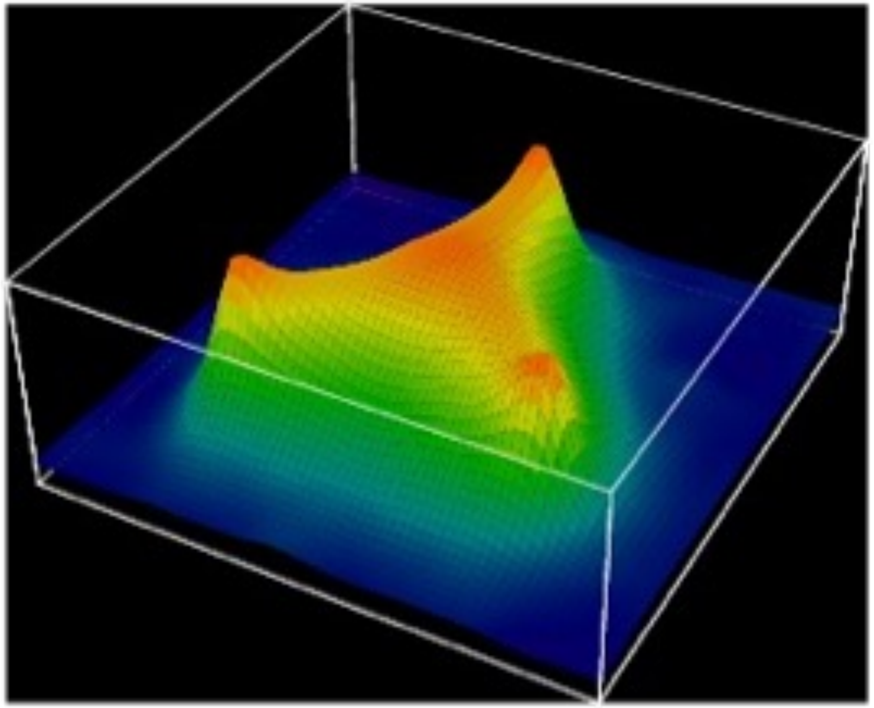
$$U(\mathcal{C}(x_1, x_2)) \equiv P \exp\left(ig \int_{\mathcal{C}(x_1,x_2)} A_\mu(x) dx^\mu \right)$$

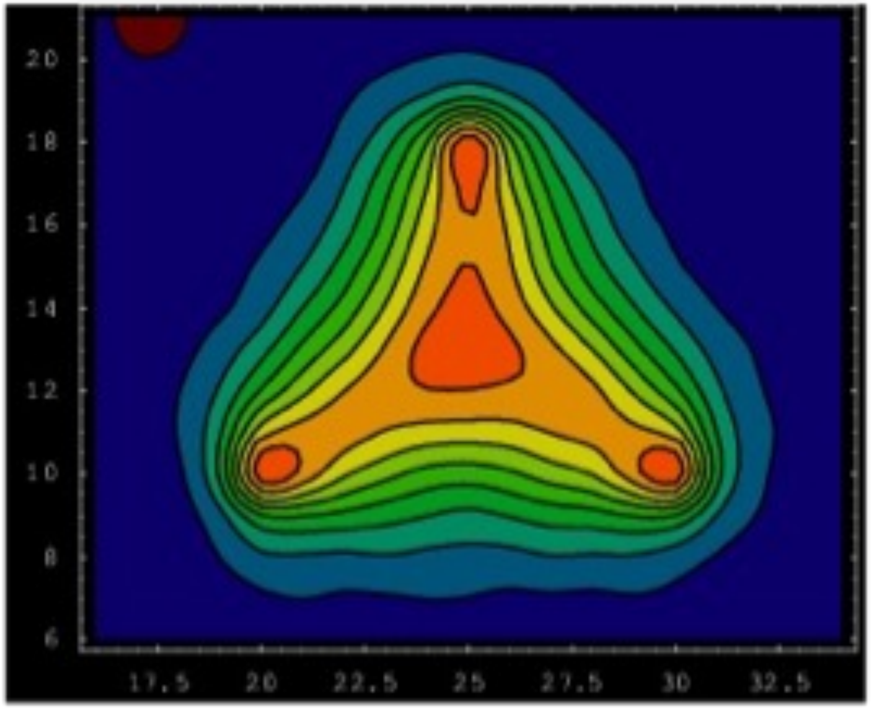


$$A_\mu \equiv t^a A_\mu^a$$

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

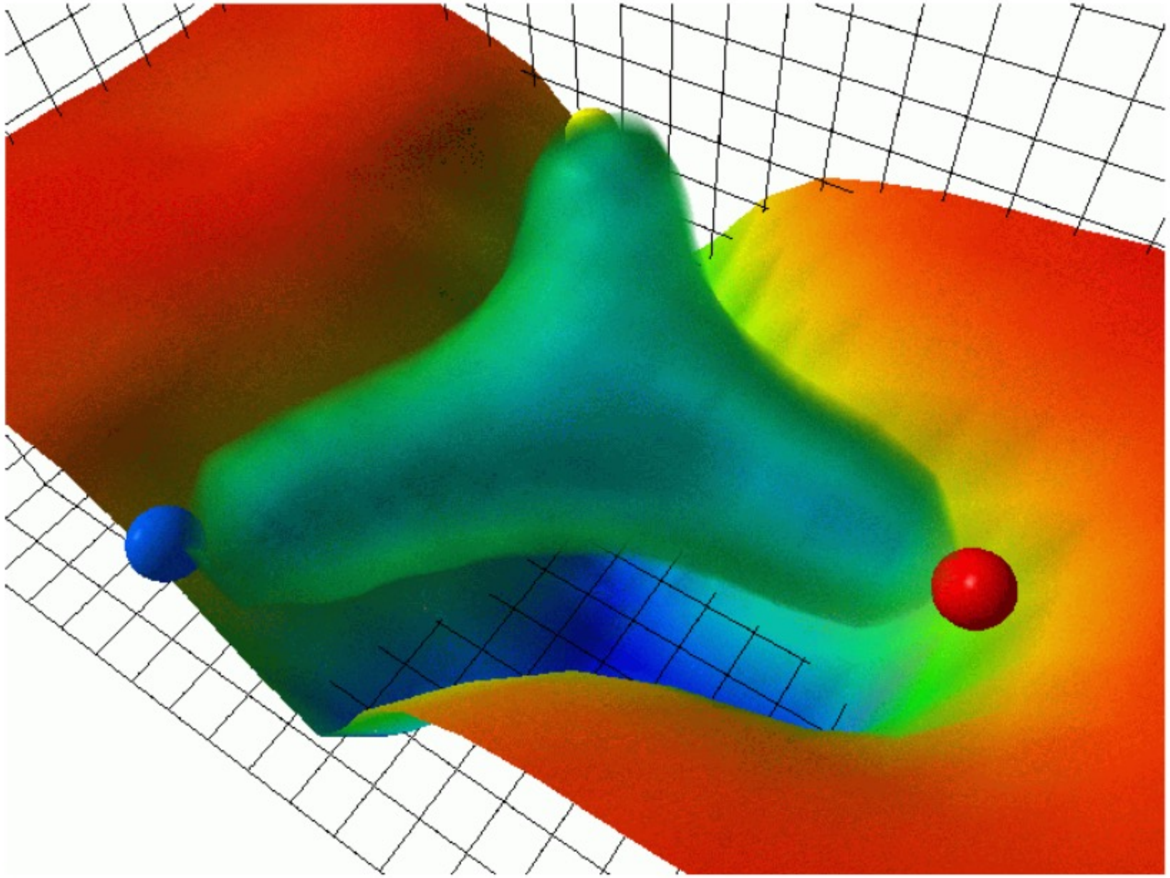
Baryon junctions





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

Baryon junctions

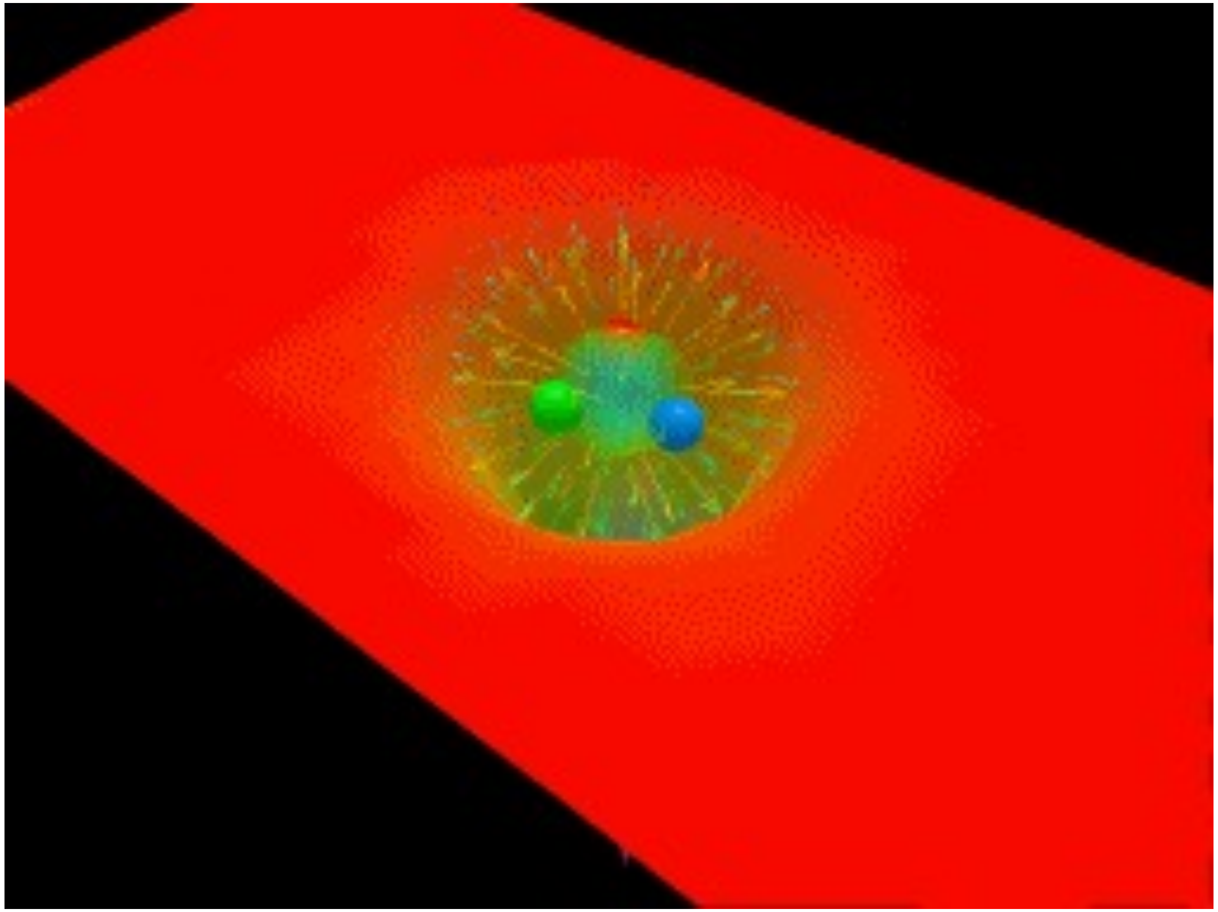


Gluon field distribution in baryons

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

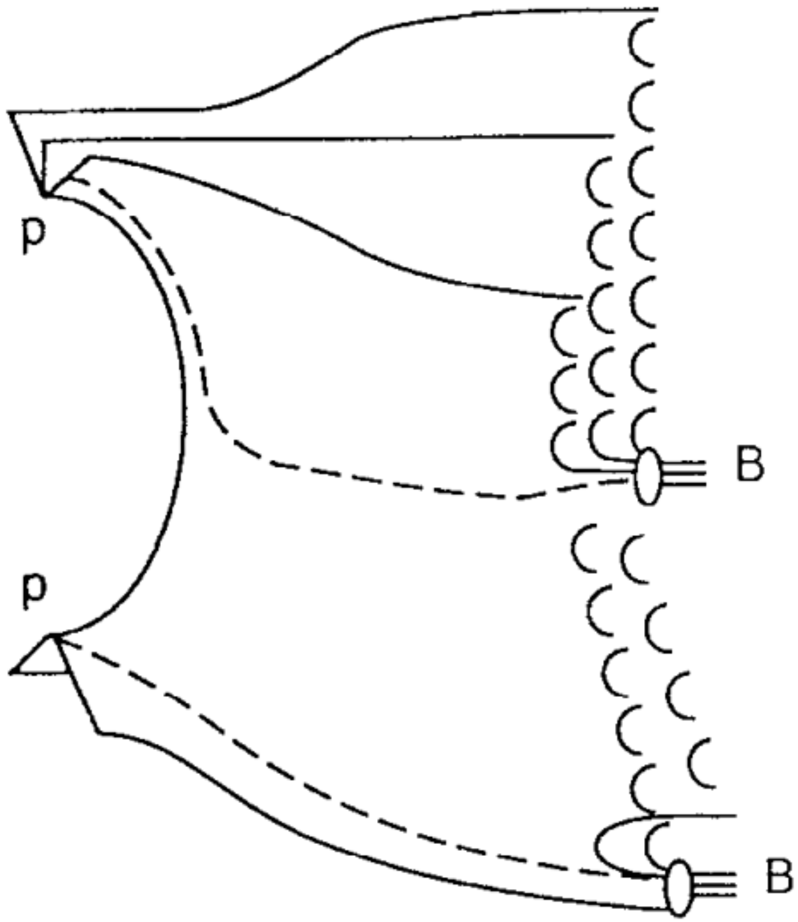
Can gluons trace baryon number?

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

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

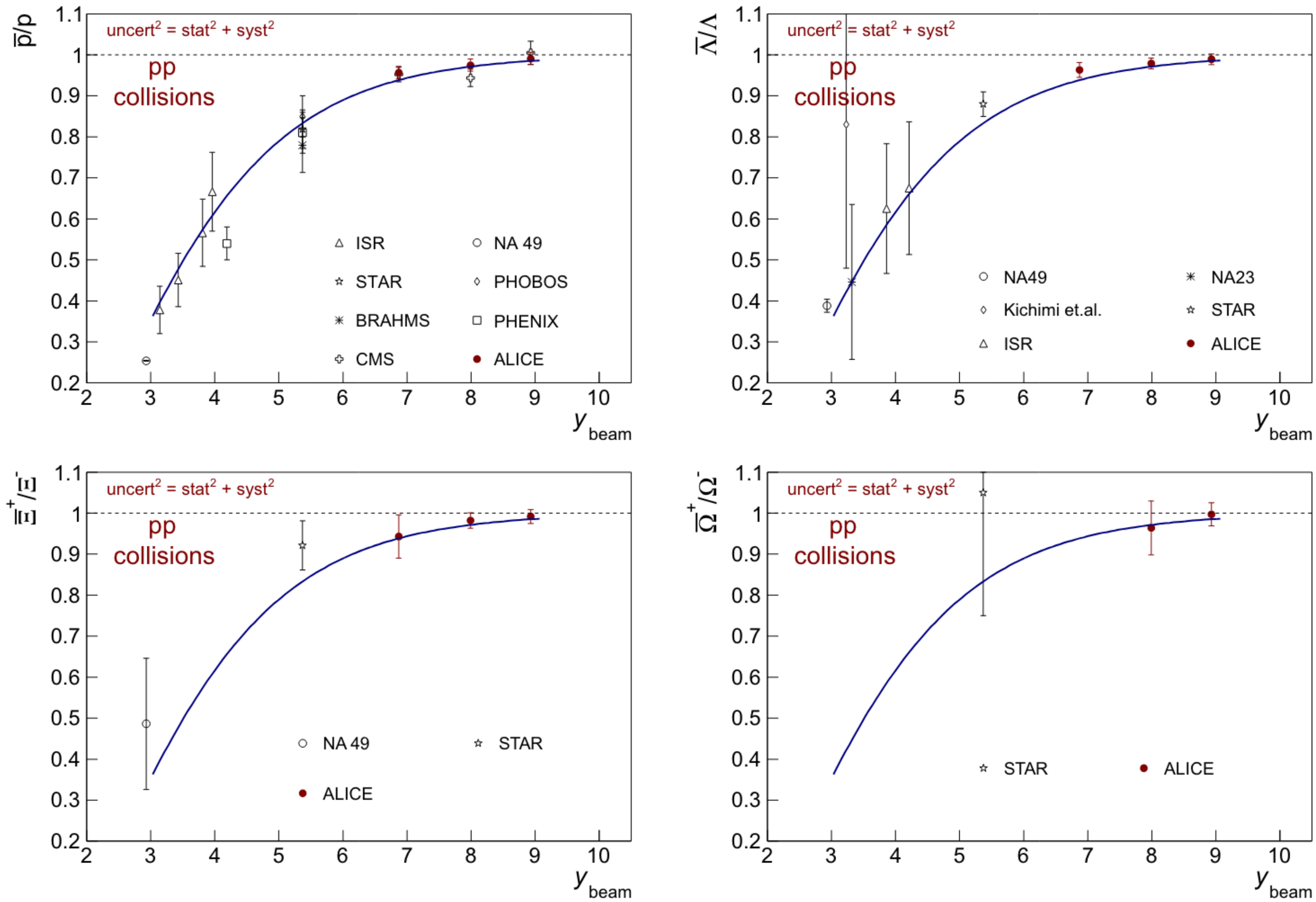
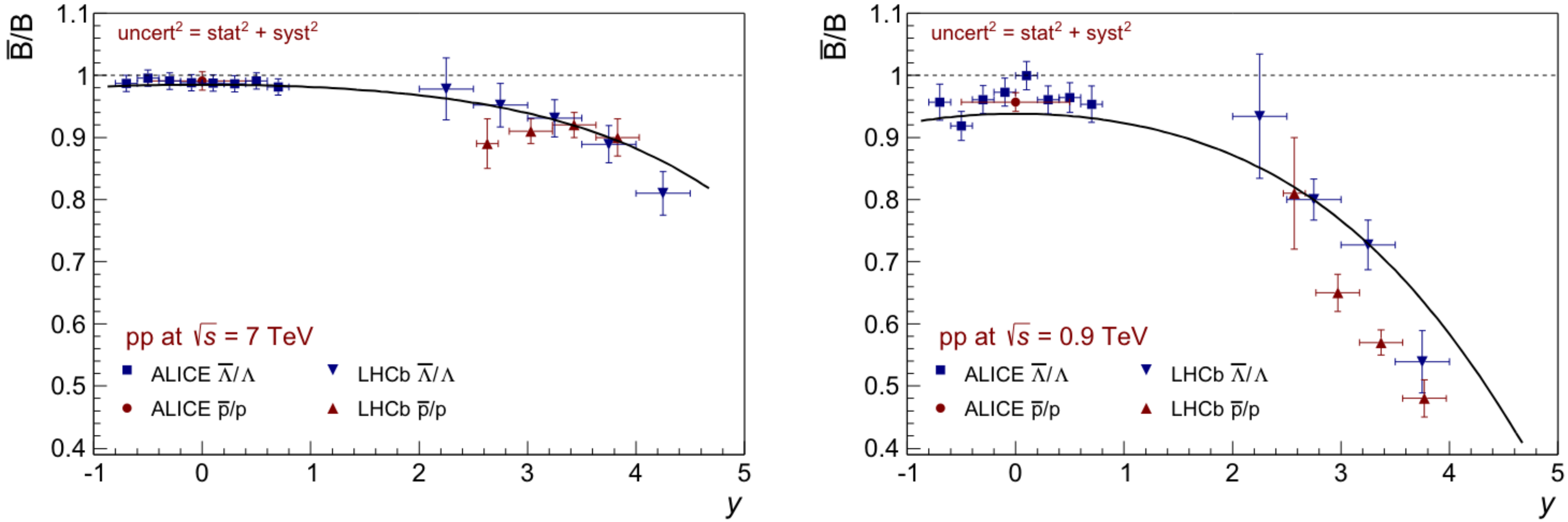


Fig. 16: (Colour online) Anti-baryon to baryon yields ratios as a function of beam rapidity for various baryons separately. The parametrisation with Eq. (4) (blue line) is shown. The red points show the ALICE measurements.



uncert² = stat² + syst²
B̄/B
pp at √s = 7 TeV
ALICE Λ̄/Λ
LHCb Λ̄/Λ
ALICE p̄/p
LHCb p̄/p
y
uncert² = stat² + syst²
B̄/B
pp at √s = 0.9 TeV
ALICE Λ̄/Λ
LHCb Λ̄/Λ
ALICE p̄/p
LHCb p̄/p
y

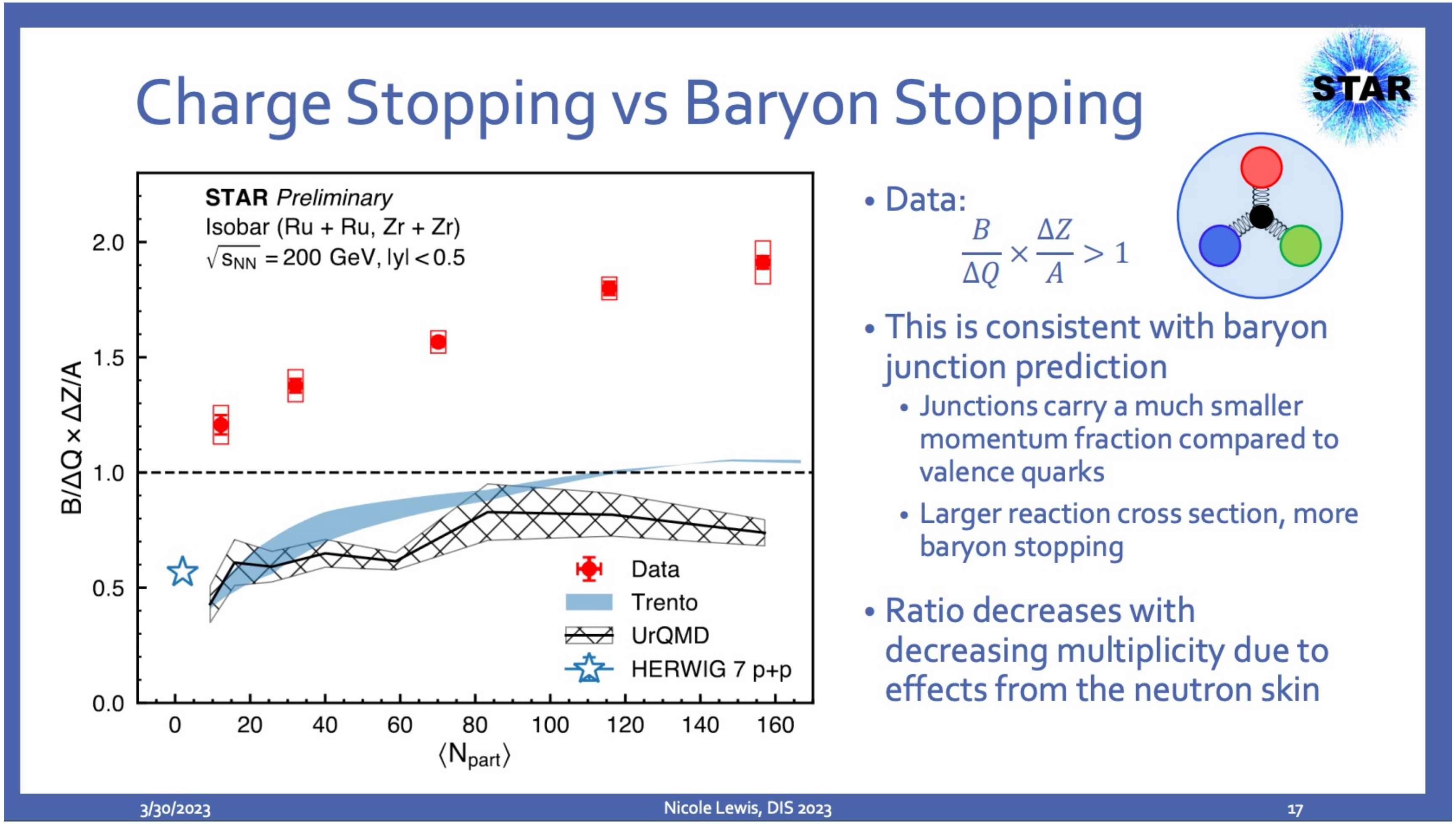
UNIVERSITY

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!



arXiv:2408.15441
(Science – to appear!)

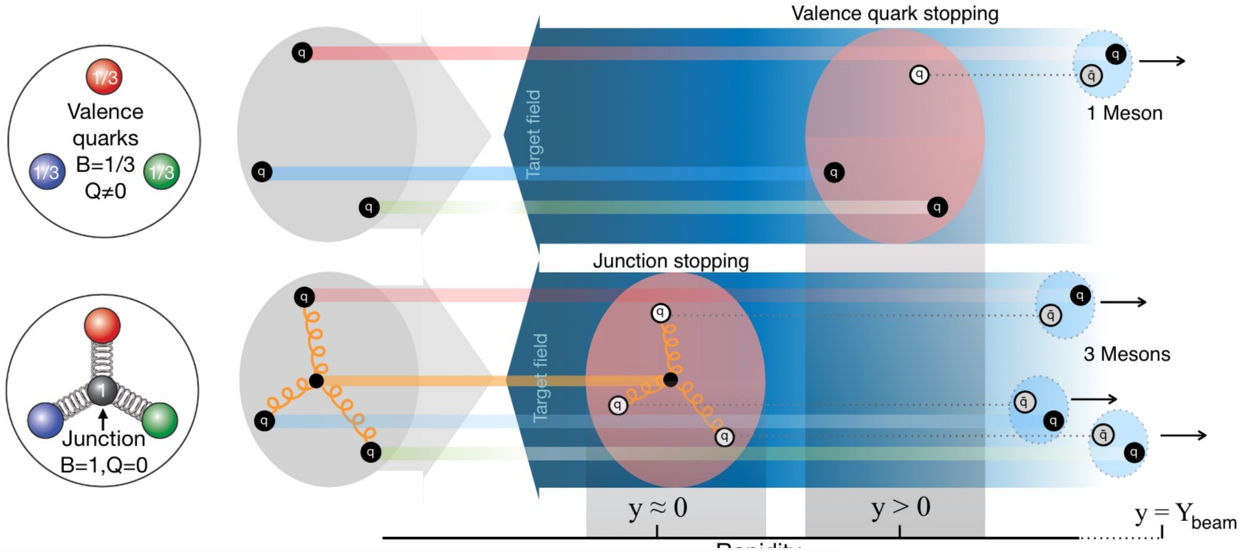
Tracking the baryon number with nuclear collisions

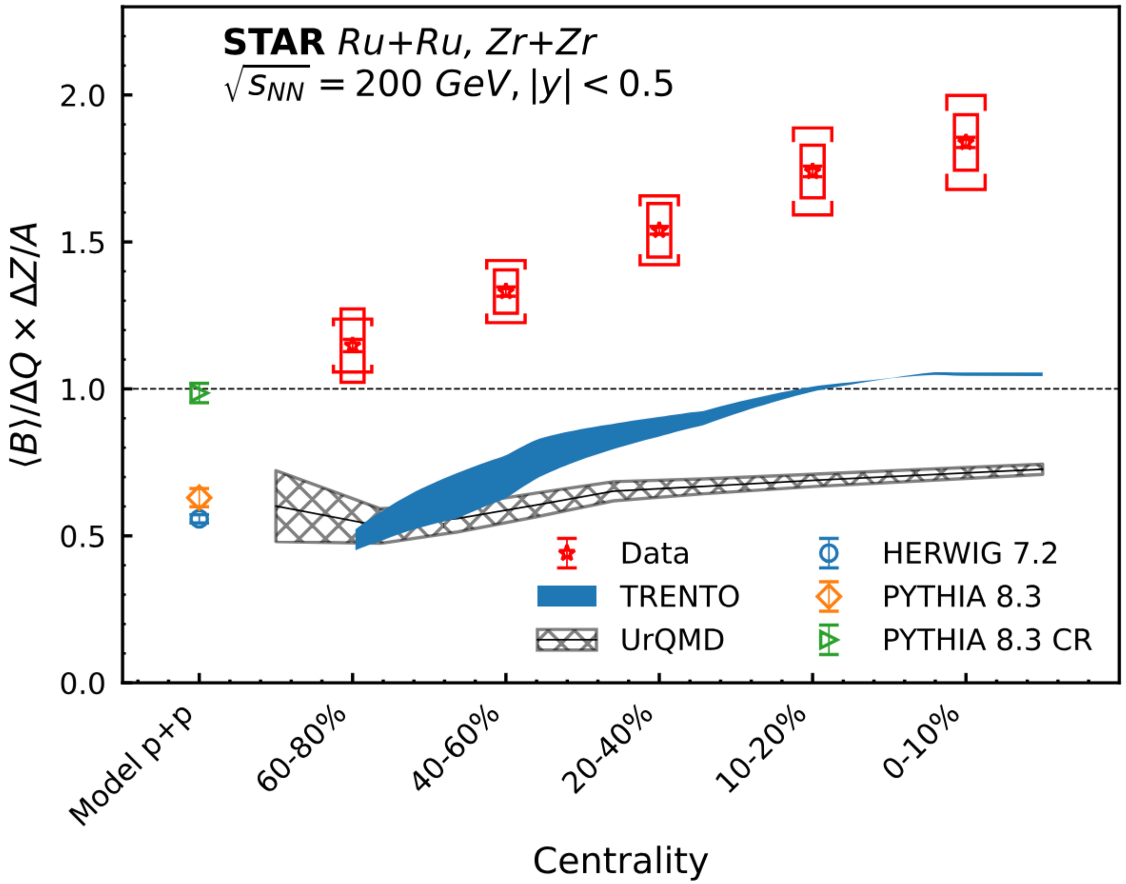
Short Title: Do quarks or gluons carry baryon number?

The STAR Collaboration

Baryon quantum number is believed to be conserved since baryogenesis in the early Universe. While fractionally charged valence quarks are understood conventionally to each carry a baryon number of 1/3, the baryon junction, a non-perturbative Y-shaped topology of neutral gluons, has also been proposed as an alternative entity tracing the baryon number. Neither scenario has been verified experimentally. The STAR Collaboration reports measurements at mid-rapidity of baryon number (B) over the electric charge number difference (ΔQ) in isobar nuclear collisions, and the net-proton yield along rapidity in photonuclear collisions. A larger $B/\Delta Q$ ratio and less asymmetric net-proton yield are observed than predicted from models assigning baryon number to valence quarks. These findings, corroborated by previous measurements in Au+Au collisions, disfavor the valence quark picture.

STAR, arXiv:2408.15441
(Science, to appear)

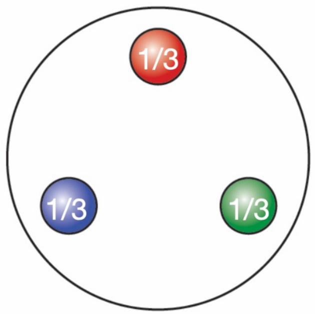




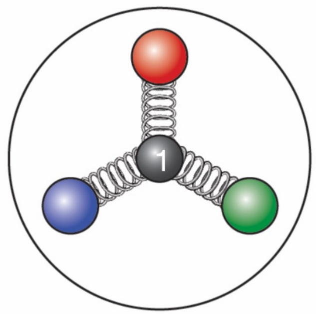
New precise data from RHIC and LHC support the existence of the baryon junction.
Motivation to revisit the problem of baryon stopping, and to derive a more precise result for the intercept.

1st Workshop on Baryon Dynamics

Jan 22 – 24, 2024
CFNS
America/New_York timezone



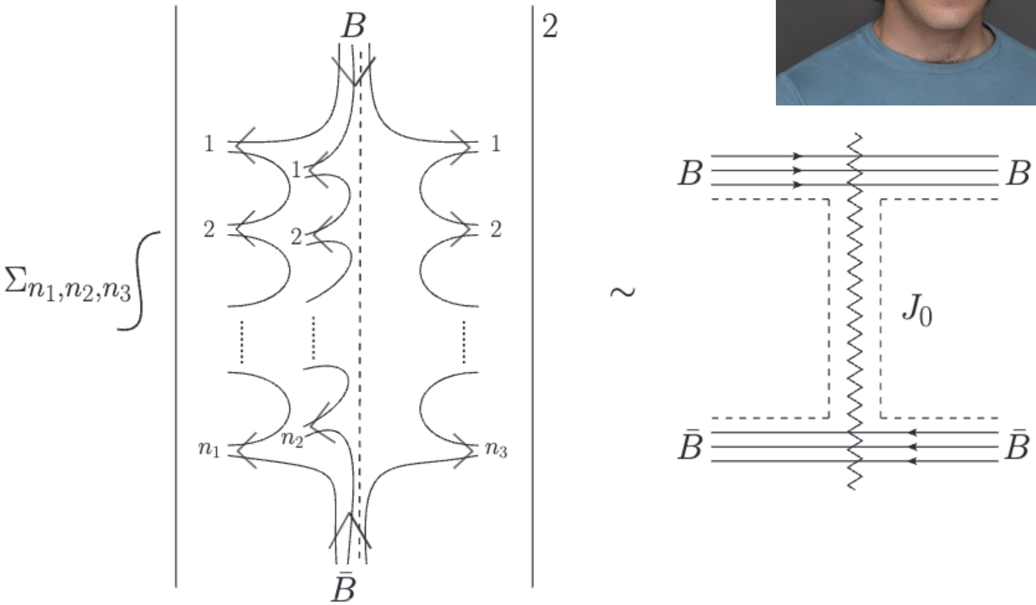
Valence quarks carry baryon number



Junctions carry baryon number

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

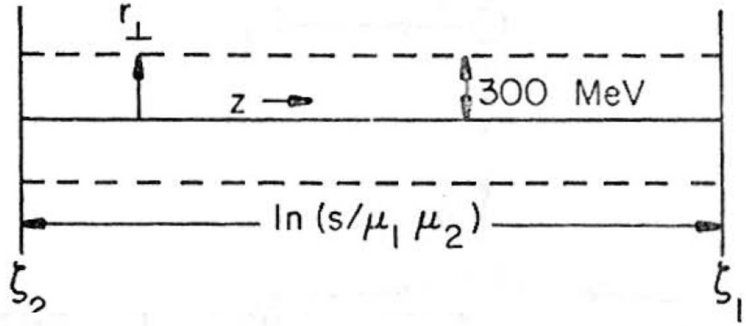
Feynman-Wilson gas

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.

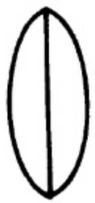
11. R. P. Feynman, private communication.

Feynman-Wilson gas

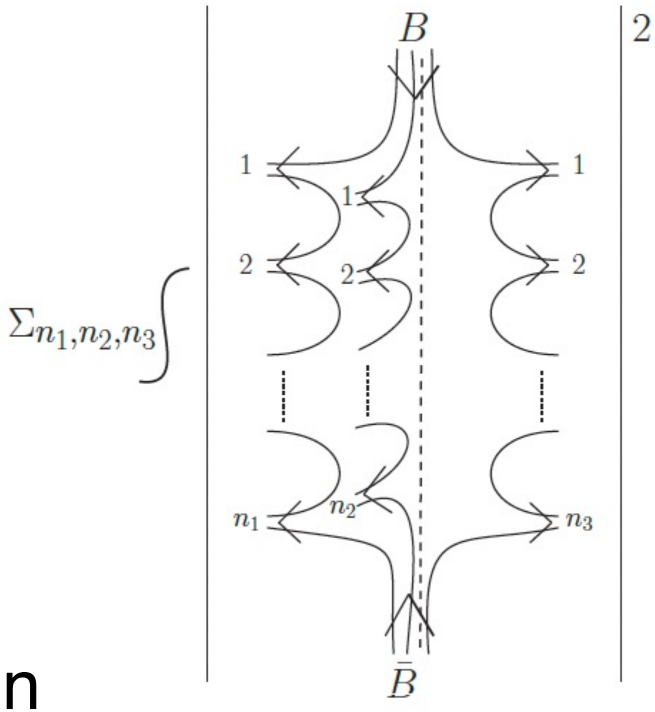
(1+1)d gas	High energy interactions
Volume	Total rapidity
Particle's coordinate	Rapidity of the produced hadron
Short-range particle correlations	Short-range rapidity correlations
Partition function	Generating function for cross sections
Fugacity	Parameter of the generating function

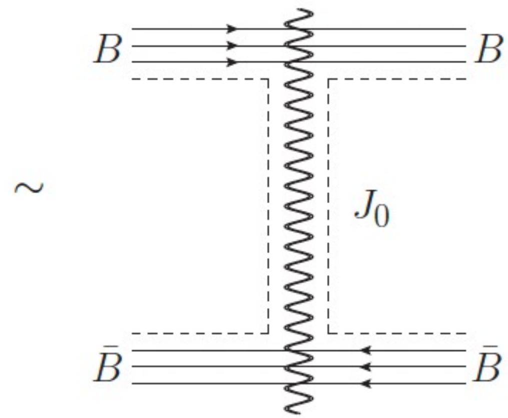
Feynman-Wilson gas with baryons

Consider baryon-antibaryon annihilation through the junction:



M_0^J





The cluster expansion

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

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

The junction-anti-junction intercept

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

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

↓

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

↓

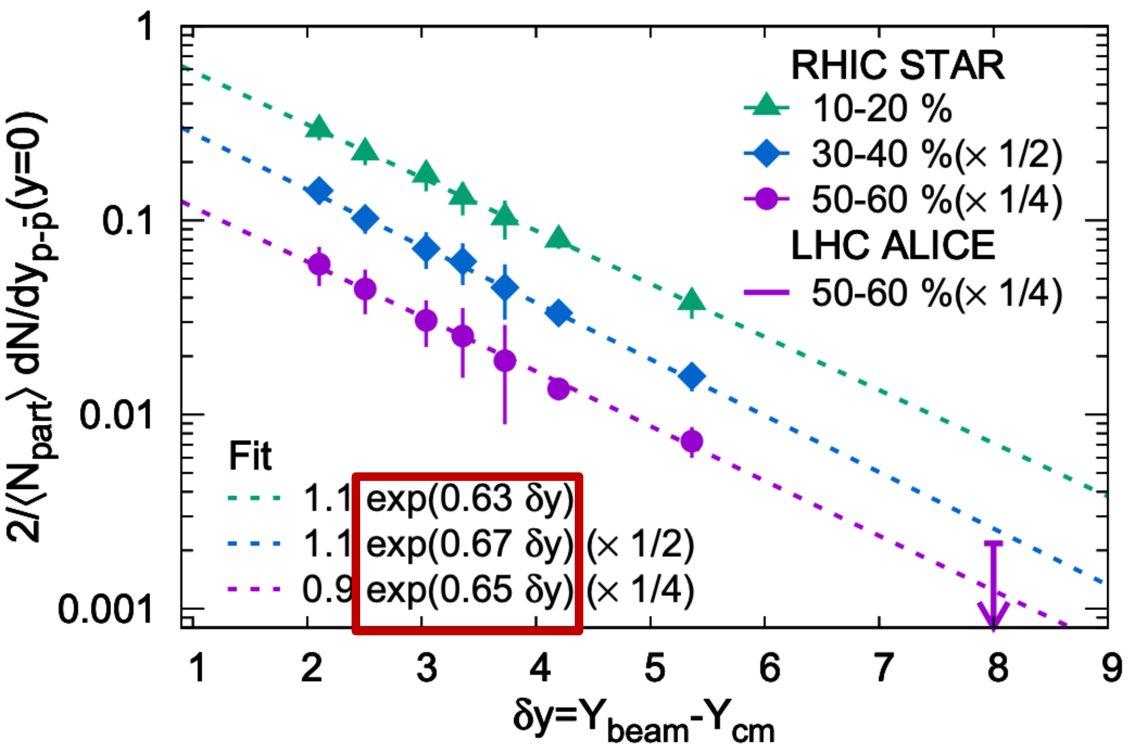
$$\text{beam rapidity dependence } e^{(\alpha_{\mathbb{J}_0} + \alpha_{\mathbb{P}} - 2)Y/2} = e^{-0.66\ Y/2}$$

D. Frenklakh, DK, G. Rossi, G. Veneziano, arXiv:2405.04569, JHEP(2024)

Feynman-Wilson gas
+ topological expansion of QCD

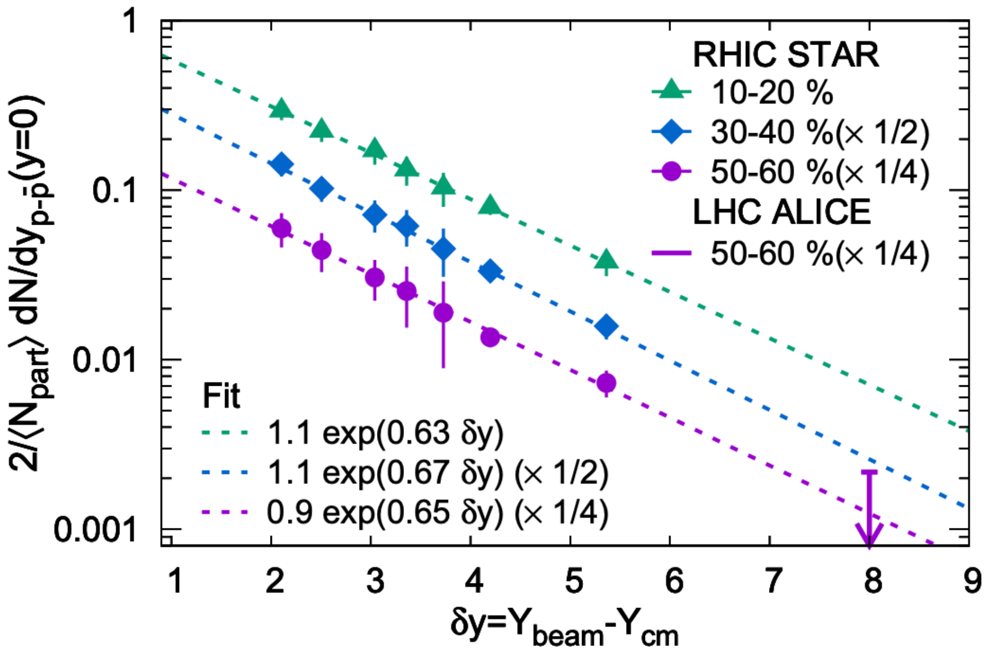
beam rapidity dependence $e^{(\alpha_{\mathbb{J}_0}+\alpha_{\mathbb{P}}-2)Y/2} = e^{-0.66\ Y/2}$

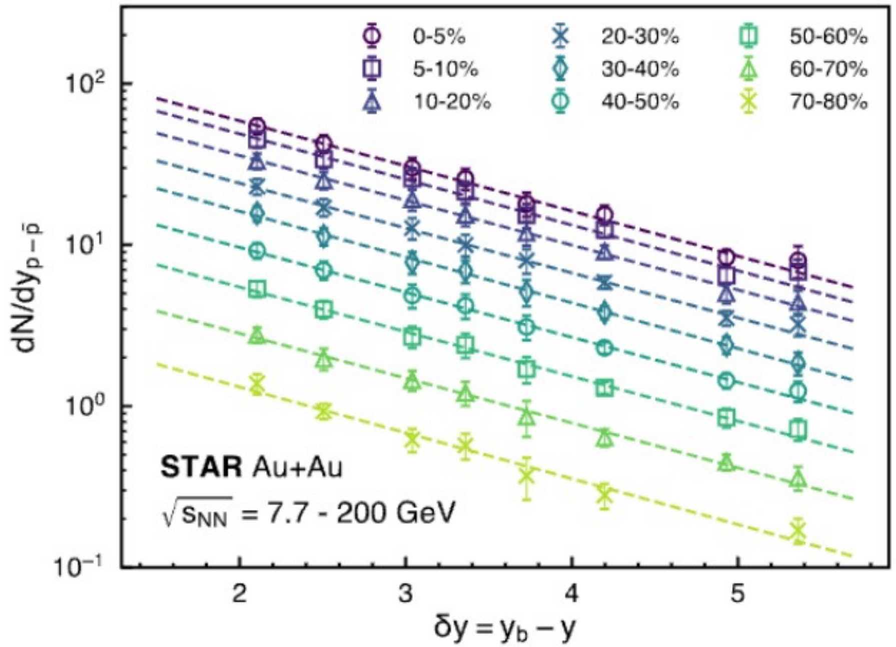
D. Frenklakh, DK, G. Rossi, G. Veneziano, arXiv:2405.04569, JHEP(2024)



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

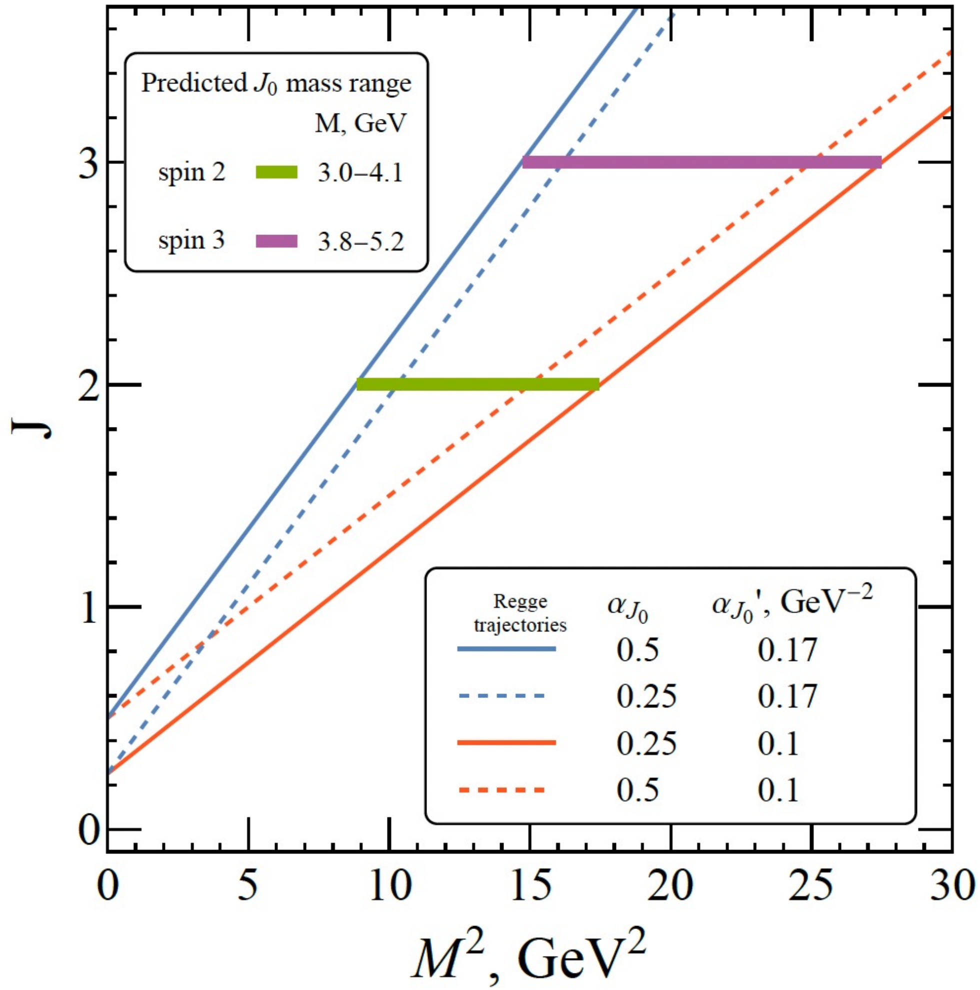
James Daniel Brandenburg,[1] *Nicole Lewis,*[1,*] *Prithwish Tribedy,*[1] *and Zhangbu Xu*[1]
[1]*Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
(Dated: August 25, 2022)





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

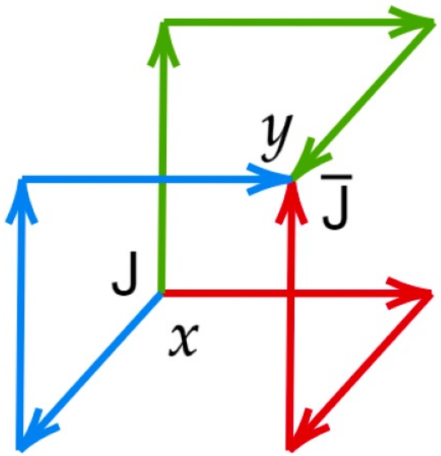


D. Frenklakh, DK, G. Rossi, G. Veneziano, arXiv:2405.04569, JHEP(2024)

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:



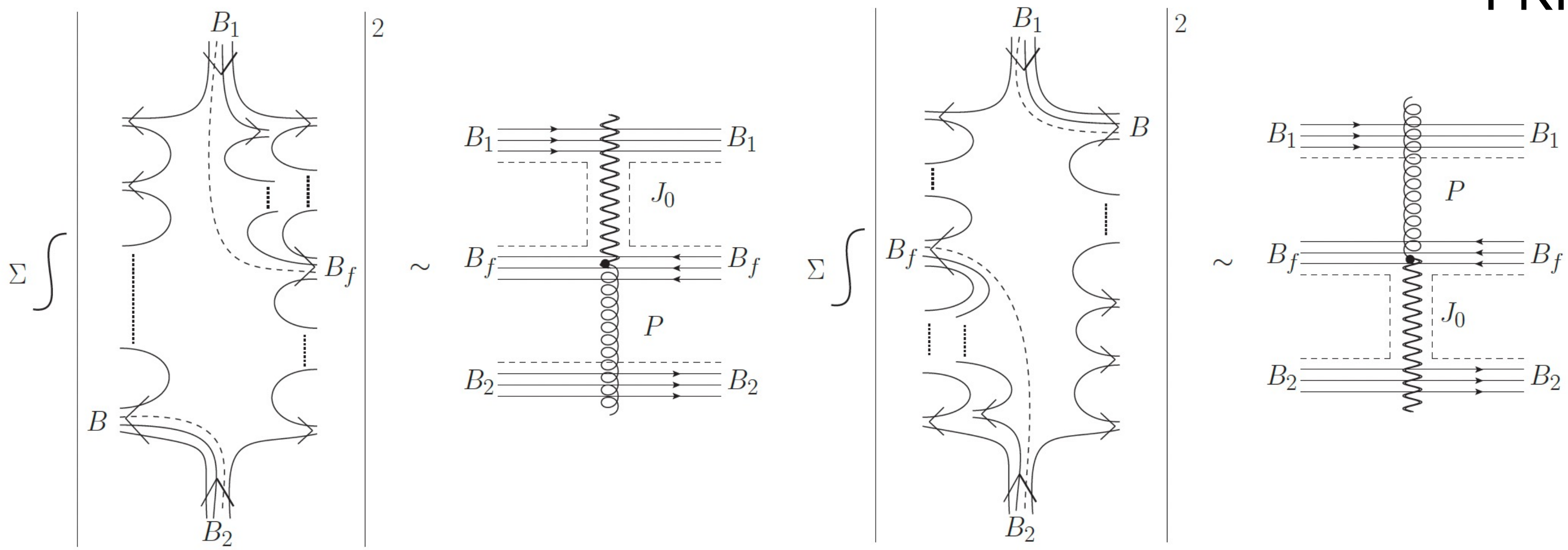
D. Frenklakh, DK, G. Rossi, G. Veneziano, arXiv:2405.04569

Future tests at RHIC, LHC, EIC

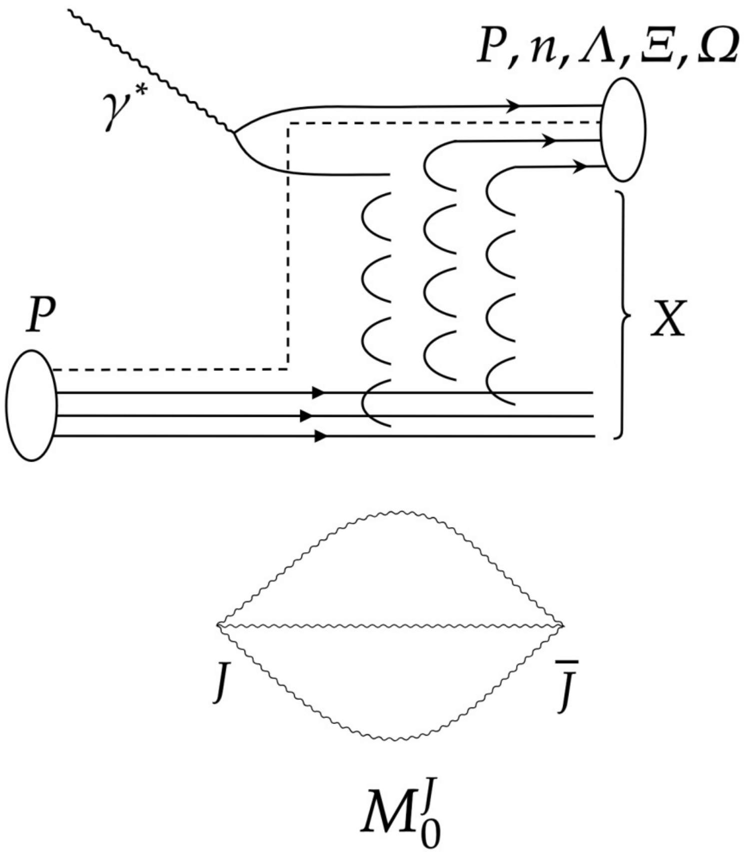
Baryon number distribution

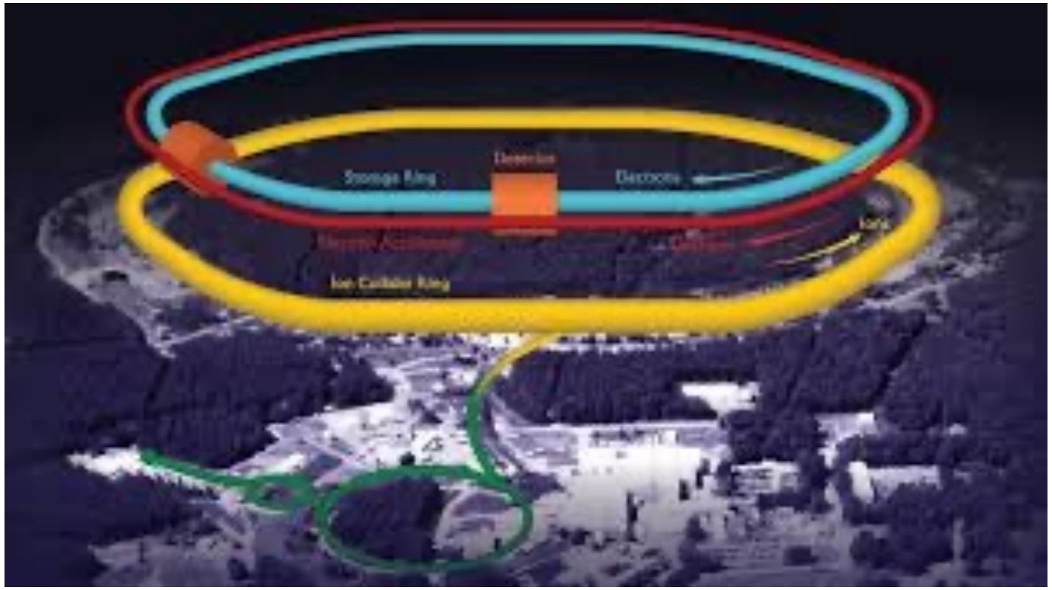
$$\frac{dN}{dy_f} \propto e^{(\alpha_{\mathbb{J}_0}+\alpha_{\mathbb{P}}-2)Y/2}[e^{(\alpha_{\mathbb{P}}-\alpha_{\mathbb{J}_0})y_f}+e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{P}})y_f}],$$

DK, 1996
FKRV 2024



Baryon junctions at EIC





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

Summary

1. The problem of gluon and quark radii of the nucleon is deeply connected to anomalies and symmetries of QCD.

2. It is likely that the scalar gluon radius of the nucleon is smaller than its quark (charge) radius.

3. The gauge invariance of QCD implies that the baryon number of the nucleon is carried by the gluon configuration. The corresponding radius should be even smaller.

4. All of this can be explored at the current and future experimental facilities (RHIC, JLab, LHC, EIC).

Summary

$$R_{BN} < R_{glue} < R_{quark}$$