Workshop Report: Baryon Junction & Stopping

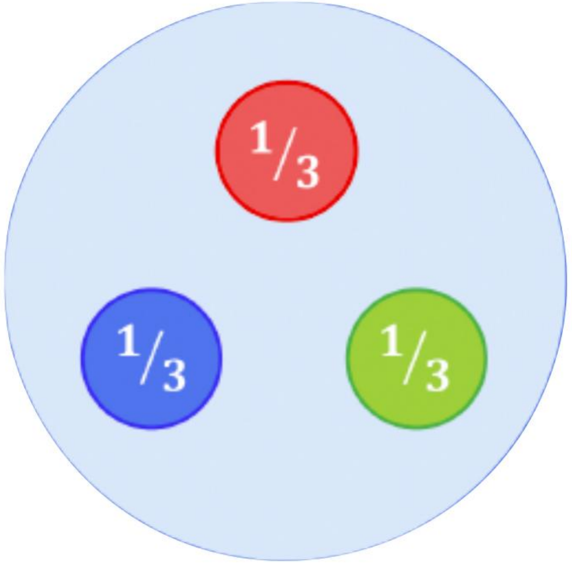
2026 RHIC/AGS Users' meeting

Chun Yuen Tsang (ANL) and Prithwish Tribedy

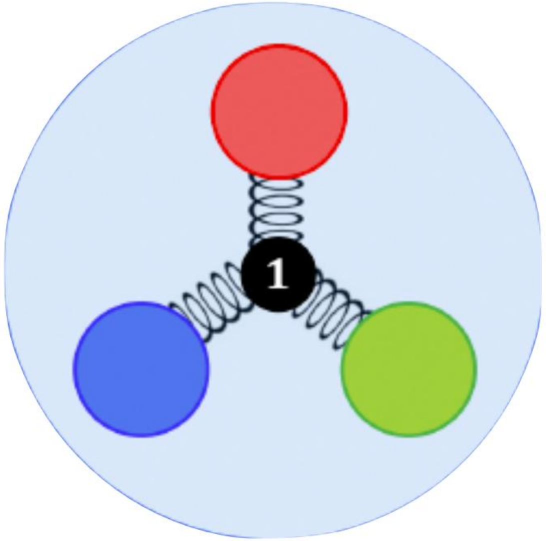
May 13, 2026

What carries baryon number, valence quark vs. baryon junction?

Naïve quark picture



Baryon junction picture [1, 2]



[1]: Nucl. Phys. B 85, 442–460 (1975).
[2]: Nucl. Phys. B 123, 507–545 (1977)

7 talks in the Baryon Junction Section

Mon 11/05

09:00

Current status of the baryon junction
Dmitri Kharzeev et al.
09:00 - 10:00

10:00

Generalized parton distributions and their implications for observables relevant to baryon junction dynamics
Simonetta Liuti
10:00 - 10:30

11:00

Probing gluon density via deep inelastic scattering, an its implications on baryon junctions
Prithwish Tribedy

Flavor-independent rapidity slope in baryon transport
Zhangbu Xu et al.
11:30 - 12:00

14:00

Measuring baryon production at HERA, and its potential on baryon junctio
Gage Tustin

Probing the Baryon Junction at the CLAS12 Experiment *Wenliang Li*
14:30 - 15:00

15:00

Finding the baryon number within the proton *Spencer Klein*
15:00 - 15:30

History of baryon junction: Gauge invariant baryon operator

Dmitri Kharzeev

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

Baryon-number – flavor separation in high energy collisions

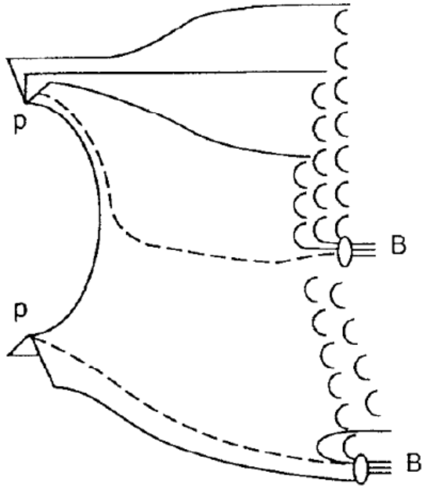
Physics Letters B 378 (1996) 238–246

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

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



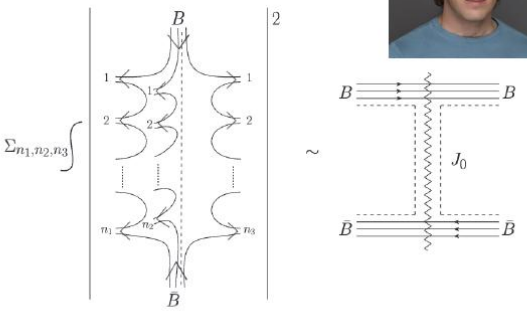
- The only way to construct a gauge-invariant baryon operator involves products of exponentials of path integrals of the gluon potential, all connecting to a common central point.
- D. Kharzeev then showed that such a topological configuration carries baryon number.

Theoretical considerations that give rise to baryon junction

Dmitri Kharzeev

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

Baryons junctions and duality

A POSSIBLE DESCRIPTION OF BARYON DYNAMICS IN DUAL AND GAUGE THEORIES

G.C. Rossi*)

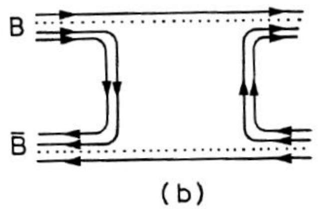
and

G. Veneziano**)

CERN - Geneva

1977

No annihilation:



The junction-anti-junction intercept

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

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

⬇

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

⬇

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

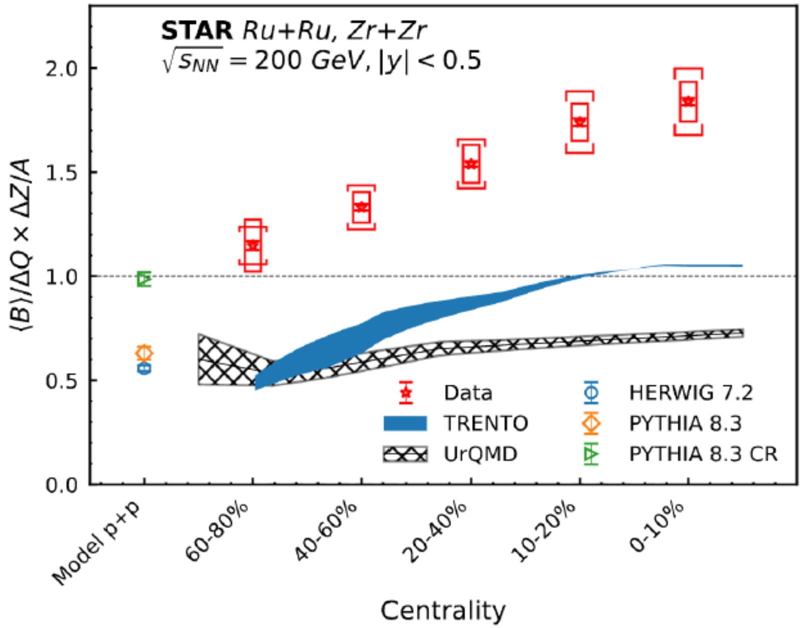
54

- Difficulty in the duality of t- and u-channels for baryons implies that baryon number is carried by a separate entity.
- Derived cross-section dependence using an analogy between high-energy interactions and a classical gas.

Current evidence for baryon junction transport

STAR Collaboration, arXiv:2408.15441;
Science, to appear

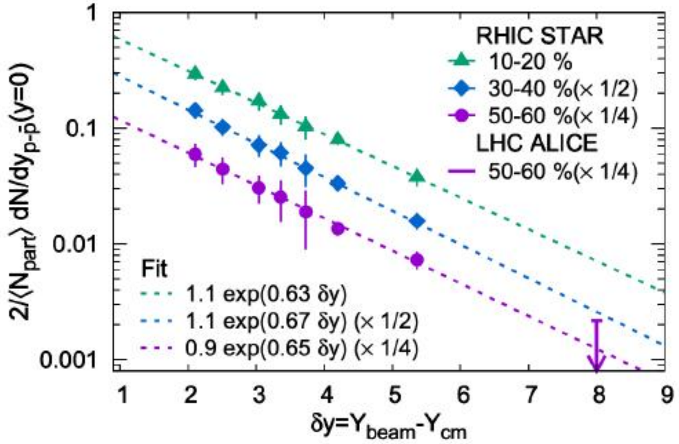
Dmitri Kharzeev

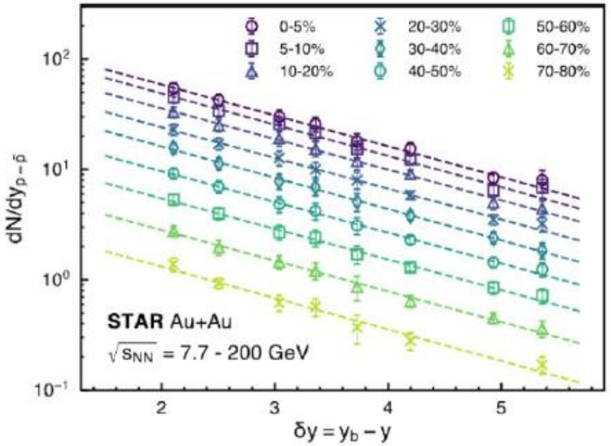


Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

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)



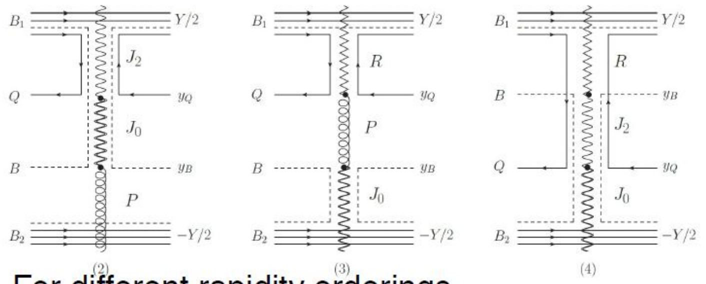


- Net-baryon/Net-charge difference between isobars at mid-rapidity: baryon and electric charge transport are decoupled.
- Net-proton vs rapidity difference between beam and fragment: Consistent with predictions of baryon junction stopping from Regge theory.

Future tests for Baryon Junction

Dmitri Kharzeev

Combined Baryon-number-charge distribution:



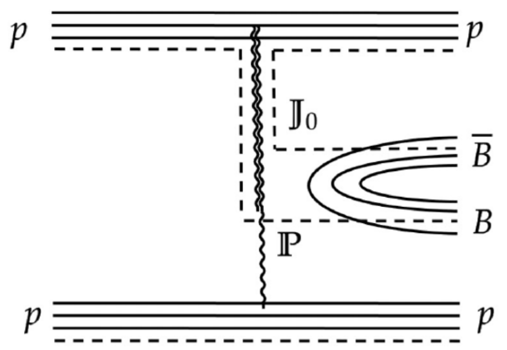
For different rapidity orderings

$$F^{(1)}_{(B,Q)} \propto e^{(\alpha_{\mathbb{P}}+\alpha_{\mathbb{J}_2}-2)\frac{Y}{2}}\ e^{(\alpha_R-\alpha_{\mathbb{J}_2})y_B}\ e^{(\alpha_{\mathbb{P}}-\alpha_R)y_Q}\ ,$$
$$F^{(2)}_{(B,Q)} \propto e^{(\alpha_{\mathbb{P}}+\alpha_{\mathbb{J}_2}-2)\frac{Y}{2}}\ e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{J}_2})y_Q}\ e^{(\alpha_{\mathbb{P}}-\alpha_{\mathbb{J}_0})y_B}\ ,$$
$$F^{(3)}_{(B,Q)} \propto e^{(\alpha_R+\alpha_{\mathbb{J}_0}-2)\frac{Y}{2}}\ e^{(\alpha_{\mathbb{P}}-\alpha_R)y_Q}\ e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{P}})y_B}\ ,$$
$$F^{(4)}_{(B,Q)} \propto e^{(\alpha_R+\alpha_{\mathbb{J}_0}-2)\frac{Y}{2}}\ e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{J}_2})y_Q}\ e^{(\alpha_{\mathbb{J}_2}-\alpha_R)y_B}\ .$$

61

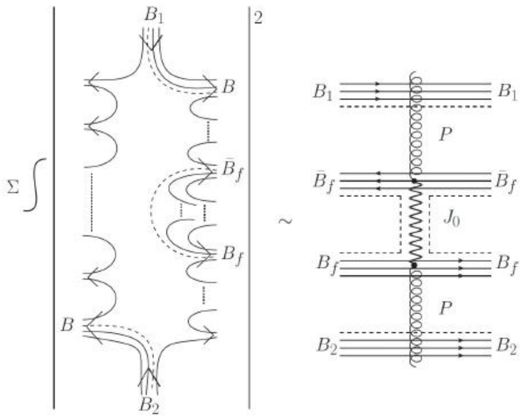
Future tests at RHIC and LHC

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



63

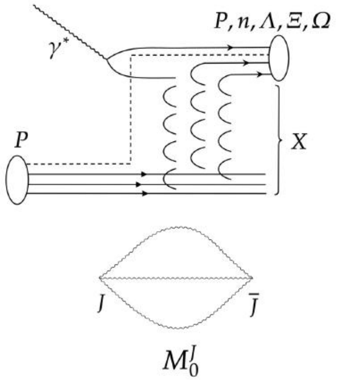
Baryon-antibaryon correlations in rapidity:

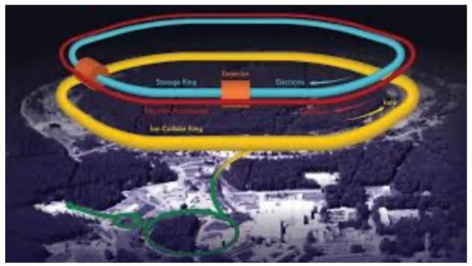


$$\rho_{B,\bar{B}}(\Delta y) \sim e^{-|\Delta y|(\alpha_{\mathbb{P}}-\alpha_{\mathbb{J}_0})}$$

62

Baryon junctions at EIC





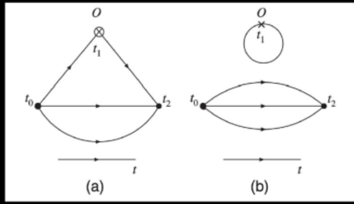
64

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

Generalized Parton Distributions, disconnected sea quarks, and baryon junction phenomenology

Simonetta Liuti

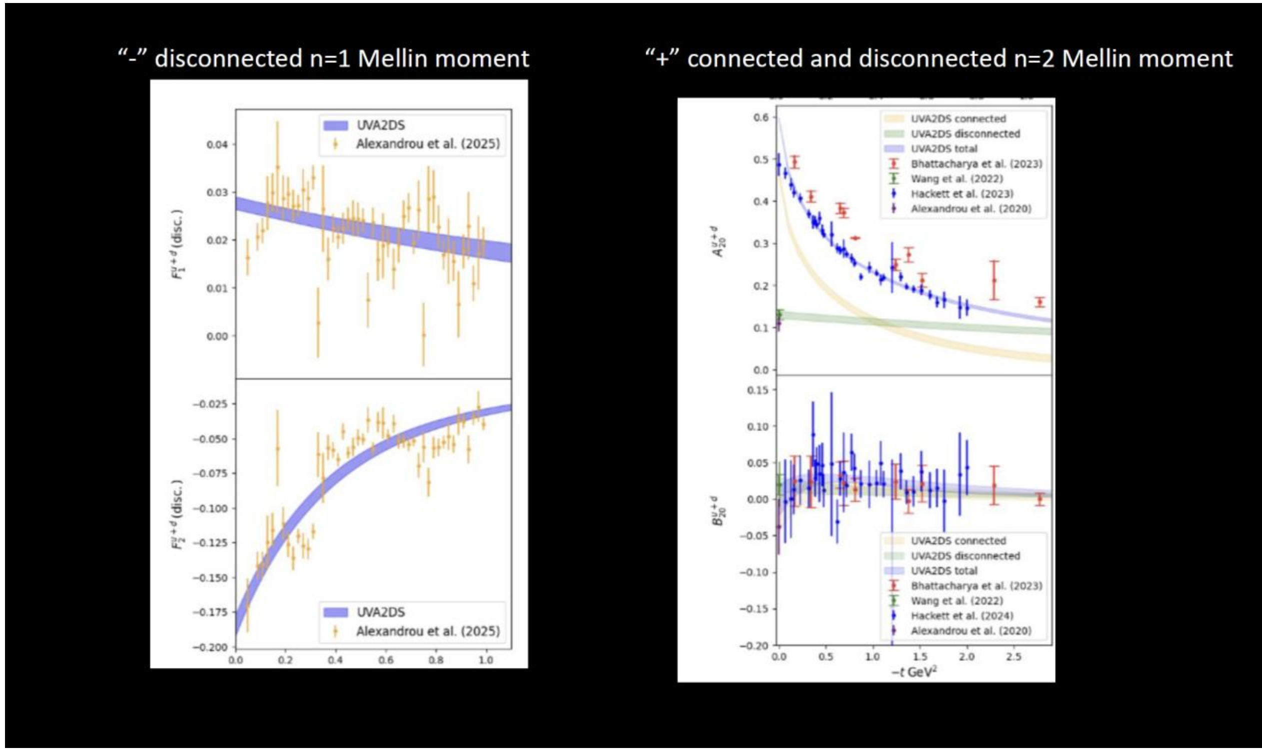
Including connected and disconnected contributions in GPD phenomenology



$$F_1^q(t) = A_{10}^q(t) = \int_{-1}^{1} dx H_q(x,\xi,t),$$
$$F_2^q(t) = B_{10}^q(t) = \int_{-1}^{1} dx E_q(x,\xi,t)$$

$$F_1^q(t) = F_1^{q,C} + F_1^{q,D} = \int_{-1}^{1} dx\, H_q^C + \int_{-1}^{1} dx\, H_q^D$$

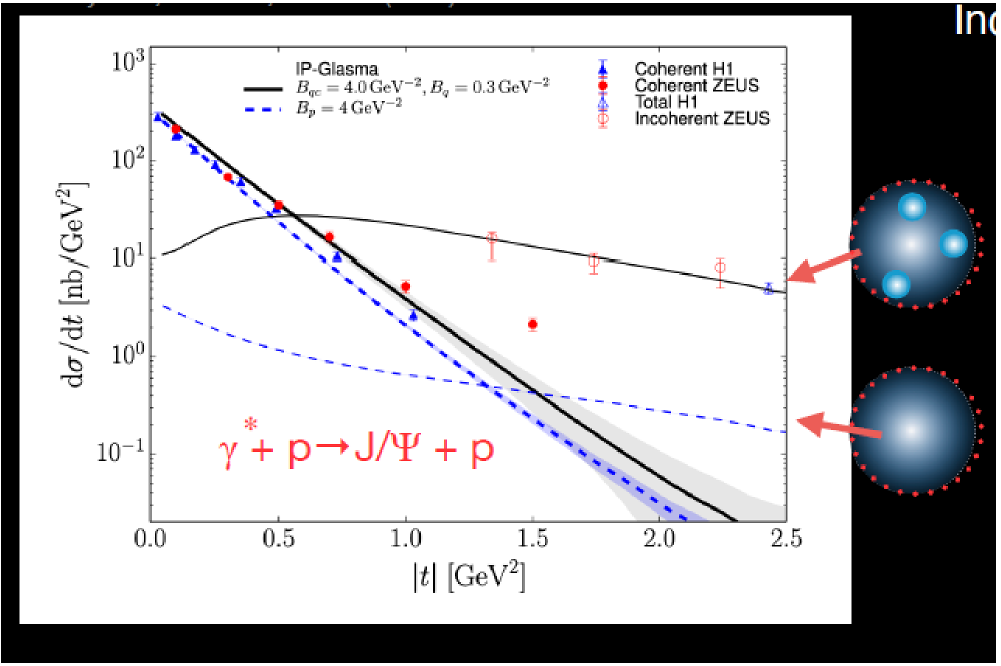
$$H_q^C = \frac{1}{2}(H_{q_v} + H_{q_{sea}}^C) = \frac{1}{2}(H_q^{-,C} + H_q^{+,C})$$
$$H_q^D = \frac{1}{2}(H_q^{-,D} + H_q^{+,D}).$$

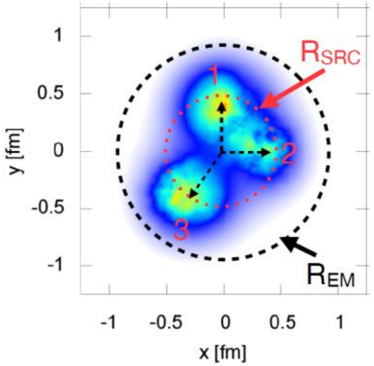


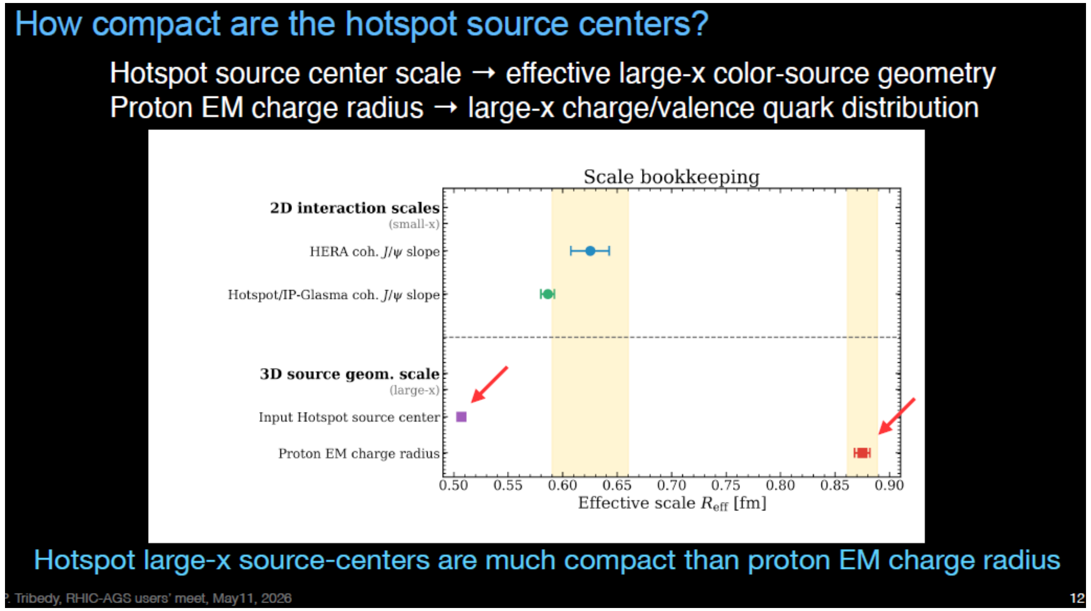
- First quantitative study of the impact of disconnected contributions to the parton distribution functions.
- Junction carries baryon number. Provide sea quarks input for recombination into mid-rapidity baryons.

Phenomenological model inspired by baryon junction

Prithwish Tribedy



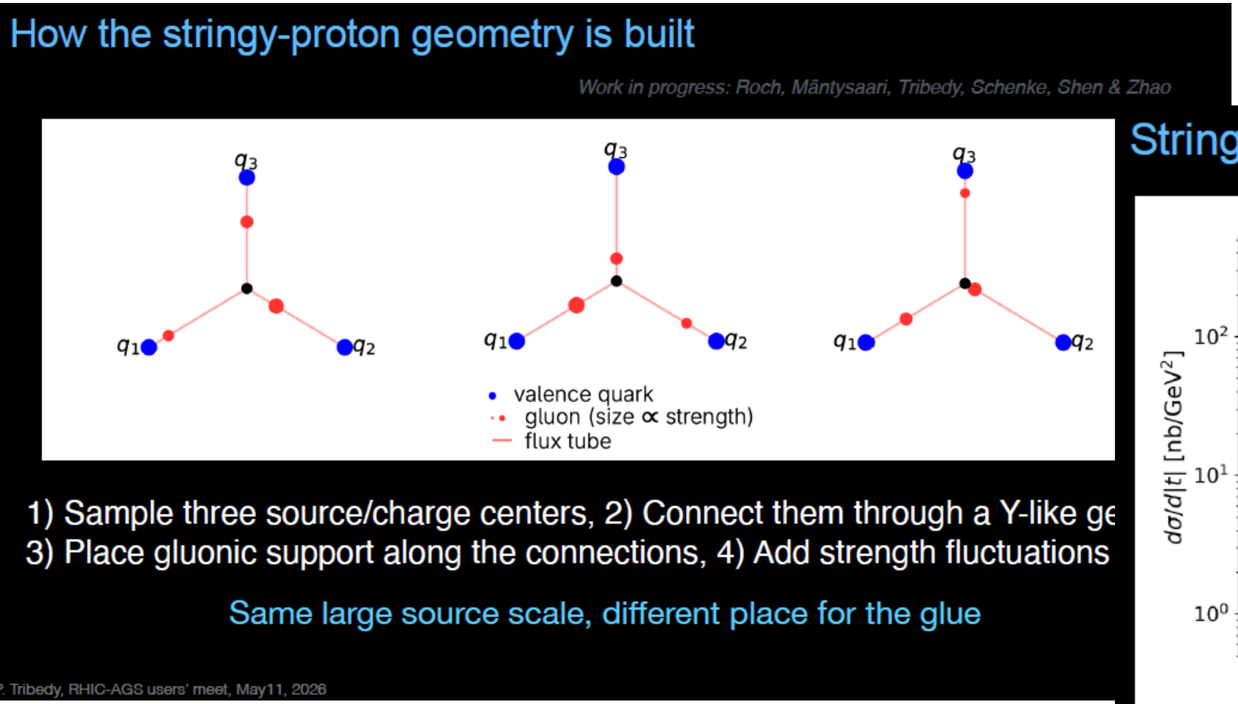


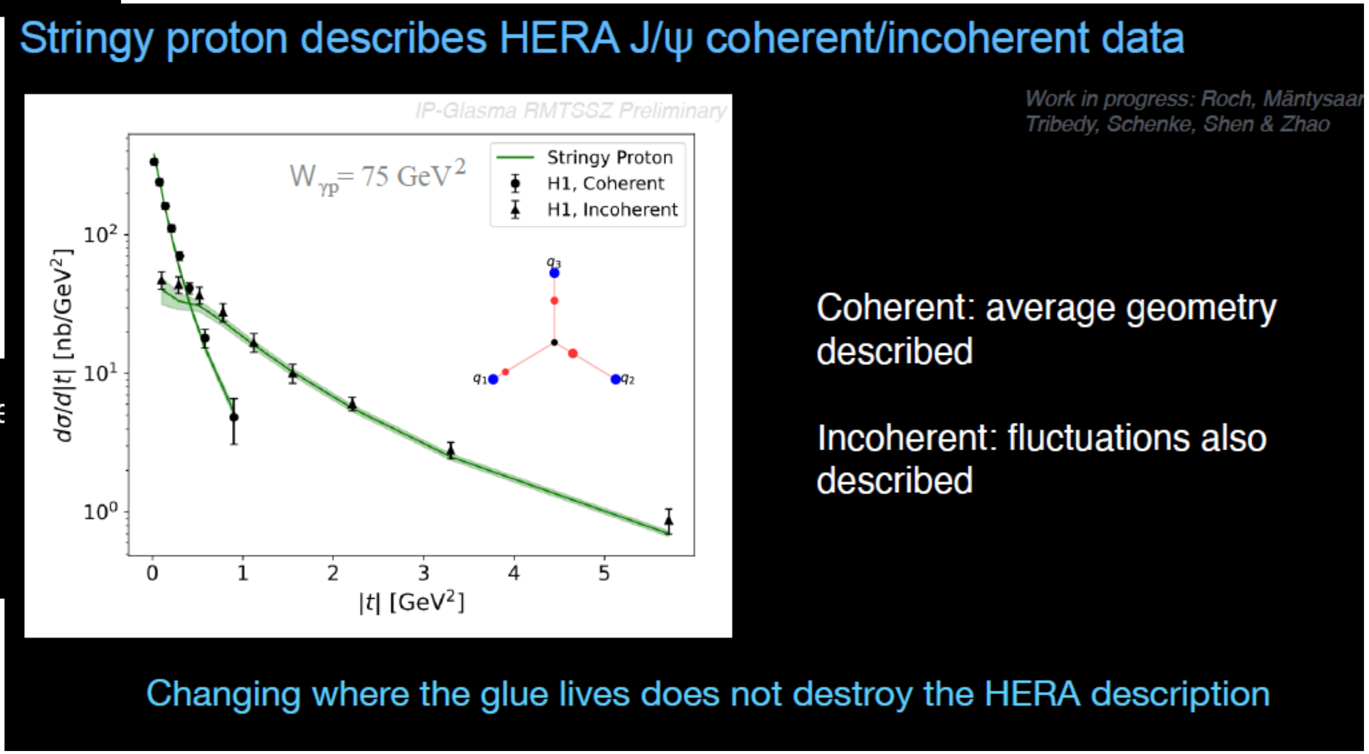


- Cross-section data of coherent small x γ+p interactions agree with the hotspot model: color source density peaks at three points.
- Problem: Effective size of the same model at large-x << proton radius?

Phenomenological model inspired by baryon junction (cont.)

Prithwish Tribedy

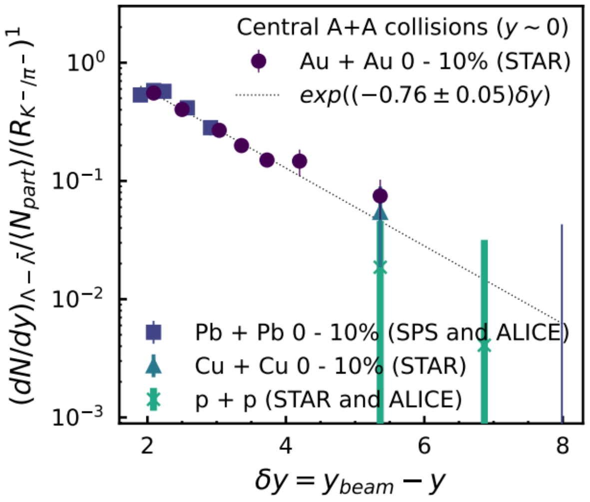


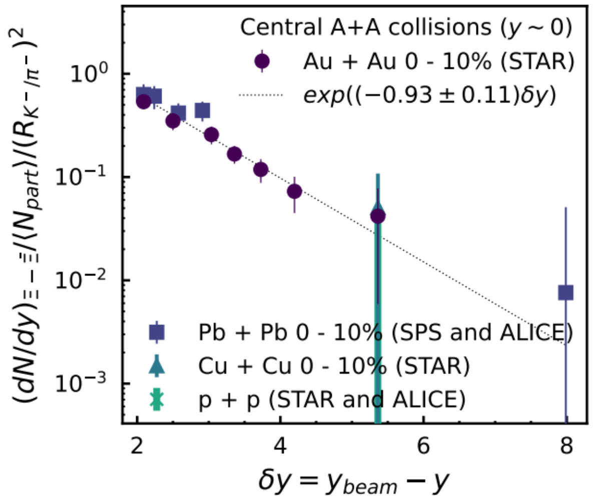


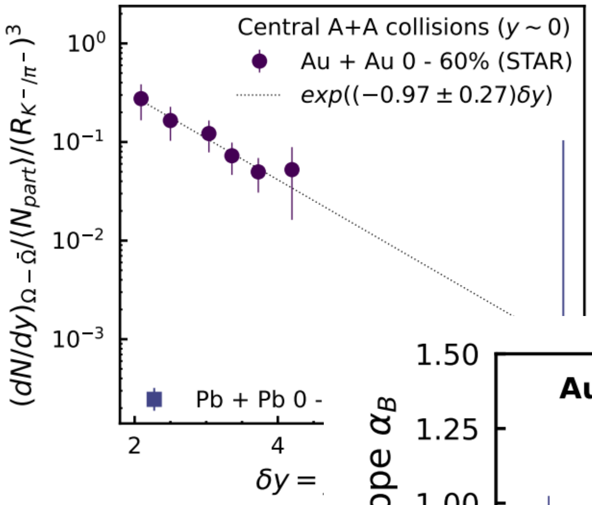
- Stringy proton model: Color sources are distributed along the three lines of the Y-shape.
- This model describes both large and small x data.

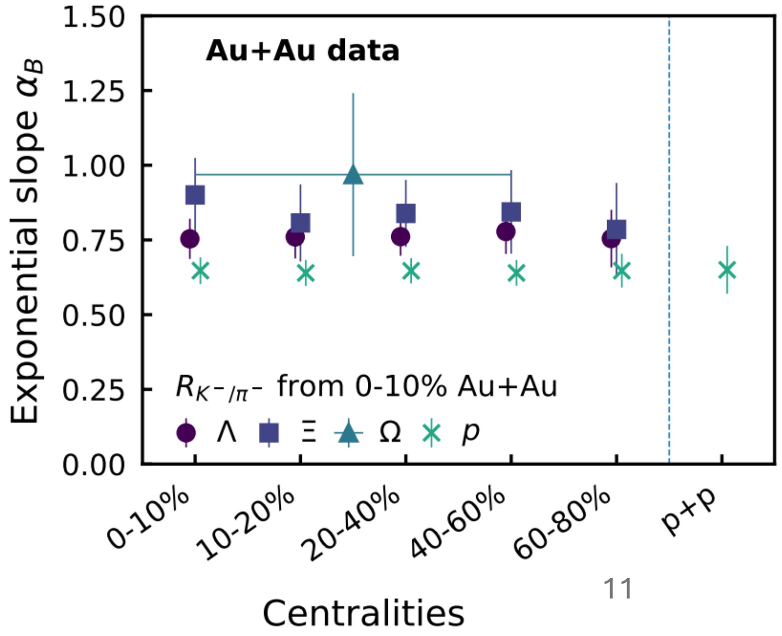
Another test of junction picture: Flavor independent

Zhangbu Xu









- Net-Λ, net-Ξ and net-Ω yields (after correcting for s-quark production rate) follows an exponential dependence on rapidity.
- Exponential slopes are consistent with each other and net-proton.
- Baryon stopping is independent of quark flavor: Consistent with the baryon junction picture.

Another test of junction picture: Flavor independent (Cont.)

Zhangbu Xu

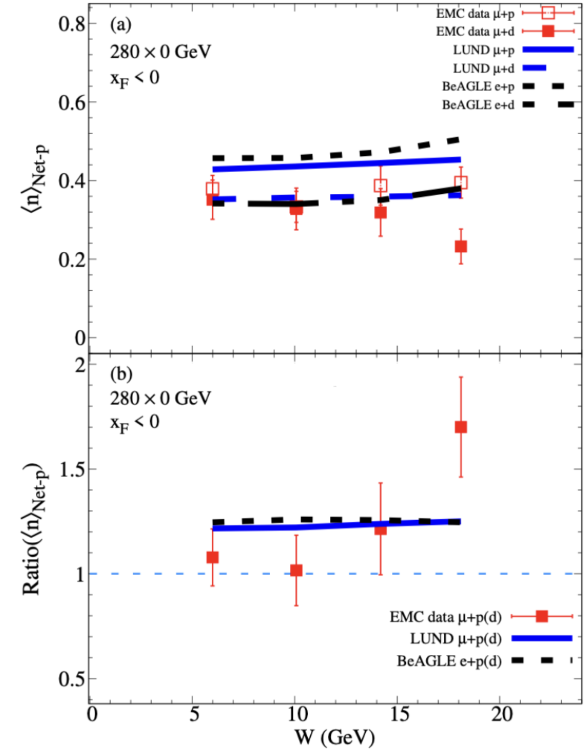
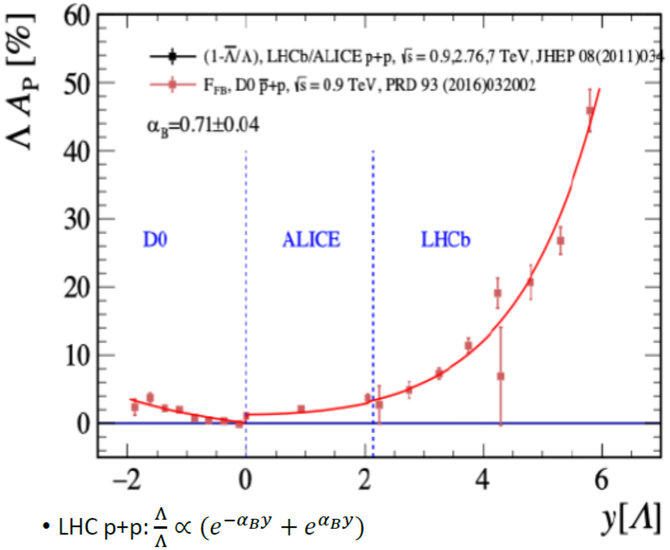


FIG. 7. The W dependence of the net-proton for μ+p and μ+d at 280-GeV muon on fixed targets are shown in panel (a). The ratios between μ+p and μ+d are presented in panel (b). Data and LUND model calculations are extracted from Ref. [15].

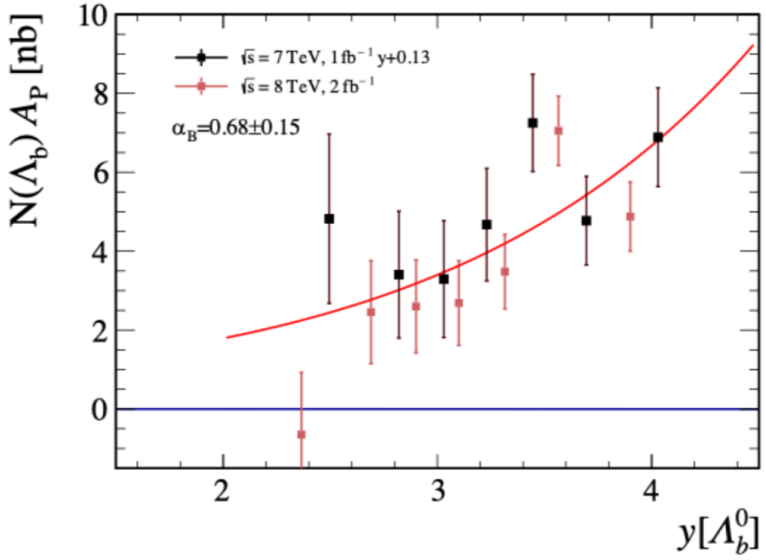
Combined ALICE/LHCb/D0 $\bar{\Lambda}/\Lambda$



- LHC p+p: $\frac{\bar{\Lambda}}{\Lambda} \propto (e^{-\alpha_B y} + e^{\alpha_B y})$
- Tevatron $\bar{p}$+p: $\frac{\bar{\Lambda}}{\Lambda} \propto (e^{-\alpha_B y} - e^{\alpha_B y})$

LHCb Λ_b

Anantha Nair (KSU)
Existing high-statistic data at 13TeV



- Measured net-proton yield of e+p and e+deuteron are consistent at $x_F < 0$: Contradicting the Lund model!
- Exponential slope of net-Λ and Λ_b from various experiments agree with that from STAR.
- Conclusion: Baryon stopping is independent of quark flavor.

Another source of data: HERA

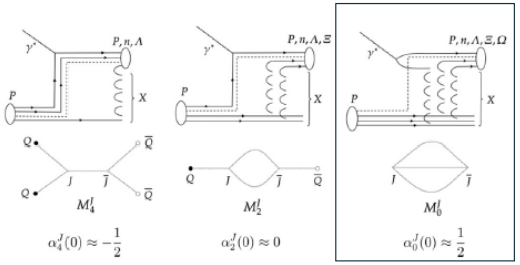
Baryon Junction Motivation

- **David Frenklakh and Dmitri Kharzeev gave us a quick calculation based on their gluon junction framework in this publication and estimate a baryon asymmetry in DIS of 0.03±0.02 within the accessible kinematic range at HERA**
  - Based on a 3→3 Forward scattering in Regge Theory framework
  - Regge intercept for purely gluonic junction exchange cannot be calculated from first principles, but they estimated it from the Au-Au RHIC Beam Energy Scan data, hence the large uncertainty
- Not a precise estimate but gives us a ballpark expectation

Signatures of baryon junctions in semi-inclusive deep inelastic scattering

David Frenklakh, Dmitri E. Kharzeev, Wenliang Li

https://doi.org/10.1016/j.physletb.2024.138680



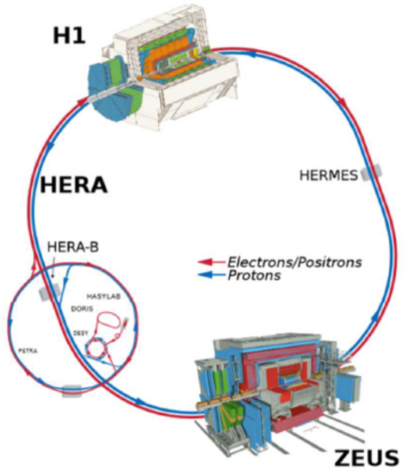
Purely gluonic exchange

7

Gage Tustin

HERA

- The only high energy *ep* collider accelerator ever operated
- Ran from 1992-2007 at DESY in Hamburg, Germany with nominal electron/positron energy of 27.6 GeV and proton energy of 920GeV ($\sqrt{s}$ = 319 GeV)
- Serviced four experiments
  - Hermes: Fixed target with electron beam
  - HERA-B: Fixed target with proton beam
  - ZEUS: General purpose hermetic detector
  - H1: General purpose hermetic detector
- **Delivered ~1 fb^{-1} of total integrated luminosity to H1/ZEUS, perfect starting point to get a head start on what baryon junction signatures in EIC may look like**



Hadron-Electron Ring Accelerator (HERA) complex, figure from [1]

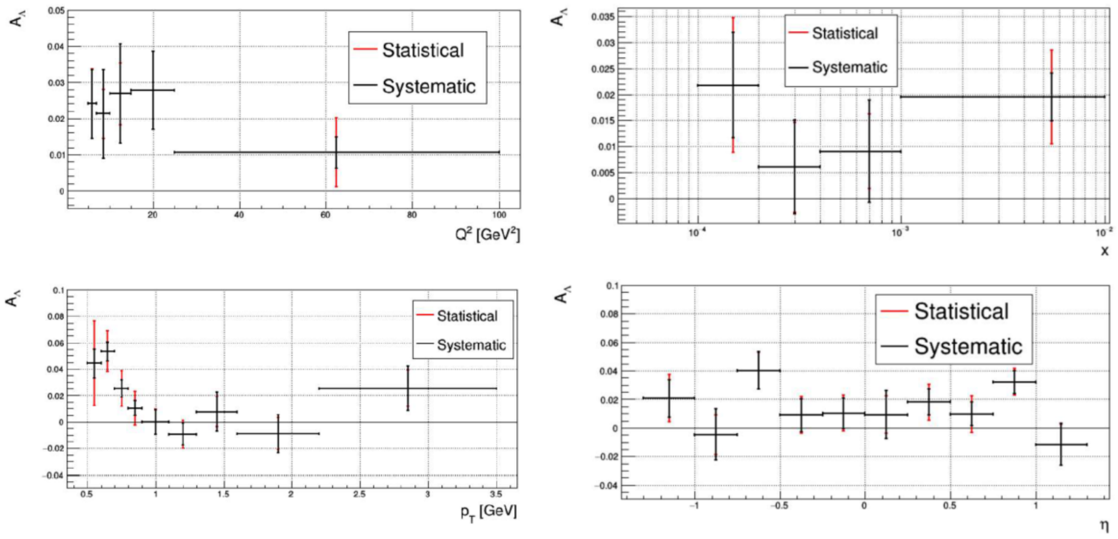
8

- HERA: e+p data at high beam energy.
- Net-Λ can be reconstructed: complement aforementioned flavor independent test on baryon stopping.

Another source of data: HERA

Gage Tustin

Asymmetry Distributions



24

- Λ - $\bar{\Lambda}$ Asymmetry defined as this ratio of cross sections, many factors cancel out

$$A_\Lambda = \frac{\sigma_{vis}(ep \to e'\Lambda X) - \sigma_{vis}(ep \to e'\bar{\Lambda} X)}{\sigma_{vis}(ep \to e'\Lambda X) + \sigma_{vis}(ep \to e'\bar{\Lambda} X)} = \frac{\frac{N_\Lambda}{\epsilon_{rec,\Lambda}} - \frac{N_{\bar{\Lambda}}}{\epsilon_{rec,\bar{\Lambda}}}}{\frac{N_\Lambda}{\epsilon_{rec,\Lambda}} + \frac{N_{\bar{\Lambda}}}{\epsilon_{rec,\bar{\Lambda}}}}$$

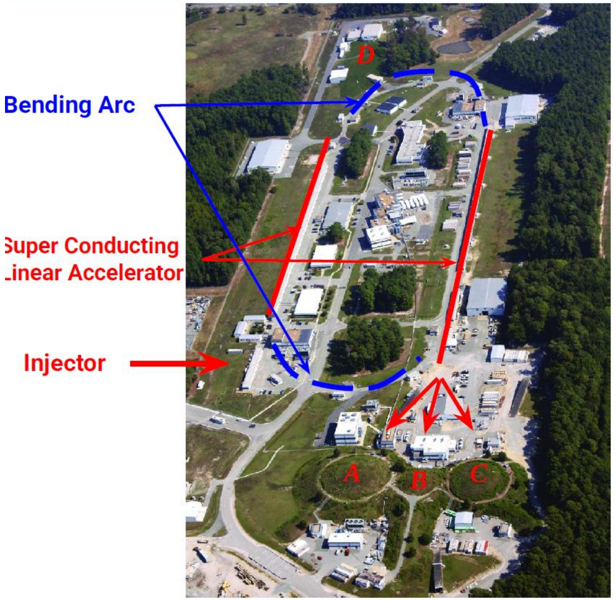
22

- Data analysis in progress. Preliminary results show non-zero net-Λ.
- Efficiency correction TBD.

Proposal to use CLAS12 experiment for baryon junction test.

Wenliang Li

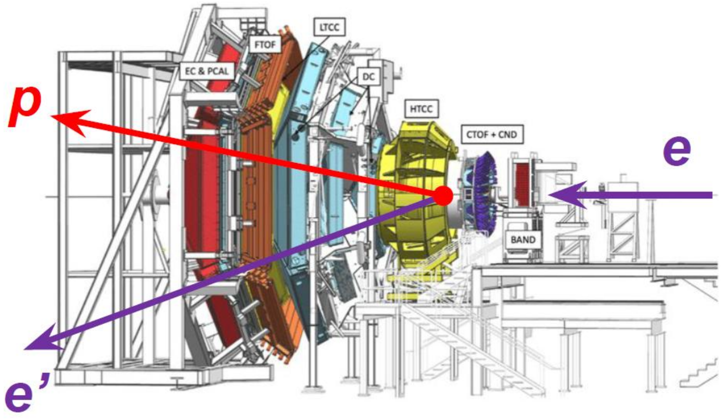
Jefferson Lab and Four Experimental Halls



- **Facility cost:**
  - Two Superconducting LINAC
  - Four experimental Halls
  - Electron beam energy up to 12 GeV
  - Duty cycle~99%
- **Peak Power Consumption: 1.2 M Watts**
- **Standard 6 month/year operation**
- **Four halls with different objectives:**
  - Hall A: preparing Moller experiment
  - Hall B: large acceptance spectrometer
  - Hall C: Narrow acceptance high precision spectrometers
  - Hall D: real photon beam,

14

Experimental configuration



Beam and target configuration:
- Upto 12 GeV e beam
- unpolarized LH2 or LD target

Detector stack
- **Time-of-flight:** CTOF, FTOF
- **PID:** HTCC, LTCC
- **Calorimeter:** EC, PCAL
- **Tracker:** DC
- **Neutron detection:** CND

Coverage:
- **Charged hadrons:** 5-125°coverage
- **Neutrons:** 40–120°, with momentum 0.2–1 GeV/c

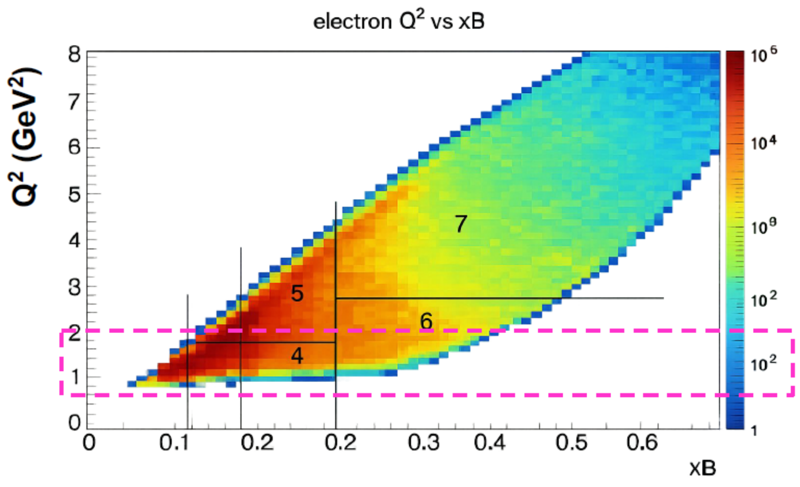
15

- JLab provides another source of e+p and e+d collision data.
- Test the consistency of net-proton yields between e+p and e+d collisions with improved statistical significance.

Details of CLAS12 experiment

Wenliang Li

Data Set Information



Q^2 vs x_B Phasespace coverage for RGA
(Image credit to the CLAS12 collaboration)

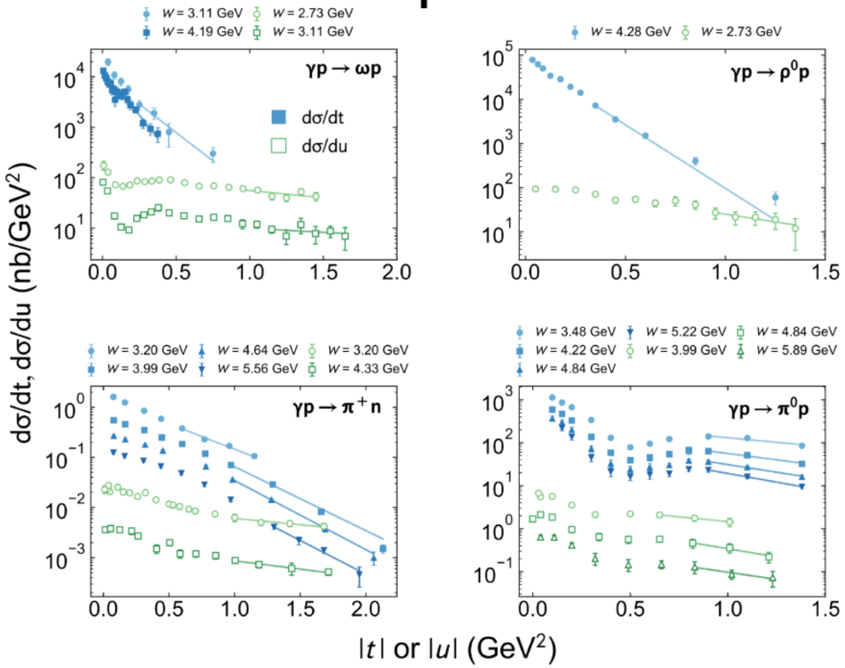
- **CLAS 12 Run group A (RGA)**
  - ~10.6 GeV Electron on unpolarized LH2
  - Completed data taking 2018–2019
  - 300 mC of integrated beam charge were collected, 500T of data size (50% completion)
- **CLAS 12 Run group B (RGB)**
  - ~ 10.6 GeV Electron on unpolarized LD2
  - Completed data taking 2019-2020
  - 136 mC of integrated beam charge were collected (50% completion)
- **More data taking is possible.**
- **Primary goal is to focus on $1 < Q^2 < 2$ GeV^2**
  - Better comparison with the prediction

17

Imaging baryon number within protons

Spencer Klein

Input data

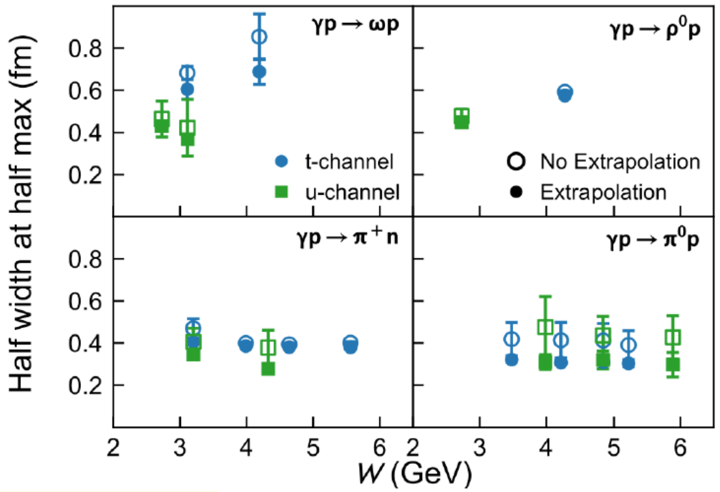


Some data exhibit diffractive minima, some do not

Diffractive minima are associated with sharp edges

Summarizing the data - FWHMs

- On average, the u-channel radii are a bit smaller than the t-channel equivalents. For the ω, the differences are significant.



- Fourier transform of $f(p_T)$ gives impact parameter distribution.
- Perform transform on $\gamma p \rightarrow \omega p, \gamma p \rightarrow \rho p, \gamma p \rightarrow \pi^0 p, \gamma p \rightarrow \pi^+ n$
- Why are the spatial sizes of protons from the four channels inconsistent?

Hypothesis: Different channels probe different entities

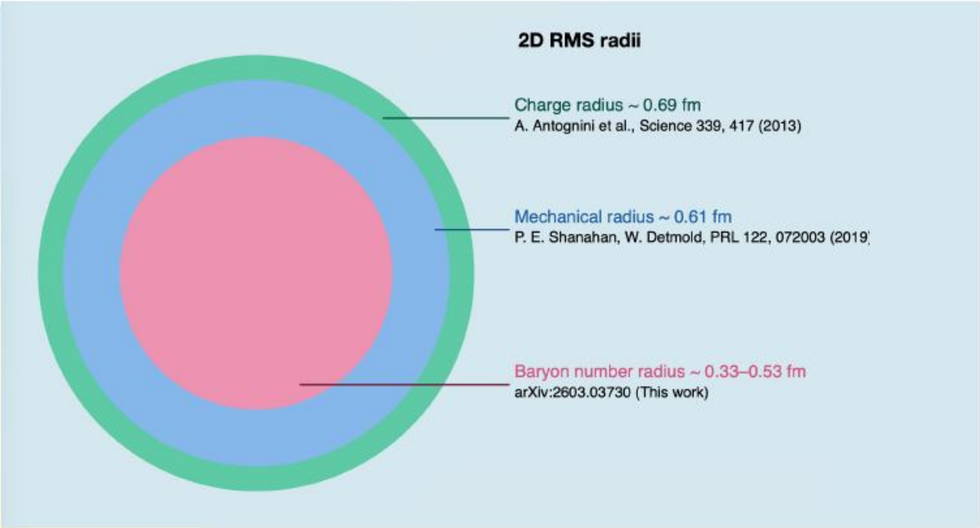
Spencer Klein

How do the sizes compare?

Reaction	Sensitive to	RMS Radius (fm)
Low-energy forward VM photoproduction	High-x quarks and gluons	0.67 – 0.77
Forward π^0 and π^+ photoproduction	High-x quarks	0.33 – 0.45
Backward meson production	Baryon number	0.33 – 0.53
High-energy forward VM photoproduction	Gluons	0.86 – 0.99
Electron scattering	Net charge	0.69 – 0.72
Hydrogen spectroscopy	Charge	0.69

- The baryon number size is in the range 0.33-0.53 fm, depending on reaction.
- This is significantly smaller than the proton size measured via reactions sensitive to gluons, net charge or charge.
- We conclude that the baryon number is somewhat concentrated in the center of the proton

The proton through different microscopes



Graphic by Mathias Labonte

- Baryon number is concentrated near the center of the proton.
- Consistent with it residing in either high-x quarks or baryon junctions.

Conclusion & Outlook

- Multiple independent lines of evidence now support the baryon junction picture.
- Active experimental programs across RHIC, HERA, and CLAS12 are providing complementary tests.
- New probes of baryon number (e.g. spatial imaging) and theories of transported baryon creation (e.g. GPDs) are being developed.
- The EIC will be indispensable: enable accurate measurement of baryon transport in e+A, decisive tests on baryon junction picture.
- **A long-term program with a bright future ahead.**