Baryon number dynamics from RHIC to the EIC

David Frenklakh

Brookhaven
National Laboratory

2312.15039 [DF, Kharzeev, Li]
2405.04569 [DF, Kharzeev, Rossi, Veneziano]

APS GHP 2025 Workshop

Anaheim *3.14.2025*

Image credit: DALLE

Outline

- ❖ Baryon junctions overview/experimental status
- ❖ Semi-inclusive DIS
- ❖ New theory results on Regge intercepts
- ❖ More experimental signatures

Motivation: what carries the baryon number?

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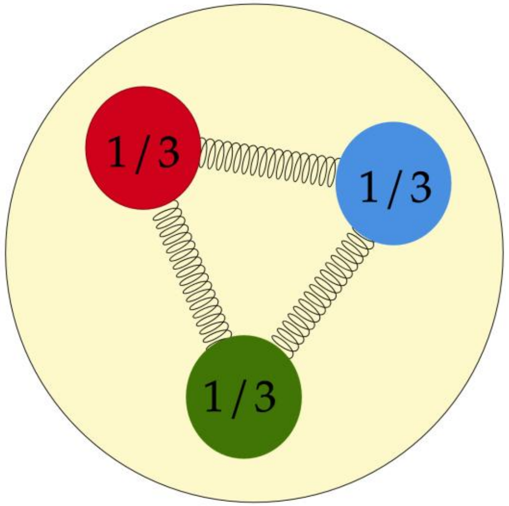
$$B(x_1, x_2, x_3) = \epsilon^{ijk} q(x_1)_i \; q(x_2)_j q(x_3)_k$$



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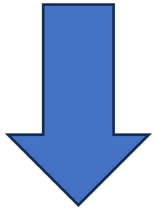
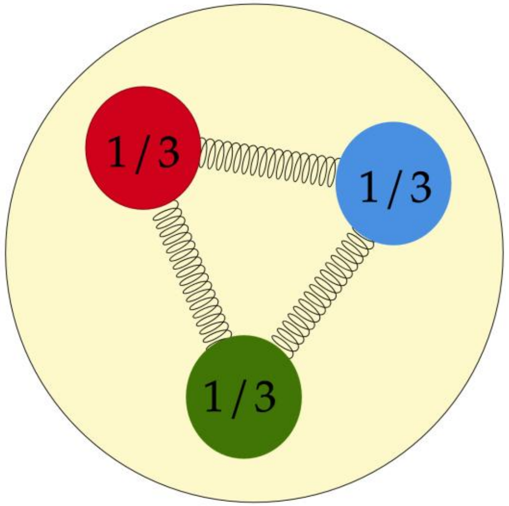


Gauge invariance



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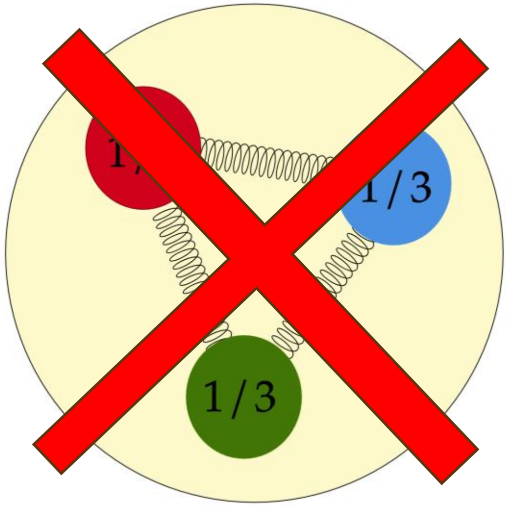

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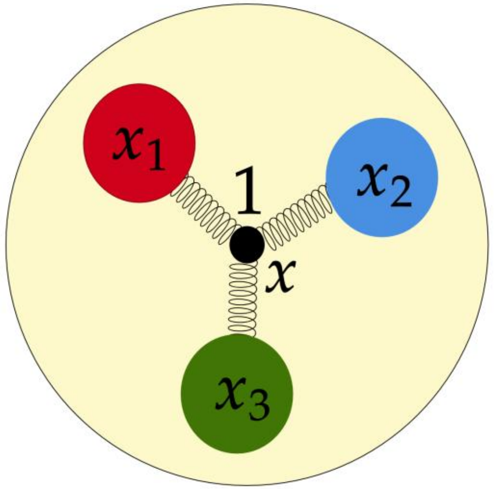
Gauge invariance

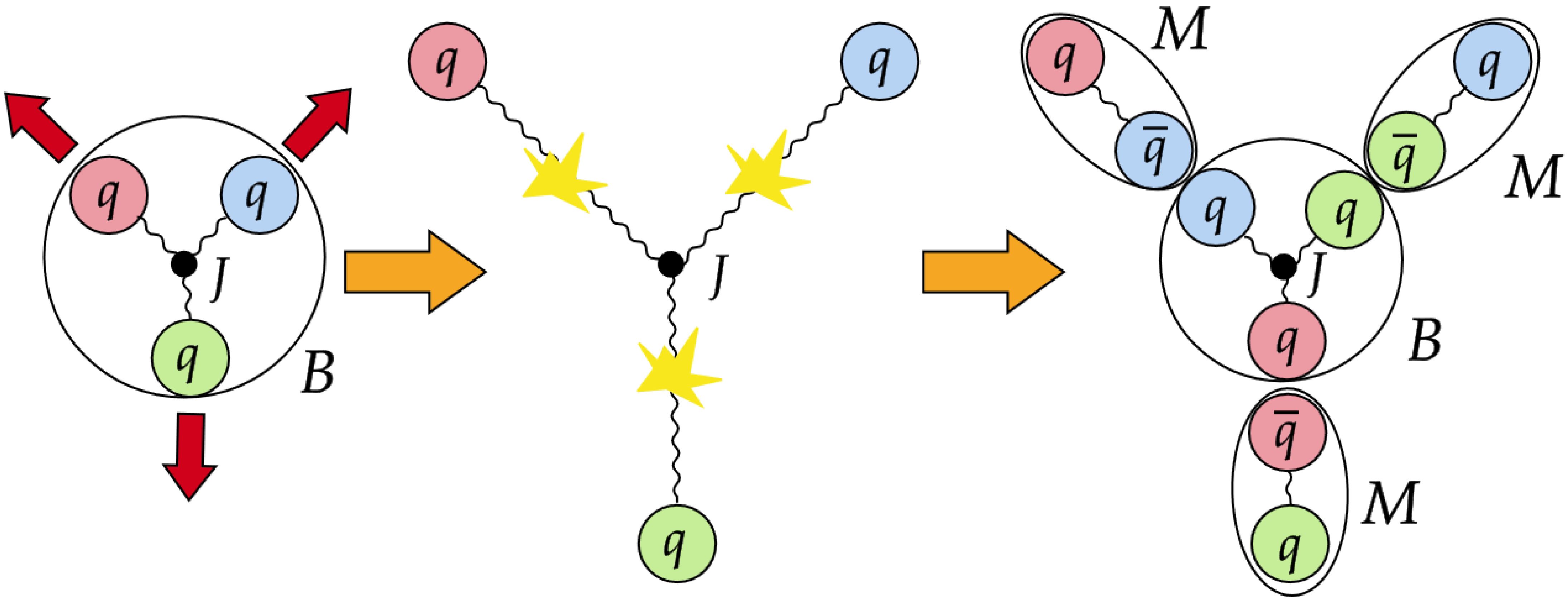
$$B(x_1, x_2, x_3, x) = \epsilon^{ijk} \; [P(x_1, x) \; q(x_1)]_i \; [P(x_2, x) \; q(x_2)]_j \, [P(x_3, x) \; q(x_3)]_k$$



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

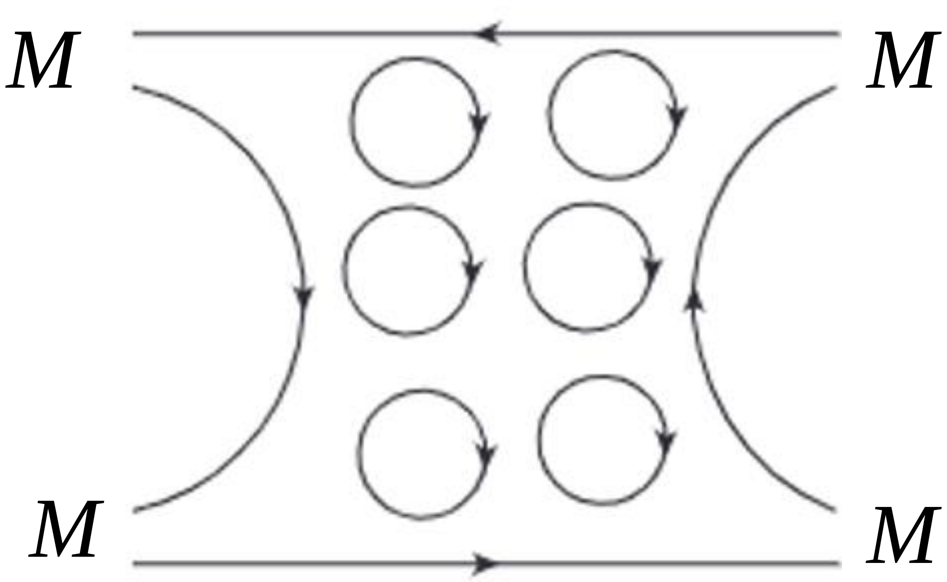
G.C. Rossi and G. Veneziano, Nucl. Phys. B 123 (1977)

Can baryon junction carry the baryon number?



Large N intuition: diagrams as surfaces

Meson elastic scattering



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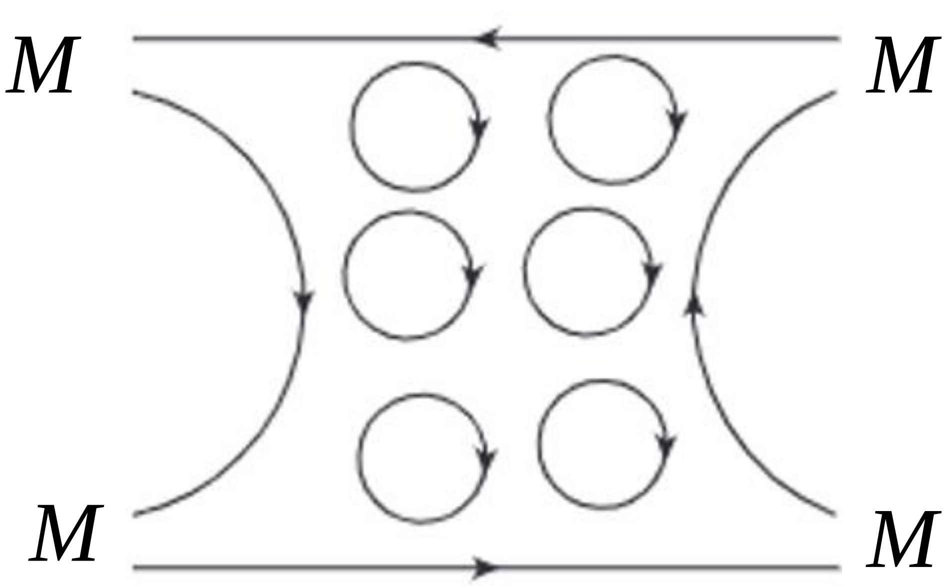

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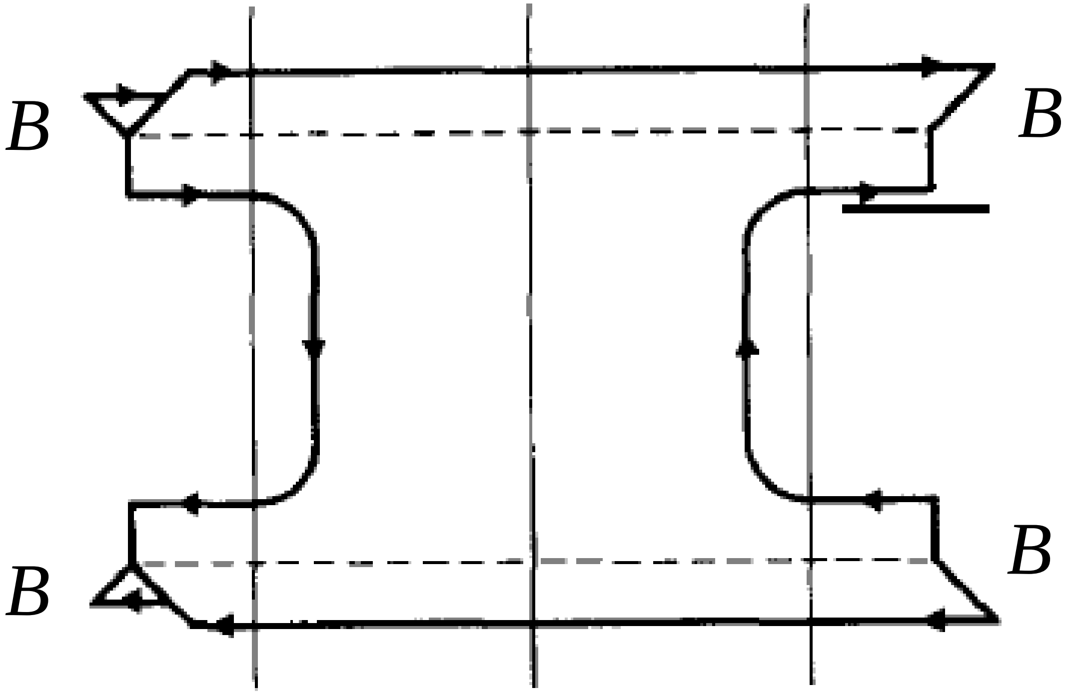

Baryons have a “book” topology – junction becomes necessary

Theoretical Aspects of Baryonium Physics

G.C. ROSSI and G. VENEZIANO

PHYSICS REPORTS (Review Section of Physics Letters) 63, No. 3 (1980)

Different processes

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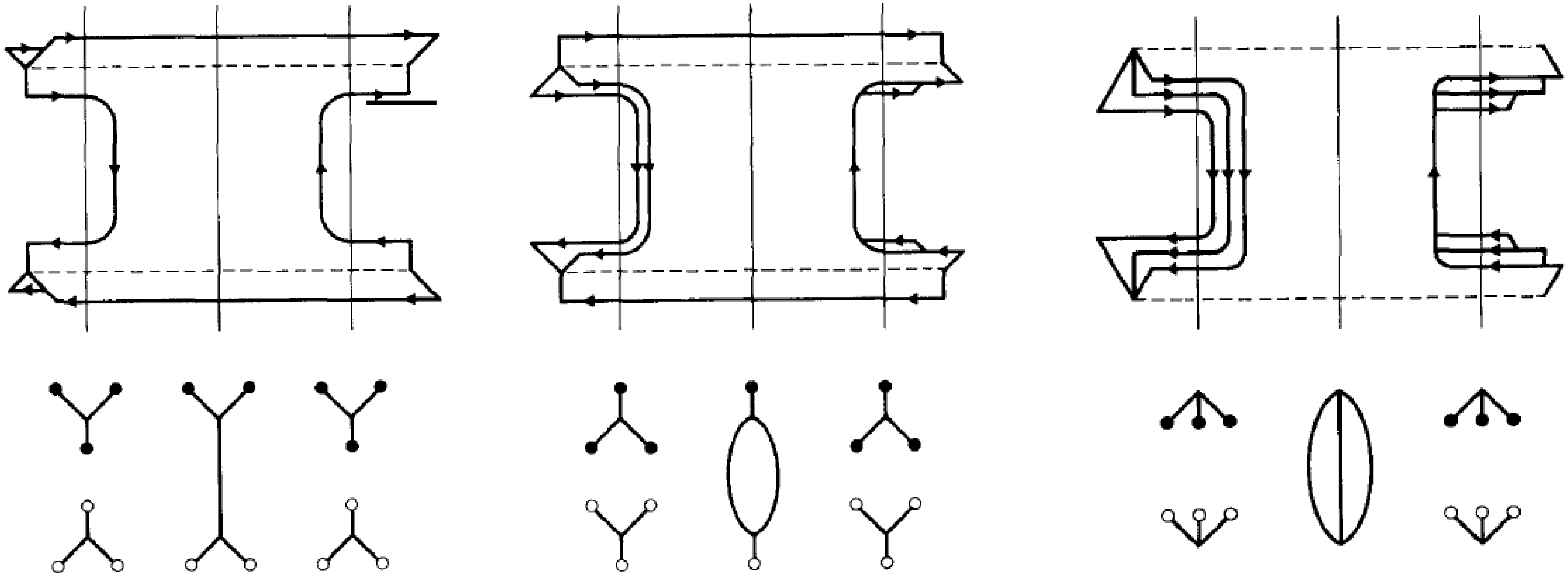

J_4 J_2 J_0

Tetraquark Meson Glueball

Baryon stopping in pp and AA

Can gluons trace baryon number?

D. Kharzeev

Physics Letters B 378 (1996) 238--246

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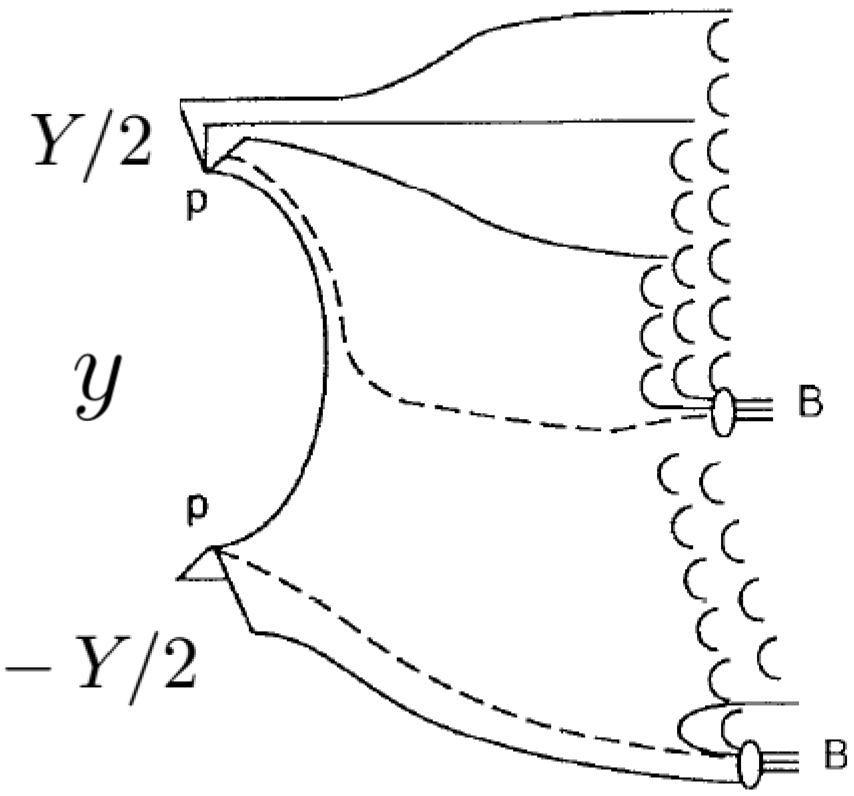
$$\left(\frac{dN_B}{dy}\right)_{net} \propto e^{(\alpha_{\mathbb{P}}+\alpha_{\mathbb{J}_0}-2)Y/2}[e^{(\alpha_{\mathbb{P}}-\alpha_{\mathbb{J}_0})y} + e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{P}})y}]$$



Dashed lines denote junctions

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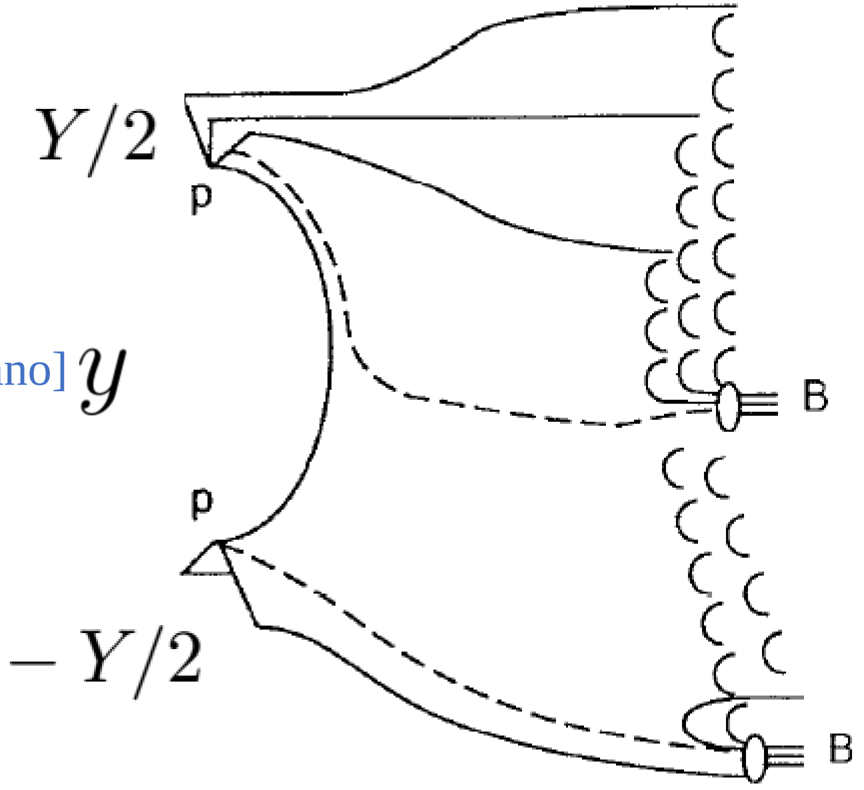
$$\alpha_{\mathbb{P}} = 1+\Delta \approx 1.08$$

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

2405.04569
[DF, Kharzeev, Rossi, Veneziano]



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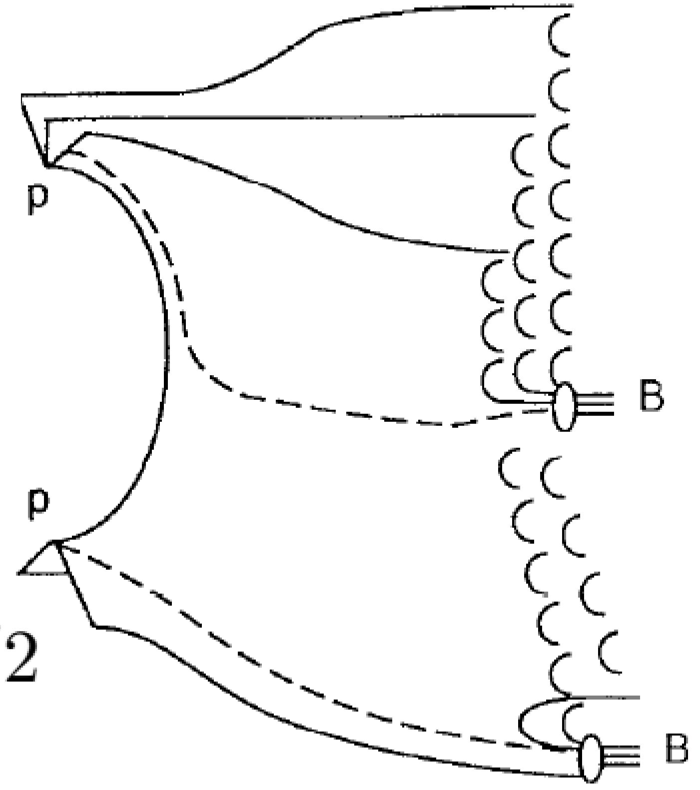

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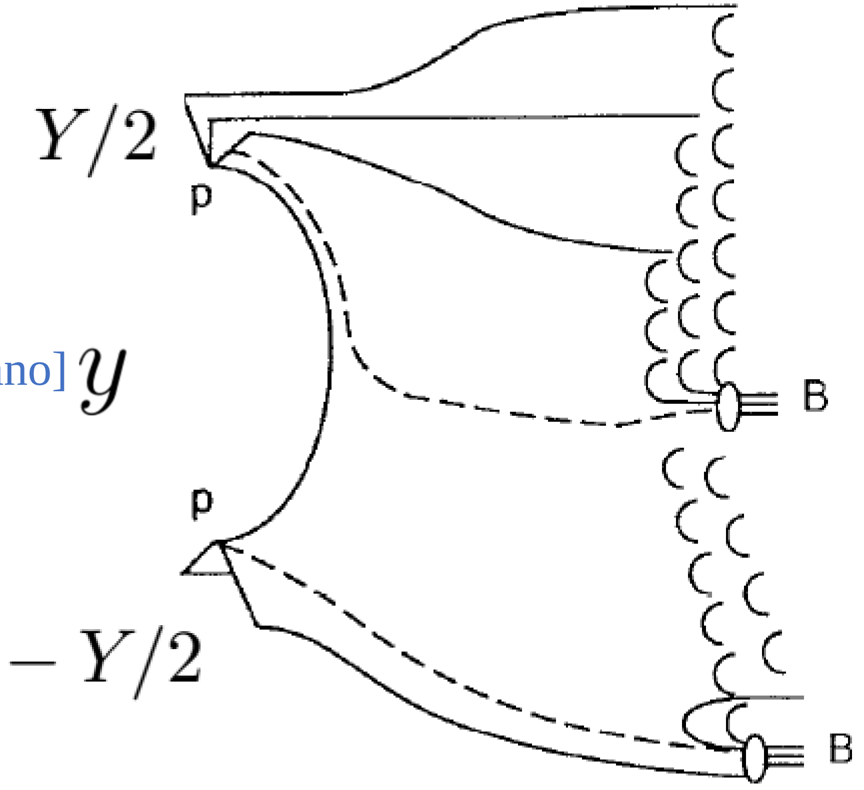
$$\left(\frac{dN_B}{dy}\right)_{net}\Bigg|_{y=0} \propto e^{(-0.65\pm0.1)y_b}$$



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From RHIC Beam Energy Scan by STAR collaboration, 2205.05685

Recent experimental results

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

2205.05685

Nicole Lewis[1], Wendi Lv[2], Mason Alexander Ross[3], Chun Yuen Tsang[4], James Daniel Brandenburg[5], Zi-Wei Lin[3], Rongrong Ma[1], Zebo Tang[2], Prithwish Tribedy[1,a], Zhangbu Xu[4]

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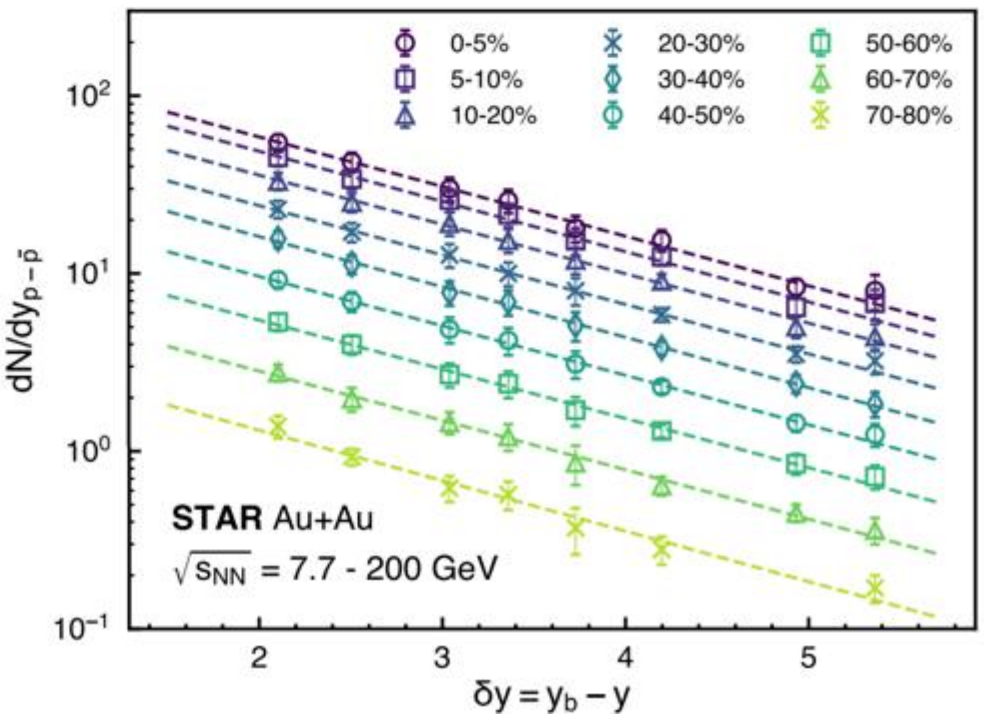

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2309.06445

Correlations of baryon and charge stopping in heavy ion collisions[*]

Wendi Lv (吕文棣)[1], Yang Li (李洋)[1], Ziyang Li (李子阳)[1], Rongrong Ma (马荣荣)[2], Zebo Tang (唐泽波)[1], Prithwish Tribedy[2], Chun Yuen Tsang[3], Zhangbu Xu (许长补)[2] and Wangmei Zha (查王妹)[1]

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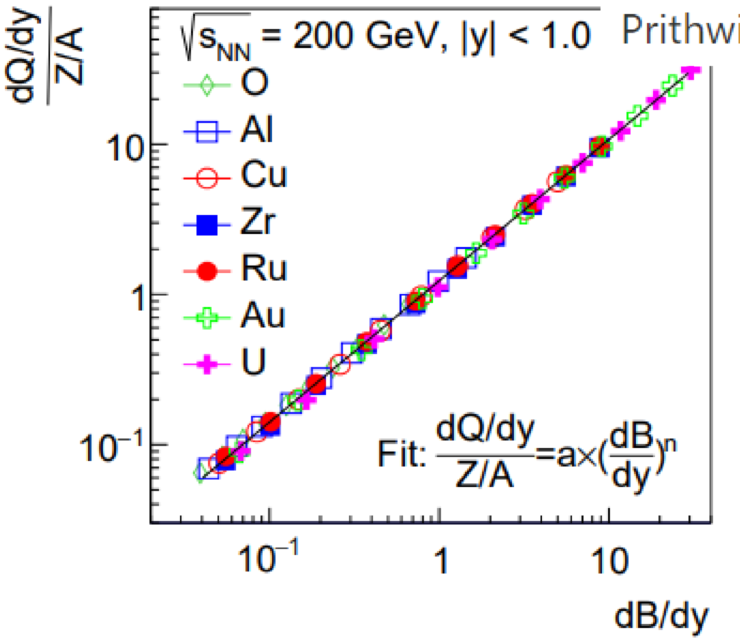

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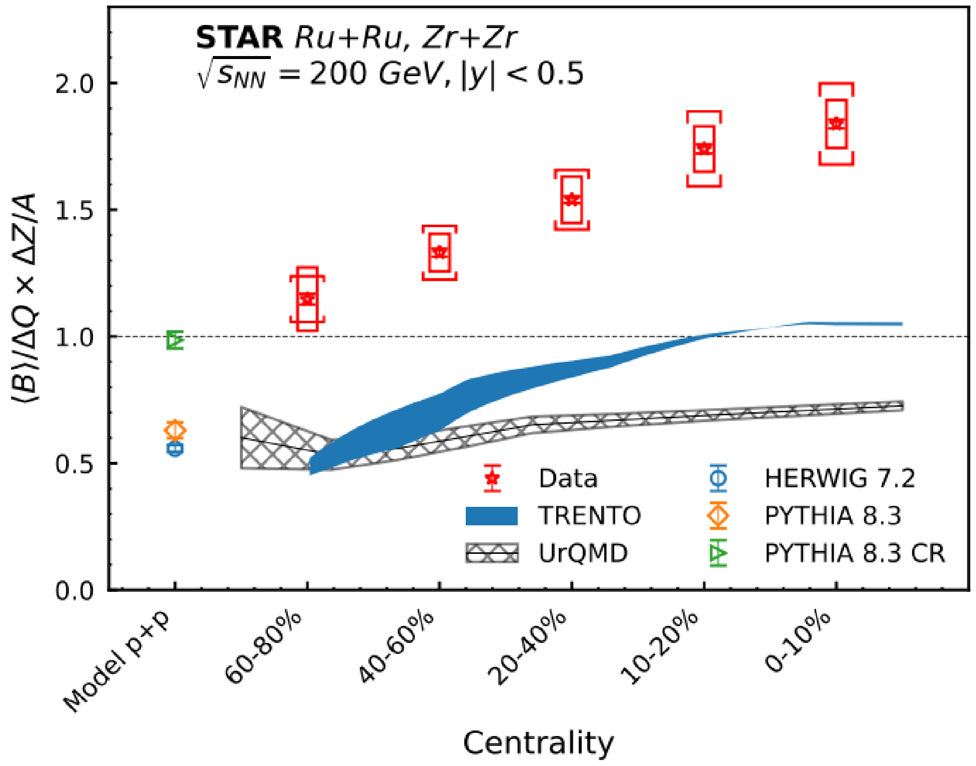
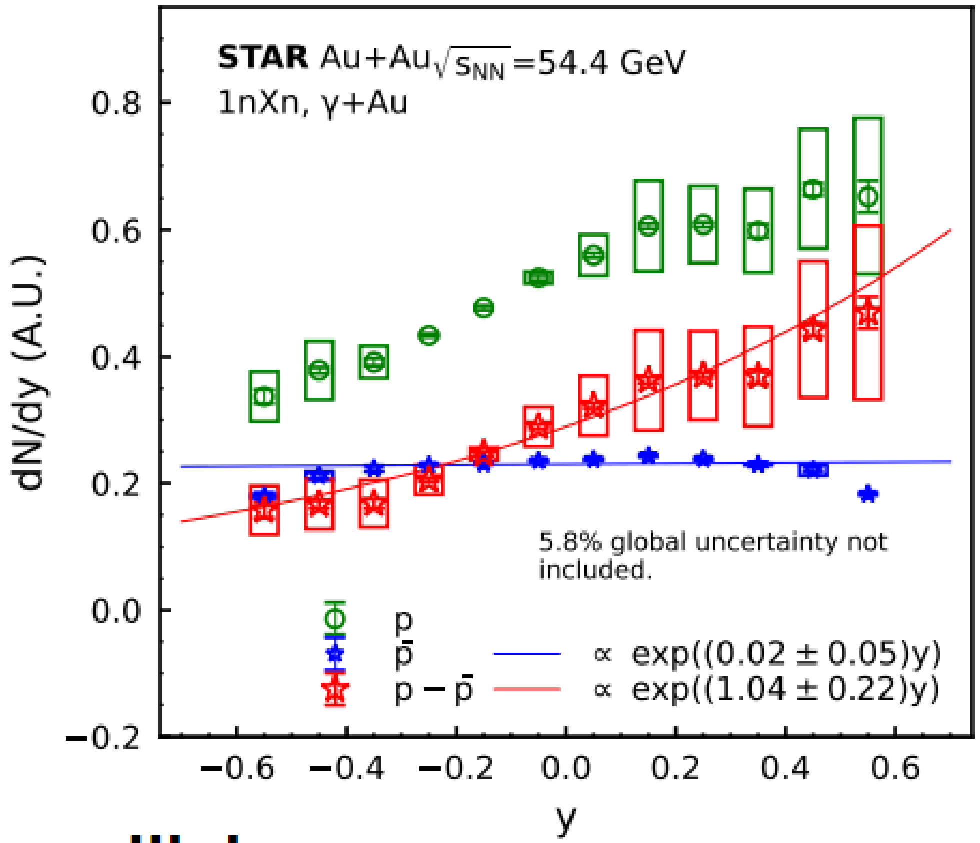
Tracking the baryon number with nuclear collisions

2408.15441

STAR Collaboration





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Beam energy dependence of net-hyperon yield and its implication on baryon transport mechanism

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Correl
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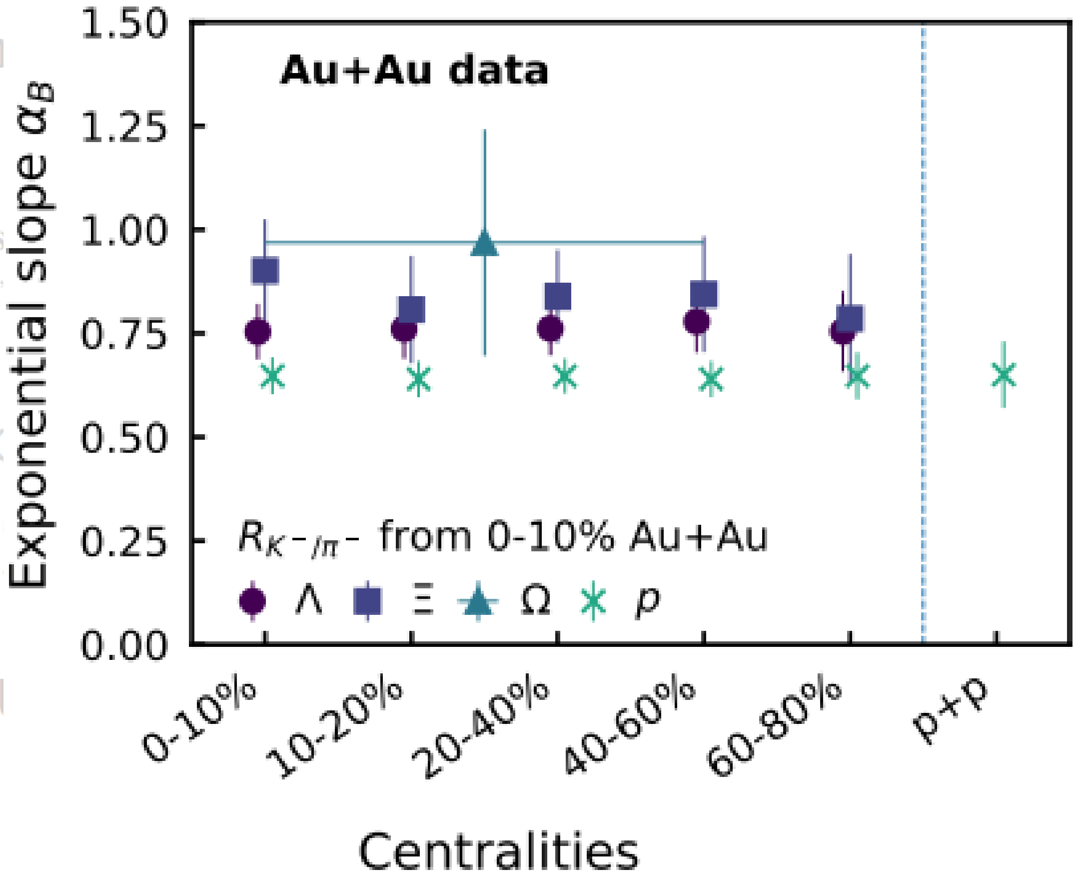

Tracking the baryon n

408.15441

STAR Collaboration

Beam energy dependence of net-hyperon yield and its implication on baryon transport mechanism

2409.06492

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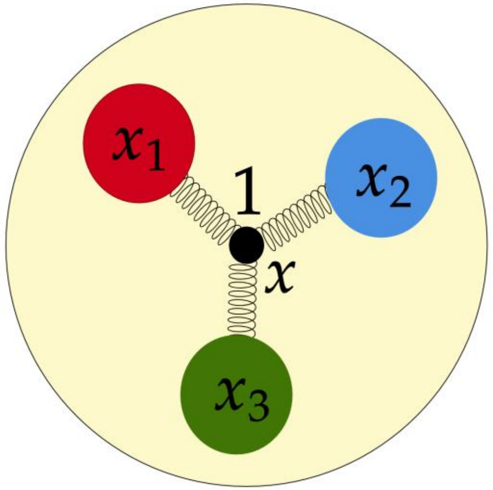
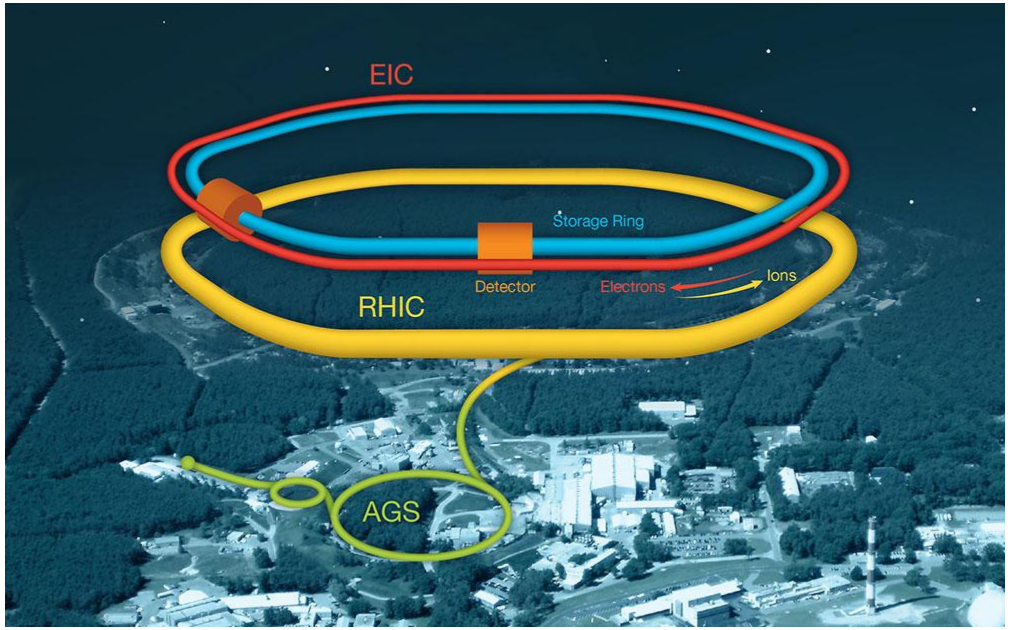
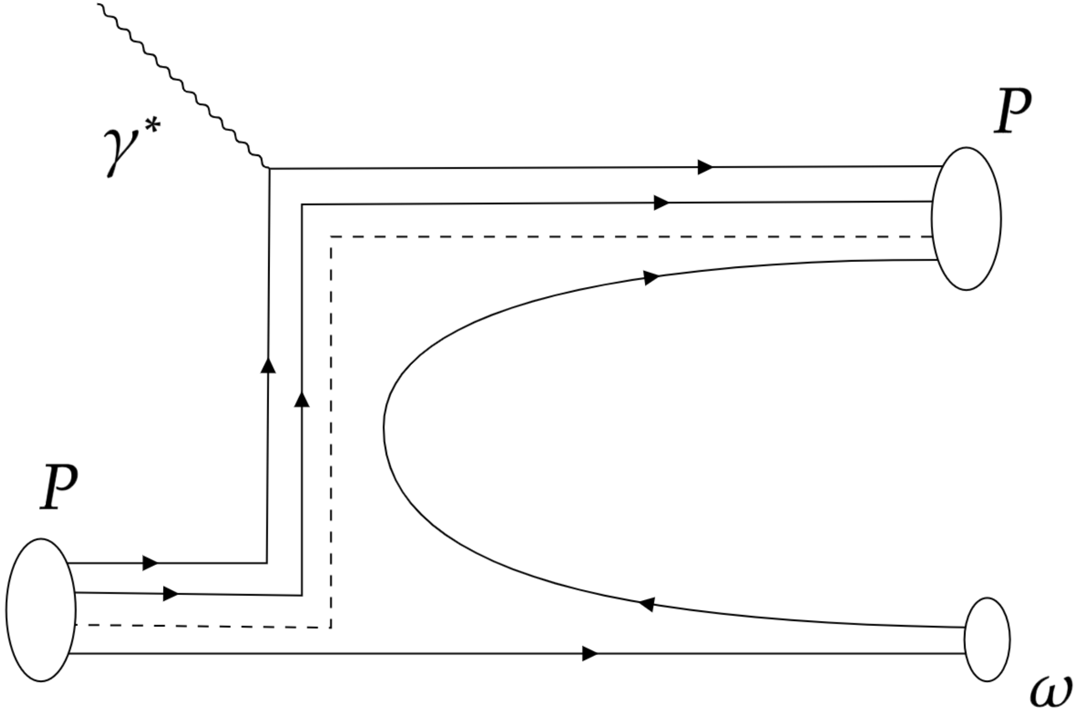
What other processes can probe the carrier of baryon number?





Initial motivation: exclusive ω production



W. B. Li *et al.*
Phys. Rev. Lett. **123**, 182501

Significant fraction of events with the proton in the γ^* fragmentation region

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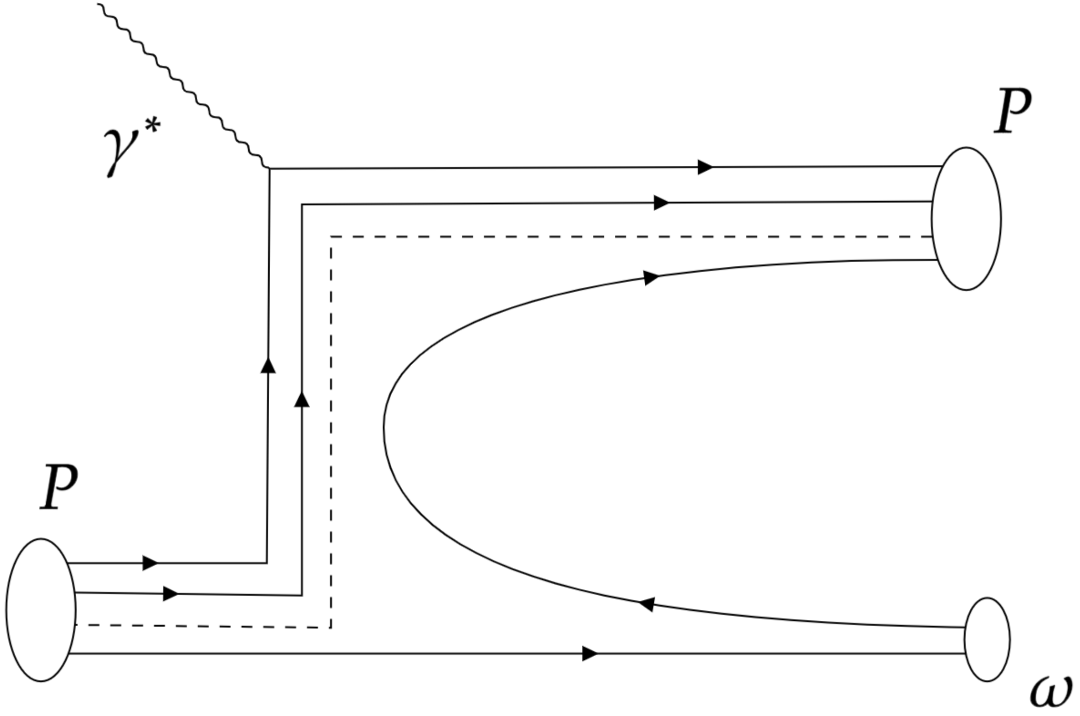

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Entire baryon is exchanged in the t-channel → Cannot separate the junction from valence quarks

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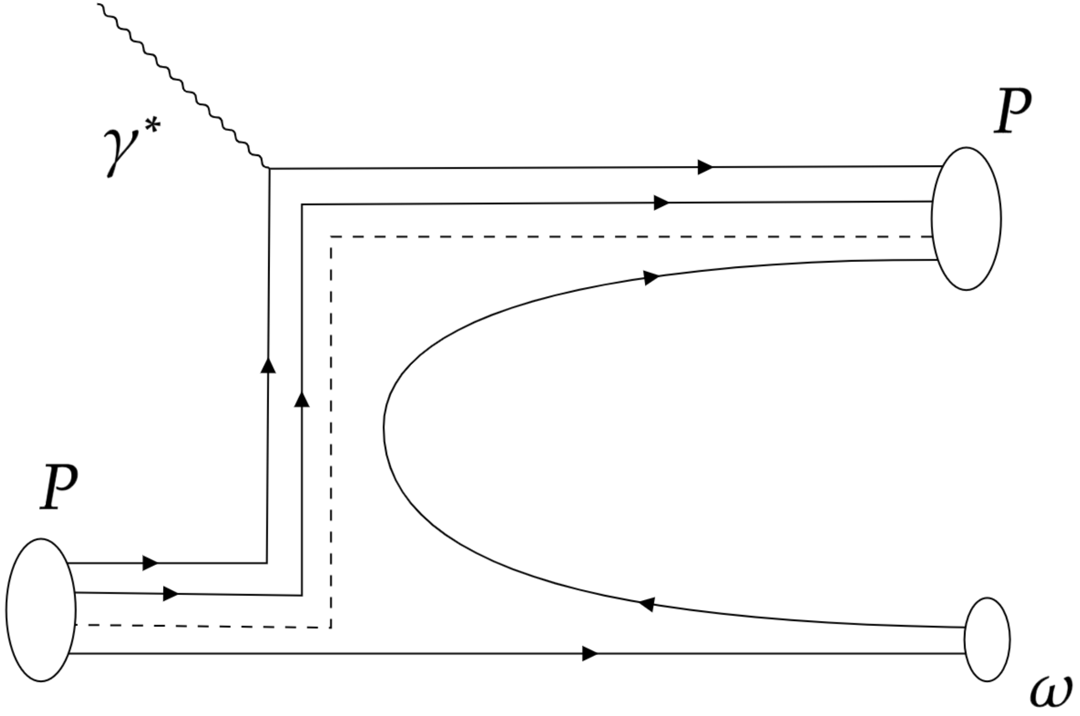

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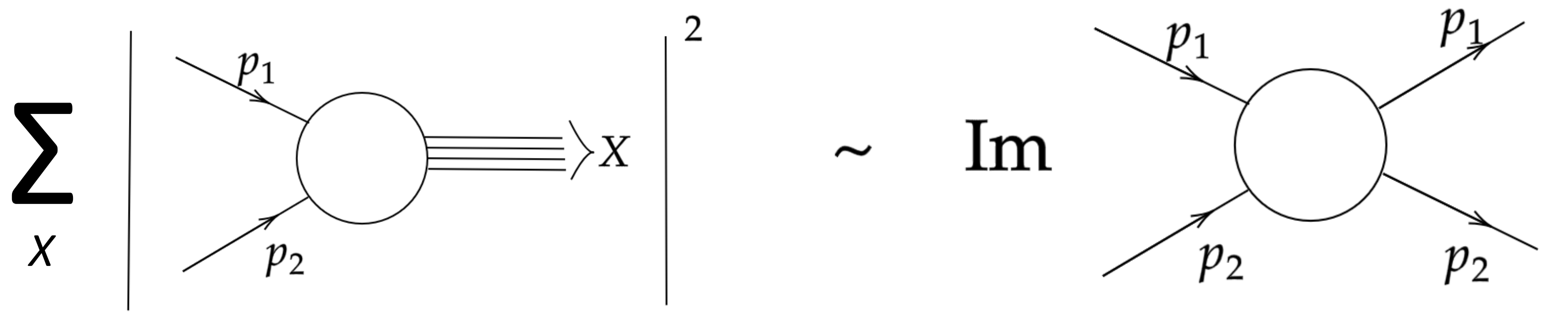
Need a semi-inclusive process

Mueller-Kancheli theorem

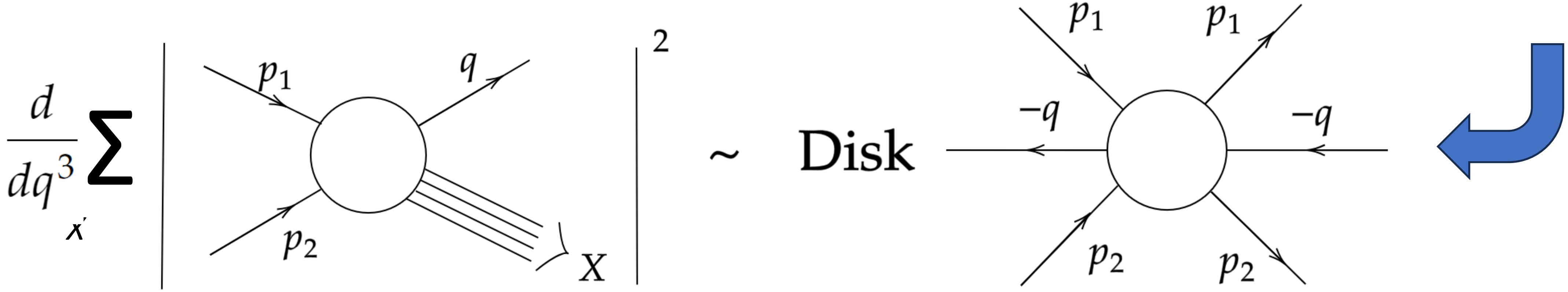
A.H. Mueller, Phys. Rev. D 2 (1970) 2963.
O.V. Kancheli, JETP Lett. 11 (1970) 397.

Optical theorem:

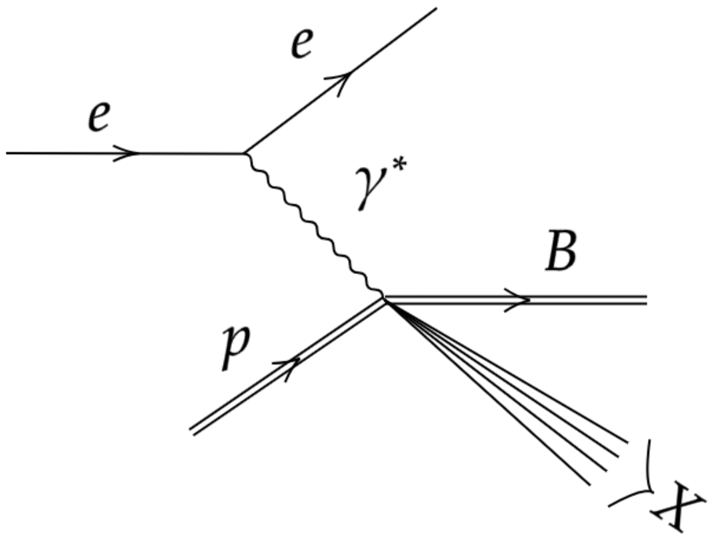


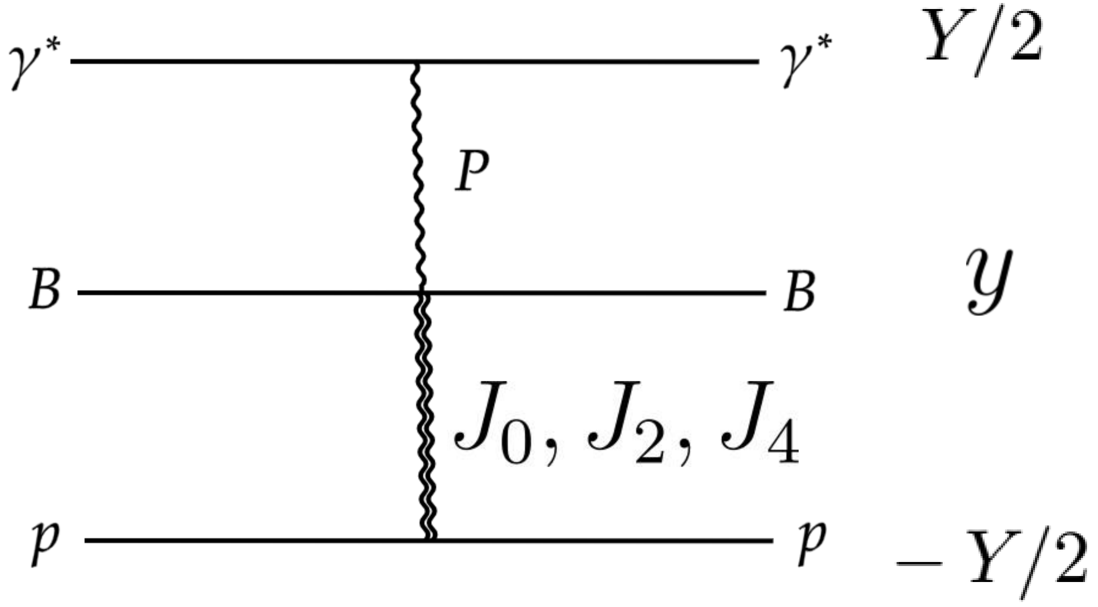
Generalized to semi-inclusive scattering:

Study in Regge theory



SIDIS as 3 → 3 forward scattering





$$\mathcal{A}(s,t) \propto s^{\alpha(t)},\, s \to \infty$$

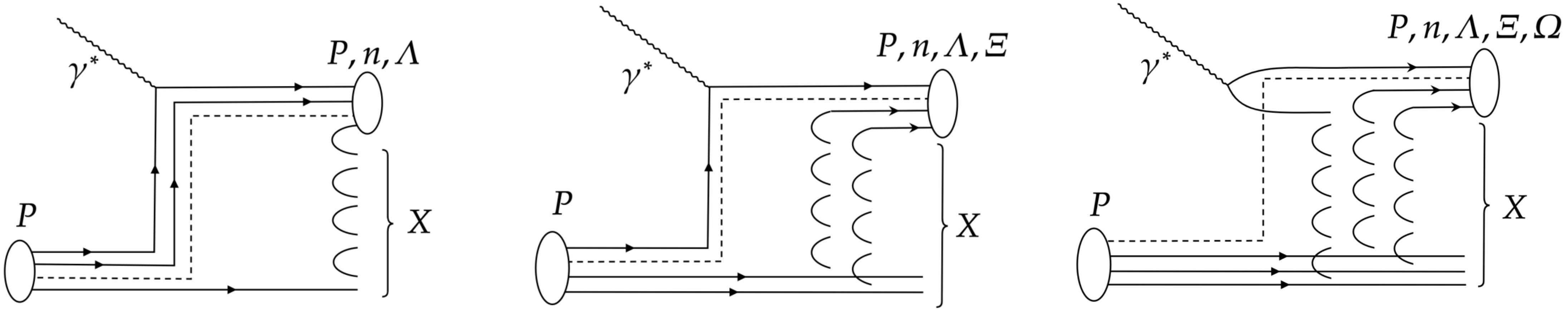
$$s_1 = (p_1 + p_B)^2 = \sqrt{s}\, m_t\, e^{-y^*}$$

$$s_2 = (p_2 + p_B)^2 = \sqrt{s}\, m_t\, e^{y^*}$$

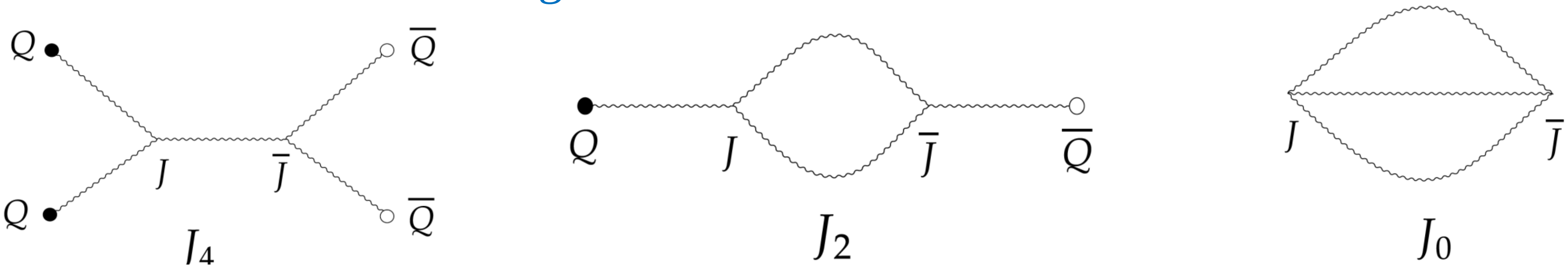
$$\left(\frac{dN_B}{dy}\right)_{net} \propto s_1^{\alpha_{\mathbb{P}}(0)-1} s_2^{\alpha_{\mathbb{J}}(0)-1}$$

The largest $\alpha_{\mathbb{J}}(0)$ is leading

Three possible processes



Mueller-Kancheli t-channel exchanges:



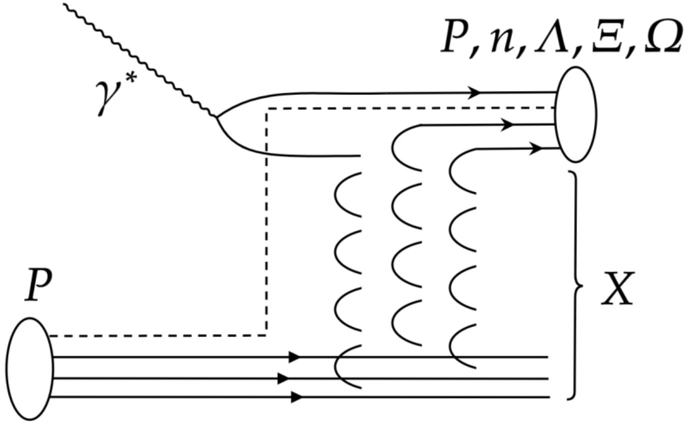
$\alpha_{\mathbb{J}_4} \approx -0.66$ $\alpha_{\mathbb{J}_2} \approx -0.24$ $\alpha_{\mathbb{J}_0} \approx 0.26$

Intercept estimates: Topological expansion+ Feynman-Wilson gas model

2405.04569 [DF, Kharzeev, Rossi, Veneziano]

Three possible processes

Leading



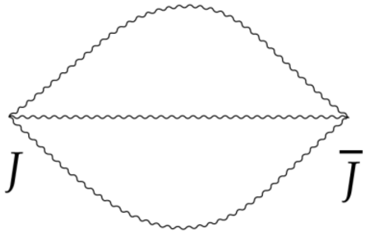
Mueller-Kancheli t-channel exchanges:

J_4

$\alpha_{\mathbb{J}_4} \approx -0.66$

J_2

$\alpha_{\mathbb{J}_2} \approx -0.24$



J_0

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

Intercept estimates: Topological expansion+ Feynman-Wilson gas model

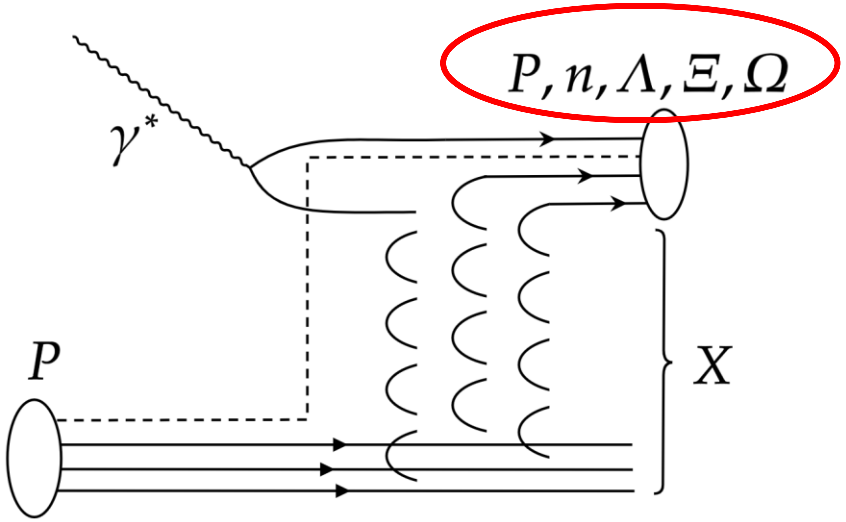
2405.04569 [DF, Kharzeev, Rossi, Veneziano]

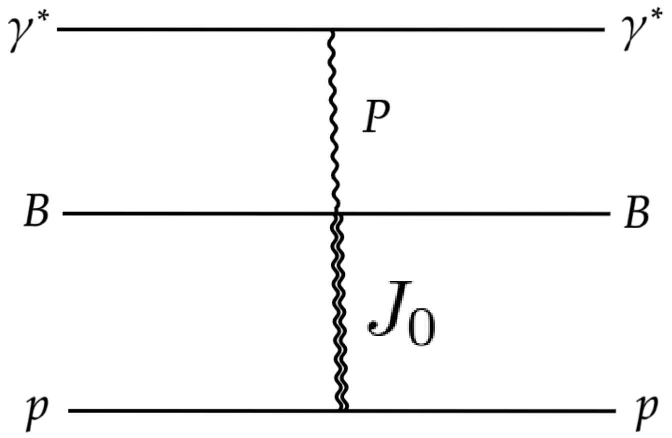
Rapidity distribution of baryons in DIS

$$\left(\frac{dN_B}{dy}\right)_{net} \propto s_1^{\alpha_{\mathbb{P}}-1} s_2^{\alpha_{\mathbb{J}_0}-1}$$

$$s_1 \propto e^{Y/2-y} \qquad s_2 \propto e^{Y/2+y}$$

$$\left(\frac{dN_B}{dy}\right)_{net} \propto e^{(\alpha_{\mathbb{P}}+\alpha_{\mathbb{J}_0}-2)Y/2} e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{P}})y}$$





Wide rapidity acceptance at the EIC will make it possible to measure both *Y/2* and *y* dependence.

Feynman-Wilson gas (FWG)

Some Experiments on Multiple Production*

Kenneth G. Wilson CLNS-131 November 1970 September 1973

Generating functional of exclusive cross-sections:

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

Exclusive cross-section

$$\left. \frac{\delta \Sigma[z]}{\delta z(x) \delta z(y) \ldots} \right|_{z=0} = \frac{1}{\sigma_t} \frac{d\sigma(a+b \to x+y+\ldots)}{dx\, dy \ldots}$$

Semi-inclusive cross-section

$$\left. \frac{\delta \Sigma[z]}{\delta z(x) \delta z(y) \ldots} \right|_{z=1} = \frac{1}{\sigma_t} \sum_X \frac{d\sigma(a+b \to x+y+\ldots+X)}{dx\, dy \ldots}$$

Connected correlators in FWG

From the generating functional to connected correlators:

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

For a large total rapidity separation $Y \propto \log s$ one has

$$\prod dx^j c_m \propto Y \quad \text{(not } Y^m\text{)}$$

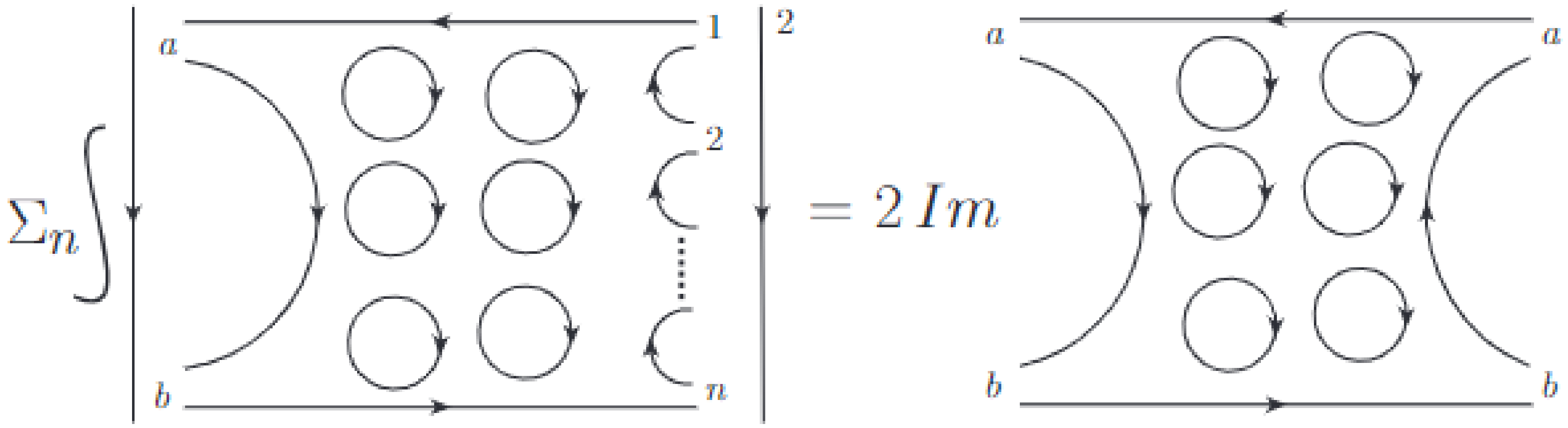
Y plays the role of the volume of the gas.

FWG on the planar level

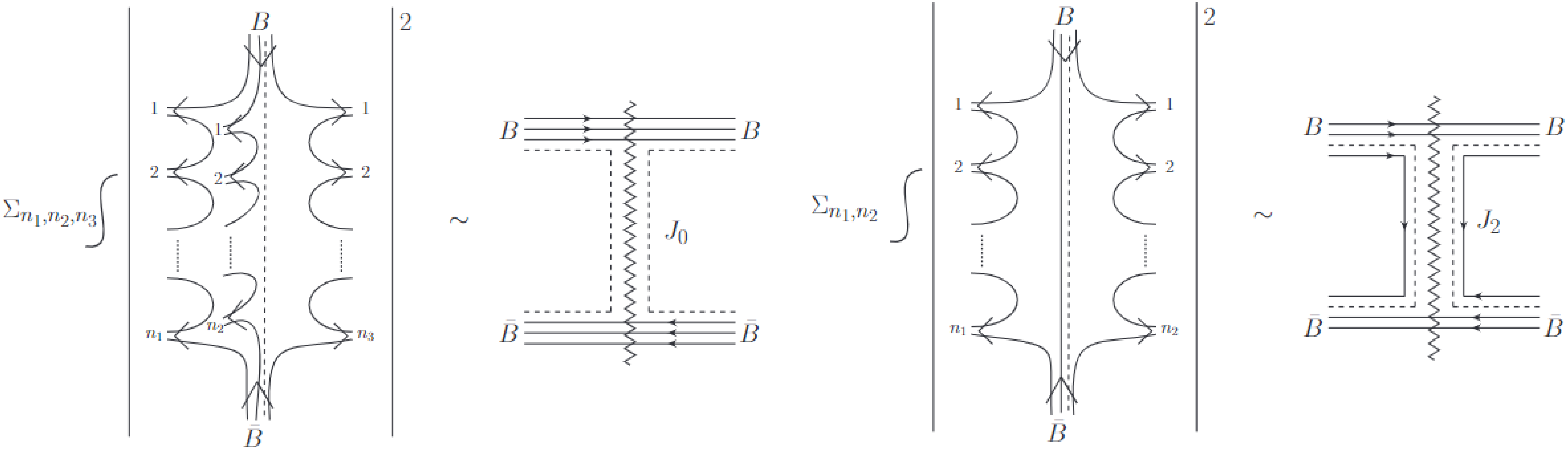
Integrating over all kinematical variables:

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

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



FWG for $B\bar{B}$ annihilation



$$\Sigma_{ann}(z_1, z_2, z_3) = \frac{1}{\sigma_t^{ann}} \sum_{\sum n_i \geq 2} z_1^{n_1} z_2^{n_2} z_3^{n_3} \sigma^{ann}(n_1, n_2, n_3) \equiv e^{Y p(z_1,z_2,z_3)}$$

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

Original baryonium intercepts

$Y \propto \log s$, so $\Sigma(\{z_i\}) \propto s^{p(\{z_i\})}$. On the other hand, e.g.

$$\Sigma_{ann}(z_1, z_2, 0) = \frac{\sigma^{ann}(X_1, X_2, 0)}{\sigma_t^{ann}} \propto \frac{s^{\alpha_{\mathbb{J}_2}-1}}{s^{\alpha_{\mathbb{J}_0}-1}} \Longrightarrow$$

$$p(1,1,0) = \alpha_{\mathbb{J}_2} - \alpha_{\mathbb{J}_0}$$

Assuming no inter-species correlations (Dalton's law)
$p(z_1, z_2, z_3) = p_1(z_1) + p_2(z_2) + p_3(z_3)$,
+ similar relations for $\alpha_{\mathbb{J}_4} - \alpha_{\mathbb{J}_0}$ and $2\alpha_B - 1 - \alpha_{\mathbb{J}_0}$
+ the result of similar analysis of planar diagram, $p_i(0) = 1 - \alpha_{\mathbb{R}}$
one recovers

$$\alpha_{\mathbb{J}_0} = 2\alpha_B - 1 + 3(1 - \alpha_R) \simeq 0.5$$ G.C. Rossi and G. Veneziano, Nucl. Phys. B 123 (1977)

and similarly $\alpha_{\mathbb{J}_2} \simeq 0$, $\alpha_{\mathbb{J}_4} \simeq -0.5$

Corrections to intercepts

Accounting for inter-species correlations

$$p(z_1, z_2, z_3) = p_1(z_1) + p_2(z_2) + p_3(z_3) + C_2(z_1, z_2) + C_2(z_1, z_3)$$
$$+C_2(z_2, z_3) + C_3(z_1, z_2, z_3)$$

one obtains

$$\alpha_{\mathbb{J}_0} = (2\alpha_{\mathbb{B}}-1)+3(1-\alpha_{\mathbb{R}})-3C_2(0,0)-C_3(0,0,0) \simeq 0.5-3C_2-C_3$$

C_2 can be separately inferred from the analysis of Pomeron-dominated cylindrical topology:

$$C_2 = \alpha_{\mathbb{P}} - 1 \simeq 0.08 \Longrightarrow \alpha_{\mathbb{J}_0} \simeq 0.26 - C_3$$

2405.04569
[DF, Kharzeev, Rossi, Veneziano]

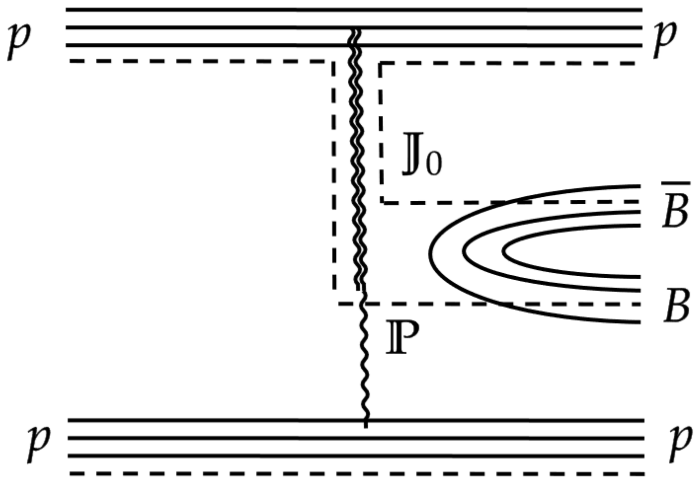
leading to beam rapidity slope $2 - \alpha_{\mathbb{P}} - \alpha_{\mathbb{J}_0} \simeq 0.66 + C_3$
(compared to 0.65 ± 0.1 from RHIC BES)

Suggestions for experiment: J_0 trajectory

- Energy and rapidity dependence of baryon stopping in AA, pp, ep - to increase precision of rapidity slope and check J_0 intercept universality.
- Stopping of Ω in AA, pp or ep collision would be a clear evidence of baryon-number – flavor separation. Rapidity distribution would allow for a clean extraction of $\alpha_{\mathbb{J}_0}$

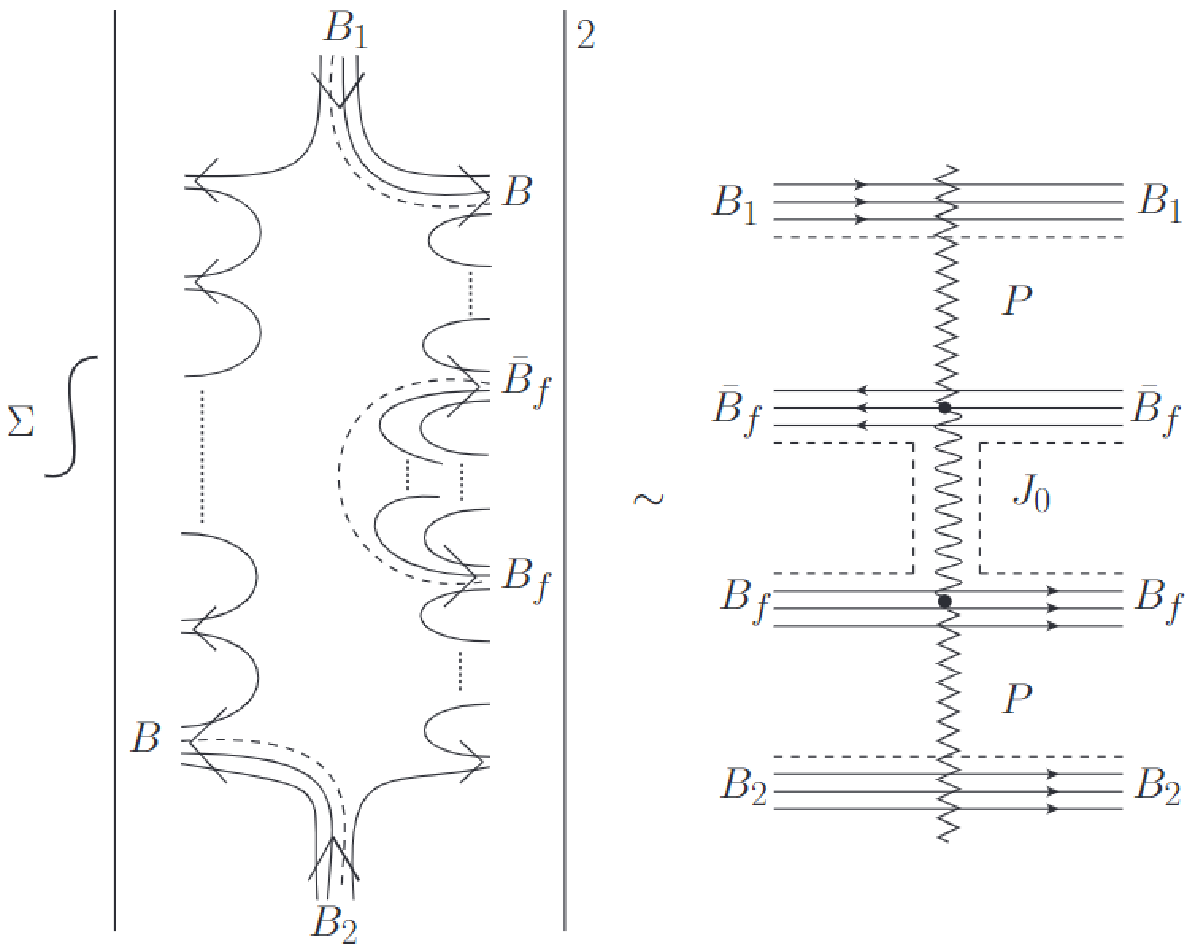
2409.06492
[Tsang, Ma, Tribedy, Xu]

- Search for doubly-diffractive production of a baryon-antibaryon pair in hp collisions to measure $\alpha_{\mathbb{J}_0}(t)$ and extract the slope of J_0 trajectory.



Suggestions for experiment: $B\bar{B}$ pair production

- Measure distribution of produced baryon-antibaryon pairs as a function of rapidity separation Δy.
- We expect $\sim e^{-0.5\Delta y}$ at large Δy due to J_0 dominance
- Also expect $\frac{n(\Delta y)}{\Delta y} \simeq \frac{3}{2}\frac{dn}{dy}\Big|_{incl}$



Summary

- Search for signatures of baryon junctions in semi-inclusive DIS
- Accounting for inter-species correlations in Feynman-Wilson gas improves agreement with the existing baryon stopping data
- Suggestions for experiment on baryon-number – flavor separation, studying J_0 trajectory further with $B\bar{B}$ production

Backup

Optical theorem

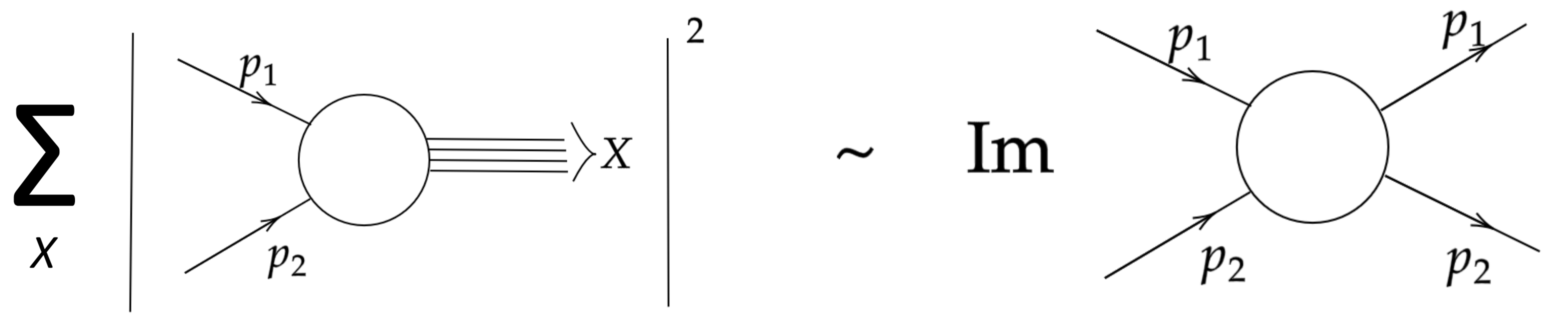
$$SS^\dagger = S^\dagger S = \mathbb{1}, \qquad S = \mathbb{1} + iT \quad \Longrightarrow \quad i(T^\dagger - T) = T^\dagger T$$

Sandwich in between $|f\rangle$ and $\langle i|$ and insert $\mathbb{1} = \sum_n |n\rangle\langle n|$:

$$2\,\mathrm{Im}\,T_{if} = \sum_n T^*_{fn}\,T_{in}$$

choosing $|i\rangle = |f\rangle$ and going to amplitudes

$$\sigma_{tot} \simeq \frac{1}{s}\mathrm{Im}\,\mathcal{A}_{el}(s, t=0) = \frac{1}{s}\mathrm{Disc}_s\,\mathcal{A}_{el}(s, t=0)$$



Mueller-Kancheli theorem

A.H. Mueller, Phys. Rev. D 2 (1970) 2963.
O.V. Kancheli, JETP Lett. 11 (1970) 397.

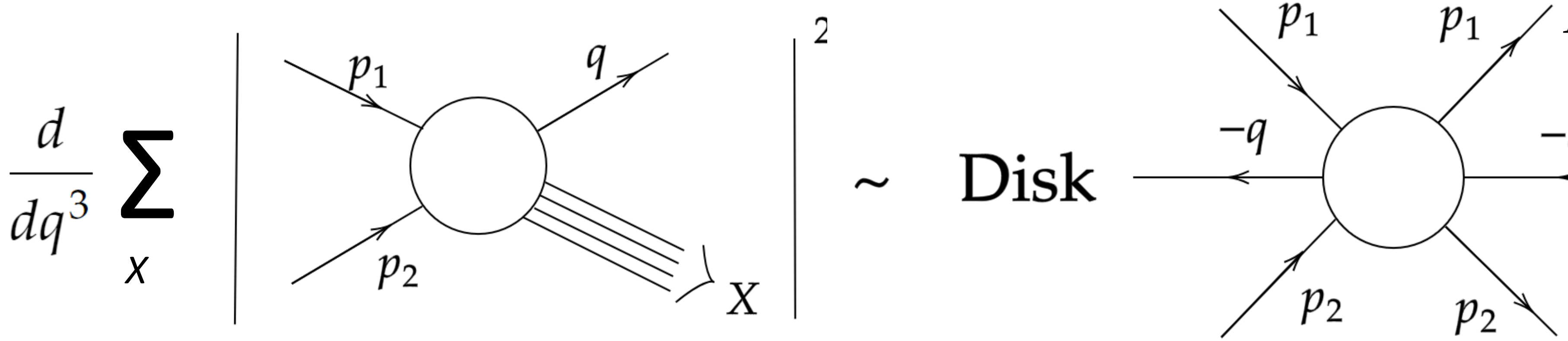
$$(2\pi)^3 2E\frac{d\sigma}{d^3q} \simeq \frac{1}{2s}\sum_X |\langle 3X|T|12\rangle|^2$$

$$\sum_X |\langle 3X|T|12\rangle|^2 = \sum_X \langle 12\bar{3}|T^\dagger|X\rangle\langle X|T|12\bar{3}\rangle$$

$$= i\langle 12\bar{3}|T^\dagger|12\bar{3}\rangle - i\langle 12\bar{3}|T|12\bar{3}\rangle$$

$$\Rightarrow (2\pi)^3 2E\frac{d\sigma}{d^3q} \simeq \frac{1}{s}\mathrm{Disc}_{M^2}\mathcal{A}^{el}_{12\bar{3}}(s,t,M^2)$$

Generalization of the optical theorem for single particle inclusive processes



Analyze in Regge theory