Baryon number dynamics from RHIC to the EIC

David Frenklakh

Brookhaven National Laboratory

2312.15039 with D. Kharzeev and W. Li
2405.04569 with D. Kharzeev, G. Rossi and G. Veneziano

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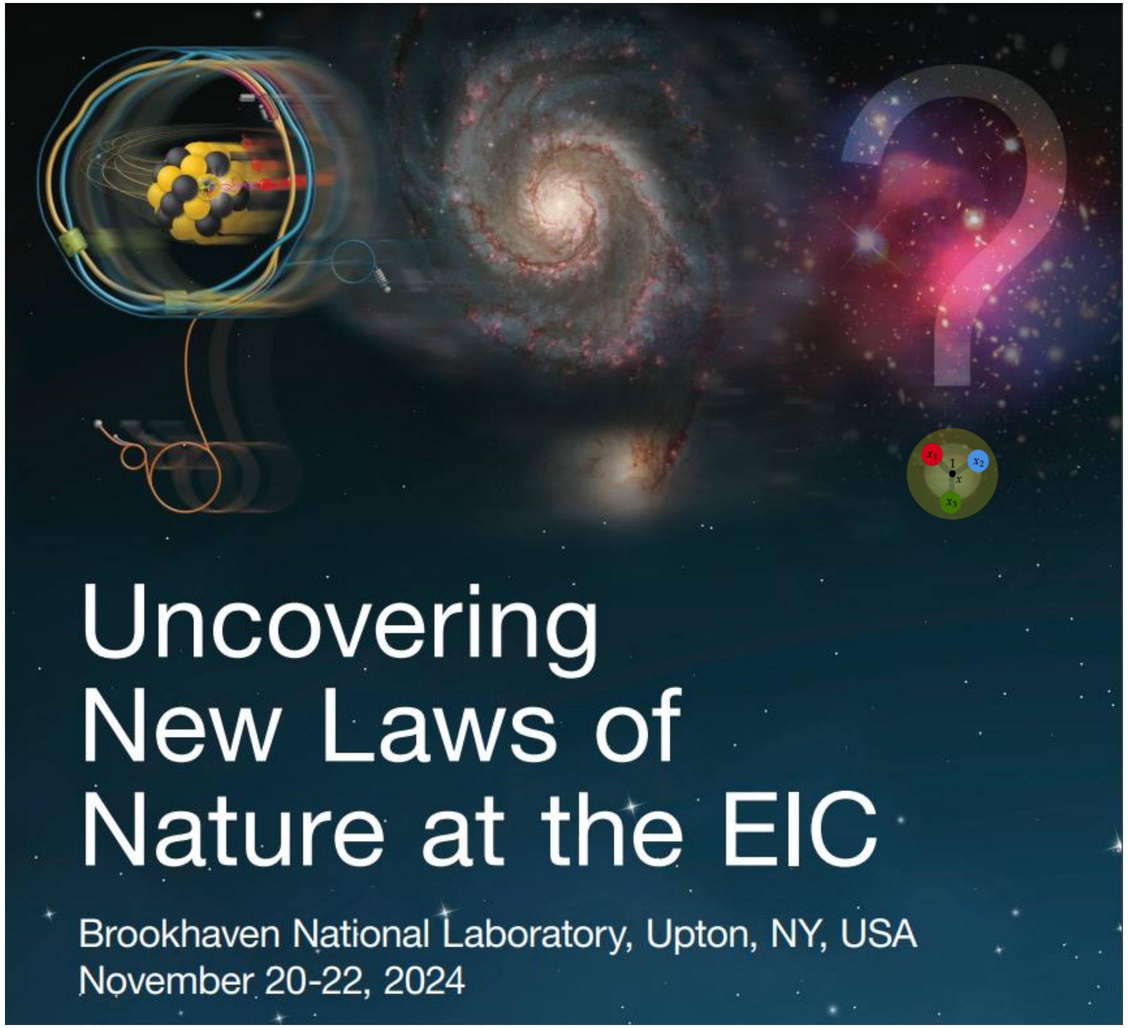

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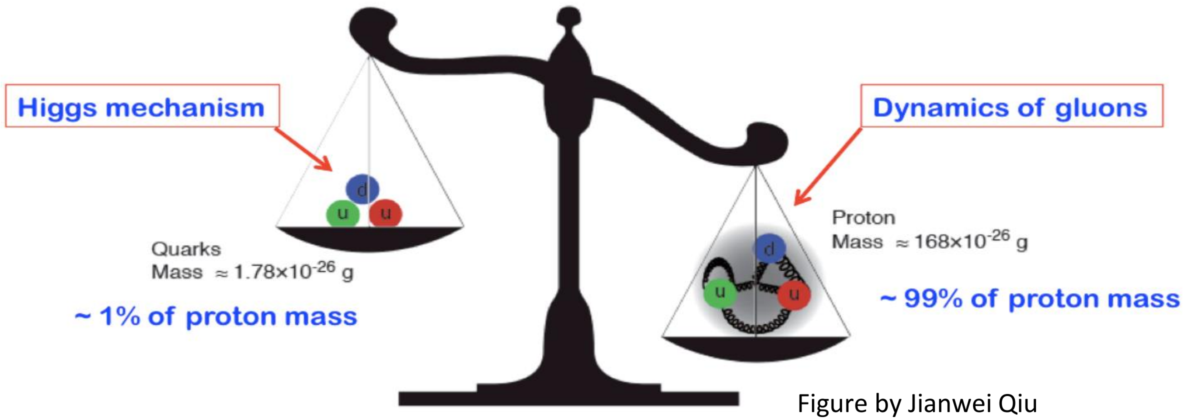

Figure by Jianwei Qiu

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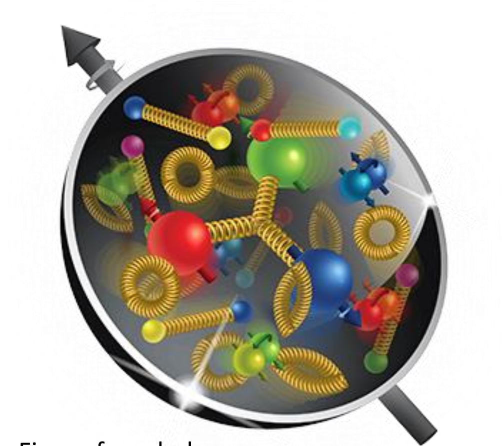

Figure from bnl.gov

$$\frac{1}{2} = \frac{\Delta\Sigma}{2} + \Delta g + L_q + L_g$$

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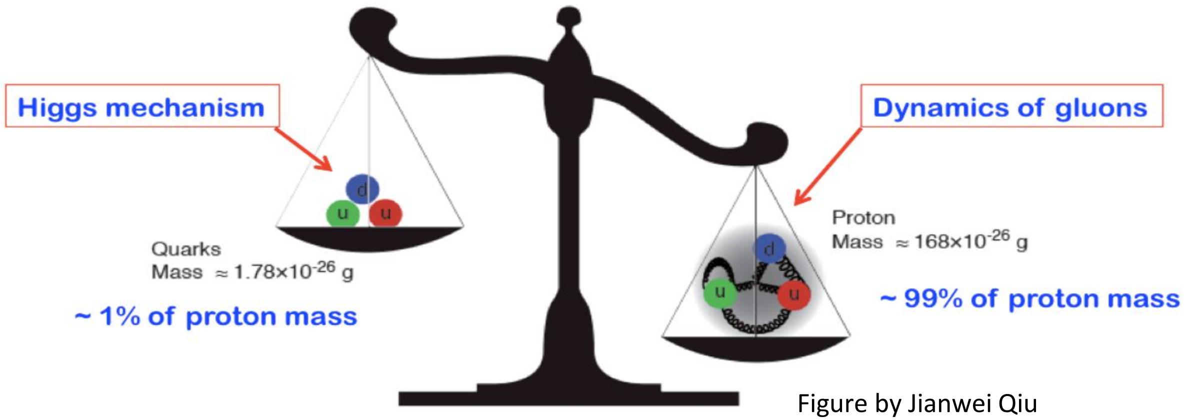

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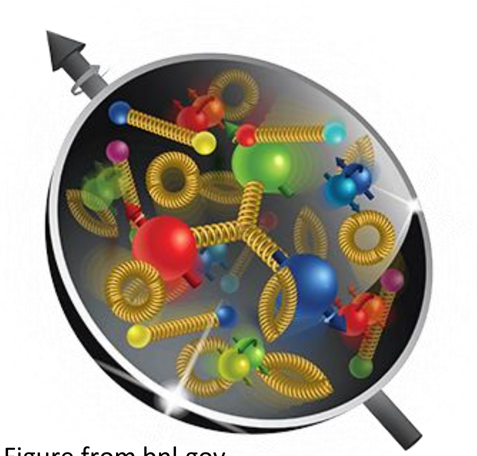

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What about baryon number?

Outline

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

Motivation: what carries the baryon number?

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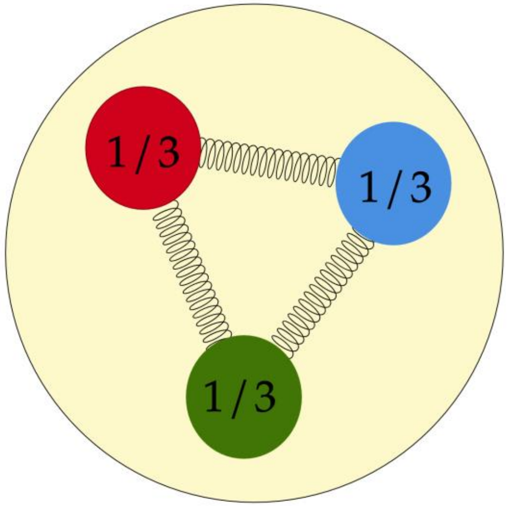
$$B(x_1, x_2, x_3) = \epsilon^{ijk} q(x_1)_i \; q(x_2)_j q(x_3)_k$$



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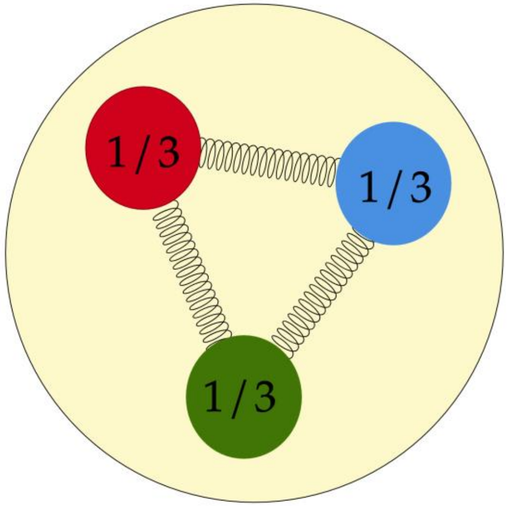
Gauge invariance



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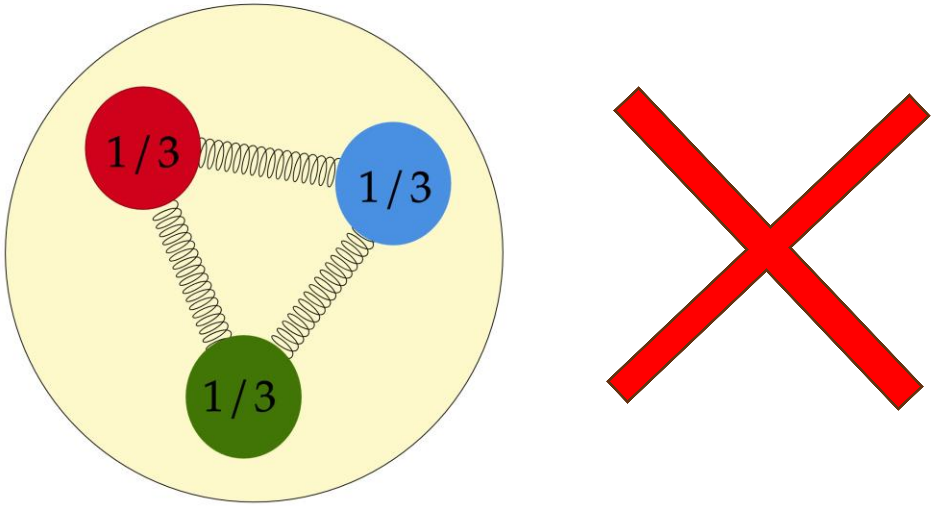
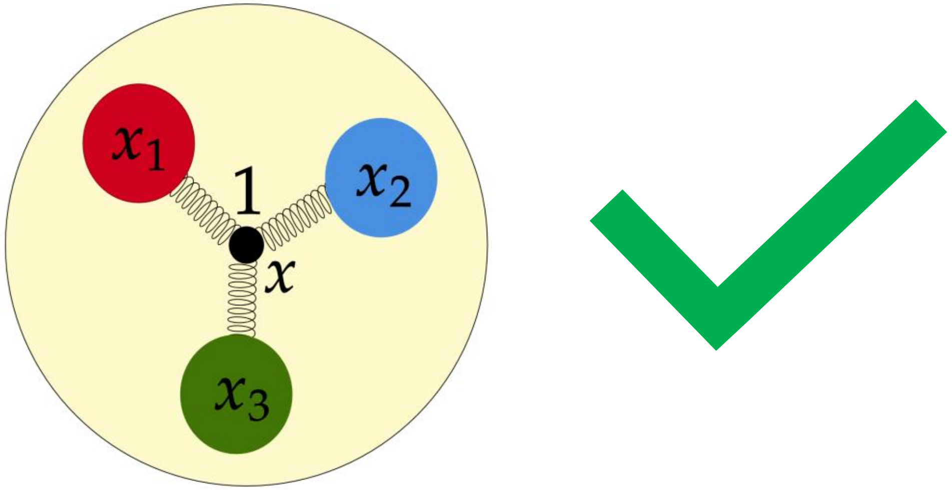


Gauge invariance

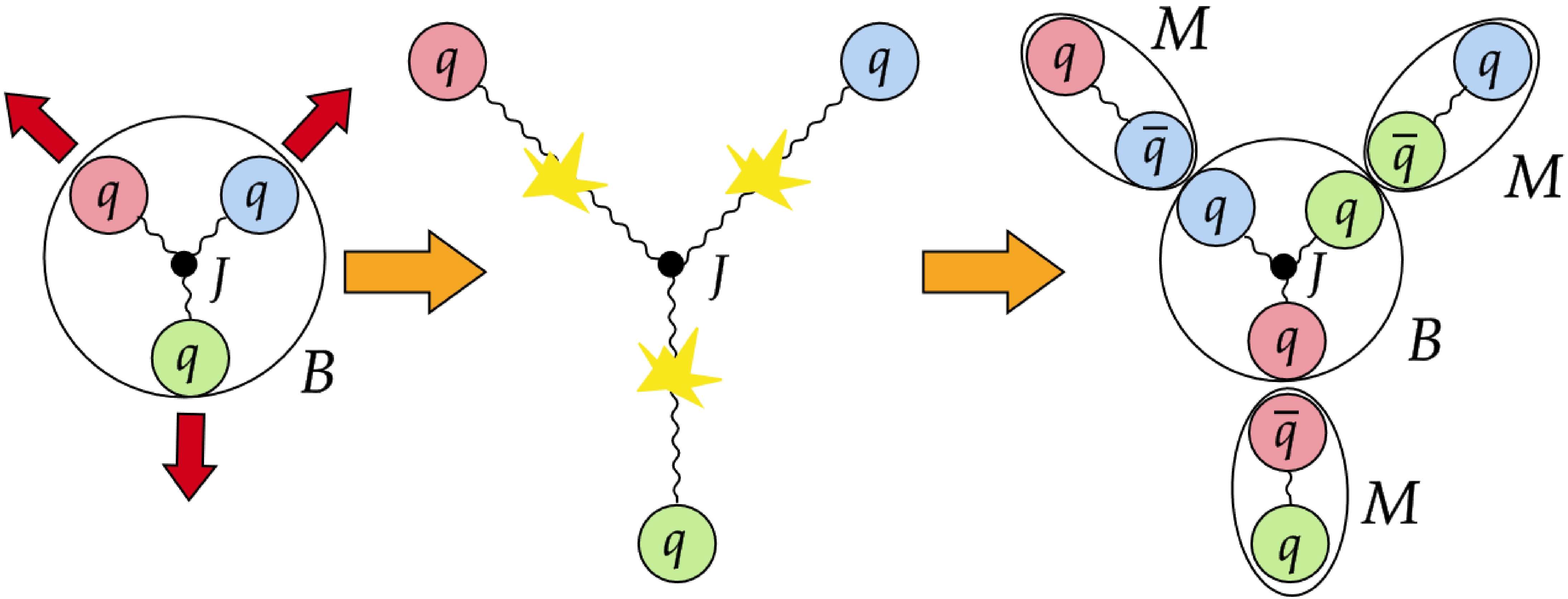
$$B(x_1, x_2, x_3, x) = \epsilon^{ijk} \; [P(x_1, x) \; q(x_1)]_i \; [P(x_2, x) \; q(x_2)]_j \, [P(x_3, x) \; q(x_3)]_k$$

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



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

Can baryon junction carry the baryon number?

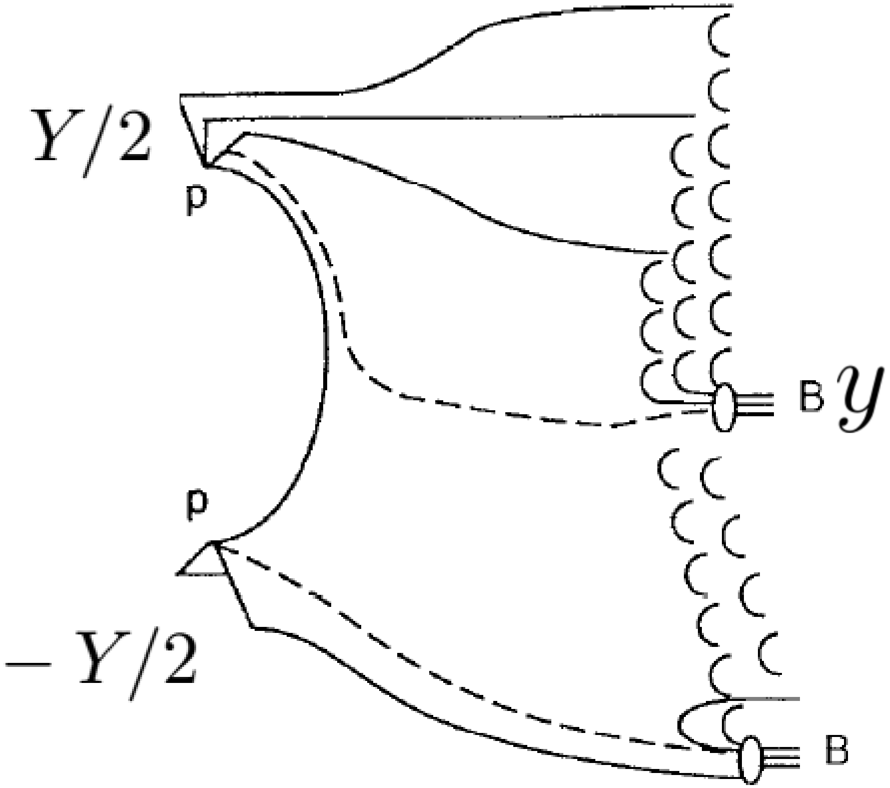


Baryon stopping in pp and AA

Can gluons trace baryon number?

D. Kharzeev

Physics Letters B 378 (1996) 238--246



Dashed lines denote junctions

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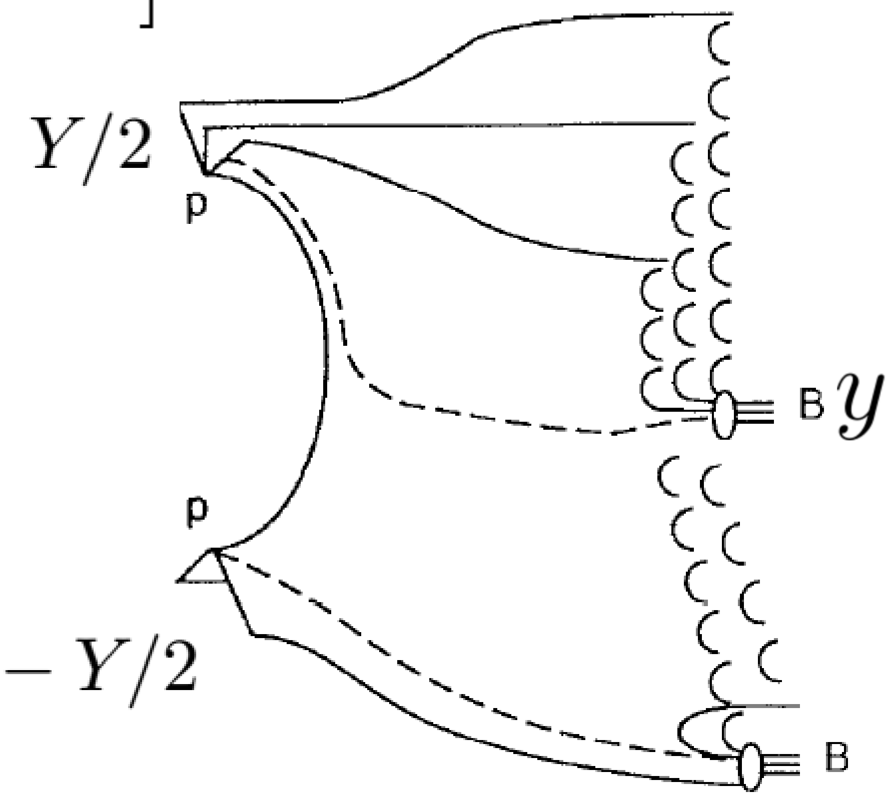

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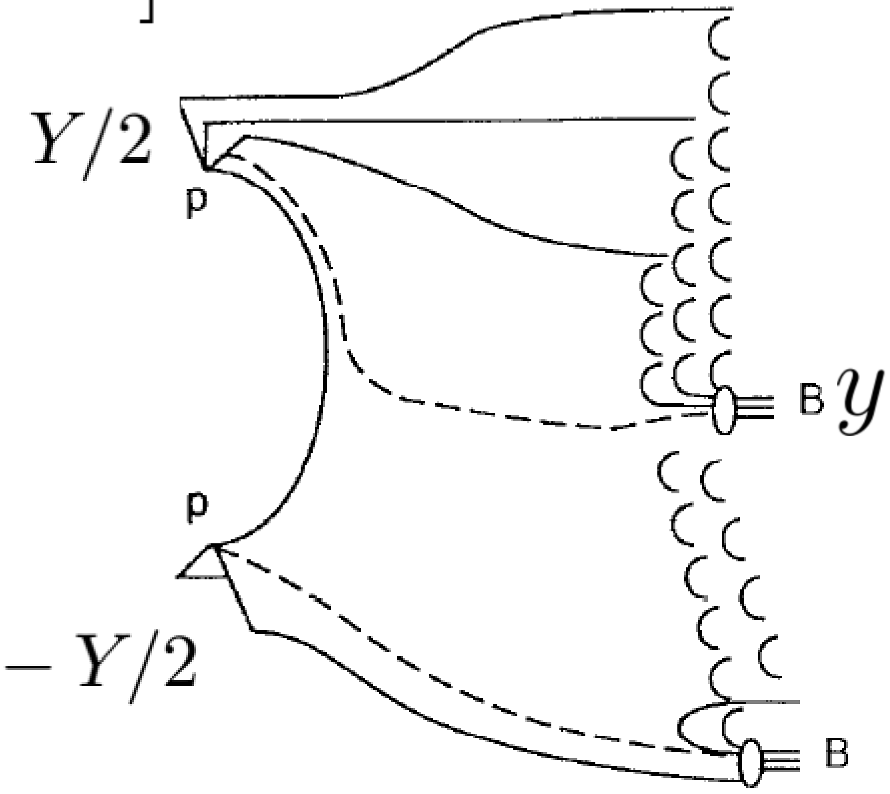

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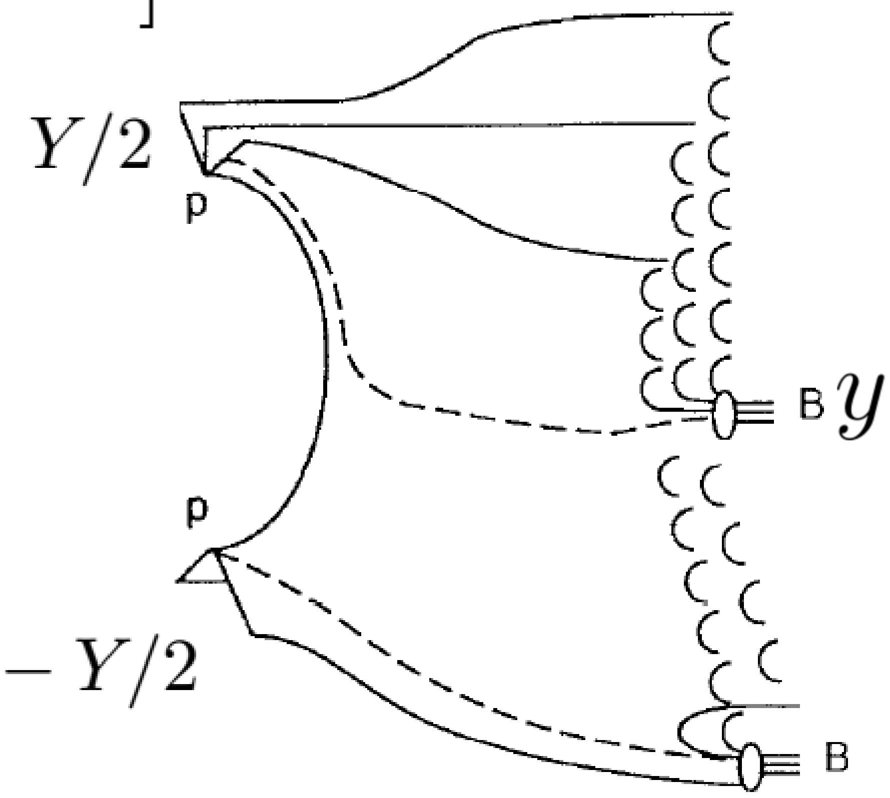
$$\frac{dN}{dy} \propto e^{-0.42Y/2}[e^{0.58y} + e^{-0.58y}]$$



Dashed lines denote junctions

Recent experimental works

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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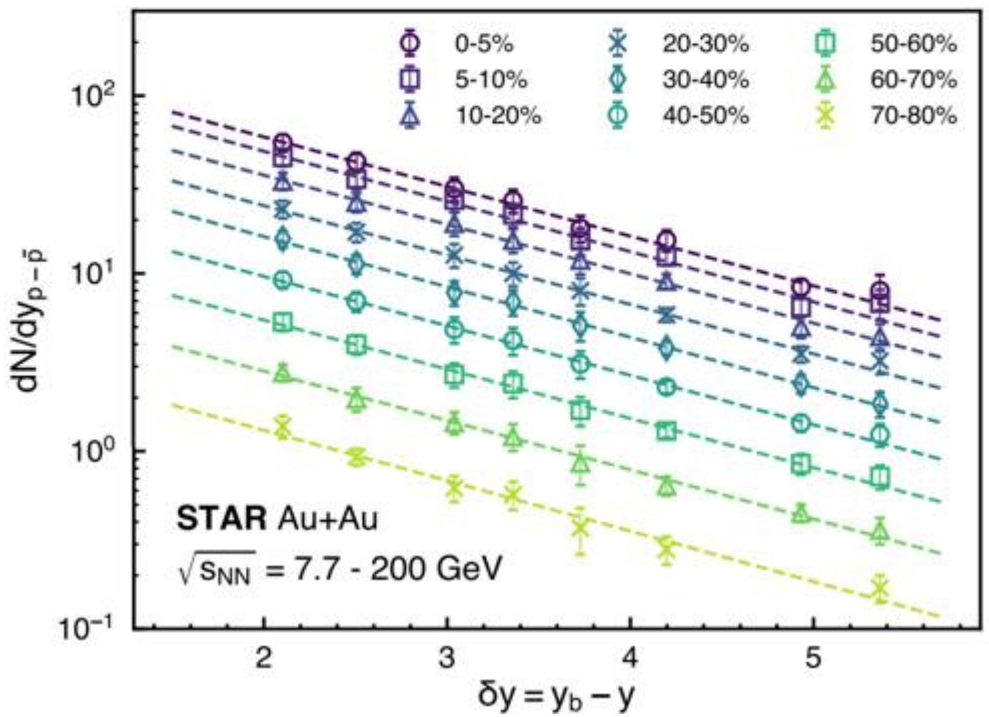

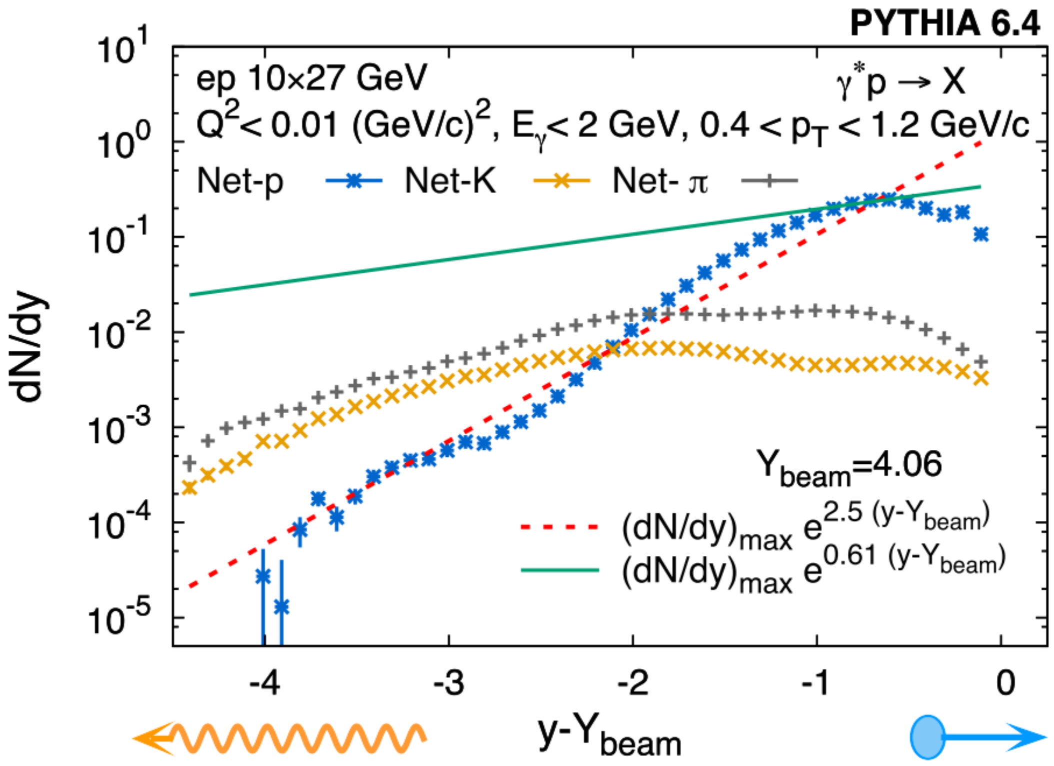

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2309.06445

Correlations of baryon and charge stopping in heavy ion collisions*

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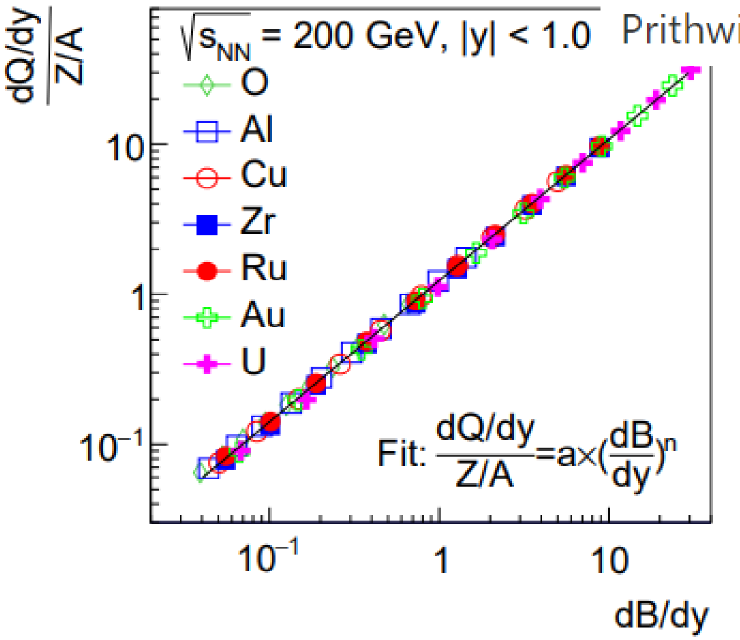

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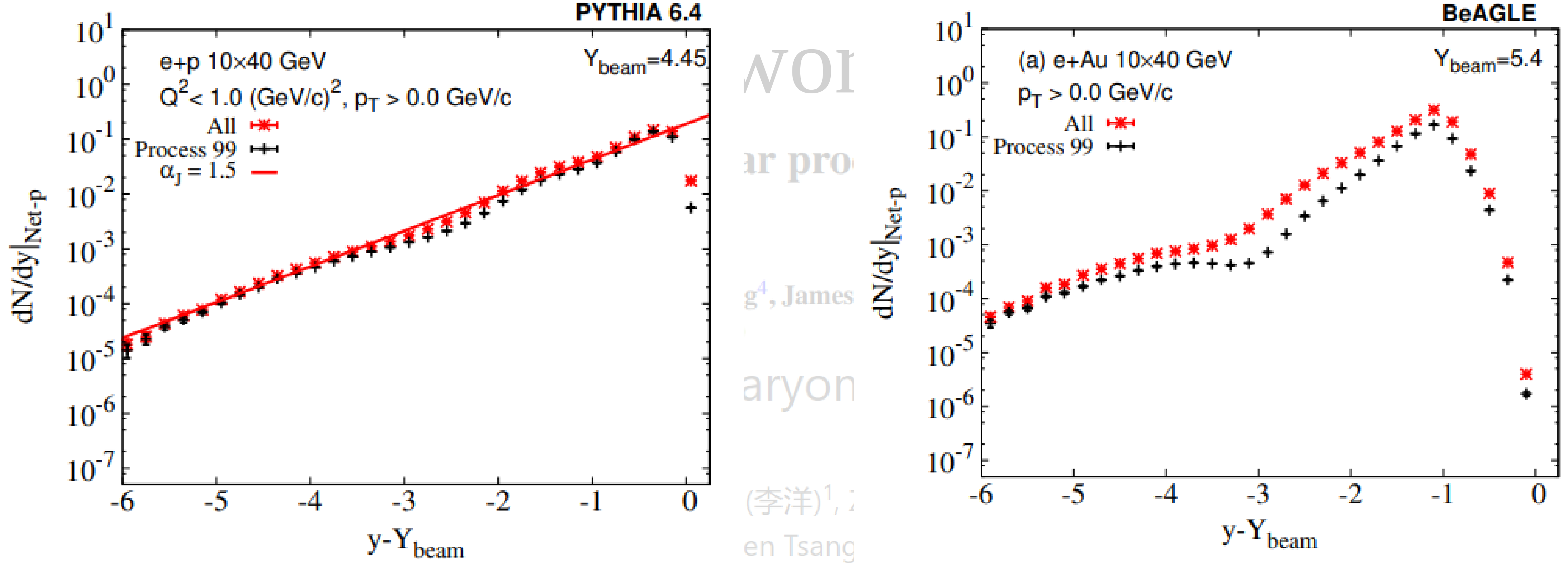
Search for baryon junctions in e+A collisions at the Electron Ion Collider

2408.07131

Niseem Magdy,[1,2,3,*] Abhay Deshpande,[4,5,2] Roy Lacey,[1,4] Wenliang Li,[4,2] Prithwish Tribedy,[5] and Zhangbu Xu[6,5]



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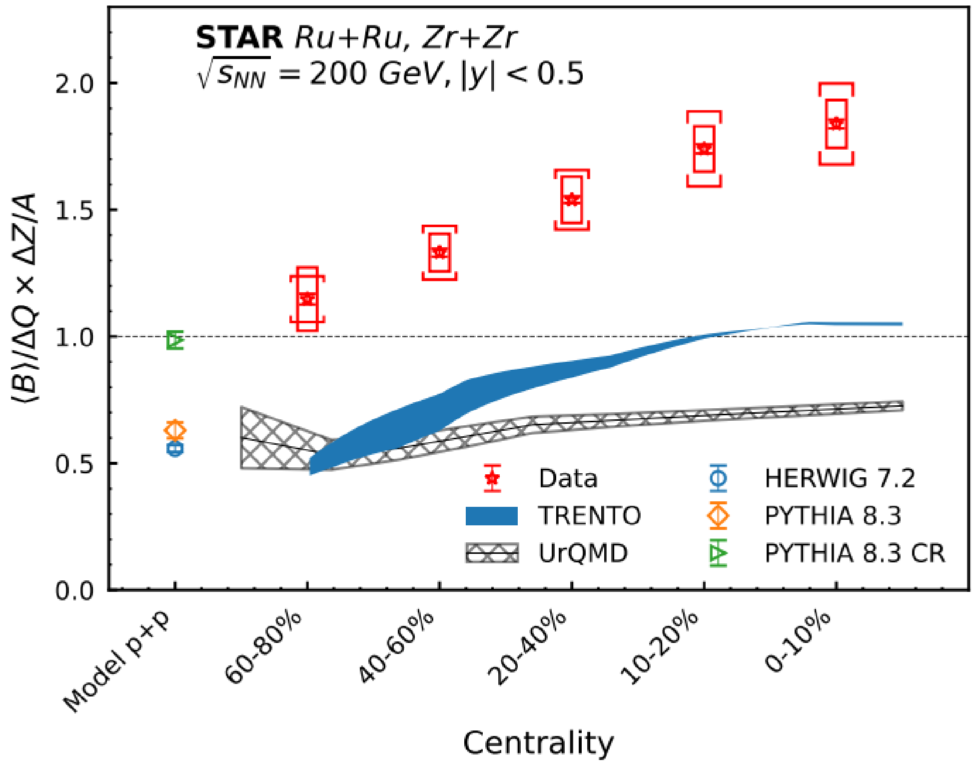
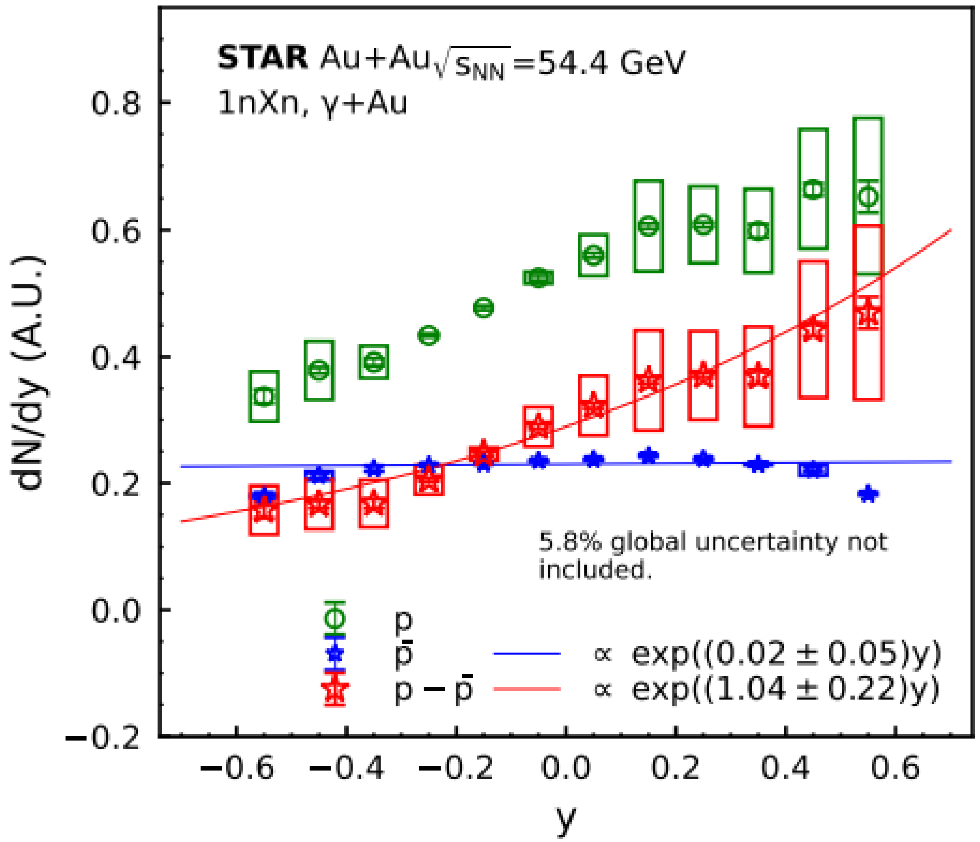
2408.15441

Tracking the baryon number with nuclear collisions

STAR Collaboration





Search for baryon junctions in e+A collisions at t

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

2409.06492

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Correl ... in heavy ion
collisi

2309.06445

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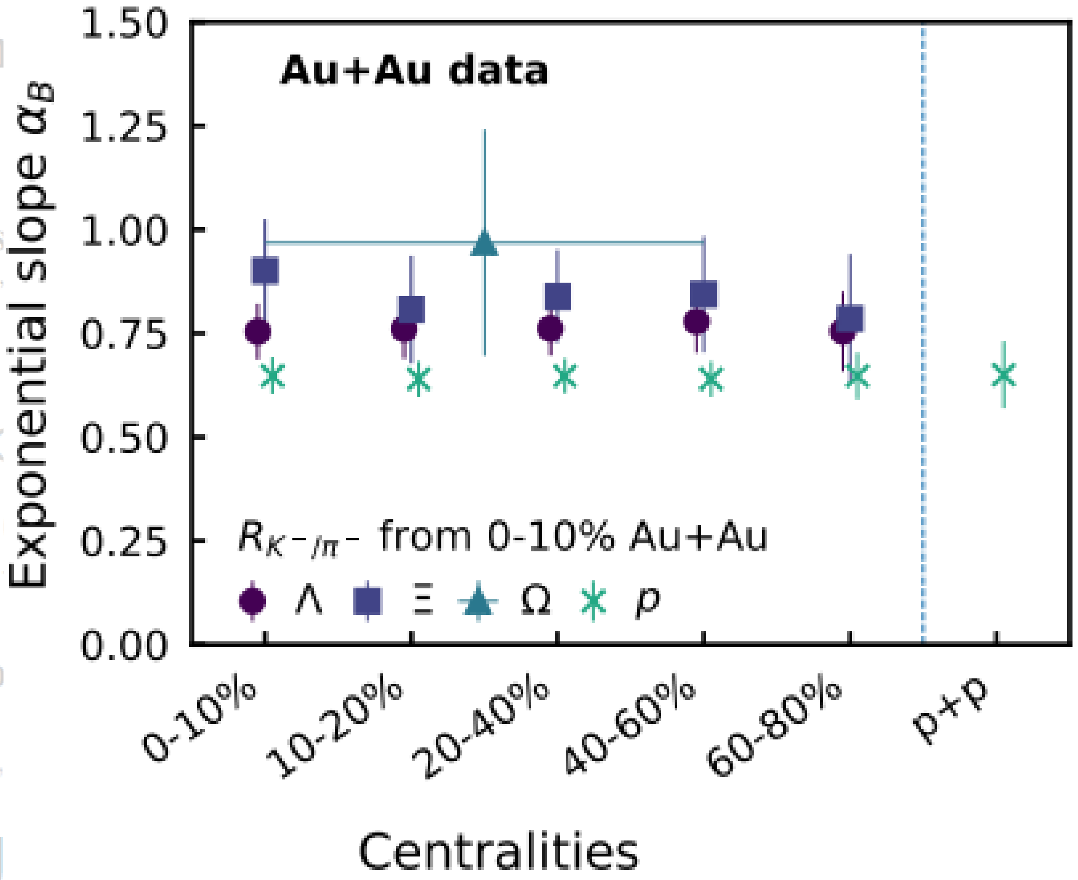

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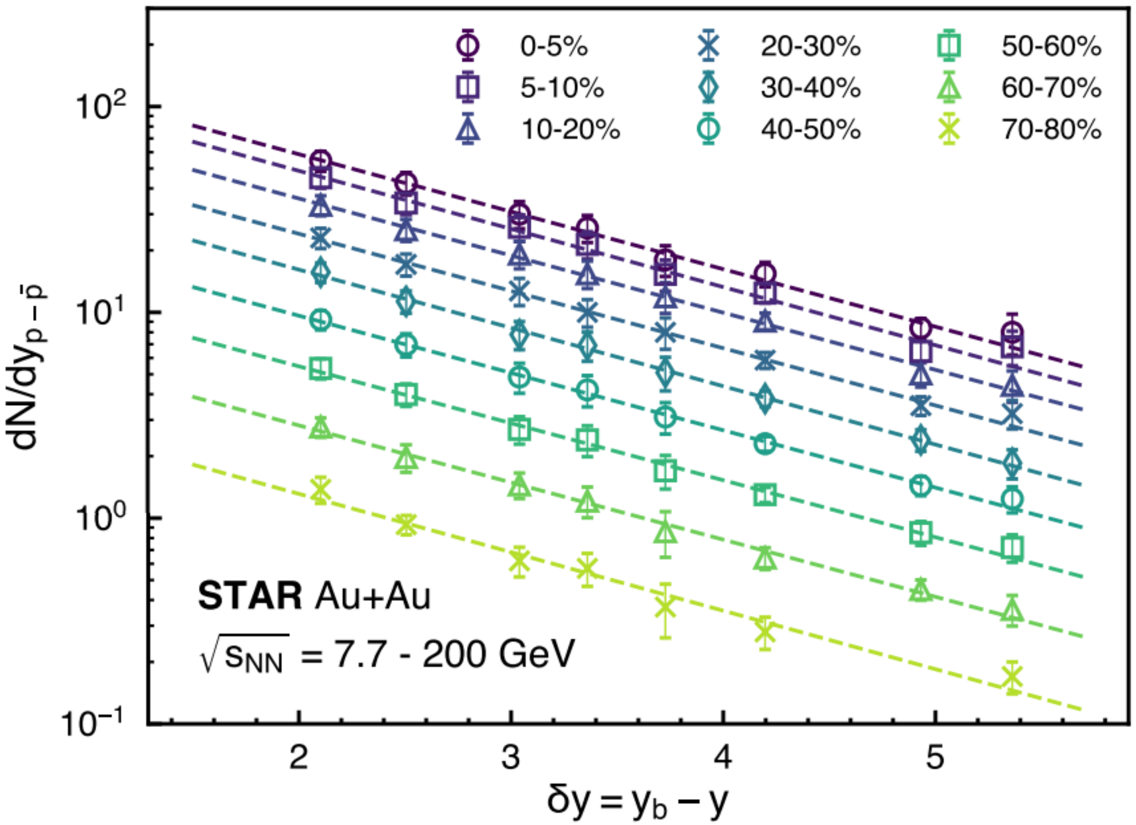
RHIC Beam Energy Scan data



N. Lewis et al
arXiv:2205.05685(2022)

Experimental rapidity slope:

$$\sim 0.65 \pm 0.1$$

$$2 - \alpha_{\mathbb{P}} - \alpha_{\mathbb{J}_0}$$

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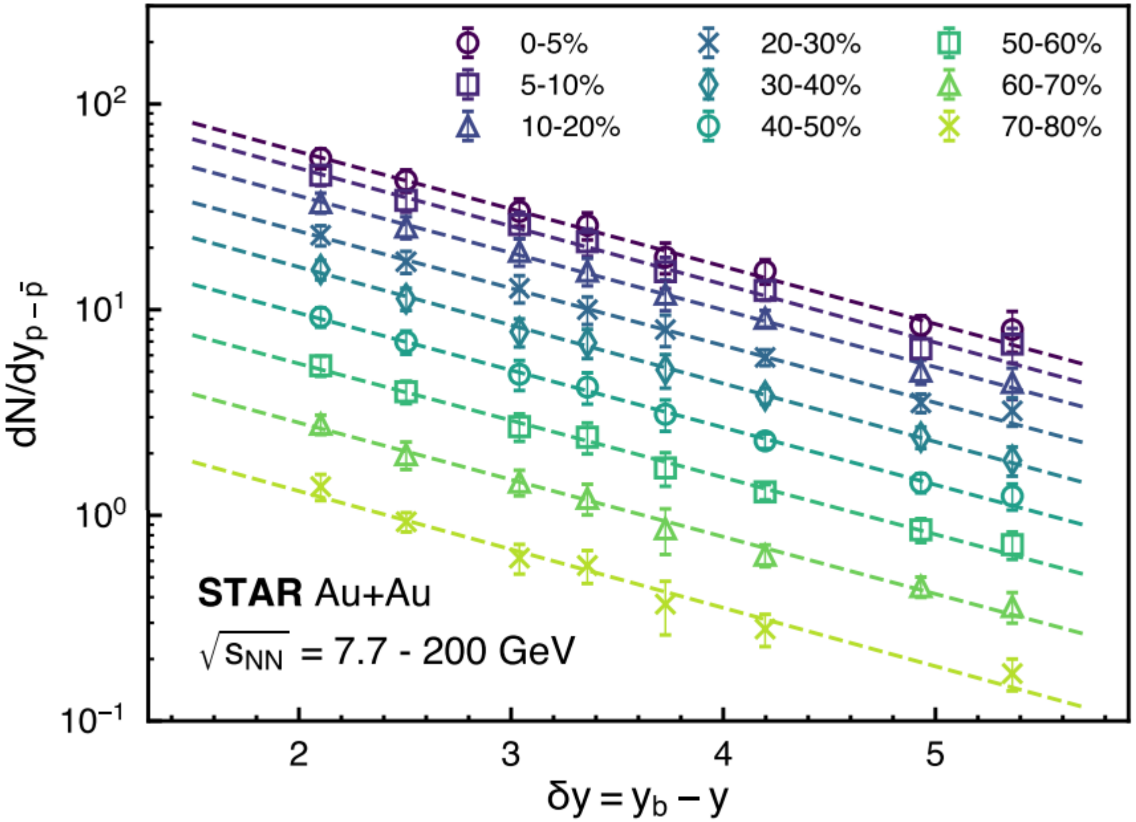

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New theory input on $\alpha_{\mathbb{J}_0}$

Topological expansion + Feynman-Wilson gas accounting for correlations in three strings breaking: $\alpha_{\mathbb{J}_0} \simeq 0.26$ 2405.04569

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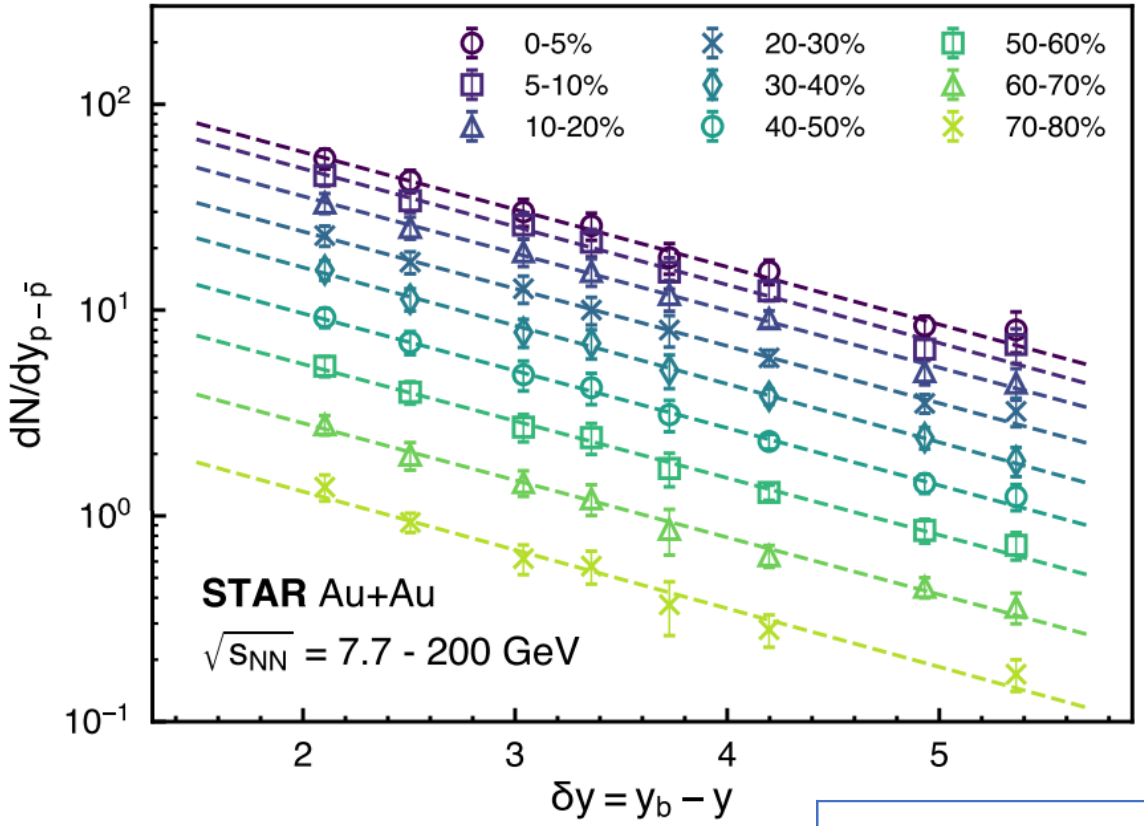

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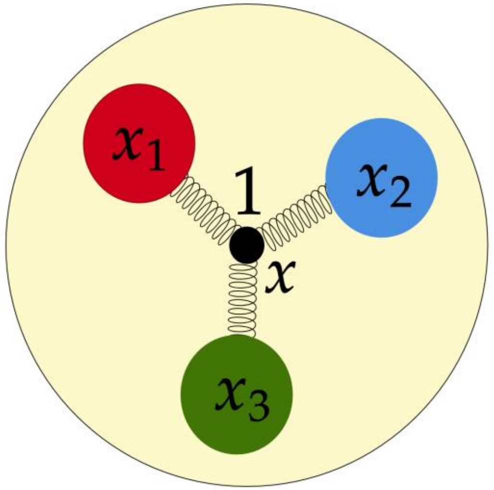
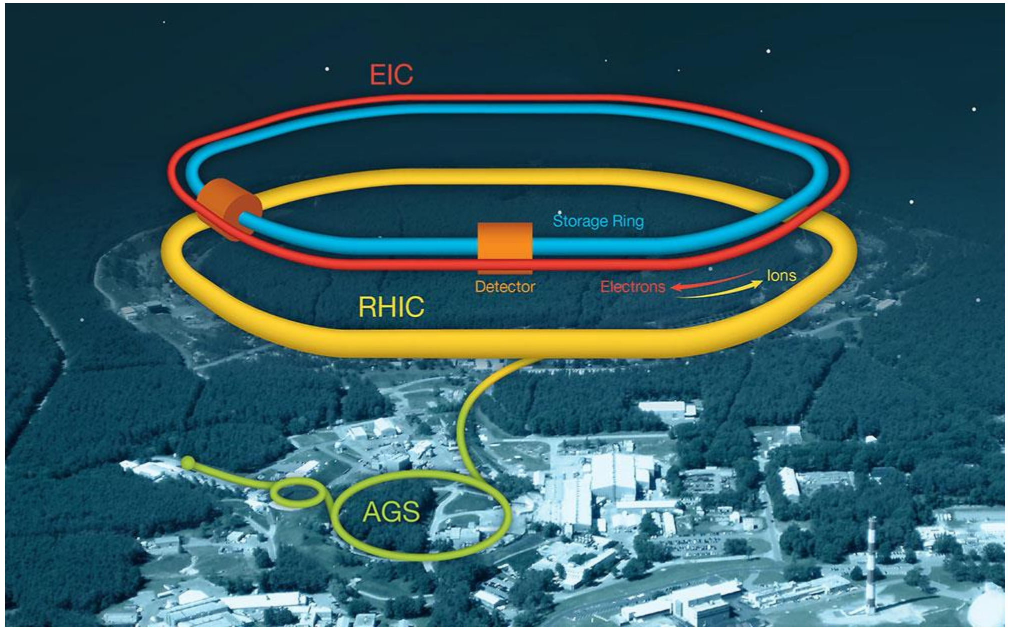
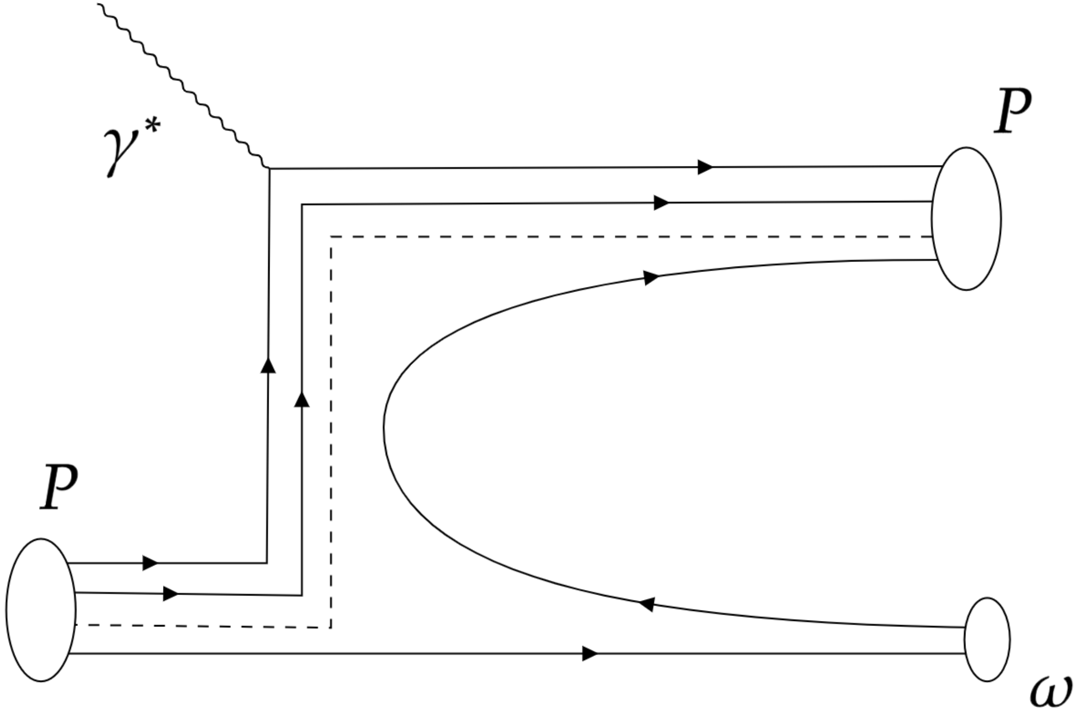
	Rapidity slope	$\alpha_{\mathbb{J}_0}$ **intercept**
Experiment	$\sim 0.65 \pm 0.1$	
"Old" theory	0.42	0.5
"New" theory	0.66	0.26

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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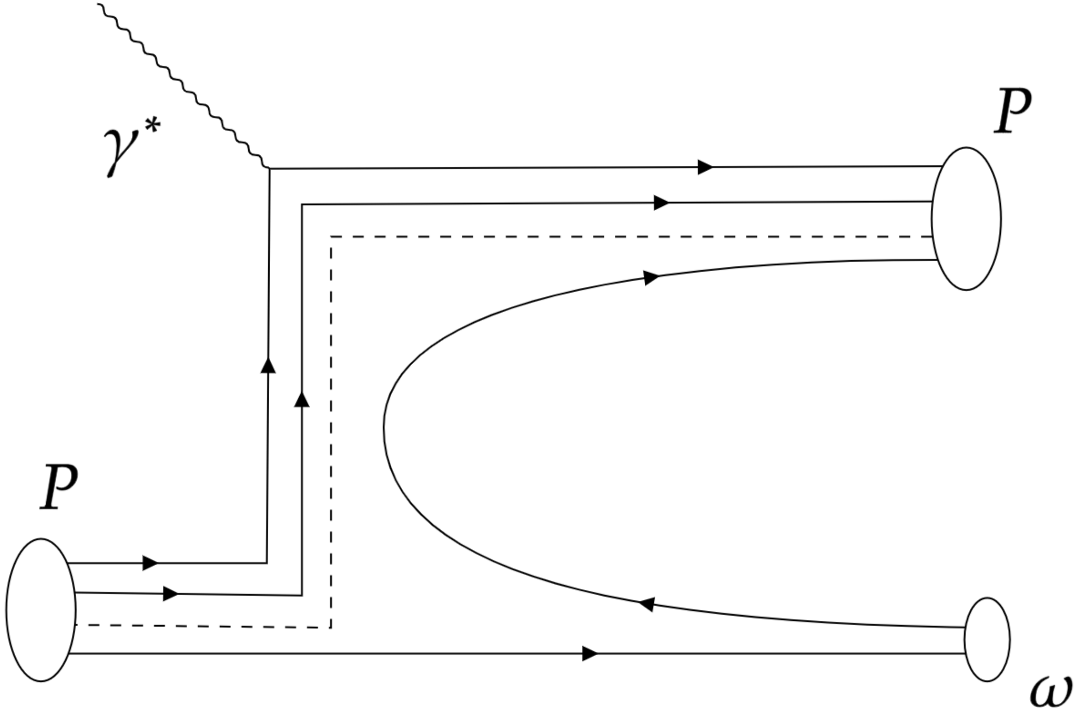

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Significant fraction of events with the proton in the γ^* fragmentation region

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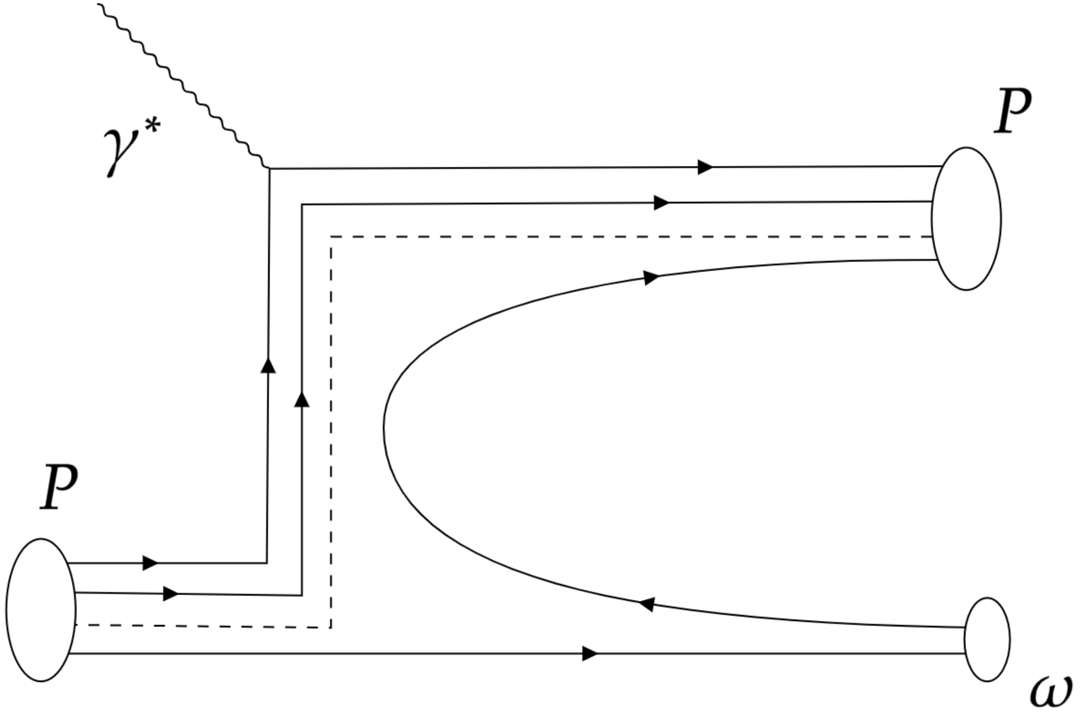

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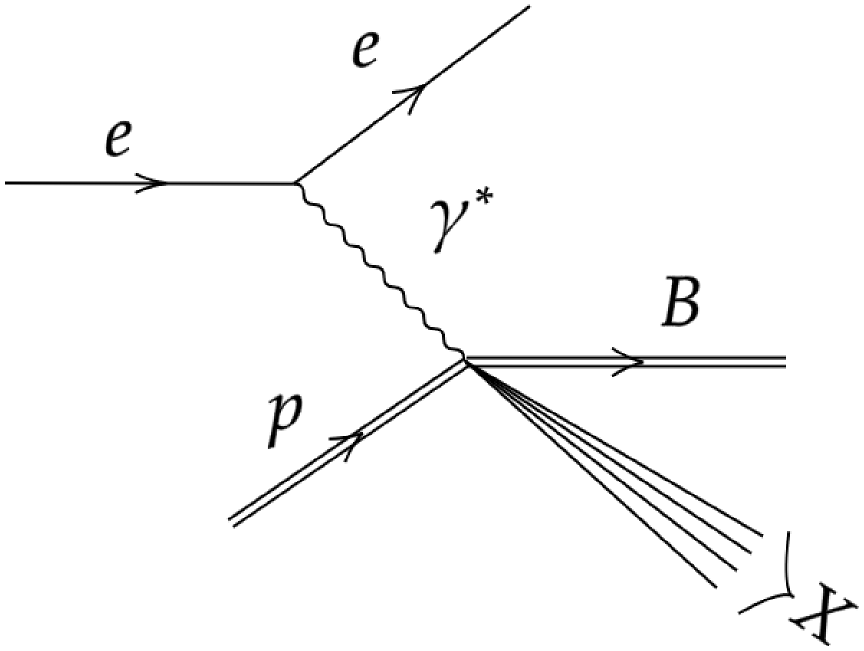
Need a semi-inclusive process

Semi-inclusive deep inelastic scattering (DIS)



$\gamma^* p$ center of mass frame:

$$p_{\gamma^*} = (\frac{\sqrt{s}}{2}, \frac{\sqrt{s}}{2}, 0^{\perp})$$

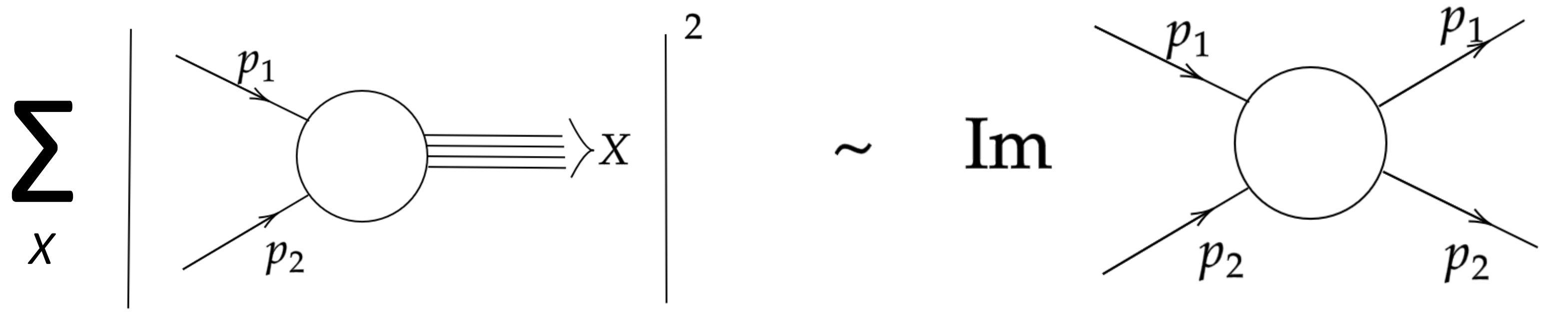
$$p_p = (\frac{\sqrt{s}}{2}, -\frac{\sqrt{s}}{2}, 0^{\perp})$$

$$p_B = (m_t \cosh y^*, m_t \sinh y^*, p_B^{\perp})$$

Mueller-Kancheli theorem

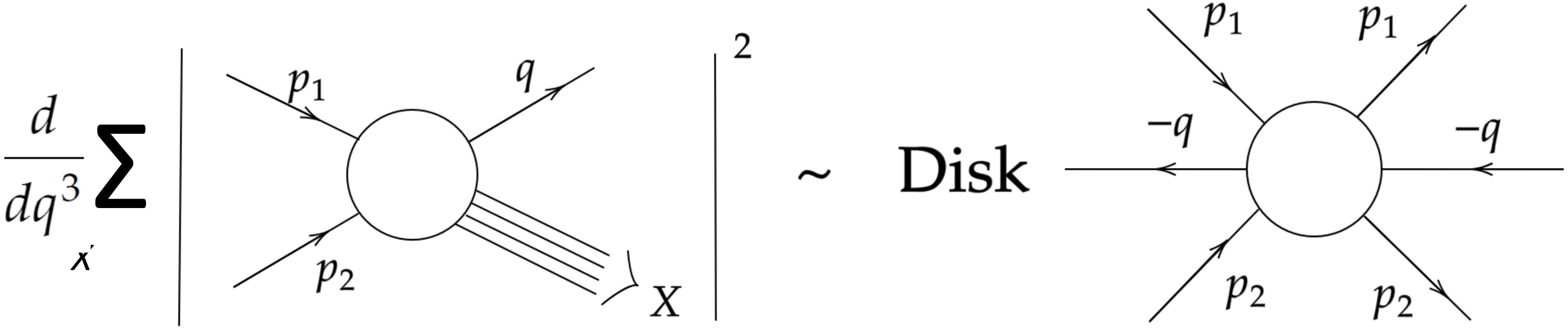
A.H. Mueller, Phys. Rev. D 2 (1970) 2963.
O.V. Kancheli, JETP Lett. 11 (1970) 397.

Optical theorem:



Generalized to semi-inclusive scattering:

Study in Regge theory



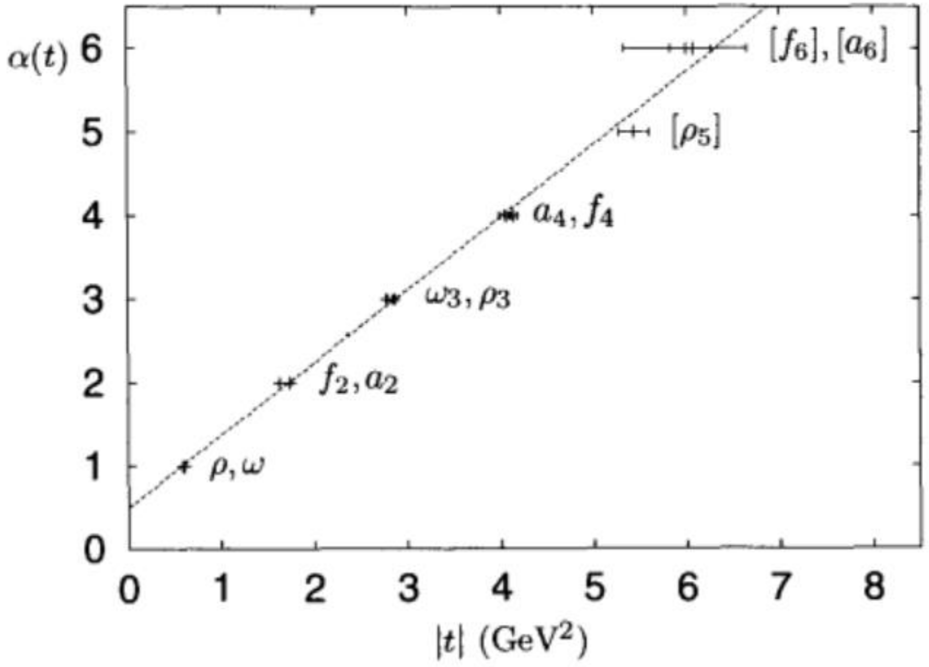
Basics of Regge theory

S-matrix unitarity + analyticity + crossing symmetry
fix the leading behavior of scattering amplitudes at very high energy.

For $2 \to 2$ scattering

$\mathcal{A}(s,t) \sim s^{\alpha(t)}$ at $s \gg |t|, m^2$

where $\alpha(t) = \alpha(0) + \alpha' t$ are Regge trajectories containing physical states that can be exchanged in the t-channel.
Then $\alpha(M^2) = J$ - spin of the exchanged state



Cross sections in Regge theory

Total inclusive cross-section: optical theorem + Regge behavior of the amplitude

$$\sigma_{tot} \simeq \frac{1}{s}\mathrm{Im}\,\mathcal{A}(s,t=0) \sim \frac{1}{s}s^{\alpha(0)} = s^{\alpha(0)-1}$$

Exclusive $2 \to 2$ cross-section:

$$\frac{d\sigma}{dt} \propto \frac{|\mathcal{A}(s,t)|^2}{s^2} \sim s^{2\alpha(t)-2}$$

When integrated over t the largest $\alpha(t) = \alpha(0)$ dominates:

$$\sigma_{2\to 2} \sim s^{2\alpha(0)-2}$$

The Pomeron

All reliably known mesons and baryons have Regge intercept $\alpha(0) < 1$.

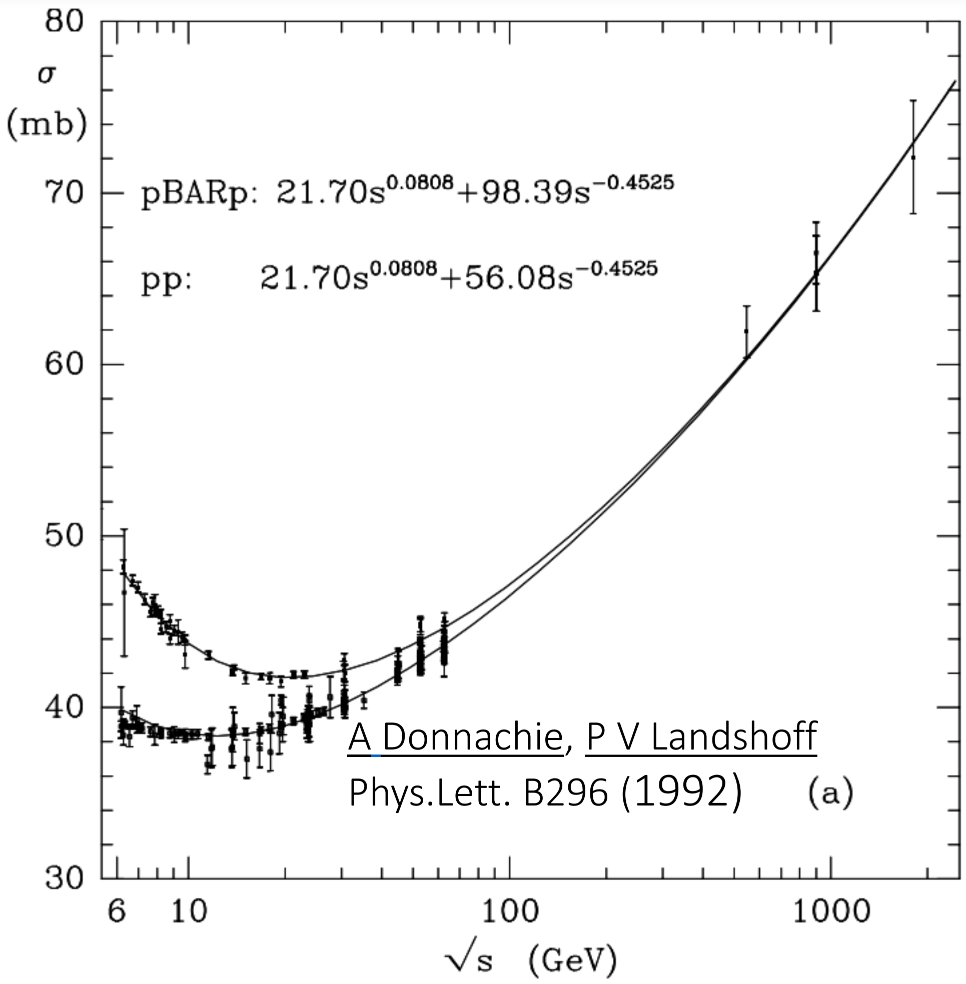
Does it imply $\sigma_{tot} \sim s^{\alpha(0)-1}$ decreases with c.o.m. energy?

Experiment: NO! Instead, it steadily grows

Introduce a new object in Regge theory: the Pomeron

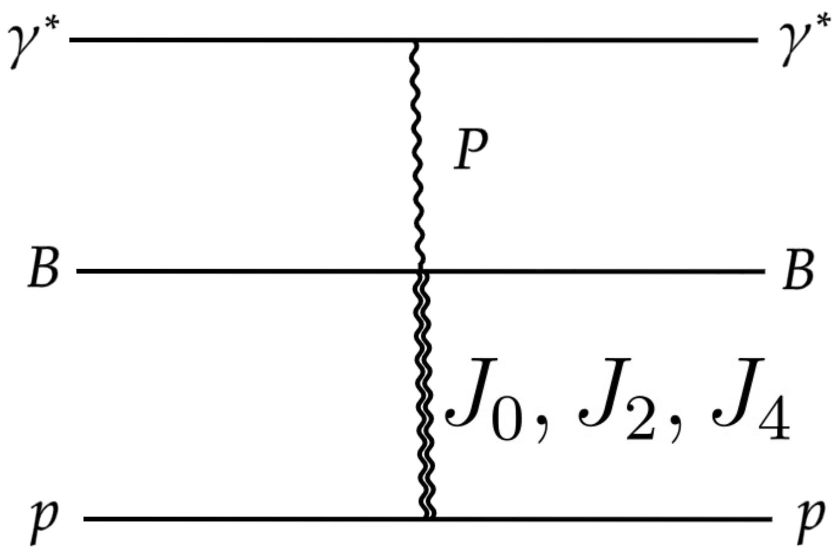
$$\alpha_{\mathbb{P}} = 1 + \Delta \simeq 1.08$$

It has vacuum quantum numbers and dominates any inclusive hadronic process at very high energy.



A Donnachie, P V Landshoff Phys.Lett. B296 (1992)

$3 \rightarrow 3$ forward scattering in double Regge limit



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

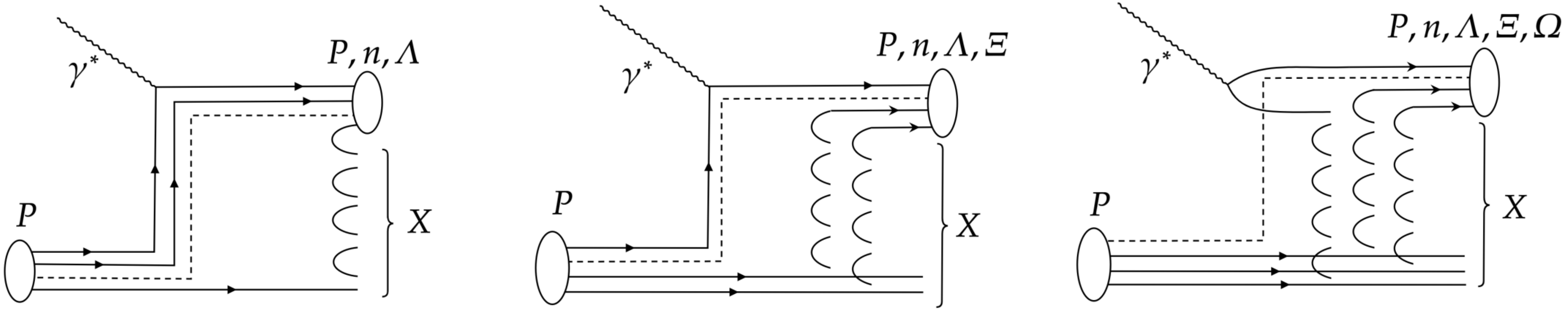
$$s_1 = (p_1 + p_B)^2 = \sqrt{s}\, m_t\, e^{-y^*}$$

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

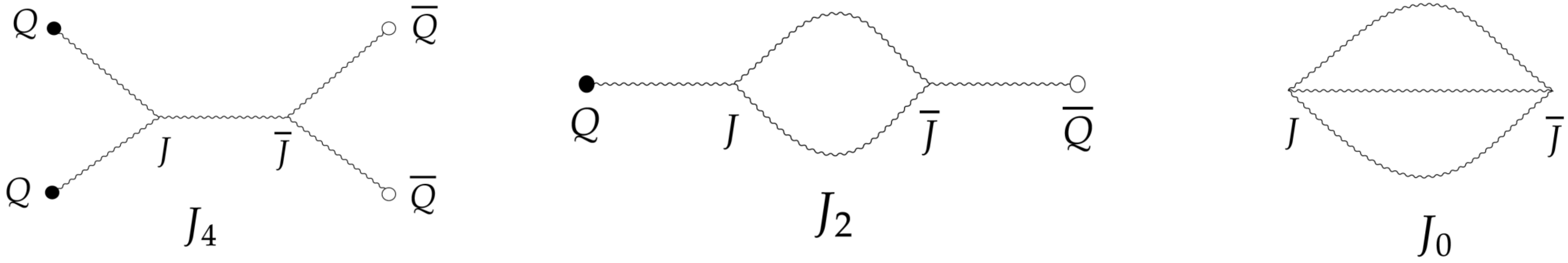
$$E_B \frac{d^3\sigma}{dp_B^3} \propto s_1^{\alpha_{\mathbb{P}}(0)-1}\, s_2^{\alpha_{\mathbb{J}}(0)-1}$$

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

Three possible processes



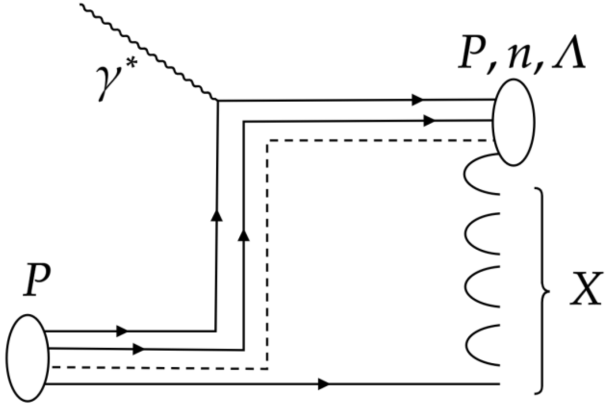
Mueller-Kancheli t-channel exchanges:

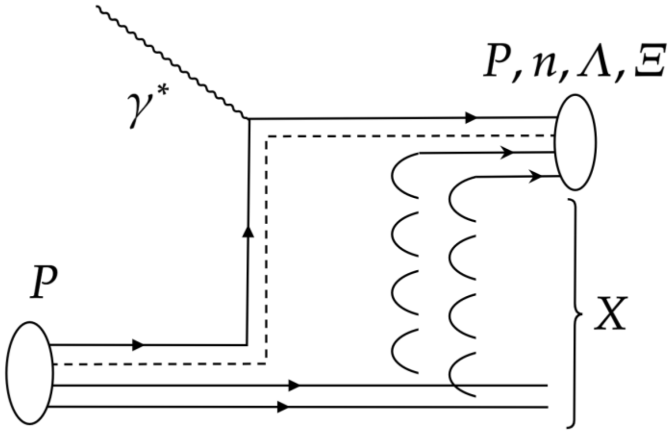


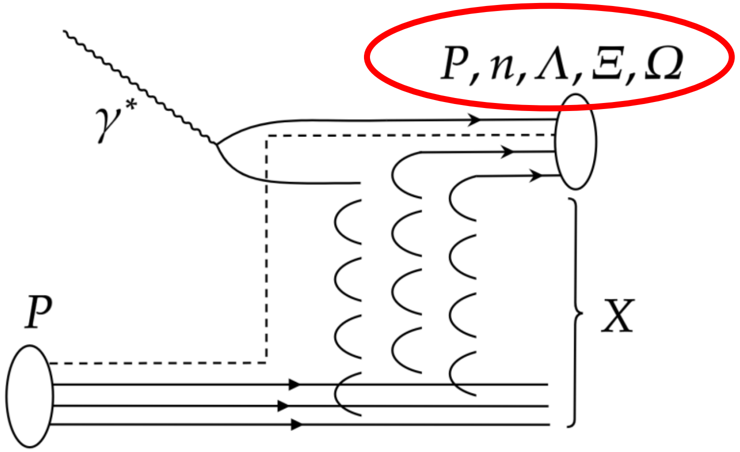
$$\alpha_4^J(0) \approx -\frac{1}{2} \qquad \alpha_2^J(0) \approx 0 \qquad \alpha_0^J(0) \approx \frac{1}{2}$$

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

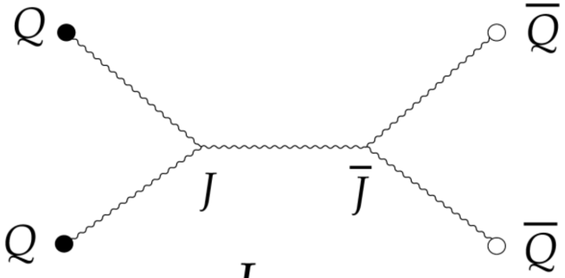
Three possible processes





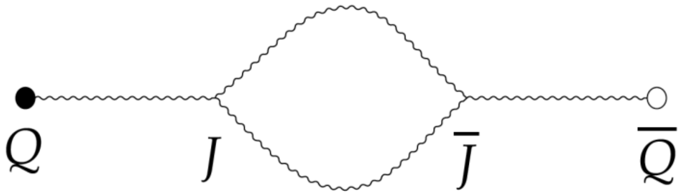


Mueller-Kancheli t-channel exchanges:



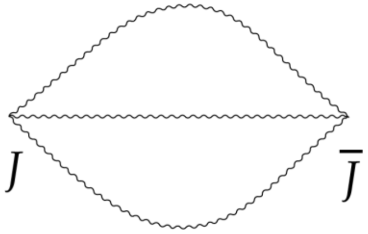
J_4

$$\alpha_4^J(0) \approx -\frac{1}{2}$$



J_2

$$\alpha_2^J(0) \approx 0$$



J_0 Leading

$$\alpha_0^J(0) \approx \frac{1}{2}$$

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

Rapidity distribution of baryons in DIS

$$E_B \frac{d^3\sigma}{dp_B^3} \propto s_1^{\alpha_{\mathbb{P}}(0)-1} s_2^{\alpha_{\mathbb{J}_0}(0)-1}$$

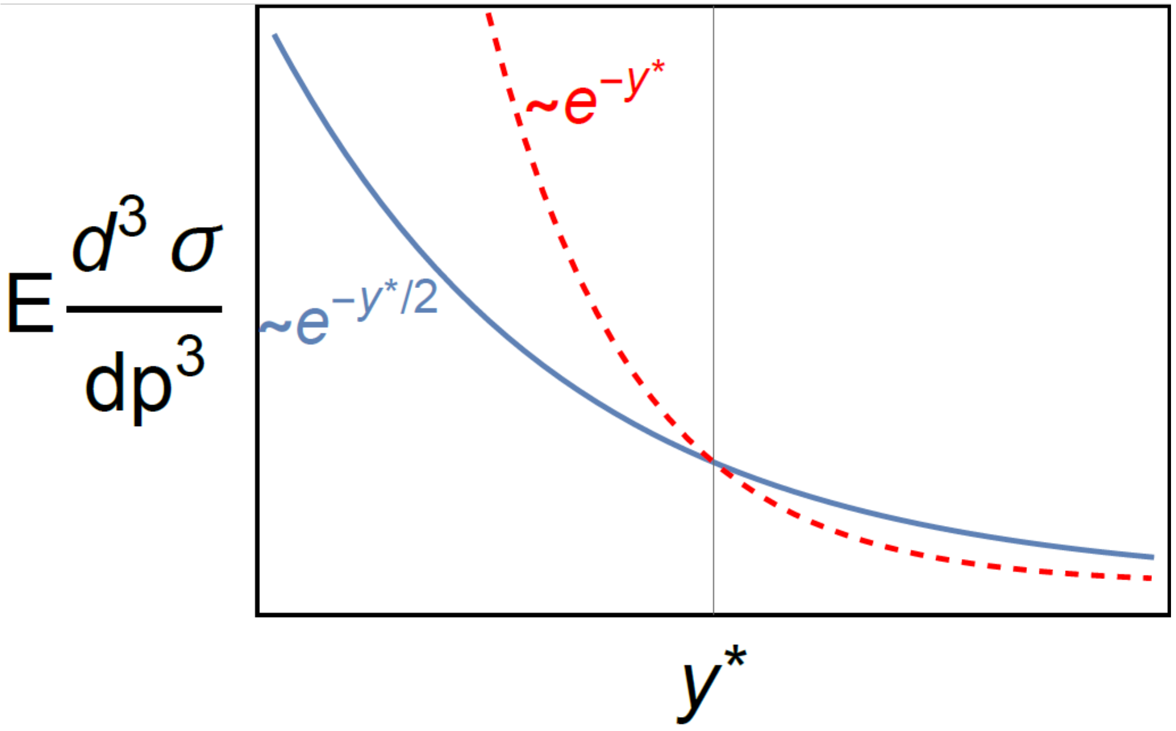
$$s_1 = (p_1 + p_B)^2 = \sqrt{s}\, m_t\, e^{-y^*}$$

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

assuming $\alpha_{\mathbb{P}}(0) \approx 1, \quad \alpha_{\mathbb{J}_0}(0) \approx 0.5$

$$E_B \frac{d^3\sigma}{dp_B^3} \propto s^{-1/4} e^{-y^*/2}$$

Prediction for the EIC



For pp collision the derivation is similar but the final baryon can arise from either of the two initial ones.

Summary

- Accounting for inter-species correlations in Feynman-Wilson gas is in excellent agreement with RHIC baryon stopping data

- Search for signatures of baryon junctions in semi-inclusive DIS:

  - ❑Beam energy dependence and rapidity distribution of net baryon number
  - ❑Flavor composition independence
  - ❑Large multiplicity of mesons in the baryon rapidity gap