Baryon number dynamics from RHIC to the EIC

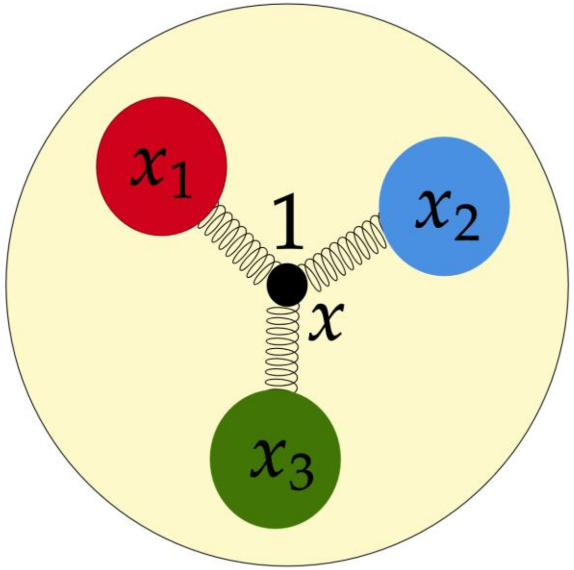
David Frenklakh

Stony Brook University

2402.06754 with D. Kharzeev and A. Palermo

Phys.Lett.B 853(2024) with D. Kharzeev and W. Li

JHEP 07 (2024) 262 with D. Kharzeev, G. Rossi, G. Veneziano



Stony Brook University

INT Program “Heavy ion physics in the EIC era”

Seattle July 31, 2024

Outline

Part 1: Anomalous baryon number transport

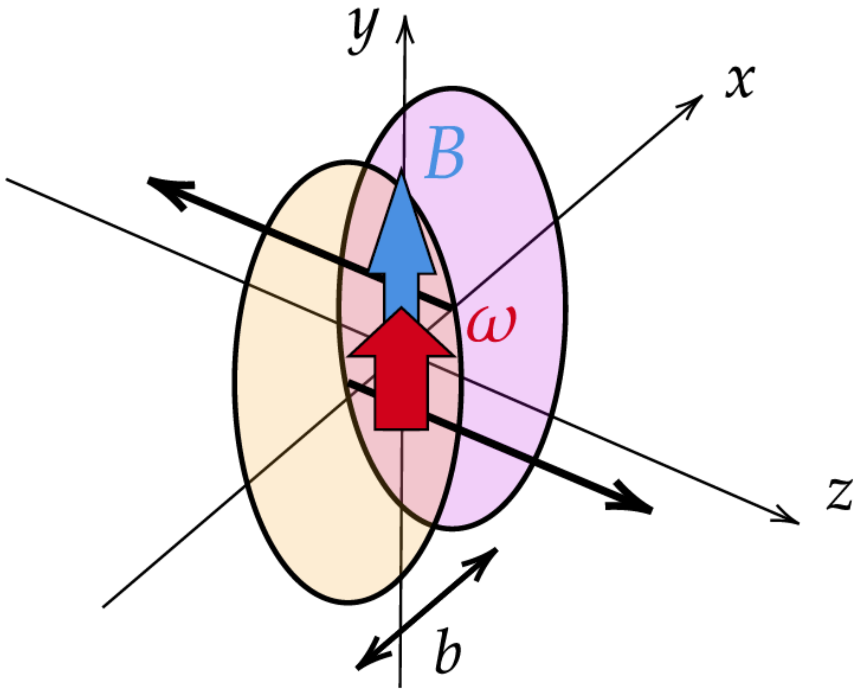
- CME/CVE overview
- New gamma-type correlator linear in baryon asymmetry

Part 2: Signatures of baryon junctions in hadronic interactions

- Baryon junctions overview
- New results on Regge intercepts
- Semi-inclusive DIS and other experimental signatures

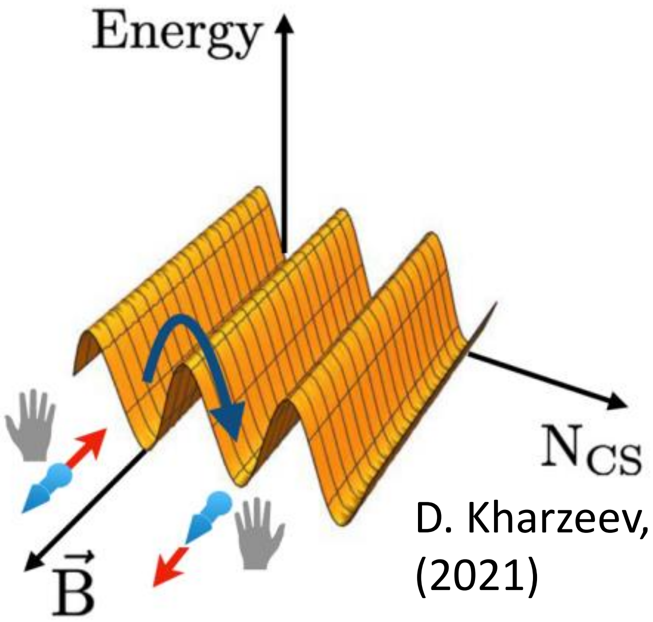
PART 1

Anomalous transport effects

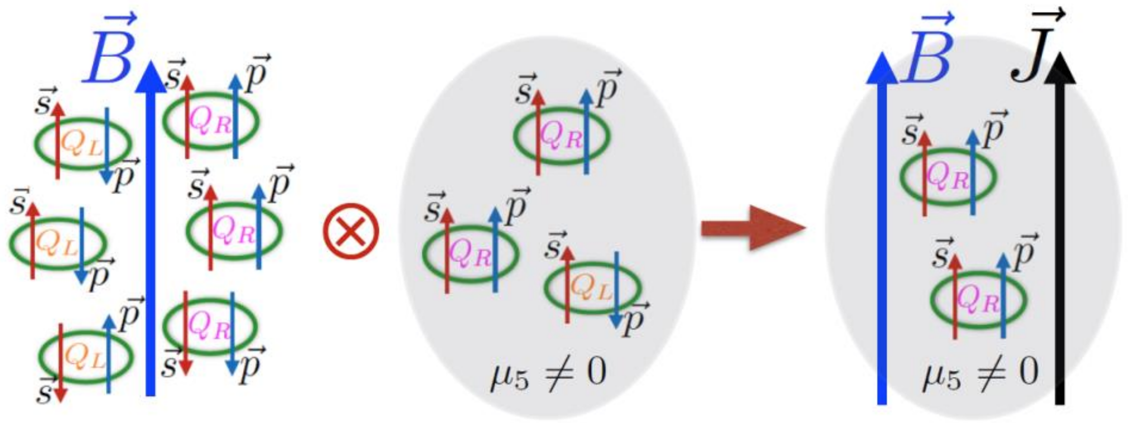


Heavy ion collision:

- Strong magnetic field
- Vorticity
- Chiral imbalance from sphaleron transitions



D. Kharzeev, J. Liao Nature Rev. Phys. 3 (2021)



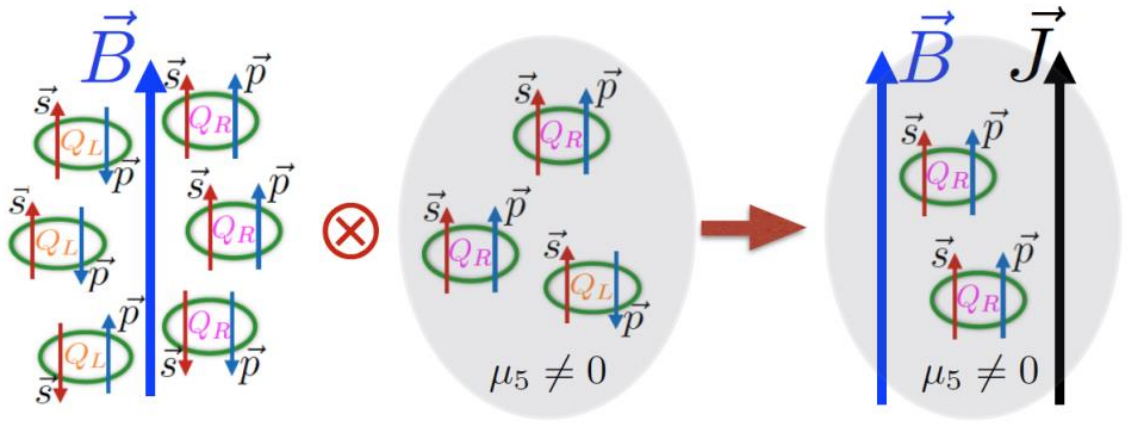
Single fermion species

$$\vec{j}_{CME} = \mu_5 \frac{e_f}{2\pi^2} \vec{B}$$

Chiral Magnetic Effect

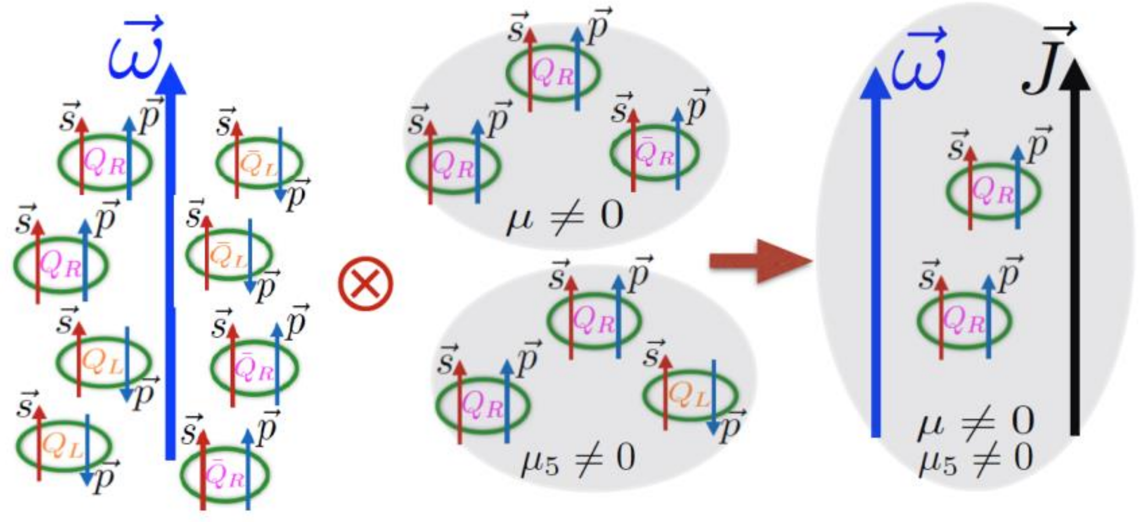
D. Kharzeev and D.T. Son (2010)
D. Kharzeev et. al. PPNP 88, 1 (2016)

Single fermion species



$$\vec{j}_{CME} = \mu_5 \, \frac{e_f}{2\pi^2} \, \vec{B}$$

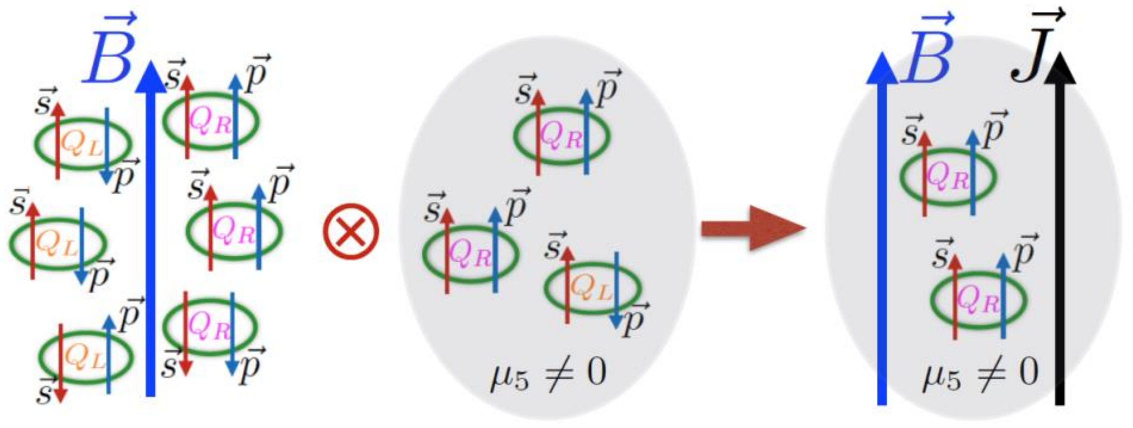
Chiral Magnetic Effect



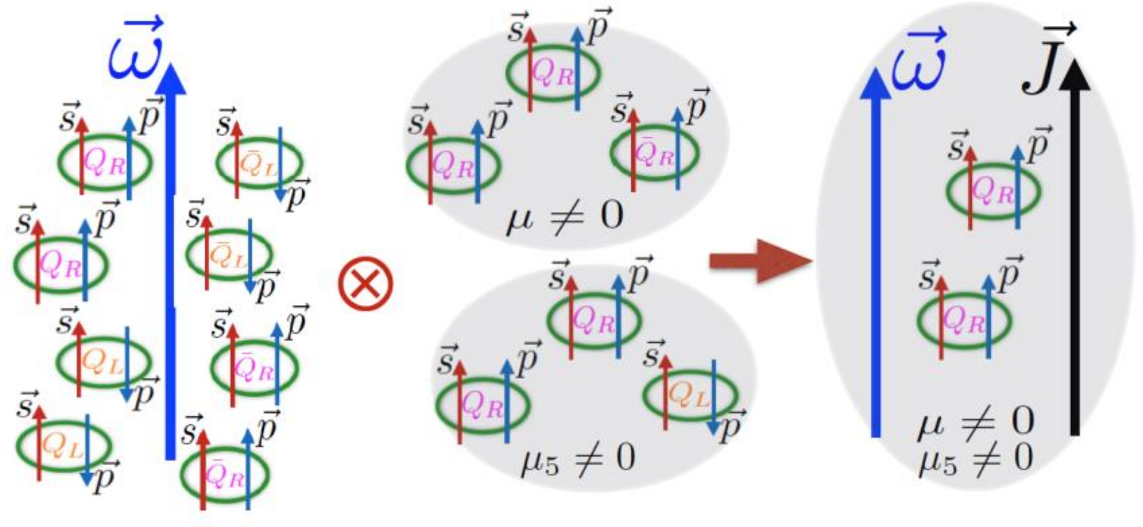
$$\vec{j}_{CVE} = \mu_5 \, \frac{\mu_f}{\pi^2} \, \vec{\omega}$$

Chiral Vortical Effect

D. Kharzeev and D.T. Son (2010)
D. Kharzeev et. al. PPNP 88, 1 (2016)



Chiral Magnetic Effect



Chiral Vortical Effect

Single fermion species

$$\vec{j}_{CME} = \mu_5 \frac{e_f}{2\pi^2} \vec{B}$$

$$\vec{j}_{CVE} = \mu_5 \frac{\mu_f}{\pi^2} \vec{\omega}$$

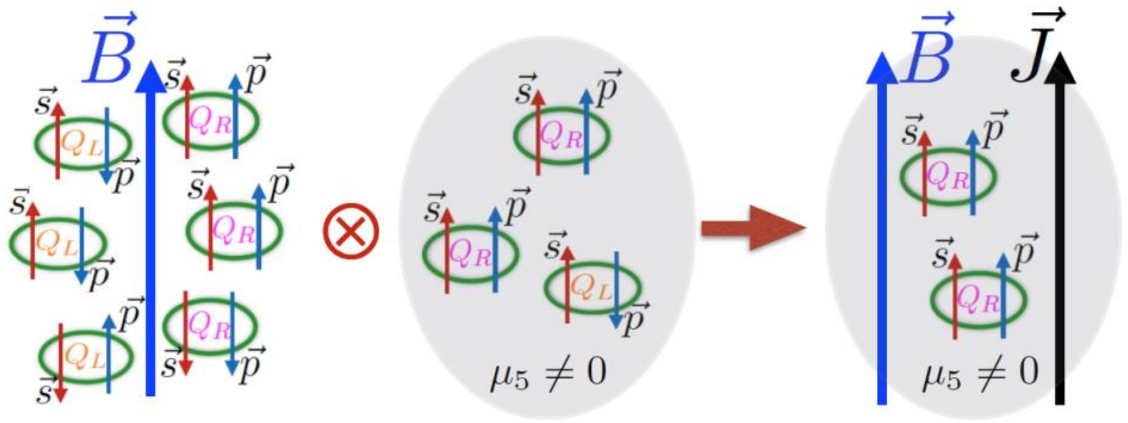
3 light flavors

$$\vec{j}^{E}_{CME} = \frac{2}{3} \frac{N_c \mu_5}{2\pi^2} e^2 \vec{B}$$

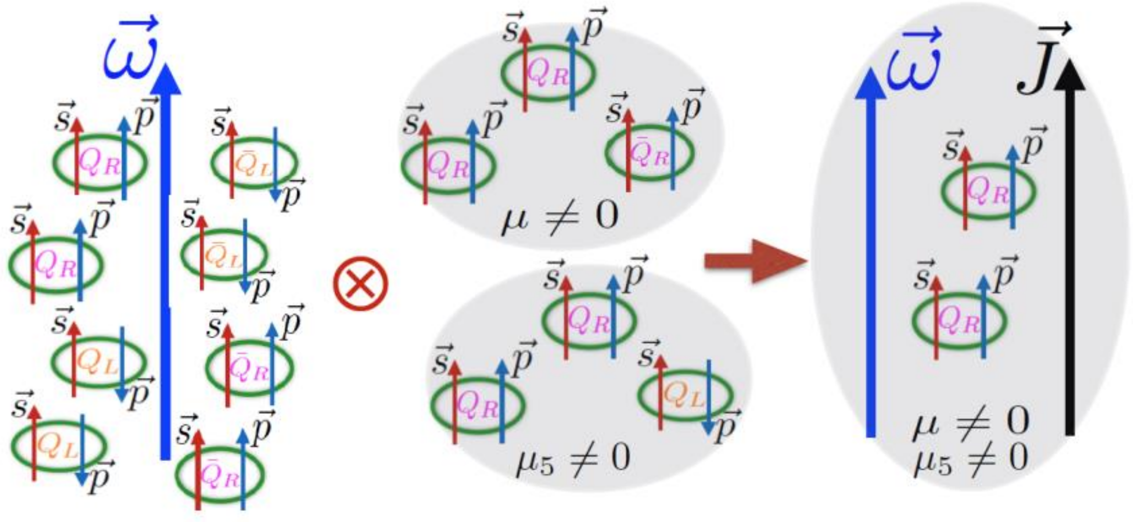
$$\vec{j}^{B}_{CME} = 0$$

D. Kharzeev and D.T. Son (2010)

D. Kharzeev et. al. PPNP 88, 1 (2016)



Chiral Magnetic Effect



Chiral Vortical Effect

Single fermion species

$$\vec{j}_{CME} = \mu_5 \, \frac{e_f}{2\pi^2} \, \vec{B}$$

$$\vec{j}_{CVE} = \mu_5 \, \frac{\mu_f}{\pi^2} \, \vec{\omega}$$

3 light flavors

$$\vec{j}^{\,E}_{CME} = \frac{2}{3} \, \frac{N_c \mu_5}{2\pi^2} \, e^2 \vec{B}$$

$$\vec{j}^{\,B}_{CME} = 0$$

$$\vec{j}^{\,B}_{\mathrm{CVE}} = \frac{N_c \mu_5 \mu_B}{\pi^2} \, \vec{\omega}$$

$$\vec{j}^{\,E}_{\mathrm{CVE}} = 0$$

D. Kharzeev and D.T. Son (2010)
D. Kharzeev et. al. PPNP 88, 1 (2016)

How to look for the CME?

CME contribution

Charged particle azimuthal distribution:

$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_1 \cos\phi + 2v_2 \cos 2\phi + \dots + 2a_\pm \sin\phi + \dots$$

However, $\langle \mu_5 \rangle = 0 \implies \langle a_\pm \rangle = 0$ averaging over many events

Solution: consider

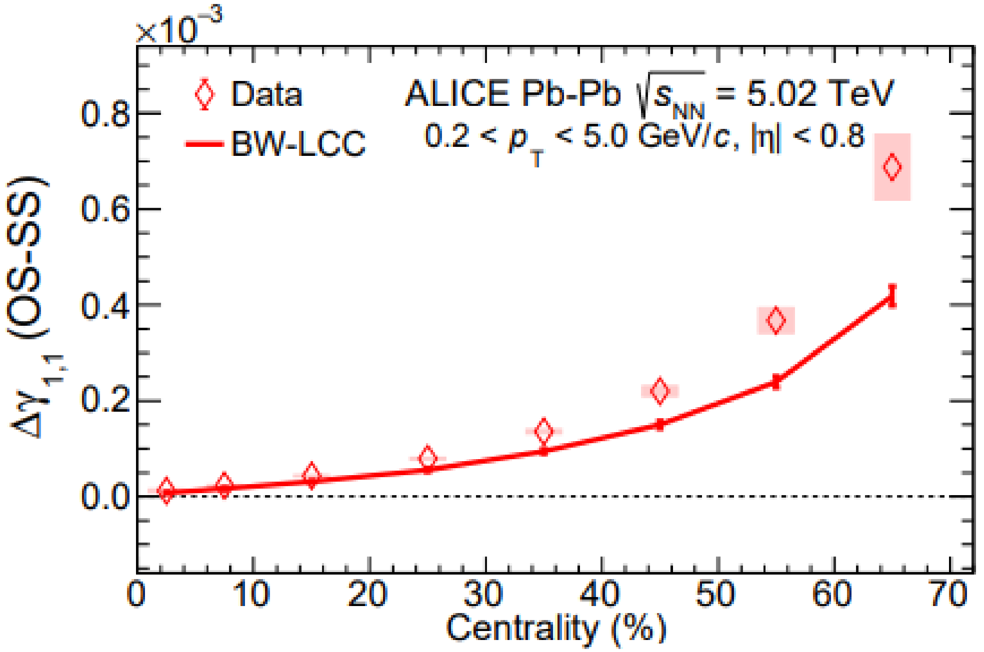
$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - \Psi_{RP}) \rangle \propto \langle a_\alpha a_\beta \rangle \propto \langle \mu_5^2 \rangle \neq 0$$

Comes at a price of introducing P-even background contributions

CME search in heavy ion collisions

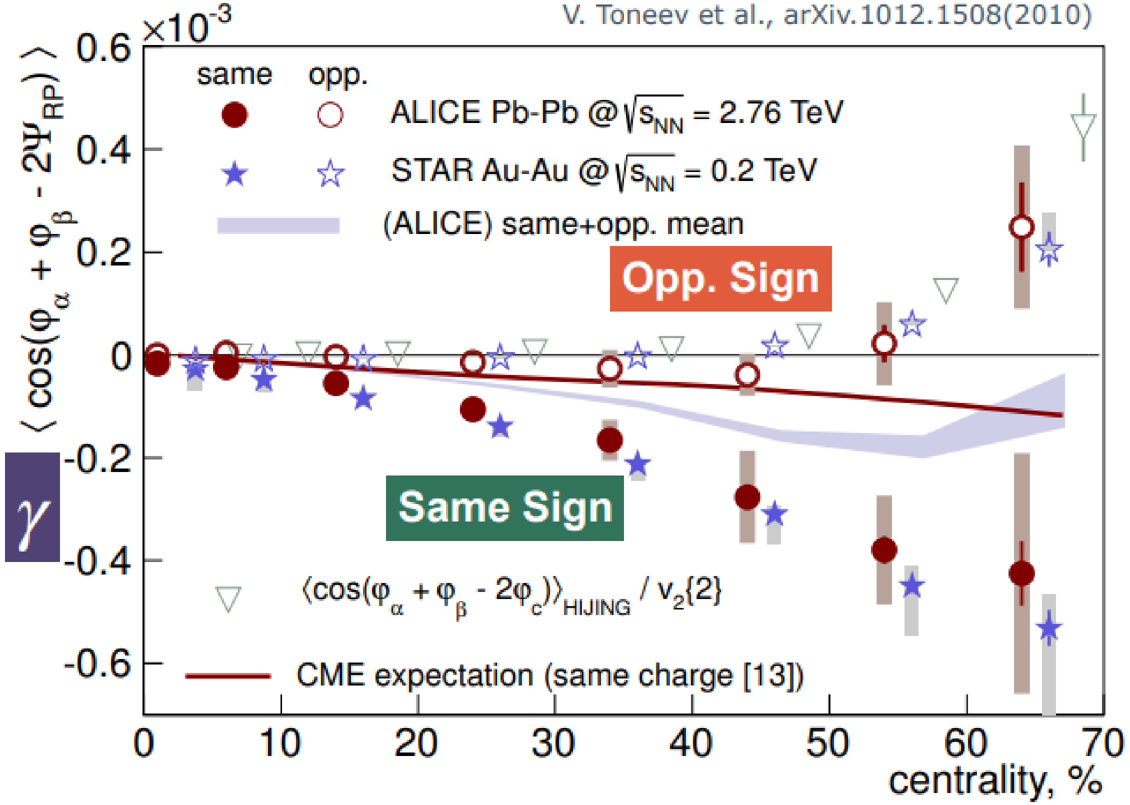
$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

Eliminates some systematic backgrounds, but many remain



JHEP 09 (2020) 160

STAR, PRL 103, 251601 (2009)
ALICE, PRL 110, 012301 (2013)
V. Toneev et al., arXiv.1012.1508(2010)



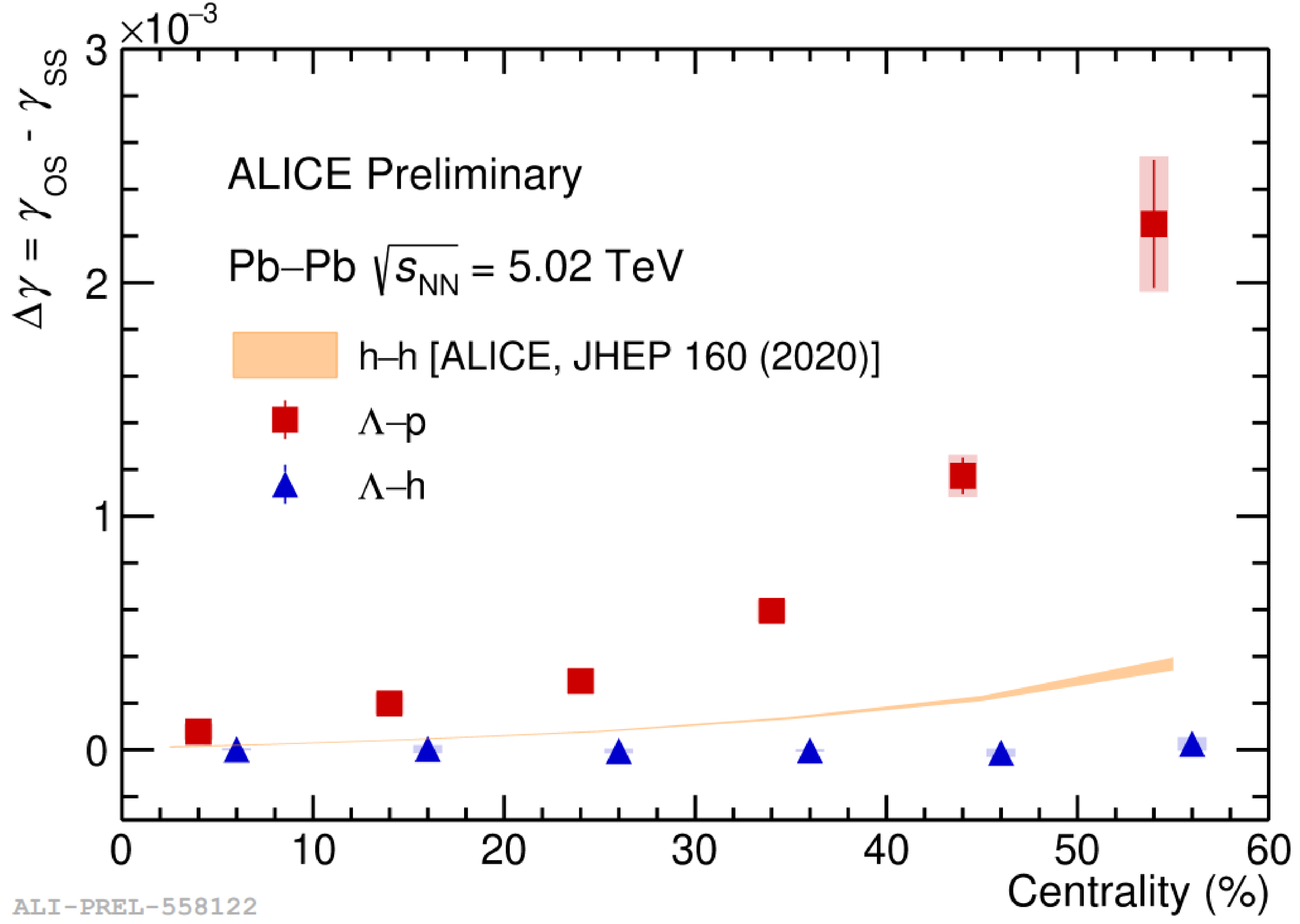
C.-Z.Wang, QM 2023

$$\Delta\gamma_{CME} = f_{CME}\Delta\gamma^{\text{obs.}}$$

$$f_{CME} \sim 10\%$$

D. Kharzeev, J. Liao, P. Tribedy 2405.05427

CVE search: baryons instead of electric charge



p, Λ are identified

$$\gamma_{OS} = \gamma_{p\bar{\Lambda}} + \gamma_{\bar{p}\Lambda}$$

$$\gamma_{SS} = \gamma_{p\Lambda} + \gamma_{\bar{p}\bar{\Lambda}}$$

C.-Z.Wang, QM 2023

Baryon separation

$$\frac{dN_i}{d\phi_i} = \frac{N_i}{2\pi}\left[1 + 2a\sin\Delta\phi_i + \sum_k 2v_k\cos\left(k\Delta\phi_i\right)\right]$$

$$\Delta N_B^{\uparrow\downarrow} = \frac{8}{\pi}a(N_p + N_\Lambda)$$

$$\Delta\gamma = 4a^2$$

Baryon separation

$$\frac{dN_i}{d\phi_i} = \frac{N_i}{2\pi}\left[1 + 2a\sin\Delta\phi_i + \sum_k 2v_k\cos\left(k\Delta\phi_i\right)\right]$$

$$\Delta N_B^{\uparrow\downarrow} = \frac{8}{\pi}a(N_p + N_\Lambda)$$

$$\Delta\gamma = 4a^2$$

$$\Delta N_B^{\downarrow\uparrow} = \int j_B^\mu d\Sigma_\mu \propto \mu_5 \int_{\tau_0}^{\tau_f} d\tau\, \tau\, \mu_B\, \omega$$

extract μ_5

Baryon separation

$$\frac{dN_i}{d\phi_i} = \frac{N_i}{2\pi}\left[1 + 2a\sin\Delta\phi_i + \sum_k 2v_k\cos\left(k\Delta\phi_i\right)\right]$$

→

$$\Delta N_B^{\uparrow\downarrow} = \frac{8}{\pi}a(N_p + N_\Lambda)$$

$$\Delta\gamma = 4a^2$$

$$\Delta N_B^{\downarrow\uparrow} = \int j_B^\mu d\Sigma_\mu \propto \mu_5 \int_{\tau_0}^{\tau_f} d\tau\, \tau\, \mu_B\, \omega$$

→ extract μ_5

$\mu_B(\tau_f) \approx 1\ \mathrm{MeV}$ + Bjorken model

$$\omega(b,\tau) = A + e^{-\tau/\tau_R}\left(\frac{\tau}{\tau_R}\right)^{0.3} B$$

from AMPT   Phys. Rev. C 94, 044910 (2016)

Baryon separation

$$\frac{dN_i}{d\phi_i} = \frac{N_i}{2\pi}\left[1 + 2a\sin\Delta\phi_i + \sum_k 2v_k\cos\left(k\Delta\phi_i\right)\right]$$

$$\Delta N_B^{\uparrow\downarrow} = \frac{8}{\pi}a(N_p + N_\Lambda)$$

$$\Delta\gamma = 4a^2$$

$$\Delta N_B^{\downarrow\uparrow} = \int j_B^\mu d\Sigma_\mu \propto \mu_5 \int_{\tau_0}^{\tau_f} d\tau\,\tau\,\mu_B\,\omega$$

extract μ_5

$\mu_B(\tau_f) \approx 1\ \mathrm{MeV}$ + Bjorken model

CVE

$$\frac{\mu_5}{T} \approx 3 - 9$$

$$\omega(b,\tau) = A + e^{-\tau/\tau_R}\left(\frac{\tau}{\tau_R}\right)^{0.3} B$$

from AMPT Phys. Rev. C 94, 044910 (2016)

Baryon separation

$$\frac{dN_i}{d\phi_i} = \frac{N_i}{2\pi}\left[1 + 2a\sin\Delta\phi_i + \sum_k 2v_k\cos\left(k\Delta\phi_i\right)\right]$$

$$\Delta N_B^{\uparrow\downarrow} = \frac{8}{\pi}a(N_p + N_\Lambda)$$

$$\Delta\gamma = 4a^2$$

$$\Delta N_B^{\downarrow\uparrow} = \int j_B^\mu d\Sigma_\mu \propto \mu_5 \int_{\tau_0}^{\tau_f} d\tau\,\tau\,\mu_B\,\omega$$

extract μ_5

$\mu_B(\tau_f) \approx 1\ \mathrm{MeV}$ + Bjorken model

$$\omega(b,\tau) = A + e^{-\tau/\tau_R}\left(\frac{\tau}{\tau_R}\right)^{0.3} B$$

from AMPT   Phys. Rev. C 94, 044910 (2016)

CVE $\frac{\mu_5}{T} \approx 3 - 9$

similarly for the CME $\frac{\mu_5}{T} \approx 7 - 10$

Baryon asymmetry-dependent correlator

$$\Delta\gamma_{CME} \propto \mu_5^2$$

from baryon stopping

$$\Delta\gamma_{CVE} \propto \mu_5^2 \mu_B^2 \propto \mu_5^2 \Delta N_B^2$$

Baryon asymmetry-dependent correlator

$$\Delta\gamma_{CME} \propto \mu_5^2$$

from baryon stopping

$$\Delta\gamma_{CVE} \propto \mu_5^2 \mu_B^2 \propto \mu_5^2 \Delta N_B^2$$

ΔN_B fluctuates event by event → group events according to ΔN_B

Baryon asymmetry-dependent correlator

$$\Delta\gamma_{CME} \propto \mu_5^2$$

from baryon stopping

$$\Delta\gamma_{CVE} \propto \mu_5^2 \mu_B^2 \propto \mu_5^2 \Delta N_B^2$$

ΔN_B fluctuates event by event → group events according to ΔN_B

A correlator linear in baryon asymmetry is desirable

New correlator is proposed

$$\Gamma_{QB} = \sum_{\substack{i=\{\pi^{\pm},p,\bar{p}\} \\ j=\{p,\bar{p},\Lambda,\bar{\Lambda}\}}} \langle\langle \cos(\phi_{C,i} + \phi_{B,j} - 2\psi_{RP}) \rangle\rangle$$

mixed in electric charge and baryon number

not normalized: $\langle\langle f(\phi) \rangle\rangle = \int d\phi \, \frac{dN}{d\phi} f(\phi)$ vs. $\langle f(\phi) \rangle = \frac{1}{N} \int d\phi \, \frac{dN}{d\phi} f(\phi)$

New correlator is proposed

$$\Gamma_{QB} = \sum_{\substack{i=\{\pi^{\pm},p,\bar{p}\} \\ j=\{p,\bar{p},\Lambda,\bar{\Lambda}\}}} \langle\langle \cos(\phi_{C,i} + \phi_{B,j} - 2\psi_{RP}) \rangle\rangle$$

mixed in electric charge and baryon number

not normalized: $\langle\langle f(\phi) \rangle\rangle = \int d\phi \, \frac{dN}{d\phi} f(\phi)$ vs. $\langle f(\phi) \rangle = \frac{1}{N} \int d\phi \, \frac{dN}{d\phi} f(\phi)$

$$\Gamma^{SS} = \Gamma_{+B} + \Gamma_{-\bar{B}}, \quad \Gamma^{OS} = \Gamma_{+\bar{B}} + \Gamma_{-B}$$

$$\Delta\Gamma_{QB} = \Gamma^{OS} - \Gamma^{SS} = \Delta N_B \frac{\mu_5^2}{N_p} \frac{N_c^2}{96\pi^2} L_x^2 \Delta\eta^2 \int d\tau \, \tau \, T \, \omega \int d\tau' \, \tau' \, eB$$

New correlator is proposed

$$\Gamma_{QB} = \sum_{\substack{i=\{\pi^{\pm},p,\bar{p}\} \\ j=\{p,\bar{p},\Lambda,\bar{\Lambda}\}}} \langle\langle \cos(\phi_{C,i} + \phi_{B,j} - 2\psi_{RP}) \rangle\rangle$$

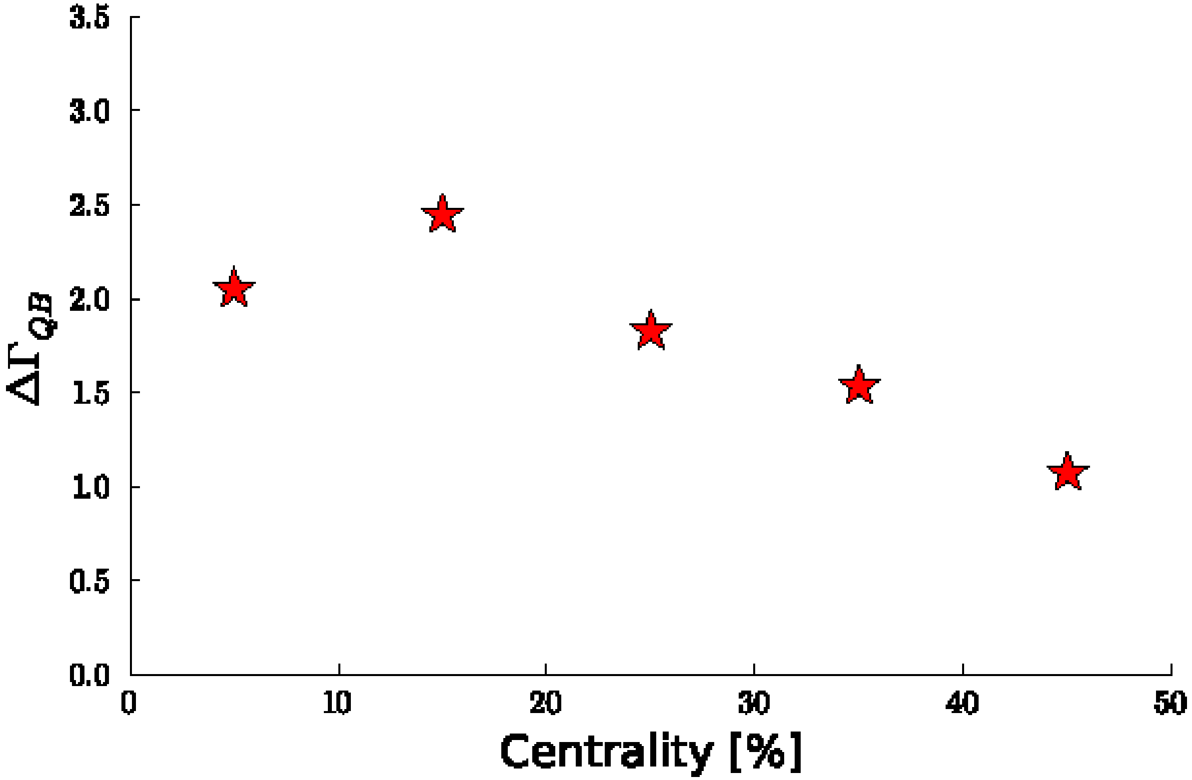
mixed in electric charge and baryon number

not normalized: $\langle\langle f(\phi) \rangle\rangle = \int d\phi \, \frac{dN}{d\phi} f(\phi)$ vs. $\langle f(\phi) \rangle = \frac{1}{N} \int d\phi \, \frac{dN}{d\phi} f(\phi)$

$$\Gamma^{SS} = \Gamma_{+B} + \Gamma_{-\bar{B}}, \quad \Gamma^{OS} = \Gamma_{+\bar{B}} + \Gamma_{-B}$$

$$\Delta\Gamma_{QB} = \Gamma^{OS} - \Gamma^{SS} = \Delta N_B \frac{\mu_5^2}{N_p} \frac{N_c^2}{96\pi^2} L_x^2 \Delta\eta^2 \int d\tau \, \tau \, T \, \omega \int d\tau' \, \tau' \, eB$$

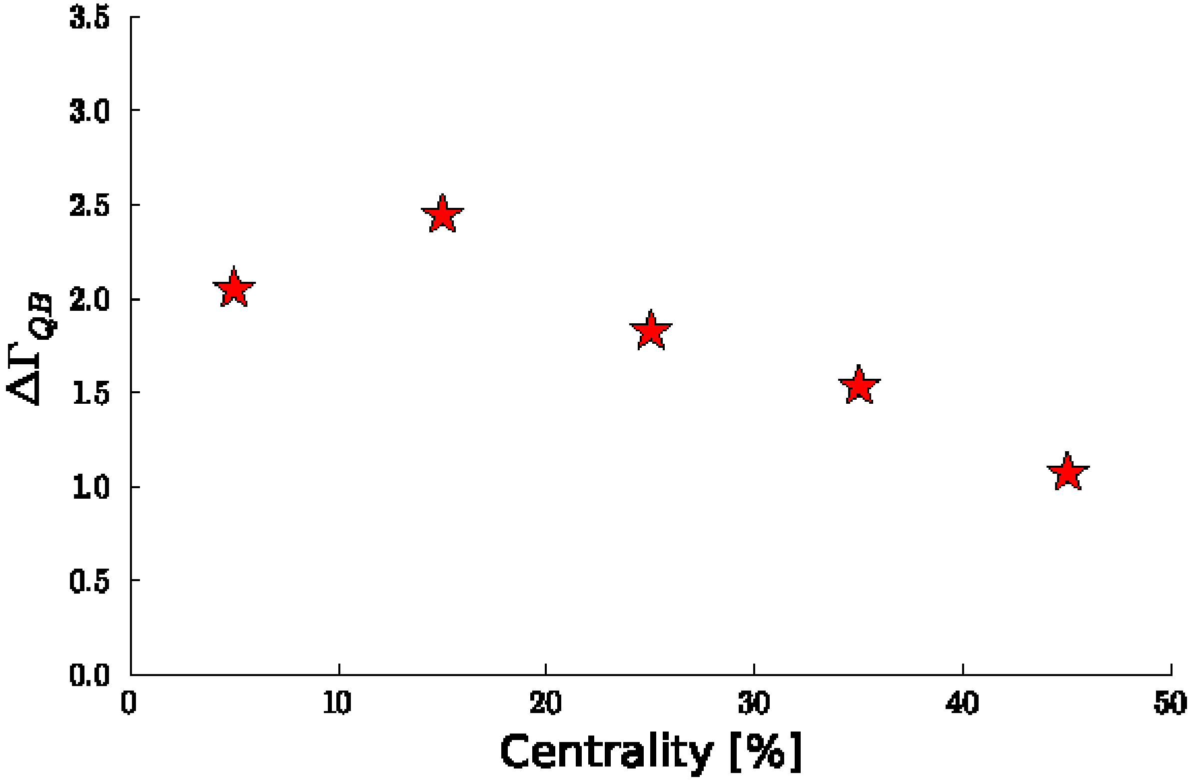
Expectations based on ALICE data

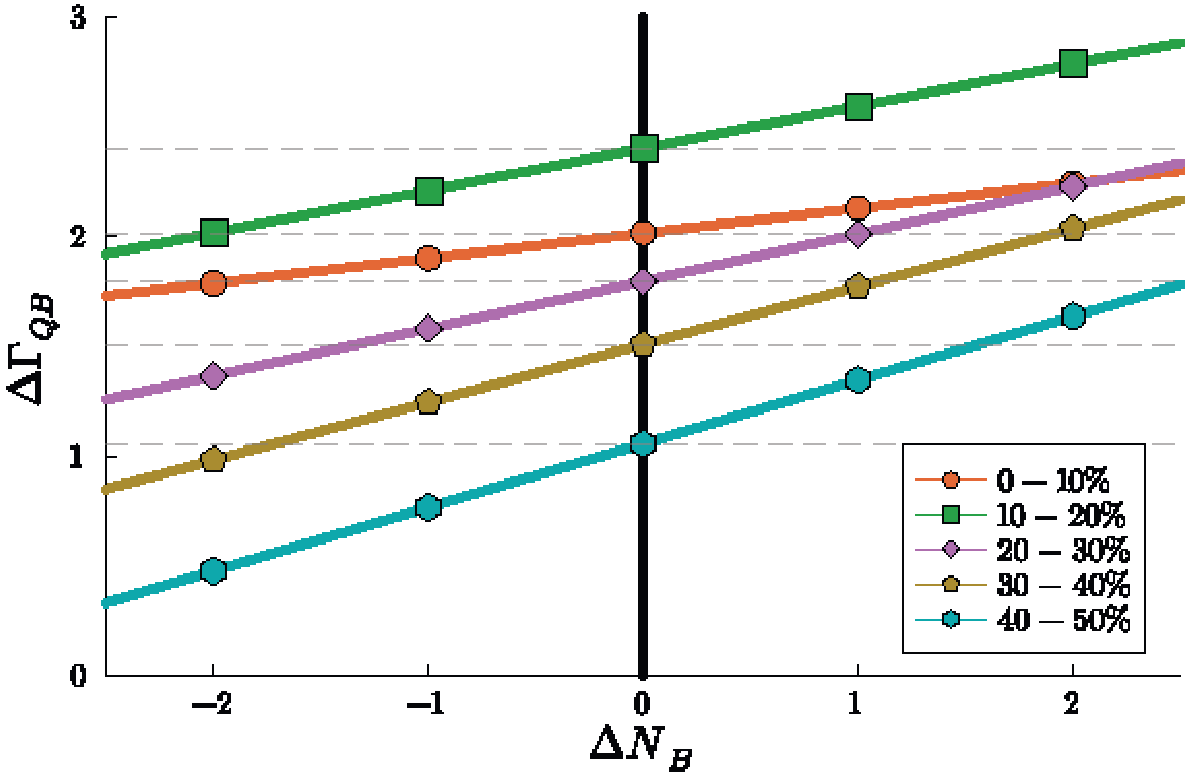


$$\Delta N_B = \Delta N_B^*$$

mean value

Expectations based on ALICE data





$$\Delta N_B = \Delta N_B^*$$

mean value

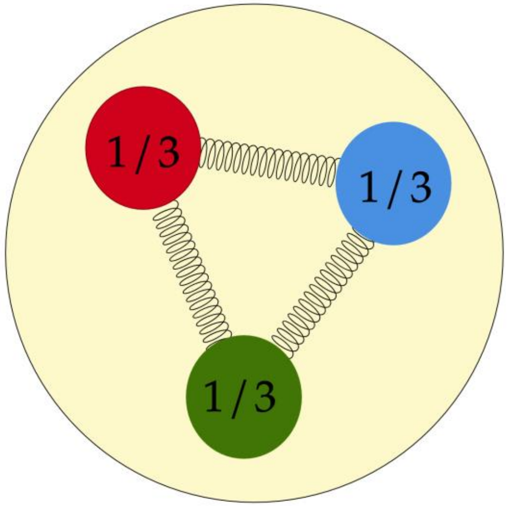
Linear dependence on ΔN_B should help separate signal and background

PART 2

Motivation: what carries the baryon number?

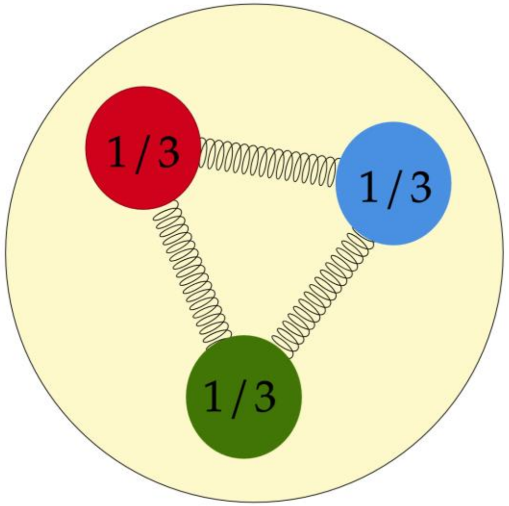
Motivation: what carries the baryon number?

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



Motivation: what carries the baryon number?

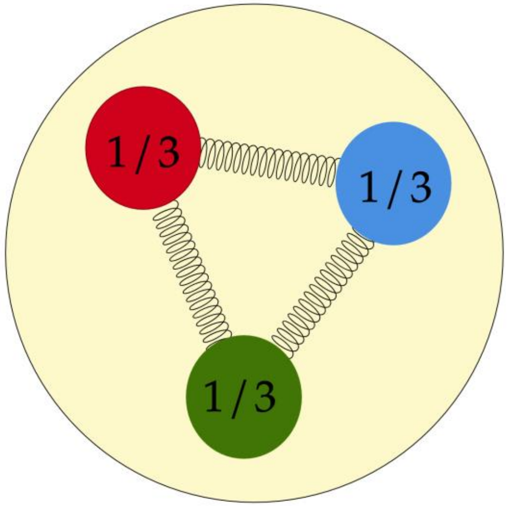
$$B(x_1, x_2, x_3) = \epsilon^{ijk} q(x_1)_i \; q(x_2)_j q(x_3)_k$$



↓ Gauge invariance

Motivation: what carries the baryon number?

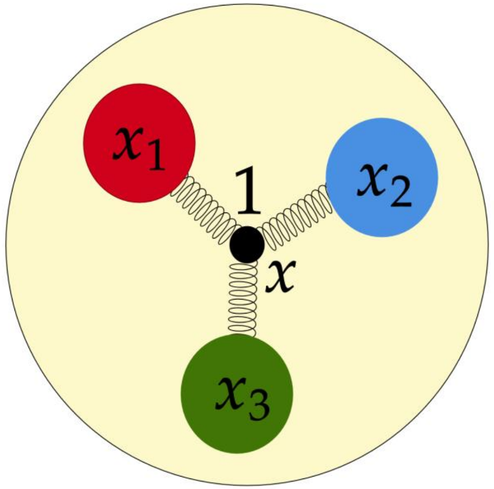
$$B(x_1, x_2, x_3) = \epsilon^{ijk} q(x_1)_i \; q(x_2)_j q(x_3)_k$$



Gauge invariance

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

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



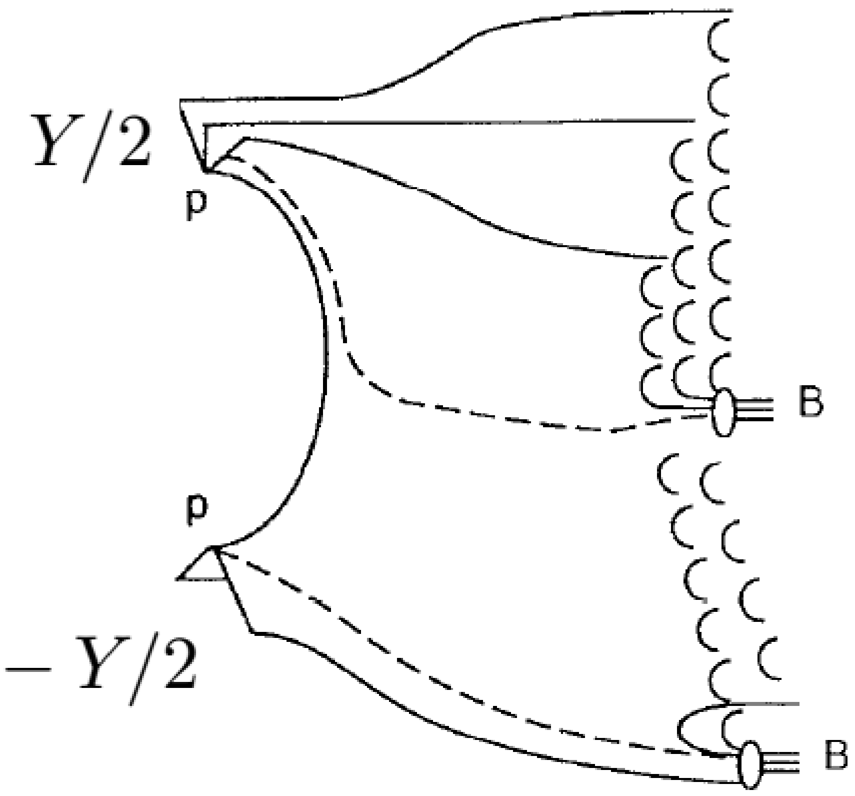
G.C. Rossi and G. Veneziano, Nucl. Phys. B 123 (1977)

Baryon stopping in pp and AA

Can gluons trace baryon number?

D. Kharzeev

Physics Letters B 378 (1996) 238–246



Dashed lines denote junctions

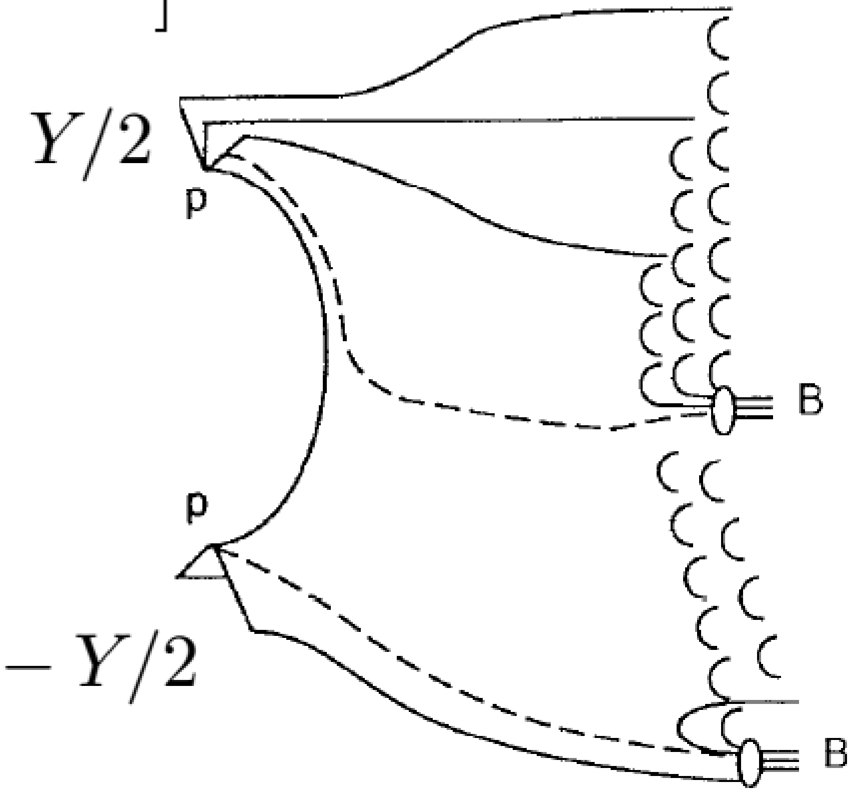
Baryon stopping in pp and AA

Can gluons trace baryon number?

D. Kharzeev

Physics Letters B 378 (1996) 238--246

$$E_B \frac{dN}{d^3p_B} \propto e^{(\alpha_{\mathbb{J}_0}+\alpha_{\mathbb{P}}-2)Y/2}\left[e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{P}})y^*} + e^{(\alpha_{\mathbb{P}}-\alpha_{\mathbb{J}_0})y^*}\right]$$



Dashed lines denote junctions

Baryon stopping in pp and AA

Can gluons trace baryon number?

D. Kharzeev

Physics Letters B 378 (1996) 238–246

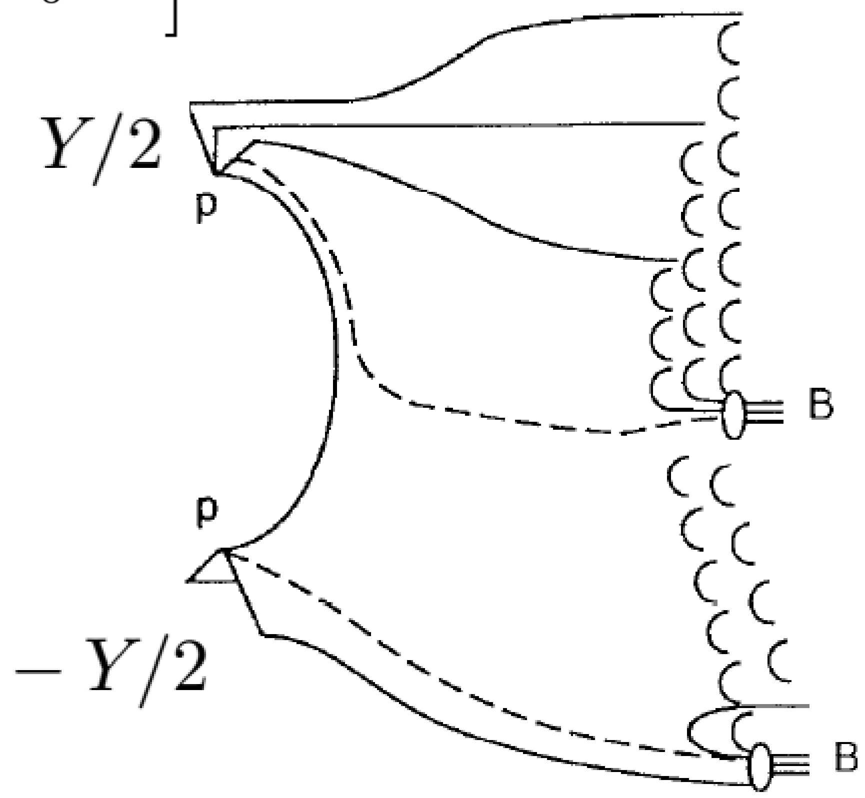
$$E_B \frac{dN}{d^3 p_B} \propto e^{(\alpha_{\mathbb{J}_0} + \alpha_{\mathbb{P}} - 2)Y/2} \left[e^{(\alpha_{\mathbb{J}_0} - \alpha_{\mathbb{P}}) y^*} + e^{(\alpha_{\mathbb{P}} - \alpha_{\mathbb{J}_0}) y^*} \right]$$

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

$$\alpha_{\mathbb{J}_0} \approx 0.5$$

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

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



Dashed lines denote junctions

Baryon stopping in pp and AA

Can gluons trace baryon number?

D. Kharzeev

Physics Letters B 378 (1996) 238–246

$$E_B \frac{dN}{d^3p_B} \propto e^{(\alpha_{\mathbb{J}_0}+\alpha_{\mathbb{P}}-2)Y/2}[e^{(\alpha_{\mathbb{J}_0}-\alpha_{\mathbb{P}})y^*} + e^{(\alpha_{\mathbb{P}}-\alpha_{\mathbb{J}_0})y^*}]$$

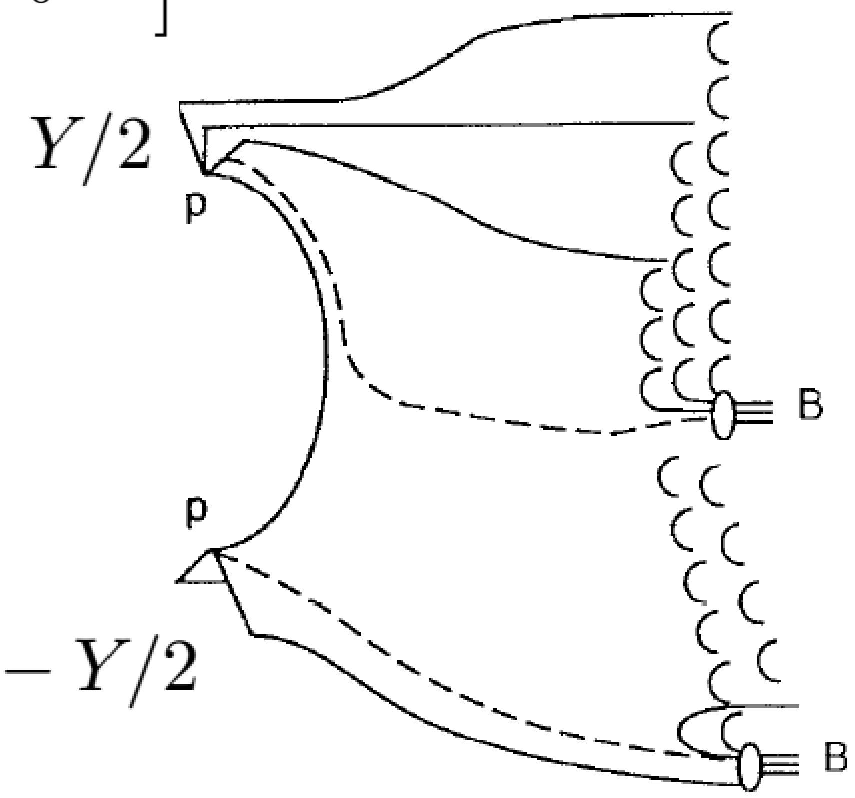
$$\alpha_{\mathbb{P}} = 1 + \Delta \approx 1.08$$

$$\alpha_{\mathbb{J}_0} \approx 0.5$$

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

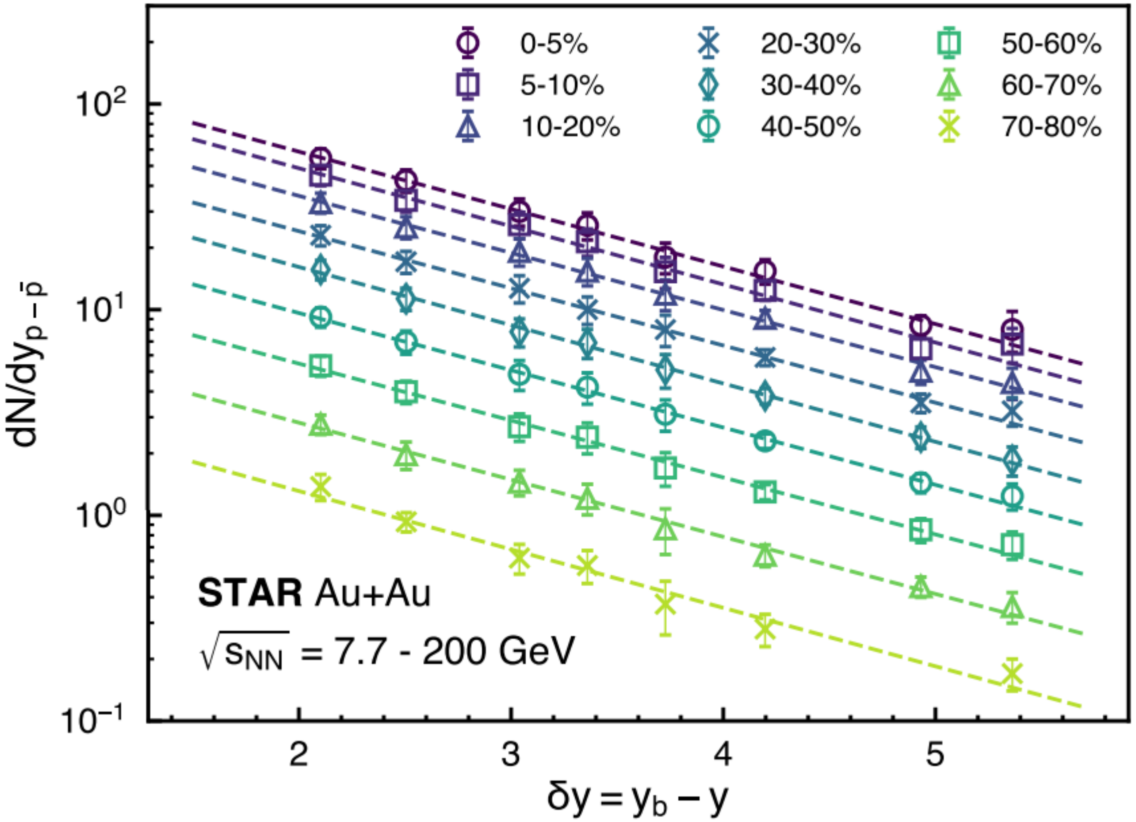
$$p_B = (m_t \cosh y^*, m_t \sinh y^*, p_B^{\perp})$$

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



Dashed lines denote junctions

RHIC Beam Energy Scan data

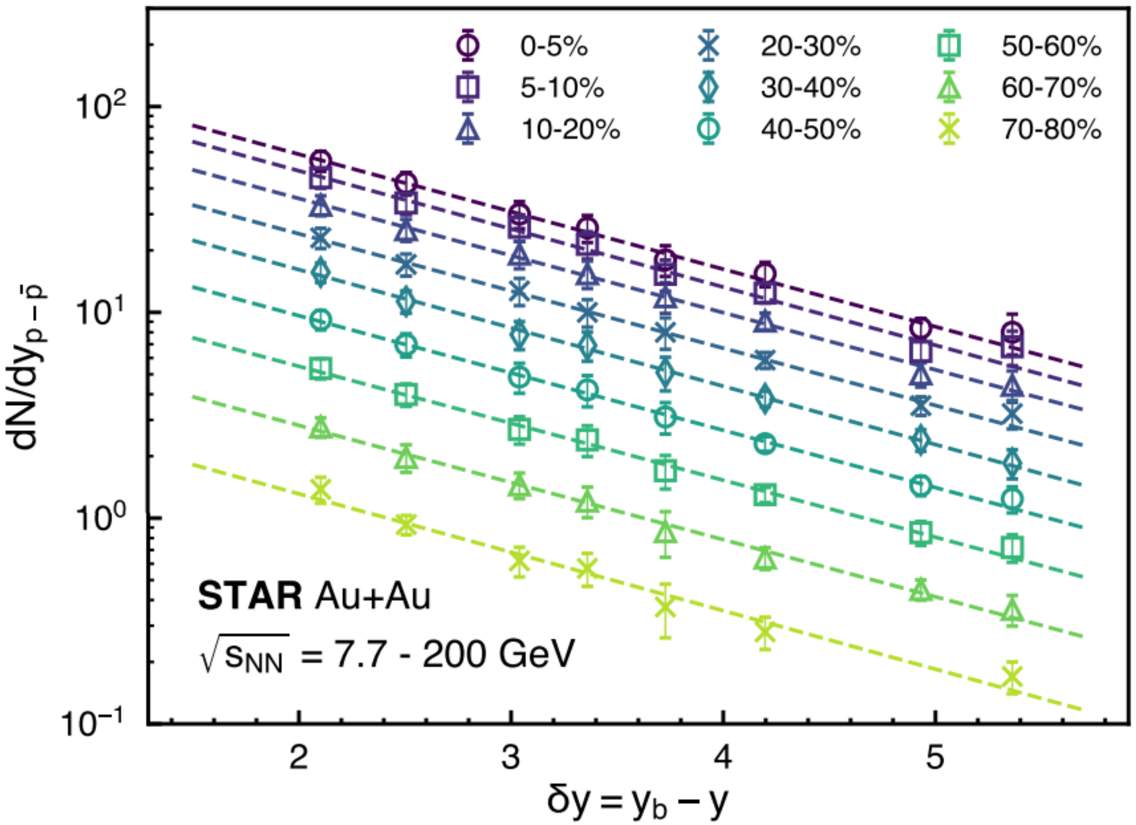


N. Lewis et al
arXiv:2205.05685(2022)

Experimental rapidity slope:

$$\sim 0.65 \pm 0.1$$

RHIC Beam Energy Scan data



N. Lewis et al
arXiv:2205.05685(2022)

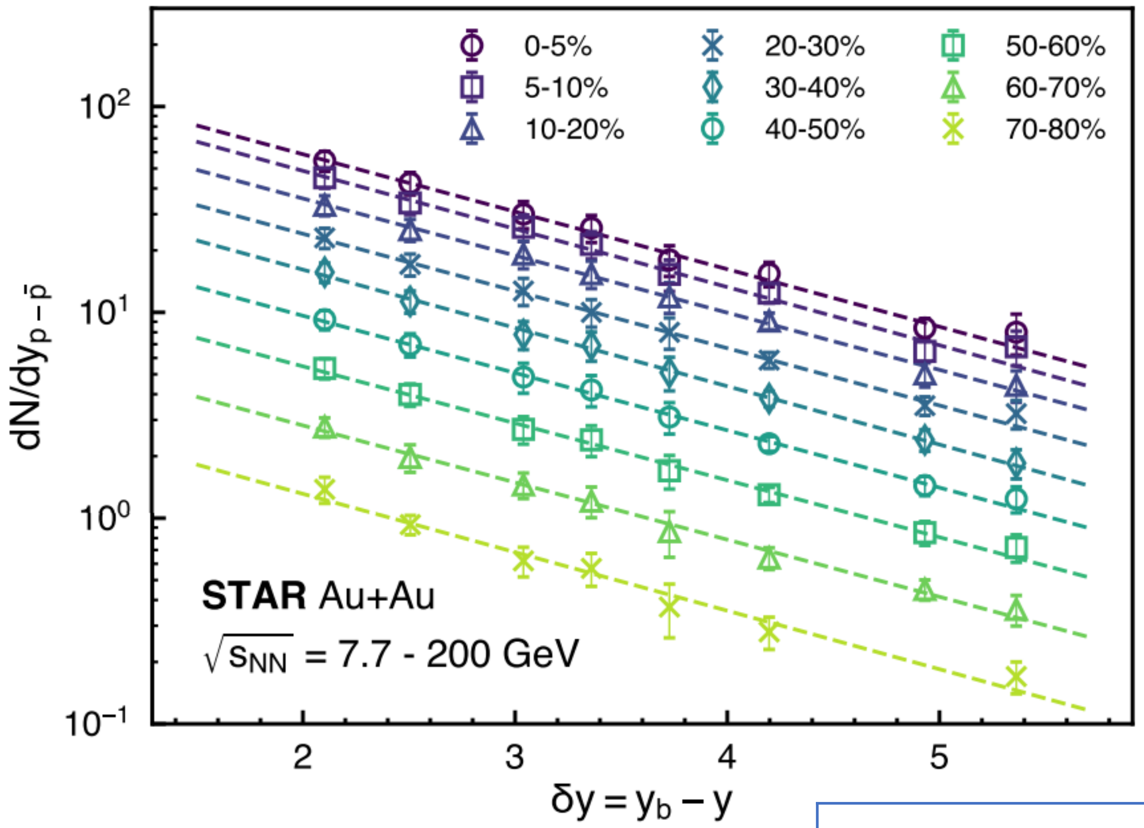
Experimental rapidity slope:

$$\sim 0.65 \pm 0.1$$

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

Topological expansion + Feynman-Wilson gas accounting for correlations in three strings breaking: $\alpha_{\mathbb{J}_0} \simeq 0.26$ *JHEP* 07 (2024) 262

RHIC Beam Energy Scan data



N. Lewis et al
arXiv:2205.05685(2022)

Experimental rapidity slope:

$$\sim 0.65 \pm 0.1$$

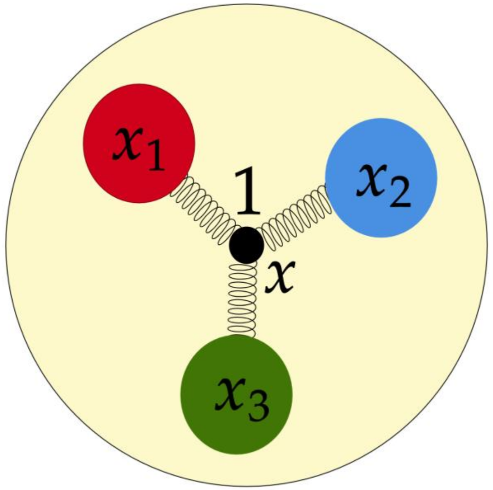
New theory input on $\alpha_{\mathbb{J}_0}$!

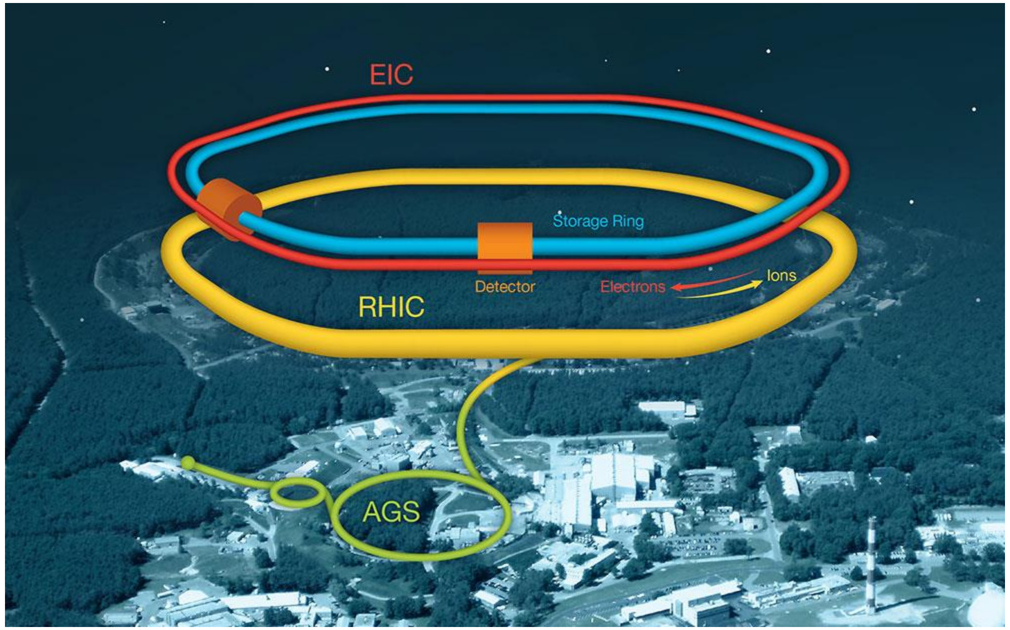
Topological expansion + Feynman-Wilson gas accounting for correlations in three strings breaking: $\alpha_{\mathbb{J}_0} \simeq 0.26$ *JHEP* 07 (2024) 262

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

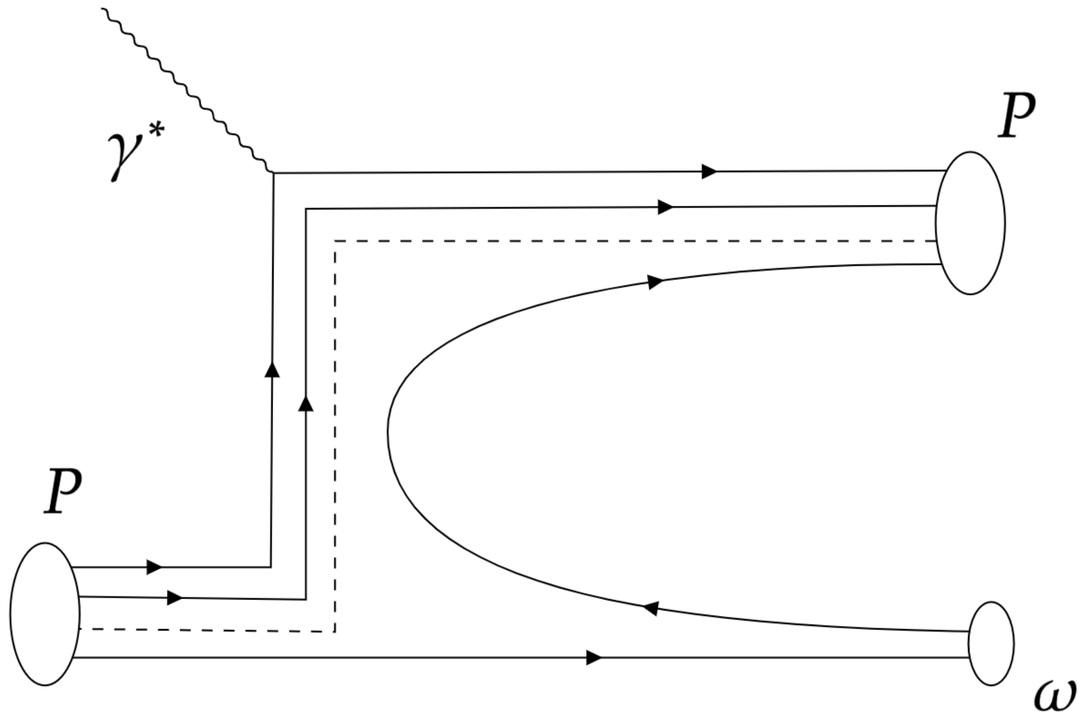
	Rapidity slope	$\alpha_{\mathbb{J}_0}$ **intercept**
Experiment	$\sim 0.65 \pm 0.1$	
“Old” theory	0.42	0.5
“New” theory	0.66	0.26

What other processes can probe the carrier of baryon number?



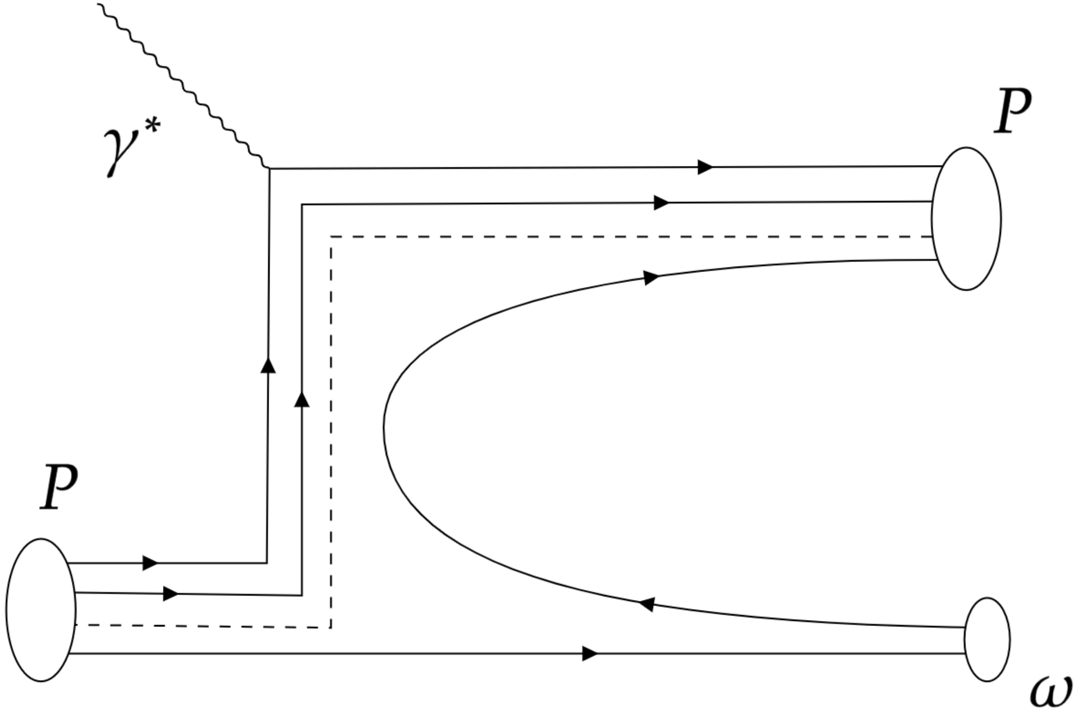


Initial motivation: exclusive ω production



Significant fraction of events have the proton in the photon fragmentation region

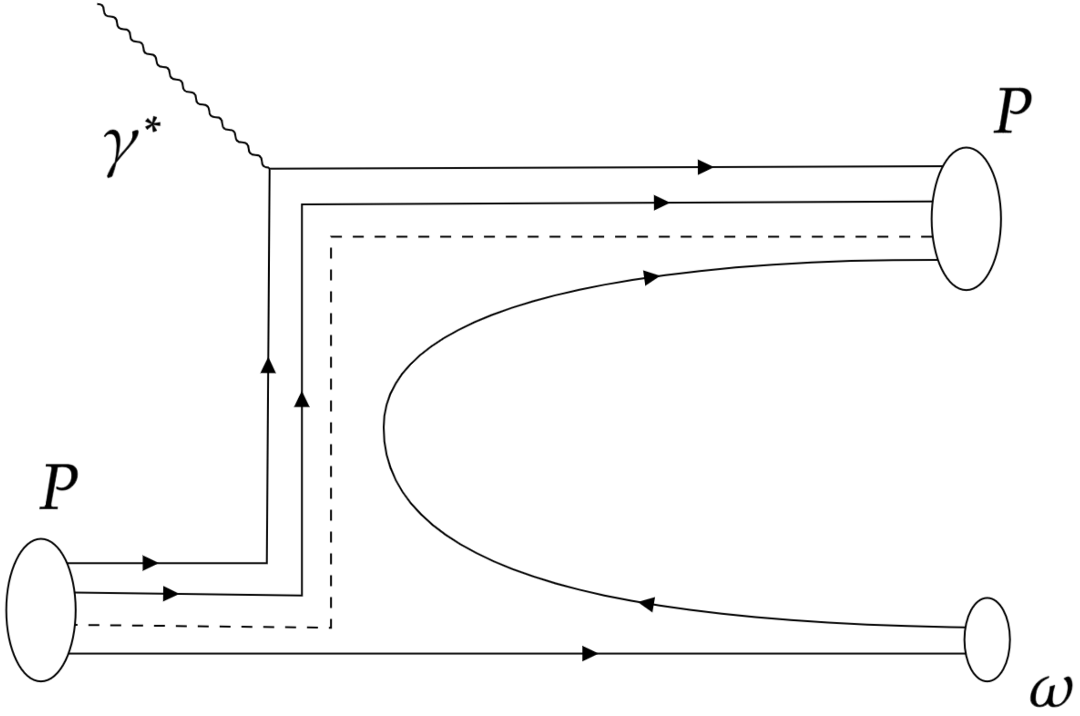
Initial motivation: exclusive ω production



Significant fraction of events have the proton in the photon fragmentation region

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

Initial motivation: exclusive ω production



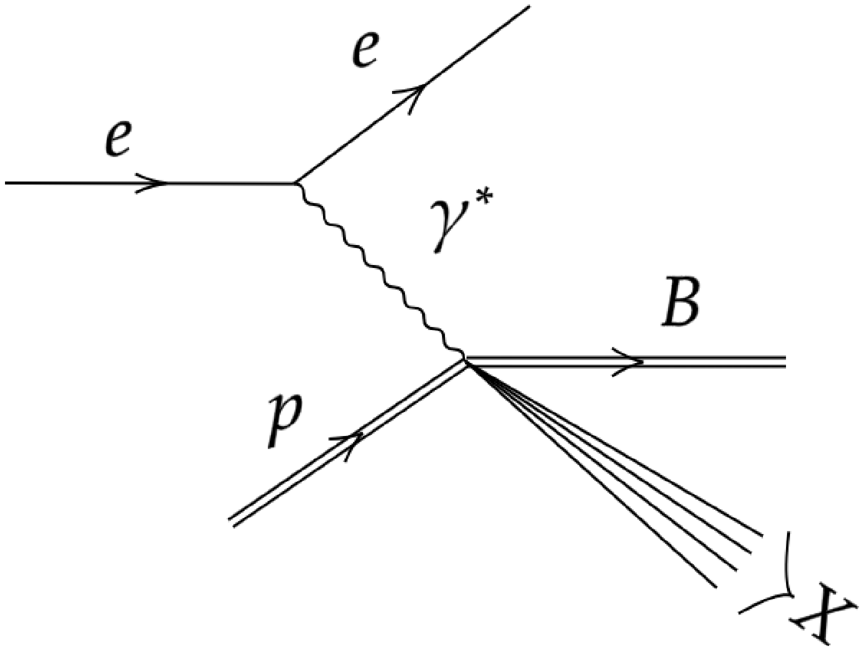
Significant fraction of events have the proton in the photon fragmentation region

Entire baryon is exchanged in the t-channel

Cannot separate the junction from valence quarks

Need a semi-inclusive process

Semi-inclusive deep inelastic scattering (DIS)



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

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

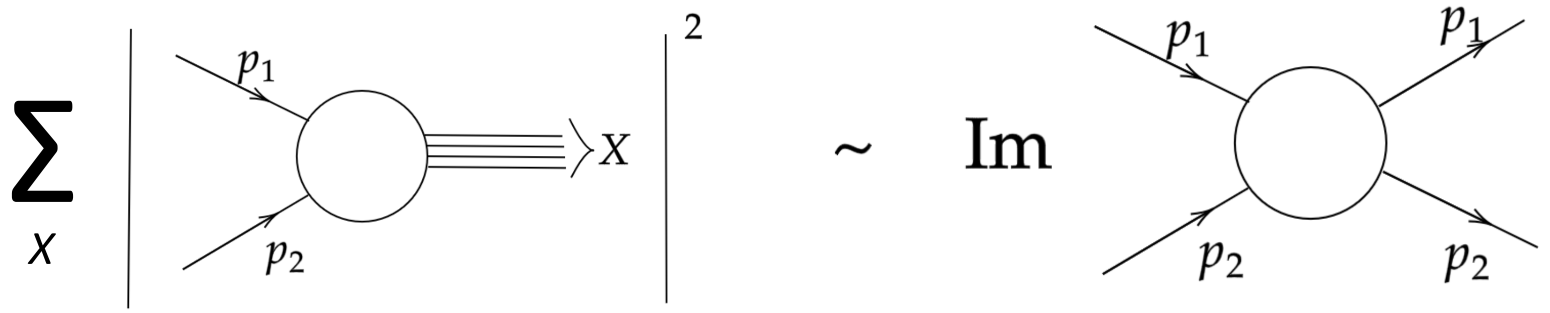
$$p_p = (\frac{\sqrt{s}}{2}, -\frac{\sqrt{s}}{2}, 0^{\perp})$$

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

Mueller-Kancheli theorem

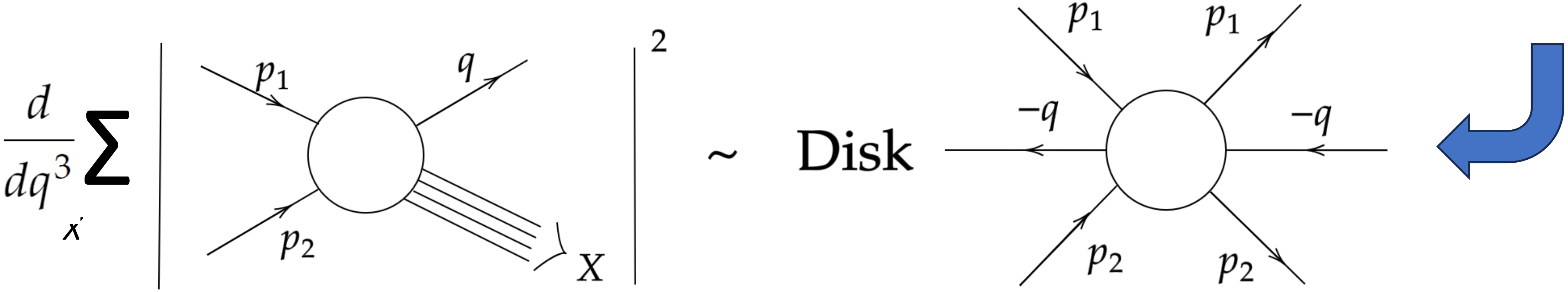
A.H. Mueller, Phys. Rev. D 2 (1970) 2963.
O.V. Kancheli, JETP Lett. 11 (1970) 397.

Optical theorem:

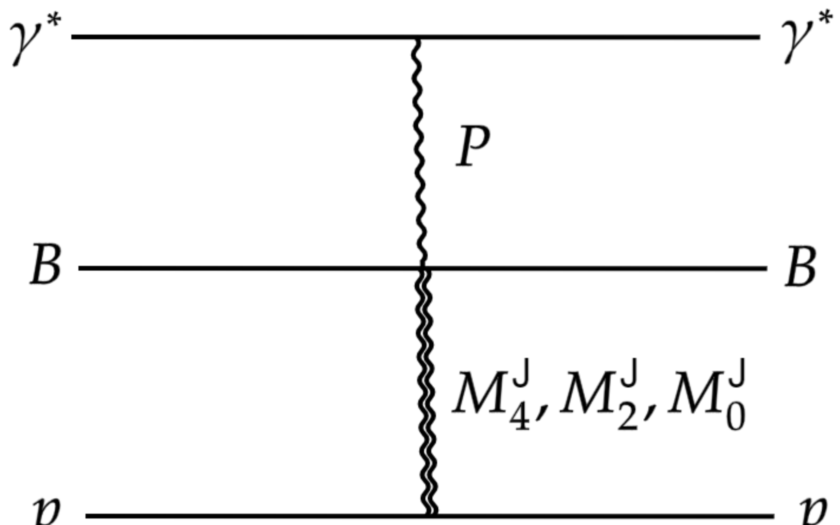


Generalized to semi-inclusive scattering:

Study in Regge theory



3 → 3 forward scattering in double Regge limit



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

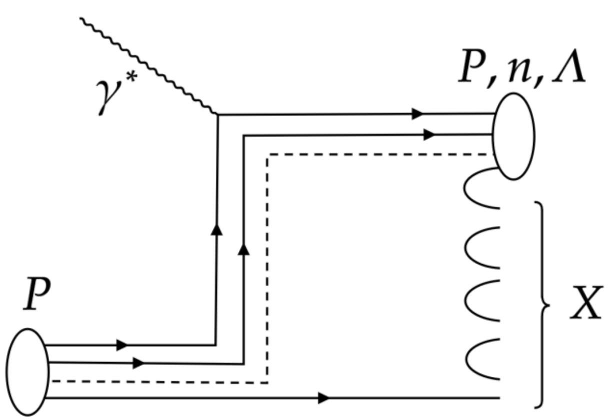
$$s_1 = (p_1 + p_B)^2 = \sqrt{s}\, m_t\, e^{-y^*}$$

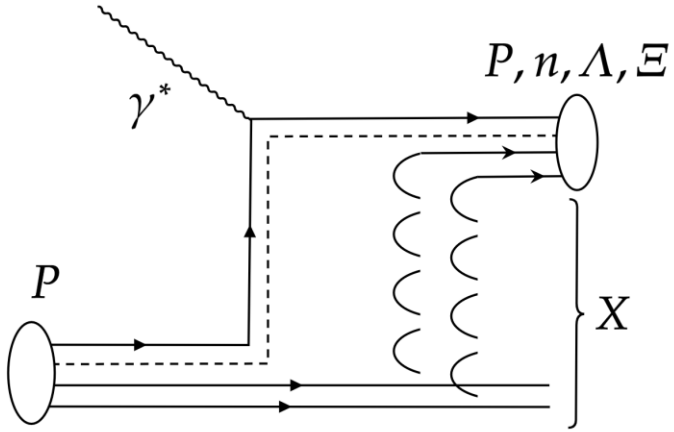
$$s_2 = (p_2 + p_B)^2 = \sqrt{s}\, m_t\, e^{y^*}$$

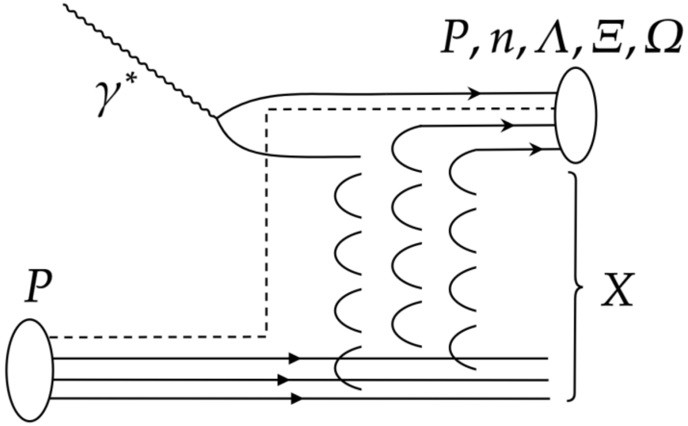
$$E_B \frac{d^3\sigma}{dp_B^3} \propto s_1^{\alpha_P(0)-1} s_2^{\alpha_M(0)-1}$$

The largest $\alpha_M(0)$ is leading

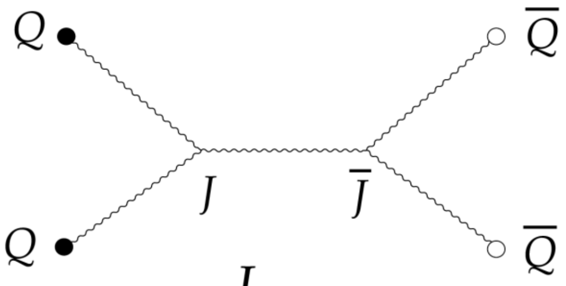
Three possible processes





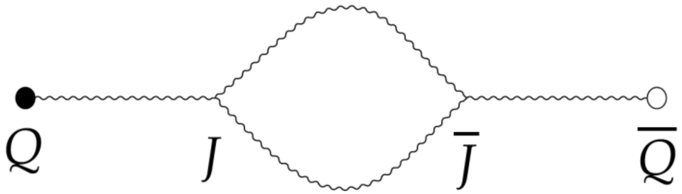


Mueller-Kancheli t-channel exchanges:



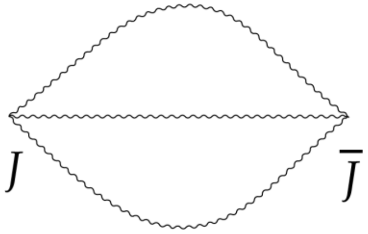
J_4

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



J_2

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

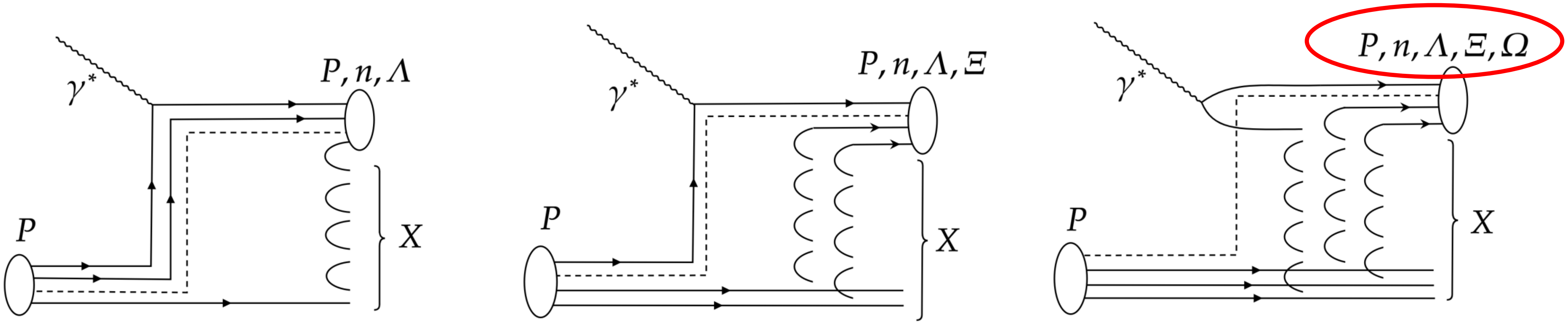


J_0

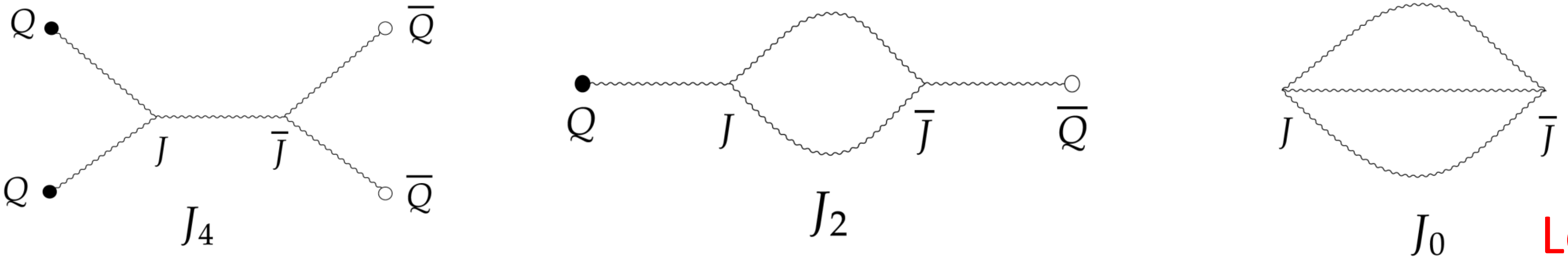
$$\alpha_0^J(0) \approx \frac{1}{2}$$

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

Three possible processes



Mueller-Kancheli t-channel exchanges:



Leading

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

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

Rapidity distribution of baryons in DIS

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

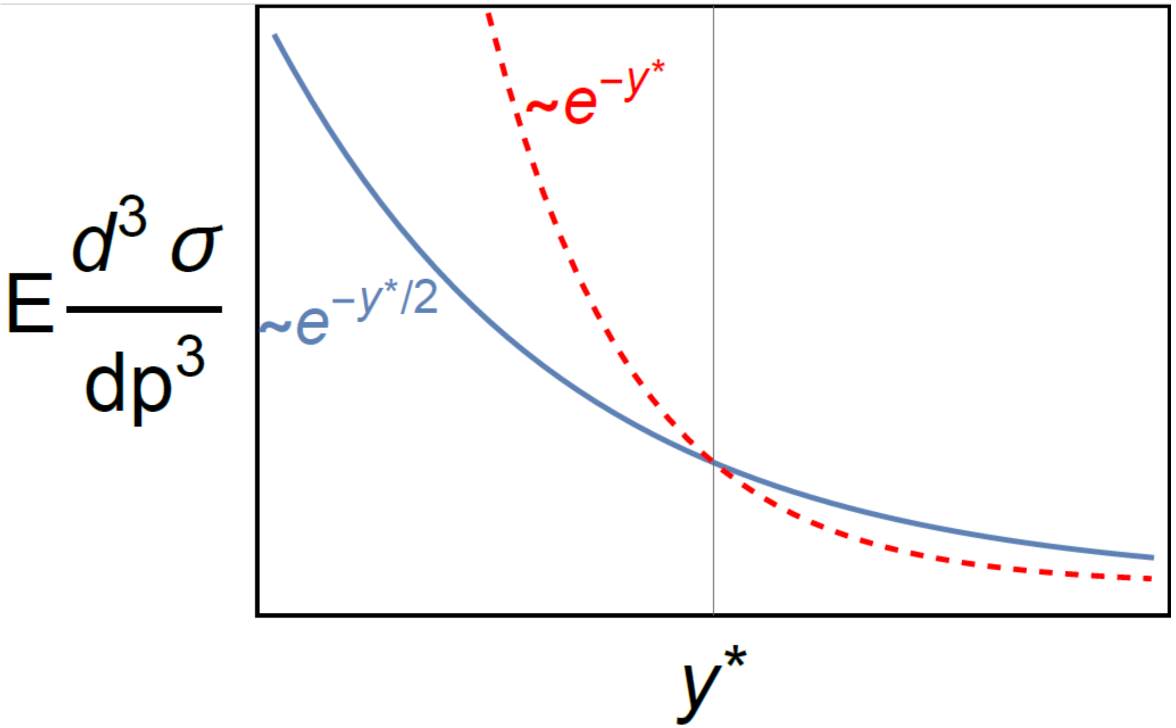
$$s_1 = (p_1 + p_B)^2 = \sqrt{s}\, m_t\, e^{-y^*}$$

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

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 and Jlab



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

Feynman-Wilson gas (FWG)

Some Experiments on Multiple Production*

Kenneth G. Wilson

CLNS-131
November 1970
September 1973

Generating functional of exclusive cross-sections:

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

Functional derivatives of the form $\frac{\delta}{\delta z(x)\delta z(y)\ldots}$ at $z(x) = 0$ yield exclusive cross sections:

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

The same functional derivatives at $z(x) = 1$ yield n-particle inclusive cross sections:

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

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

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

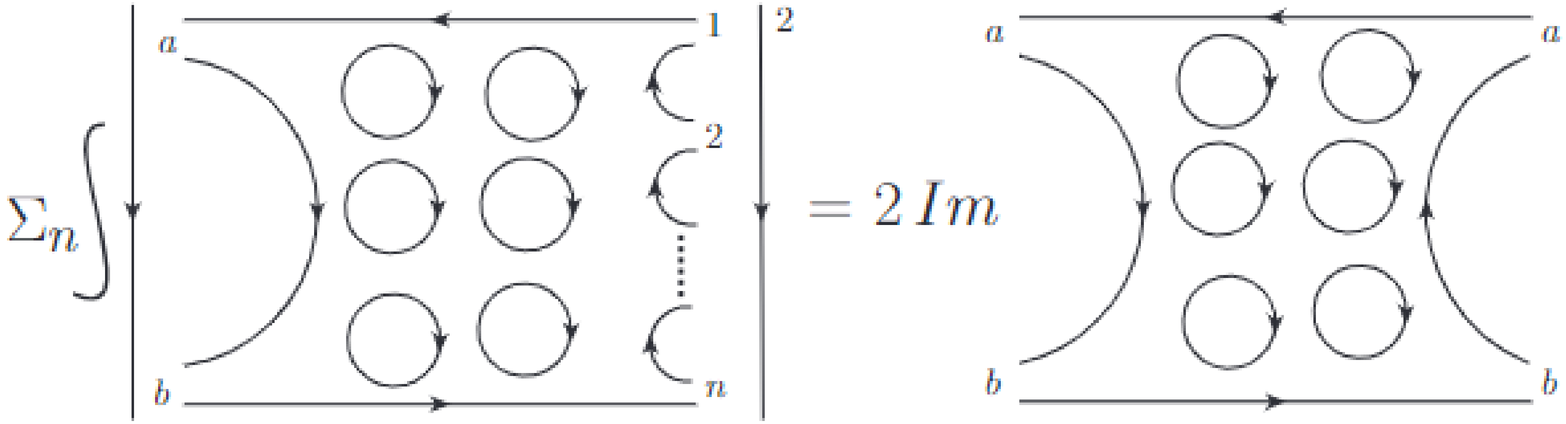
Y plays the role of the volume of the gas.

Grand canonical partition function of FWG on the planar level

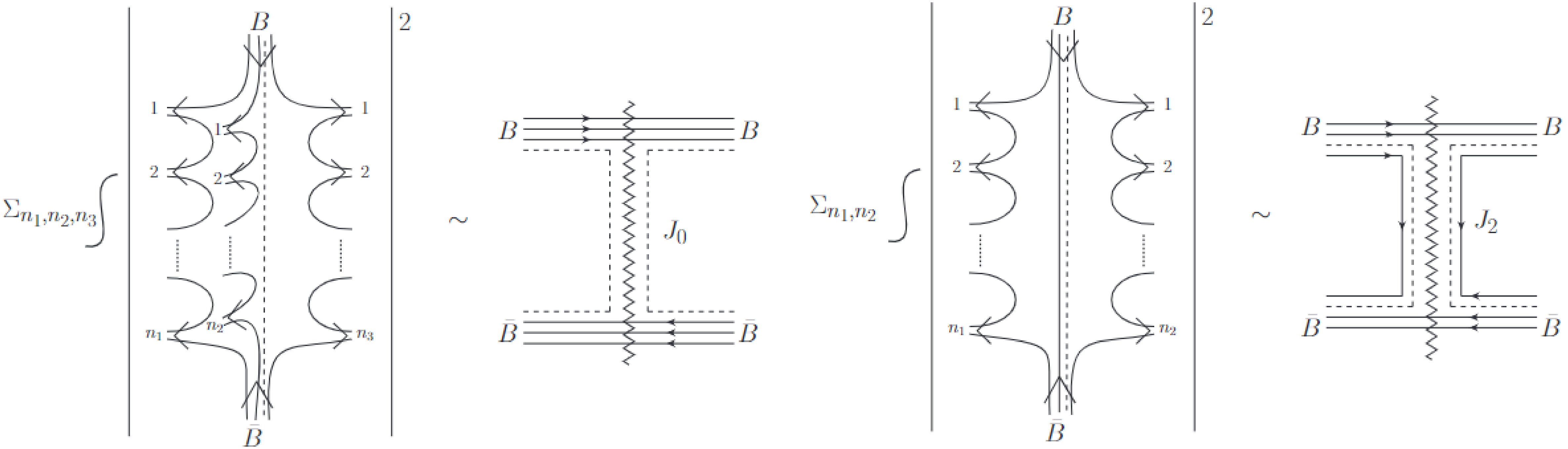
Integrating over all kinematical variables:

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

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



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

$$\alpha_{\mathbb{J}_0} \simeq 2\alpha_B - 1 + 3(\alpha_{\mathbb{R}} - 1) \simeq 0.5$$

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

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

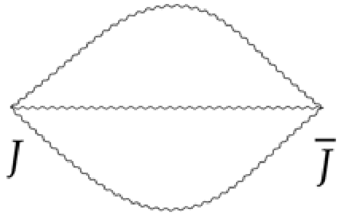
C_2 can be separately inferred from the analysis of Pomeron-dominated cylindrical topology:

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

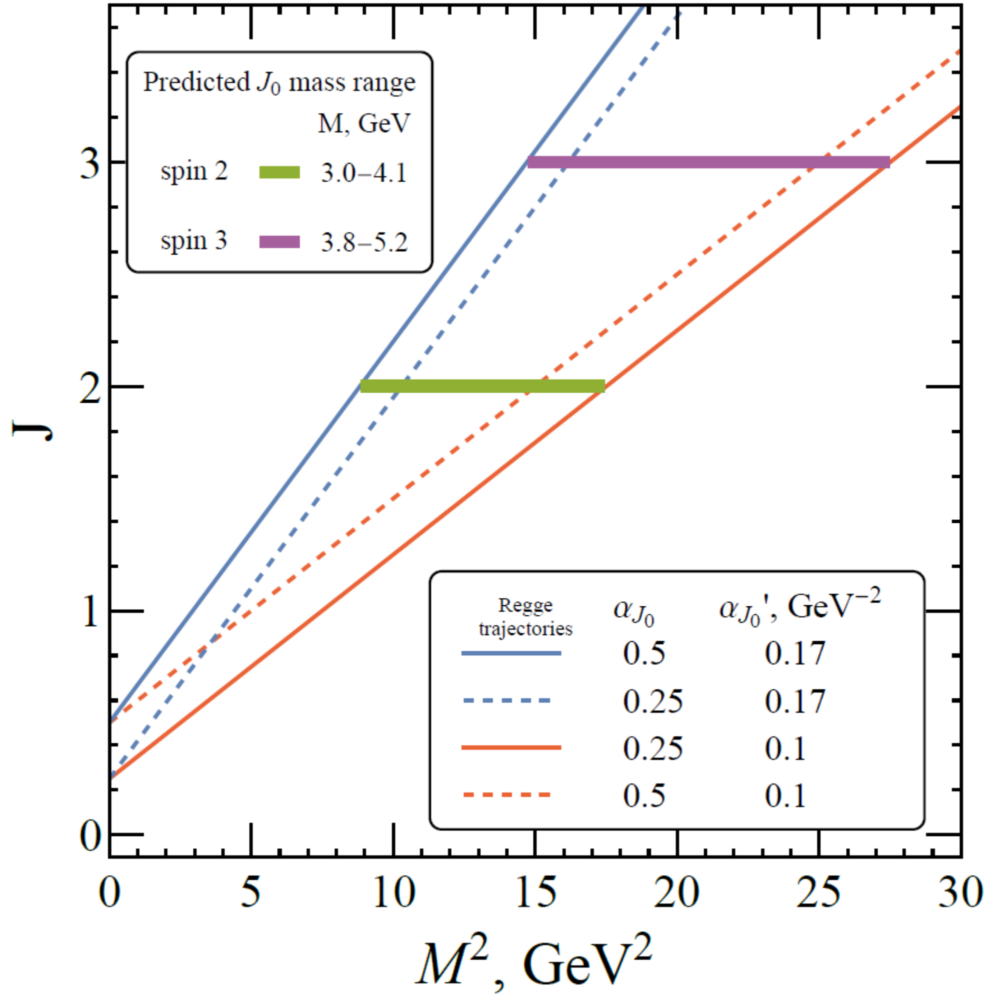
leading to beam rapidity slope $|\alpha_{\mathbb{J}_0} + \alpha_{\mathbb{P}} - 2| \simeq 0.66 + C_3$ (compared to 0.65 ± 0.1 from RHIC BES)

J_0 gluonic structure and Regge trajectory

$$G_{J\bar{J}}(x,y) = \epsilon^{ijk}\epsilon_{i'j'k'} P\exp\left[ig\int_x^y dz^\mu A_\mu(z)\right]_{i'}^{i} P\exp\left[ig\int_x^y dz'^\nu A_\nu(z')\right]_{j'}^{j} P\exp\left[ig\int_x^y dz''^\lambda A_\lambda(z'')\right]_{k'}^{k}$$



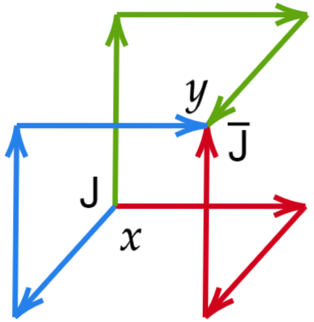
J_0



$$\alpha(M^2) = \alpha(0) + \alpha' M^2$$

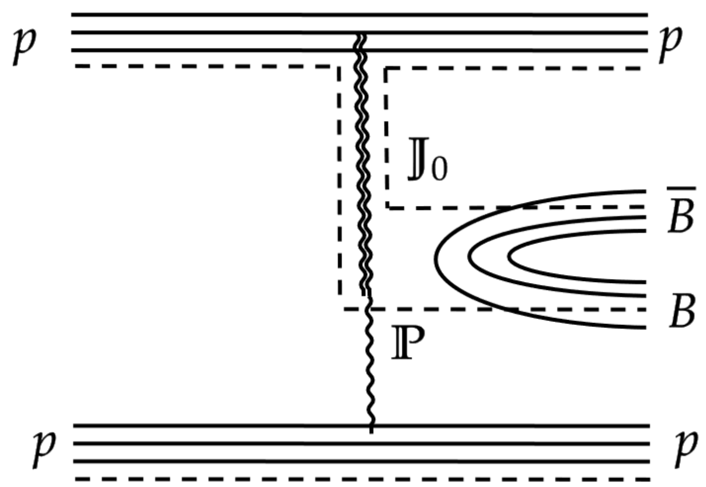
$$\alpha'_{\mathbb{J}_0} \simeq \frac{2}{3}\alpha'_{\mathbb{P}} \simeq 0.10 - 0.17\,\mathrm{GeV}^{-2}$$

Can search for such glueballs on the lattice, using operators incorporating junctions.



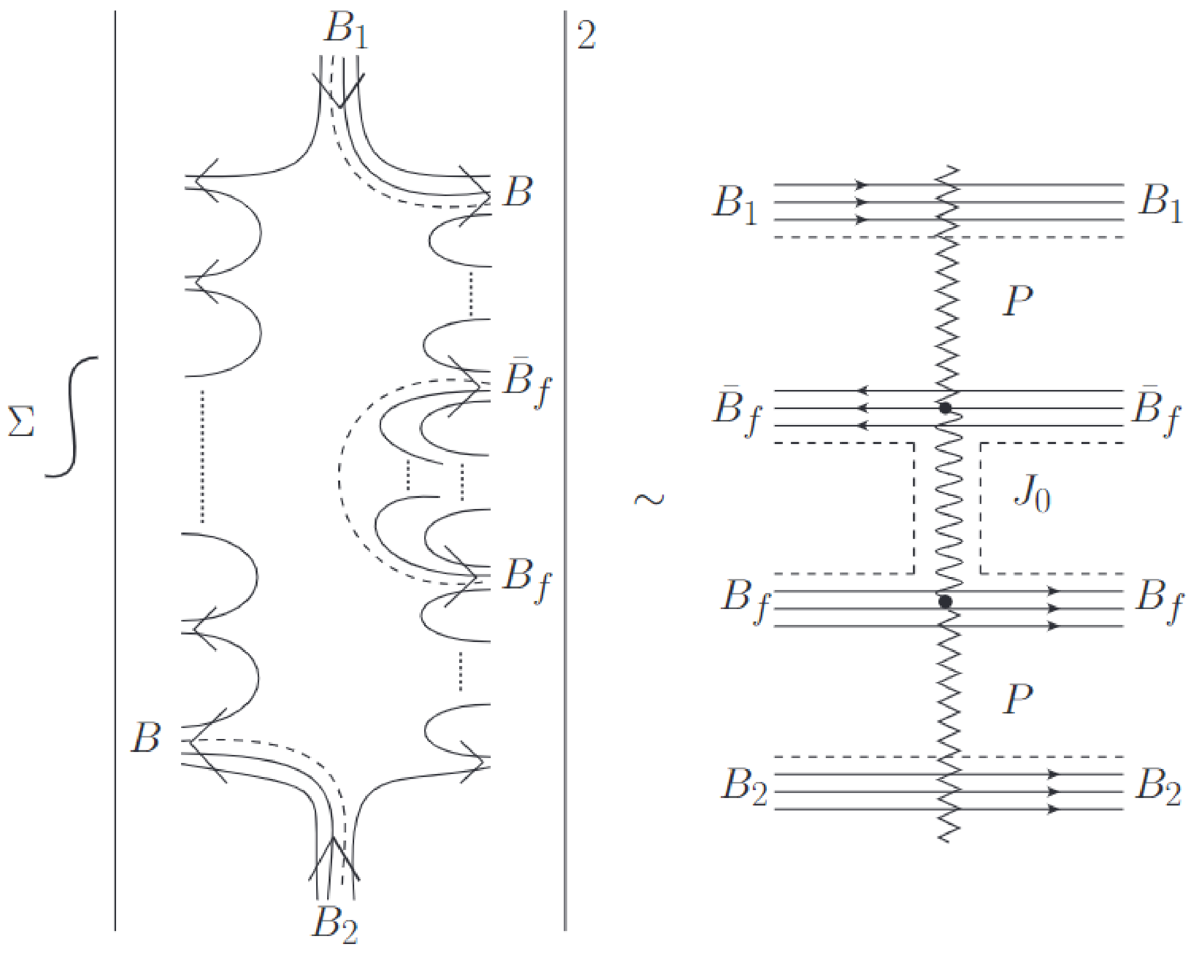
Suggestions for experiment: J_0 trajectory

- 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 $\alpha_{\mathbb{J}_0}$
- 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.
- Search for heavy $2^{++}, 3^{--}$ and 3^{-+} glueballs on the lattice.



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 of part 2

- 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
- There is a candidate for J_0 glueball in the lattice QCD measurements
- Suggestions for experiment on baryon-number – flavor separation, studying J_0 trajectory further with tetraquark production and analyzing $B\bar{B}$ pair production

Backup

Optical theorem

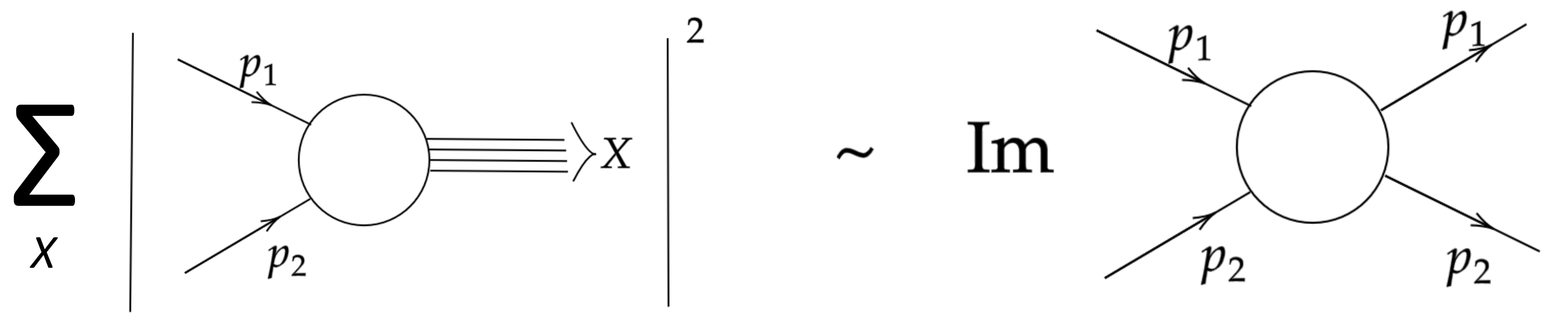
$$SS^\dagger = S^\dagger S = \mathbb{1}, \qquad S = \mathbb{1} + iT \quad \Longrightarrow \quad i(T^\dagger - T) = T^\dagger T$$

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.

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

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

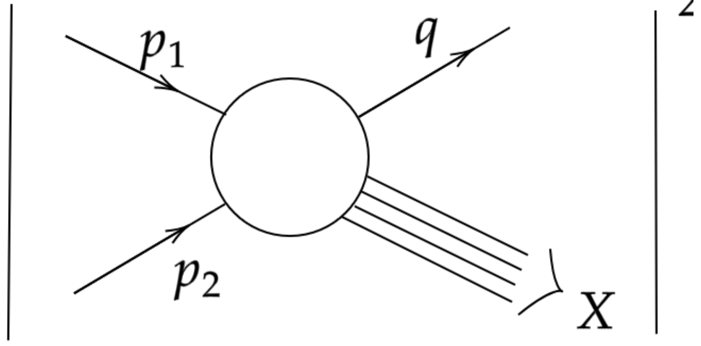
$$= i\langle 12\bar{3}|T^\dagger|12\bar{3}\rangle - i\langle 12\bar{3}|T|12\bar{3}\rangle$$

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

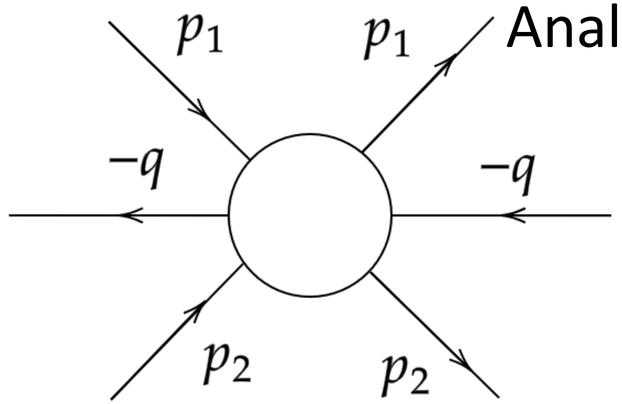
Generalization of the optical theorem for single particle inclusive processes

Analyze in Regge theory

$\frac{d}{dq^3} \sum_X$



$|^2 \sim$ Disk



Basics of Regge theory

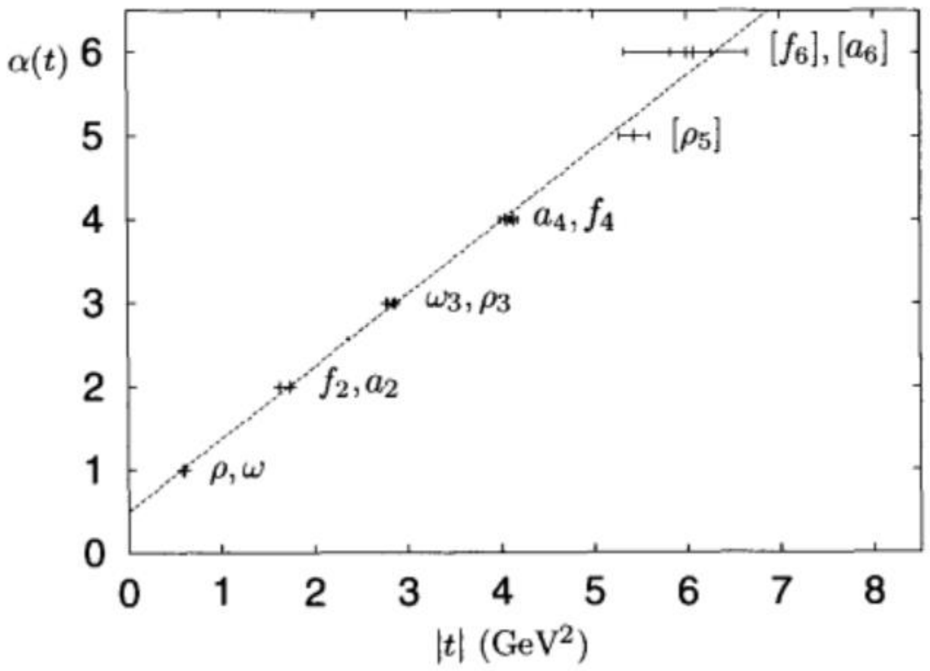
S-matrix unitarity + analyticity + crossing symmetry

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 $\alpha(0) < 1$.

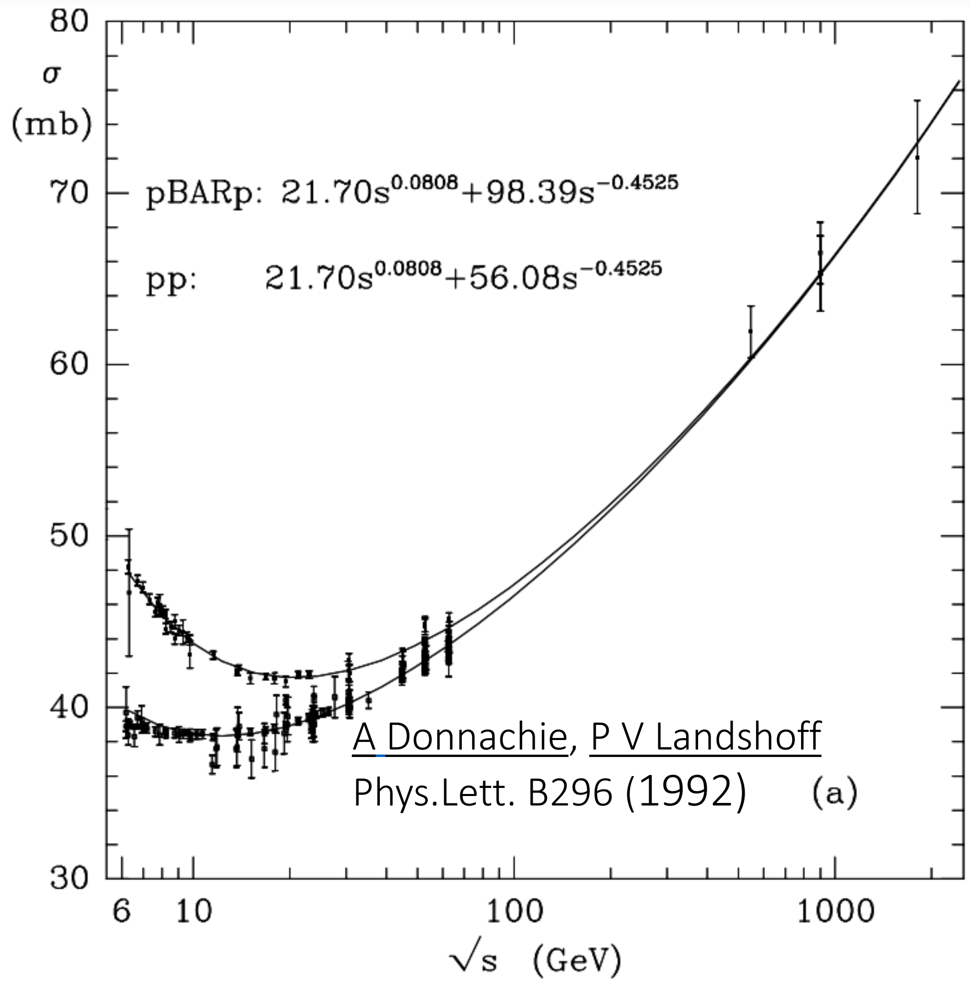
Does it imply $\sigma_{tot} \sim s^{\alpha(0)-1}$ decreases with c.o.m. energy?

Experiment: NO! Instead, it steadily grows.

To describe it in Regge theory a new object - the Pomeron is introduced

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

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



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

P.S.

Call for proposals

- Looking for collaboration on weekend outdoor adventures
- Ideally 20-25 km mountain hike
- (Nothing arranged yet)