Baryon number dynamics in heavy ion collisions

David Frenklakh

Stony Brook University

based on

arXiv: 2312.15039 with D. Kharzeev and W. Li

arXiv: (appearing tonight) with D. Kharzeev and A. Palermo

Stony Brook University

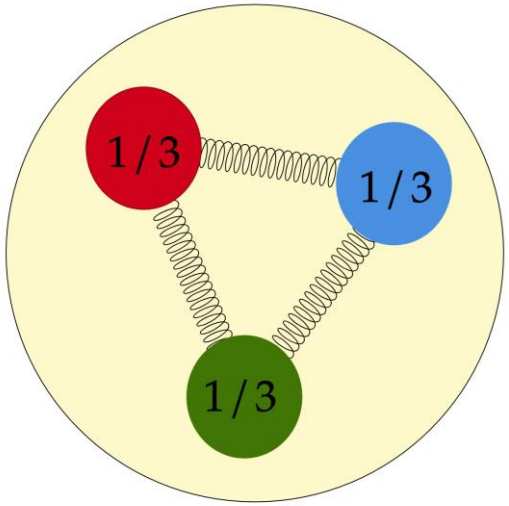
The 39th Winter Workshop on Nuclear Dynamics

Jackson, WY February 12, 2024

Motivation: what carries the baryon number?

Motivation: what carries the baryon number?

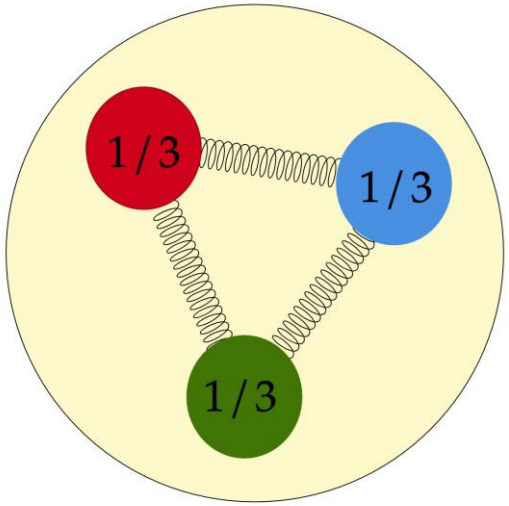
$$B(x_1, x_2, x_3) = \epsilon^{ijk} q(x_1)_i \; q(x_2)_j q(x_3)_k$$



Motivation: what carries the baryon number?

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

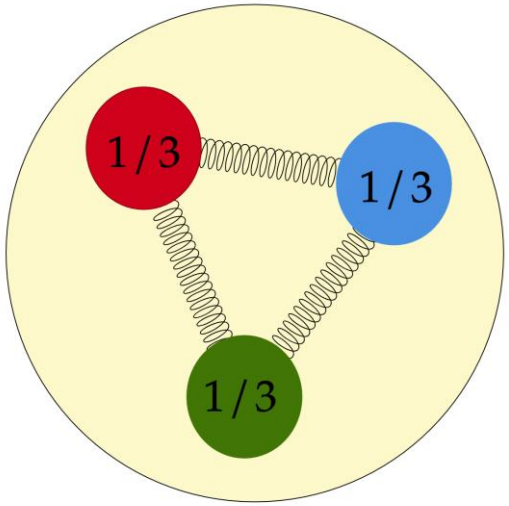
Gauge invariance



Motivation: what carries the baryon number?

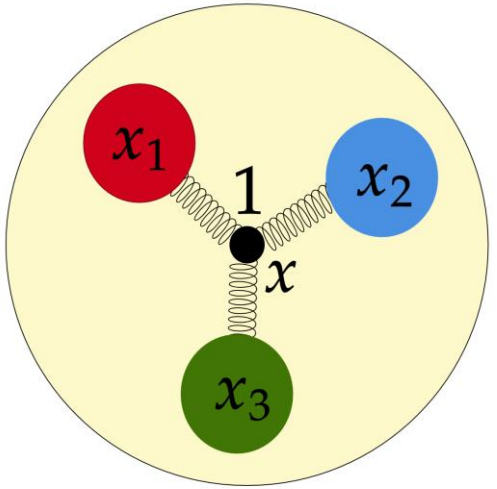
$$B(x_1, x_2, x_3) = \epsilon^{ijk} q(x_1)_i \; q(x_2)_j q(x_3)_k$$

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)

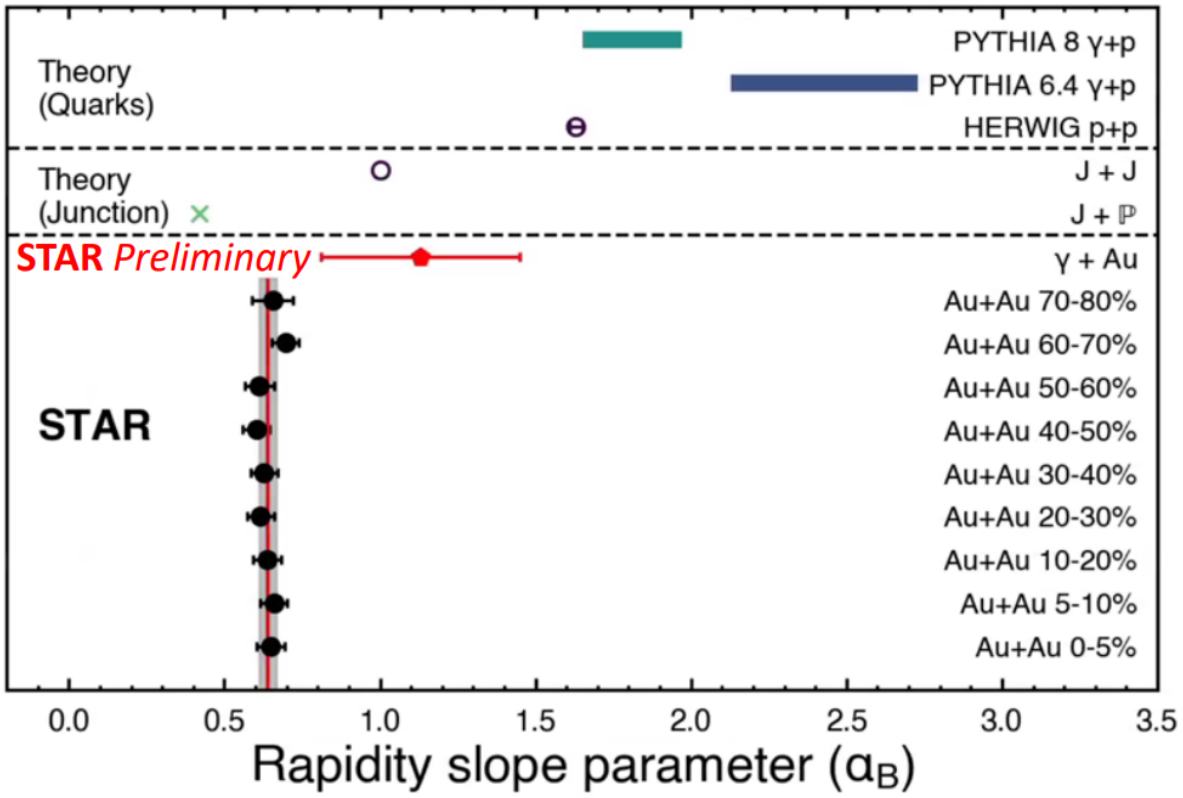
Experimental status: heavy ion collisions

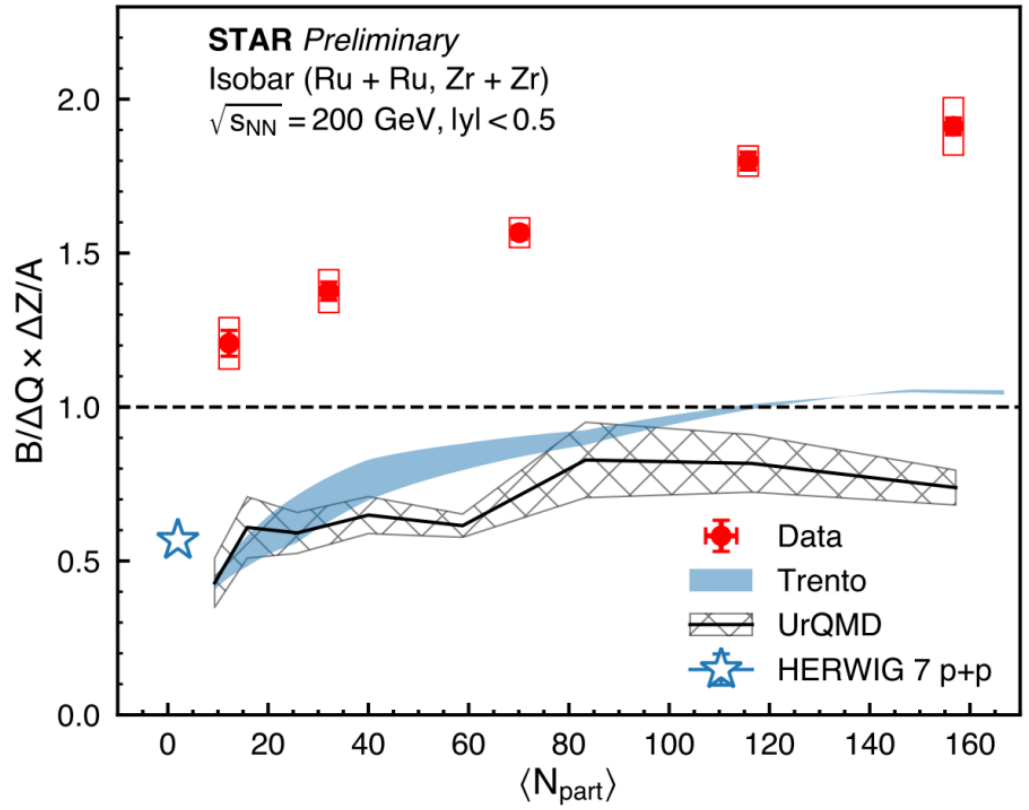
Can gluons trace baryon number?

D. Kharzeev

Physics Letters B 378 (1996) 238–246

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





C.Y.Tsang, QM 2023

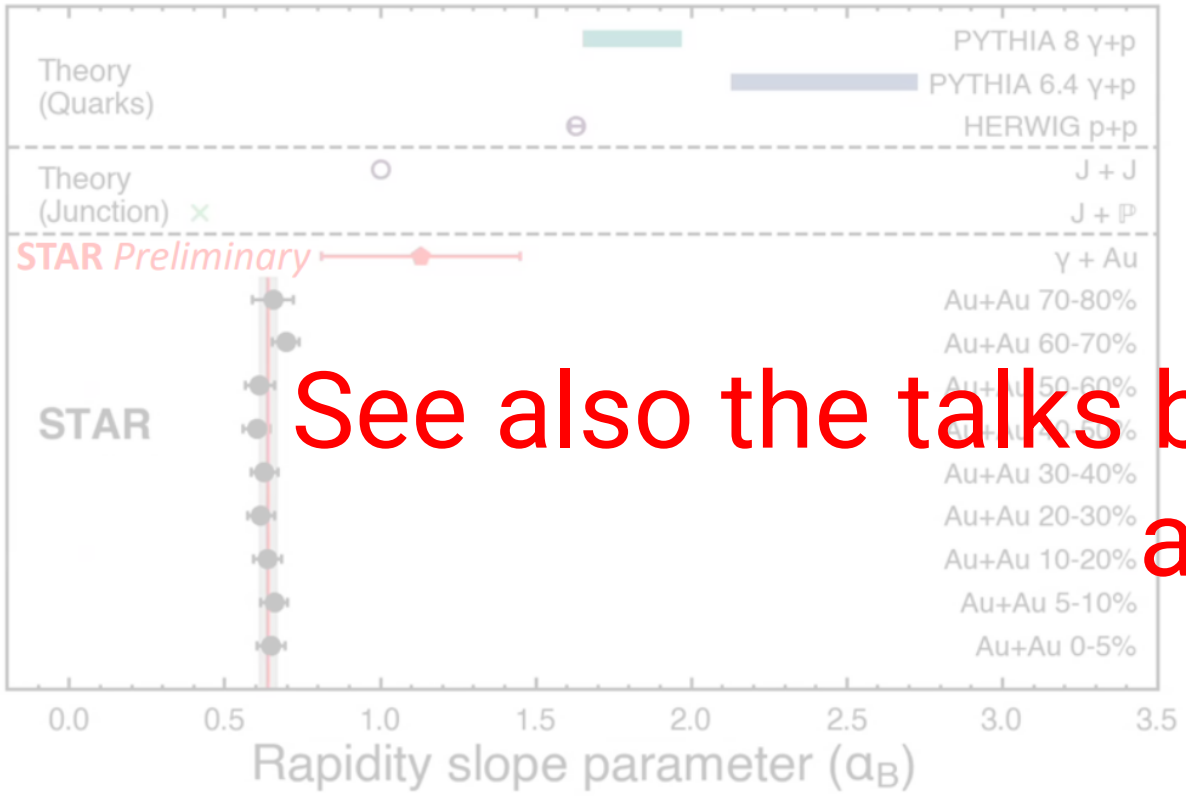
Experimental status: heavy ion collisions

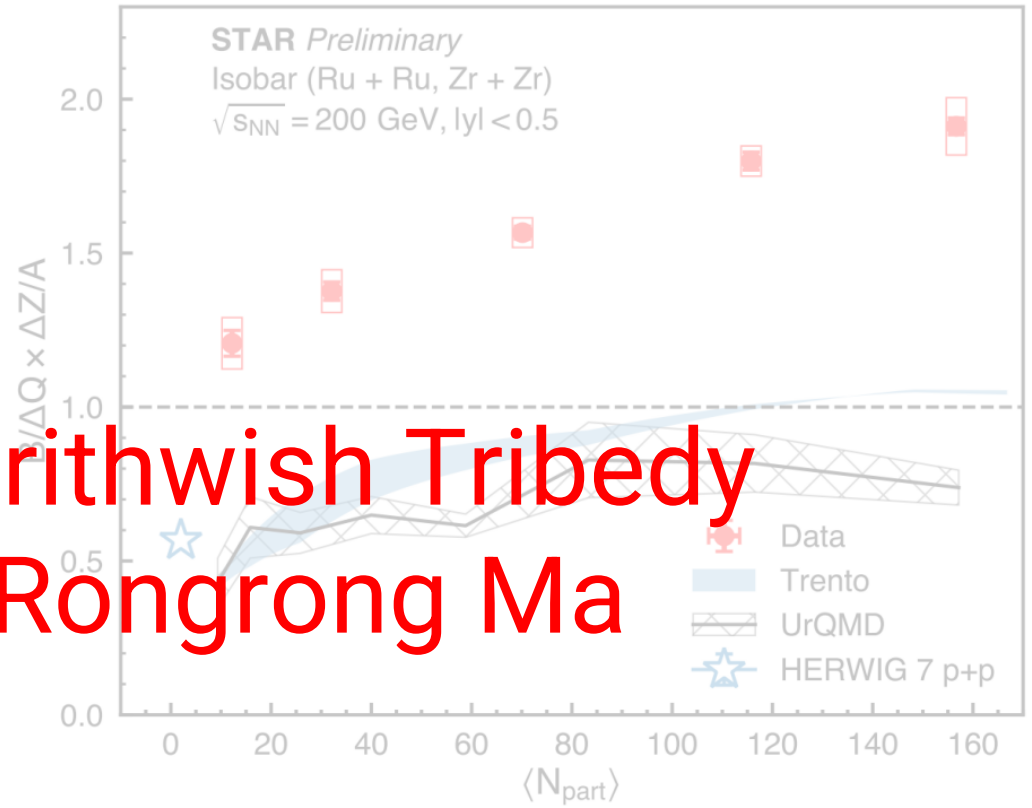
Can gluons trace baryon number?

D. Kharzeev

Physics Letters B 378 (1996) 238–246

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

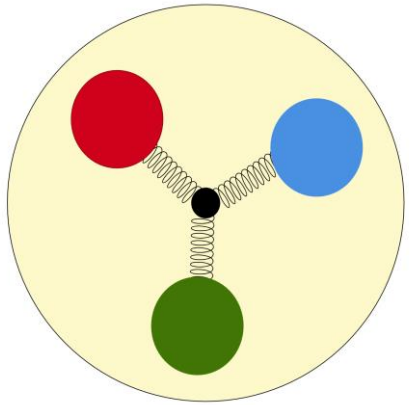


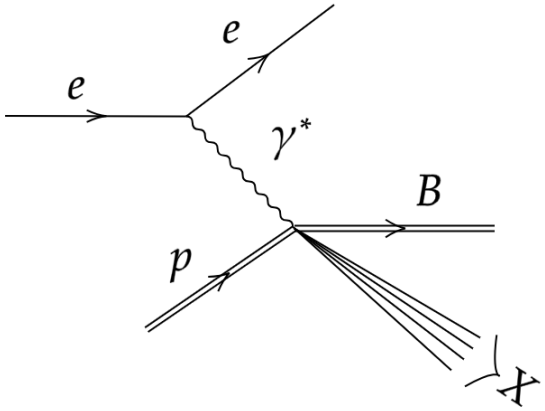


See also the talks by Prithwish Tribedy and Rongrong Ma

What this talk is about

1) Signatures of baryon junctions in semi-inclusive DIS

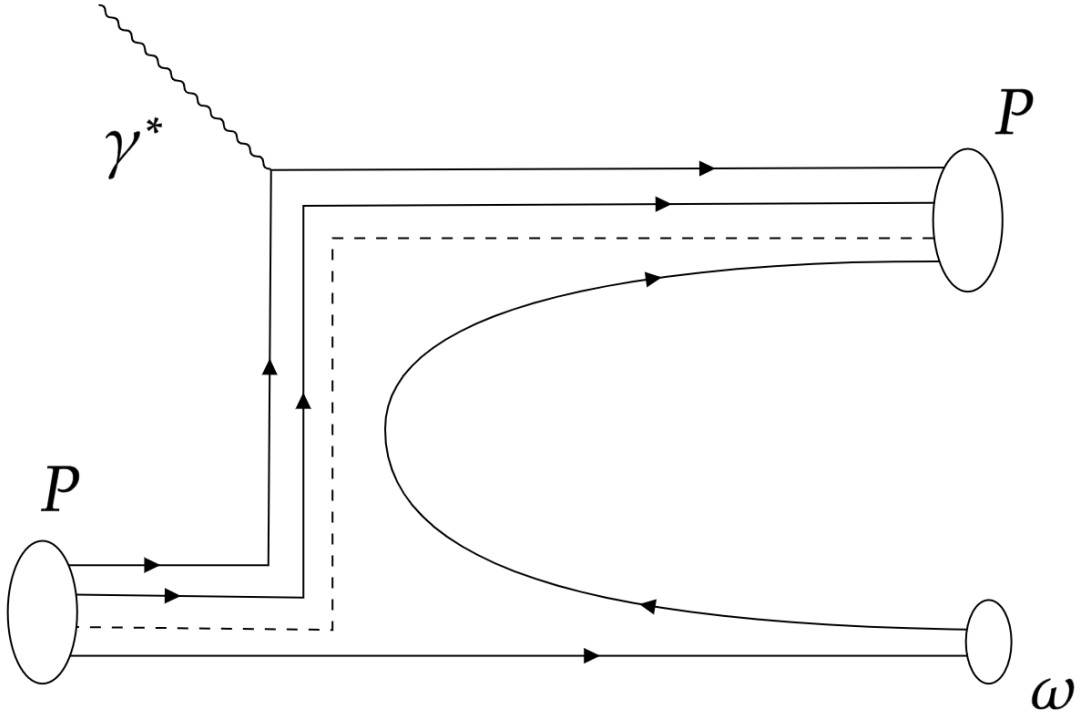




2) Connection between anomalous transport effects and baryon stopping

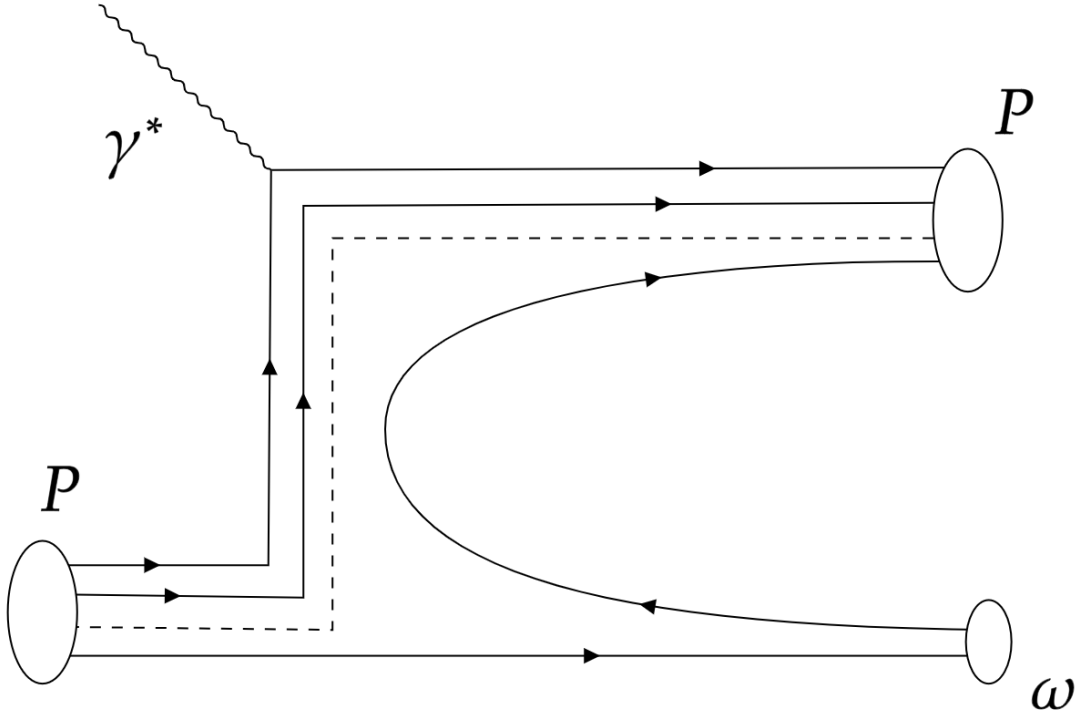
A new correlator of $\Delta\gamma$ -type will be proposed

Initial motivation: exclusive ω production



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

Initial motivation: exclusive ω production

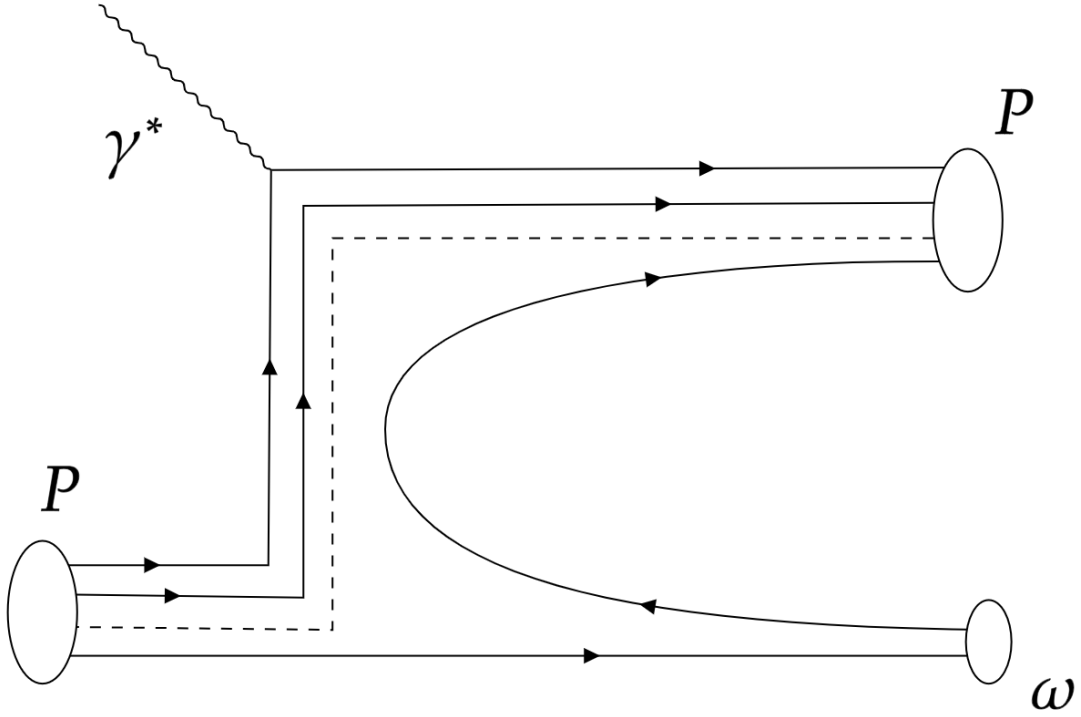


Significant fraction of events have the proton in the photon fragmentation region

Entire baryon is exchanged in the t-channel

Cannot separate the junction from valence quarks

Initial motivation: exclusive ω production



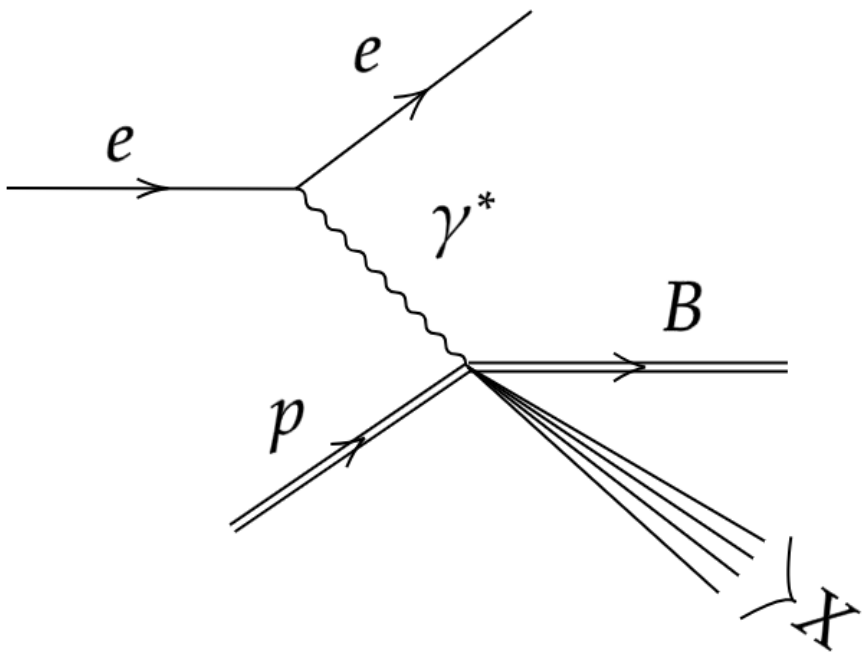
Significant fraction of events have the proton in the photon fragmentation region

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:

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

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

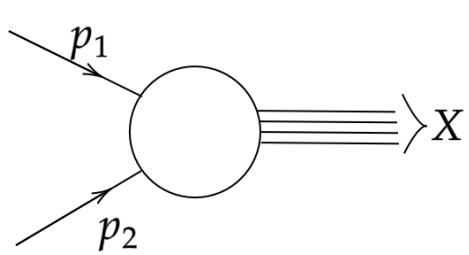
$$p_B = (m_t \cosh y^*, m_t \sinh y^*, p_B^\perp)$$

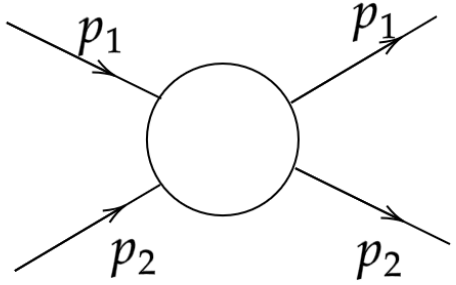
Mueller-Kancheli theorem

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

Optical theorem:

$$\sum_X \left| \right. \quad \left. \right|^2 \sim \mathrm{Im}$$

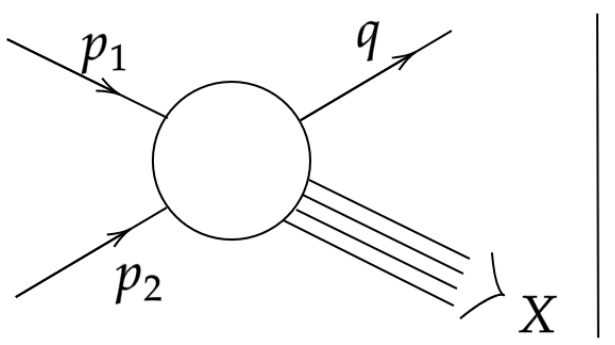


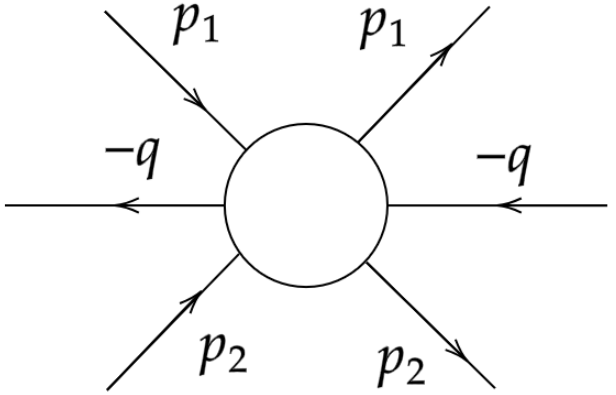


Generalized to semi-inclusive scattering:

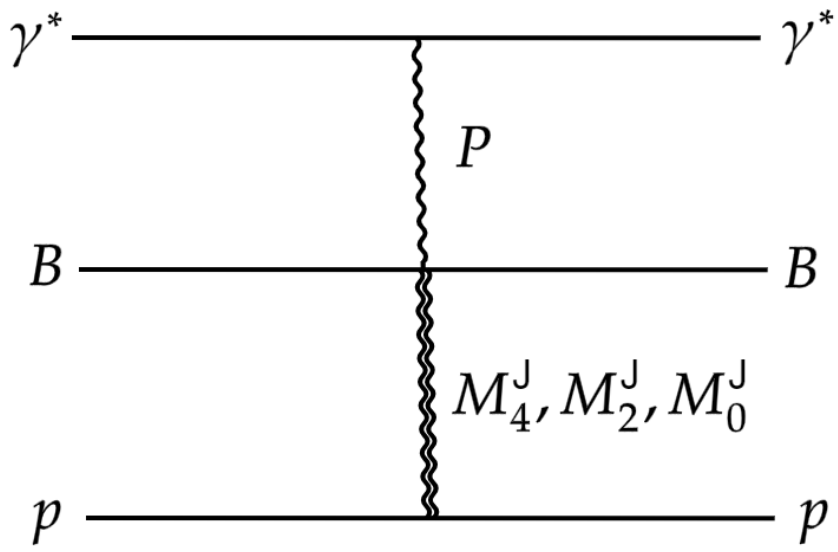
Study in Regge theory

$$\frac{d}{dq^3}\sum_{X'} \left| \right. \quad \left. \right|^2 \sim \mathrm{Disk}$$





$3 \to 3$ forward scattering in Regge limit



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

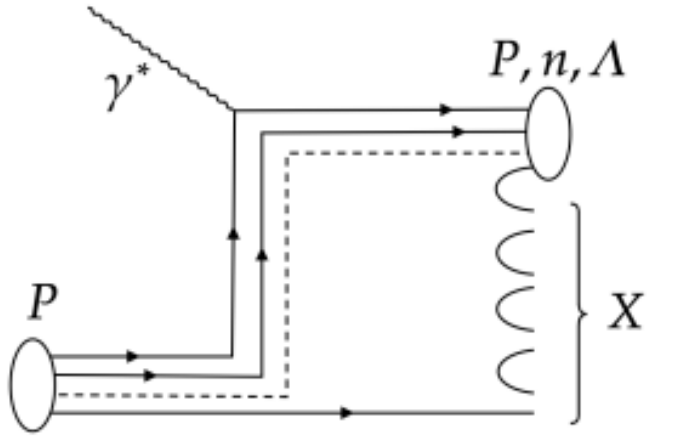
$$s_1 = (p_1 + p_B)^2 = \sqrt{s}\, m_t\, e^{-y^*}$$

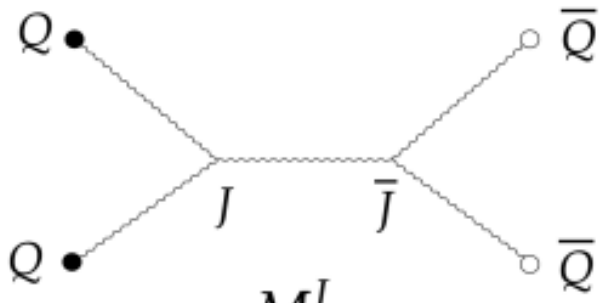
$$s_2 = (p_2 + p_B)^2 = \sqrt{s}\, m_t\, e^{y^*}$$

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

The largest $\alpha_M(0)$ is leading

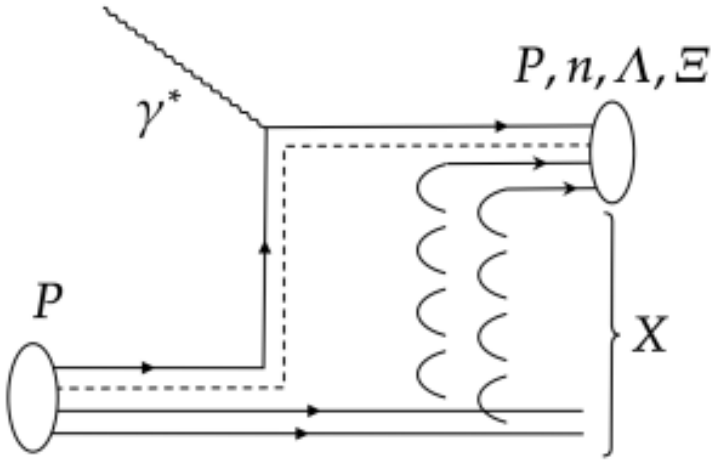
Possible processes





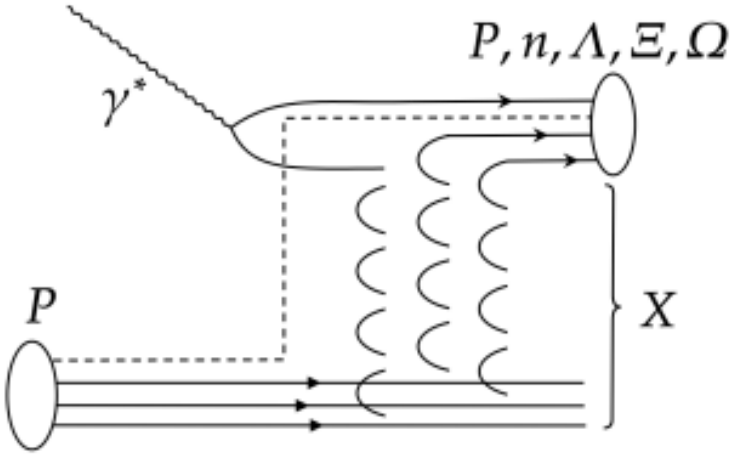
M_4^J

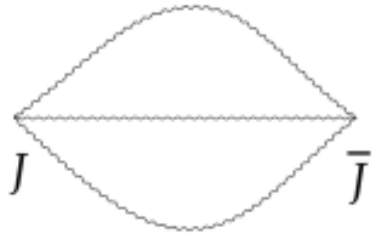
$$\alpha_4^J(0) \approx -\frac{1}{2}$$



M_2^J

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



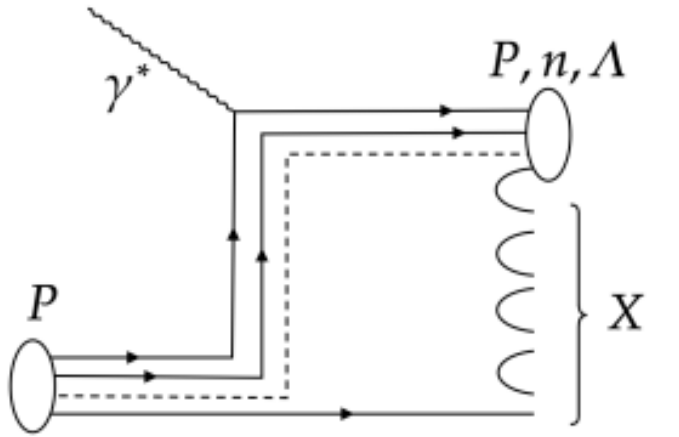


M_0^J

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

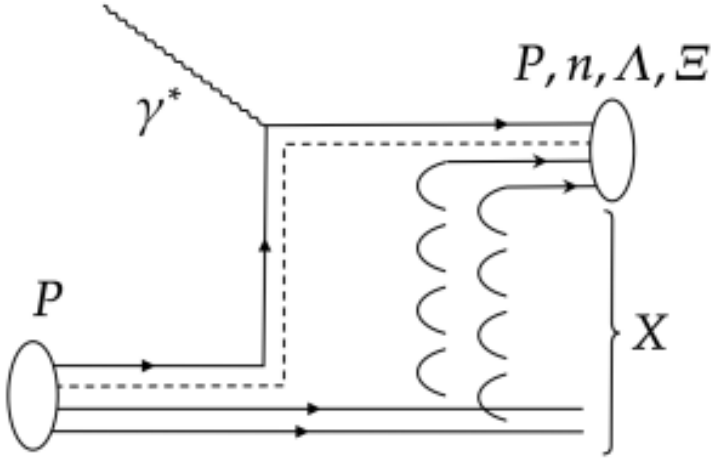
Intercept estimates: G.C. Rossi and G. Veneziano, Nucl. Phys. B 123 (1977)

Possible processes



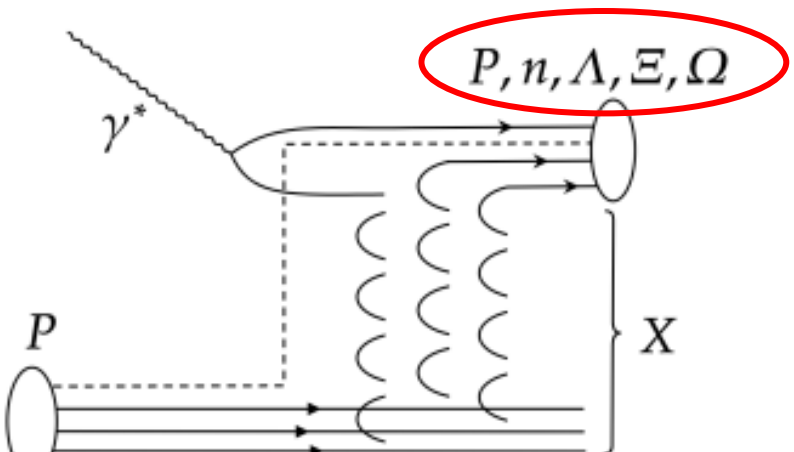
M_4^J

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



M_2^J

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



Leading

M_0^J

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

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

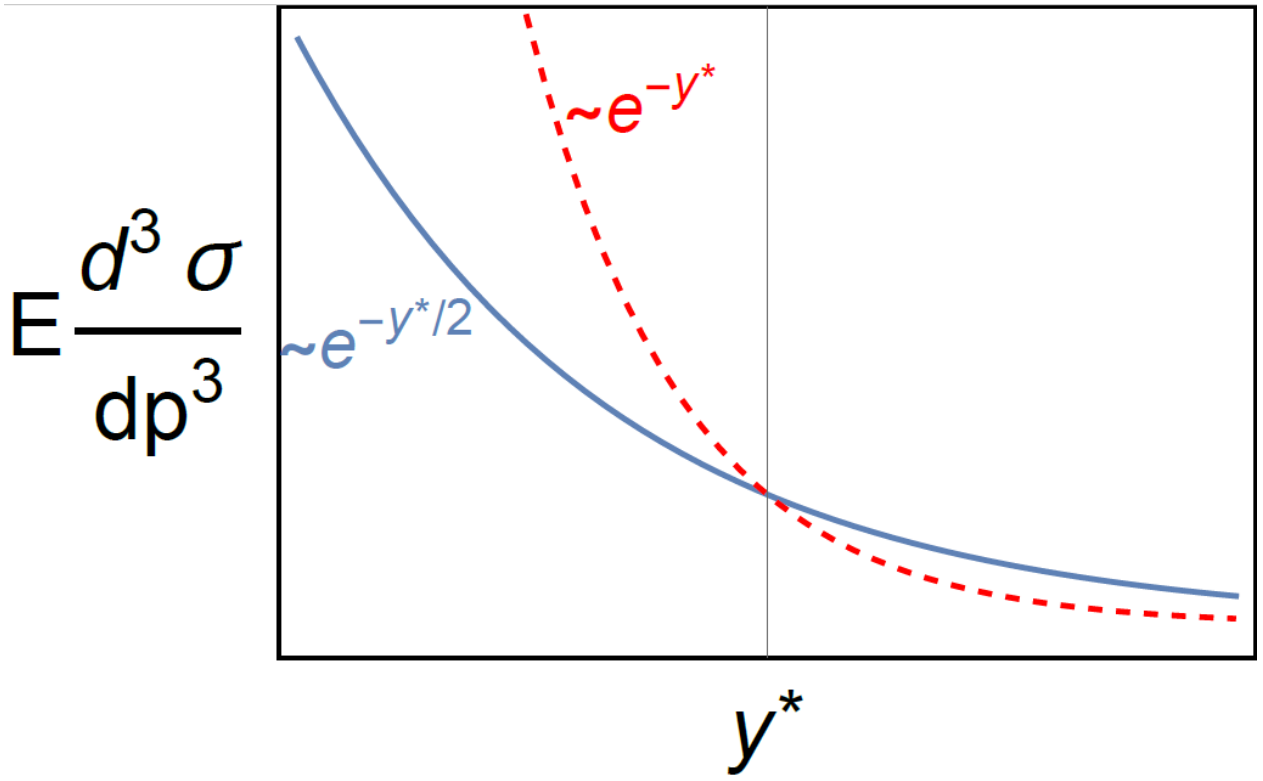
Rapidity distribution

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

$$s_1 = \sqrt{s}\ m_t\ e^{-y^*}\ ,\ s_2 = \sqrt{s}\ m_t\ e^{y^*}$$

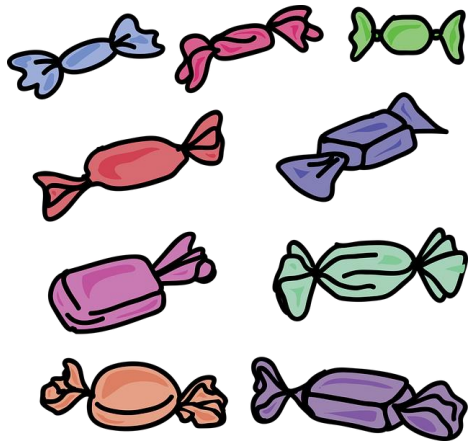
$$\alpha_P \approx 1, \alpha_M \approx \frac{1}{2}$$

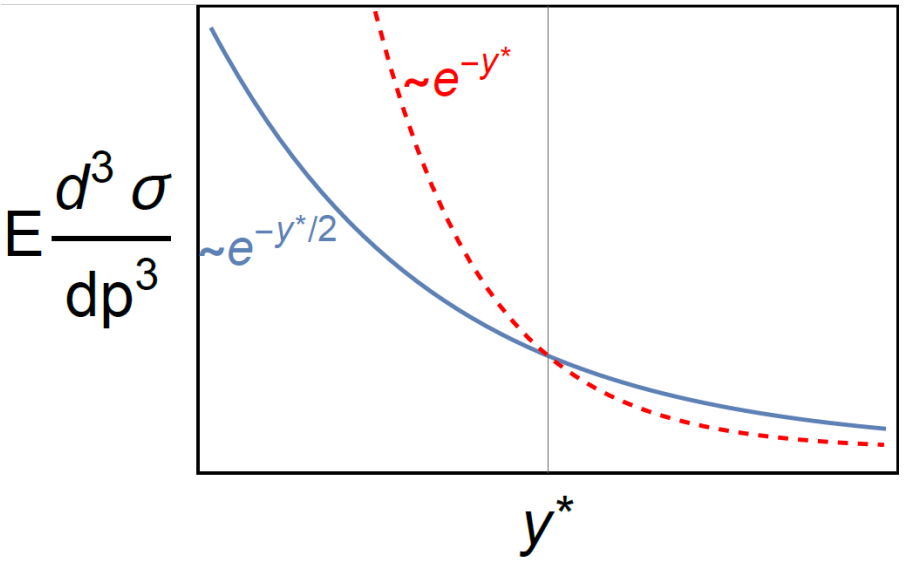
$$E_B \frac{d^3\sigma}{dp_B^3} \propto s^{-1/4} e^{-y^*/2}$$



Part 1 summary: predictions

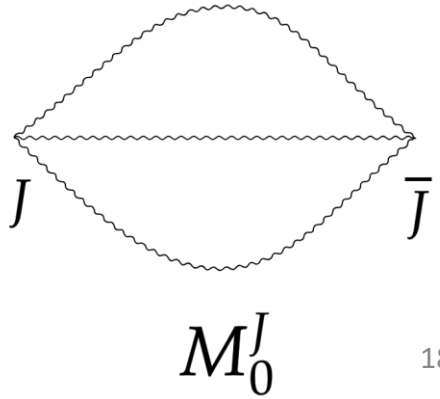
Flavor content of forward baryons: all flavors



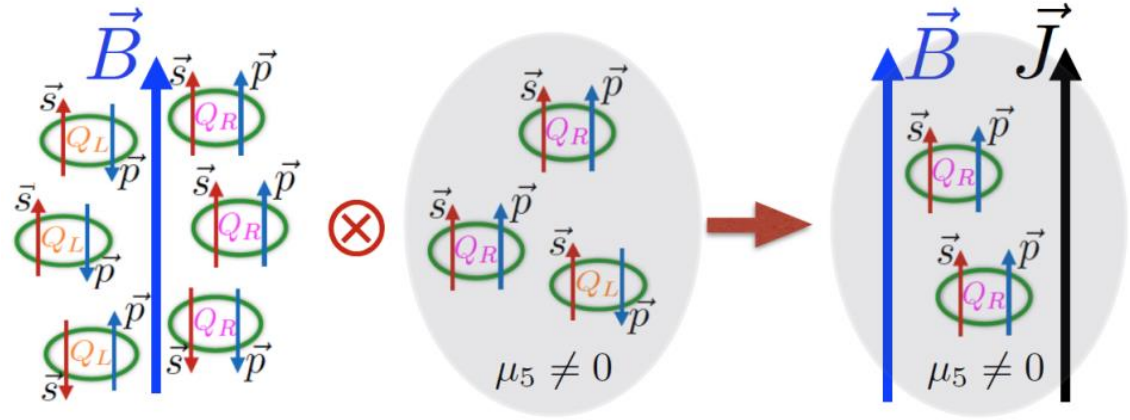


Rapidity dependence of forward baryon distribution

Large meson multiplicity from 3 fragmenting strings



Part 2: anomalous baryon number transport

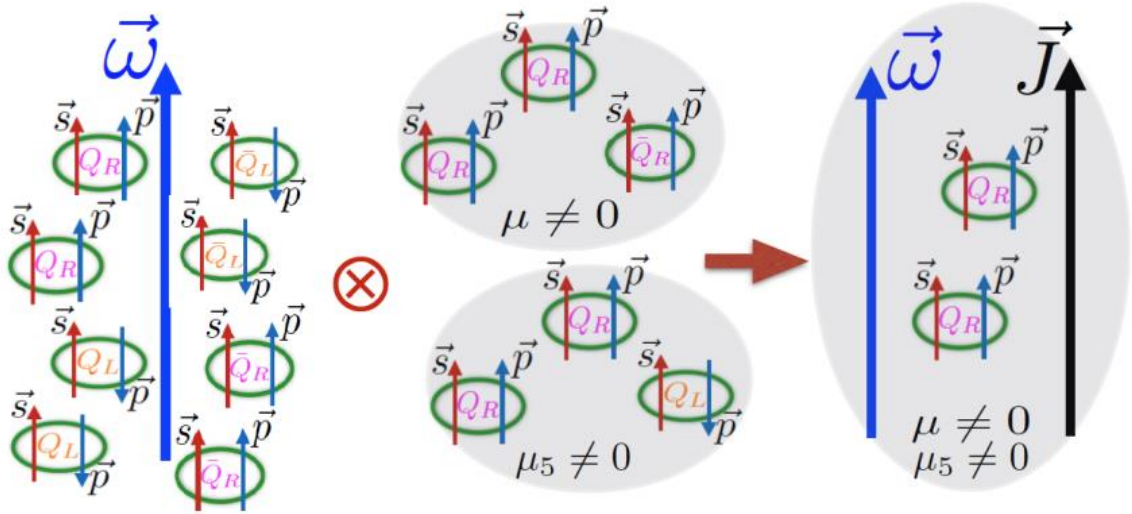


Chiral Magnetic Effect

3 light flavors

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

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



Chiral Vortical Effect

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

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

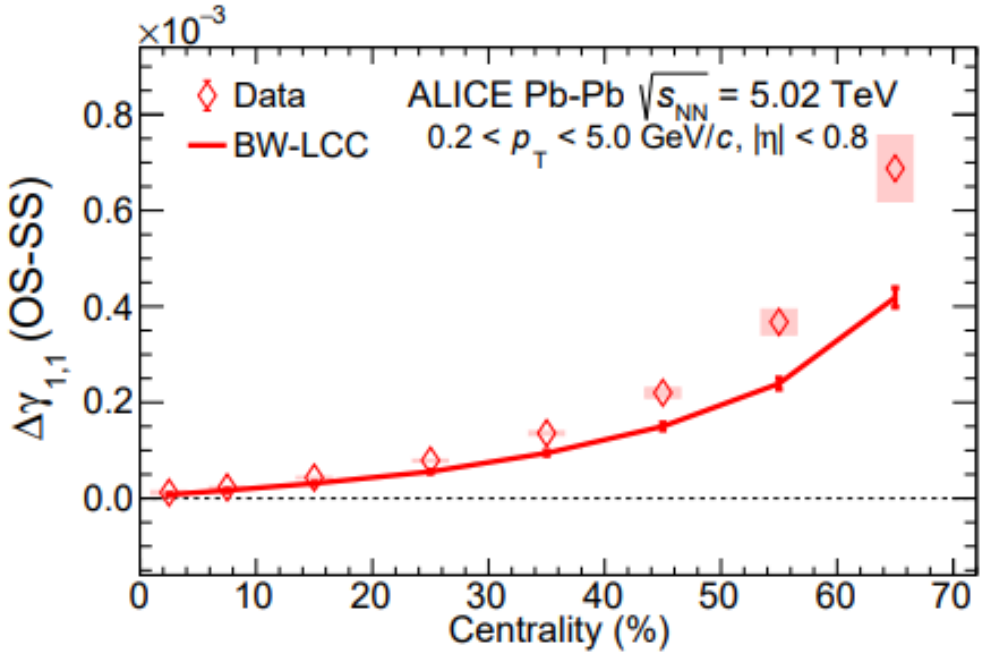
D. Kharzeev and D.T. Son (2010)
D. Kharzeev, et al , PPNP 88, 1 (2016)

CME search in heavy ion collisions

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle$$

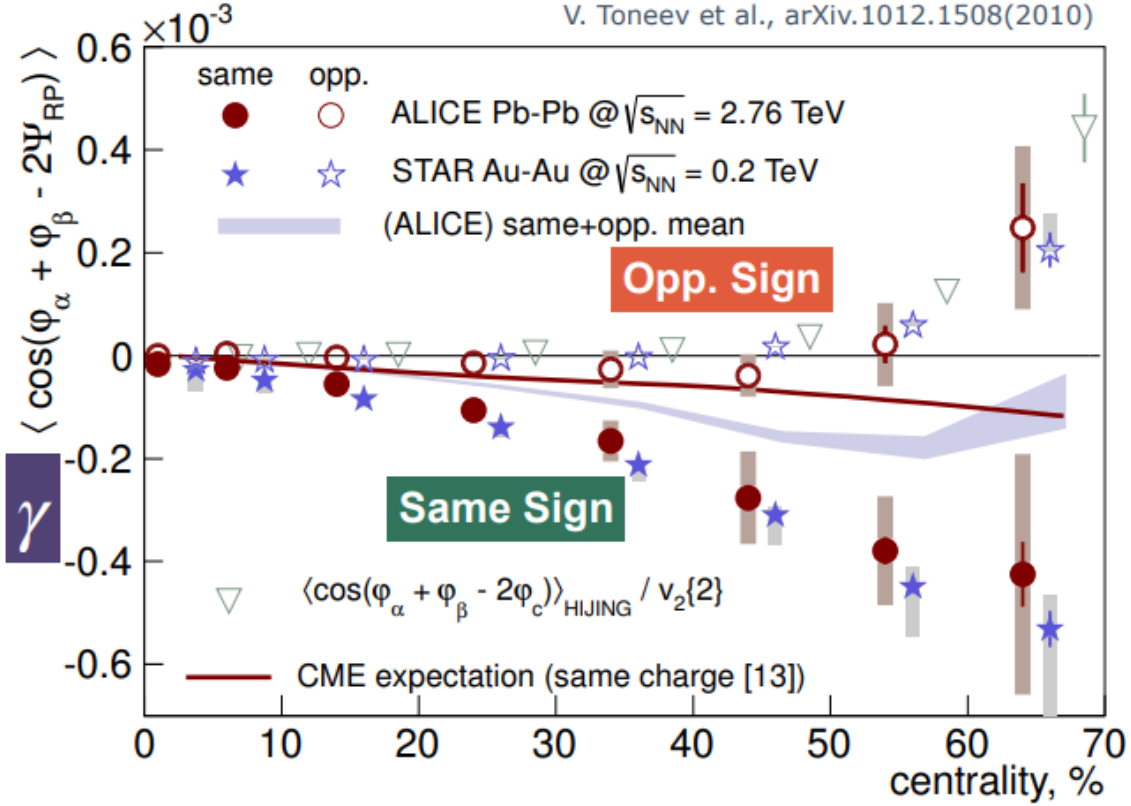
$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

$$\Delta\gamma^{CME} \propto \mu_5^2, \quad \langle \mu_5 \rangle = 0, \quad \langle \mu_5^2 \rangle \neq 0$$



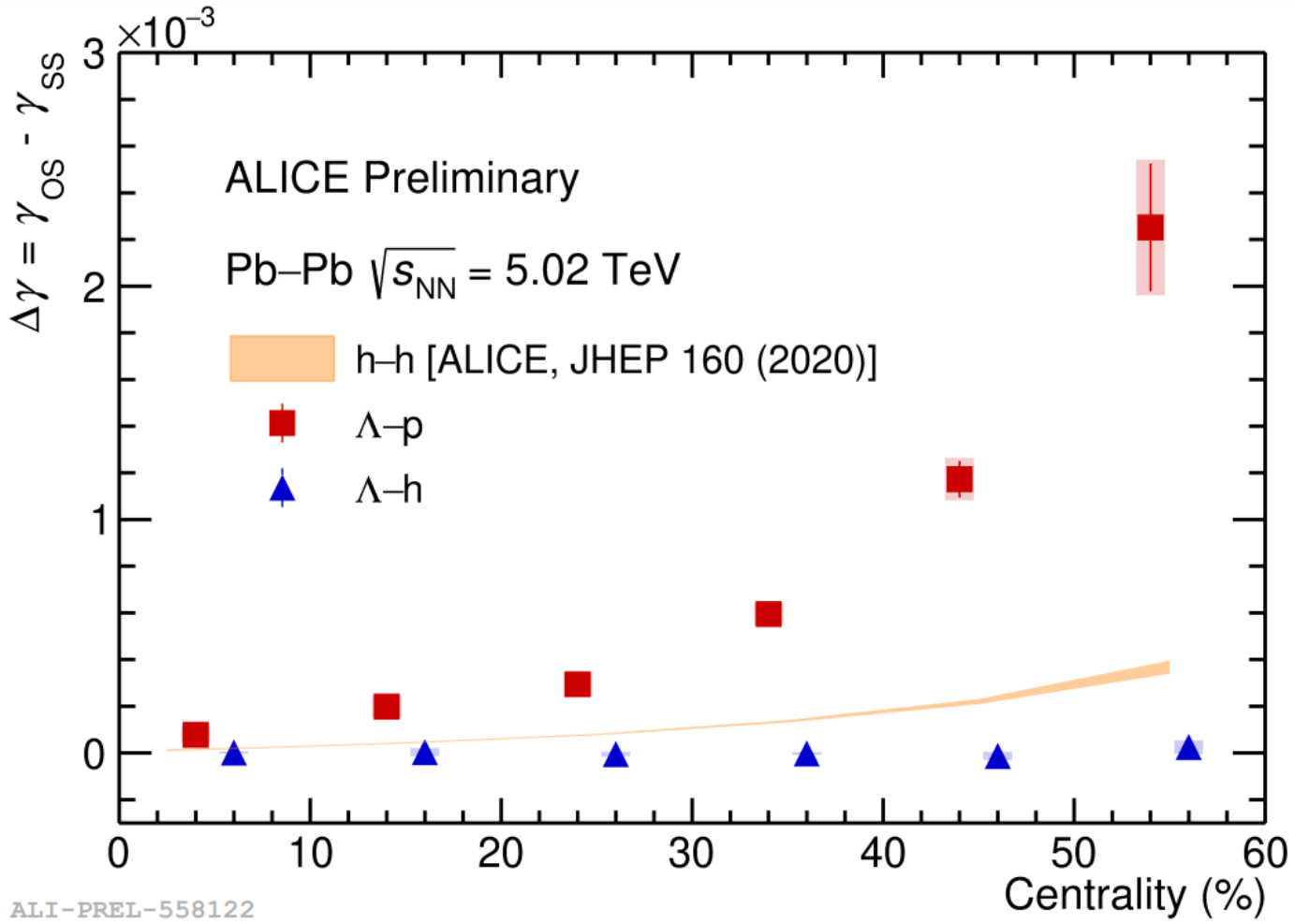
JHEP 09 (2020) 160

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



C.-Z.Wang, QM 2023

ALICE has data on the CVE



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

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

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

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

$$\Delta N_B^{\downarrow\uparrow} = \frac{N_c}{\pi^2}\mu_5 L_x \Delta\eta \int_{\tau_0}^{\tau_f} d\tau\,\tau\,\mu_B\,\omega$$

extract μ_5

Baryon separation

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

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

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

$$\Delta N_B^{\downarrow\uparrow} = \frac{N_c}{\pi^2}\mu_5 L_x \Delta\eta \int_{\tau_0}^{\tau_f} d\tau\,\tau\,\mu_B\,\omega$$

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

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

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

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

$$\Delta N_B^{\downarrow\uparrow} = \frac{N_c}{\pi^2}\mu_5 L_x \Delta\eta \int_{\tau_0}^{\tau_f} d\tau\,\tau\,\mu_B\,\omega$$

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)

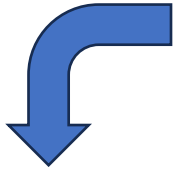
CVE $\dfrac{\mu_5}{T} \approx 3 - 9$

CME $\dfrac{\mu_5}{T} \approx 7 - 10$

Baryon asymmetry-dependent correlator

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

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



from baryon stopping

Baryon asymmetry-dependent correlator

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

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

from baryon stopping

ΔN_B fluctuates event by event → group events according to ΔN_B

Baryon asymmetry-dependent correlator

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

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

from baryon stopping

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

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

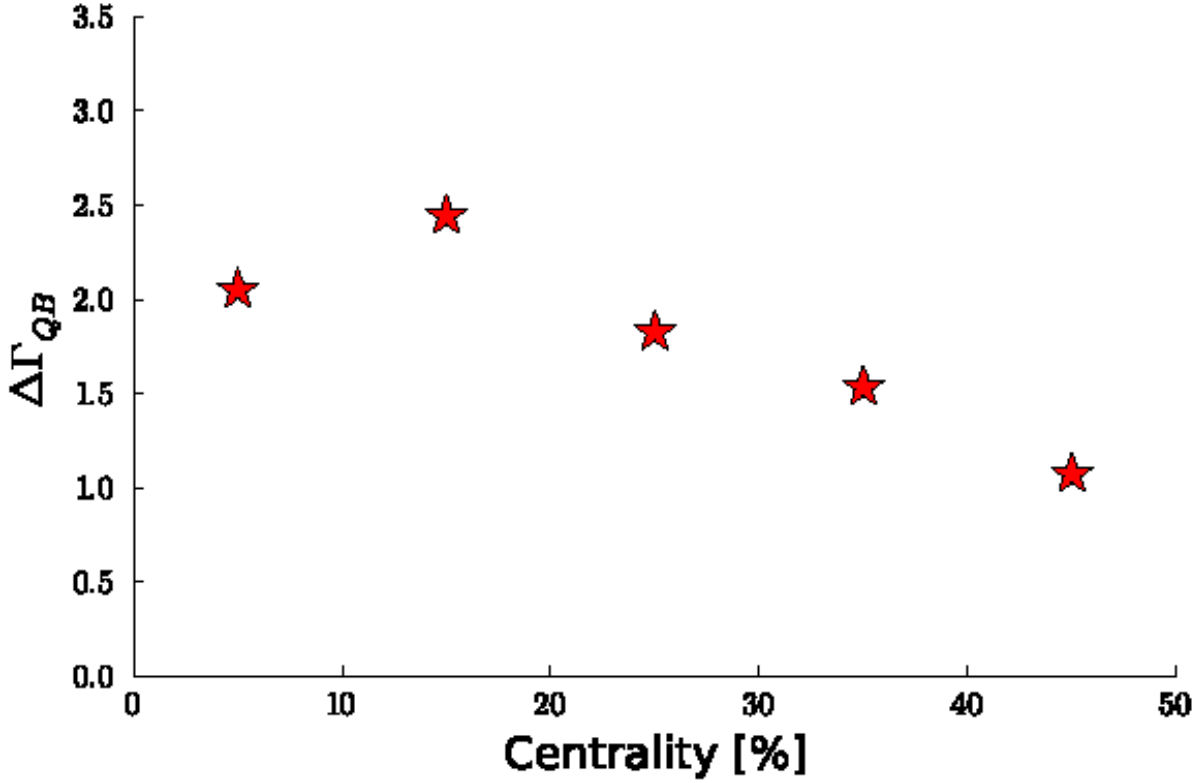
mixed in electric charge and baryon number

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

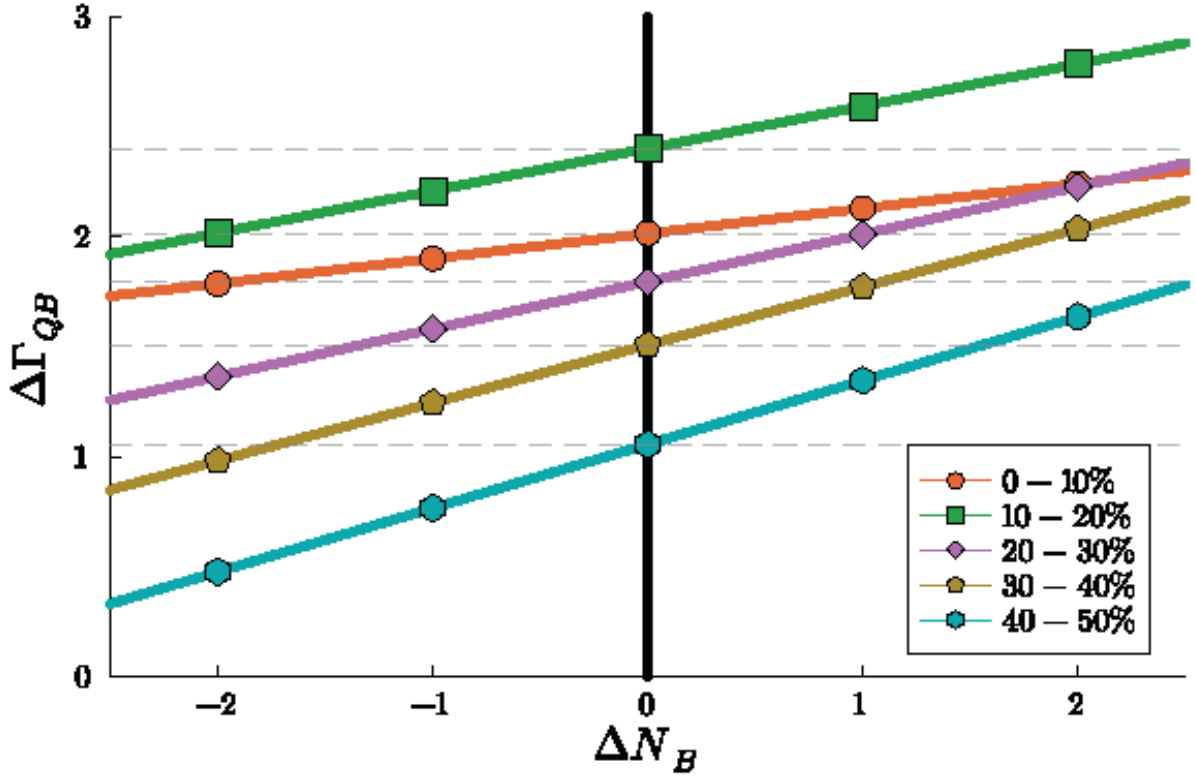
$$\Gamma^{SS} = \Gamma_{+B} + \Gamma_{-\bar{B}}, \quad \Gamma^{OS} = \Gamma_{+\bar{B}} + \Gamma_{-B}$$

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

Expectations based on ALICE data



mean value of ΔN_B



Linear dependence on ΔN_B should help separate signal and background

Conclusion

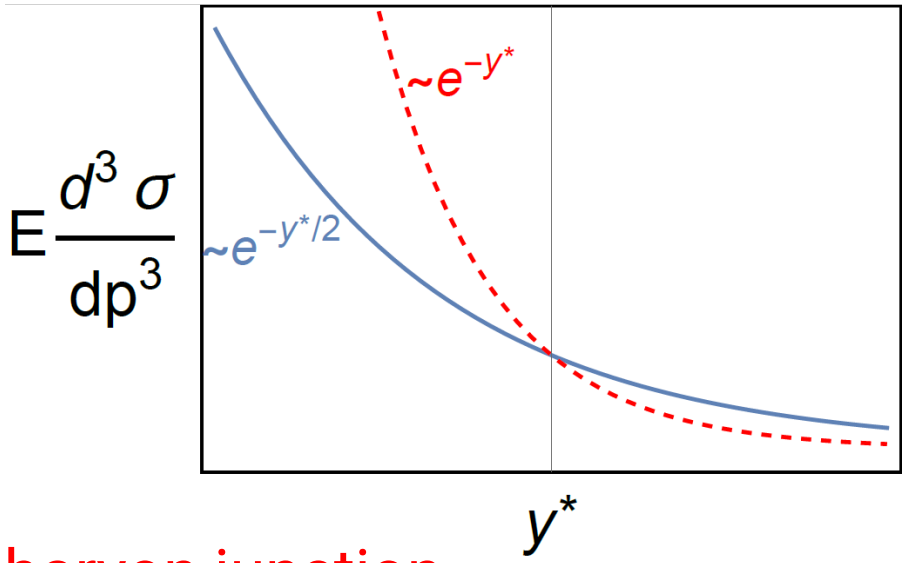
Semi-inclusive DIS with forward baryon:

characteristic rapidity dependence,

baryon flavor content,

large meson multiplicity

would signal that baryon number is carried by the baryon junction.



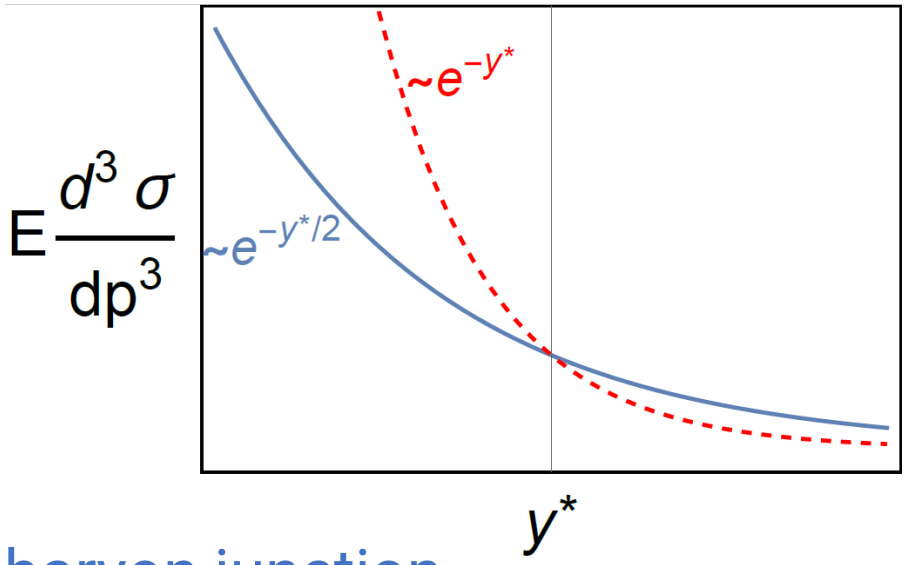
Conclusion

Semi-inclusive DIS with forward baryon:

characteristic rapidity dependence,

baryon flavor content,

large meson multiplicity



would signal that baryon number is carried by the baryon junction.

New azimuthal angle correlator in heavy ion collisions:

probes both CME and CVE,

is linear in baryon asymmetry.

can help disentangle signal from the background.