

Tracing QCD Vacuum Fluctuations during Hadronization with Conserved Currents 守恒流探测强子化

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Based on: Weiyao Ke (柯伟尧), Hai Tao Li (李海涛), Wanchen Li,
Xiaohui Liu (刘晓辉), Ding Yu Shao (邵鼎煜), arXiv: 2608.19708

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Outline

- ① Charge flow.
- ② Defects in n -collinear fragmentations.
 - No perturbative contribution,
 - Non-perturbative mechanism,
 - Jet Gell-Mann–Nishijima relation:

$$\langle Q_{\text{flow}} \rangle_f \simeq I_{3,f} + \frac{1}{2} (\langle B_{\text{flow}} \rangle_f + \langle S_{\text{flow}} \rangle_f).$$

- ③ Tests with Monte-Carlo simulations.
- ④ Summary and outlooks.

Charge Flow in Factorized Fragmentation

- The cross section factorization takes the form

$$d\sigma[Q_{\text{flow}}] \sim f_a \otimes f_b \otimes \hat{\sigma}_{ab \rightarrow f} J_f[Q_{\text{flow}}].$$

- $J_f[Q_{\text{flow}}]$ is the charge flow jet function measured on the detectors,

$$J_f[Q_{\text{flow}}] \sim \langle 0 | \xi_{n,f} W_n^\dagger \mathcal{M}_{Q,\text{flow}} W_n \bar{\xi}_{n,f} | 0 \rangle.$$

- $\mathcal{M}_{Q,\text{flow}}$ measures the total charge of the hadronic final state $|X\rangle$:

$$\mathcal{M}_{Q,\text{flow}} = \sum_X \hat{Q} \delta(k^- - P_X^-) |X\rangle \langle X|,$$

where $\hat{Q}|X\rangle = Q_X|X\rangle$.

Hadronic charge and quark charge

Does the measured hadronic charge equal the initiating quark's charge?

- **Event by event.**

Q_X is integer and Q_f is fractional, so $Q_X \neq Q_f$.

- **Ensemble average.**

An integer-valued charge can have a fractional mean:

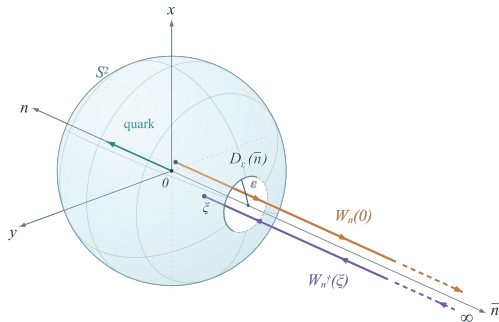
$$\langle Q_{\text{flow}} \rangle_f \stackrel{?}{=} Q_f.$$

Charge conservation alone does not establish this equality for the measured sector.

Defects in the Fragmentation

The fragmentation contains Wilson lines that extend to infinity,

$$J_f[Q_{\text{flow}}] \sim \langle 0 | \xi_{n,f} W_n^\dagger \mathcal{M}_{Q, \text{flow}} W_n \bar{\xi}_{n,f} | 0 \rangle.$$



- Celestial sphere S^2 covers the angular space of the factorized n -collinear sector.
- The Wilson line extends along $\bar{n}$; its endpoint is the excluded puncture $D_\epsilon(\bar{n})$.
- Charge bound to this endpoint is absent from the measured flow.

$$\hat{Q}_{\text{flow}} = \lim_{\epsilon \rightarrow 0} \int_{S^2 \setminus D_\epsilon(\bar{n})} d\Omega \hat{Q}(\Omega).$$

Charge at the Wilson-line endpoint

Let x be the radiation's fraction of the jet's longitudinal momentum.

- Radiations with larger momentum contribute to common measured charge flow.
- **Zero momentum fraction, finite charge.** The disk contain only extreme soft radiations $x \rightarrow 0$. Its momentum weight vanishes, but the charge measurement has no such weight.
- The Wilson line itself is neutral under Q, B, S ; dynamical quarks dressing it can carry these charges.

$$\underbrace{\langle Q_{\text{flow}} \rangle_f}_{\text{measured hadrons}} + \underbrace{\langle Q_D \rangle_f}_{\text{endpoint sector}} = \underbrace{Q_f}_{\text{initiating quark}}, \quad Q = Q, B, S.$$

- A similar picture was proposed in different language by Collins and Rogers.
J. Collins and T. C. Rogers, [arXiv:2309.03346](#).

Perturbative cancellation at the endpoint

Can a finite mean charge survive in endpoint $0 < x < \delta$ as $\delta \rightarrow 0$?

- Pure virtual insertions carry no net Q, B, S .
- Singlet contribution is charge-even. Equal perturbative weights and opposite charges cancel in the mean for a soft $q\bar{q}$.
- The **charge-odd nonsinglet contribution** is integrable at $x = 0$: its charge in the shrinking interval vanishes.

For example, splitting kernel $P_{NS}(x)$ only contain log divergent terms in $x \rightarrow 0$,

$$\int_0^\delta dx \ln x = \delta \ln \delta - \delta \longrightarrow 0.$$

Thus, at leading power perturbative contribution,

$$\langle Q_D \rangle_f^{\text{pert}} = 0, \quad \langle Q_{\text{flow}} \rangle_f^{\text{pert}} = Q_f.$$

Scale independence and flavor differences

- The μ dependence comes from ultraviolet renormalization, even when the matrix element has a nonperturbative contribution.
- Perturbatively, the bare (unrenormalized) charge sum rule gives $\langle Q_{\text{flow}} \rangle_f^{\text{pert}} = Q_f$,
J. C. Collins and D. E. Soper, Nucl. Phys. B 194 (1982) 445.

$$\mu \frac{d}{d\mu} \langle Q_{\text{flow}} \rangle_f = 0.$$

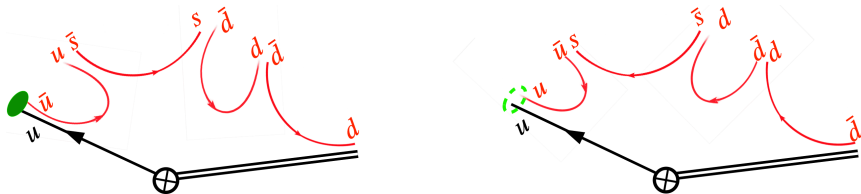
- Even if hadronization can generate a nonzero endpoint charge:

$$\langle Q_D \rangle_f = Q_f - \langle Q_{\text{flow}} \rangle_f \quad \Longrightarrow \quad \mu \frac{d}{d\mu} \langle Q_D \rangle_f = 0.$$

- If we respect the light-flavor symmetry. The loss of initiating-flavor memory give

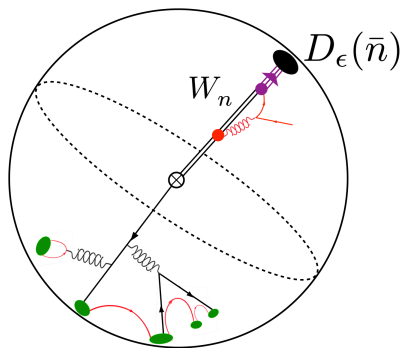
$$\langle Q_D \rangle_u \simeq \langle Q_D \rangle_d \quad \Longrightarrow \quad \langle Q_{\text{flow}} \rangle_u - \langle Q_{\text{flow}} \rangle_d \simeq Q_u - Q_d = 1.$$

Hadronization correlates the endpoints



- Consider a string breaking picture, the initiating u can bind to a neighboring $\bar{u}$. The reversed ordering with a neighboring u is suppressed.
- The two orderings leave a d or a $\bar{d}$ at the endpoint.
- Confinement prefer $u\bar{u}$ (left) over uu (right). Therefore, unequal probabilities give a nonzero net charge at the defect Q_D .

Color screening at the puncture



- Dynamical quarks and antiquarks combine with the colored Wilson-line endpoint to form a color singlet. These attached constituents form the screening cloud.
- Suppose attached quarks form the *screening cloud*: k quarks and ℓ antiquarks.
- For a q initiated fragmentation, color triality requires

$$\underbrace{1}_{\text{initiating}} - \underbrace{(k - \ell)}_{\text{cloud}} = 0 \pmod{3}.$$

$$B_D = \frac{k - \ell}{3} = \frac{1}{3} + m, \quad m \in \mathbb{Z},$$

- Triality fixes allowed quantum numbers; dynamics determines their probabilities.

Allowed screening clouds

Screening cloud	k	ℓ	B_D	Q_D	B_{flow}	Q_{flow}
q_a	1	0	1/3	Q_a	0	$Q_f - Q_a$
$(\bar{q}_a \bar{q}_b)_3$	0	2	-2/3	$-(Q_a + Q_b)$	1	$Q_f + Q_a + Q_b$
Higher clouds	k	ℓ	$1/3 + m$	$\sum_a Q_a N_a$	$-m$	$Q_f - \sum_a Q_a N_a$

with $N_a = k_a - \ell_a$.

- For example, in a u initiated jet,
 - Another u flows out from the defect, now

$$Q_{\text{flow}} = Q_u - Q_u = 0, \quad B_{\text{flow}} = B_u - B_u = 0,$$

- $\bar{d}\bar{d}$ flows out from the defect, now

$$Q_{\text{flow}} = Q_u - 2Q_{\bar{d}} = 0, \quad B_{\text{flow}} = B_u - 2B_{\bar{d}} = 1.$$

Baryon flow and the channel probabilities

- **Endpoint probability.** Retain only the two minimal clouds. Then p_B is the fraction of endpoints screened by an anti-diquark, summed over flavors:

$$P[q] = 1 - p_B, \quad P[(\bar{q}\bar{q})_3] = p_B.$$

- The two clouds give $B_{\text{flow}} = 0$ and 1:

$$\langle B_{\text{flow}} \rangle_f \simeq \underbrace{(1 - p_B) \times 0}_{q \text{ screening}} + \underbrace{p_B \times 1}_{\bar{q}\bar{q} \text{ screening}} = p_B.$$

- **Vacuum production ratio.** r_{qq} is the effective vacuum diquark-to-quark production ratio. If screening weights are homogeneous, the endpoint samples the same ratio:

$$r_{qq} \simeq \frac{P[(\bar{q}\bar{q})_3]}{P[q]} = \frac{p_B}{1 - p_B}, \quad \langle B_{\text{flow}} \rangle_f \simeq \frac{r_{qq}}{1 + r_{qq}}.$$

Electric charge of the screening cloud

- **Flavor average.** Let the production rate $u : d : s = 1 : 1 : r_s$, thus the mean charge

$$\overline{Q}_q = \underbrace{\frac{2}{3} \cdot \frac{1}{1+1+r_s}}_u - \underbrace{\frac{1}{3} \cdot \frac{1}{1+1+r_s}}_d - \underbrace{\frac{1}{3} \cdot \frac{r_s}{1+1+r_s}}_s = \frac{1-r_s}{3(2+r_s)}.$$

- **Channel average.** Independent antiquark flavors give $\overline{Q}_{\bar{q}\bar{q}} = -2\overline{Q}_q$:

$$\langle Q_D \rangle_f \simeq \underbrace{(1-p_B)\overline{Q}_q}_{q \text{ cloud}} + \underbrace{p_B(\overline{Q}_{\bar{q}\bar{q}})}_{\bar{q}\bar{q} \text{ cloud}} = (1-3p_B)\overline{Q}_q.$$

- **Measured flow.** Subtract $\langle Q_D \rangle_f$ from Q_f and use $p_B \simeq \langle B_{\text{flow}} \rangle_f$:

$$\boxed{\langle Q_{\text{flow}} \rangle_f \simeq Q_f - \frac{1-r_s}{2+r_s} \left(\frac{1}{3} - \langle B_{\text{flow}} \rangle_f \right)}$$

Strangeness of the screening cloud

- **Flavor average.** Only the strange quark contributes, with $S_s = -1$:

$$\bar{S}_q = \underbrace{S_s}_{-1} \cdot \underbrace{\frac{r_s}{1+1+r_s}}_{\text{strange fraction}} = -\frac{r_s}{2+r_s}.$$

- **Channel average.** Use the same probabilities as for electric charge, with $\bar{S}_{\bar{q}\bar{q}} = -2\bar{S}_q$:

$$\langle S_D \rangle_f \simeq \underbrace{(1-p_B)\bar{S}_q}_{q \text{ cloud}} + \underbrace{p_B(\bar{S}_{\bar{q}\bar{q}})}_{\bar{q}\bar{q} \text{ cloud}} = (1-3p_B)\bar{S}_q.$$

- **Measured flow.** Subtract the endpoint strangeness from S_f :

$$\boxed{\langle S_{\text{flow}} \rangle_f \simeq S_f + \frac{3r_s}{2+r_s} \left(\frac{1}{3} - \langle B_{\text{flow}} \rangle_f \right)}.$$

The jet Gell-Mann–Nishijima relation

- Combine the charge deficit with the strangeness excess to eliminate r_s :

$$2(Q_f - \langle Q_{\text{flow}} \rangle_f) + (\langle S_{\text{flow}} \rangle_f - S_f) \simeq \underbrace{\frac{2(1 - r_s) + 3r_s}{2 + r_s}}_{=1} \left(\frac{1}{3} - \langle B_{\text{flow}} \rangle_f \right).$$

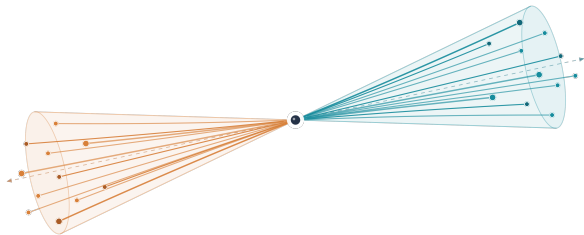
- Use $B_f = 1/3$ and $I_{3,f} = Q_f - (B_f + S_f)/2$:

$$\boxed{\langle Q_{\text{flow}} \rangle_f \simeq I_{3,f} + \frac{1}{2}(\langle B_{\text{flow}} \rangle_f + \langle S_{\text{flow}} \rangle_f)}.$$

- Equal mean u, d screening gives $\langle I_{3,D} \rangle_f \simeq 0$: **the jet retains the initiating isospin.** Higher clouds can satisfy the same condition. GMN needs less than the two-channel probability extraction.

Monte Carlo setup for hemisphere flows

$$e^+e^- \rightarrow q\bar{q}, \quad q = u, d, s, \quad T > 0.95$$



Hadronization models

Pythia 8.3

Lund string hadronization

Herwig 7.3

Cluster hadronization

$$E_{\text{CM}} = 50, 100, 200, 500, 1000 \text{ GeV}$$

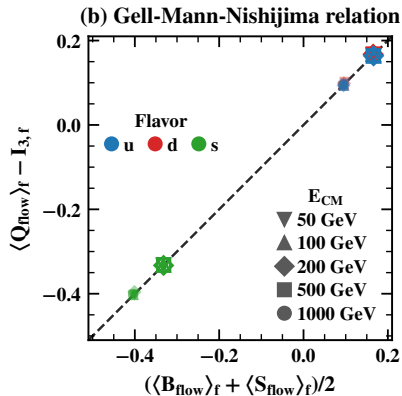
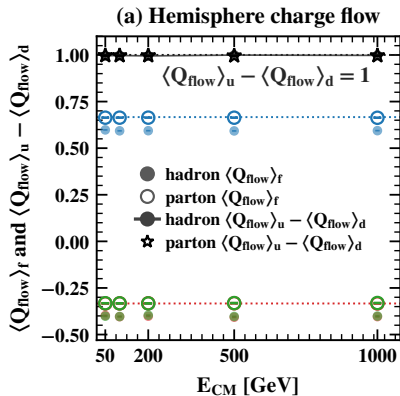
Parton level

After QCD final-state shower.
QED and weak showers off.

Hadron level

After hadronization.
Hadron decays disabled.

Pythia: charge shifts and jet GMN



Hadron level: $(\langle Q_{\text{flow}} \rangle_u, \langle Q_{\text{flow}} \rangle_d, \langle Q_{\text{flow}} \rangle_s) \simeq (0.594, -0.403, -0.401)$.

Equal-weight mean over $E_{\text{CM}} = 50, 100, 200, 500, 1000 \text{ GeV}$.

Extracting the screening ratios

Scan hadronization parameters to test the linear Q - B - S relations and extract effective screening ratios.

Baryonic screening

$$r_{qq} \simeq \frac{\langle B_{\text{flow}} \rangle_f}{1 - \langle B_{\text{flow}} \rangle_f}$$

Assuming two minimal screening channels

Strange-to-light screening

$$-\frac{1 - r_s}{3r_s} \simeq \frac{\langle Q_{\text{flow}} \rangle_f - Q_f}{\langle S_{\text{flow}} \rangle_f - S_f}$$

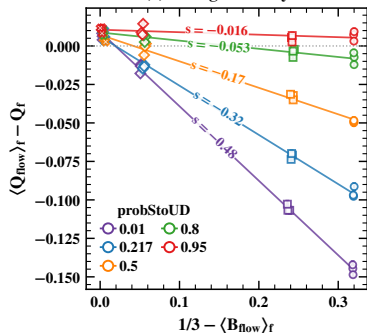
Hadronization parameters varied in the MC scans

Generator	Strangeness	Baryon production
Pythia	probStoUD Suppression of s -quark production relative to u or d .	probQQtoQ Diquark suppression relative to quark production.
Herwig	PwtSquark Weight for choosing a strange quark. SplitPwtSquark Strangeness weight in nonperturbative gluon splitting.	MesonToBaryonFactor Relative distance scale of mesonic and baryonic clusters. Reconnection model: <code>BaryonicMesonic</code> .

$E_{\text{CM}} = 100 \text{ GeV}$, $T > 0.95$; the two Herwig strange weights are varied together.

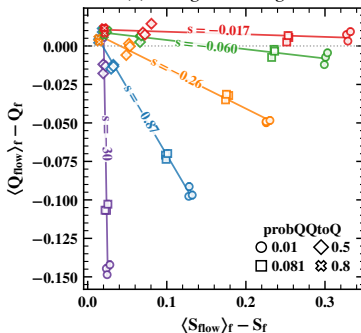
Pythia: joint Q , B , S correlations

(a) Charge vs. baryon



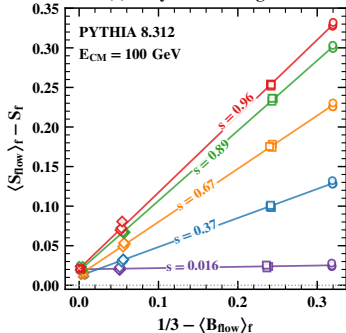
$$\langle Q_{\text{flow}} \rangle_f - Q_f \simeq -\frac{1-r_s}{2+r_s} \left(\frac{1}{3} - \langle B_{\text{flow}} \rangle_f \right)$$

(b) Charge vs. strangeness



$$\langle Q_{\text{flow}} \rangle_f - Q_f \simeq -\frac{1-r_s}{3r_s} (\langle S_{\text{flow}} \rangle_f - S_f)$$

(c) Baryon vs. strangeness



$$\langle S_{\text{flow}} \rangle_f - S_f \simeq \frac{3r_s}{2+r_s} \left(\frac{1}{3} - \langle B_{\text{flow}} \rangle_f \right)$$

Colors: probStoUD; markers: probQQtoQ. $E_{\text{CM}} = 100$ GeV, $T > 0.95$; free-intercept fits.

Effective screening ratios

Strangeness: three projections of the same correlations

Generator / input	r_s^{Q-B}	r_s^{Q-S}	r_s^{S-B}
Pythia / 0.217	0.273(13)	0.2766(61)	0.2785(25)
Herwig / 0.2	0.2047(33)	0.1996(23)	0.1975(38)

Inputs: Pythia probStoUD; Herwig PwtSquark and SplitPwtSquark.

General-purpose event generators include more detailed nonperturbative models, e.g. spin-dependent diquark production, popcorn, and cluster colour reconnection.

Baryonic screening With Pythia probQQtoQ= 0.081, we get

$$\langle B_{\text{flow}} \rangle_f = 0.0922 \quad \Rightarrow \quad r_{qq} \simeq \frac{\langle B_{\text{flow}} \rangle_f}{1 - \langle B_{\text{flow}} \rangle_f} = 0.1016.$$

Extensions and Experimental Availability

Additional screening mechanisms

- **Color reconnection and recombination**

Allow screening by surrounding partons.

- **Beam remnants and baryon junctions**

Modify B transport and Q - B correlations.

Christiansen-Skands (2015); Fries et al. (2003);
Kharzeev (1996); STAR, 2408.15441.

What joint Q, B, S flows can test

- Track strange and baryonic screening versus multiplicity in pp , pA and AA .
- Strangeness and baryon-to-meson enhancements motivate testing a possible thermodynamic limit.

ALICE, Nature Phys. 13 (2017) 535;
PRC 99 (2019) 024906; JHEP 09 (2024) 102.

Experimental starting points

Identified-hadron measurements at LEP, RHIC and the LHC provide a basis for joint-flow studies.

DELPHI, EPJC 17 (2000) 207; SLD, PRD 59 (1999) 052001; ALICE, JHEP 09 (2024) 102.

Recent work measures electric-charge flow at DELPHI and proposes heavy-flavor flow measurements.

Zhang, Lee, Moulton et al., 2608.14779, 2608.15357, 2608.15367; Lee-Moulton, 2609.13366.

Summary

- **Conserved currents provide a perturbative baseline.**

At leading power, charge-flow shifts measure nonperturbative endpoint screening.

- **Joint Q, B, S flows resolve the screening content.**

With minimal clouds and common flavor weights, B fixes r_{qq} and correlated Q, S shifts fix r_s . Pythia and Herwig support these relations.

Jet GMN follows from isospin-symmetric screening

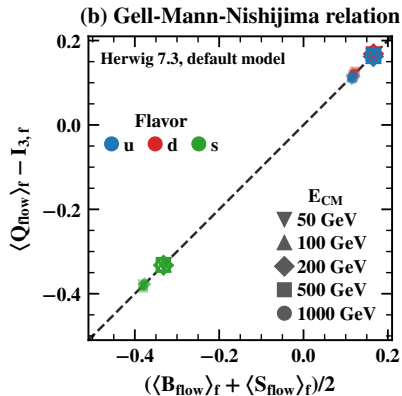
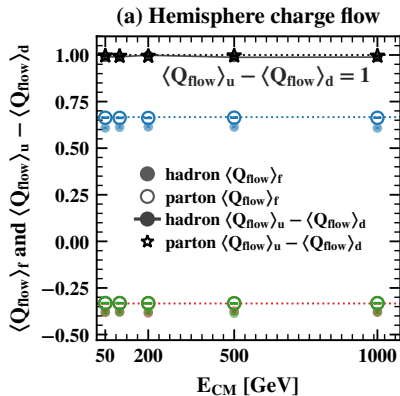
$$\langle Q_{\text{flow}} \rangle_f \simeq I_{3,f} + \frac{1}{2} (\langle B_{\text{flow}} \rangle_f + \langle S_{\text{flow}} \rangle_f) \quad (\langle I_{3,D} \rangle_f \simeq 0).$$

A further test with heavy-flavor jets Net charm and bottomness survive hadronization. With the same light-flavor screening, before weak decays,

$$\langle Q_{\text{flow}} \rangle_c \simeq \langle Q_{\text{flow}} \rangle_u, \quad \langle Q_{\text{flow}} \rangle_b \simeq \langle Q_{\text{flow}} \rangle_d, \quad Q = Q, B, S.$$

Thank you!

Herwig: charge shifts and jet GMN

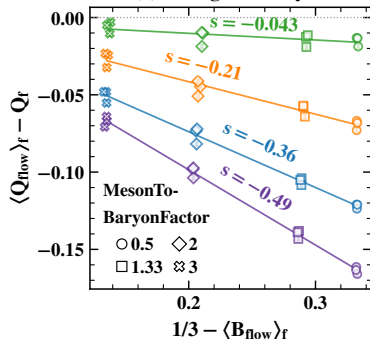


Hadron level: $(\langle Q_{\text{flow}} \rangle_u, \langle Q_{\text{flow}} \rangle_d, \langle Q_{\text{flow}} \rangle_s) \simeq (0.611, -0.379, -0.379)$.

Equal-weight mean over $E_{\text{CM}} = 50, 100, 200, 500, 1000 \text{ GeV}$.

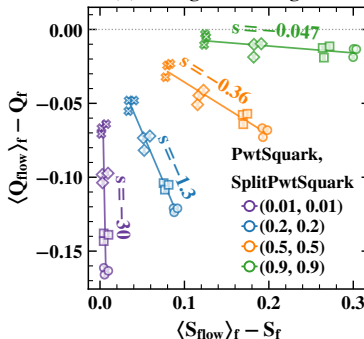
Herwig: joint Q , B , S correlations

(a) Charge vs. baryon



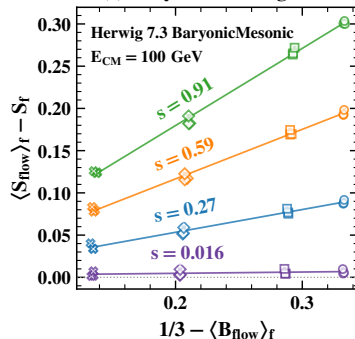
$$\langle Q_{\text{flow}} \rangle_f - Q_f \simeq -\frac{1-r_s}{2+r_s} \left(\frac{1}{3} - \langle B_{\text{flow}} \rangle_f \right)$$

(b) Charge vs. strangeness



$$\langle Q_{\text{flow}} \rangle_f - Q_f \simeq -\frac{1-r_s}{3r_s} (\langle S_{\text{flow}} \rangle_f - S_f)$$

(c) Baryon vs. strangeness



$$\langle S_{\text{flow}} \rangle_f - S_f \simeq \frac{3r_s}{2+r_s} \left(\frac{1}{3} - \langle B_{\text{flow}} \rangle_f \right)$$

BaryonicMesonic; matched strange weights; varying MesonToBaryonFactor. $E_{\text{CM}} = 100 \text{ GeV}$, $T > 0.95$.

Charge correlators: the OPE connection

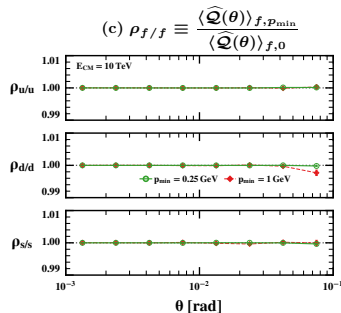
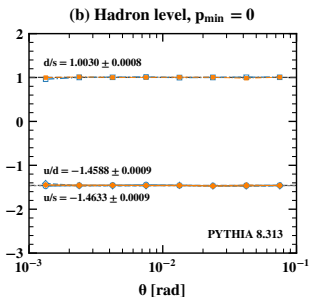
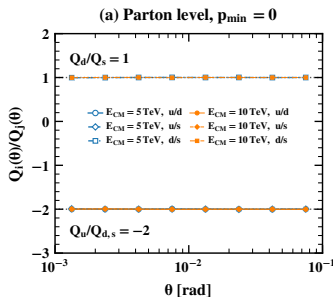
The OPE in the perturbative small-angle region gives

$$\langle \hat{\mathcal{Q}}(\theta) \rangle_f \simeq \mathcal{K}_q(\theta) \langle \mathcal{Q}_{\text{flow}} \rangle_f, \quad \mathcal{Q} = Q, B, S.$$

- $\mathcal{K}_q(\theta)$ is the common perturbative angular function decided by OPE and Sudakov evolutions, see [W. Li, X. Liu and D. Y. Shao, arXiv:2607.16392](#).
- Hadronization modifies total measured charge flow.
- The common factor cancels in flavor ratios. The integrated Q, B, S relations therefore also govern the angular distributions.

Charge correlators and momentum acceptance

$$\frac{\langle \hat{Q}(\theta) \rangle_{f_1}}{\langle \hat{Q}(\theta) \rangle_{f_2}} \simeq \frac{\langle Q_{\text{flow}} \rangle_{f_1}}{\langle Q_{\text{flow}} \rangle_{f_2}}, \quad \theta \ll 1$$



(a, b) Flavor ratios

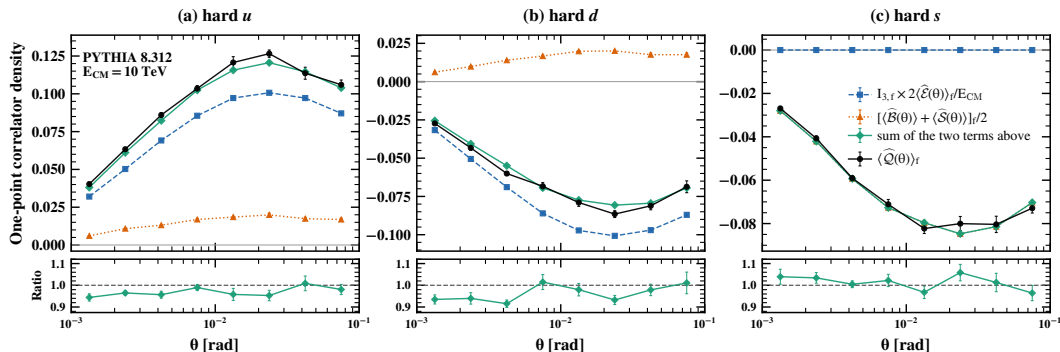
$u/d, u/s: -2 \rightarrow \simeq -1.46; \quad d/s \simeq 1.$

(c) Hadron acceptance momentum

$p_{\min} = 0, 0.25, 1 \text{ GeV}.$

A differential test of the GMN relation

$$\langle \hat{Q}(\theta) \rangle_f \simeq I_{3,f} \frac{\langle \hat{\mathcal{E}}(\theta) \rangle_f}{E_{\text{CM}}/2} + \frac{\langle \hat{B}(\theta) \rangle_f + \langle \hat{S}(\theta) \rangle_f}{2}$$



Energy-correlator normalization at LL accuracy. $E_{\text{CM}} = 10$ TeV; no thrust cut.

Backup: Pythia strange-screening ratios

probStoUD	r_s^{Q-B}	r_s^{Q-S}	r_s^{S-B}
0.010	0.0217(59)	0.01105(61)	0.01080(69)
0.217	0.273(13)	0.2766(61)	0.2785(25)
0.500	0.560(15)	0.566(11)	0.5771(31)
0.800	0.8489(64)	0.8477(61)	0.8381(57)
0.950	0.952(17)	0.952(16)	0.948(11)

- The three determinations show broadly consistent trends.
- The effective ratio tracks the input, with visible model-dependent shifts.

Parentheses: propagated one-standard-error uncertainties.

Backup: Herwig strange-screening ratios

Matched strange weights	r_s^{Q-B}	r_s^{Q-S}	r_s^{S-B}
0.01	0.0177(65)	0.0110(16)	0.0104(14)
0.2	0.2047(33)	0.1996(23)	0.1975(38)
0.5	0.479(27)	0.483(23)	0.486(16)
0.9	0.876(35)	0.878(34)	0.876(34)

- Matched weights: `PwtSquark = SplitPwtSquark`.
- The correlations test a common screening description across two generators.

Parentheses: propagated one-standard-error uncertainties.

Backup: Pythia baryonic screening and topology

$$r_{qq} \simeq r_B \equiv \frac{\langle B_{\text{flow}} \rangle_f}{1 - \langle B_{\text{flow}} \rangle_f}, \quad r_{\text{topology}} = \frac{P(B_{\text{flow}} = 1)}{P(B_{\text{flow}} = 0)}$$

probQQtoQ	$\langle B_{\text{flow}} \rangle_f$	r_B	r_{topology}
0.010	0.0139	0.01410(9)	0.01526(9)
0.081	0.0922	0.1015(3)	0.1102(3)
0.500	0.2790	0.3869(7)	0.4215(6)
0.800	0.3298	0.4921(8)	0.5341(8)

- probQQtoQ weights eligible local steps; r_B includes the full fragmentation history.
- r_B and r_{topology} agree within 9%, supporting the two-channel approximation.