Balance Functions: A Signal of Late-Stage Hadronization
Narrow distribution in Qy signals late production of bb pairs. *a therm.*

- Many pairs created dur. 

\[ \approx \]

0.5 \text{ fm/c.}

Hadrons appear at \( t \approx \)

\( \\approx \)

Hadronization at 5-

\( \\approx \)

\( \\approx \)

\( \\approx \)

Suppose one could identify balancing charges? (E.g., \( K^+, K^- \).)

**Motivation**

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During hadronization, quarks should make $\approx I$ hadron due to entropy conservation.

At fixed $L$, each quark should make $\approx J$ hadron due to entropy conservation.

At fixed $L$, each gluon should make $\approx K$ hadrons.

I. Gluons $\rightarrow$ Hadrons.

2. Quarks $\rightarrow$ Hadrons.


(e.g. DCC) Probably a small fraction of particile creation.

Each hadron contains at least two quarks, so number of quarks should more than double during hadronization.

$\nabla S > 0$.

$J$ to keep

Coallescing quark gas would require rise in $\nabla S$.
or to specific charges, e.g. (all antibaryons)/(all baryons).

Can be applied to specific particle/antiparticle pairs, e.g. + \rightarrow -,

2. \( z_{d} \) refers to relative rapidity.

1. \( d_{1} \) is anywhere in detector.

Common binning choice:

\[
\frac{(d_{1}', n)}{(z_{d}, q)} = (d_{1}, n) \cdot \frac{(z_{d}, q)}{d}
\]

Here \( (d_{1} | z_{d}, q) \) is the conditional probability.

\[
\{ (d_{1}', n + |z_{d}', n +) d - (d_{1}, n + |z_{d}, n +) d + (d_{1}', n - |z_{d}', n -) d - (d_{1}, n - |z_{d}, n -) d \} / z_{d} \equiv (d_{1} | z_{d}) B_{z_{d}}
\]

Charge with momentum \( z_{d} \) describe the probability of seeing a particle or opposite

Given the existence of a particle with momentum \( d_{1} \), balance

What are Balance Functions?

Balance Functions: A Signal of Late-Stage Hadronization
May be analyzed event-by-event.

Class, e.g. analyze only $K^+K^-$, e.g. analyze only $K^+K^-$. Normalization reduced for finite ac-

Norm for both cases:

$$I = \left( \frac{d}{d\theta} B \right) \sum_{\Delta\theta}$$

If $\Delta\theta$ refers to all +/- particles:

$\sum_{\Delta\theta}$ refers to unity.

Properties of Balance Functions

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\( \mathbf{B}(\Delta\theta) \)
10^6 events makes good balance function.

And \( v^+ + K^- \) give similar errors.

Error \( \propto 1/N_{\text{events}} \) independent of \( N \).

Denominator also increases \( \propto N \).

Statistical error for numerator \( \propto \sqrt{N} \).

\[
\frac{(1d', q_N)}{(2d', q_1)} = (1d', q_2d', q_d)
\]
Thanks to T. Sjöstrand for references!

- JETSET fits data.
- Several pairs analyzed: e.g. AV.
- M. Althoff et al., ZPC 17 (1983) 5.
- R. Brandelik et al., PLB 100 (1981) 357.

Similar analyses performed with:

Balance Functions From Jets
Balance Functions: A Signal of Late-Stage Hadronization
(B\nabla y) provides signal of late stage hadronization.  

\[ \frac{1}{Z} = \sqrt{L} \]

\[ \langle p/p_0 \rangle_{\text{initial}} \approx \langle f/N \rangle \]

\[ \frac{L}{W} \approx 2 \]

I. Temperature is lower, hadronization for two reasons:

2. High initial p/p_0 separates early-produced pairs through diffusion.

Relation to Hadronization Time

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greater sensitivity. Heavier particles provide $B(\gamma)$ determined by $T/m$. Rapidity $y$. Pairs generated thermally at $\gamma = y$ with same collective $u$. Collective velocity: $\beta = \tanh \left( t/z \right)$. Position: $z = \tanh \left( t/z \right)$. Time: $\tau = \tanh \left( t/z \right)$. Bjorken 1-d expansion: Thermal Model.
\[
\left( u_0 \phi + \frac{2 u_0 \phi \gamma_{\text{therm}}}{\sqrt{2}} \right)_z = 2 u_0 \phi
\]

- Larger for small \( t_0 \).
- \( z \cdot t = t_0 \) (no collisions)
- \( \frac{1}{t} = 0 \) (coll. rate \( \propto \))
- No diffusion when

\[
\left( \frac{u_0 \phi}{\sqrt{2}} \right) z / \ln \frac{z / \phi}{\ln \frac{z / \phi}{\ln \frac{z / \phi}{\ln \frac{z / \phi}{\ln \frac{z / \phi}}}}}
\]

Solution:

\[
\frac{(\phi + u_0)}{\phi + t_0} = \frac{\phi}{t_0}
\]

Diffusion Eq:

\[
\left( u_0, \psi \right) f \frac{\phi + u_0 + \frac{1}{\sqrt{2}} \theta}{\phi + t_0} = \left( u_0, \psi \right) f \frac{\phi + \frac{1}{\sqrt{2}} \theta}{\psi}
\]

Diffusion: An Analytic Picture

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Collisions/Annihilations Magnify Sensitivity to Creation Time

Procedure:
1. Generate pair thermally at $T_0 = 0$, $U = 0$
2. Follow straight-line trajectory
3. Perform $N_{\text{coll}}$ collisions
4. Readjust momenta to local domain in $1/T$
   - thermal conditions
   - rises between collisions
   - $T = 225 - 7.5(T - 1)$, $T \rightarrow 15$
   - Model by convoluting
   - Annihilations:

   $$B(\Delta y) = \frac{f \cdot 15}{T_0}$$

   $$T = 225 - 7.5(T - 1)$$

   $$T \rightarrow 15$$

Collisions and Annihilations: A Simple Model
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Even pions become sensitive to hadronization time:

\[ N_{\text{coll}} \sim 2 \]

If \( t_0 \approx 9 \text{ fm/c} \),

\[ N_{\text{coll}} \sim 6 \]

If \( t_0 \approx 1 \text{ fm/c} \).

**Collisions Model Summary**

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Conclusions

Balance Functions: A Signal of Late-Stage Hadronization

- Strangeness/Antistrangeness
- a long-lived GP
- Provide clear signal of event-by-event production as function of \( t \)
- Gating on \( t \) allows one to study production issues can be studied.

PyTHIA

\( \gamma = 9, t = 165 \)

\( \gamma = 1, t = 225 \)
Most jet energy loss calculations are misguided.

\[ \Box / \Box \]

\( \text{QGP explanations of } J / \gamma \text{ are misguided.} \)

Most jet energy loss calculations are misguided.

\( \text{QGP explanations of strong energy enhancement are wrong.} \)

\( \text{Most explanations of strange enhancement are wrong.} \)

rate particles (unless temperature jumped at hadronization).

\( \text{Quarks and antiquarks did not contribute to entropy for a substantial time.} \)

\( \text{Gluonic modes did not contribute to entropy for a substantial time.} \)

\( B \text{ if } A > d d \text{ balance functions appear identical,} \)

very early times.

\( \text{Mean free paths of partons were anomalously short during} \)

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near \( \Delta y \approx 0 \text{, characteristic of } J \text{, \( J \approx 165 \text{ MeV, then either} \)} \)

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\( \text{If measured balance functions have significant extra strength} \)

For example,

\( \text{Far reaching implications} \)

\( \text{Balance Functions: } A \text{ Signal of Late-Stage Hadronization} \)