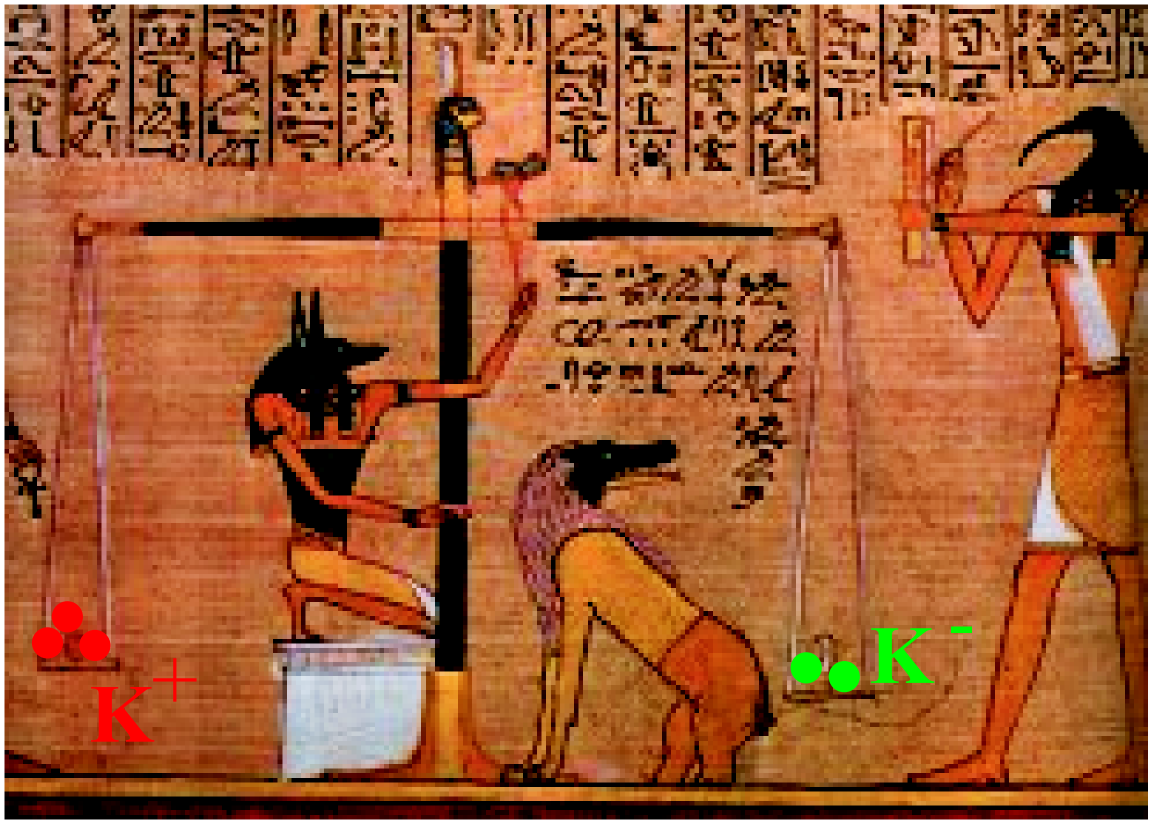
S. Bass, P. Danielewicz and S. Pratt – PRL 85, 2689 (2000)

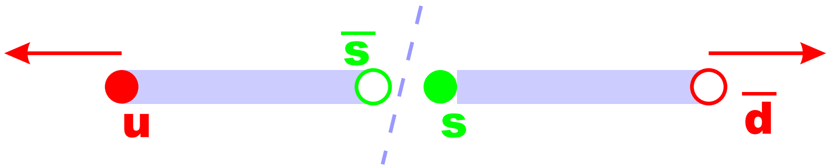
Balance Functions: A Signal of Late-Stage Hadronization



Motivation

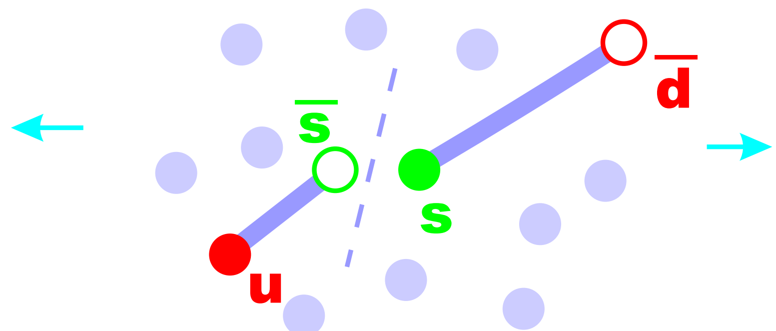
Suppose one could identify *balancing* charges? (e.g. K^+, K^-)

Hadronic Picture



- Hadrons appear at $\tau \approx$ 0.5 fm/c.
- String dynamics separate balancing Q–$\bar{Q}$ by $\Delta y \sim 1$.
- Strangeness annihilates with time, reduces probability of small Δy.

QGP Picture



- Hadronization at 5-10 fm/c into collision, $T \approx 165$.
- Many $q\bar{q}$ pairs created during hadronization.
- Balancing charges separated by $\Delta y \sim v_{\rm therm.}$.

Narrow distribution in Δy signals late production of $q\bar{q}$ pairs.
$\rightarrow$ novel phase persisted substantial time.

Creation of $q\bar{q}$ Pairs at RHIC

During hadronization, $q\bar{q}$ pairs are created for three reasons.

1. Gluons $\rightarrow$ Hadrons.
   At fixed T, each gluon should make ≈ 1 hadron due to entropy conservation.
2. Quarks $\rightarrow$ Hadrons.
   At fixed T, each quark should make $\approx$ one hadron due to entropy conservation.
3. Non. Pert. Vacuum $\rightarrow$ Hadrons.
   (e.g. DCC) Probably a small fraction of particle creation.

- Each hadron contains at least two quarks, so number of quarks should more than double during hadronization.
- Coalescing quark gas would require rise in T to keep $\Delta S \geq 0$.

What are Balance Functions?

Given the existence of a particle with momentum p_1, balance functions describe the probability of seeing a particle of opposite charge with momentum p_2.

$$\begin{aligned} B(p_2|p_1) \equiv \frac{1}{2}\{&\rho(+Q,p_2|-Q,p_1) - \rho(-Q,p_2|-Q,p_1) \\ &+\rho(-Q,p_2|+Q,p_1) - \rho(+Q,p_2|+Q,p_1)\} \end{aligned}$$

Here $\rho(b,p_2|a,p_1)$ is the conditional probability,

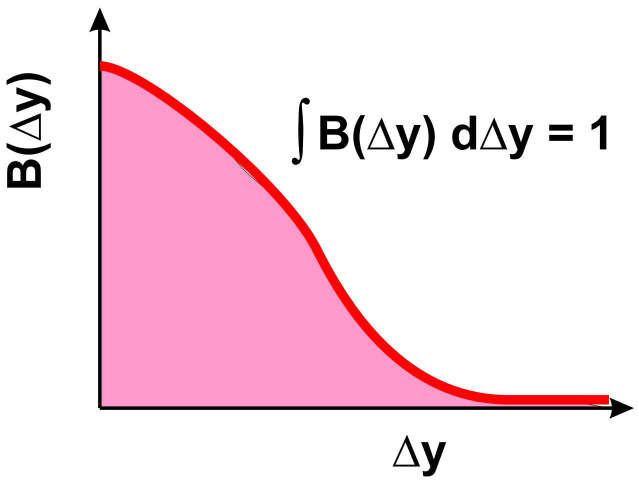
$$\rho(b,p_2|a,p_1) = \frac{N(a,p_1;b,p_2)}{N(a,p_1)}$$

Common binning choice:

1. p_1 is anywhere in detector.
2. p_2 refers to relative rapidity.

Can be applied to specific particle/antiparticle pairs, e.g. π^+/π^-, or to specific charges, e.g. (all antibaryons)/(all baryons).

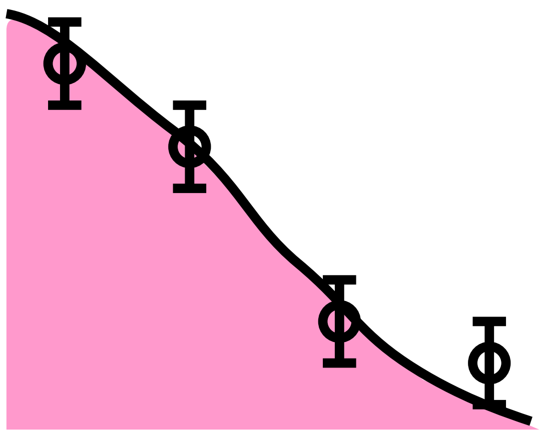
Properties of Balance Functions



- Normalized to unity:
  If $+Q/-Q$ refers to ALL +/- particles
  $$\sum_{p_2} B(p_2|p_1) = 1$$
- Works for both cases:
  1. $\Sigma_i q_i = 0$, e.g. strange/antistrange
  2. $\Sigma_i q_i \neq 0$, e.g. baryon/antibaryon
- Normalization reduced for finite acceptance or for using subset of particles, e.g. analyze only K^+/K^-.
- May be analyzed event-by-event.

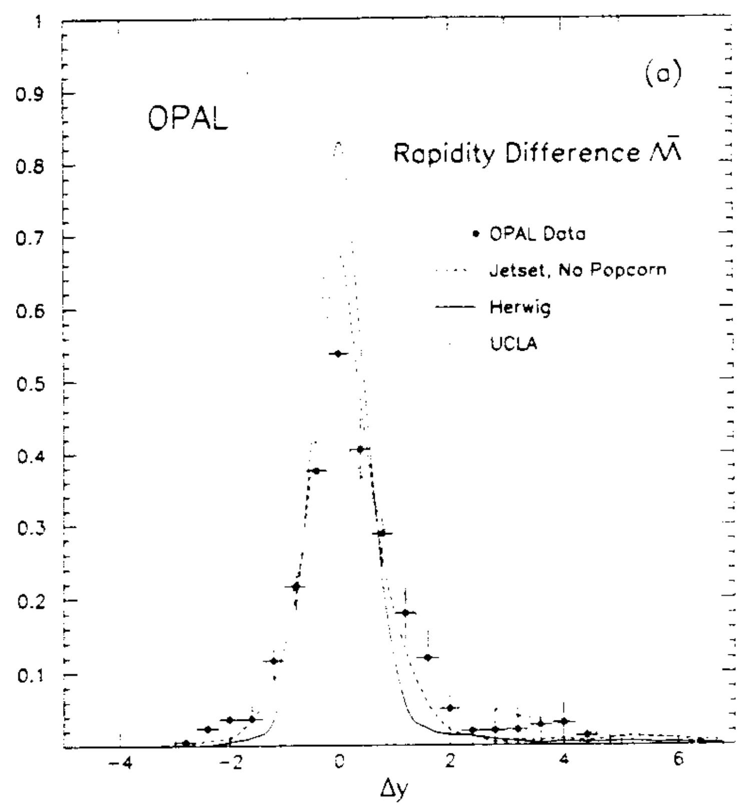
Statistical Error and Multiplicity M

$$\rho(b, p_2|a, p_1) = \frac{N(a, p_1; b, p_2)}{N(a, p_1)}$$



- Statistical error for numerator $\propto \sqrt{M^2}$.
- Denominator also increases $\propto M$.
- Error $\propto 1/\sqrt{N_{\mathrm{events}}}$, independent of M.
- $p\bar{p}$, K^+K^- and $\pi^+\pi^-$ give similar errors.
- 10^5 events makes good balance function.

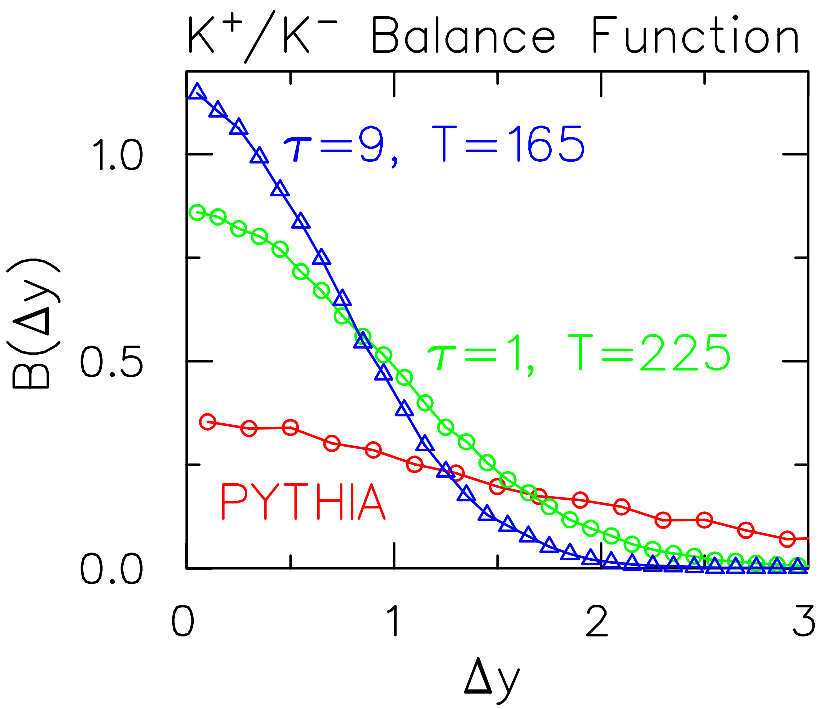
Balance Functions from Jets



- Similar analyses performed with:
  - ppdata:
    D. Drijard et al., NPB **155** (1979) 269.
    D. Drijard et al., NPB **166** (1980) 233.
    I.V. Ajinenko et al., ZPC **43** (1989) 37.
  - eedata:
    R. Brandelik et al., PLB **100** (1981) 357.
    M. Althoff et al., ZPC **17** (1983) 5.
    H. Aihara et al., PRL **53** (1984) 2199.
    H. Aihara et al., PRL **57** (1986) 3140.
    P.D. Acton et al., PLB **305** (1993) 415.
- Several pairs analyzed, e.g. $\Lambda\bar{\Lambda}$.
- JETSET fits data.

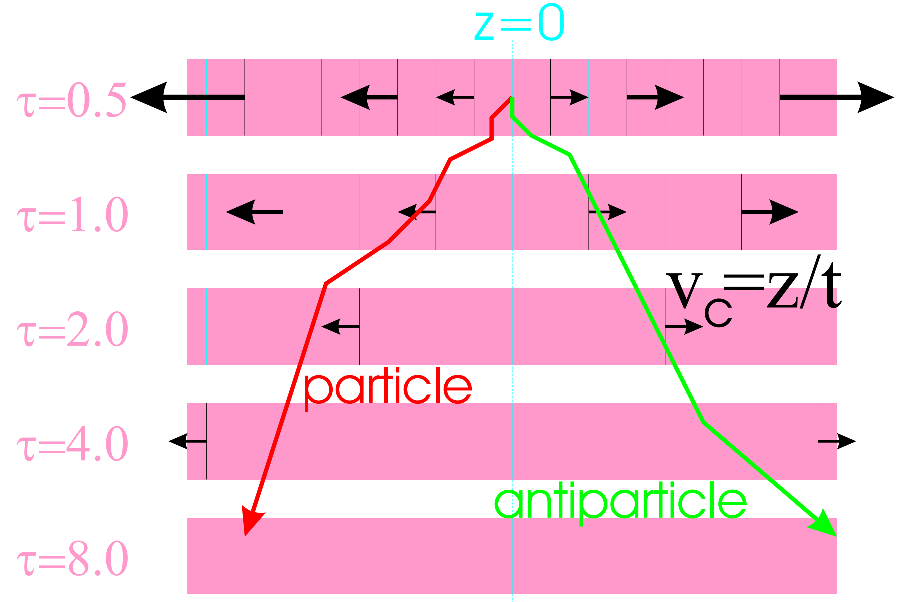
Thanks to T. Sjöstrand for references!

Relation to Hadronization Time



$B(\Delta y)$ narrower for late-stage hadronization for two reasons:

1. Temperature is lower,
$$\langle \Delta y \rangle \approx \sqrt{2T/M}$$
2. High initial dv/dz separates early-produced pairs through diffusion.



$B(\Delta y)$ provides signal of late stage hadronization.

Thermal Model

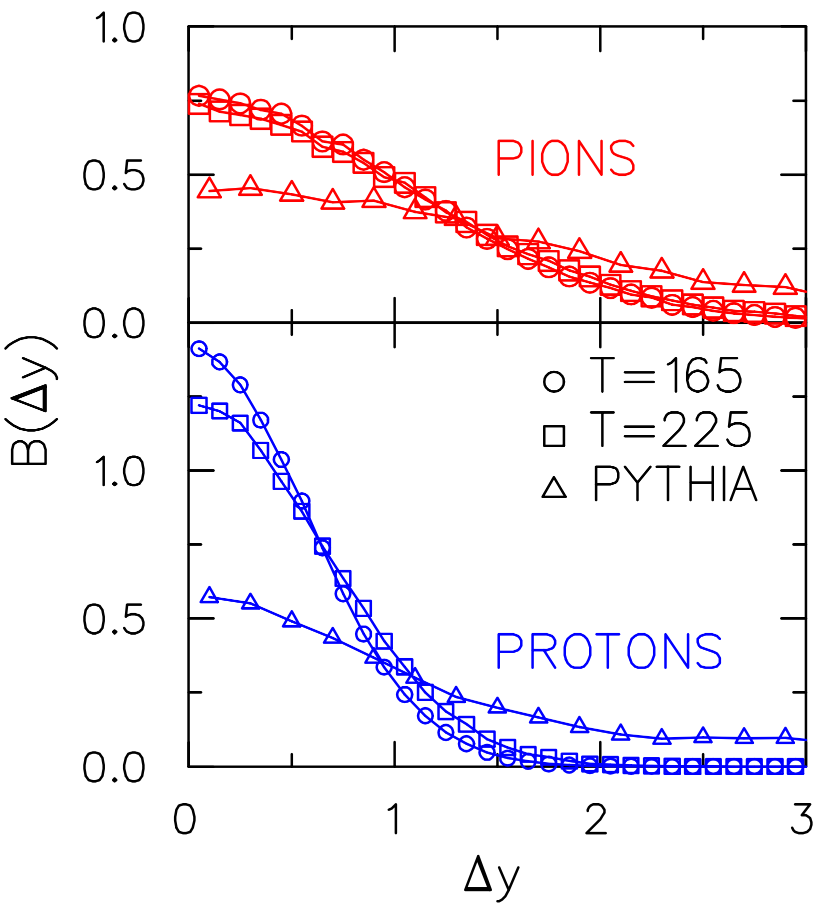
Bjorken 1-d expansion:

Time: $\tau = \sqrt{t^2 - z^2}$

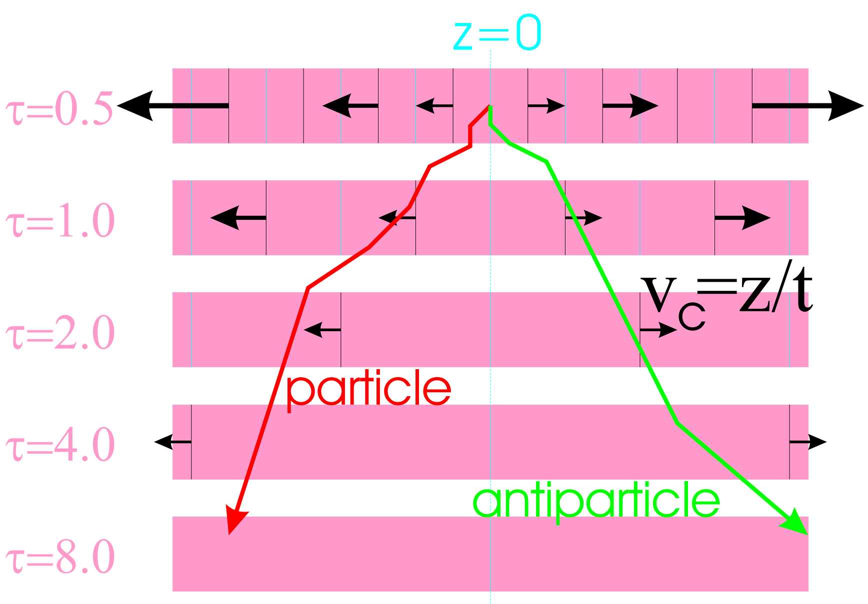
Position: $\eta = \tanh^{-1}(z/t)$

Collective velocity: $y = \eta$.

- Pairs generated thermally at same η with same collective rapidity y.
- $B(\Delta y)$ determined by T/m.
- Heavier particles provide greater sensitivity.



Diffusion: An Analytic Picture



Diffusion Eq:

$$\frac{\partial}{\partial \tau} f(\tau,\eta) = -\frac{\beta}{\tau}\frac{\partial^2}{\partial \eta^2} f(\tau,\eta),$$

$$\beta = v_t/(n\tau\sigma)$$

Solution:

$$f(\tau,\eta) \sim \exp\left(-\frac{\eta^2}{2\sigma_\eta^2}\right),$$

$$\sigma_\eta^2 = 2\beta \ln(\tau/\tau_0)$$

- No diffusion when
  1. $\beta = 0$ (Coll. Rate$\rightarrow \infty$)
  2. $\tau = \tau_0$ (No Collisions)
- σ_η largest for small τ_0.

$$\sigma^2_{\rm balance} = 2\left(\sigma^2_{y,{\rm therm.}} + \sigma^2_\eta\right)$$

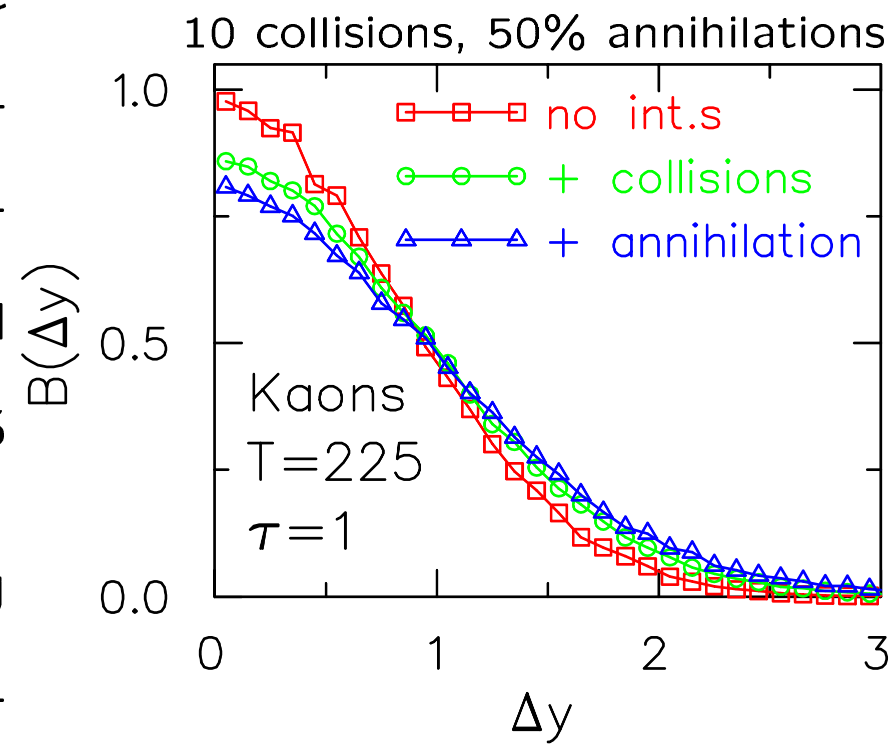
Collisions and Annihilations: A Simple Model

Procedure:

1. Generate pair thermally at $\eta = 0, \tau = \tau_0$.
2. Follow straight-line trajectories between collisions.
3. Perform $N_{\rm coll}$ collisions randomly in $\ln \tau$.
4. Readjust momenta to local thermal conditions. $T = 225 - 7.5(\tau - 1), \tau_f = 15$

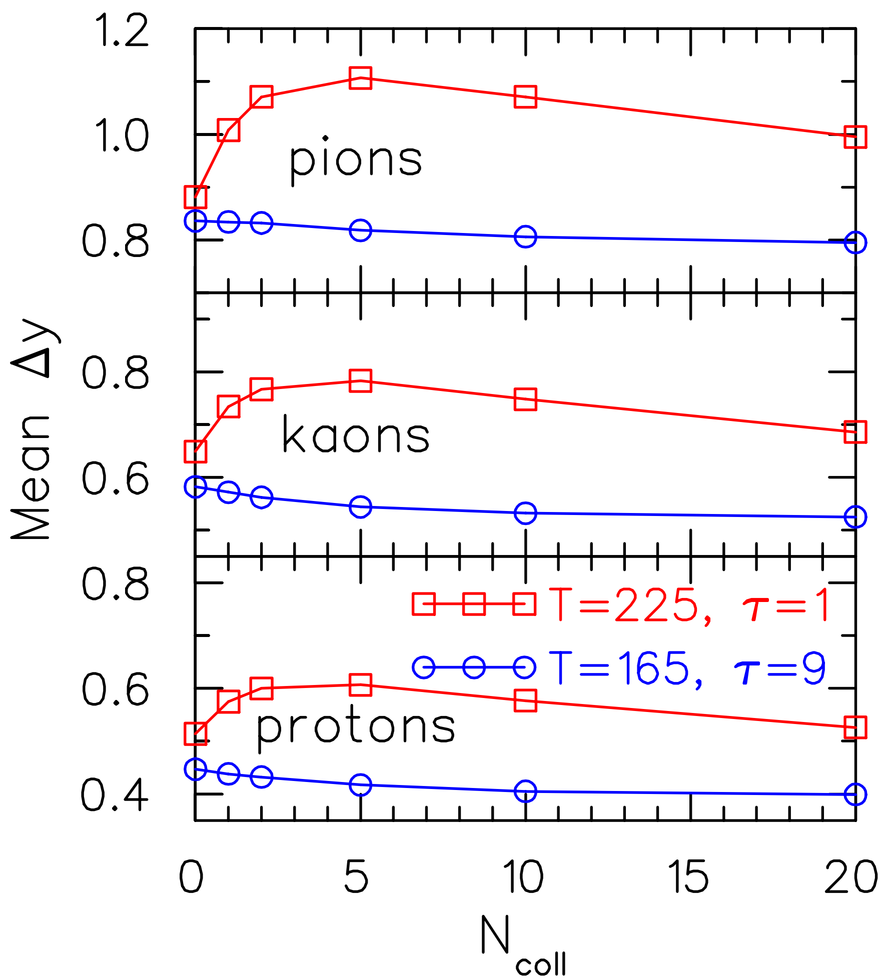
Annihilations:

- Modeled by convoluting pairs.
- If annihilation rate = creation rate → no effect.



Collisions/Annihilations magnify sensitivity to creation time!

Collisions: Model Summary

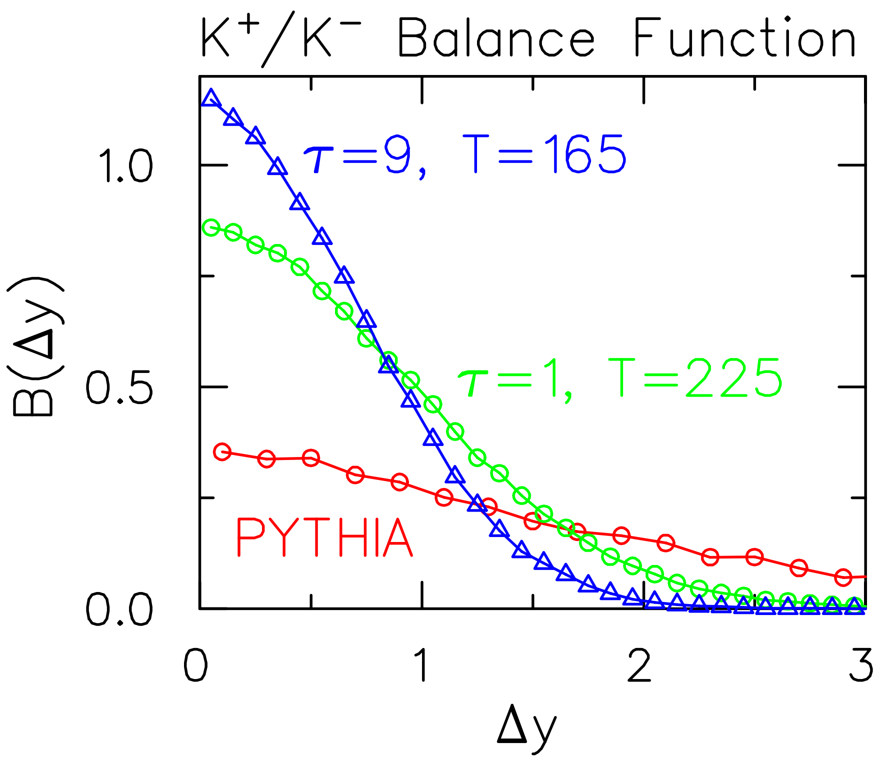


If $\tau_0 \approx 1$ fm/c, $N_{coll.} \sim 6$

If $\tau_0 \approx 9$ fm/c, $N_{coll.} \sim 2$

Even pions become sensitive to hadronization time!

Conclusions



- **Provide clear signal of late stage hadronization – a long-lived QGP.**
- Strangeness/Antibaryon production issues can be studied.
- Gating on p_t allows one to study production as function of $r_\perp$.

Far reaching implications

For example,

A. If measured balance functions have significant extra strength near Δy=0, characteristic of $T \sim 165$ MeV, then either

- Large numbers of new charges were created late in the reaction, e.g. hadronization of gluons.
- Mean free paths of partons were anomalously short during very early times.

B. If pp & AA balance functions appear identical,

- Gluonic modes did not contribute to entropy for a substantial time.
- Quarks and antiquarks did not contribute to entropy as separate particles (unless temperature jumped at hadronization).
- Most explanations of strangeness enhancement are wrong.
- Most jet energy loss calculations are misguided.
- QGP explanations of J/Ψ suppression are misguided.