Transverse-velocity scaling of femtoscopy in $\sqrt{s} = 7$ TeV proton-proton collisions

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Outline

- $m_T$ scaling of $R_{\text{inv}}$ in LHC experiments
- $\beta_T$ scaling of $R_{\text{inv}}$ seen in LHC pp collisions
- Toy MC model to mock-up $\beta_T$ scaling
Transverse-mass ($m_T$) scaling in 1-D identical two-particle femtoscopy

Collision region

$\mathbf{p}_1, m_0$

$\mathbf{p}_2, m_0$

$C_{\text{fit}} (q_{\text{inv}}) = 1 + \lambda \exp(-q_{\text{inv}}^2 R_{\text{inv}}^2)$

$q_{\text{inv}} = \sqrt{(|\Delta \mathbf{p}|^2 - |\Delta E|^2)}$

Example of perfect $m_T$ scaling

$m_T$ scaling – dependence of $R_{\text{inv}}$ on $m_T$ does not depend on the particle mass

$C(q_{\text{inv}})$ (GeV/c)

$R_{\text{inv}}$

$C_{\text{fit}} (q_{\text{inv}})$

$0.5$ $1$ $1.5$ $2$

$2$ $3$ $4$ $5$

$0$ $0.1$ $0.2$ $0.3$

$q_{\text{inv}}$ (GeV/c)

$0$ $1$ $2$ $3$ $4$ $5$
A good example of approximate $m_T$ scaling of $R_{inv}$ in LHC 2.76 TeV/N Pb-Pb collisions


A. Kisiel, M. Galazyn and P. Bozek

→ generally considered to be a signature of collective flow resulting from early-stage hydrodynamic flow and/or final-state rescattering of the many particles produced in the heavy-ion collision, e.g.

A good example of a lack of $m_T$ scaling of $R_{\text{inv}}$ in LHC 7 TeV pp collisions


For each species, $R_{\text{inv}}$ increases with multiplicity, and decreases with $m_T$ for high multiplicity and increases with $m_T$ for low multiplicity, but no $m_T$ scaling between pions and kaons. No serious model calculations exist in the literature describing these results.
Instead of $R_{\text{inv}}$ vs. $m_T$, plot the ALICE 7 TeV pp results vs. $\beta_T = k_T/m_T$ to see how this looks (T.H., J.Phys.G 45 (2018))

There appears to be an approximate $\beta_T$ scaling of $R_{\text{inv}}$ seen in the ALICE 7 TeV pp results
**HI collisions** $\Rightarrow R_{\text{inv}}$ scales with transverse “energy” ($m_T$)
- correlation length $\sim$ scales with local thermalization volume

**pp collisions** $\Rightarrow R_{\text{inv}}$ scales with transverse velocity ($\beta_T$)
- correlation length $\sim$ scales with “free-streaming” of particles to hadronization

$\Rightarrow$ Not surprising that HI and pp collisions have different scaling since they proceed in different ways

**HI collisions**
- Particle production via many soft parton-parton collisions
- Hydrodynamic flow in early stage of collision
- Final-state rescattering of the many produced particles thermalize the system

**pp collisions**
- Particle production via one or a few hard parton-parton collisions, e.g. Lund String Model picture
- Relatively few particles produced in the collision resulting in little chance of final-state rescattering or thermalization
In summary....... 

\(m_T\) scaling is seen in many HI collision experiments and can be explained by models 

\(\beta_T\) scaling of \(R_{\text{inv}}\) for 7 TeV pp is an empirical observation so far only seen in these data (but potentially interesting.....)

Construct a simple toy model to try to mock-up \(\beta_T\) scaling in the 7 TeV pp data
A simple toy MC model to mock-up $\beta_T$ scaling

Requirements for model to agree with 7 TeV pp experiment:

- $\beta_T$ scaling between pions and kaons
- Increasing $R_{\text{inv}}$ with increasing $\beta_T$ for $N_{\text{ch}}$ 1-11
- Increasing $R_{\text{inv}}$ with increasing $N_{\text{ch}}$
- Decreasing $R_{\text{inv}}$ with increasing $\beta_T$ for $N_{\text{ch}}$ 12-22 and $N_{\text{ch}} > 22$

Main assumptions of toy model:

- Quasi-particle initially created from pp collision
- Quasi-particle “free-streams” to the hadronization point
- Hadronization time obeys a Gaussian distribution in pp frame
- Particle momenta follow experimental distributions
A simple toy MC model to mock-up $\beta_T$ scaling

Consider a space-time point of the $i^{\text{th}}$ particle of rest mass $m_{0i}$ at hadronization in the pp collision frame $(x_i, y_i, z_i, t_i)$ with $(p_{xi}, p_{yi}, p_{zi}, E_i) \rightarrow$ set from ALICE, CMS $p_T$ and $\eta$ distributions
A simple toy MC model to mock-up $\beta_T$ scaling

* Hadronization time distribution: $\frac{dn}{dt_i} \propto \exp\left(-\frac{t_i^2}{2\sigma_i^2}\right)$

* Quasi-particles “free-stream” to hadronization point:

$$x_i = x_{0i} + t_i \beta_{Ti} \cos \phi_i \quad y_i = y_{0i} + t_i \beta_{Ti} \sin \phi_i \quad z_i = t_i \frac{p_{zi}}{E_i}$$

where, $\beta_{Ti} = \frac{p_{Ti}}{E_i}$

$x_{0i}$ and $y_{0i}$ are the initial transverse coordinates from a uniform distribution of radius 1 fm, and $\phi_i$ is from a flat distribution between 0 - $2\pi$

The hadronization time width $\sigma_i$ is a free parameter to be adjusted to get the best agreement with the $R_{inv}$ vs. $\beta_T$ measurements
A simple toy MC model to mock-up $\beta_T$ scaling

Quantum statistics and the Coulomb interaction are imposed pair-wise on a charged boson pair by weighting them at their hadronization phase-space points

$$W_{ij} = G(q_{\text{inv}}^{ij}) \left[ 1 + \cos (r_{ij} \cdot p_{ij} - t_{ij} E_{ij}) \right] \quad \text{where} \quad X_{ij} \equiv X_i - X_j \quad q_{\text{inv}}^{ij} = \sqrt{|p_{ij}|^2 - |E_{ij}|^2}$$

and $G(q_{\text{inv}}^{ij})$ is the Gamow factor

The correlation function is the ratio of weighted to un-weighted pairs

$$C(q_{\text{inv}}) = \frac{N(q_{\text{inv}})}{D(q_{\text{inv}})}$$

and fitted with the Bowler-Sinyukov equation to extract $R_{\text{inv}}$,

$$C_{\text{fit}}(q_{\text{inv}}) = a \left\{ 1 - \lambda + \lambda G(q_{\text{inv}}) \left[ 1 + \exp \left( -q_{\text{inv}}^2 R_{\text{inv}}^2 \right) \right] \right\}$$
Sample correlation function from the model
With typical fit to extract $R_{\text{inv}}$

The fits to the MC are not great, but adequate to extract at least qualitative values for $R_{\text{inv}}$
Comparison of toy model with experiment

The model can be forced to be close to the experiment and to show approximate $\beta_T$ scaling with the appropriate choices of $\sigma_t$

- $\sigma_t$ increases with increasing $N_{ch}$ range for both $\pi\pi$ and $KK$
- $\sigma_t$ is larger for $KK$ than $\pi\pi$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$N_{ch}$</th>
<th>$\pi\pi$</th>
<th>$K^{ch}K^{ch}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1–11</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>$\sigma_t$ (fm/c)</td>
<td>12–22</td>
<td>1.5</td>
<td>4.5</td>
</tr>
<tr>
<td>±0.1</td>
<td>&gt; 22</td>
<td>2.0</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Summary and conclusions

- Although $R_{\text{inv}}$ does not show $m_T$ scaling in 7 TeV pp collisions for $\pi\pi$ and KK, it does seem to show an approximate $\beta_T$ scaling instead.
- A simple toy model based on “free streaming” can be forced to approximately mock-up this scaling seen in experiment by suitable adjustments of the hadronization time width parameter.
- It would be interesting to see if other experimental pp collision studies at different energies also see this $\beta_T$ scaling of $R_{\text{inv}}$.
- It would also be interesting to see if serious models, e.g. EPOS, HKM..., can describe this $R_{\text{inv}}$ behavior seen in 7 TeV pp collisions.