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

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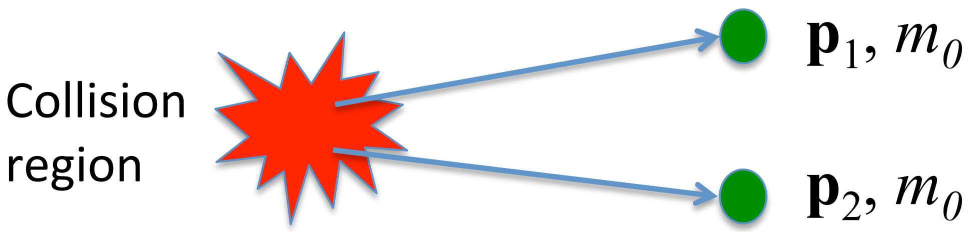
Outline

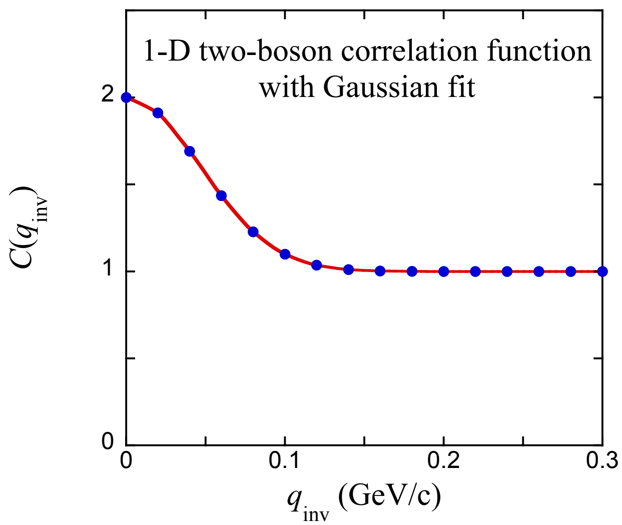
- m_T scaling of R_{inv} in LHC experiments
- β_T scaling of R_{inv} seen in LHC pp collisions
- Toy MC model to mock-up β_T scaling

Transverse-mass (m_T) scaling in 1-D identical two-particle femtoscopy



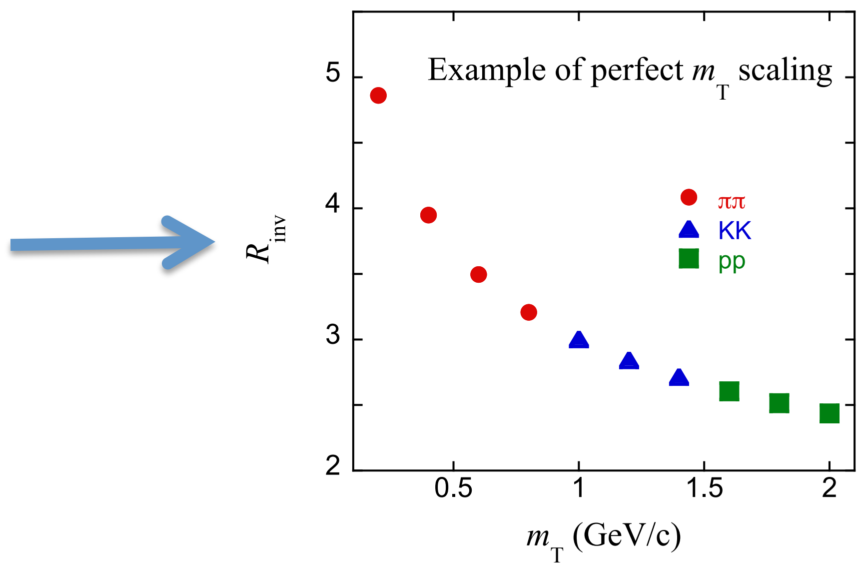
$$k_T \equiv \left| \frac{\mathbf{p}_{T1} + \mathbf{p}_{T2}}{2} \right|$$

$$m_T \equiv \sqrt{k_T^2 + m_0^2}$$



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

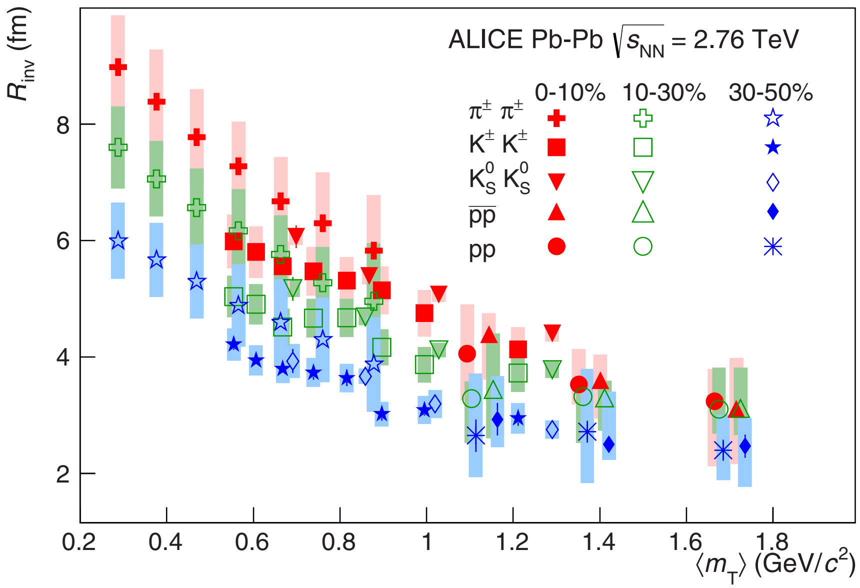
$$q_{inv} = \sqrt{|\Delta \mathbf{p}|^2 - |\Delta E|^2}$$



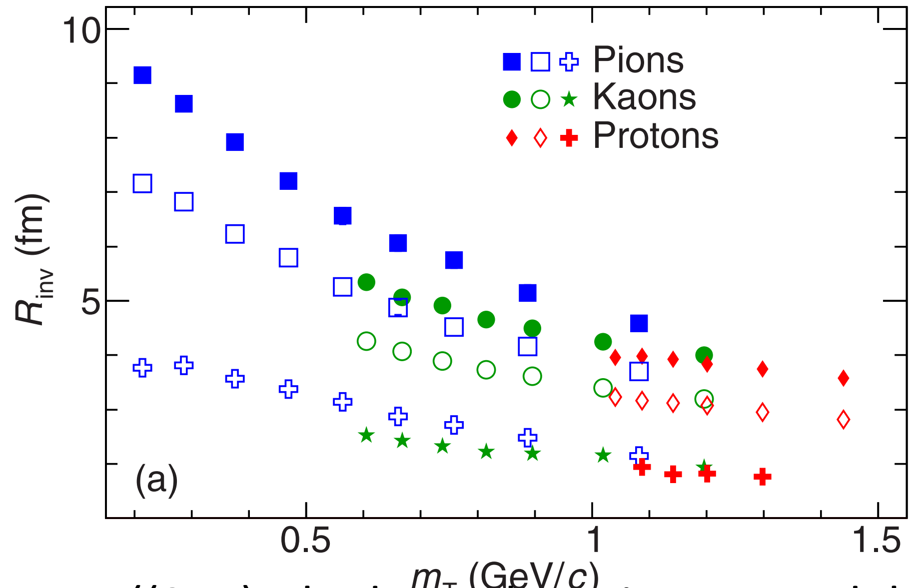
***m*$_T$ scaling** – dependence of R_{inv} on m_T does not depend on the particle mass

A good example of approximate m_T scaling of R_{inv} in LHC 2.76 TeV/N Pb-Pb collisions

ALICE collaboration,
Phys. Rev. C **92**, 054908 (2015)



A. Kisiel, M. Galazyn and P. Bozek
Phys. Rev. C **90**, 064914 (2014)

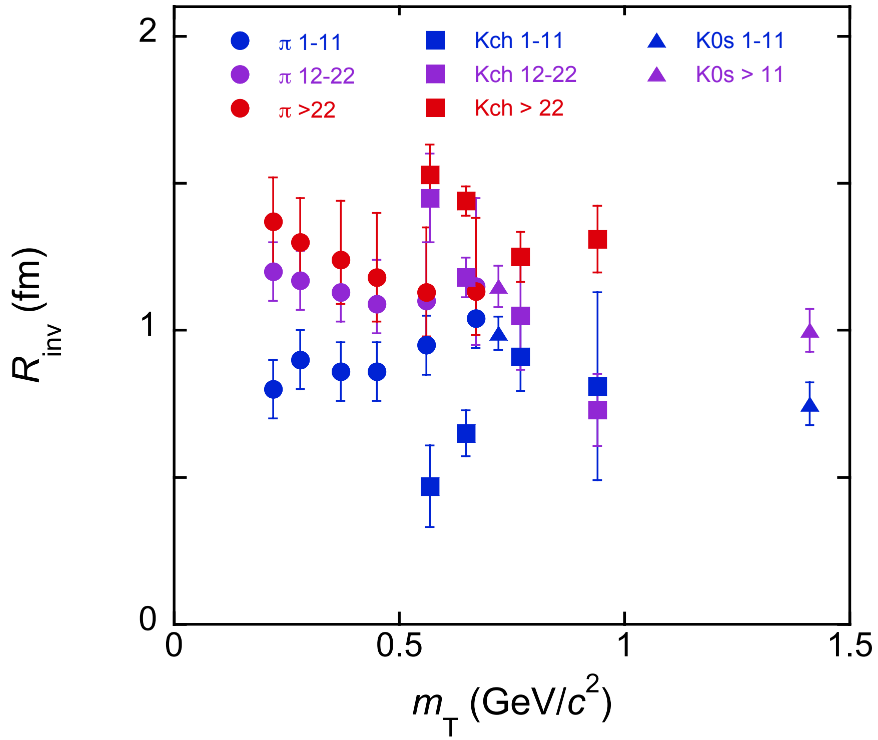


((3+1)D hydro + Therminator model

→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.
HKM (V. Shapoval, PBM, A. Karpenko, Y. Sinyukov, Nucl. Phys. A **929**, 1 (2014))

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

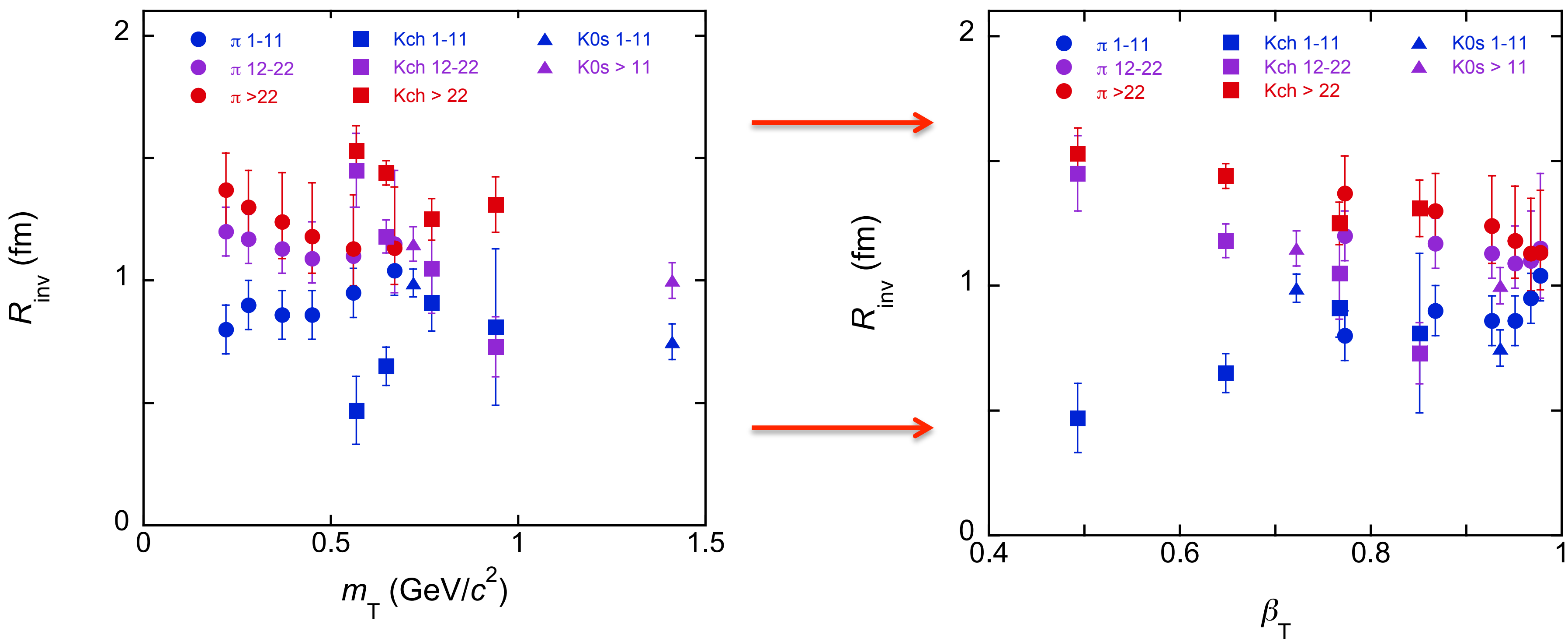
ALICE collaboration, Phys. Rev. D **87**, 052016 (2013)



For each species, R_{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_{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 β_T **scaling** of R_{inv} seen in the ALICE 7 TeV pp results

HI collisions → R_{inv} scales with transverse "energy" (m_T)
→ correlation length ~ scales with local thermalization volume
pp collisions → R_{inv} scales with transverse velocity (β_T)
→ correlation length ~ scales with "free-streaming" of particles to hadronization

→ 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

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

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→ Construct a simple toy model to try to mock-up β_T scaling in the 7 TeV pp data

A simple toy MC model to mock-up β_T scaling

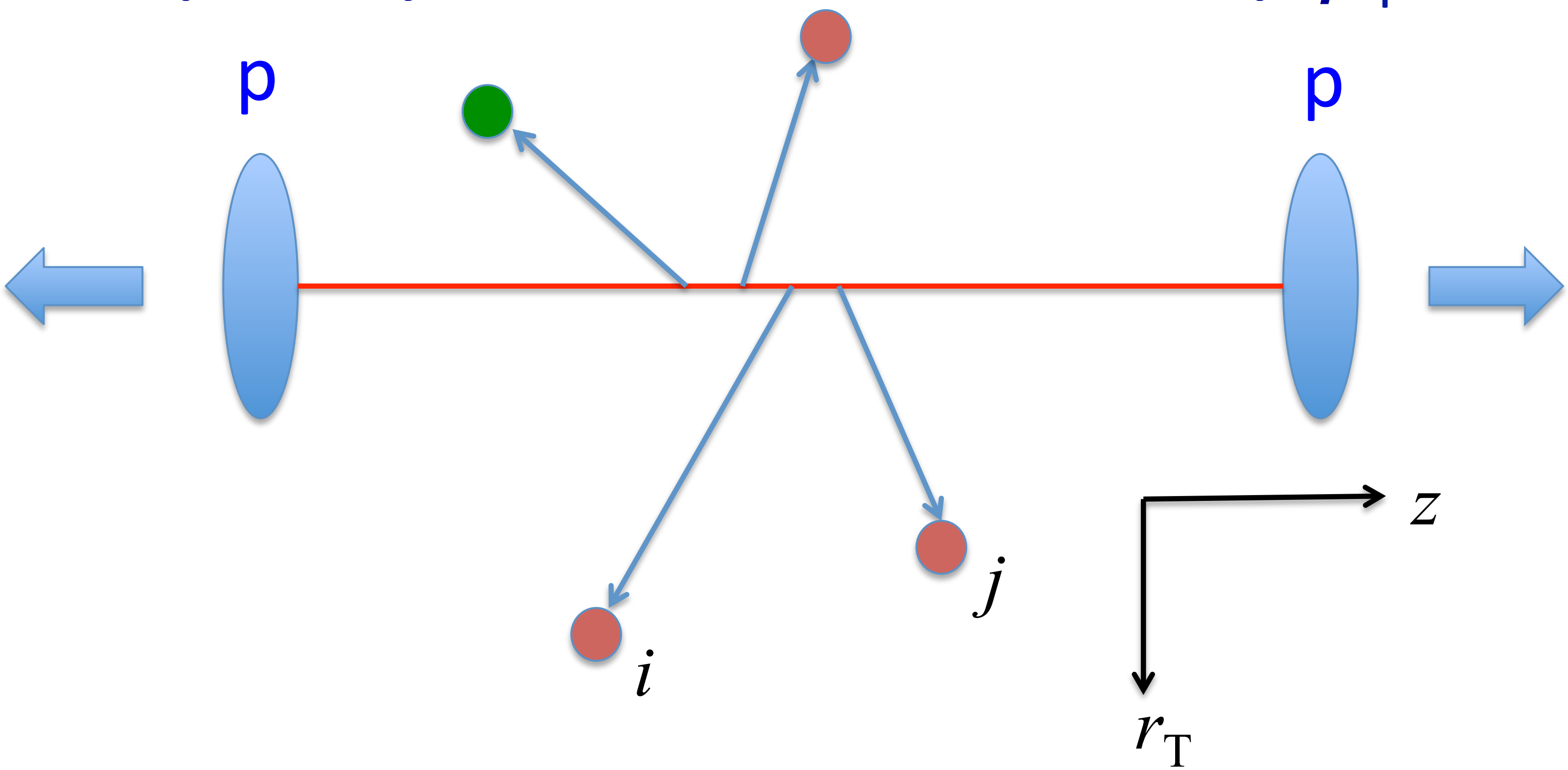
Requirements for model to agree with 7 TeV pp experiment:

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

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 β_T scaling



Consider a space-time point of the i^{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) → set from ALICE, CMS p_T and η distributions

A simple toy MC model to mock-up β_T scaling

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

* Quasi-particles "free-stream" to hadronization point:

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

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 ϕ_i is from a flat distribution between 0 - 2π

The hadronization time width σ_i is a free parameter to be adjusted to get the best agreement with the R_{inv} vs. β_T measurements

A simple toy MC model to mock-up β_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

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

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

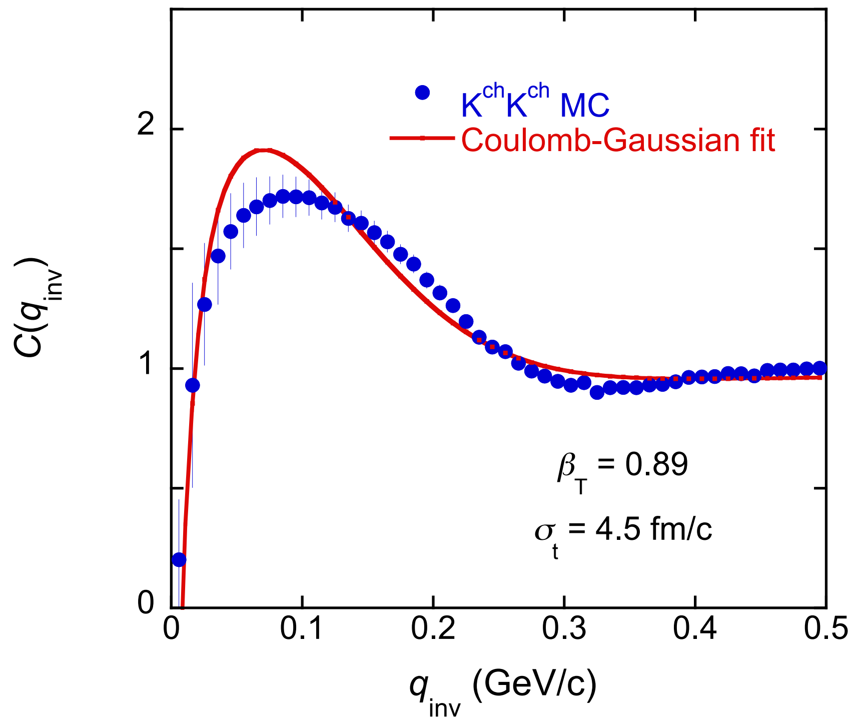
The correlation function is the ratio of weighted to un-weighted pairs

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

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

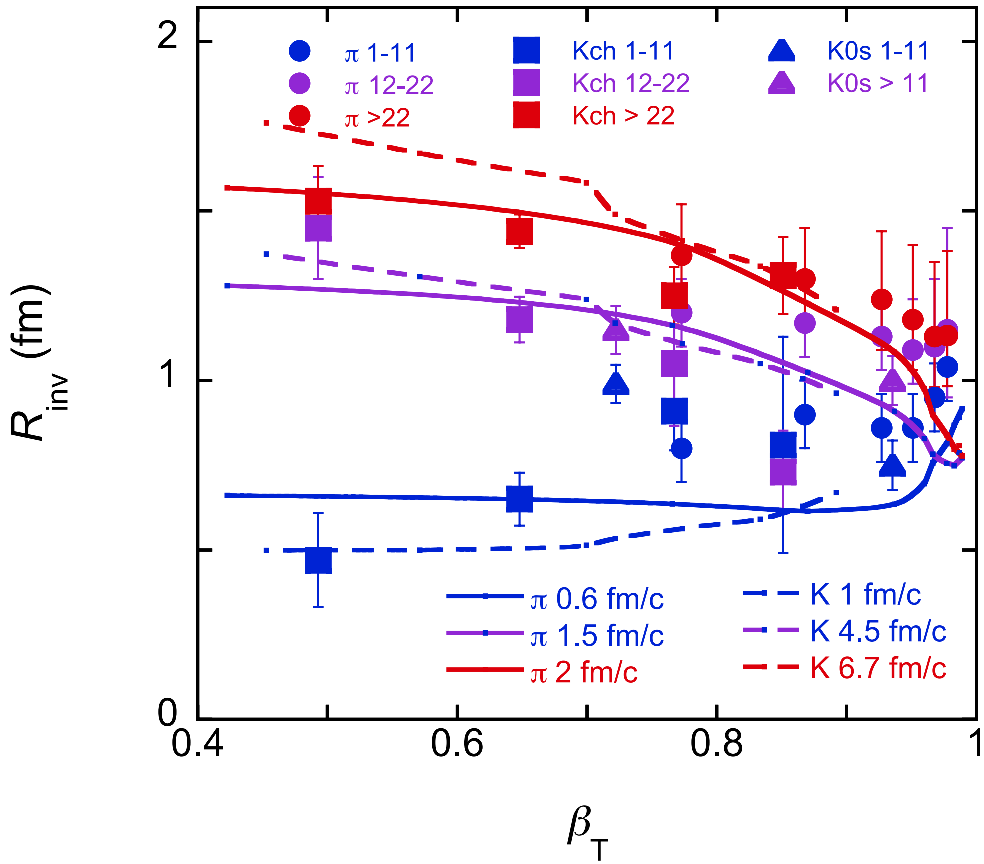
$$C_{\text{fit}}\left(q_{\text{inv}}\right) = a\left\{1-\lambda+\lambda G\left(q_{\text{inv}}\right)\left[1+\exp\left(-q_{\text{inv}}^2 R_{\text{inv}}^2\right)\right]\right\}$$

Sample correlation function from the model With typical fit to extract R_{inv}



The fits to the MC are not great, but adequate to extract at least qualitative values for R_{inv}

Comparison of toy model with experiment



Parameter	N_{ch}	ππ	$K^{ch}K^{ch}$
	1 – 11	0.6	1.0
σ_t (fm/c)	12 – 22	1.5	4.5
±0.1	> 22	2.0	6.7

- σ_t increases with increasing N_{ch} range for both ππ and KK
- σ_t is larger for KK than ππ

→ The model can be forced to be close to the experiment and to show approximate β_T scaling with the appropriate choices of σ_t

Summary and conclusions

- **Although R_{inv} does not show m_T scaling in 7 TeV pp collisions for $\pi\pi$ and KK, it does seem to show an approximate β_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 β_T scaling of R_{inv}**
- **It would also be interesting to see if serious models, e.g. EPOS, HKM…., can describe this R_{inv} behavior seen in 7 TeV pp collisions**