Strangeness Correlations and Signatures of Flux Tube Fragmentation in pp Collisions

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1. Introduction
2. Signatures of flux tube fragmentation:
   (i) an ordered, correlated chain of hadrons in every flux-tube fragmentation event
   (ii) two-hadron angular correlations in the charge sector and strangeness sector
   (iii) comparison with experiment
3. The boundary separating flux tube fragmentation and hard scattering in the space of $(p_T, \sqrt{s_{pp}})$.
4. Conclusions

This talk on flux tube fragmentation is based on

- C.Y.Wong, *Signatures of the fragmentation of a color flux tube,* Phys. Rev. D 92, 074007 (2015)
- C.Y.Wong, *Event-by-event study of space-time dynamics in flux-tube fragmentation,* arxiv:1510.07194 (2015)

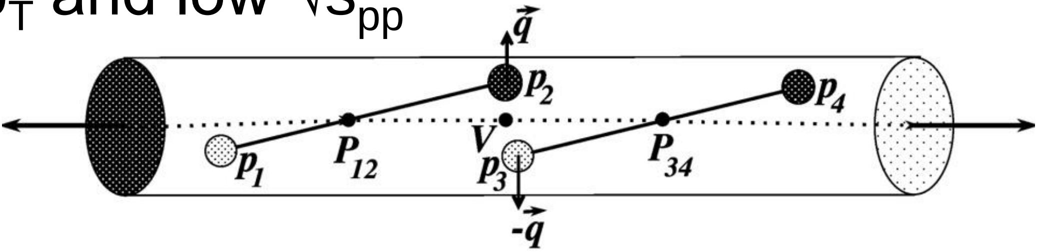
Related articles on hard scattering and flux tube fragmentation:-

- C.Y.Wong , G.Wilk, *Tsallis fits to pT spectra for pp collisions at LHC,* ActaPhysPol B43,247(2012).
- C.Y.Wong , G.Wilk, *Tsallis fits to pT spectra and multiple hard scattering in pp Collisions at the LHC*, Phys.Rev.D87,114007(2013)
- C.Y.Wong, G.Wilk, L.Cirto, C.Tsallis, *From QCD-based hard-scattering to nonextensive statistical mechanical descriptions of transverse momentum spectra in high-energy pp and p-pbar collisions,* Phys.Rev.D91,114027(2015)

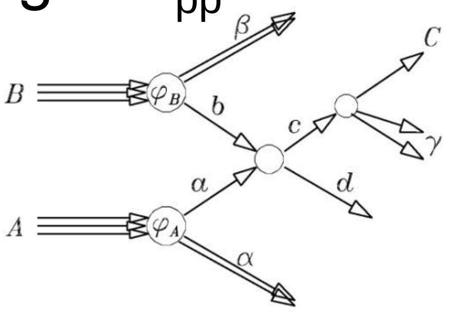
Introduction (I)

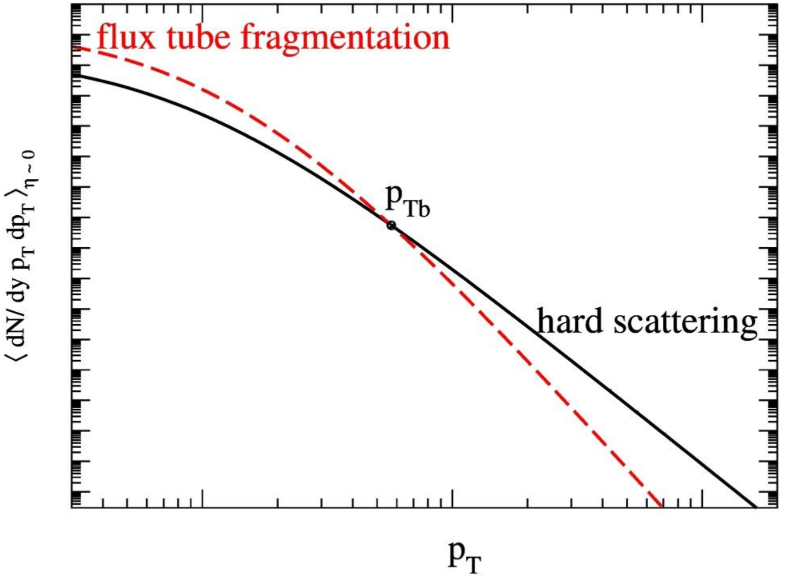
(i) pp reaction mechanisms provide insights in AA collision.

(ii) In a pp collision, flux-tube fragmentation is expected to dominate at low p_T and low $\sqrt{s_{pp}}$



(iii) Hard scattering is expected to dominate at high p_T and high $\sqrt{s_{pp}}$



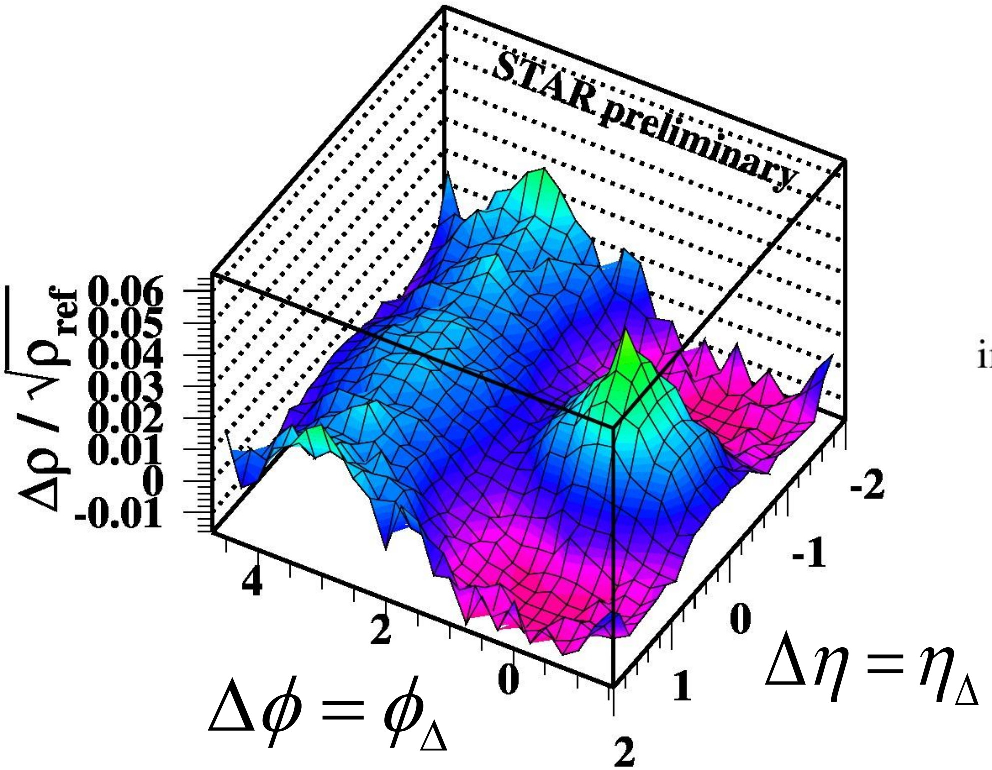


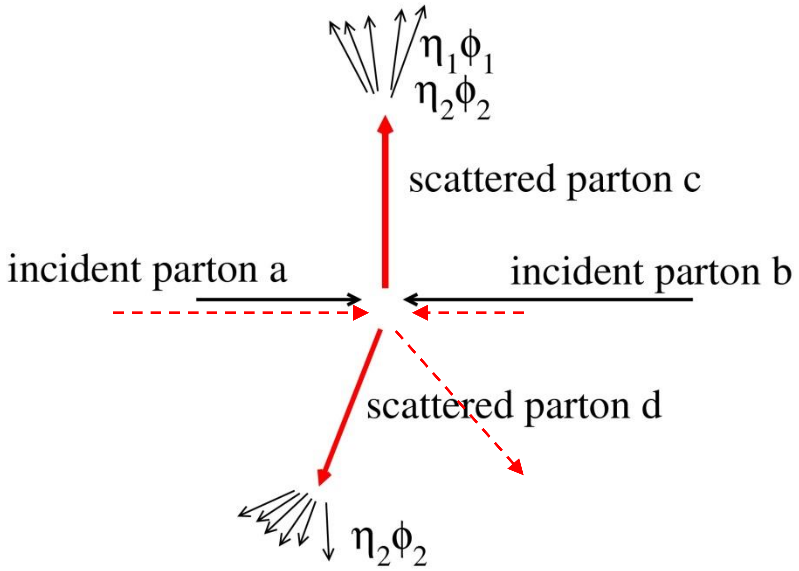
The two processes cross over at the boundary $p_{Tb}(\sqrt{s_{pp}})$

(iii) Other processes, resonance production, recombinations,…

Introudction (II)

The signature for hard scattering is well known.
It is provided by two-hadron angular correlations.





But, what is the signature for flux tube fragmentation?

Introduction (III)

(i) The *signature* for flux tube fragmentation is not known.

(ii) The *boundary* $p_{Tb}(\sqrt{s_{pp}})$ between flux tube fragmentation and hard-scattering is not known.

(iii) The *number of flux tubes in a pp collision* is not known. (Is it one flux tube? two flux tubes? or more flux tubes?)

Therefore, we need the signature of flux tube fragmentation.

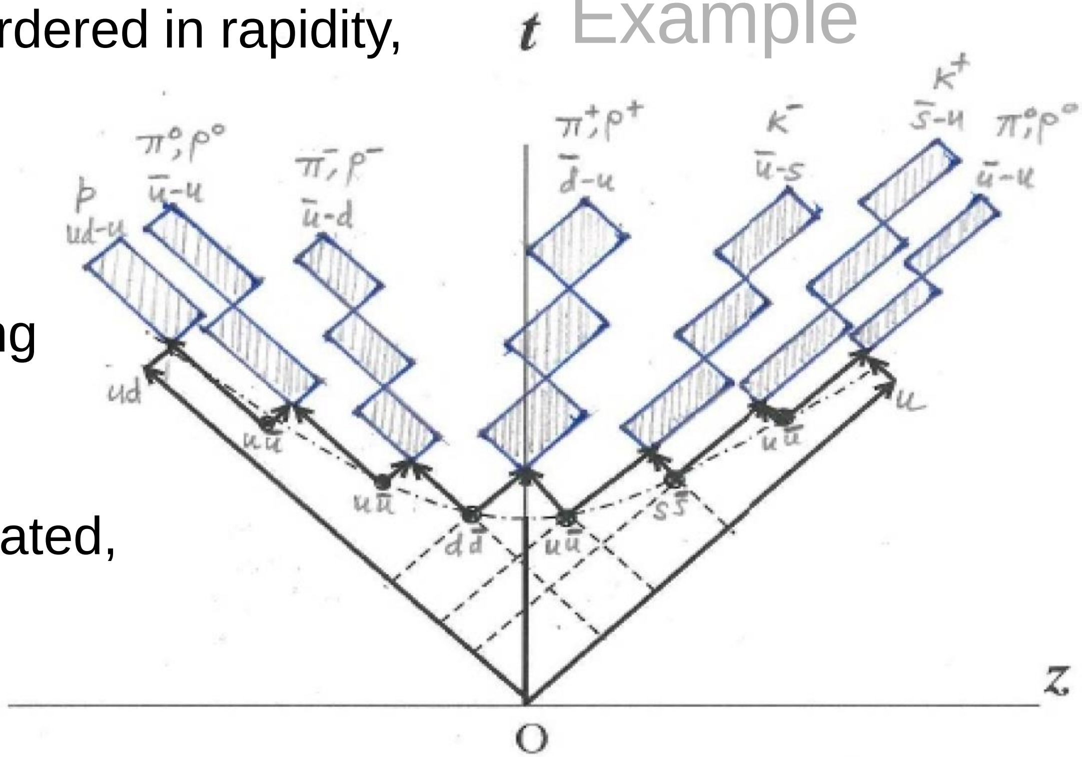
Two signatures of flux tube fragmentations

(I) A many-hadron signature of flux tube fragmentation

A flux tube fragmentation produces a chain of hadrons ordered in rapidity, and all $q\bar{q}$ pair production obeys local conservation laws.

Therefore, when hadrons are ordered in rapidity, the flavors of all constituents of the hadrons are correlated along the chain, and neighboring hadrons are likely to be azimuthally back-to-back correlated, on an event-by event basis.

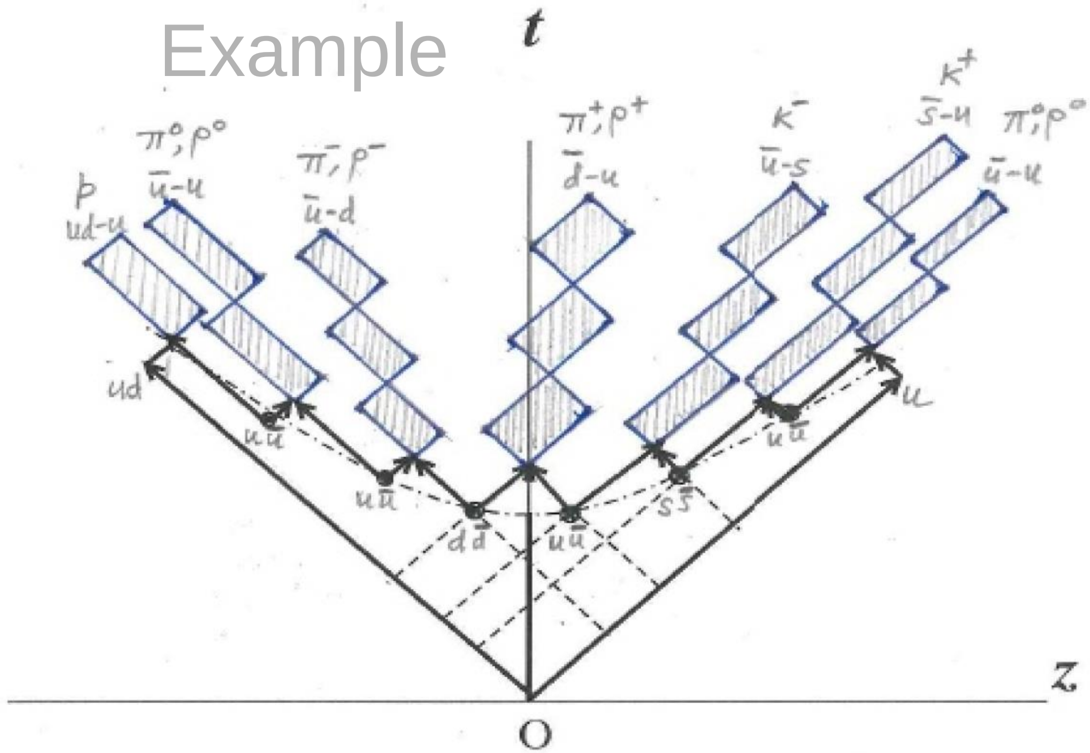
Example



C.Y.Wong, *Event-by-event study of space-time dynamics in flux-tube fragmentation,* arxiv:1510.07194 (2015)

The many-hadron signature requires the identification of particles detected in the events. This predicted signature is yet to be observed.

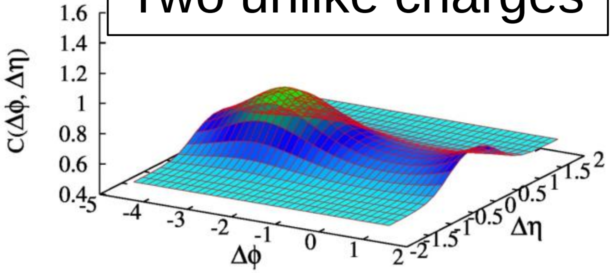
Example



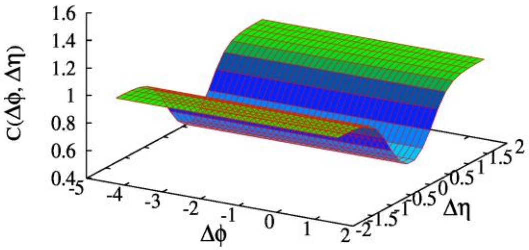
C.Y.Wong, *Event-by-event study of space-time dynamics in flux-tube fragmentation,* arxiv:1510.07194 (2015)

(II) Two-hadron angular correlation signature of flux tube fragmentation

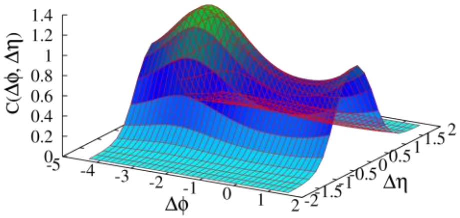
Two unlike charges



Two like charges



Two mesons with opposite strangeness



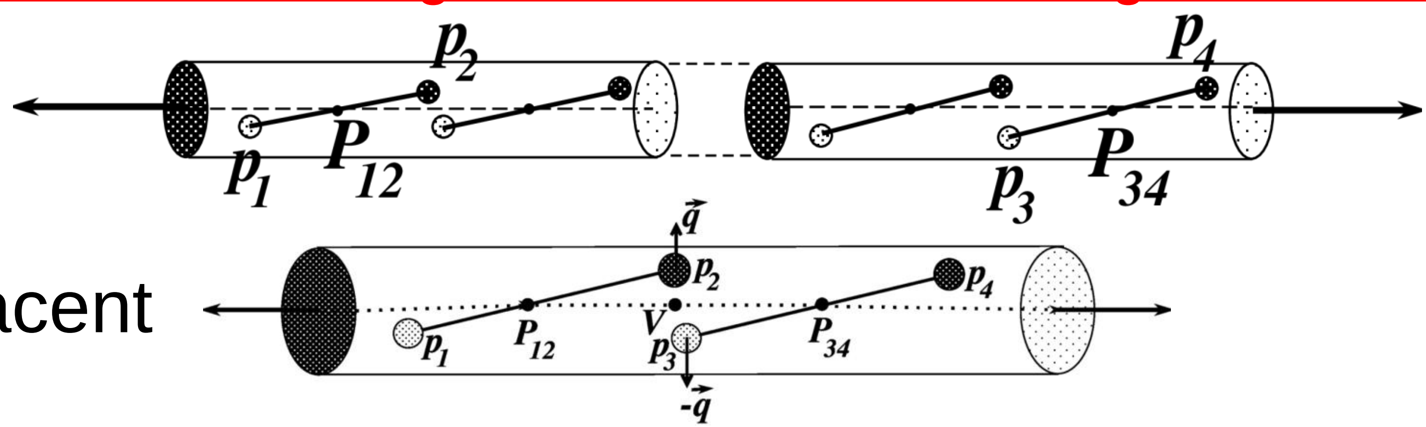
C.Y.Wong, *Signatures of the fragmentation of a color flux tube,* Phys. Rev. D 92, 074007 (2015)

How are these results obtained?

How to obatin two-hadron signatures for flux tube fragmentation

non-adjacent

adjacent

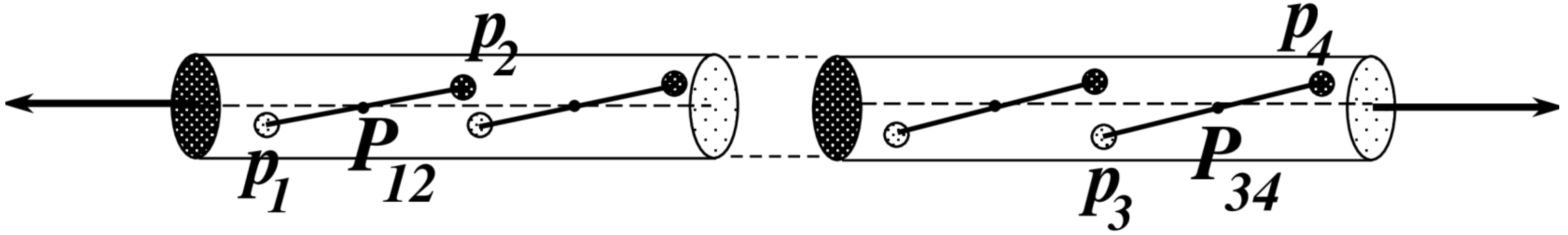


Pairs of q and $\bar{q}$ are produced: p_1, p_2, p_3, p_4 ($\vec{p}_{Ti}$, p_{zi}, charge, flavor).

Antiquark p_1 combines with quark p_2 to form meson P_{12}.
Antiquark p_3 combines with quark p_4 to form meson P_{34}.

We would like to calculate two-hadron
transverse momentum correlations between mesons P_{12} and P_{34}
longitudinal momentum correlations between mesons P_{12} and P_{34}
charge correlations between mesons P_{12} and P_{34}
flavor correlations between mesons P_{12} and P_{34}

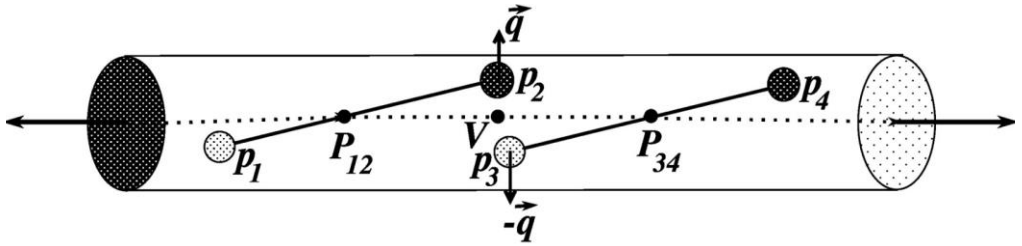
Transverse correlations between mesons P_{12} and P_{34}



Transverse momentum distribution for non-adjacent hadrons or uncorrelated mesons

$$\frac{dN_T^N}{d\vec{p}_{Ti}d\vec{p}_{Ti}d\vec{p}_{Ti}d\vec{p}_{Ti}} = \left(\prod_{i=1,2,3,4} \frac{d\vec{q}_i \exp\left(-\frac{\vec{q}_i^{\,2}}{2\sigma_q^2}\right)}{\left(\sqrt{2\pi}\sigma_q\right)^2}\right)\left(\prod_{i=1}^{4} \frac{d\vec{p}_{Ti} \exp\left(-\frac{\vec{p}_{Ti}^{\,\prime 2}}{2\sigma_u^2}\right)}{\left(\sqrt{2\pi}\sigma_u\right)^2}\delta(\vec{p}_{Ti} - \vec{p}_{Ti}^{\,\prime} - \vec{q}_i)\right)$$

Transverse momentum distribution for adjacent hadrons with correlations



$$\frac{dN_T^A}{d\vec{p}_{Ti}d\vec{p}_{Ti}d\vec{p}_{Ti}d\vec{p}_{Ti}} = \left(\prod_{i=1,2,4} \frac{d\vec{q}_i \exp\left(-\frac{\vec{q}_i^{\,2}}{2\sigma_q^2}\right)}{\left(\sqrt{2\pi}\sigma_q\right)^2}\right)\left(\prod_{i=1}^{4} \frac{d\vec{p}_{Ti} \exp\left(-\frac{\vec{p}_{Ti}^{\,\prime 2}}{2\sigma_u^2}\right)}{\left(\sqrt{2\pi}\sigma_u\right)^2}\delta(\vec{p}_{Ti} - \vec{p}_{Ti}^{\,\prime} - \vec{q}_i)\right)$$

$[\vec{q}_3 = -\vec{q}_2]$

Transverse correlations between mesons P_{12} and P_{34}

From the variables $\vec{p}_{T1}$, $\vec{p}_{T2}$, $\vec{p}_{T3}$, $\vec{p}_{T4}$, we construct

$$\vec{P}_{T12} = \vec{p}_{T1} + \vec{p}_{T1}\,, \qquad \vec{p}_{T12} = \vec{p}_{T1} - \vec{p}_{T1}$$

$$\vec{P}_{T34} = \vec{p}_{T3} + \vec{p}_{T4}, \qquad \vec{p}_{T34} = \vec{p}_{T3} - \vec{p}_{T4}$$

We integrate over $\vec{p}_{T12}$ and $\vec{p}_{T34}$.

We label $\quad \vec{P}_{T12} = (|\vec{P}_{T12}|, \varphi_{12})$

$\vec{P}_{T34} = (|\vec{P}_{T34}|, \varphi_{34})$

We further integrate over all variables except

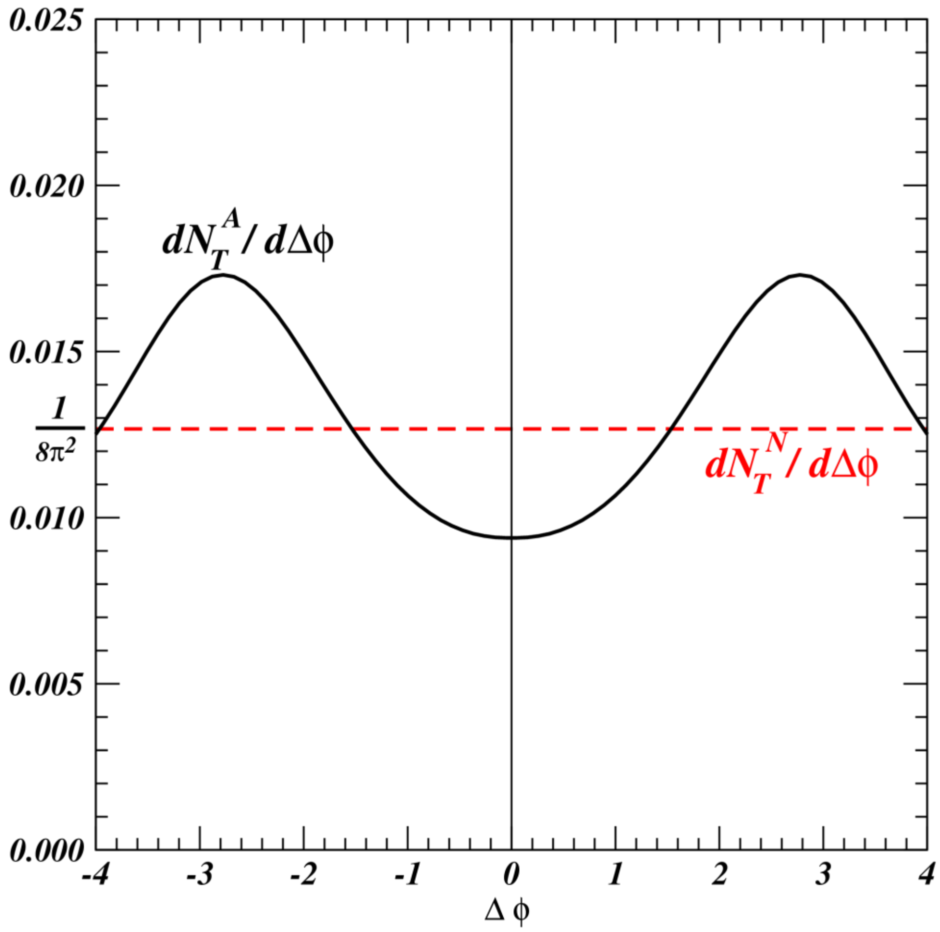
$$\Delta\varphi = \varphi_{12} - \varphi_{34}\,,$$

we get from $\dfrac{dN_T^N}{d\vec{p}_{Ti} d\vec{p}_{Ti} d\vec{p}_{Ti} d\vec{p}_{Ti}}$ to $\dfrac{dN_T^N}{d\Delta\varphi}$

and from $\dfrac{dN_T^A}{d\vec{p}_{Ti} d\vec{p}_{Ti} d\vec{p}_{Ti} d\vec{p}_{Ti}}$ to $\dfrac{dN_T^A}{d\Delta\varphi}$

Results of two-hadron transverse correlation

$\frac{dN_T^A}{d\Delta\varphi}$ and $\frac{dN_T^N}{d\Delta\varphi}$ in flux tube fragmentation



A=adjacent hadrons
N=non-adjacent hadrons

Longitudinal Momentum Distributions of Mesons P_{12} and P_{34}

From $p_{z1}, p_{z2}, p_{z3}, p_{z4},$ we construct

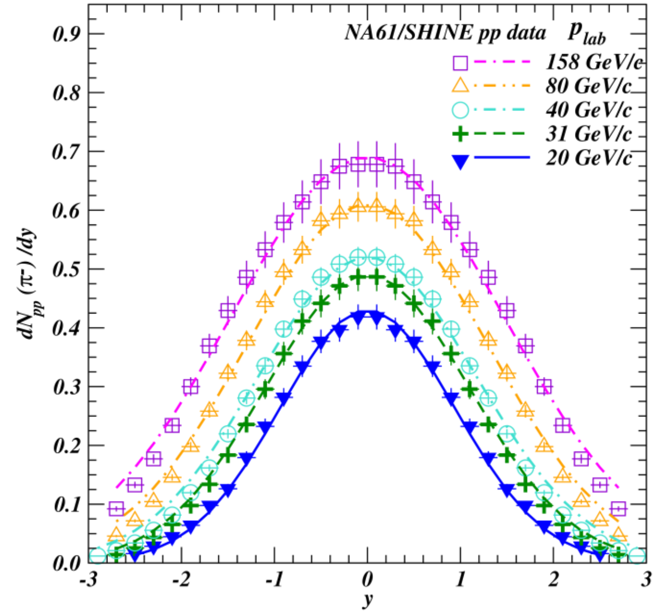
$$P_{z12} = p_{z1} + p_{z1}\,, \qquad p_{z12} = p_{z1} - p_{z2}$$
$$P_{z34} = p_{z3} + p_{z4}\,, \qquad p_{z34} = p_{z3} - p_{z4}$$

The relative degrees of freedom, p_{z12} and p_{z34}, have to do with the binding of the individual mesons through a relative longitudinal interaction. They are implicitly included when we consider bound mesons P_{12} and P_{34}.

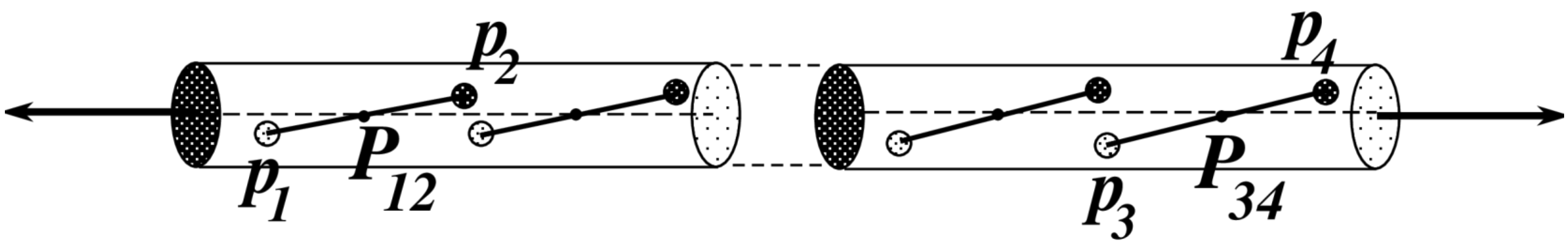
The remaining degrees of freedom, P_{z12} and P_{z34} can be represented by y_{12} and y_{34}.

What is the hadron longitudinal momentum distribution at NA61/SHINE energies of $\sqrt{s_{pp}}$~20 GeV?

$$\frac{dN_\pi}{dy_{12}} = \frac{N_{\pi 0}\exp\left(-\frac{y_{12}^2}{2\sigma_y^2}\right)}{\left(\sqrt{2\pi}\sigma_y\right)^2}$$



Two-hadron longitudinal correlations between P_{12} and P_{34}



Longitudinal momentum distribution for a non-adjacent or an uncorrelated hadron pairs

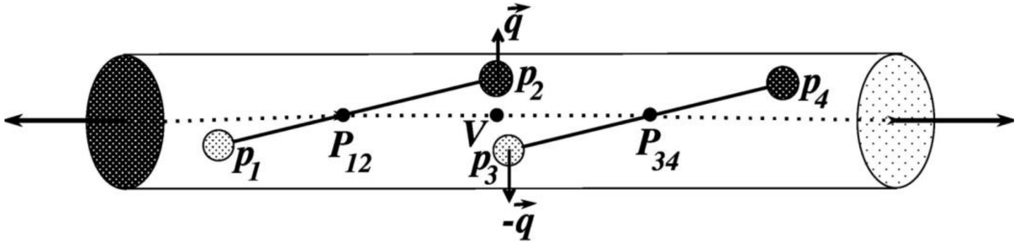
$$\frac{dN_y^{uncor}}{dy_{12}dy_{34}} = \frac{N_{\pi 0}^2 \exp(-\frac{y_{12}^2}{2\sigma_y^2} - \frac{y_{34}^2}{2\sigma_y^2})}{\left(\sqrt{2\pi}\sigma\right)^2}$$

$$\frac{dN_y^{uncor}}{d\Delta y\, d\Sigma_y} = \frac{N_{\pi 0}^2 \exp(-\frac{(\Delta y)^2 + \Sigma_y^2}{4\sigma_y^2})}{\left(\sqrt{2\pi}\sigma\right)^2}, \qquad \Delta y = y_{12} - y_{34}, \;\; \Sigma_y = y_{12} + y_{34}$$

Upon integration over Σ_y, we get for non-adjacent or uncorrelated pair Δy distribution

$$\frac{dN_y^{mixed\ event}}{d\Delta y} = \frac{dN_y^{uncor}}{d\Delta y} \propto \frac{N_{\pi 0}^2 \exp(-\frac{(\Delta y)^2}{4\sigma_y^2})}{\left(\sqrt{2\pi}\sigma\right)^2}$$

Two-hadron longitudinal correlations between Mesons P_{12} and P_{34}



Longitudinal momentum distribution for two adjacent hadrons

$$\frac{dN_y^A}{dy_{12}dy_{34}} = \frac{N_{\pi 0}^2 \exp(-\frac{y_{12}^2}{2\sigma_y^2} - \frac{y_{34}^2}{2\sigma_y^2})}{(\sqrt{2\pi}\sigma)^2} \frac{1}{1+\exp(\frac{|y_{12}-y_{34}|-w}{a})}, \qquad w = \frac{1}{\frac{dN}{dy}}$$

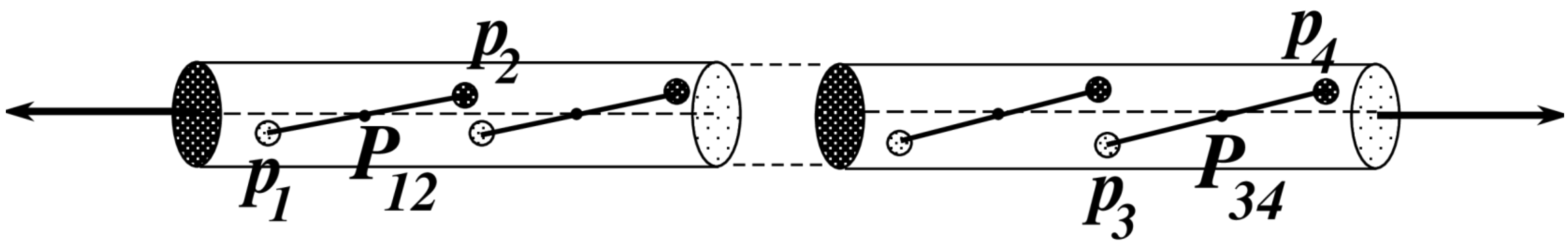
$$\frac{dN_y^A}{d\Delta y\, d\Sigma_y} = \frac{N_{\pi 0}^2 \exp(-\frac{(\Delta y)^2 + \Sigma_y^2}{4\sigma_y^2})}{(\sqrt{2\pi}\sigma)^2} \frac{1}{1+\exp(\frac{|\Delta y|-w}{a})}, \qquad \Delta y = y_{12} - y_{34}$$

Upon integration over Σ_y, we get for adjacent hadron pair

$$\frac{dN_y^A}{d\Delta y} \propto \frac{N_{\pi 0}^2 \exp(-\frac{(\Delta y)^2}{4\sigma_y^2})}{(\sqrt{2\pi}\sigma)^2} \frac{1}{1+\exp(\frac{|\Delta y|-w}{a})}$$

$$\frac{dN_y^A}{d\Delta y} \Big/ \frac{dN_y^{mixed\ event}}{d\Delta y} = \frac{1}{1+\exp(\frac{|\Delta y|-w}{a})}$$

Two-hadron longitudinal correlations between P_{12} and P_{34}



Longitudinal momentum distribution for two non-adjacent hadrons

$$\frac{dN_y^N}{dy_{12}dy_{34}} = \frac{N_{\pi 0}^2 \exp(-\frac{y_{12}^2}{2\sigma_y^2} - \frac{y_{34}^2}{2\sigma_y^2})}{\left(\sqrt{2\pi}\sigma\right)^2} \frac{1}{1+\exp(\frac{w-|y_{12}-y_{34}|}{a})}, \qquad w = \frac{1}{\frac{dN}{dy}}$$

$$\frac{dN_y^N}{d\Delta y\, d\Sigma_y} = \frac{N_{\pi 0}^2 \exp(-\frac{(\Delta y)^2 + \Sigma_y^2}{4\sigma_y^2})}{\left(\sqrt{2\pi}\sigma\right)^2} \frac{1}{1+\exp(\frac{w-|\Delta y|}{a})}, \qquad \Delta y = y_{12} - y_{34}$$

Upon integration over Σ_y, we get for adjacent hadron pair

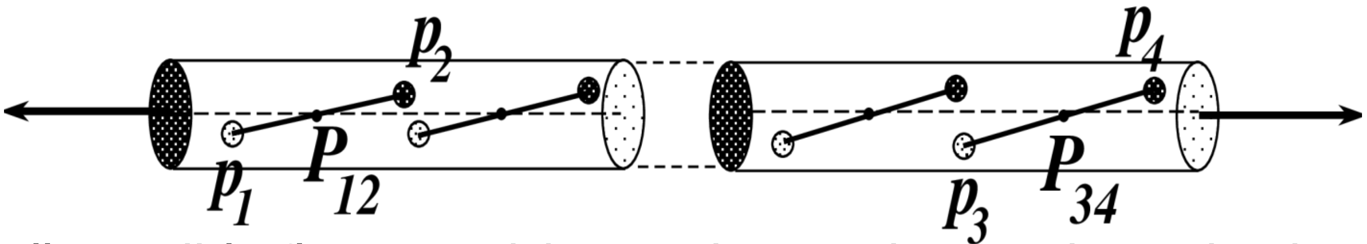
$$\frac{dN_y^N}{d\Delta y} \propto \frac{N_{\pi 0}^2 \exp(-\frac{(\Delta y)^2}{4\sigma_y^2})}{\left(\sqrt{2\pi}\sigma\right)^2} \frac{1}{1+\exp(\frac{w-|\Delta y|}{a})}$$

$$\frac{dN_y^N}{d\Delta y} \Big/ \frac{dN_y^{mixed\ event}}{d\Delta y} = \frac{1}{1+\exp(\frac{w-|\Delta y|}{a})}$$

Charge and flavor correlations between mesons P_{12} and P_{34}

In non-adjacent case, $q\bar{q}$ pairs are produced at p_1, p_2, p_3, p_4.

Non-adjacent



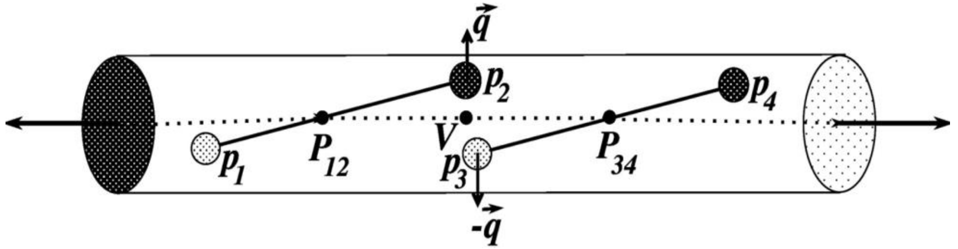
We enumerate all possible flavor SU(3) $q\bar{q}$ pairs. Each $s\bar{s}$ pair production is associated with a reduced probability f_s.

We shall keep contributions only up to the order f_s.

$$p_1 = (u, d, s), \quad p_2 = (\bar{u}, \bar{d}, \bar{s}), \quad p_3 = (u, d, s), \quad p_4 = (\bar{u}, \bar{d}, \bar{s}),$$

In adjacent case, the $q\bar{q}$ pair at p_2, and p_3 are correlated:

Adjacent



$$p_1 = (u, d, s), \qquad (p_2, p_3) = (u, \bar{u}), (d, \bar{d}), (s, \bar{s}), \qquad p_4 = (\bar{u}, \bar{d}, \bar{s}),$$

Charge and flavor correlations between mesons P_{12} and P_{34}

We enumerate all possible flavor SU(3) quark-antiquark pairs.

We get the charges and flavors quantum numbers of P_{12} and P_{34}.
This enumeration gives the probability

$P^A(\nu)$ for configuration ν in adjacent P_{12} and P_{34}

$P^N(\nu)$ for configuration ν in non-adjacent P_{12} and P_{34}.

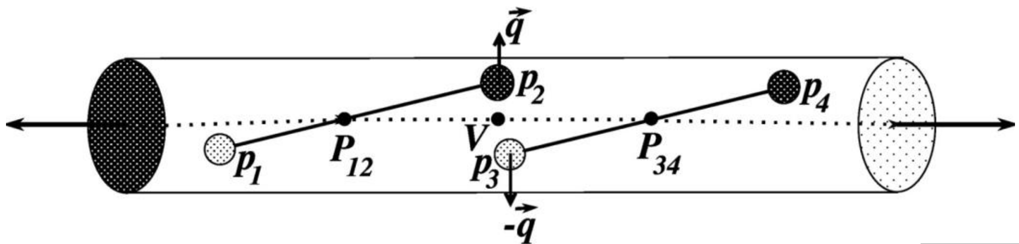
Two meson distribution function $\frac{dN^{AN}(\nu)}{d\Delta\phi\, d\Delta y}$ is

$$\frac{dN(\nu)}{d\Delta\phi\, d\Delta y} = \frac{dN^A(\nu)}{d\Delta\phi\, d\Delta y} \times P^A(\nu) + \frac{dN^N(\nu)}{d\Delta\phi\, d\Delta y} \times P^N(\nu)$$

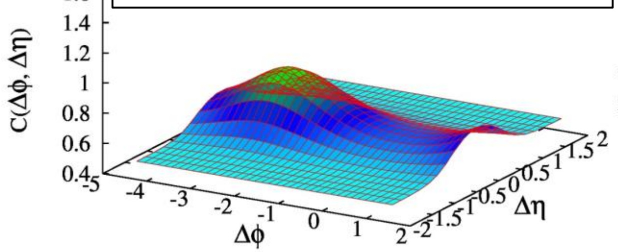
Correlation function for two flux tubes

$$C(\Delta\phi, \Delta y) = \frac{\frac{dN_{sib}(\nu)}{d\Delta\phi\, d\Delta y}}{\frac{dN_{mixed}(\nu)}{d\Delta\phi\, d\Delta y}} = \frac{\frac{dN^A(\nu)}{d\Delta\phi\, d\Delta y} \times P^A(\nu) + \frac{dN^N(\nu)}{d\Delta\phi\, d\Delta y} \times P^N(\nu) + P^N(\nu))\frac{1}{8\pi^2}}{\left(P^A(\nu) + P^N(\nu)\right)\frac{1}{8\pi^2} + P^N(\nu))\frac{1}{8\pi^2}}$$

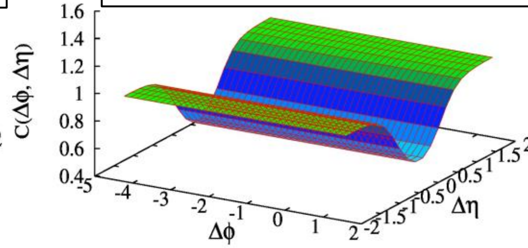
We obtain two-hadron angular correlations as signatures for flux tube fragmentation



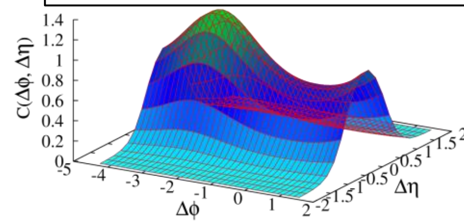
Two unlike charges



Two like charges



Two hadron with opposite strangeness

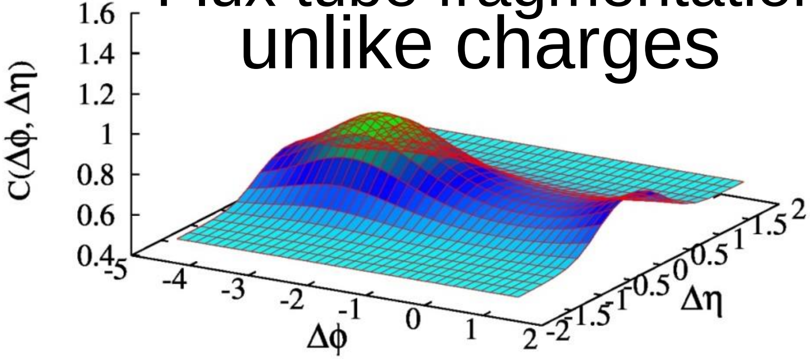


C.Y.Wong, *Signature of the fragmentation of a color flux tube,* Phys. Rev. D 92, 074007 (2015)

Remarks

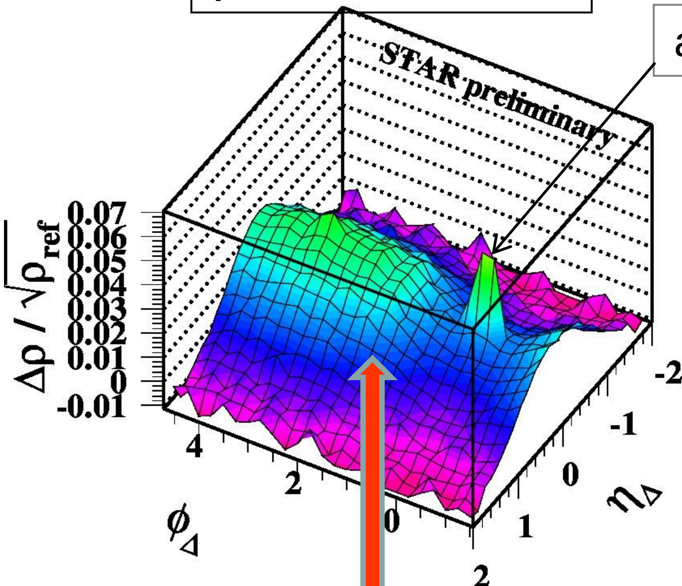
- Resonance production and subsequent resonance decay also lead to signals similar to the flux tube fragmentation.
- They are estimate to be about 10-20% at SPS and RHIC energies in central rapidity region, but higher at the projectile fragmentation and target fragmentation regions.

Flux tube fragmentation
unlike charges

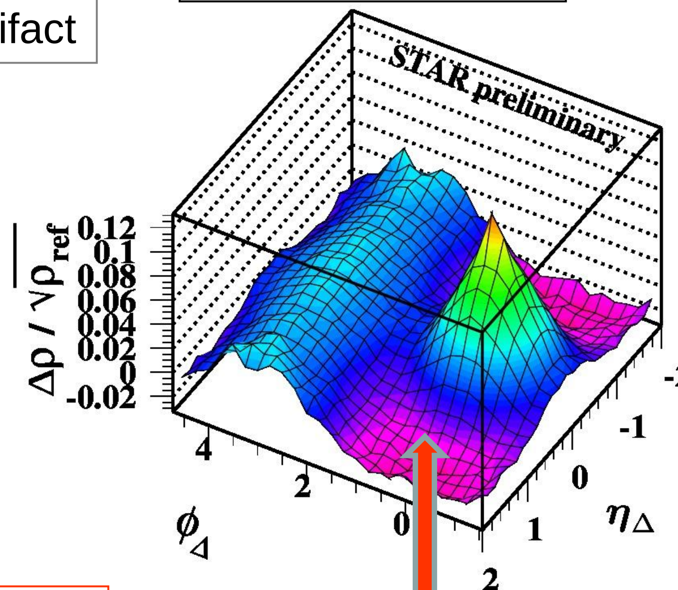


Comparison of theoretical results with STAR data

pT < 0.5 GeV/c



pT> 0.5 GeV/c

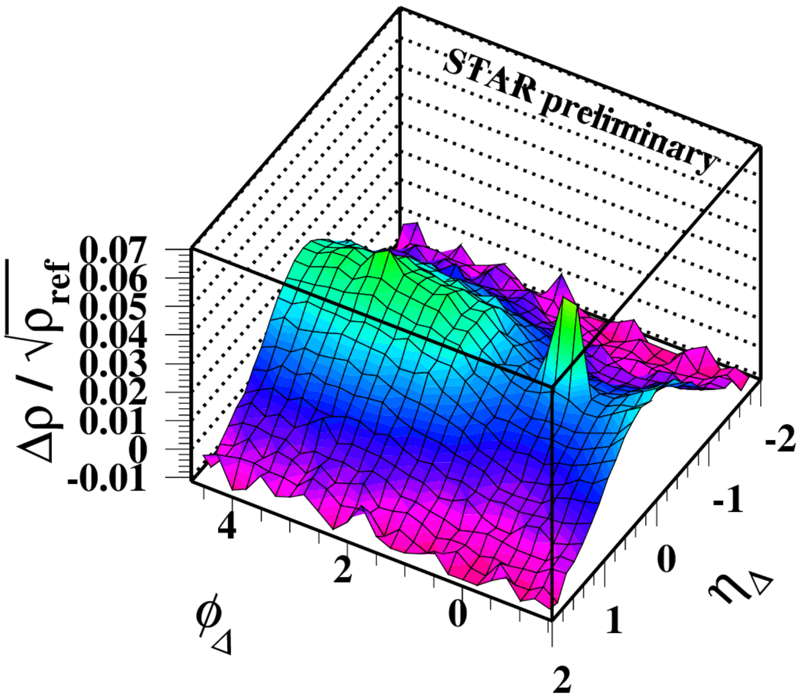


This is flux tube fragmentation.

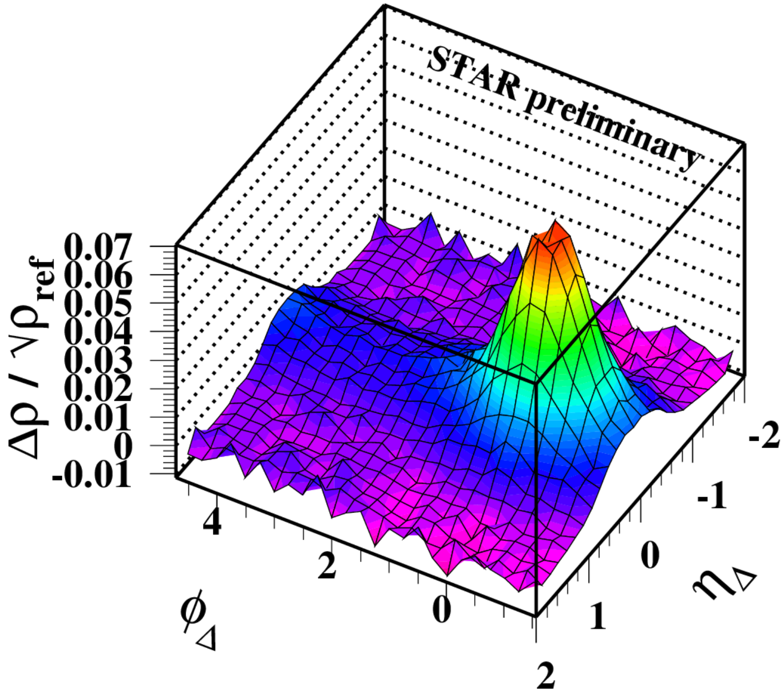
This is hard scattering

The boundary between flux tube fragmentation and hard-scattering at $\sqrt{s_{pp}}$=200 GeV is p_{Tb}~0.5 GeV/c.

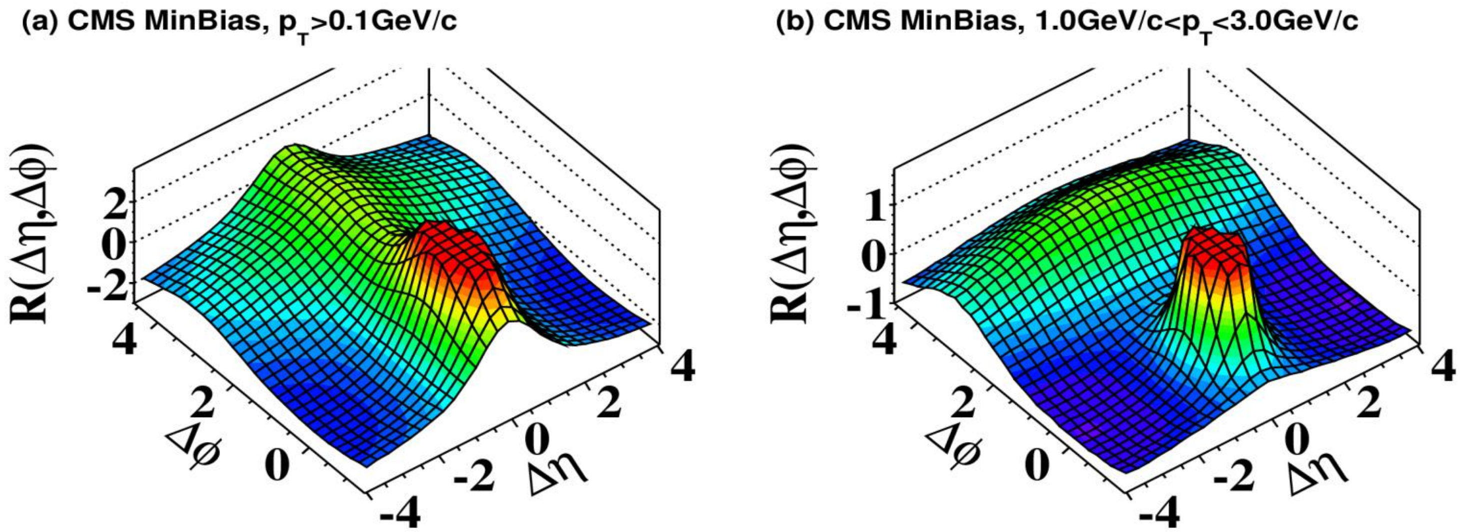
STAR data at $\sqrt{s_{pp}}$=200 GeV for $p_T < 0.5$ GeV/c



unlike charge hadrons



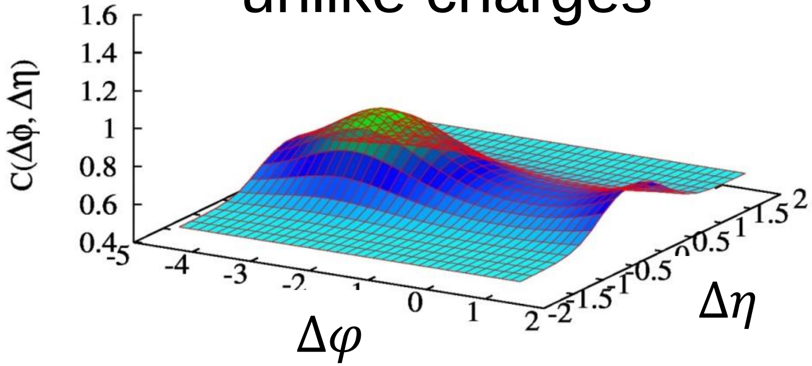
like charge hadrons



1. For pT > 0.1 GeV/c, the production mechanism is a combination of flux tube fragmentation and hard scattering

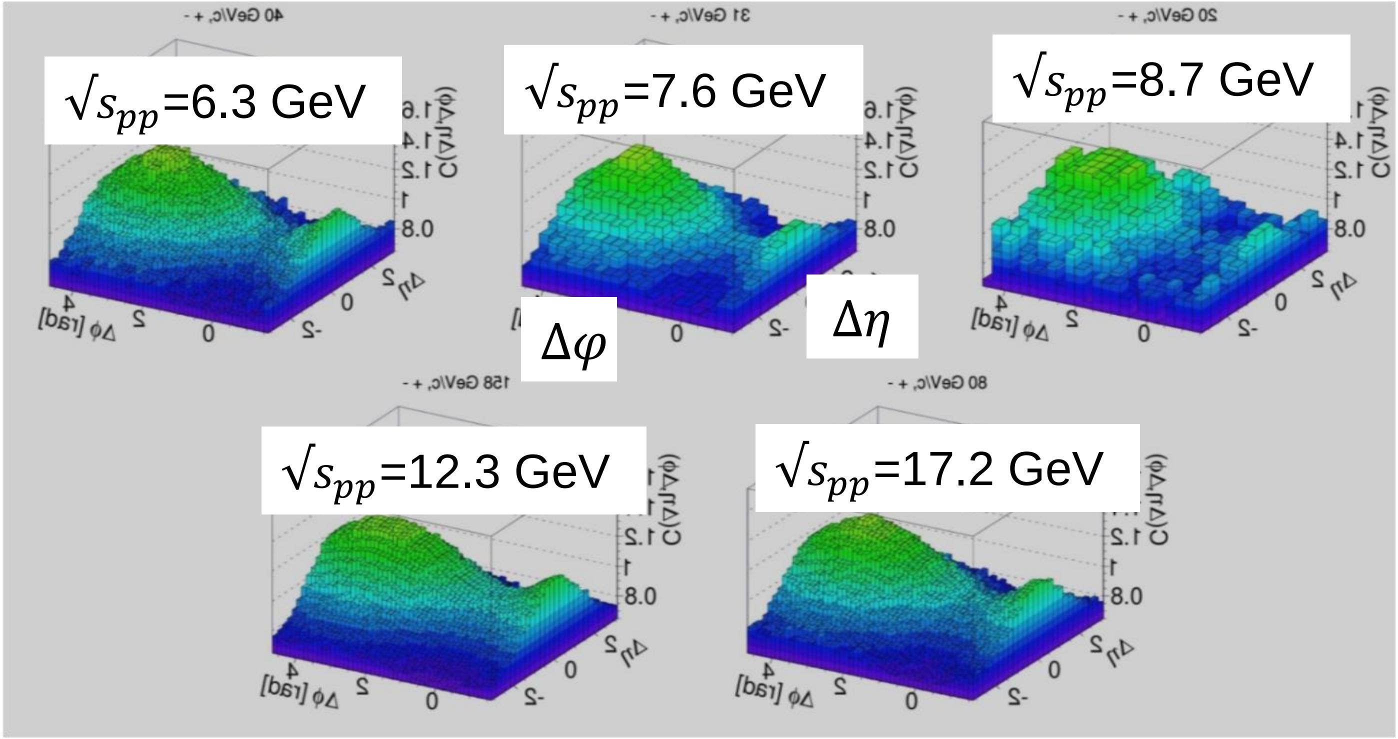
2. For pT > 1GeV, production mechanism is predominantly hard scattering

Flux tube fragmentation unlike charges

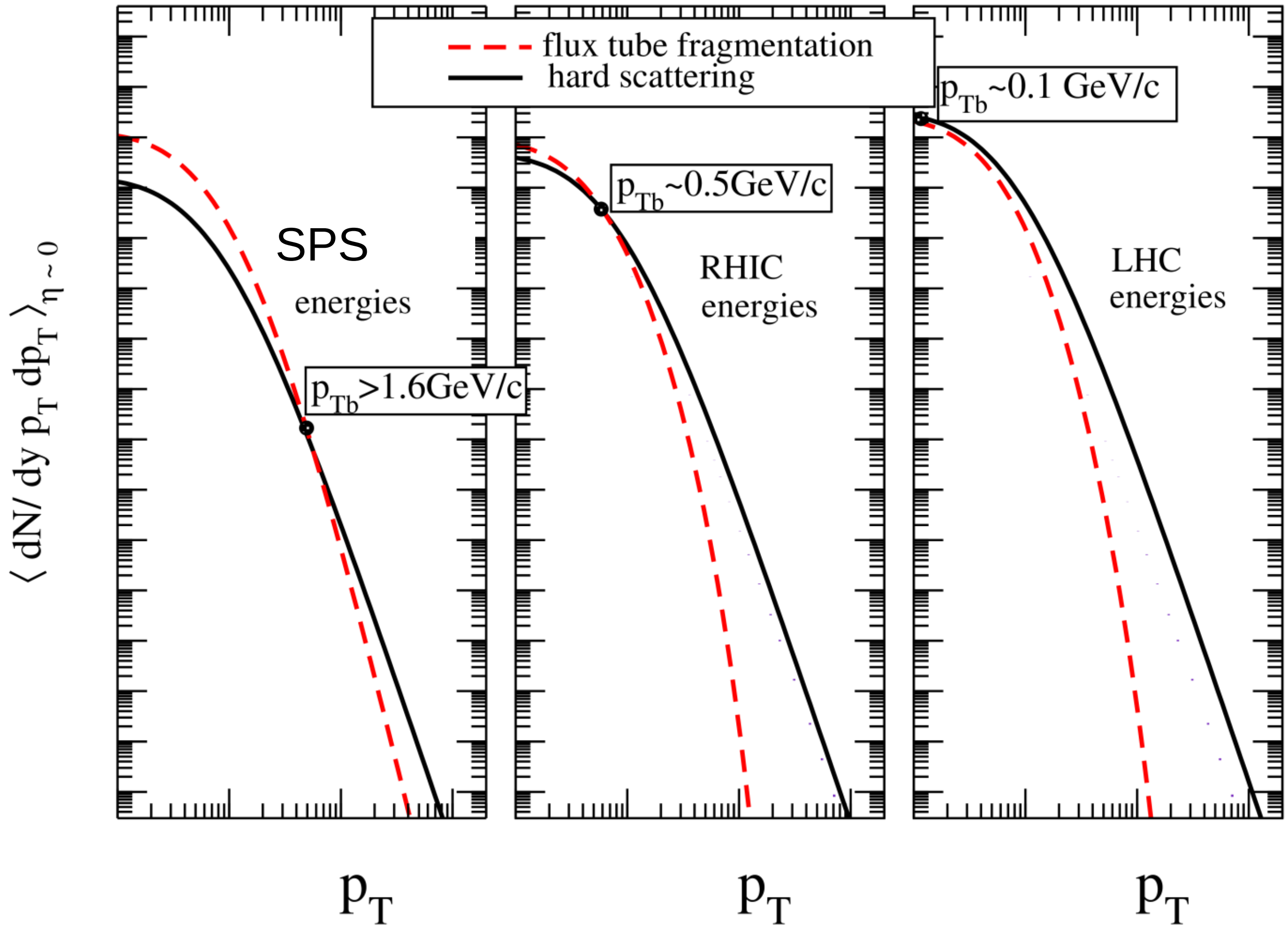


Comparison of theoretical results with NA61/SHINE data

NA61/SHINE pp data for two unlike charges



Schematic illustration:



As the collision energy increases, the cross-over boundary p_{Tb} moves to lower values of p_T.

Conclusions

- The occurrence of a chain of ordered and correlated hadrons provides a signature of flux tube fragmentation. This signature is yet to be observed.

- Two-hadron angular correlations in the charge and strangeness sectors provide other signatures of flux tube fragmentation.

- Two-hadron correlation data reveal that flux tube fragmentation dominates the low p_T, low $\sqrt{s_{pp}}$ region whereas hard scattering dominates the high p_T, high $\sqrt{s_{pp}}$ region.

- The cross over boundary between flux tube fragmentation and hard scattering moves to a lower p_T as collision energy increases. At LHC energies, hard scattering dominates over a very extensive region of p_T.