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The Fragmentation of a Color Flux Tube

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1. The many processes of particle production
2. Dynamical scenario of flux tube fragmentation
3. Space-time-rapidity ordering of produced particle
4. The signature of flux tube fragmentation signature
   (i) local production of $q\bar{q}$ pairs
   (ii) local conservation laws lead to various correlations of quantities between adjacent pions
   (iii) adjacent pions are signaled by proximity in rapidities

Chapter 7, CYWong,"Intrduction to High-energy Heavy-Ion Collisions"
C.Y.Wong, arxiv:1505.07817(2015)

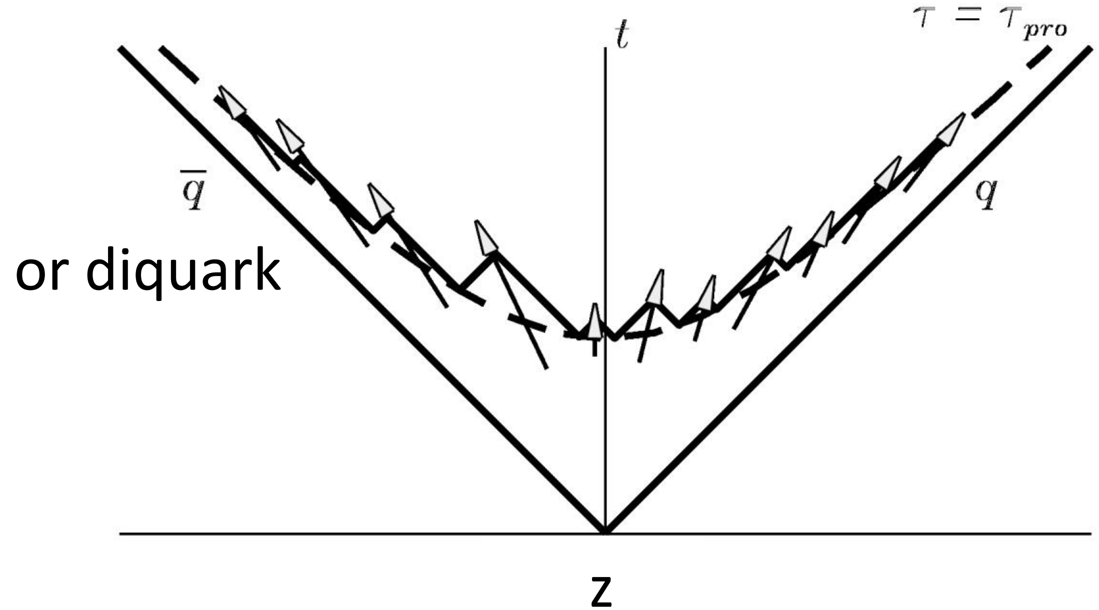
Why search for the signature of flux tube fragmentation

Particle production at high energies processes:

1. Flux-tube fragmentaion
2. Direct fragmentation
3. Hard-scattering

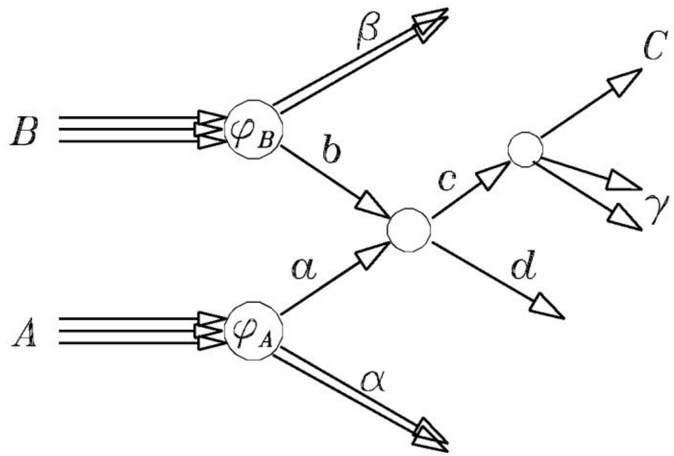
At central rapidity, direct fragmentation is unimportant, and there are only two production processes.

Flux tube fragmentation



- In an e+e- annihilation at high energies, a flux tube is formed between the produced q-q̄ pair.
- In a nucleon-nucleon collision, two flux tubes are formed between a quark of one nucleon with the diquark of the other nucleon.
- As the quark pulls away from the q̄ (or diquark) at high energies, q-q̄ pairs are produced which subsequently combined together to form mesons.

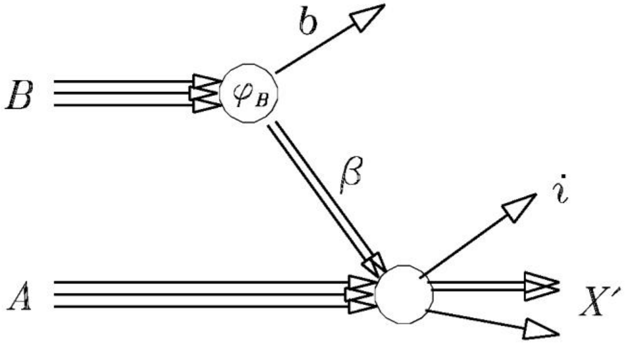
Hard scattering



Partons of one nucleon collide with partons of another particle to produce reaction products.

The hard scattering process gains importance as energy increases.

Direct fragmentation



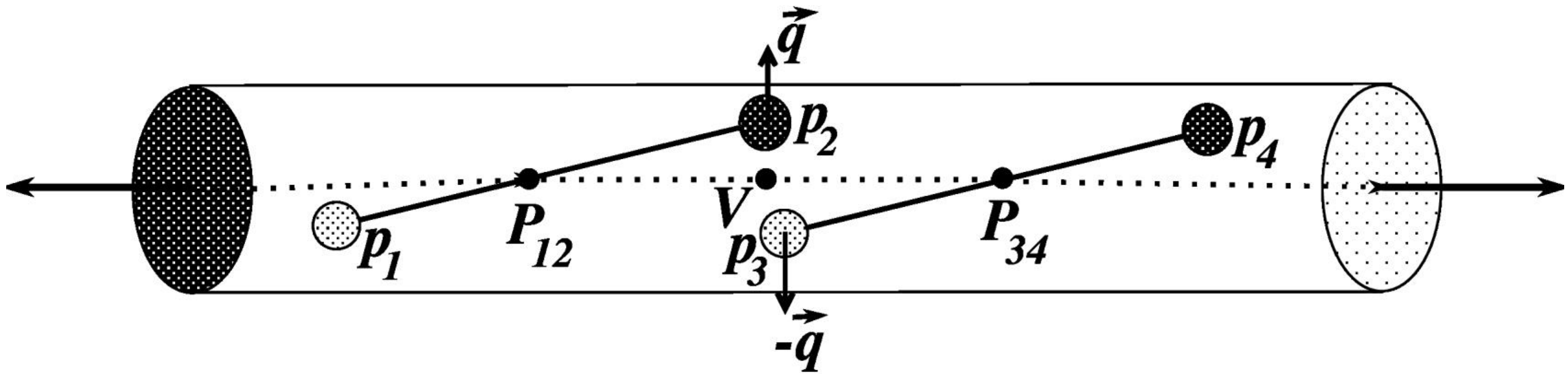
Wong&Blankenbecler,PRC22,2433(1980)

There is an intrinsic momentum distribution of partons.

Partons travel forward, when the other parts of the system suffers collisions.

Important at projectile-fragmentation and target fragmentation regions at forward and backward rapidities.

They may not be not important at mid-rapidities for low energy collisions but may become important at mid-rapidity at high energy collision.



$\vec{q}$
p_2
p_4
P_{12}
V
P_{34}
p_1
p_3
$-\vec{q}$

Degrees of freedom

$p_{1,} p_{2,} p_3, p_4$

Out of these degrees of freedom,

$p_{1,} p_{2,} \rightarrow P_{12}, p_{12}$

$\overbrace{P_{z12}, P_{T12}} \; \overbrace{p_{z12}, p_{T12}}$

Upon assuming a two-body longitudinal interaction,

the bound state problem in p_{z12} can be solved.

The remaining degrees of freedom are:

$P_{z12}, P_{T12}, p_{T12}$

or

y_{12}, P_{T12}, p_{T12}

The two-particle distribution depends on

$y_{12}, P_{T12}, p_{T12}, y_{34}, P_{T34}, p_{T34}$

$$dN = F(y_{12}, P_{T12}, p_{T12}, y_{34}, P_{T34}, p_{T34}) dy_{12}, dP_{T12} dp_{T12} dy_{34} dP_{T34} dp_{T34}$$

Two-Pion Distribution without correlations

Two pions produced far aprt are not correlated. Their two-pion distribution are

$$dN = dN_y dN_T$$

$$dN_y = C dy_{12} dy_{34}$$

$$dN_T = \frac{dp_{T1} dp_{T2} dp_{T3} dp_{T4}}{(\sqrt{2\pi}\sigma)^8} \exp\left\{ - \frac{p_{T1}^2 + p_{T2}^2 + p_{T3}^2 + p_{T4}^2}{2\sigma^2} \right\}$$

$$= \frac{dP_{T12} dP_{T34} dp_{T12} dp_{T34}}{(\sqrt{2\pi}\sigma)^8} \exp\left\{ - \frac{P_{T12}^2/2 + 2p_{T12}^2 + P_{T34}^2/2 + 2p_{T34}^2}{2\sigma^2} \right\}$$

where $P_{T12} = p_{T1} + p_{T2}$, $p_{T12} = p_{T1} - p_{T2}$

The p_{T12} and p_{T34} degrees of freedom can be intergrated out to give

$$dN_T = \frac{dP_{T12} dP_{T34}}{(\sqrt{2\pi}\sigma)^4} \exp\left\{ - \frac{P_{T12}^2/2 + P_{T34}^2/2}{2\sigma^2} \right\}$$

Adjacently produced pions are correlated

$$dN = dN_y dN_T$$

$$dN_T = d\vec{q}\,\frac{d\vec{p}_{T1}d\vec{p}_{T2}d\vec{p}_{T3}d\vec{p}_{T4}}{(\sqrt{2\pi}\sigma)^{10}}\exp\left\{-\frac{\vec{q}^{\,2}}{2\sigma^2}-\frac{\vec{p}_{T1}^{\,2}+(\vec{p}_{T2}-\vec{q})^2+(\vec{p}_{T3}+\vec{q})^2+\vec{p}_{T4}^{\,2}}{2\sigma^2}\right\}$$

$$= d\vec{q}\,\frac{d\vec{P}_{T12}d\vec{P}_{T34}d\vec{p}_{T12}d\vec{p}_{T34}}{(\sqrt{2\pi}\sigma)^{8}}\exp\left\{-\frac{\vec{q}^{\,2}}{2\sigma^2}-\frac{\frac{(\vec{P}_{T12}-\vec{q})^2}{2}+2(\vec{p}_{T12}+\frac{\vec{q}}{2})^2+\frac{(\vec{P}_{T34}+\vec{q})^2}{2}+2(\vec{p}_{T34}+\frac{\vec{q}}{2})^2}{2\sigma^2}\right\}$$

where $\vec{P}_{T12}=\vec{p}_{T1}+\vec{p}_{T2}$, $\vec{p}_{T12}=\vec{p}_{T1}-\vec{p}_{T2}$

For a fixed q, the p_{T12} and p_{T34} degrees of freedom can be intergrated out to give

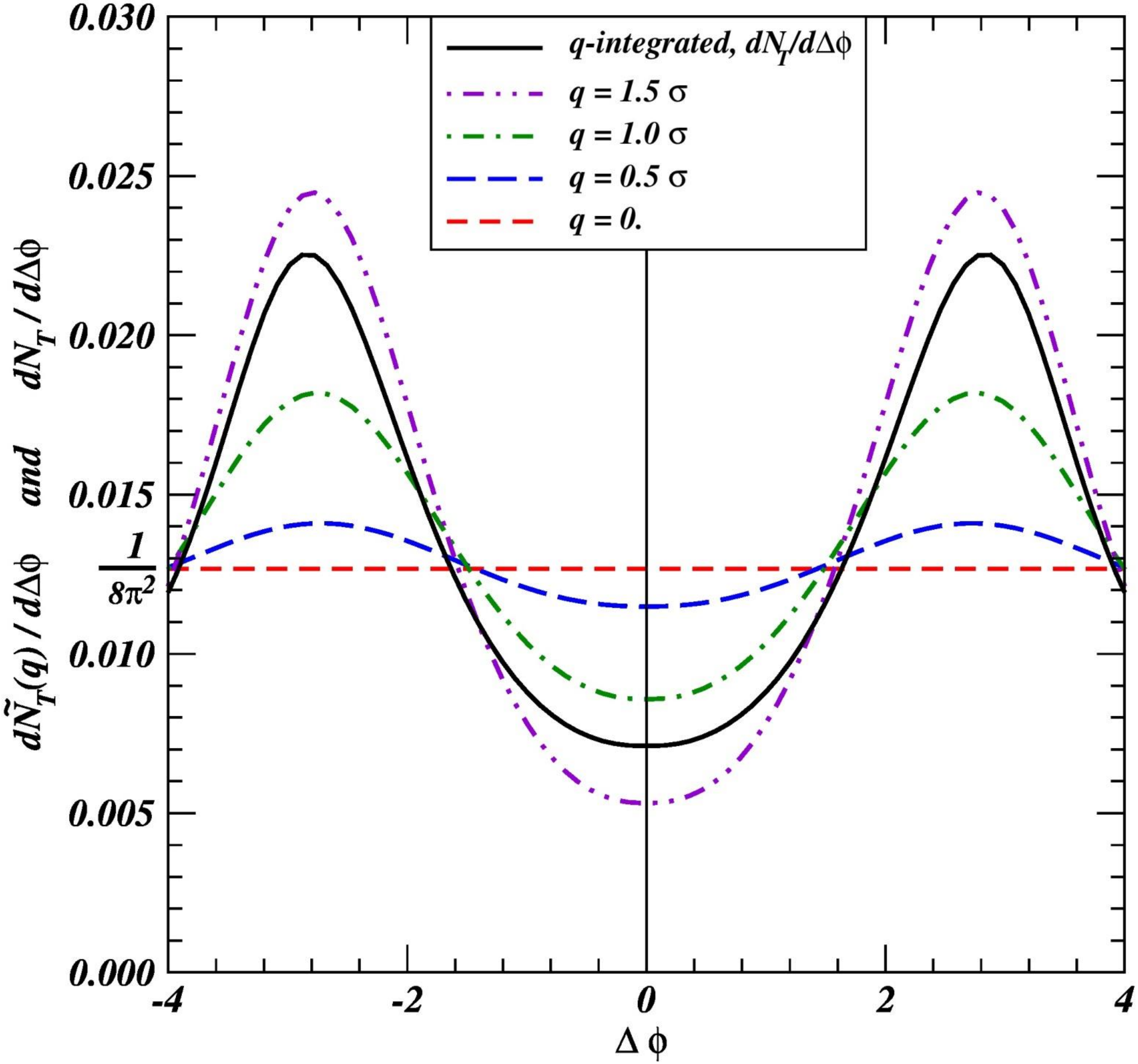
$$dN_T = d\vec{q}\,\frac{d\vec{P}_{T12}d\vec{P}_{T34}}{(\sqrt{2\pi}\sigma)^{4}}\exp\left\{-\frac{\vec{q}^{\,2}}{2\sigma^2}-\frac{\frac{(\vec{P}_{T12}-\vec{q})^2}{2}+\frac{(\vec{P}_{T34}+\vec{q})^2}{2}}{2\sigma^2}\right\}$$

$$\vec{P}_{T12}=(P_{T12},\phi_{12}),\quad \vec{P}_{T34}=(P_{T34},\phi_{34})$$

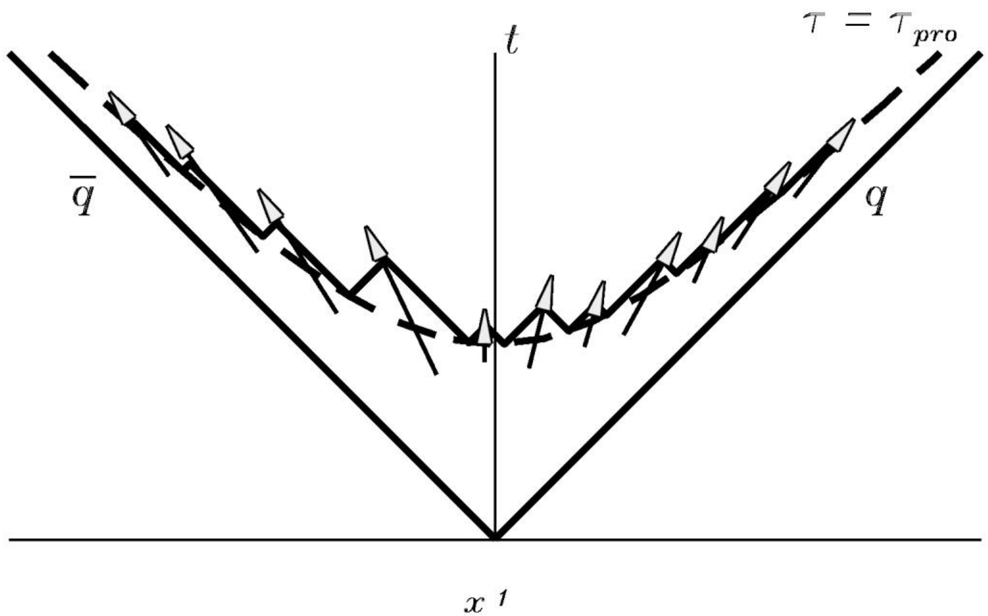
Introduce $\Delta\phi=\phi_{12}-\phi_{34}$, $\Sigma=\phi_{12}+\phi_{34}$

$$dN_T = d\vec{q}\,\frac{d\Delta\phi\, d\Sigma\, P_{T12}dP_{T12}P_{T34}dP_{T34}}{(\sqrt{2\pi}\sigma)^{4}}\exp\left\{-\frac{\vec{q}^{\,2}}{2\sigma^2}-\frac{\frac{(\vec{P}_{T12}-\vec{q})^2}{2}+\frac{(\vec{P}_{T34}+\vec{q})^2}{2}}{2\sigma^2}\right\}$$

$$\equiv d\vec{q}\,d\widetilde{N}_T(q)$$



q-integrated, dN_T/dΔφ
q = 1.5 σ
q = 1.0 σ
q = 0.5 σ
q = 0.
0.030
0.025
0.020
0.015
0.010
0.005
0.000
1/8π²
-4
-2
0
2
4
Δ φ
dÑ_T(q) / dΔφ and dN_T / dΔφ



$\tau = \tau_{pro}$
t
$\overline{q}$
q
x^1

Rapidity distribution

For pions produced along a proper time curve τ_{pro}

$$\frac{dN_\pi}{dy} = \frac{\kappa \tau_{\text{pro}}}{m_T}$$

Adjacently produced pions are signalled by

$$\frac{dN^{\text{A}}}{d\Delta y} = \frac{1}{1+\exp\{(|\Delta y|-w)/a\}}$$

Upon approximating y by η

$$\frac{dN^{\text{A}}}{d\Delta \eta} = \frac{1}{1+\exp\{(|\Delta \eta|-w)/a\}}$$

Combining with the transverse distribution, the two - pion distribution for adjacently produced pions are

$$\frac{dN^{\text{A}}}{d\Delta\phi \ d\Delta \eta} = \frac{1}{1+\exp\{(|\Delta \eta|-w)/a\}} \frac{1}{8\pi}(1-0.61\cos\Delta\phi)$$

In constrast, the two - pion distribution for distantly produced pions are

$$\frac{dN^{\text{D}}}{d\Delta\phi \ d\Delta \eta} = \frac{1}{1+\exp\{(w-|\Delta \eta|)/a\}} \frac{1}{8\pi}$$

$$\frac{dN^{\text{A}}}{d\Delta\phi \ d\Delta \eta} = P^A \frac{dN^{\text{A}}}{d\Delta\phi \ d\Delta \eta} + P^D \frac{dN^{\text{D}}}{d\Delta\phi \ d\Delta \eta}$$

Charge configuration of two adjacently produced pions

p_1	p_2	Q_{12}	p_3	p_4	Q_{34}
$\bar{u}$	u	0	$\bar{u}$	d	-1
$\bar{d}$	u	1	$\bar{u}$	d	-1
$\bar{u}$	u	0	$\bar{u}$	u	0
$\bar{d}$	u	1	$\bar{u}$	u	0
$\bar{u}$	d	-1	$\bar{d}$	d	0
$\bar{d}$	d	0	$\bar{d}$	d	0
$\bar{u}$	d	-1	$\bar{d}$	u	1
$\bar{d}$	d	0	$\bar{d}$	u	1

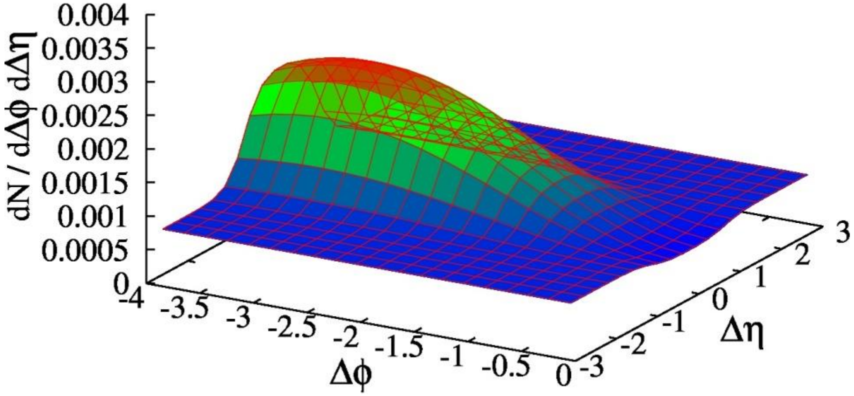
	Q_{34}=-1	$Q_{34} = 0$	Q_{34}=1
Q_{12}=-1	0	0.125	0.125
Q_{12}= 0	0.125	0.250	0.125
Q_{12}=+1	0.125	0.125	0

Charge configuration of two distantly produced pions

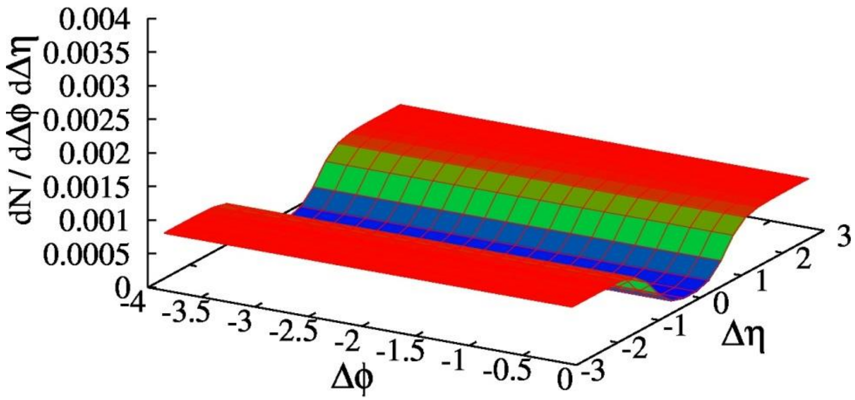
p_1	p_2	Q_{12}	p_3	p_4	Q_{34}
$\bar{u}$	u	0	$\bar{u}$	d	-1
$\bar{d}$	u	1	$\bar{u}$	d	-1
$\bar{u}$	u	0	$\bar{u}$	u	0
$\bar{d}$	u	1	$\bar{u}$	u	0
$\bar{u}$	d	-1	$\bar{d}$	d	0
$\bar{d}$	d	0	$\bar{d}$	d	0
$\bar{u}$	d	-1	$\bar{d}$	u	1
$\bar{d}$	d	0	$\bar{d}$	u	1
$\bar{u}$	u	0	$\bar{d}$	d	0
$\bar{d}$	u	1	$\bar{d}$	d	0
$\bar{u}$	u	0	$\bar{d}$	u	1
$\bar{d}$	u	1	$\bar{d}$	u	1
$\bar{u}$	d	-1	$\bar{u}$	d	-1
$\bar{d}$	d	0	$\bar{u}$	d	-1
$\bar{u}$	d	-1	$\bar{u}$	u	0
$\bar{d}$	d	0	$\bar{u}$	u	0

	Q_{34}=-1	$Q_{34}=0$	Q_{34}=1
Q_{12}=-1	0.0625	0.125	0.0625
Q_{12}= 0	0.125	0.250	0.125
Q_{12}=+1	0.0625	0.125	0.0625

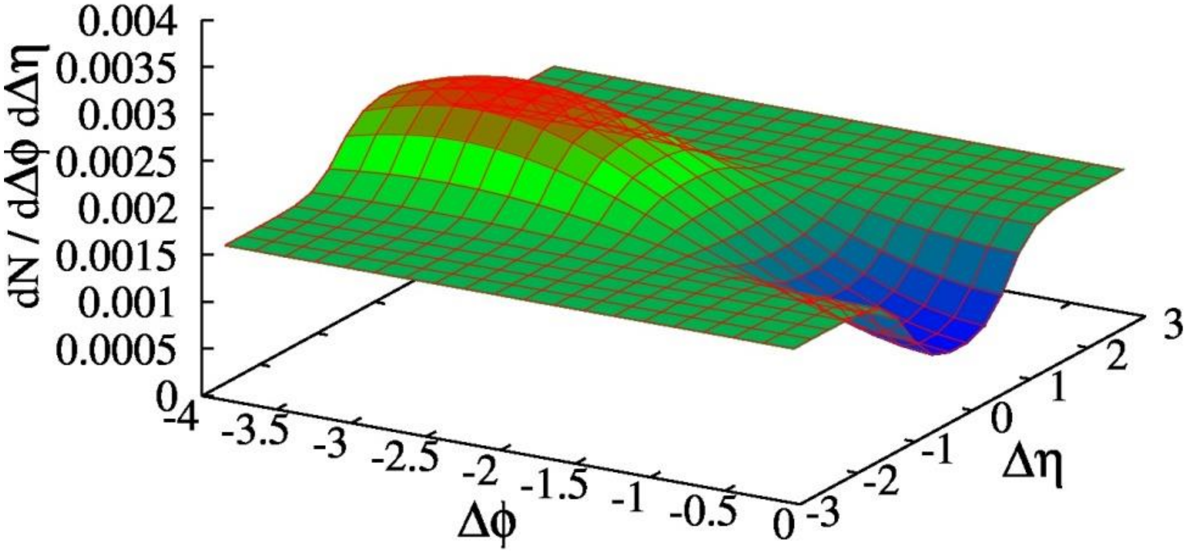
Correlation of two unlike charged particles in a flux tube fragmentation



Correlation of like charged particles in a flux tube fragmentation



Correlation of two charged particles in a flux tube fragmentation



Conclusions

- Quark-antiquark pairs are produced prior to flux tube fragmentation
- Local Conservation laws lead to correlation of adjacent mesons
- Adjacent mesons are signaled by their proximity in rapidity because of space-time-rapidity ordering
- Two-particle angular can be used as signature for Flux-tube fragmenation for pp collisions