# Initial Conditions in High-Energy pp Collisions

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1. Introduction
2. Production mechanism as inferred from experimental pp data.
3. The hard-scattering process dominates the particle production process over a large $p_T$-domain (from about 0.5 to 200 GeV/c) in pp collisions at LHC
4. The initial conditions in pp collisions at LHC energies
5. Conclusions

# Introduction (I)

How are medium partons produced at the earliest time before equilibrium?

What are their properties in y and $p_T$?

Near-side ridge can be used to probe the momentum distribution of the initial momentum distribution of the mdium at the moment of parton-medium collision.

C.Y.Wong, ChinesePhys.Lett.25,3936(2008)
C.Y.Wng,Phy. Rev.C76,054908(2007)

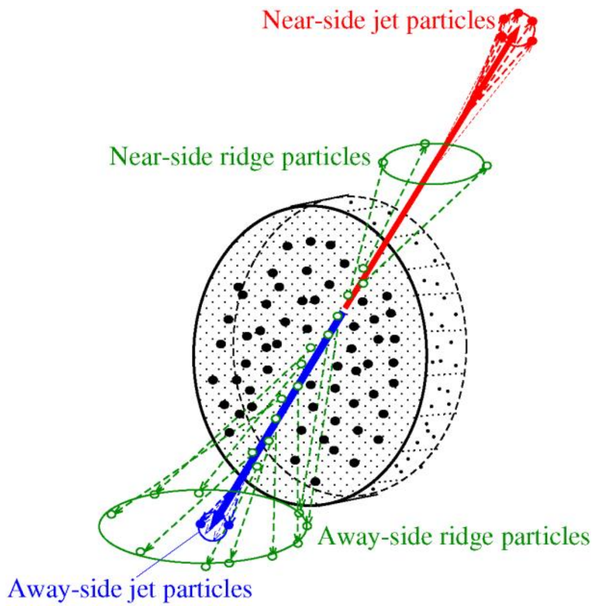
# Introduction (II)

The jet-medium collisions do occurs.   They lead to jet quenching.

The jet-medium collision contributes to the ridge and $v_n$.

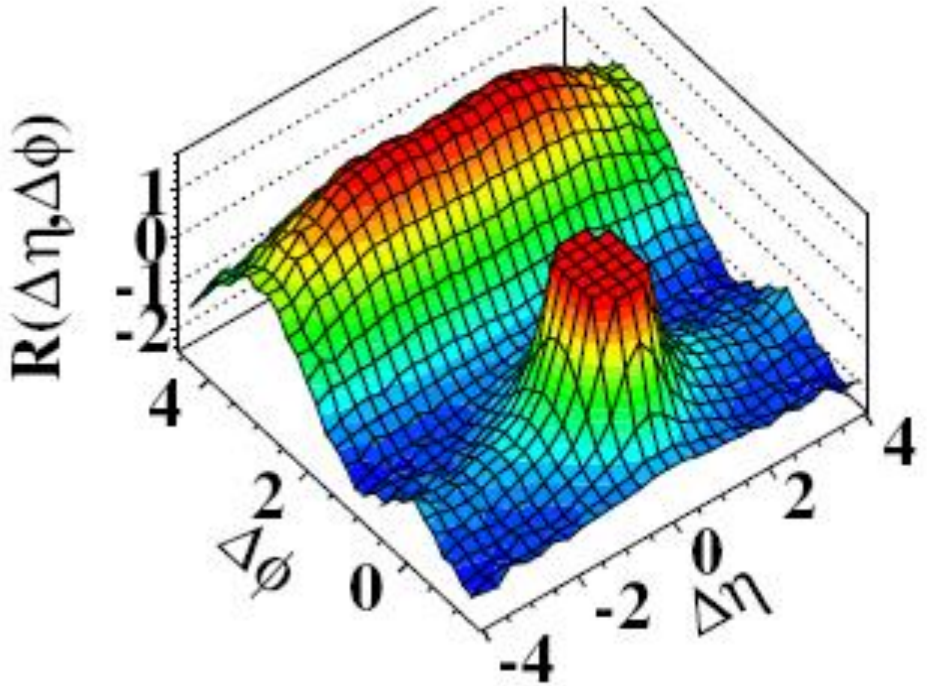
The contribution must be subtracted to extract the collective flow behavior.

It is necessary to study the jet-medium collision.



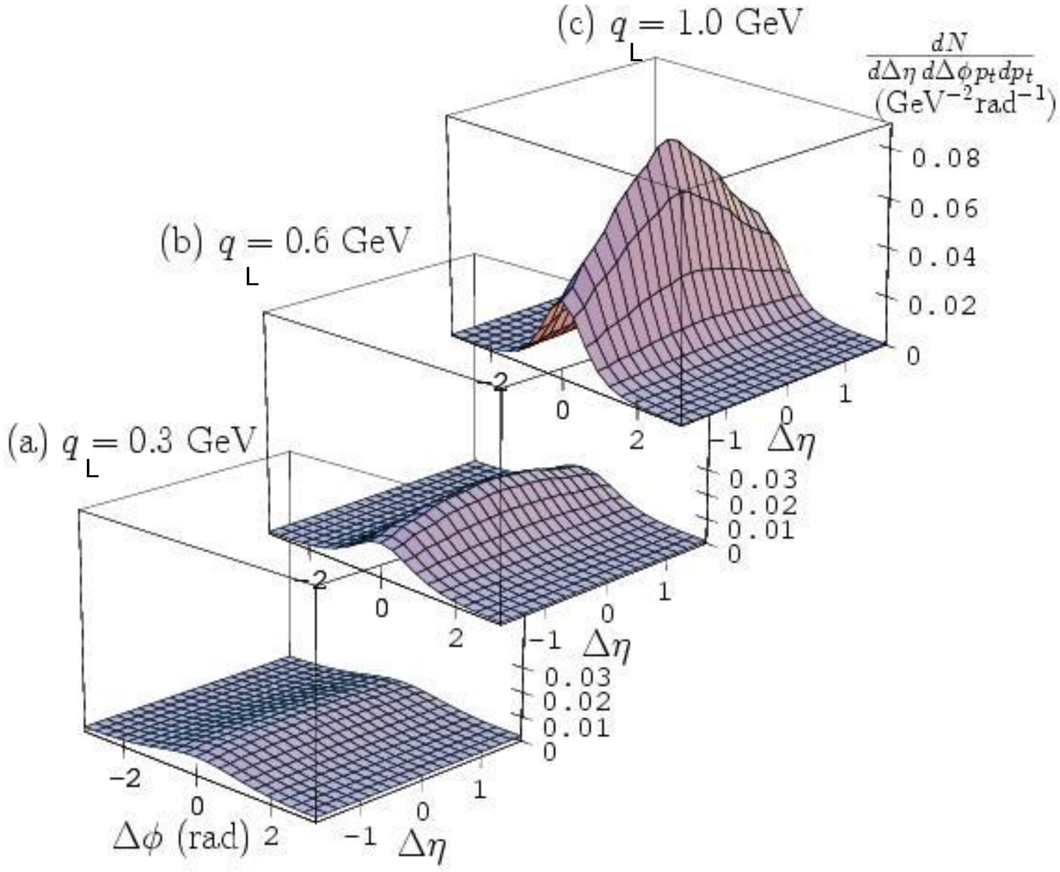

CYWong,Chin.Phys.Lett.25,3936(2008)
CYWong,Phys.Rev.C76,054908(2007)
CYWong,Phys.Rev.C78,064905(2011)
CYWong,Phys.Rev.C84,024981(2011))

**CMS pp 7 TeV data**
**N>110, 1 GeV/c < pT< 3 GeV/c**




Previous investigations indicated that the contribution from jet-medium collision to the near-side ridge can be quite large.

# Jet-medium collisions contribute to the near-side ridge



# Central questions:

1. How are these medium partons produced?

2. What is the origin of the rapidity plateau distribution of the medium partons, *at the moment of jet-medium collision*?

# Central questions (contd):

So, we seeks answers to these central questions from

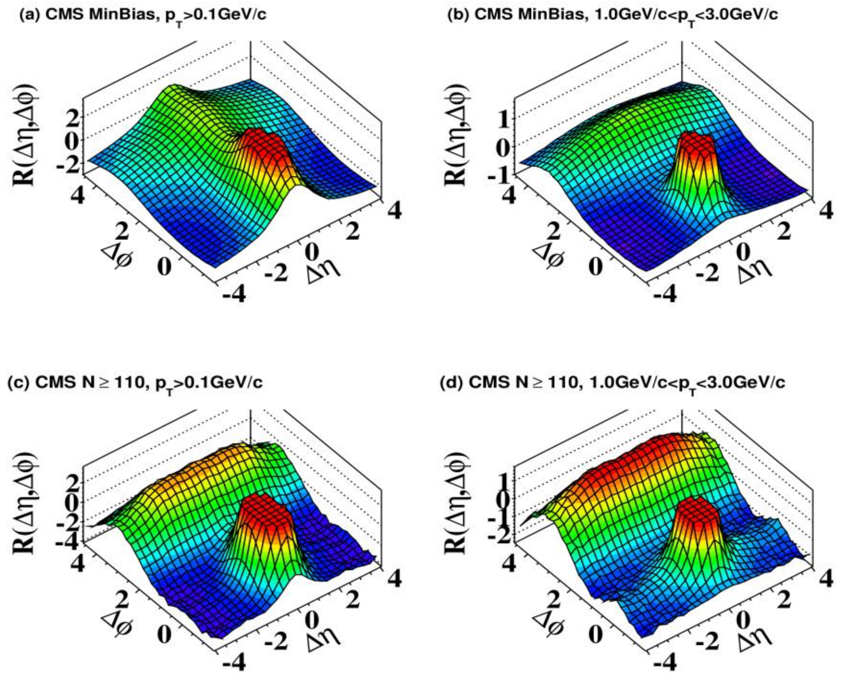
(i) two-hadron correlation data in pp collisions

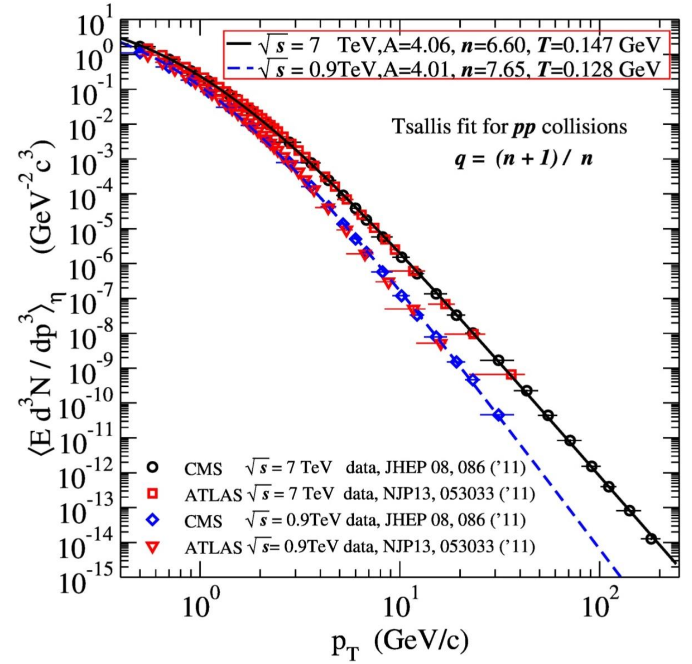
(ii) jet and hadron $p_T$ spectra in pp collisions

(iii) the hard scattering model

(iv) flux tube fragmentation model


- 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)
- C.Y.Wong, *Signature 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:1510.07194v2 (2015)




The above and related data show:

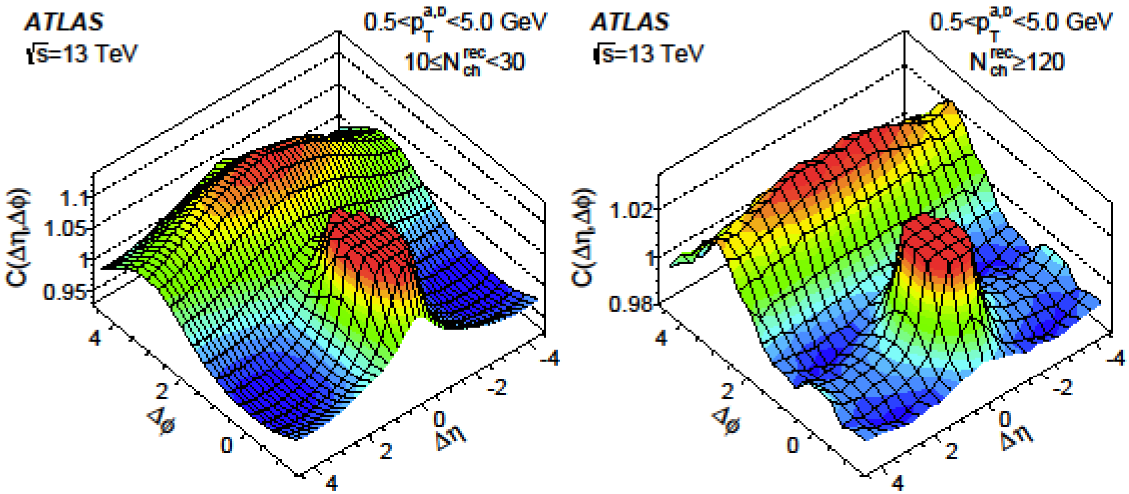
1. For 0.1 < pT < 1GeV, the production mechanism is a combination of flux tube fragmentation and hard scattering
2. For pT > 1GeV, production mechanism is predominantly hard scattering

This implies the dominance of hard-scattering over a large pT domain. The dominance of hard scattering is further supported by the analysis of jet & hadron pT spectra.

3 No near-side ridge for 0.1<pT<1GeV for high multiplicity event

4 Near-side ridge for pT>1GeV for high multiplicity event in pp collisions

This implies that near-side ridge is associated with hard-scattering

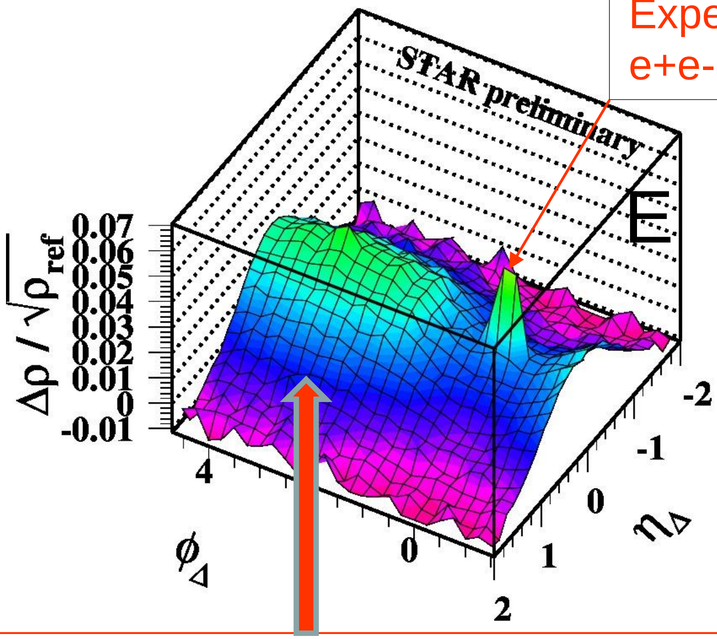

ATLAS
√s=13 TeV
0.5<p_T^{a,b}<5.0 GeV
10≤N_ch^rec<30
C(Δη,Δϕ)
Δϕ
Δη
ATLAS
√s=13 TeV
0.5<p_T^{a,b}<5.0 GeV
N_ch^rec≥120
C(Δη,Δϕ)
Δϕ
Δη

# Flux tube fragmentation and hard scattering can be distinguished by two-hadron angular correlations

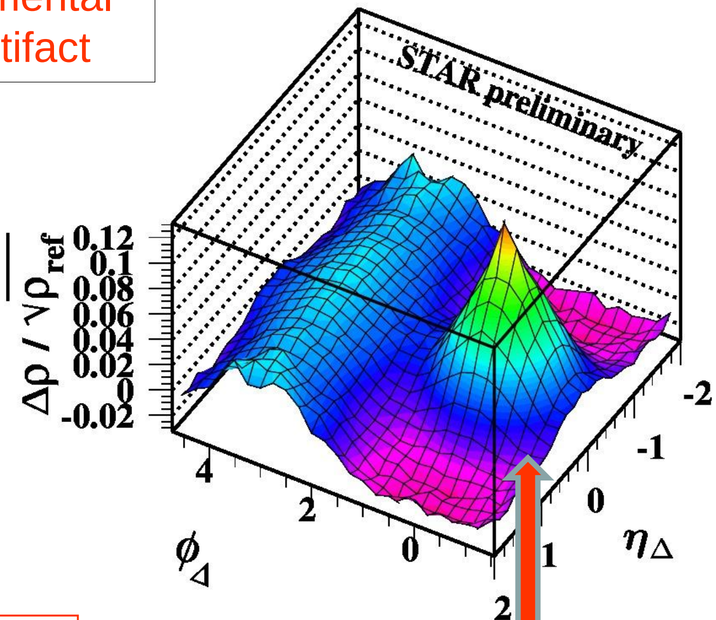
## STAR pp data @ $\sqrt{s}$=200 GeV
## for two hadrons with unlike charges

pT < 0.5 GeV/c

Experimental
e+e- artifact




pT> 0.5 GeV/c

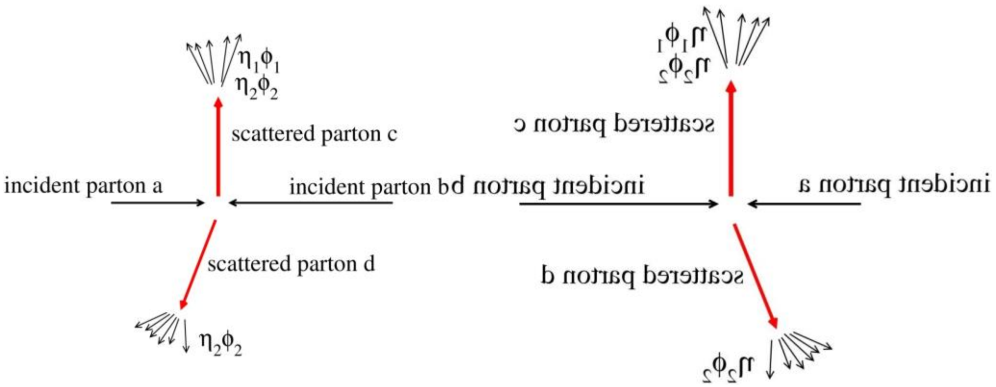


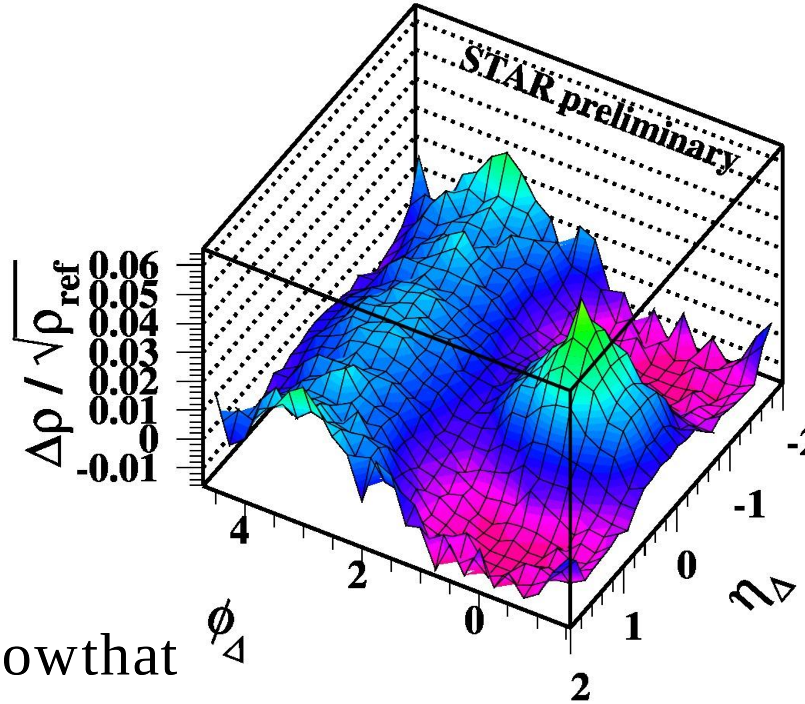

This is flux tube fragmentation

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

# Two-hadron angular correlation signature for hard scattering

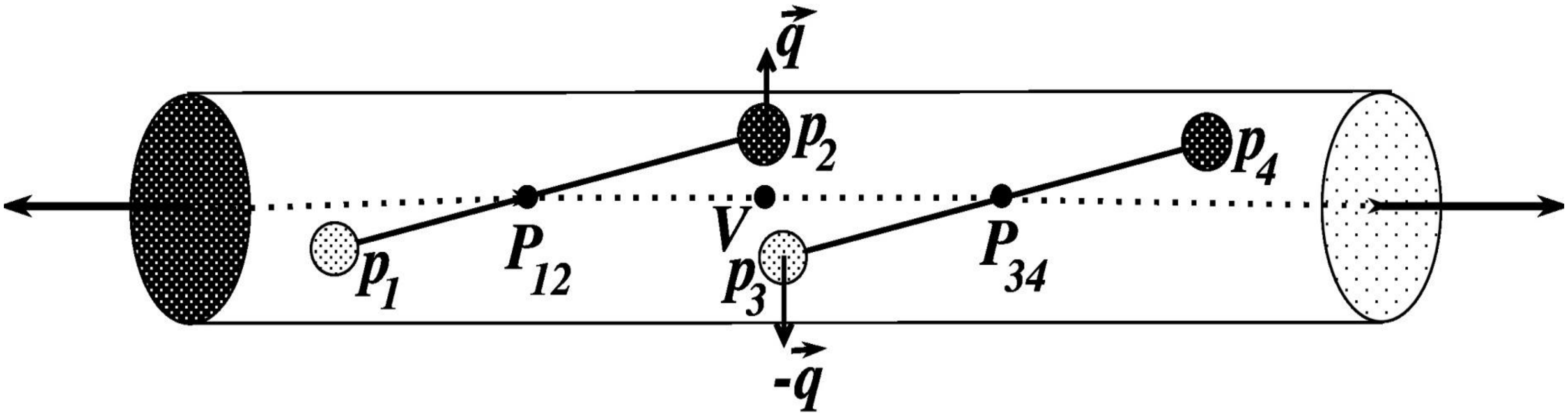



From the hard-scattering model, one can show that when we trigger a jet at $y_1=0$ and $\varphi_1=0$, the distribution of the associated particle at $y_2=\Delta y$ and $\varphi_2=\Delta\varphi$ is

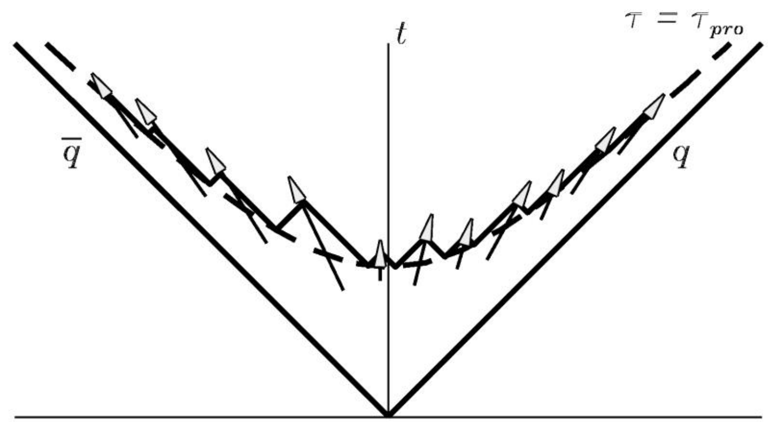
$$\frac{dN}{d\Delta y\, \mathrm{d}\Delta\phi} \propto \frac{\left(\sqrt{s}\right)^{1/2}}{\sigma_{in}} \left(1-\frac{2\sqrt{m^2+p_T^2}}{\sqrt{s}}\cosh\Delta y\right)^g D(\Delta\phi-\pi)$$

where $D(\Delta\phi-\pi)$ peaks sharply at $\Delta\phi-\pi=0$



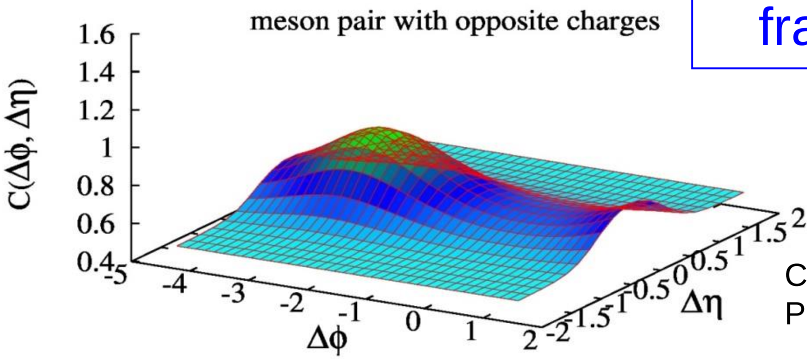

- On the average, adjacent mesons are azimuthally back-to-back correlated because of momentum conservation .
- Adjacent mesons are indicated by their proximity in rapidity because of rapidity-space-time ordering.

- Consequently, dN/dΔηdΔφ for two adjacent hadrons are suppressed at Δφ~0, enhanced at Δφ~π, within a small window of Δη~0




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

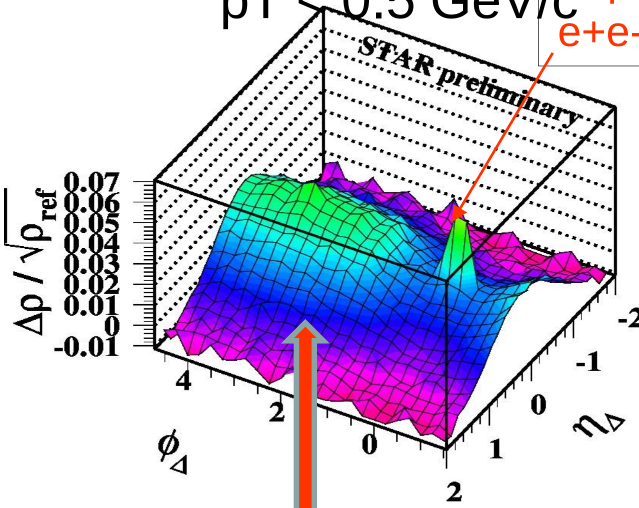
Theoretical signature for flux tube fragmentation for unlike charges



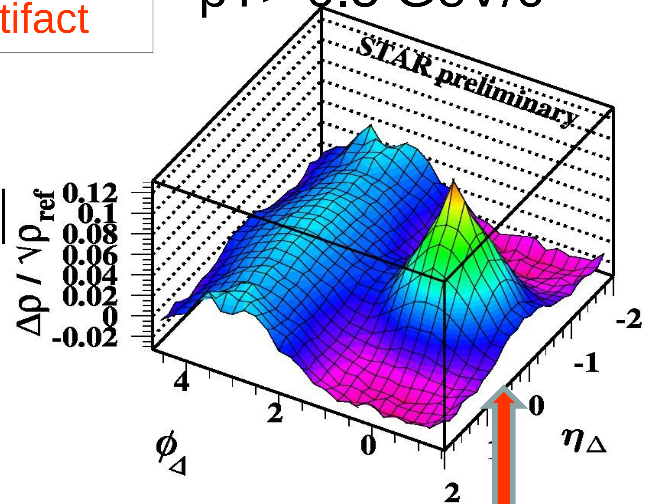

C.Y.Wong, *Signature of the fragmentation of a color flux tube,* Phys. Rev. D 92, 074007 (2015)

pT < 0.5 GeV/c

Experimental e+e- artifact



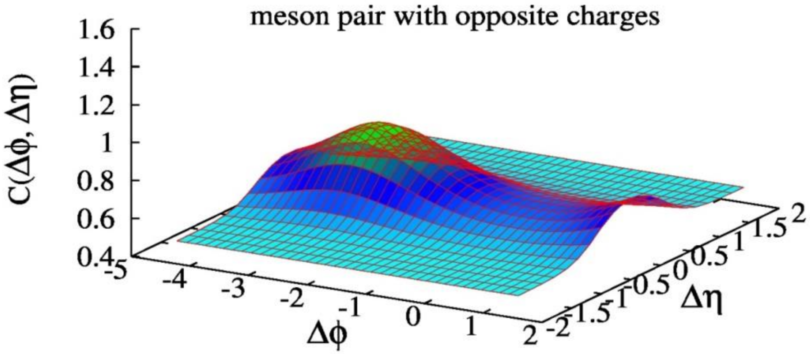

pT> 0.5 GeV/c



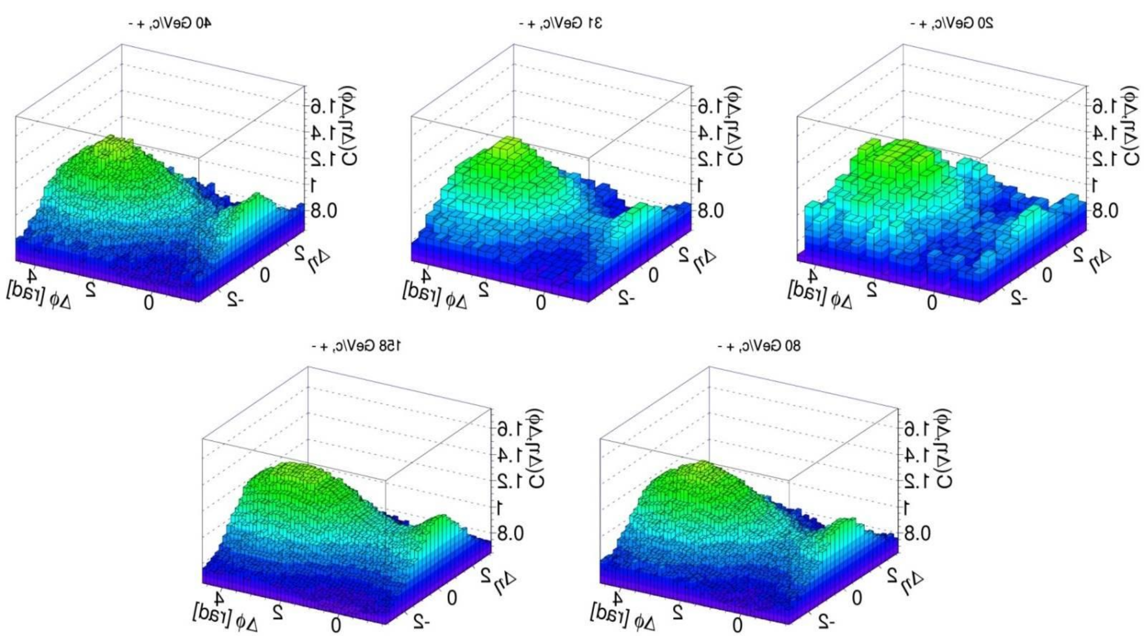

This is flux tube fragmentation

This is hard scattering

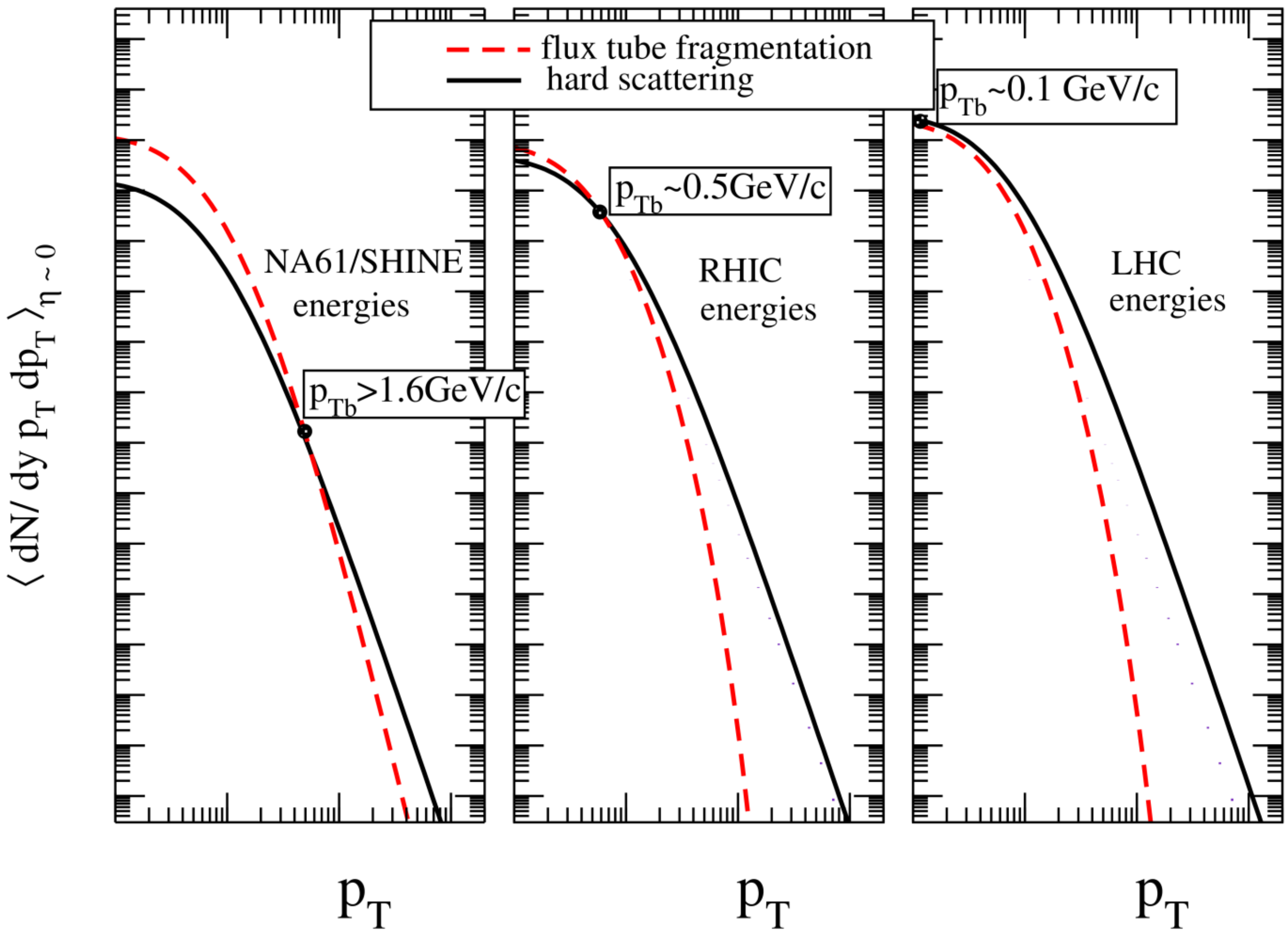
Theoretical shape




NA61/SHINE data indicate dominance of flux tube fragmentation at $\sqrt{s_{pp}}$ from 6.3 to 17.3 GeV, and pT<1.6 GeV/c



Schematic illustration:




As a function of increasing collision energy, the boundary $p_{Tb}$ moves to lower and lower $p_T$.

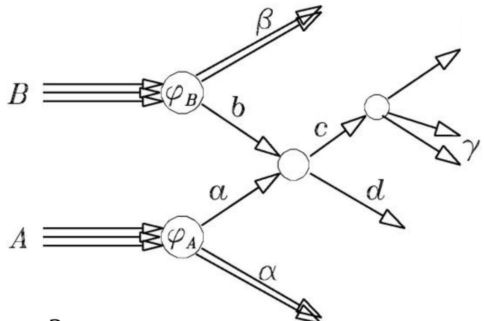
# Relativistic Hard-Scattering Model

$$E_p \frac{d\sigma(AB \to cX)}{d^3p} = \sum_{ab} \int dx_a dx_b G_{a/A}(x_a) G_{b/B}(x_b)\, E_c \frac{d\sigma(ab \to cd)}{d^3p}$$

The basic differential cross section is

$$E_c \frac{d\sigma(ab \to cd)}{d^3p} = \frac{\hat{s}}{\pi} \frac{d\sigma(ab \to cd)}{d\hat{t}} \delta(\hat{s} + \hat{t} + \hat{u}).$$

p




$$a = (x_a \frac{\sqrt{s}}{2}, \vec{O}_T, x_a \frac{\sqrt{s}}{2})$$

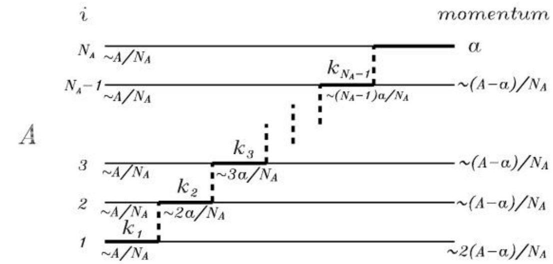
$$b = (x_b \frac{\sqrt{s}}{2}, \vec{O}_T, -x_b \frac{\sqrt{s}}{2})$$

$$c = (x_c \frac{\sqrt{s}}{2} + \frac{c_T^2}{2x_c\sqrt{s}},\ \vec{c}_T,\ \ x_c \frac{\sqrt{s}}{2} - \frac{c_T^2}{2x_c\sqrt{s}})$$

The delta function can be used to integrate $dx_a$ and we get

$$E_p \frac{d\sigma(AB \to cX)}{d^3p} = \sum_{ab} \int dx_b \frac{x_a G_{a/A}(x_a) x_b G_{b/B}(x_b)}{\pi(x_b - c_T^2 / x_c s)} \frac{d\sigma(ab \to cd)}{d\hat{t}}$$

# Relativistic Hard-Scattering Model




We assume

$$x_a G_{a/A}(x_a) = A_a (1 - x_a)^g ,$$

We use saddle-point integration method to get

$$\int dx_b \, e^{f(x_b)} g(x_b) = \int dx_b \, e^{f(x_{b0}) + f''(x_{bo})(x_b - x_{b0})^2/2} g(x_b)$$

$$\approx e^{f(x_{b0})} g(x_{b0}) \sqrt{\frac{2\pi}{-\partial^2 f(x_b)/dx_b^2 |_{x_b = x_{b0}}}}$$

We then obtain for $\eta = 0$

$$E_p \frac{d\sigma(AB \to cX)}{d^3 c} = \sum_{ab} A_a A_b \frac{(1 - x_{a0})^{g + \frac{1}{2}} (1 - x_{b0})^{g + \frac{1}{2}}}{\sqrt{\pi g} \sqrt{x_c (1 - x_c)}} \frac{d\sigma(ab \to cd)}{d\hat{t}}$$

where $\quad x_c = \dfrac{c_T}{\sqrt{s}}, \qquad x_{a0} = x_{b0} = 2x_c = \dfrac{2c_T}{\sqrt{s}}$

For production of parton $c$ at $(y, c_T)$ in a $pp$ collsion is

$$E_c \frac{d\sigma_{HS}(pp \to cX)}{d^3c} \propto \frac{(1-x_{a0}(y,c_T))^{g+\frac{1}{2}}(1-x_{b0}(y,c_T))^{g+\frac{1}{2}}}{(m_{cT}/\sqrt{s})^{1/2}} \frac{\alpha_s^2(c_T)}{t^2}$$

$$\frac{dN_{HS}(pp \to cX)}{dy\, c_T dc_T} \propto \frac{(\sqrt{s})^{1/2}}{\sigma_{in}} \frac{(1-x_{a0}(y,c_T))^{g+\frac{1}{2}}(1-x_{b0}(y,c_T))^{g+\frac{1}{2}}}{m_{cT}^{1/2}} \frac{\alpha_s^2(c_T)}{t^2}$$

where

$$x_{a0}(y,c_T) = x_{cT}e^{y} + x_{cT}\sqrt{\frac{1-x_{cT}e^{y}}{1-x_{cT}e^{-y}}}$$

$$x_{b0}(y,c_T) = x_{cT}e^{-y} + x_{cT}\sqrt{\frac{1-x_{cT}e^{-y}}{1-x_{cT}e^{y}}}$$

$$x_{cT} = \frac{m_{cT}}{\sqrt{s}} = \frac{\sqrt{m^2+c_T^2}}{\sqrt{s}}$$

$$t^2 = m_{cT}^4\left(1+e^{-y}\sqrt{\frac{1-x_{cT}e^{y}}{1-x_{cT}e^{-y}}}\right)^2$$

The distribution $\frac{dN_{HS}(pp \to cX)}{dy\, c_T dc_T}$ for produced partons has a rapidity plateau structure in $y$.

The (s) ¼ factor leads to hard-scattering dominance at high energies.
The $(1-x_{a0})^g$ $(1-x_{b0})^g$ actor leads to a rapidity plateau of produced partons in hard scattering.
The $1/m_{cT}^{4.5}$ gives the power index of the pT dependence.

# Dominance of hard scattering shows up also in jet and hadron pT spectra

1. Reduction in the number of degrees of freedom to describe the jet and hadron pT spectra
2. The power index n, in $Ed\sigma/d^3p \sim 1/p_T^n$ , for jet should be n ~ 4.5, down to relatively

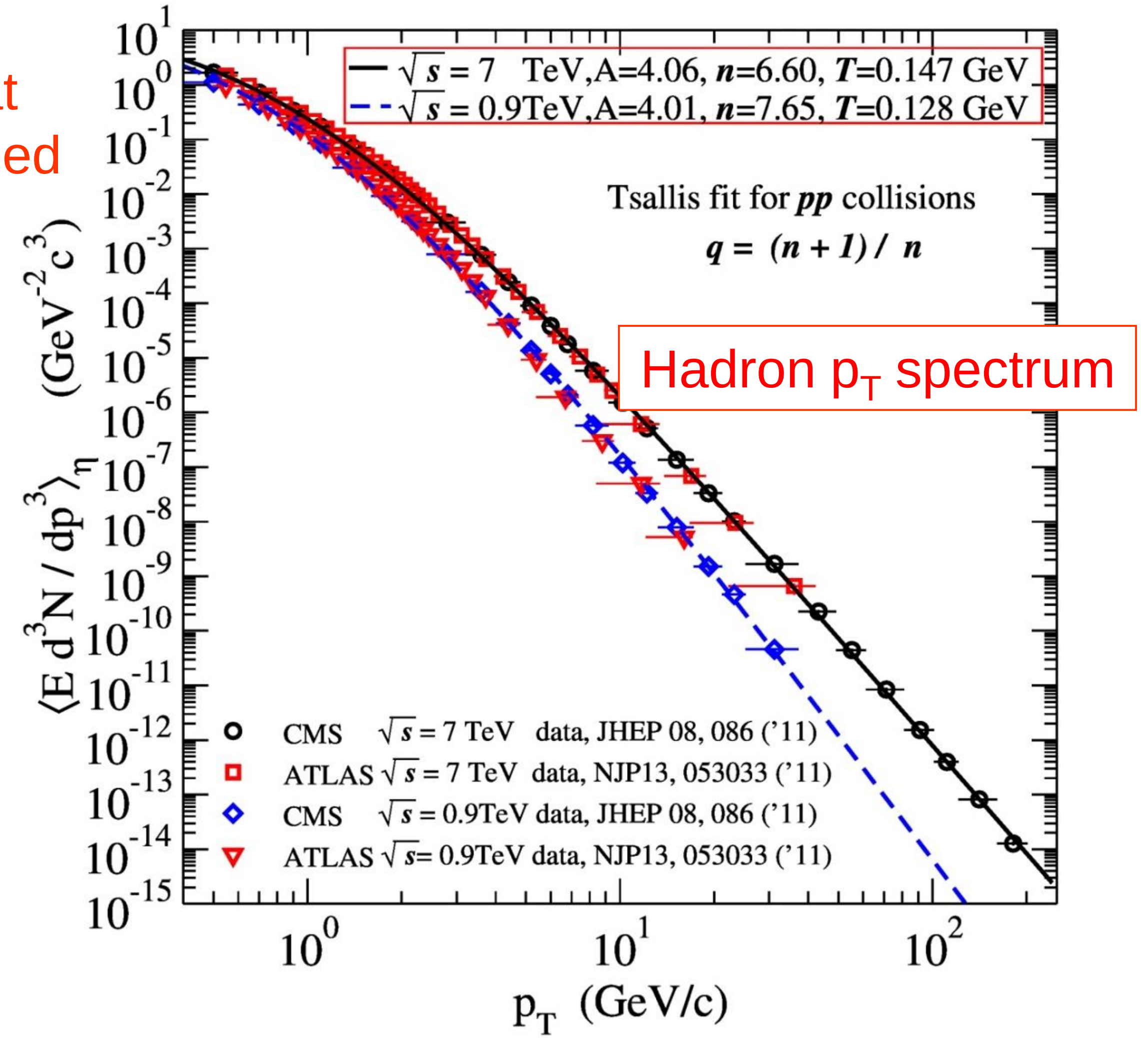
   low pT(jet)~ 5GeV
3. A cluster of a cone of particles are present with low pT~1-2 GeV trigger particles (PHENIX)

Hadron hadron pT spectrum at central rapidity can be described by three degrees of freedom:
A, n, and T.

Tsallis distribution

$$E\frac{d\sigma}{d^3p} = \frac{A}{\left(1+\frac{m_T - m}{nT}\right)^n}$$

$$m_T = \sqrt{m_\pi^2 + p_T^2}$$




Wong and Wilk, ActaPhysPol.B43,2047(2012)

Only a single component, the hard scattering, suffices to describe the hadron pT spectra in pp collisions at LHC

# Quantitative analysis of the jet spectrum

We consider running coupling constant

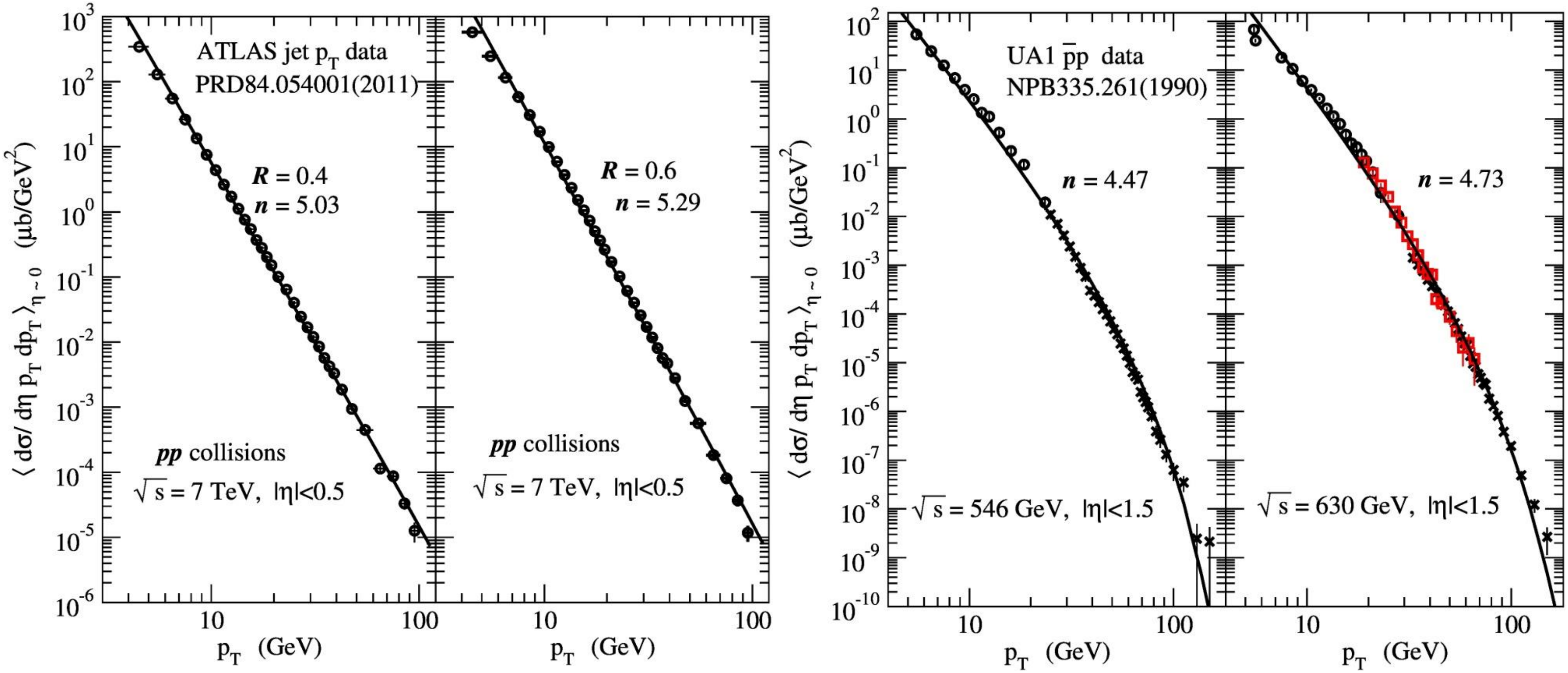
$$\alpha_s(p_T) = \frac{12\pi}{27\ln((Q_0^2 + p_T^2)/\Lambda_{\mathrm{QCD}}^2))},$$

$$\Lambda_{\mathrm{QCD}} = 0.25\,\mathrm{GeV},\ \ Q_0^2 = 10\Lambda_{\mathrm{QCD}}^2$$

[Wong, Barnes, Swanson, Phy.Rev.C65,014903(2001)]

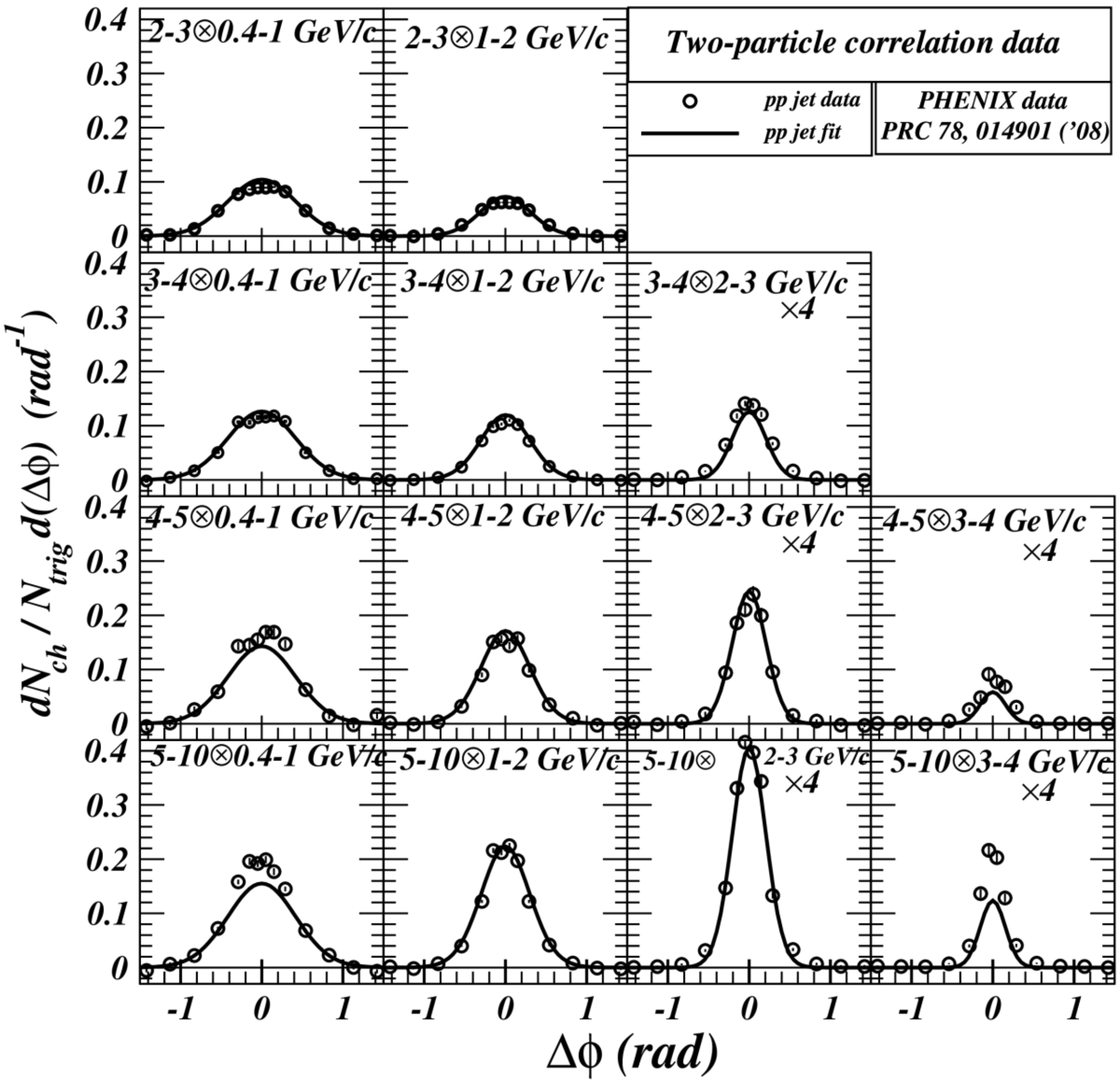
$$\frac{d\sigma(AB \to cX)}{dy\, d\vec{c}_T} = \frac{A\alpha_s^2(c_T)\ (1-2x_c)^{g+\frac{1}{2}}(1-2x_c)^{g+\frac{1}{2}}}{c_T^n\sqrt{1-x_c}},$$

$$x_c = \frac{c_T}{\sqrt{s}}$$




The experimental UA1 and ATLAS jet data for the production of jets (hadron clusters) from low-pT region (of a few GeV) give n ~ 4.5-5.3, providing evidence for the dominance of the hard-scattering process at these low pT regions.

A cluster cone of particles is associated with a low pT trigger (pT>2GeV or even lower).



## Dominance of hard-scattering provides answers to our central questions:

1. How are these medium partons produced?

Answer: by the hard scattering process

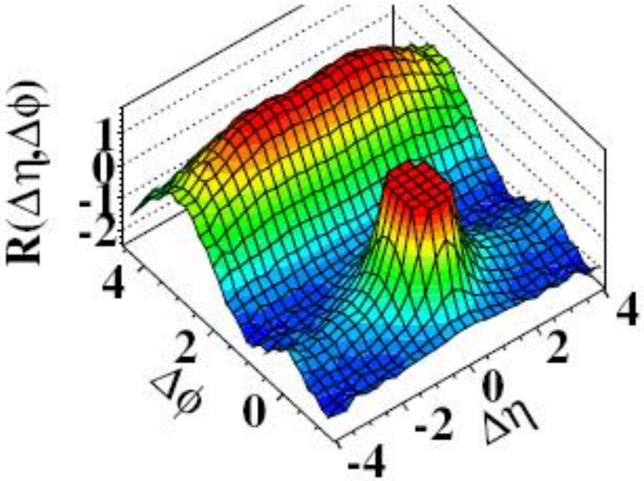
2. What is the origin of the rapidity plateau momentum distribution of the medium partons, ***at the moment of jet-parton collision***?

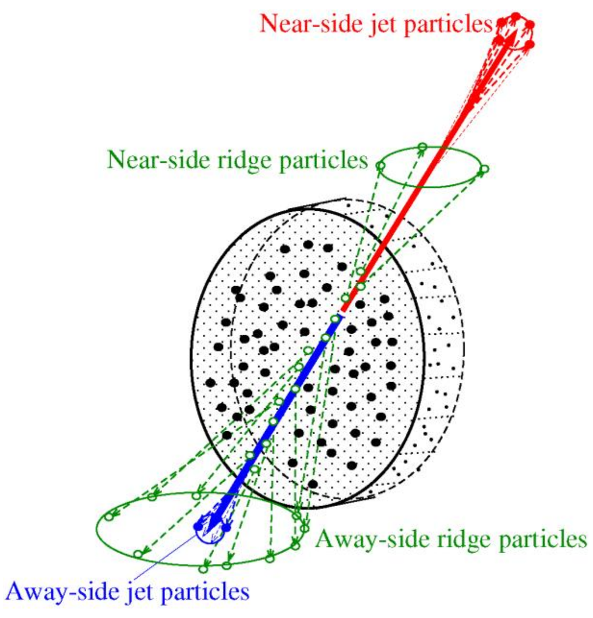
Answer: parallel hard scatterings of partons contribute to the rapidity plateau of the medium partons, **at the moment of jet-parton collision**

# Momentum kick model

- Near-side ridge particles are medium partons produced by hard-scattering
- The medium partons have an initial rapidity plateau momentum distribution.
- Those medium partons that are hit by the jet acquire a momentum kick along the jet direction and retains its rapidity plateau structure. The jet-medium collision contributes at least partially to the near-side ridge.

**CMS pp 7 TeV data**
**N>110, 1 GeV/c < pT< 3 GeV/c**



# Conclusions

A large collection of experimental two-particle and single-particle data indicate dominance of hard-scattering over a large $p_T$ domain in pp collisions at high energies

Partons produced by hard scattering have a rapidity plateau structure.

These medium partons produced by hard scattering contribute at least partially to the near-side ridge in pp collisions at LHC.