Collective Recoil of Medium Scatters in the Passage of a Jet in a Dense Medium

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- Extraction of physical parameters from ridge data
- Extracted physical parameters poses theoretical puzzles
- Puzzles are resolved : coherent collisions of jet with medium scatterers at RHIC & LHC
- Coherent collisions of jet with medium scatterers lead to
  (i) interference of Feynman amplitudes
  (ii) the collective longitudinal recoils of scatterers
  (iii) the ridge phenomenon

C.Y.Wong, Phys. Rev.C76,054908('07)
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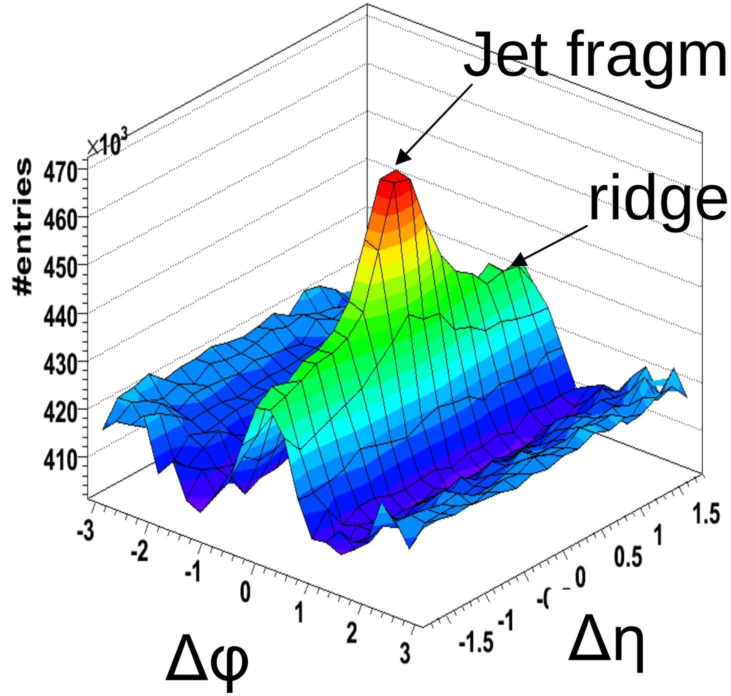
C.Y.Wong. J. Phys.Conf.Ser.387,012009(2012)

The highlight of Quark Matter 2006 in Shanghai, China

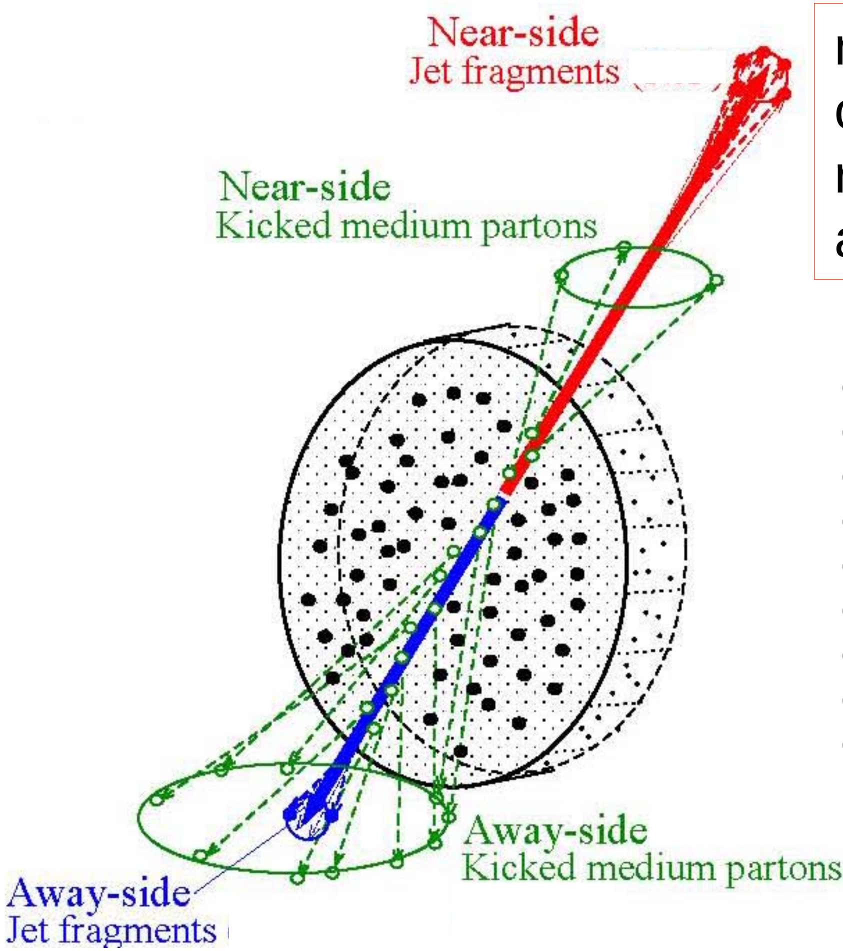
High p_t trigger, p_t^{assoc}>2GeV



Central AuAu collisions
at $\sqrt{s_{NN}}$=200 GeV

The discovery of the near-side ridge phenomenon in high-energy heavy-ion collisions

Momentum kick model to explain the ridge phenomenon



medium partons (possessing their own intrinsic momentum distribtuion), receive a momentum kick q_z along the jet direction

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The momentum kick model

$$\left.\frac{dN_{ch}}{N^{trig}\,d\Delta\eta\; d\Delta\phi\; p_t\, dp_t}\right|_{total}$$

$$= f\left(\frac{2}{3} n \left.\frac{dN_{medium-parton}}{d\Delta\eta\; d\Delta\phi\; p_t\, dp_t}\right|_{ridge} + \left.\frac{dN_{pp}}{d\Delta\eta\; d\Delta\phi\; p_t\, dp_t}\right|_{jet\ fragment} \right)$$

n is the number of kicked medium partons per jet

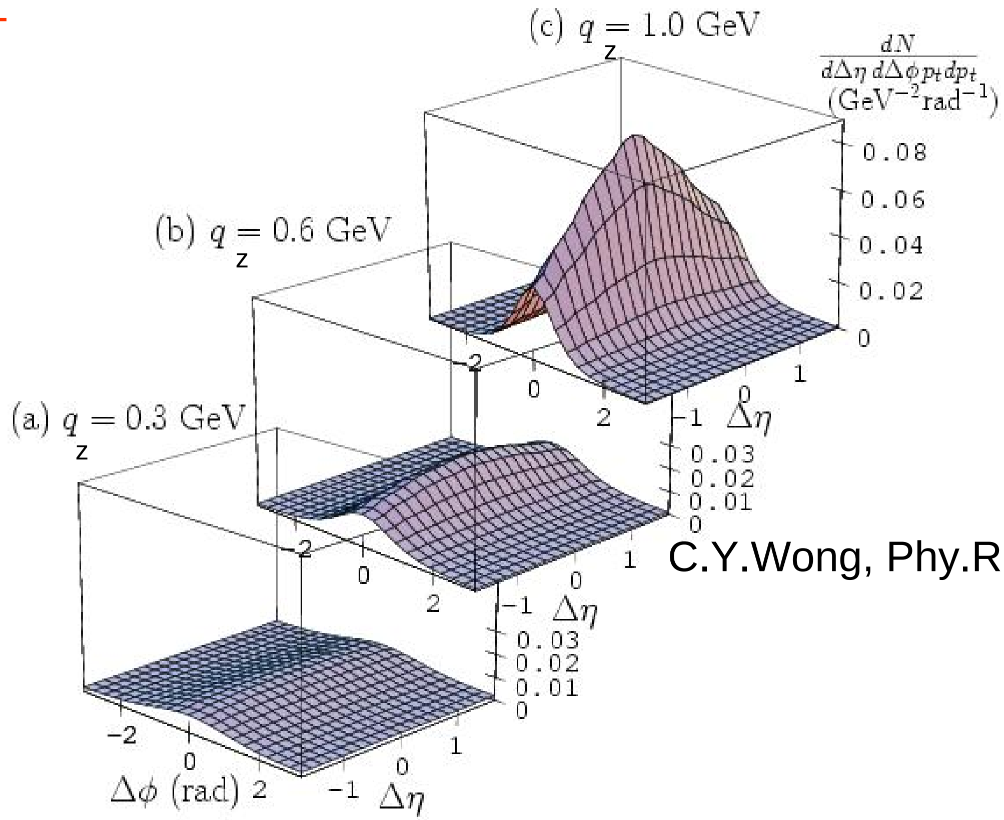
n depends on impact parameter

f is the survival factor due to final state interactions.

$$\left.\frac{dN_{medium-parton}}{d\eta_f d\phi_f\; p_{tf}\, dp_{tf}}\right|_{ridge} = \left[\frac{dN_{medium-parton}}{dy_i d\phi_i p_{t\,i} dp_{t\,i}} \frac{E_f}{E_i} \right]_{\vec{p}_i = \vec{p}_f - q_z \vec{e}_{jet}} \sqrt{1 - \frac{m^2}{m_{tf}^2 \cosh^2 y_f}}$$

Experimental data determine q_z, n, and initial dN/dyd^2p_T ?

- the ridge width in Δφ determines q_z
- the overall height of the ridge yield determines the number of kicked medium partons n
- the shape of the ridge yield in Δη and p_T determines the initial medium partons distribution dN/dyd^2p_T



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Initial parton momentum distribution

We parametrize the shape of the normalized initial parton distribution by

$$\frac{dN_{medium\ parton}}{dy\, d\phi\, p_t\, dp_t} = A\,(1-x)^a\, \frac{\exp\left\{-\left(\sqrt{m^2+p_t^2}-m\right)/T\right\}}{\sqrt{m_d^2+p_t^2}}$$

$$x = \frac{(p_0+p_z)_{parton}}{(p_0+p_z)_{parent}} = \frac{\sqrt{m^2+p_t^2}}{m_b}\exp\{|y|-y_B\} \le 1$$

$$m = m_{parton} = m_\pi\,; \qquad y_B = y_{beam}$$

A is a normalization constant such that

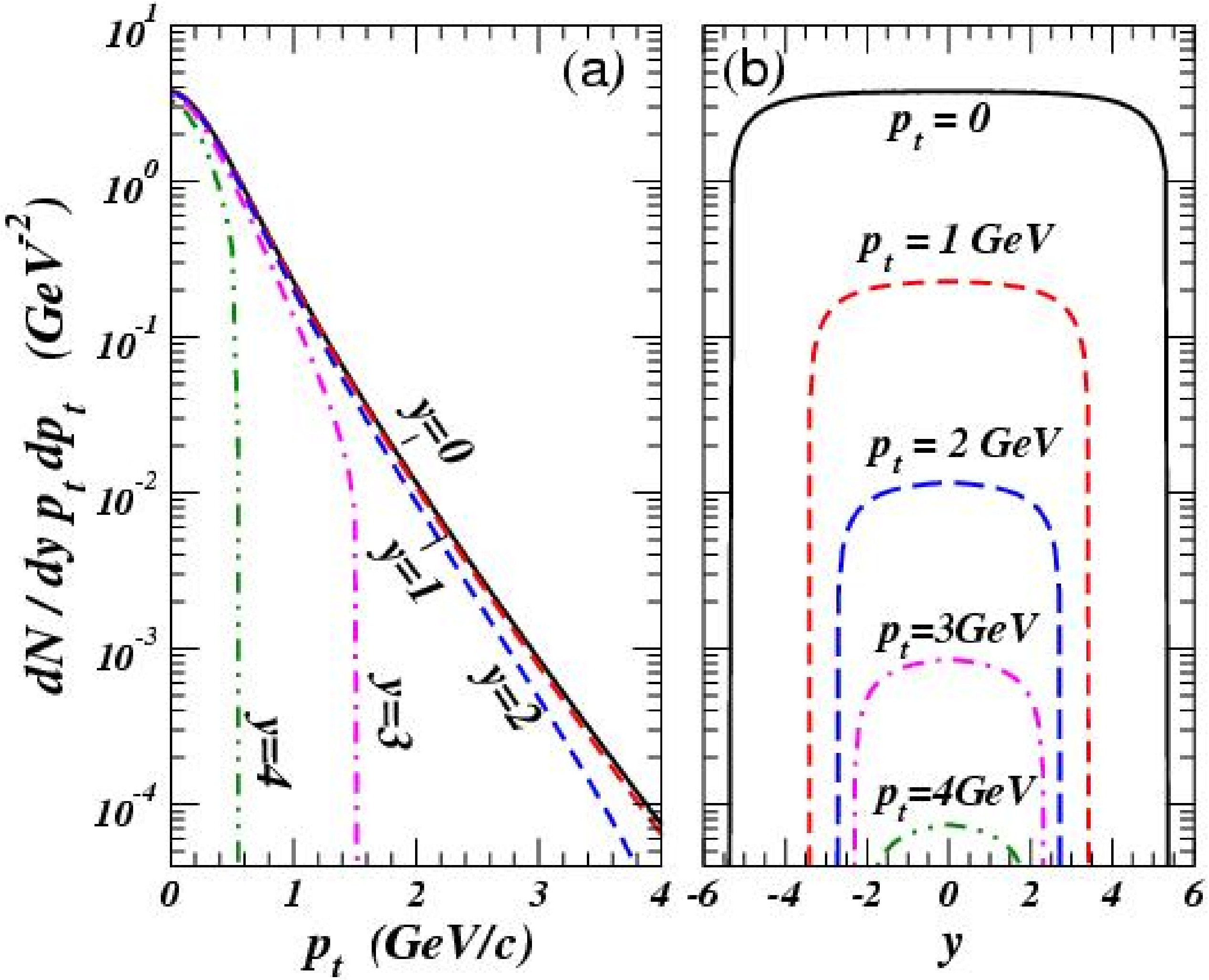
$$\int \frac{dF}{dy\, d\phi\, p_t\, dp_t}\, dy\, d\phi\, p_t\, dp_t = 1$$

The parameters are:

$$a,\ T,\ m_d$$

$$\frac{dN_{medium\ parton}}{dy\, d\phi\, p_t\, dp_t}$$

Medium parton momentum distribution at the moment of jet-parton collision



q_z, n, $dN/dydp_T$ extracted from STAR data

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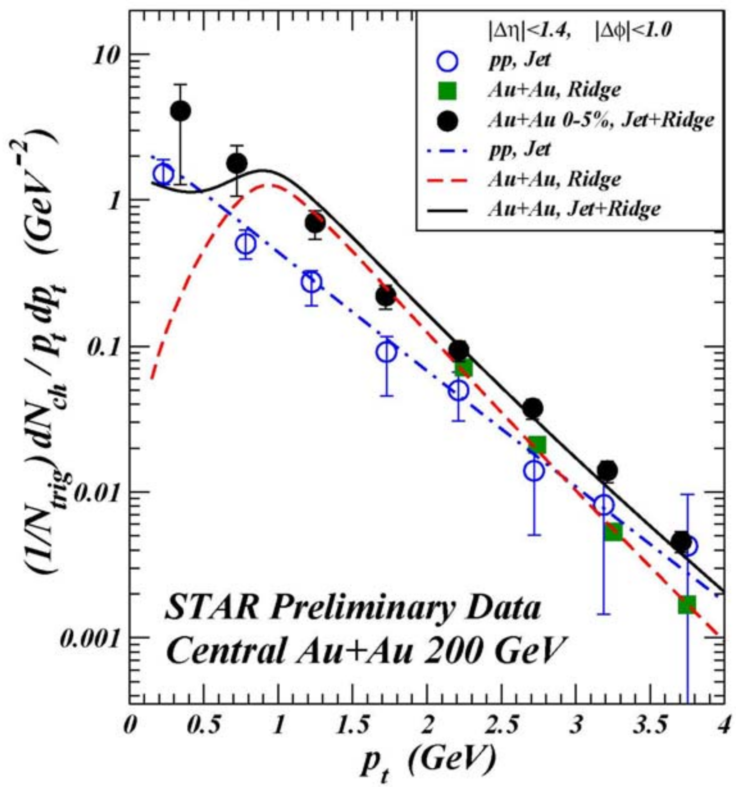
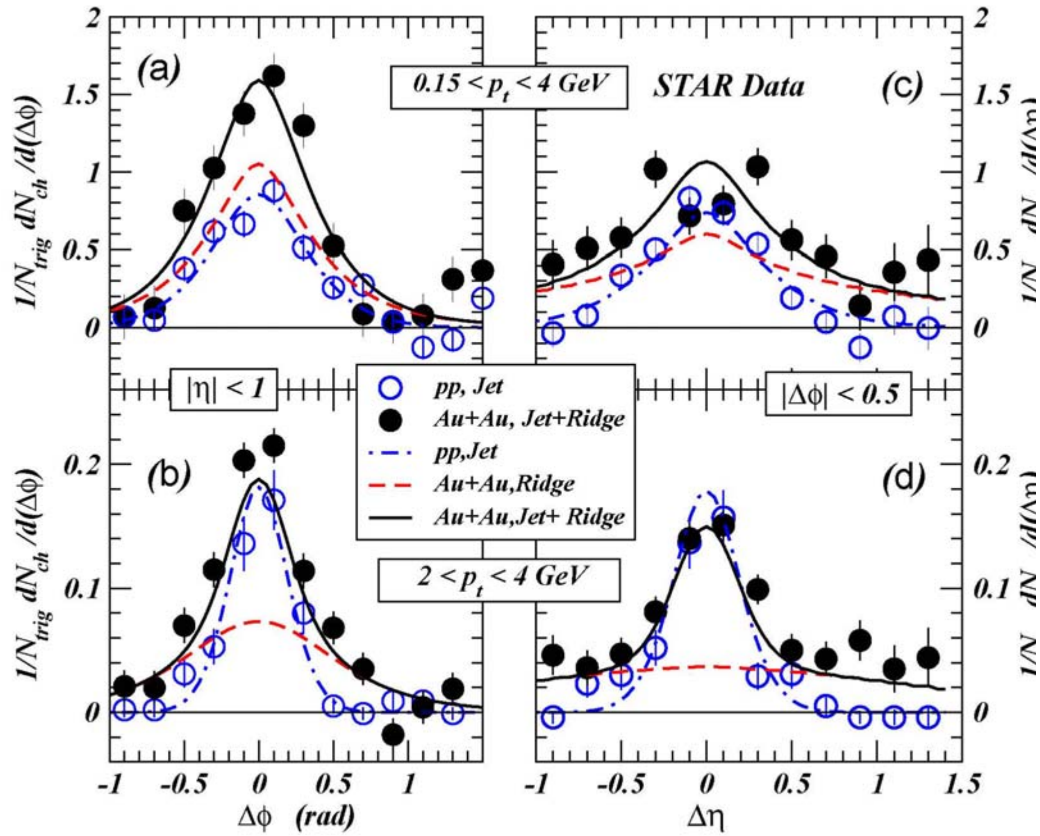


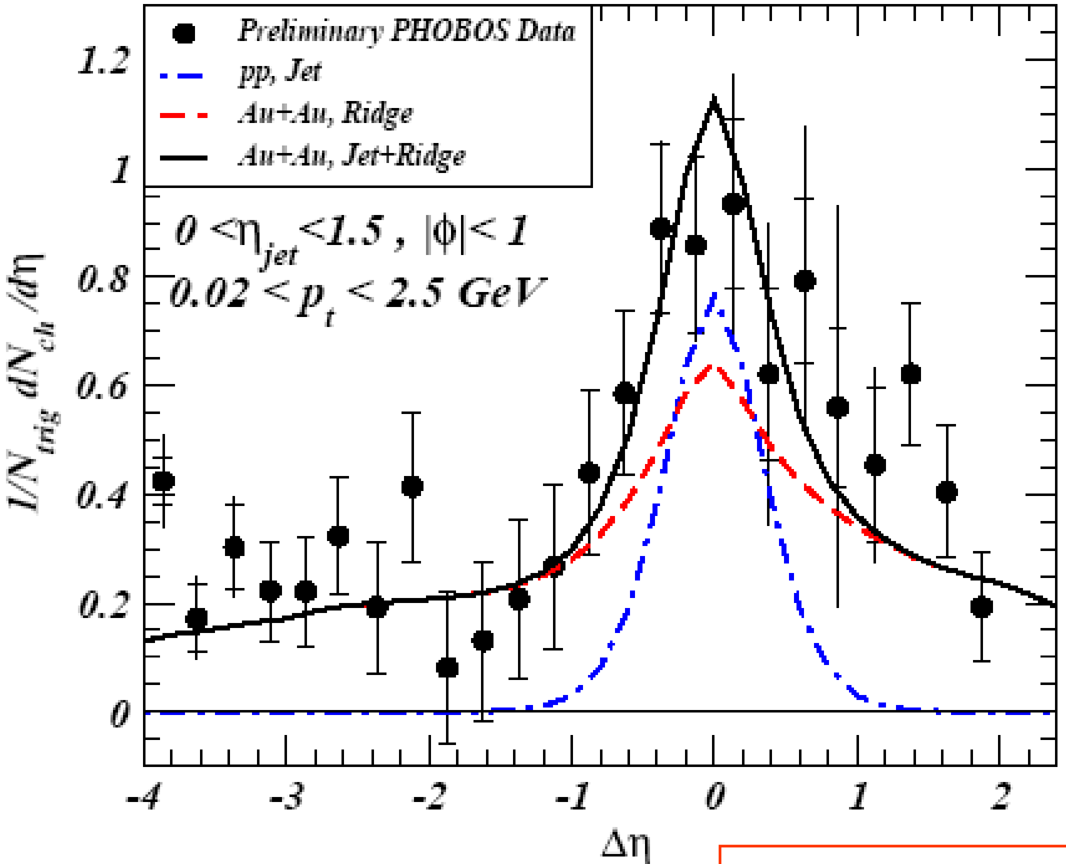


q_z=1 GeV/c, n ~ 6

Data from
PRL95,152301(05) & J. Phy. G34, S679 (07)

Momentum kick model gives the correct prediction for PHOBOS

C.Y.Wong, Phys. Rev.C78,064905('08)

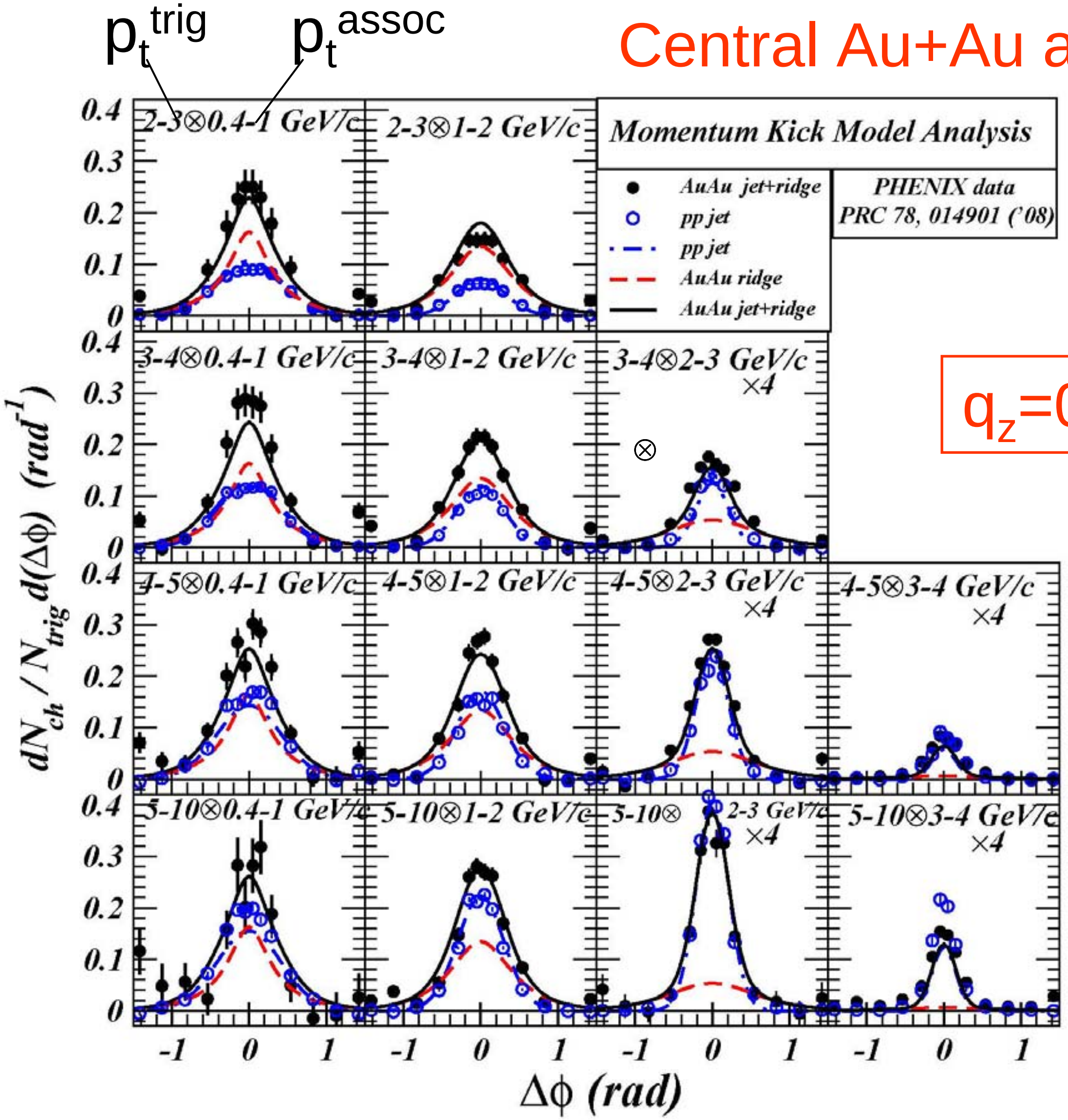


q_z=1 GeV/c, n ~ 6

Momentum Kick Model extracts q_z, n, $dN/dydp_T$ from PHENIX data

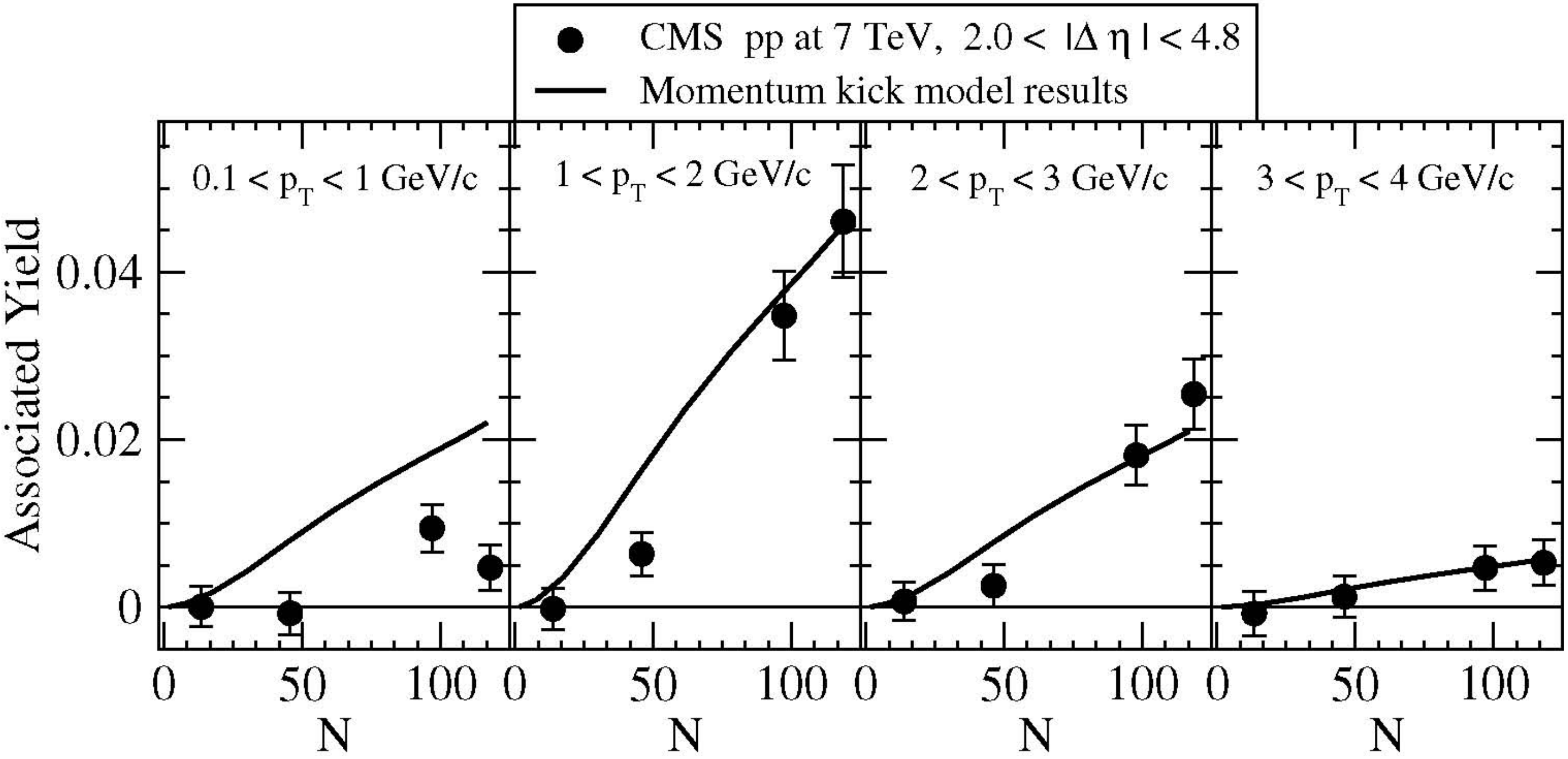
C.Y.Wong, Phys. Rev.C80,034908('09)

Central Au+Au at √s=200 GeV



q_z=0.8 GeV/c, n ~ 6

For pp collisions at 7 TeV



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q_z=2 GeV/c, n ~ 2, for N ~ 110

1. For the most central AuAu at $s^{1/2}$=200 GeV,

   q_z~0.8-1.0 GeV/c, n ~ 6

2. For the most inelastic pp at $s^{1/2}$=7 TeV

   q_z~ 2.0 GeV/c, n ~ 2

q_z increases as n decreases

Extracted data poses theoretcial puzzles

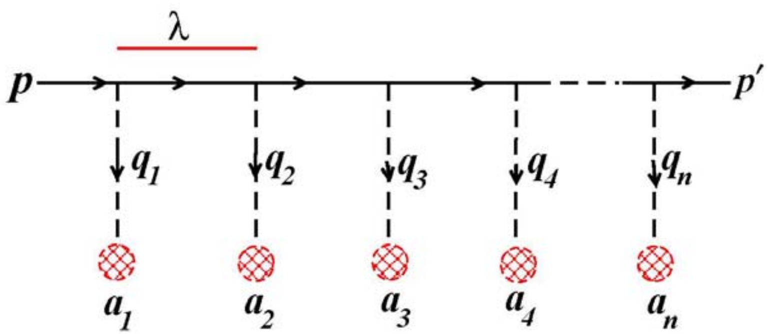
1. Why $\Delta\varphi = \varphi_{\text{medium parton}} - \varphi_{\text{jet}} \sim 0$?

   (Why collective recoils of n scatterers along the jet direction ?)

   (Why the jet kicks the scatterers with a kick q_z along the jet direction ?)

2. Why q_z so large, of order 1 GeV?
3. Why q_z increases as n decreases ?

Longitudinal recoils of medium partons after jet collision ?



$$M_i(p_i, p_{i-1}) = \frac{2\pi\delta(q_i^0)(-2ig^2)E_0 T^a T_i^a e^{-iq_i \bullet x_i}}{q^2 + \mu^2}$$

Potential model: (Glauber'58; Gyulassy+Wang,'94,…)

(i) Medium partons are represented by static screened potentials in the medium.

In the lowest order, no scatterer longitudinal recoil.

(ii) In the next order, each medium parton longitudinal recoil is determined after collision

$q_z = \; p_{jet} - p_{jet} \cos\theta \; = \; p_{jet}\, \theta^2 / 2 \; = \; q_T^2 / 2\, p_{jet},$ $\quad q_z$ is very small

(iii) Medium parton longitudinal recoils are not independent variables.

Minijet p_{jet} ~ 10 GeV

q_T(deflection of jet) ~ 0.4 GeV in each 2-body collision

q_z (along jet) ~ $q_T^2/2p_{jet}$ ~ 0.008 GeV

Nature of jet-medium collisions

The exchange of a gluon between the jet and a medium parton takes time. The longitudinal coherence time is

$$\Delta \mathbf{t}_{\mathbf{lcoh}} = \Delta \mathbf{z}_{\mathbf{lcoh}} \Big/ c = (\hbar / q_z) \Big/ c = 2\, \hbar\, p_{jet} \Big/ q_T^2 c.$$

For the collisions of a jet with many medium partons.

If $\Delta \mathbf{t}_{\mathbf{lcoh}} \ll \lambda / c$, the exchange of one gluon is finished before another collision begins, these jet collisions are **incoherent**.

If $\Delta \mathbf{t}_{\mathbf{lcoh}} \gg \lambda / c$, the exchange of one gluon is **not** completed before another collision begins, these jet collisions are **coherent.**

What is the nature of jet-(medium parton) multiple collisions at RHIC and LHC?

Minijet p_{jet} ~ 10 GeV

q_T(deflection of jet) ~ 0.4 GeV in a 2-body collision

q_z (along jet) ~ $q_T^2/2p_{jet}$ ~ 0.008 GeV

Δz_{coh} (along jet) = $\hbar / q_z$ ~ 25 fm >> λ(mean-free path)

Δt_{lcoh} (gluon exchange time) = $\hbar / q_z c$ ~ 25 fm / c

>> λ / c (mean free-time)

Jet-(medium parton) collisions at RHIC and LHC are coherent collisions

Effects of coherent collisions

1. The number of degrees of freedom is enlarged.

   q_z (or p_z of each scatterer) is free to vary!

2. The same initial and final states can be connected by many different Feynman diagrams

- each Feynman diagram gives a probability amplitude
- and these Feynman amplitudes interfere

Degrees of freedom in incoherent collisions

There are two degrees of freedom in each 2-two-body collision : $\vec{p}_T = (|\vec{p}_T|, \varphi)$

2 final particles, each p_0, p_1, p_2, p_3,

4 degrees of freedom = 8

1 4-momentum conversation condition = - 4

2 mass-shell condition $p_0^2 - \vec{p}^{\,2} = m^2$ = - 2

2

In the incoherent collisions of a jet with n scatterers, there are 2n degrees of freedom.

Degrees of freedom in coherent collisions

Coherent collisions of a jet with n scatterers correspond to a (1+n)-body collision

There are 3n-1 degrees of freedom:

$\vec{p}_{T1}, p_{z1}, \ \vec{p}_{T2}, p_{z2}, \ldots, \ \vec{p}_{Tn}, p_{zn},$

+ 1 energy-conservation condition

p_z of each scatterer is allowed to vary !

n+1 final particles, each p0, p1, p2, p3,

4 degrees of freedom = 4(n+1)

1 4-momentum conversation condition = - 4

n mass-shell condition $p_0^2 - \vec{p}^{\,2} = m2$ = - (n+1)

Degrees of freedom in a (1+n)-body collision : 3n - 1

Feynman amplitude approach

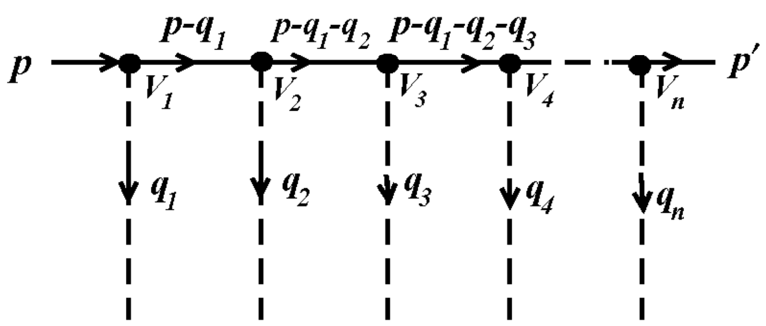
- Feynman amplitude gives the probability amplitude as a function of medium parton recoil momentum
- The same initial and final states are connected by different Feynman diagrams
- The Feynman amplitudes in these different Feynman diagrams interfere.

In the collision of a jet with n scatterers, there are $n!$ Feynman amplitudes. All these $n!$ Feynman amplitudes must be added together before squaring.

Bose-Einstein interference in coherent collisions

Hung Cheng & Ta-Tsun Wu (1969)

Chi-Sing Lam & Ke-Fei Liu (1997)



+ *symmetric permutations of q_i at vertices V_i*

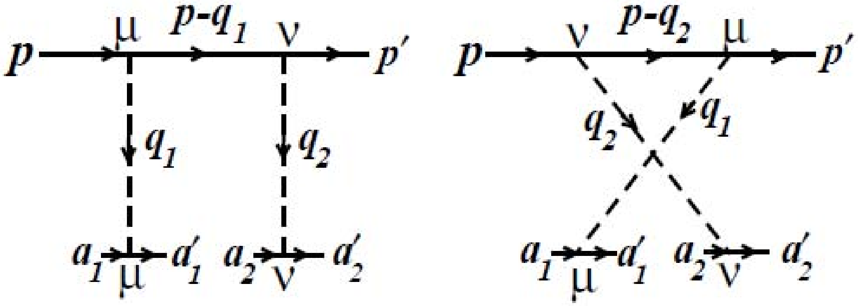
We consider the high-energy limit: $|\vec{p}| >> |q_i|, m$

We consider the scattered particle p' to be on mass shell: $(p')^2 = m^2$

The sum of $n!$ symmetrized Feynman amplitudes is

$$M\,\delta(p'^2 - m^2) \;\propto\; \delta(2p\cdot q_1)\delta(2p\cdot q_2)\delta(2p\cdot q_3)\ldots\delta(2p\cdot q_n)$$

Example:



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$$M_1 = \frac{g^4}{2m^3}\left(\frac{2p\cdot\tilde{a}_1}{q_1^2}\right)\left(\frac{2p\cdot\tilde{a}_2}{q_2^2}\right)\frac{1}{2p\cdot q_1 - i\varepsilon}$$

$$M_2 = \frac{g^4}{2m^3}\left(\frac{2p\cdot\tilde{a}_1}{q_1^2}\right)\left(\frac{2p\cdot\tilde{a}_2}{q_2^2}\right)\frac{1}{2p\cdot q_2 - i\varepsilon}$$

$$\tilde{a}_i = \begin{cases} \sqrt{\dfrac{a_{i0}+m}{a_{i0}'+m}}\dfrac{a_i}{2m} + \sqrt{\dfrac{a_{i0}'+m}{a_{i0}+m}}\dfrac{a_i'}{2m} & \text{for quark scatterers} \\ \dfrac{a_i + a_i'}{2} & \text{for gluon scatterers} \end{cases}$$

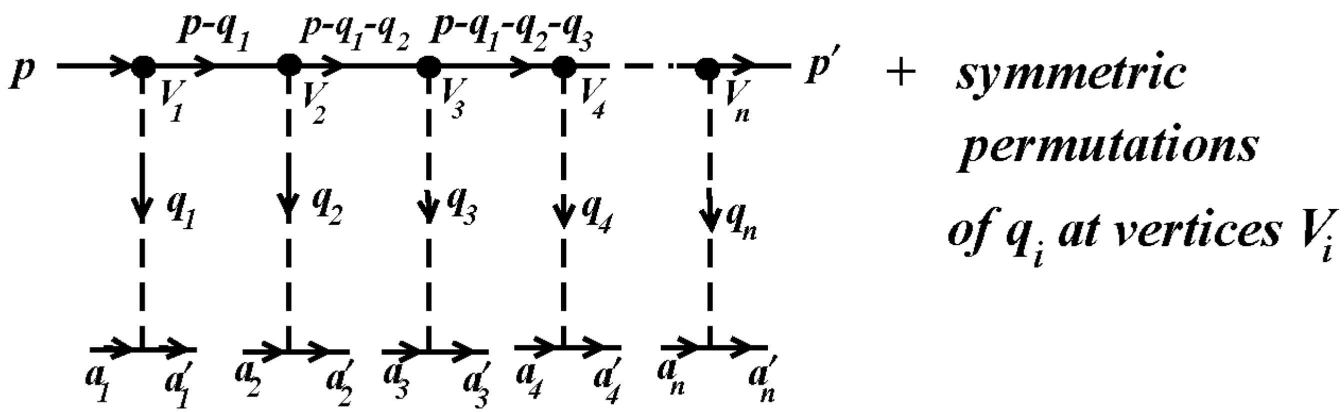
Particle p' is on the mass shell, and in the high-energy limit,

$$(p')^2 = (p - q_1 - q_2)^2 \approx -2p\cdot q_1 - 2p\cdot q_2 \approx m^2 \cong 0$$

The real parts of the two Feynaman amplitudes approximately cancel.

$$(M_1 + M_2)\delta(p'^2 - m^2) \approx \frac{g^4}{2m^3}\left(\frac{2p\cdot\tilde{a}_1}{q_1^2}\right)\left(\frac{2p\cdot\tilde{a}_2}{q_2^2}\right)2\mathrm{i}\delta(2p\cdot q_1)\delta(2p\cdot q_2)$$

For jet coherent collisions with n medium partons



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In the high energy limit, the sum of $n!$ Feynman amplitudes with symmetrized interchange of virtual gluon vertices is

$$M\,\delta(p'^2 - m^2) \;\propto\; \prod_{i=1}^{n}\left(\frac{2p\cdot\tilde{a}_i}{q_i^2}\,\delta(2p\cdot q_i) \right)$$

It can be generalized to non - Abelian theory by inlcuding color factors.

Consequences of the Bose-Einstein interference

$$\delta(2p\cdot q_i) \quad \Rightarrow \quad p_0 q_{i0} - p_z q_{iz} - p_T\cdot q_{iT} = 0$$

$$q_{i0} - q_{iz} = \frac{p_T\cdot q_{iT}}{p_z} \approx 0$$

Virtual gluon propagator $\quad \dfrac{1}{q_i^2} = \dfrac{1}{q_{i0}^2 - q_{iz}^2 - |q_{iT}|^2} \approx \dfrac{1}{-|\vec{q}_{iT}|^2}$

Cross section is given by

$$d\sigma \propto \prod_{i=1}^{n}\left(\frac{(2p\cdot\tilde{a}_i)^2}{|\vec{q}_{iT}|^4}\frac{d\vec{q}_{iT}dq_{iz}}{2a'_{i0}}\right)\delta(p_0 - p'_0 - q_{10} - q_{20} - \ldots - q_{n0})$$

Therefore, $\vec{q}_{iT}$ and $x_i = q_{iz}/p_z$ are distributed according to

$$d\sigma \propto \frac{d\vec{q}_{1T}}{|\vec{q}_{1T}|^4}\frac{d\vec{q}_{2T}}{|\vec{q}_{2T}|^4}\cdots\frac{d\vec{q}_{nT}}{|\vec{q}_{nT}|^4}dx_1dx_2\ldots dx_n f(x_1,x_2,\ldots,x_n)\delta(1 - x_1 - x_2\ldots - x_n - \frac{p'_z}{p_z})$$

Here, $\begin{cases} f(x_1,x_2,\ldots,x_n) \approx 1, & \langle x_i\rangle = \dfrac{1}{2n} \quad \text{for quark scatterers} \\ f(x_1,x_2,\ldots,x_n) \approx \dfrac{1}{x_1x_2\ldots x_n}, & \langle x_i\rangle = \dfrac{1 - m_{gT}/p_{jet}}{n\cosh^{-1}(p_{jet}/nm_{gT})} \quad \text{for gluon scatterers} \end{cases}$

$$0 < x_i \le \frac{1}{n}$$

Bose-Einstein interference Signatures

$$d\sigma \propto \frac{d\vec{q}_{1T}}{|\vec{q}_{1T}|^4}\frac{d\vec{q}_{2T}}{|\vec{q}_{2T}|^4}\cdots\frac{d\vec{q}_{nT}}{|\vec{q}_{nT}|^4} dx_1 dx_2 \ldots dx_n f(x_1, x_2, .., x_n)\delta(1 - x_1 - x_2 \ldots - x_n - \frac{p'_{jet}}{p_{jet}})$$

$$\begin{cases} f(x_1, x_2, .., x_n) \approx 1, & \langle x_i \rangle = \left\langle \frac{q_{zi}}{p_{jet}} \right\rangle = \frac{1}{2n} \quad \text{for fermion scatterers} \\ f(x_1, x_2, .., x_n) \approx \frac{1}{x_1 x_2 \ldots x_n}, & \langle x_i \rangle = \frac{1 - m_{gT}/p_{jet}}{n \cosh^{-1}(p_{jet}/n m_{gT})} \quad \text{for gluon scatterers} \end{cases}$$

Signature I: medium scatterers recoil collectively along the jet direction

Signature II: q_z increases as n decreases

Signature III: BE interference is a quantum many-body effect, $n \geq 2$.

Extracted data poses theoretcial puzzles

1. Why $\Delta\varphi = \varphi_{\text{medium parton}} - \varphi_{\text{jet}} \sim 0$?

   (Why collective recoils of n scatterers along the jet direction ?)

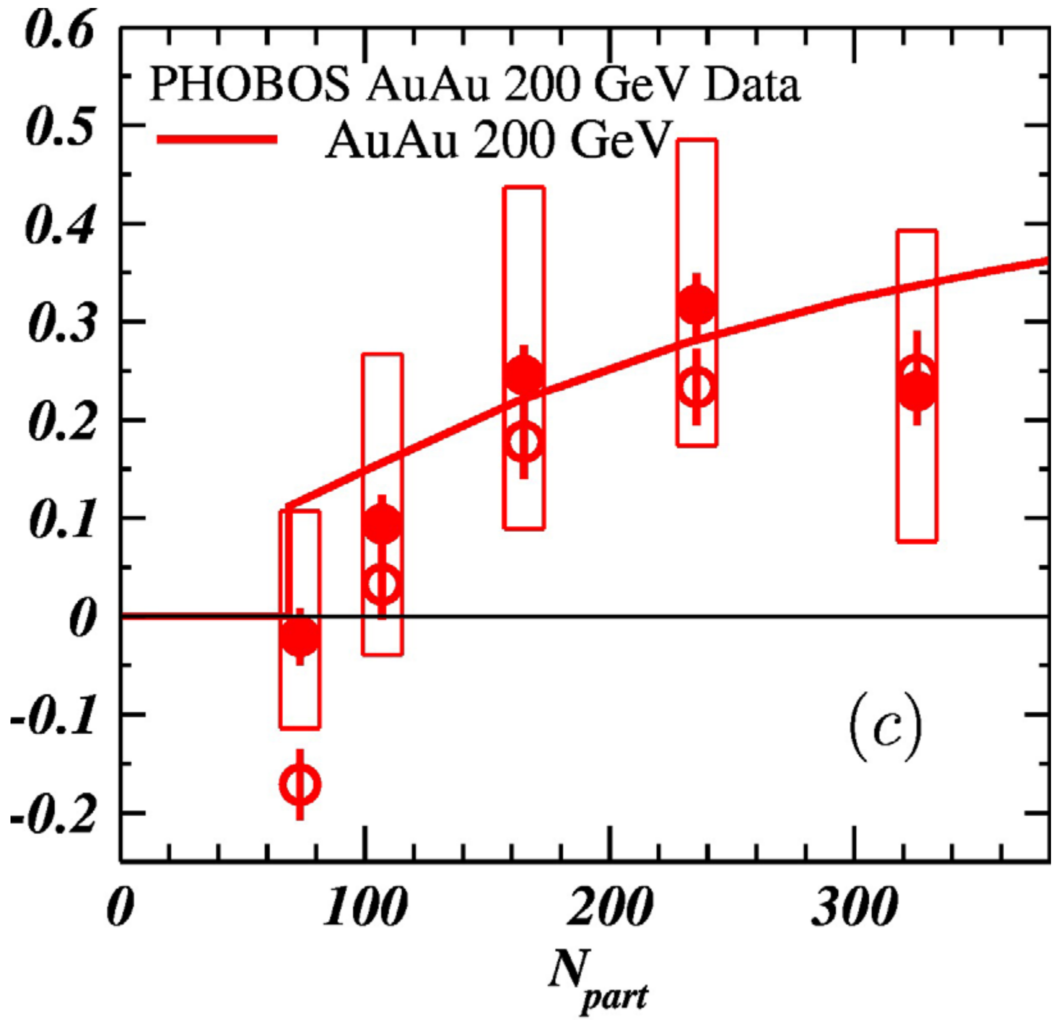
   (Why the jet kicks the scatterers with a kick q_z along the jet direction ?)

2. Why q_z so large, of order 1 GeV?
3. Why q_z increases as n decreases ?

BE Signature III: Threshold at n = 2 ?

- n increases with centrality
- threshold at $n \geq 2$ will show up as a threshold of the ridge yield as a function of centrality

Is there a threshold?



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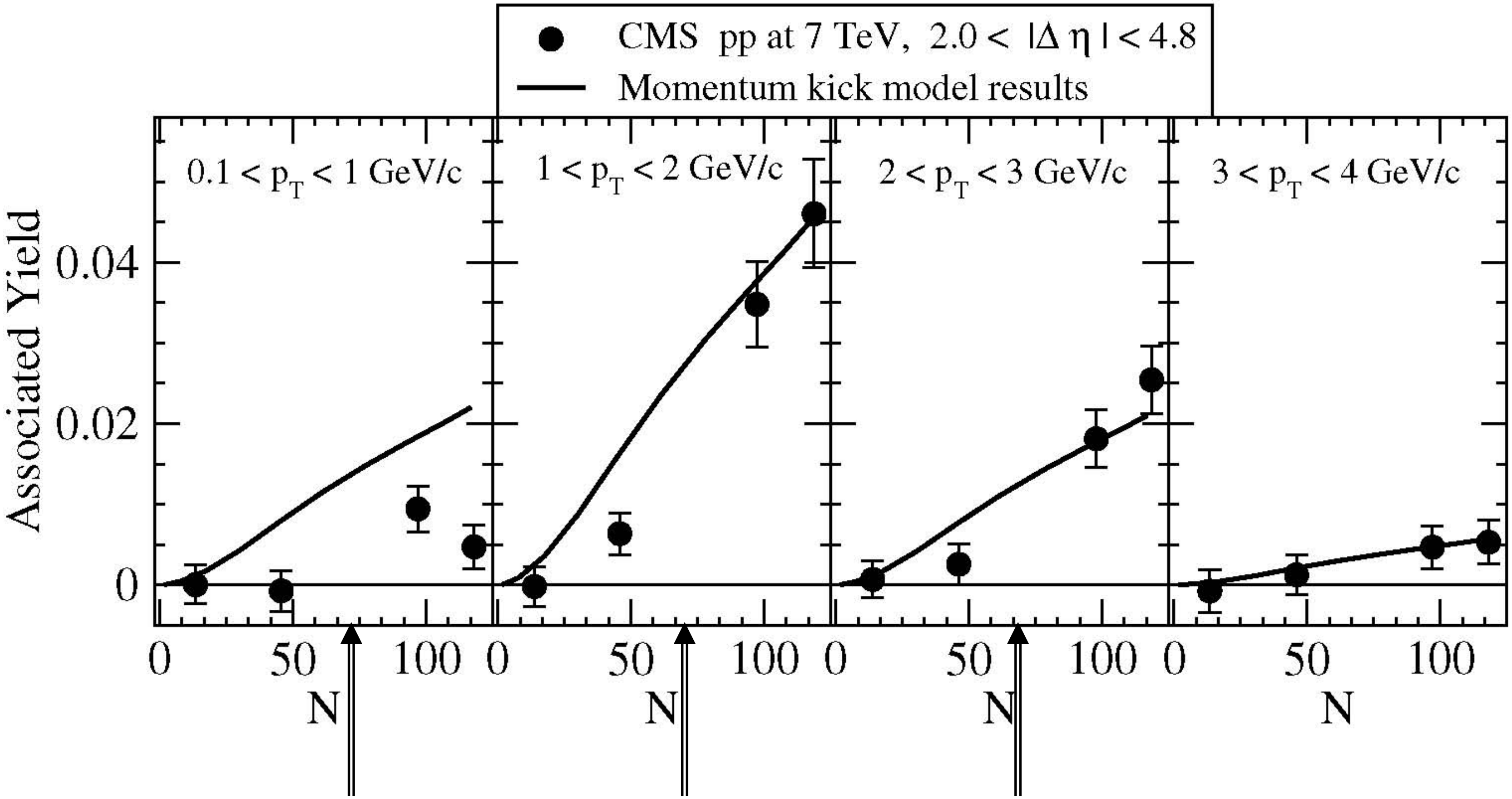
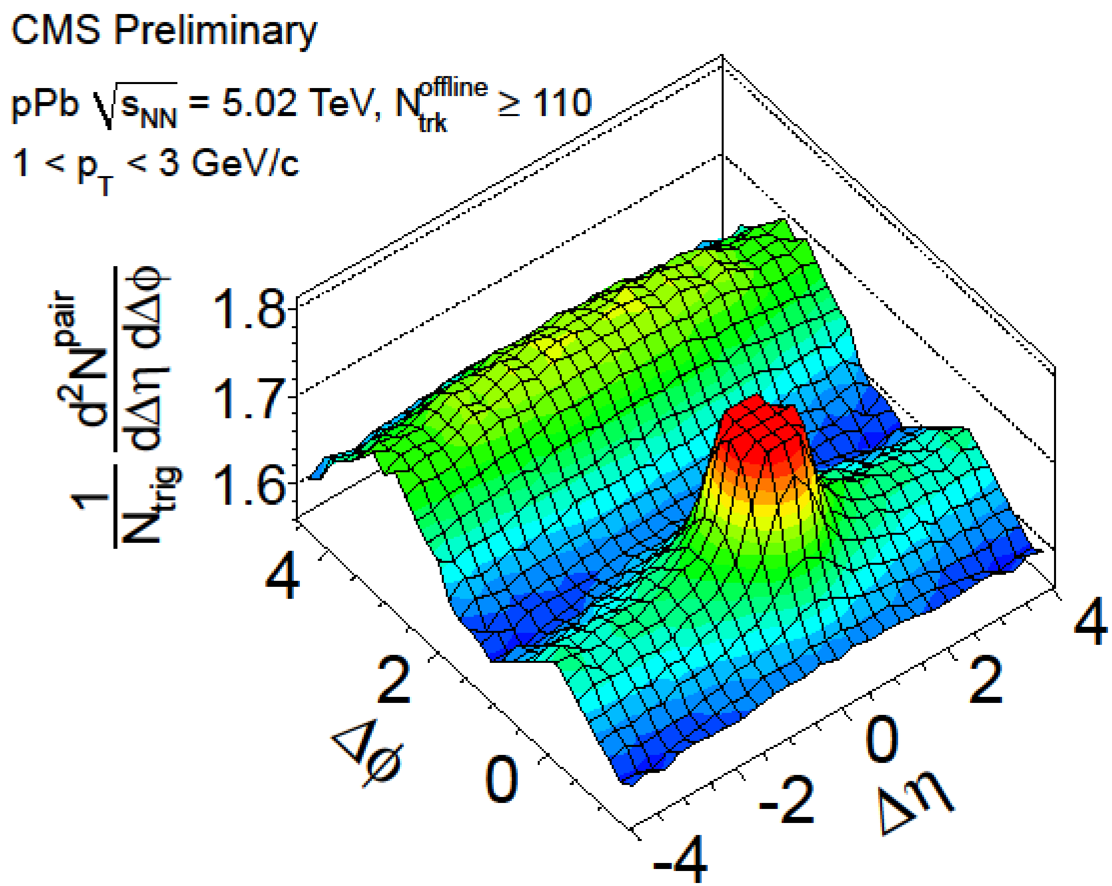
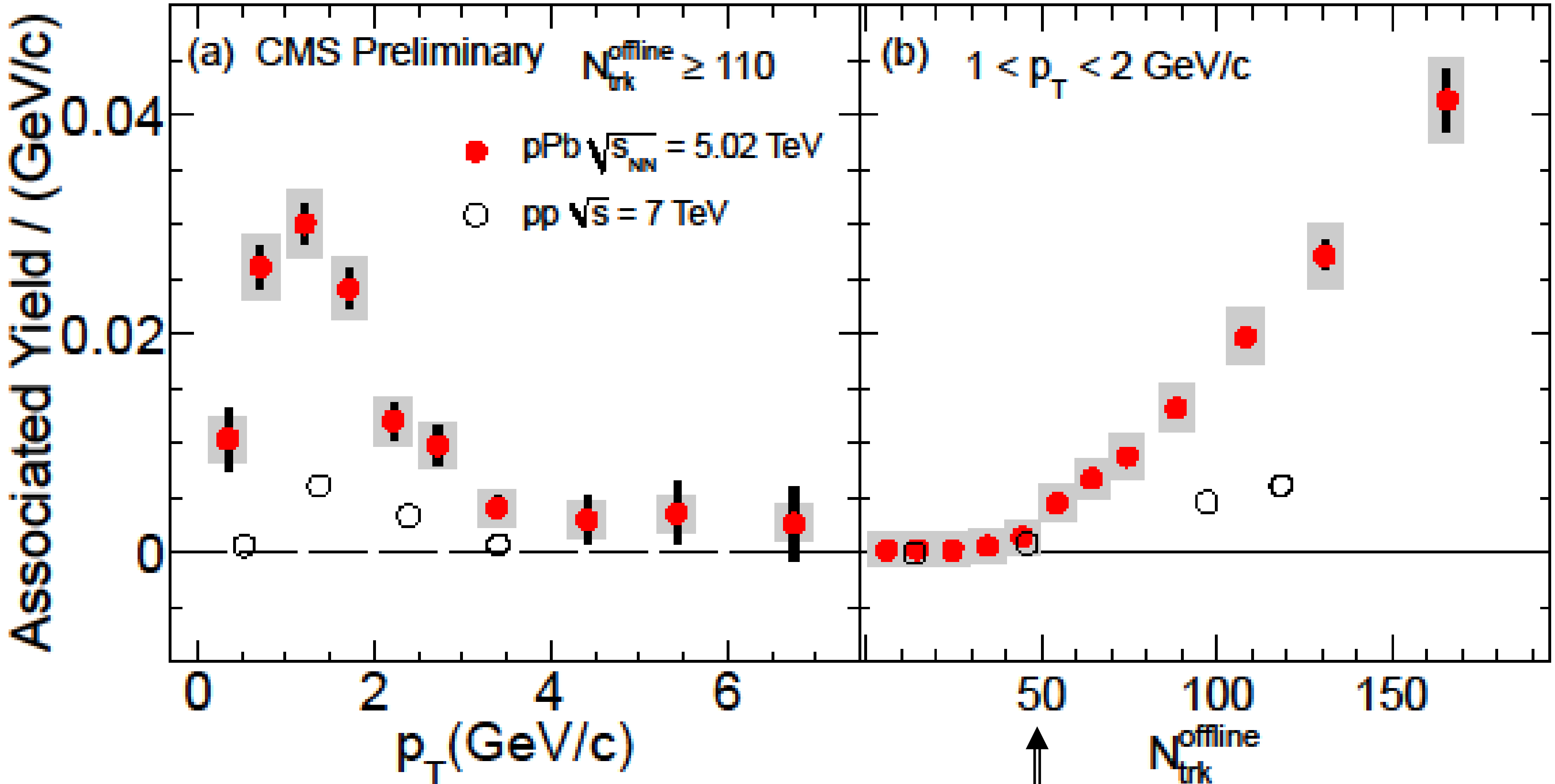


Threshold ?



CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $N_{trk}^{offline} \geq 110$
1 < p_T < 3 GeV/c
$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
1.8
1.7
1.6
4
2
0
$\Delta\phi$
-4
-2
0
2
4
$\Delta\eta$

Is there a n=2 threshold?



Threshold ?

Experimental data appear to indicate thresholds but with a high degree of uncertainty

BE Signature III: Threshold at n=2 ?

Conclusions

- Ridge data provide information on q_z, n, $dN/dy\, d^2p_t$
- Extracted physical parameters pose theoretical puzzles
- Puzzles are resolved:

  coherent collisions of jet with medium scatterers
- Coherent collisions of jet with medium scatterers lead to

  (i) interference of Feynman amplitudes

  (ii) the collective longitudinal recoils of scatterers

  (iii) the ridge phenomenon

Is there a threshold?