Status of Theoretical Understanding of “the Ridge”

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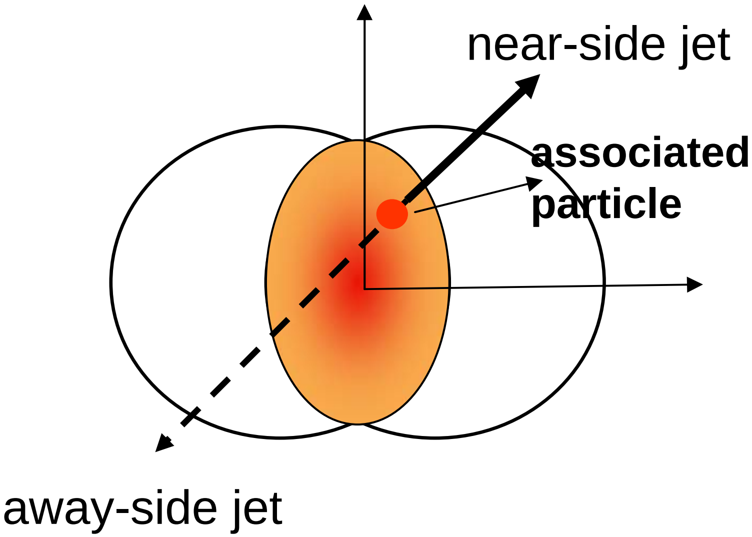
- What is the ridge? What are its properties?
  - Ridge with a high-pT trigger
  - Ridge without a high-pT trigger
- Many different theoretical models of the ridge
- The momentum kick model & the near-side ridge data
- Ridge as a tool to probe early parton momentum distribution
- Momentum kick model analysis of CMS pp ridge data
- Conclusions

C.Y.Wong, Phy.Rev.C76,054908(’07)
C.Y.Wong, ChinesePhys.Lett.25,3936(’08)
C.Y.Wong, J.Phys.G35,104085(’08)
C.Y.Wong, Phys. Rev.C78,064905(’08)
C.Y.Wong, Phys. Rev.C80,034908(’08)
C.Y.Wong, Phys. Rev.C80,054917(’08)
C.Y.Wong, arxiv:1105.5871 (’11)

What is the ridge ?

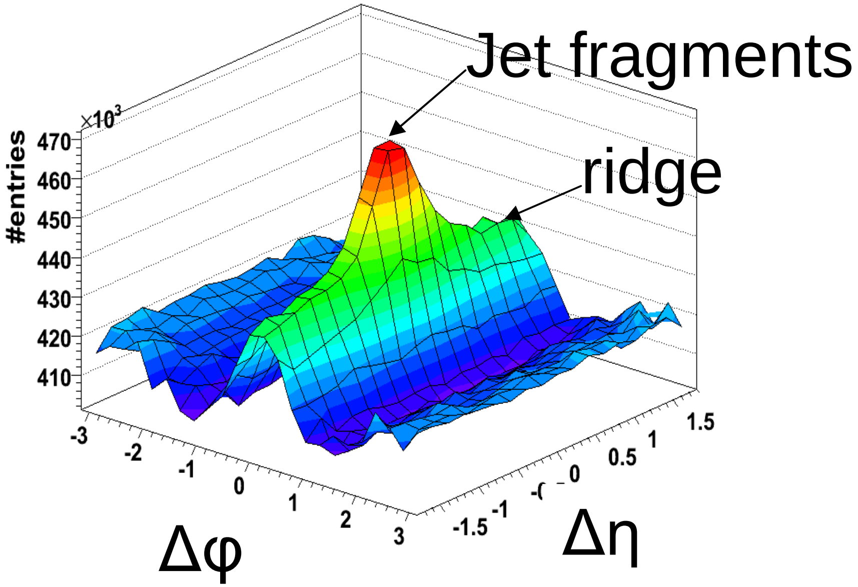


near-side jet

associated particle

away-side jet

p_t^{assoc}>2GeV



Jet fragments

ridge

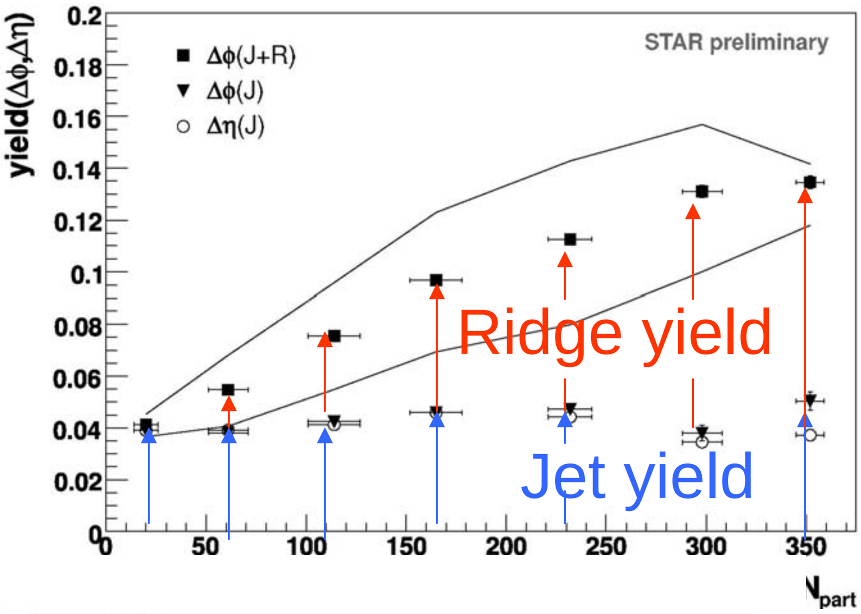
Δφ

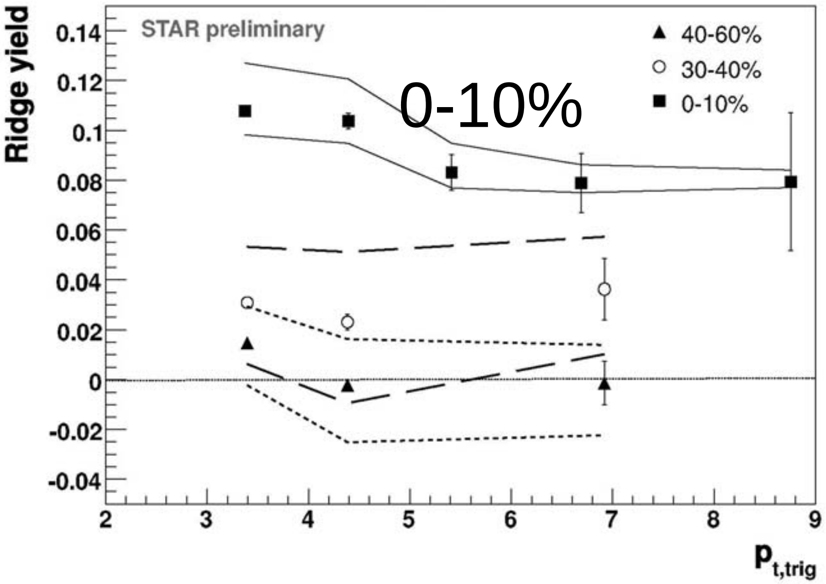
Δη

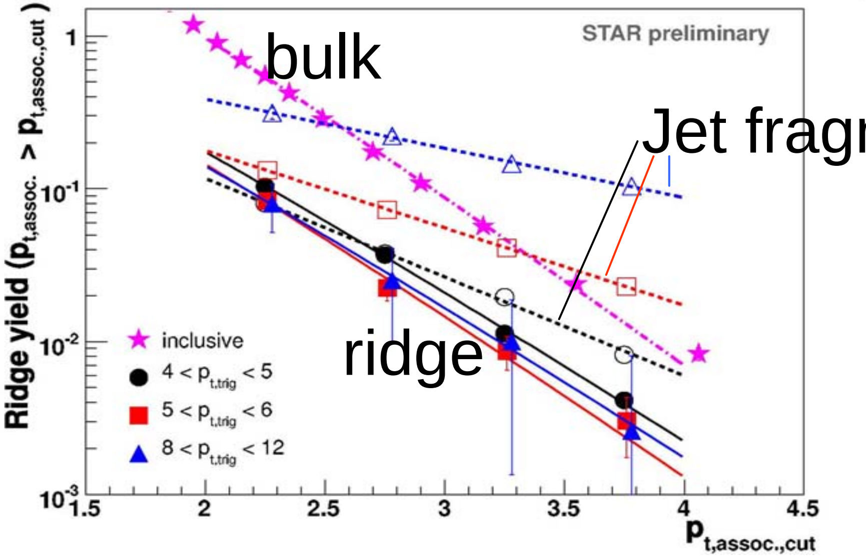
- Occurrence of a near-side “jet” and an away-side jet
- We detect associated particles in coincidence with the jet
- We measure the φ and η of these associated particles,

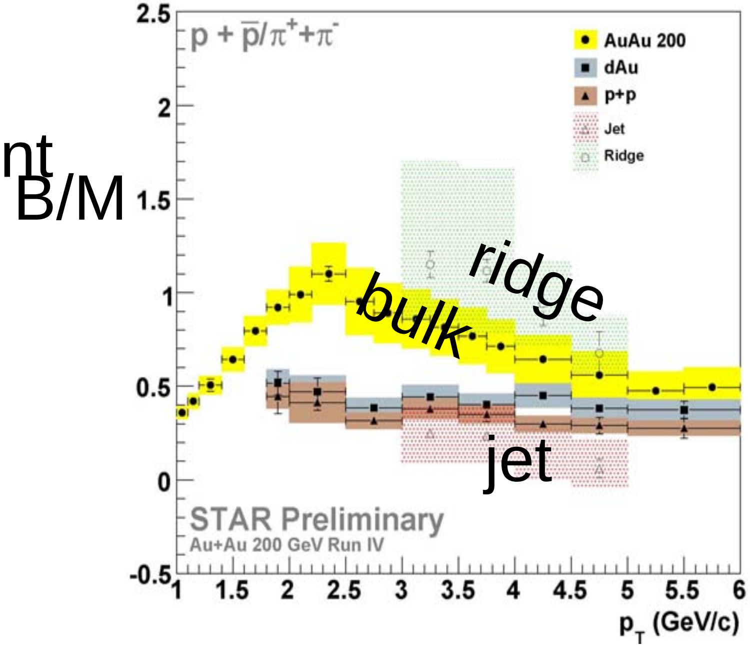
  Δφ=φ (associated particle)- φ (jet trigger)

  Δη=η (associated particle) - η (jet trigger)
- The probability distribution in Δφ- Δη is in the form of a ridge and a peak


STAR preliminary
yield(Δφ,Δη)
■ Δφ(J+R)
▼ Δφ(J)
○ Δη(J)
Ridge yield
Jet yield
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
50
100
150
200
250
300
350
N_part


STAR preliminary
Ridge yield
0-10%
▲ 40-60%
○ 30-40%
■ 0-10%
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
2
3
4
5
6
7
8
9
p_t,trig

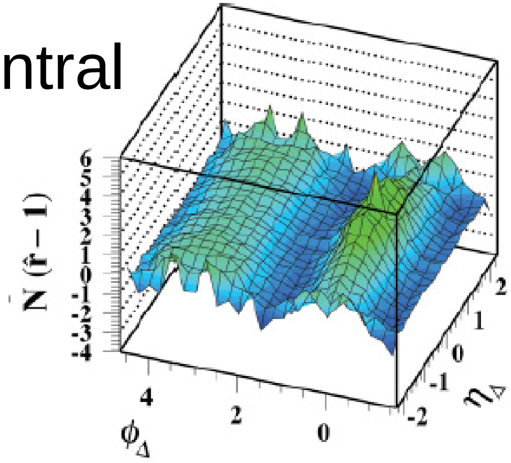

STAR preliminary
bulk
Jet fragment
ridge
Ridge yield (p_t,assoc. > p_t,assoc.,cut)
★ inclusive
● 4 < p_t,trig < 5
■ 5 < p_t,trig < 6
▲ 8 < p_t,trig < 12
1
10⁻¹
10⁻²
10⁻³
1.5
2
2.5
3
3.5
4
4.5
p_t,assoc.,cut


B/M
p + p̄/π⁺+π⁻
● AuAu 200
■ dAu
▲ p+p
Jet
Ridge
ridge
bulk
jet
STAR Preliminary
Au+Au 200 GeV Run IV
2.5
2
1.5
1
0.5
0
-0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
p_T (GeV/c)

Two-particle autocorrelation without a high-pT trigger

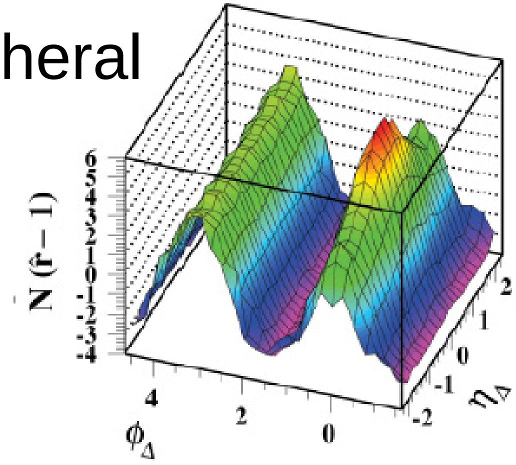
STAR (PRC73,064907('06))

central



(a)

peripheral



(c)

CMS pp data at 7 TeV

Results

Intermediate p_T: 1-3 GeV/c

MinBias high multiplicity (N>110

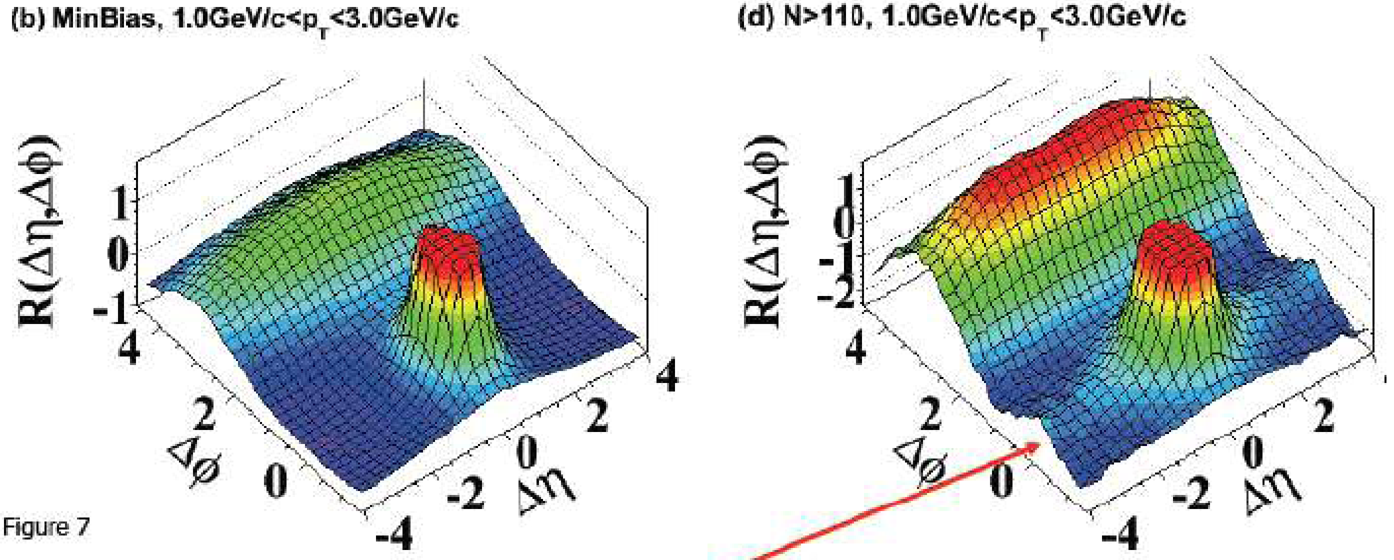
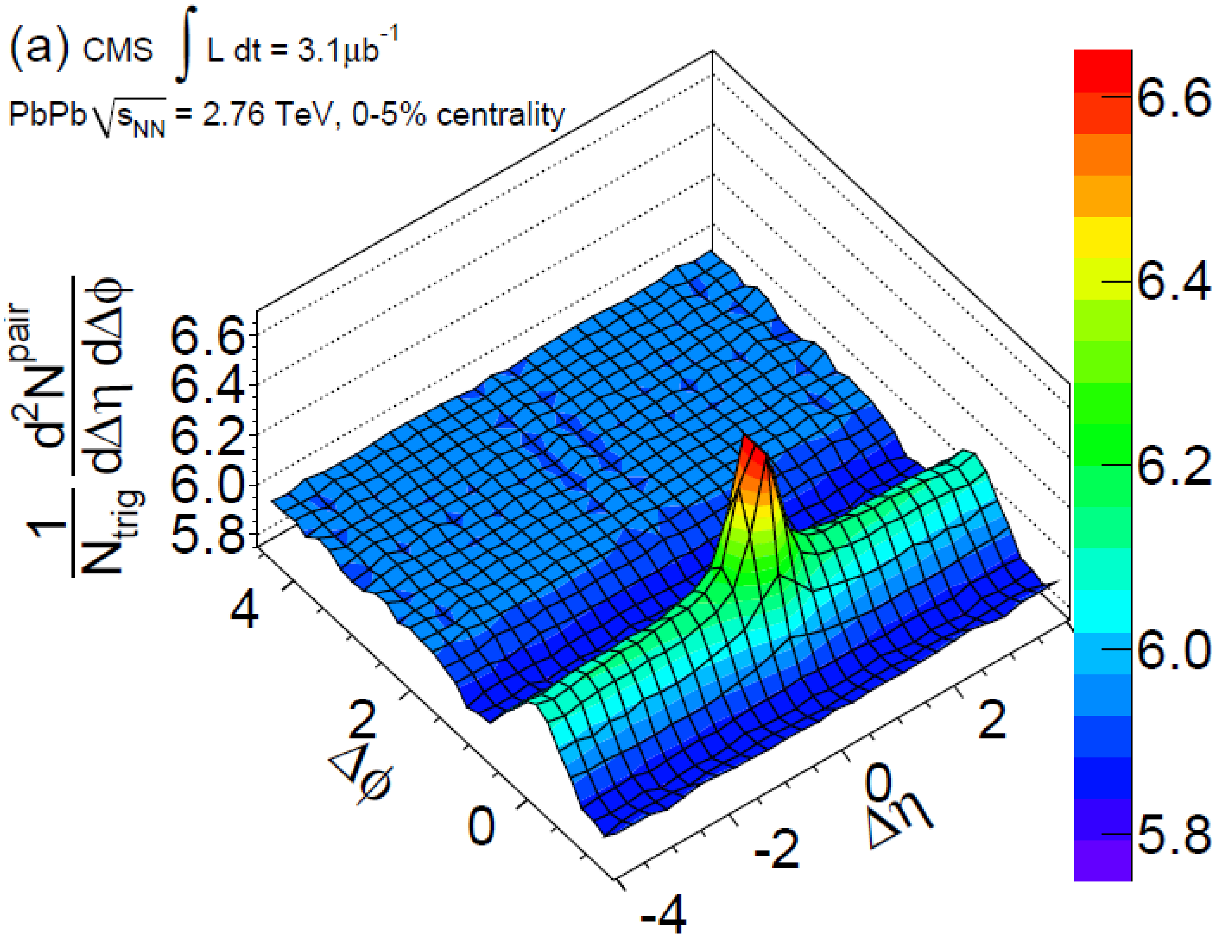


Figure 7

Pronounced structure at large $\delta\eta$ around $\delta\phi \sim 0$!

CMS PbPb data at 2.76 TeV, arxiv:1105.2438



The CMS ridge data raise many questions

1. Is the ridge for real (removed by v3,fluctuating initial conditions? etc) ?
2. How do the ridges arise in *pp* and *AA* collisions?
3. Can the ridges at LHC and RHIC be described by the same physical phenomenon?
4. If so, what are the similarities and differences?

5 Why is the ridge yield greatest at $1 < p_T < 3$ GeV/c?

6 What interesting physical quantities do the ridge data reveal?

7 What is the relationship between

the ridges with a high-p_T trigger

and the ridges in autocorrelation ?

Many Ridge Models (I)

- C.Y.Wong,PhyRevC76,054908('07);Chin.Phys.Lett.25,3936('08);PhysRevC78,064905
  8);J.PhysG35,104085('08);PhysRevC80,034908('09);PhysRevC80,054917('09)
- S.A.Voloshin, Phys. Lett. B632, 490 (`06)
- E. Shuryak, Phys.Rev.C76, 047901 (`07)
- V. S. Pantuev, arxiv:0710.1882('07)
- C. B. Chiu and R.C. Hwa, Phys. Rev. C76, 047901 ('08)
- N. Armesto, C. A. Salgado, U. A. Wiedemann, Phys.Rev.C76,054908('07)
- **A.Dumitru,Y.Nara,B.Schenke,M.Strickland,** Phys.Rev.C78,024909('08)
- A.Majumder,B.Mueller,and S.A.Bass, Phys. Rev. Lett. 99, 042301 ('07)
- **R.Mizukawa,T.Hirano,M.Isse,Y.Nara,A.Ohnishi,** J.Phys.G35,104083('08)
- **S.Gavin,L.McLerran,G.Moschelle,Phys.Rev.C79,051902('09)**
- A. Dumitru,F. Gelis, L. McLerran, and R. Venugoplan, **Nucl.Phys.A810,91('09)**
- **Y.Hama et al,arxiv:1012.1342**
- Jianyong Jia, Eur. Phys. J. C **61**, 255 (2009)
- A. Dumitru et al.,Phys. Lett. **B697** 21 (2011)
- K. Werner, Iu. Karpenko, K. Mikhailov,T. Pierog, Phys.Rev.C82,044904('10); arXiv:1104.3269
- R. C. Hwa, C. B. Yang, Phys. Rev. **C 83**, 024911 (2011)
- T. A. Trainor, arXiv:1008.4757

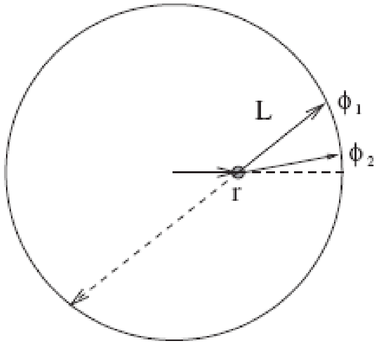
Many Ridge Models (II)

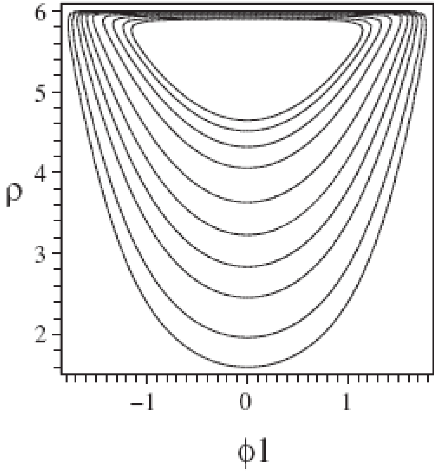
- B. A. Arbuzov, E. E. Boos, V. I. Savrin, arXiv:1104.1283
- M.Yu. Azarkin, I.M. Dremin, A.V. Leonidov, arXiv:1102.3258
- H. R. Grigoryan, Yuri V. Kovchegov arXiv:1012.5431
- I. Bautista, J. Dias de Deus, C. Pajares, arXiv:1011.1870
- I.O. Cherednikov, N.G. Stefanis, arXiv:1010.4463
- Igor M. Dremin, Victor T. Kim, arXiv:1010.0918
- E. Levin, A. H. Rezaeian arXiv:1105.3275
- B. Alver, G. Roland, Phys.Rev.C82, 034913(2010)
- B.A.Alver, C. Gombeaud, M. Luzum, J-Y. Ollitrault, Phys.Rev.C82, 034913(2010).
- Many more to come ………..

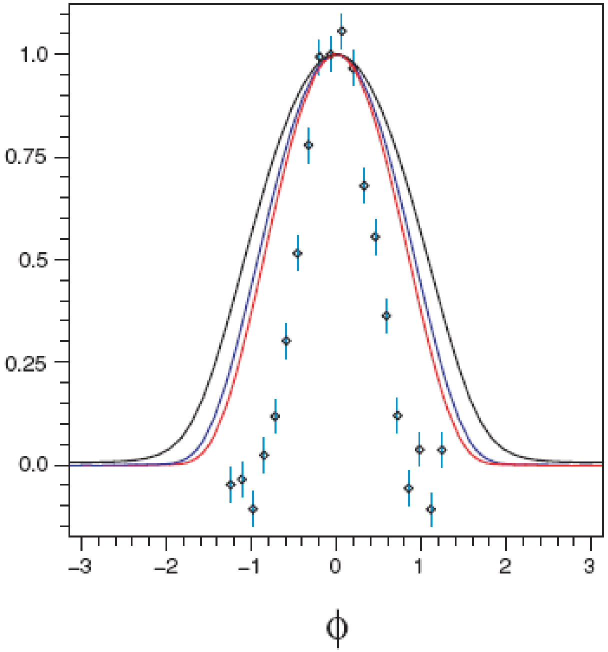
Types of models

- $\Delta\varphi$ correlation by flow
- $\Delta\varphi$ correlation by jet collisions
- etc,etc,etc

Transverse flow model (Voloshin & Shuryak)

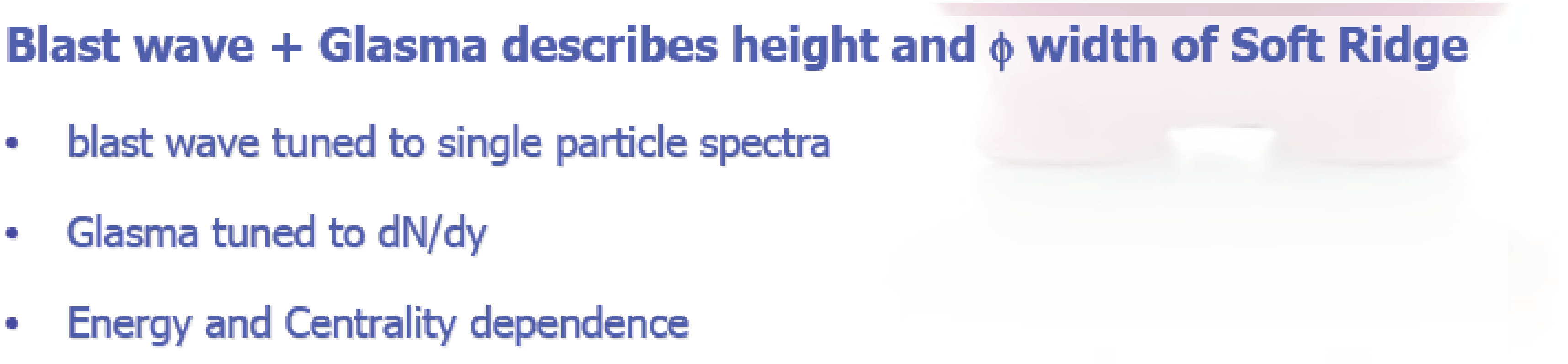






Width too wide?

Gavin,McLerran,Moshelli(BNLWorkshop’09)



Blast wave + Glasma describes height and ϕ width of Soft Ridge

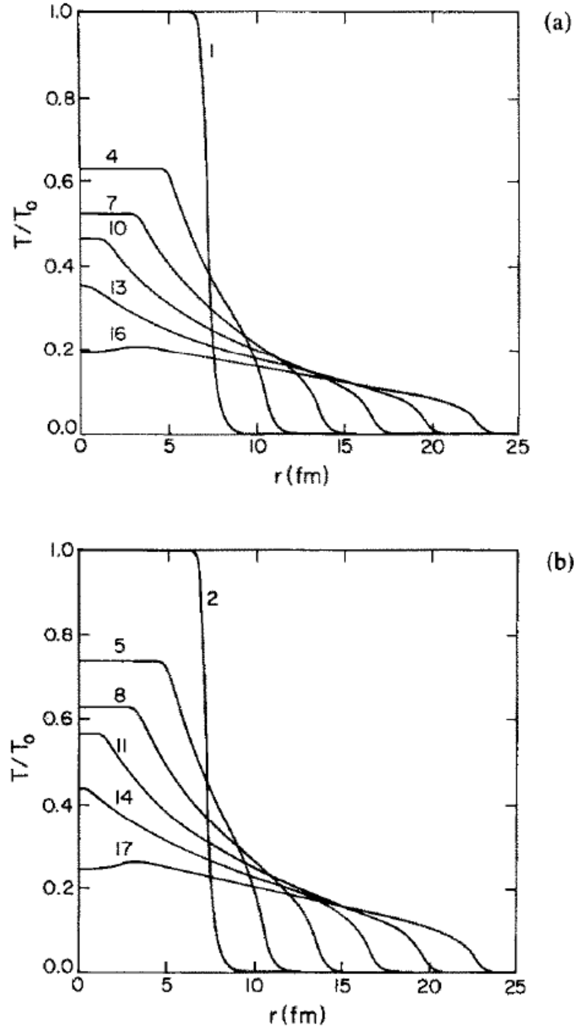
- blast wave tuned to single particle spectra
- Glasma tuned to dN/dy
- Energy and Centrality dependence

A.Dumitru,F. Gelis, L. McLerran, and R. Venugoplan, **Nucl.Phys.A810,91(’08)**

- Dumitru, K. Dusling, F. Gelis, J. Jalilian-Marian,T. Lappi, R. Venugopalan, Phys. Lett. **B697** 21 (2011)

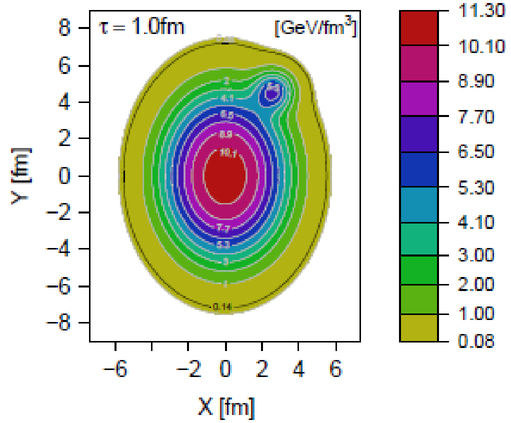
Δφ correlations occur by flow without a jet

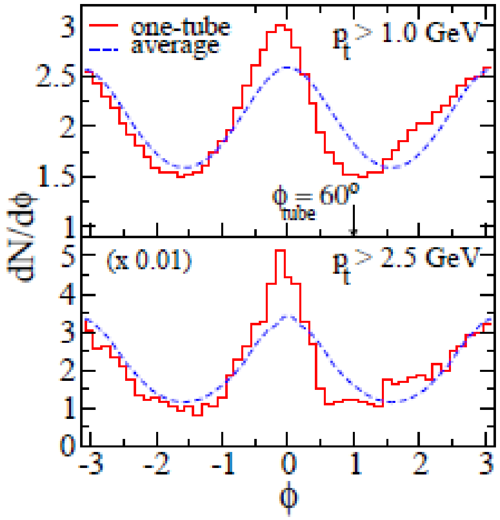
G. Baym et al. / Ultra-relativistic heavy ions 557

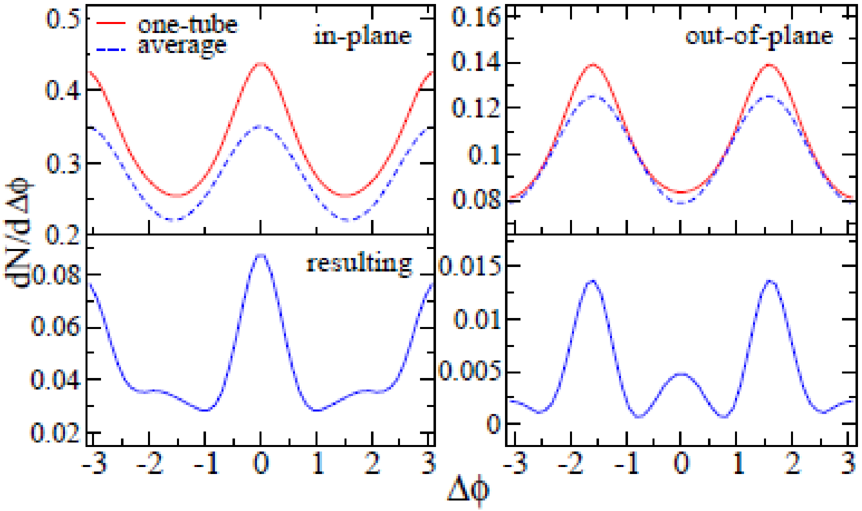


ig. 9. Temperature distributions as functions of r for cylindrical transverse expansion coupled to ongitudinal expansion. Each curve is labelled by the time (in fm) that has elapsed since the collision. In (a) hydrodynamic behavior is assumed to commence at $t_0 = 1$ fm, while in (b), $t_0 = 2$ fm.

Hama et al. `arxiv:1012.1342`

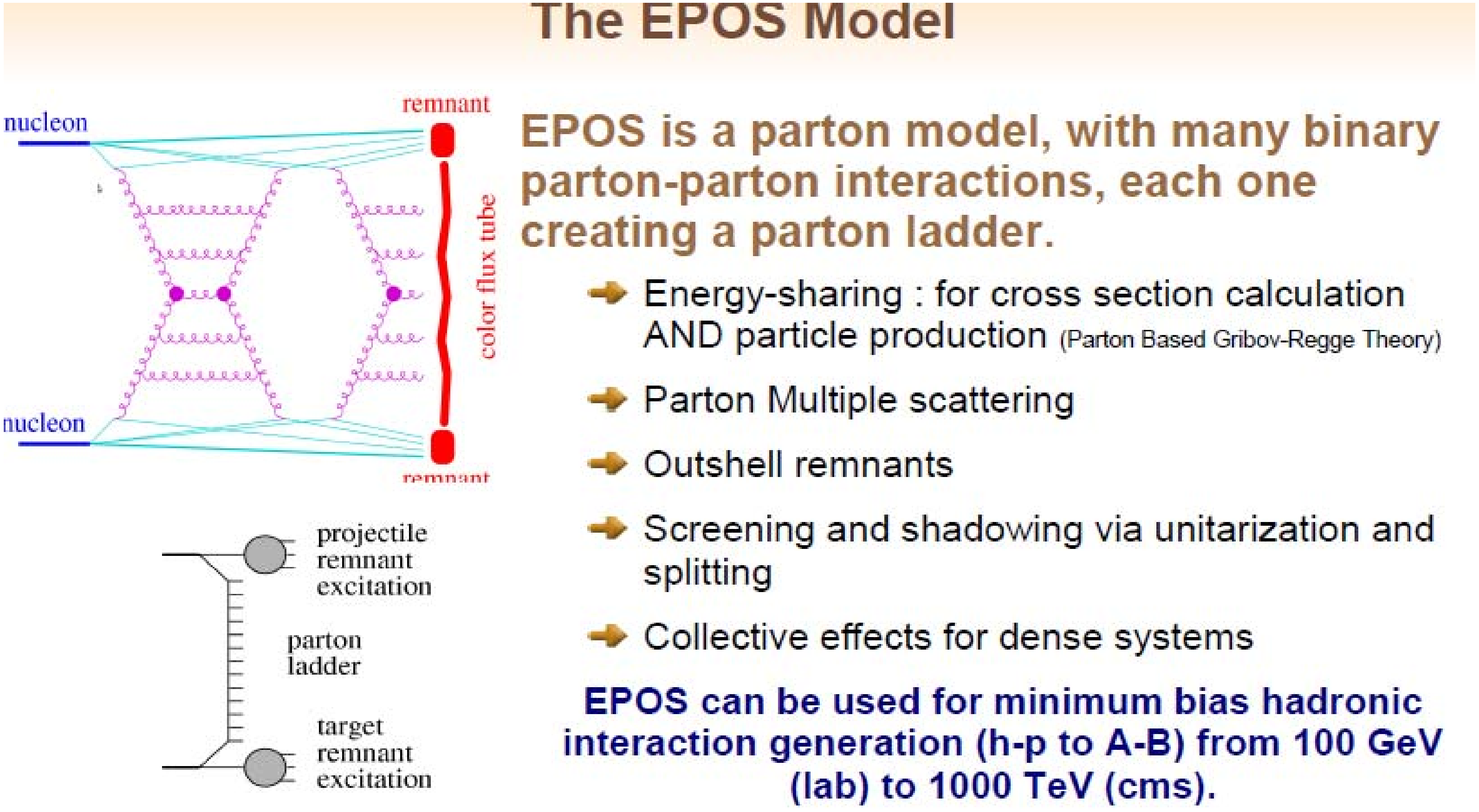






K. Werner, Iu. Karpenko, K. Mikhailov, T. Pierog,

Phys.Rev. C82 (2010) 044904, arXiv:1011.0375,1104.3269



The EPOS Model

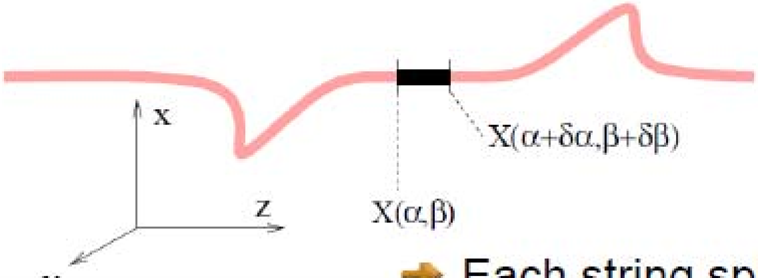
EPOS is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.

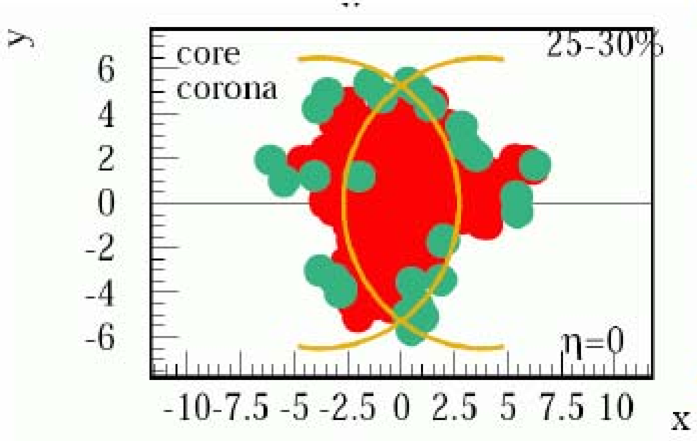
- Energy-sharing : for cross section calculation AND particle production (Parton Based Gribov-Regge Theory)
- Parton Multiple scattering
- Outshell remnants
- Screening and shadowing via unitarization and splitting
- Collective effects for dense systems

EPOS can be used for minimum bias hadronic interaction generation (h-p to A-B) from 100 GeV (lab) to 1000 TeV (cms).

High Density Core Formation

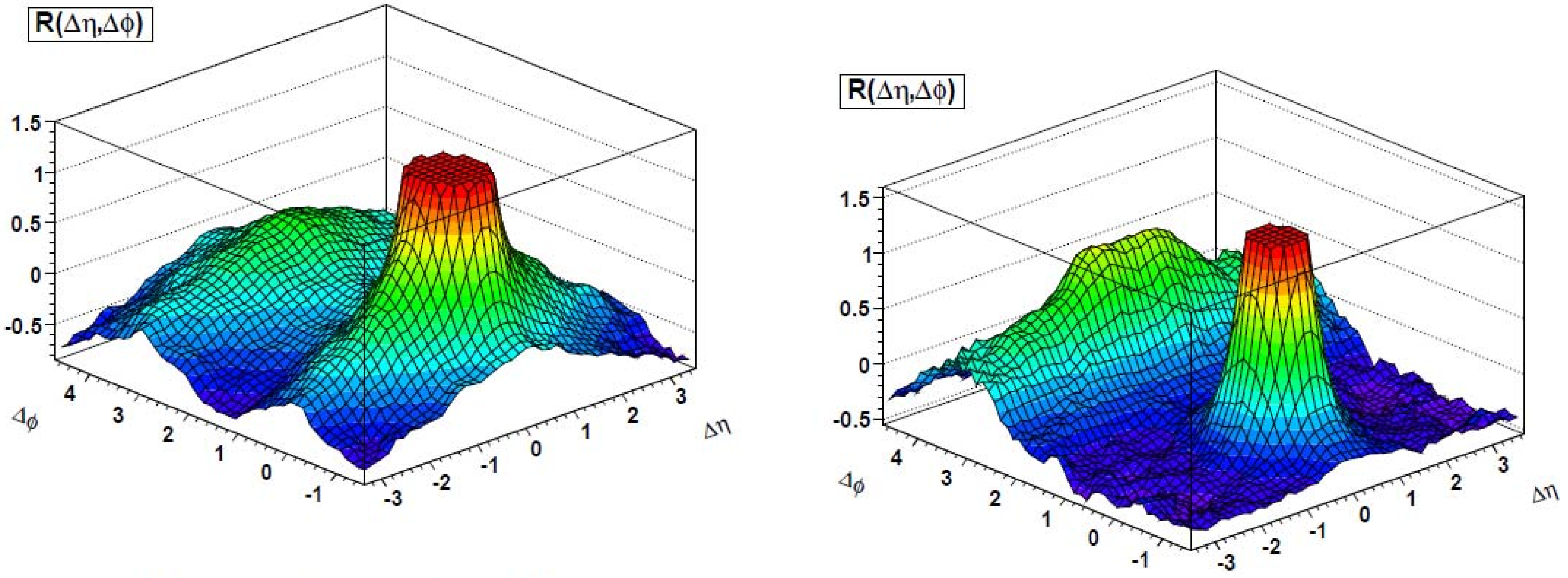
- **Heavy ion collisions or very high energy proton-proton scattering:**
  - the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently : core





- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
- If low density (corona)
  - segments remain hadrons

K. Werner, Iu. Karpenko, T. Pierog,(arxiv:1011.0375)



With hydrodynamical flow

No flow

Figure 1: (Color online) Two particle correlation function R

Theoretical EPOS results for pp at 7 TeV

EPOS theory

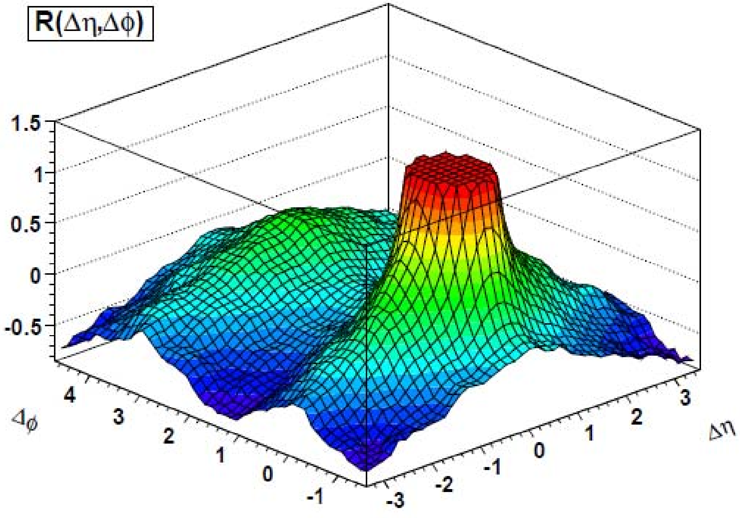
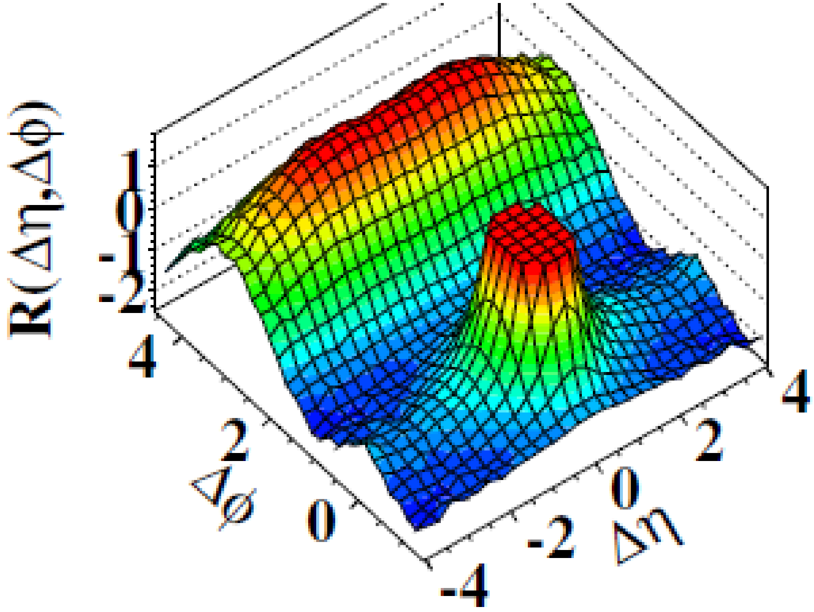


Figure 1: (Color online) Two particle correlation function R

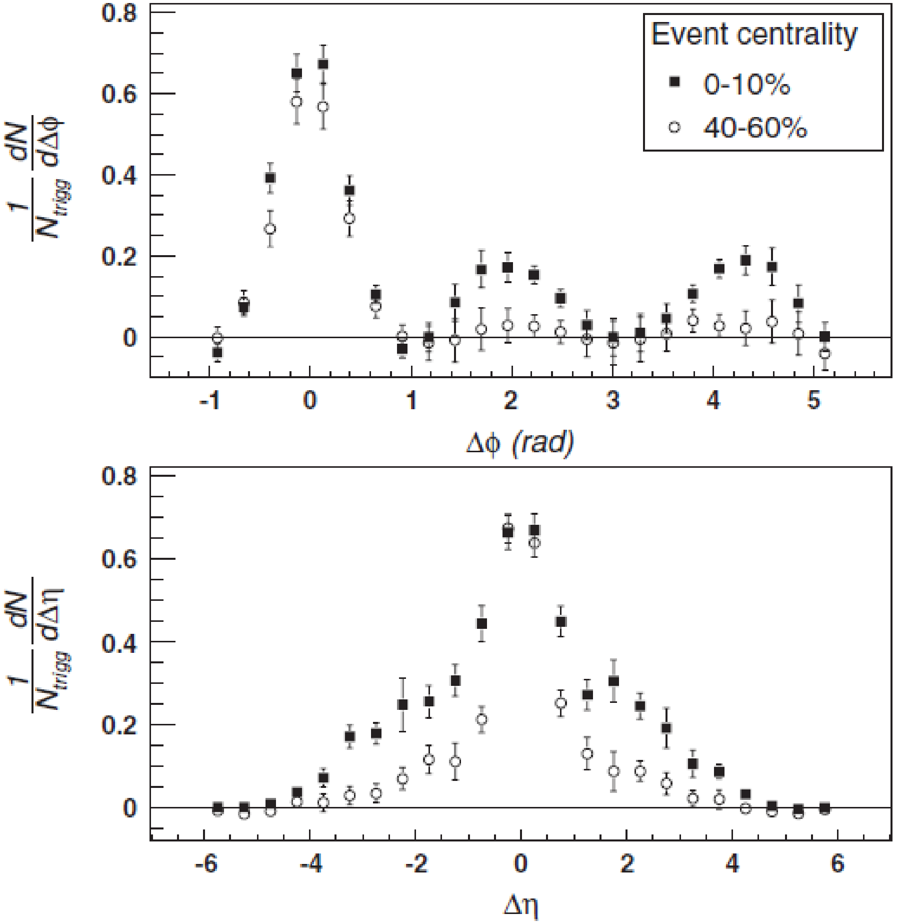
Experimental data

(d) CMS $N \geq 110$, $1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$



Fluctuating initial conditions can lead to two-particle correlations

J. Takahashi et al. PRL103, 242301 ('09)



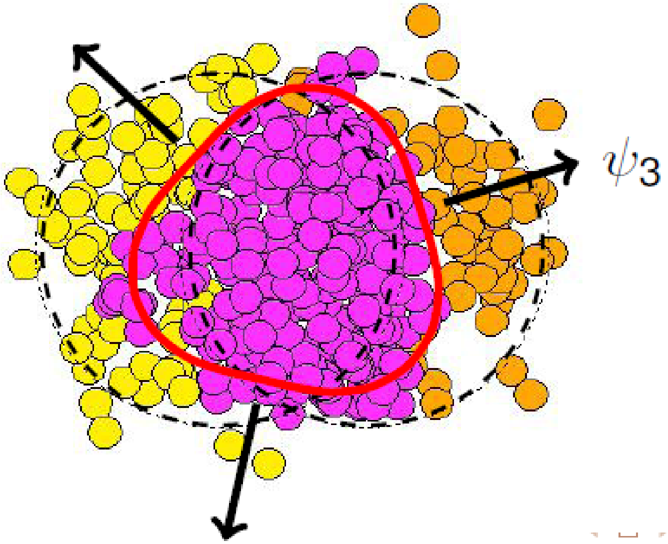
FLOW FLUCTUATIONS

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n \cos n(\phi - \psi_n)$$

$$\Longrightarrow \left\langle \frac{dN_{\text{pairs}}}{d\Delta\phi} \right\rangle \overset{\text{(flow)}}{\propto} 1 + \sum_{n=1}^{\infty} 2 \left\langle {v_n}^2 \right\rangle \cos n(\Delta\phi)$$

$$v_3 e^{3i\psi_3} \propto \varepsilon_3 e^{3i\Phi_3} \equiv -\frac{\{r^3 e^{3i\phi}\}}{\{r^3\}}$$

(Qin, Petersen, Bass, Muller, Phys. Rev. C 82, 064903 (2010); Qiu, Heinz, arXiv:1104.0650)



Remarks

Jets and minijets in the near-side lead to groups of particles in a pointed direction, and contribute to v3. They are not hydrodynamical flows. Experimental v3 may include a large contribution of jets and minijets that are not hydrodynamical.

Quantum mechanics has a tendency to smooth out classical granularity. Particles in a classical cascade calculations are not real particles. They are test particles. They are cells in the phase space of the Wigner function f(x,y). We need to use a large number of test particles to represent the Wigner function f(x,p) in a single calculation. [C.Y.Wong, Phys.Rev.C 25, 1460–1475 (1982)].

More work remains to look into the quantum treatment of the initial conditions from the Wigner function viewpoint!

Correlation coming from jet-medium collision

- Momentum kick model

  C.Y.Wong (Phys.Rev.C76,054908('07),….

  medium partons kicked by jet

- Local enhancement of temperature

  R.Hwa & C.B.Yang (Phys.Rev.C83,024911('10)

  medium partons gets higher temperature after the passage of jet

Experimental data implies that ridge particles are medium partons kicked by the jet

C.Y.Wong, Phy.Rev.C76,054908('07)

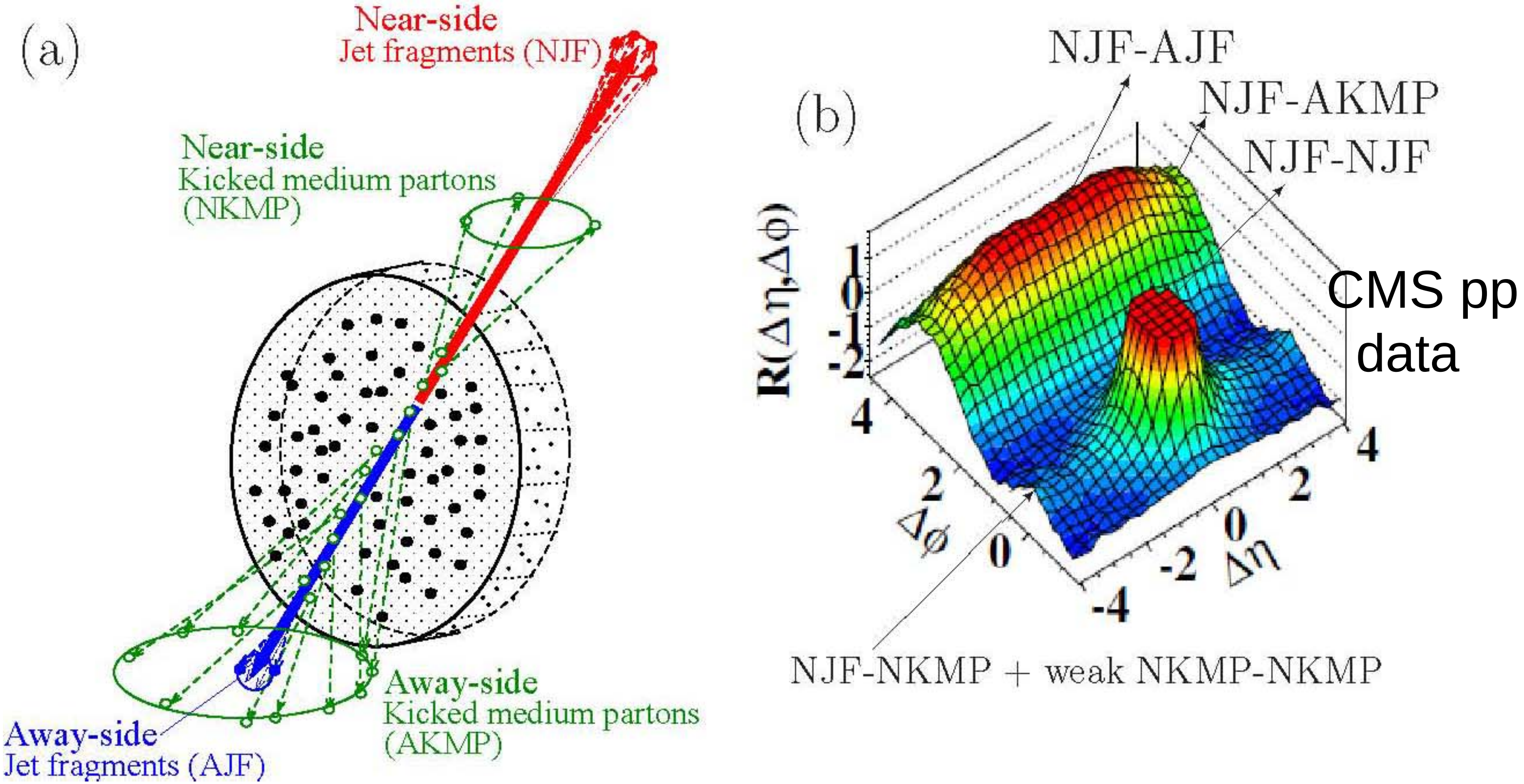
1. Ridge yield increases with increasing N_participants
2. Ridge yield nearly independent of the jet trigger properties
3. $T_{jet} > T_{ridge} > T_{bulk}$
4. $B/M|_{ridge} \sim B/M|_{bulk}$, but $B/M|_{jet} \neq B/M|_{bulk}$

   → ridge particles are medium partons
5. $\Delta\varphi \sim 0$ implies that the ridge particles acquire additional longitudinal momentum from the jet.

   → ridge particles and the jet are related by collisions
6. Ridge particles nearly flat in $\Delta\eta$

   → the flat $\Delta\eta$ comes from the ridge particles momentum distribution before they are kicked by the jet

Schematic picture of the momentum kick model



CMS pp
data

Wong, arxiv:1105.5871

Jet fragments come in high p_T and low p_T

Evidences:

1. STAR autocorrelation measurements with low pT particles show a (Δφ~0,Δη~0) minijet component
2. PHENIX two-particle correlations with trigger hadrons of pT down to 2 GeV gives

$$N_{JF} \sim 0.15 + (0.10/\mathrm{GeV}) \langle p_T^{trig} \rangle$$

which is non-zero even down to $\langle p_T^{trig} \rangle \to 0$

Therefore,

1. Both high pT hadrons and low pT hadrons can be used as markers for jet
2. Low pT hadrons can also come from the kicked medium partons.

High pT and low pT triggers

- High pT trigger gives the correlations of

  (Near-side jet fragment) - (Near-side jet fragment)
  (Near-side jet fragment) - (Near-side kicked medium parton)

- Low pT trigger gives the correlations of

  (Near-side jet fragment) - (Near-side jet fragment)
  (Near-side jet fragment) - (Near-side kicked medium parton)
  (Near-side kicked med parton) - (Near-side kicked med parton)

- For pp collisions, NKMP-NKMP contribution is small.

Momenum kick model unifies the description of ridges with high-pT and low-pT triggers

The momentum distribution in the momentum kick model consists of two components

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

$$=f_R\frac{2}{3}\langle N_k\rangle\left.\frac{dF}{d\Delta\eta\,d\Delta\phi\,p_t\,dp_t}\right|_{ridge}+f_{JF}\left.\frac{dN_{jet\ fragment}}{d\Delta\eta\,d\Delta\phi\,p_t\,dp_t}\right|_{jet\ fragment}$$

$\langle N_k\rangle$ is the number of kicked medium partons per jet

$\langle N_k\rangle$ depends on impact parameter

f_R and f_{JF} are the syrvival factor due to final state interactions.

$$\left.\frac{dF}{d\eta\,d\phi\,p_t\,dp_t}\right|_{ridge}=\left[\frac{dF}{dy_i d\phi_i p_{t\,i} dp_{t\,i}}\frac{E}{E_i}\right]_{\vec{p}_i=\vec{p}_f-q_L\vec{e}_{jet}}\sqrt{1-\frac{m^2}{m_t^2\cosh^2 y}}$$

Initial parton momentum distribution

We parametrize the shape of the initial parton distribution by

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

A is a normalization constant such that

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

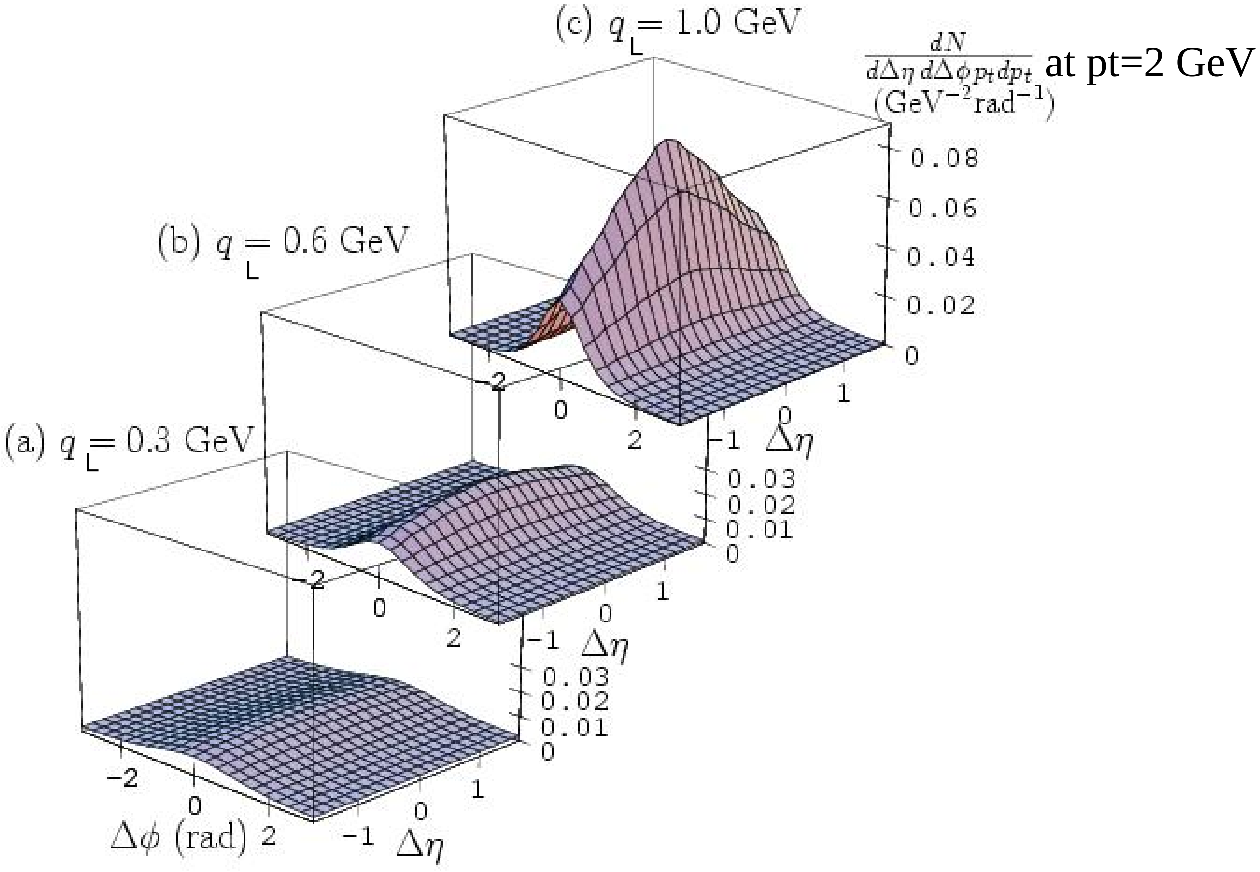
$$x = \frac{(p_0+p_z)_{parton}}{(p_0+p_z)_{parent}} = \frac{\sqrt{m^2+p_t^2}}{m_b}\exp\{|y|-y_B\} \le 1$$

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

The parameters are:

$$a,\ T_{MP},\ m_d$$

The width in Δφ depends on the magnitude of q_L.



The pp near-side jet data can be described by

$$\left.\frac{dN_{jet\ fragment}}{d\Delta\eta d\Delta\phi p_t dp_t}\right|_{\rm pp} = N_{JF} A_{JF} \exp\left\{-\sqrt{m^2+p_t^2}/T_{JF}\right\} \frac{\exp\left\{-\left((\Delta\varphi)^2+(\Delta\eta)^2\right)/2\sigma^2\right\}}{2\pi\sigma^2}$$

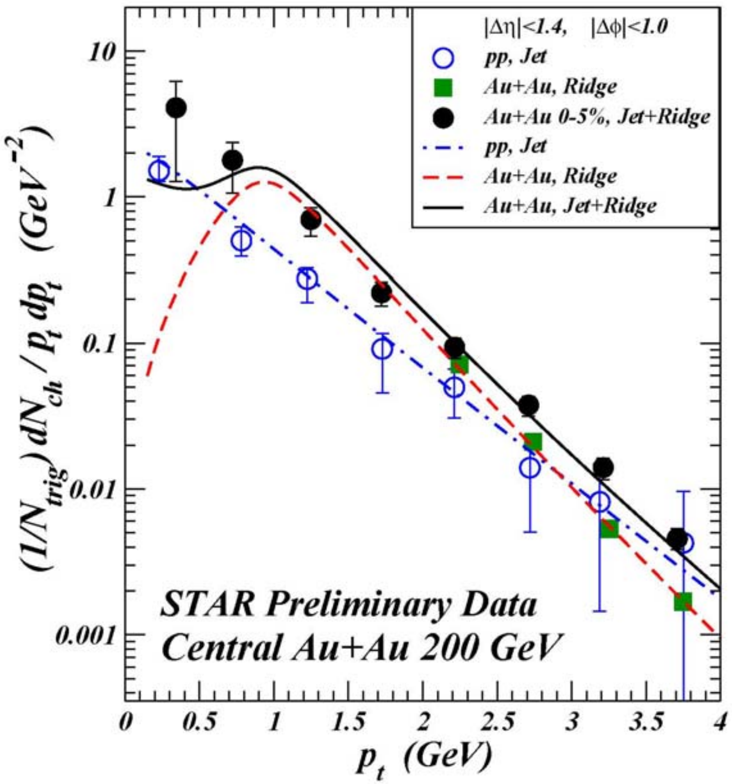
$$A_{JF} = \frac{\exp\{m/T_{JF}\}}{T_{jet}(m+T_{JF})} \text{ is a normalization constant,}$$

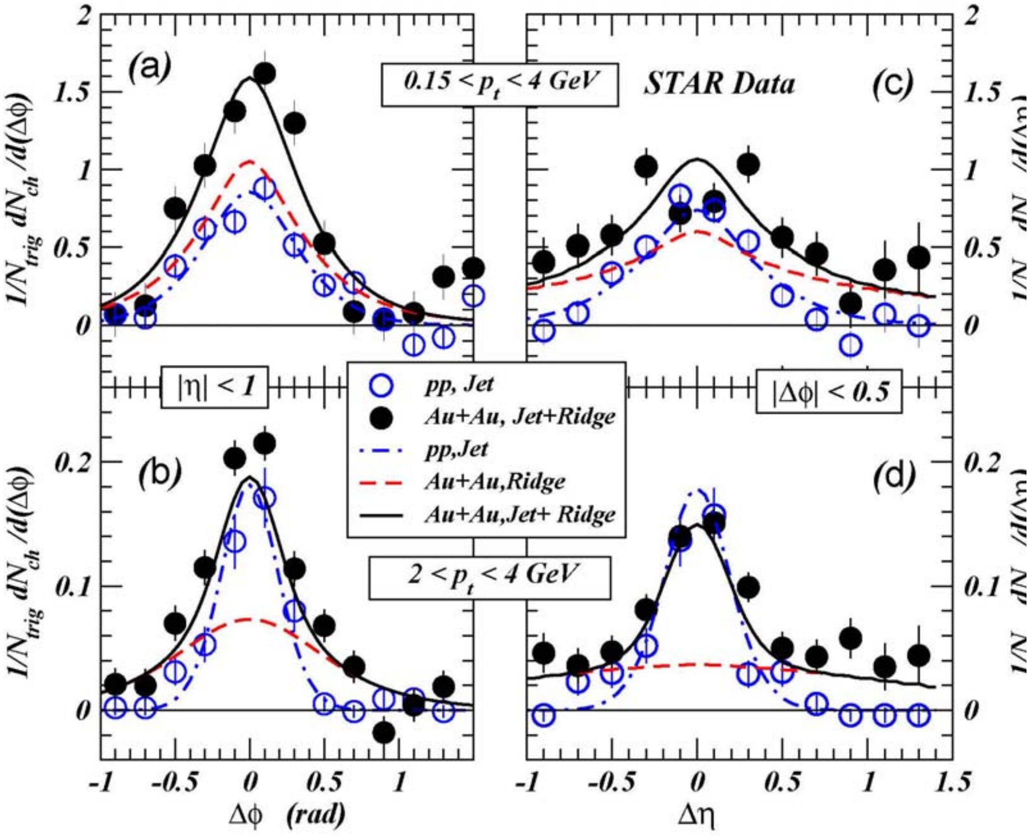
$$\sigma = \sigma_0 \frac{m_a}{\sqrt{m_a^2+p_t^2}},$$

Parameters are: N_{JF}, T_{JF}, σ_0 and m_a.

Empirically, N_{JF}, T_{JF} are linear function of p_t^{trig}.

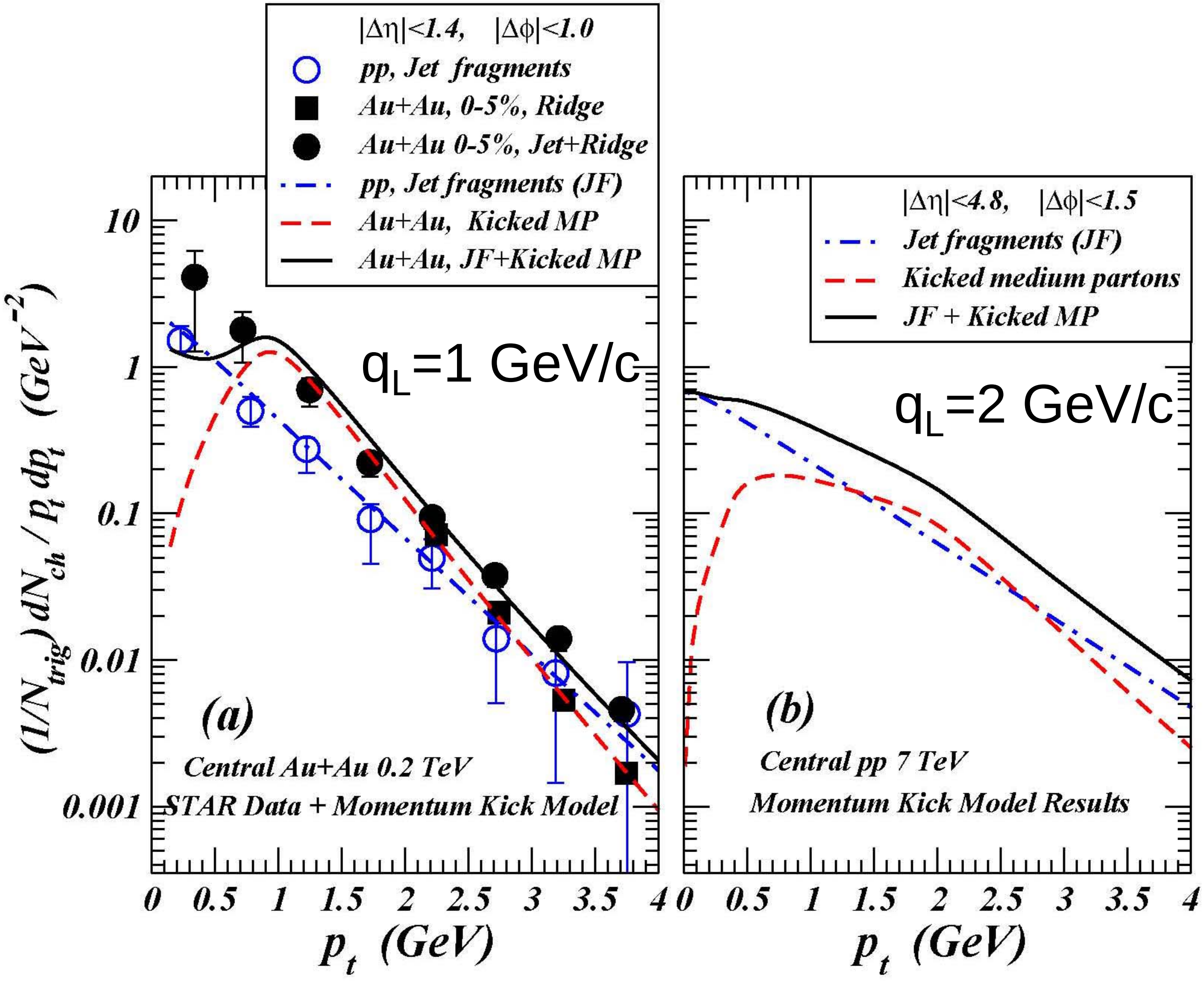
Momentum Kick Model explains STAR ridge data



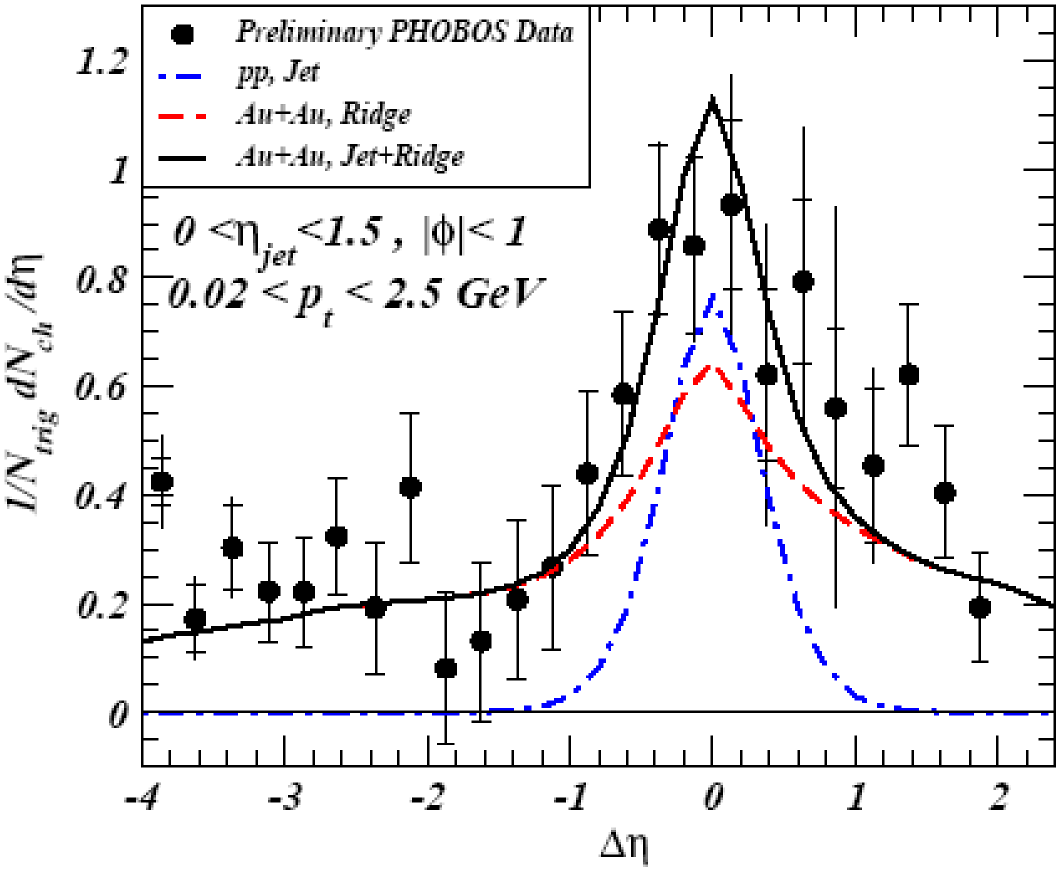


Data from
PRL95,152301(05) & J. Phy. G34, S679 (07)

Why is the ridge mpost prominent between 1<pT<3 GeV/c?

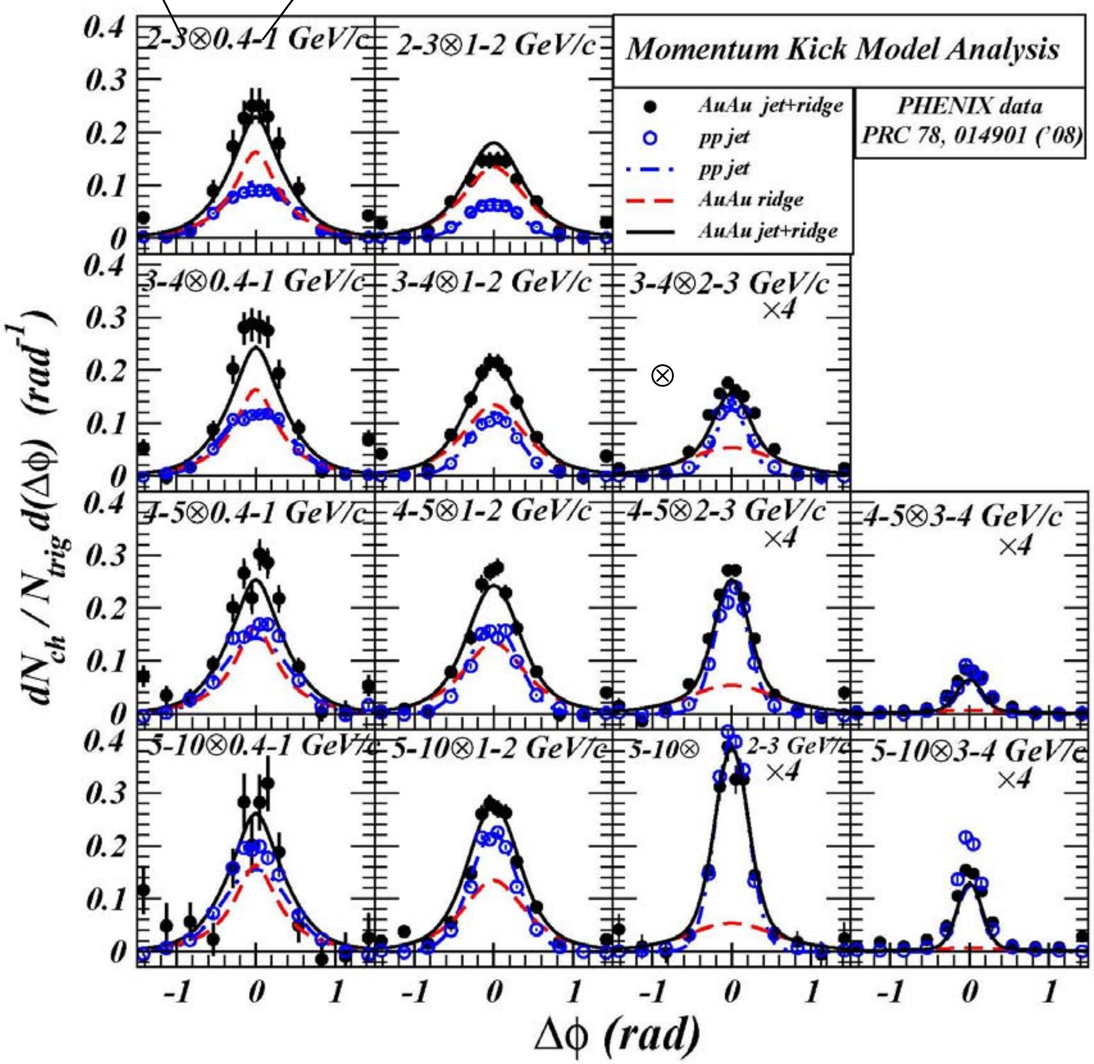


Momentum kick model gives the correct prediction for PHOBOS

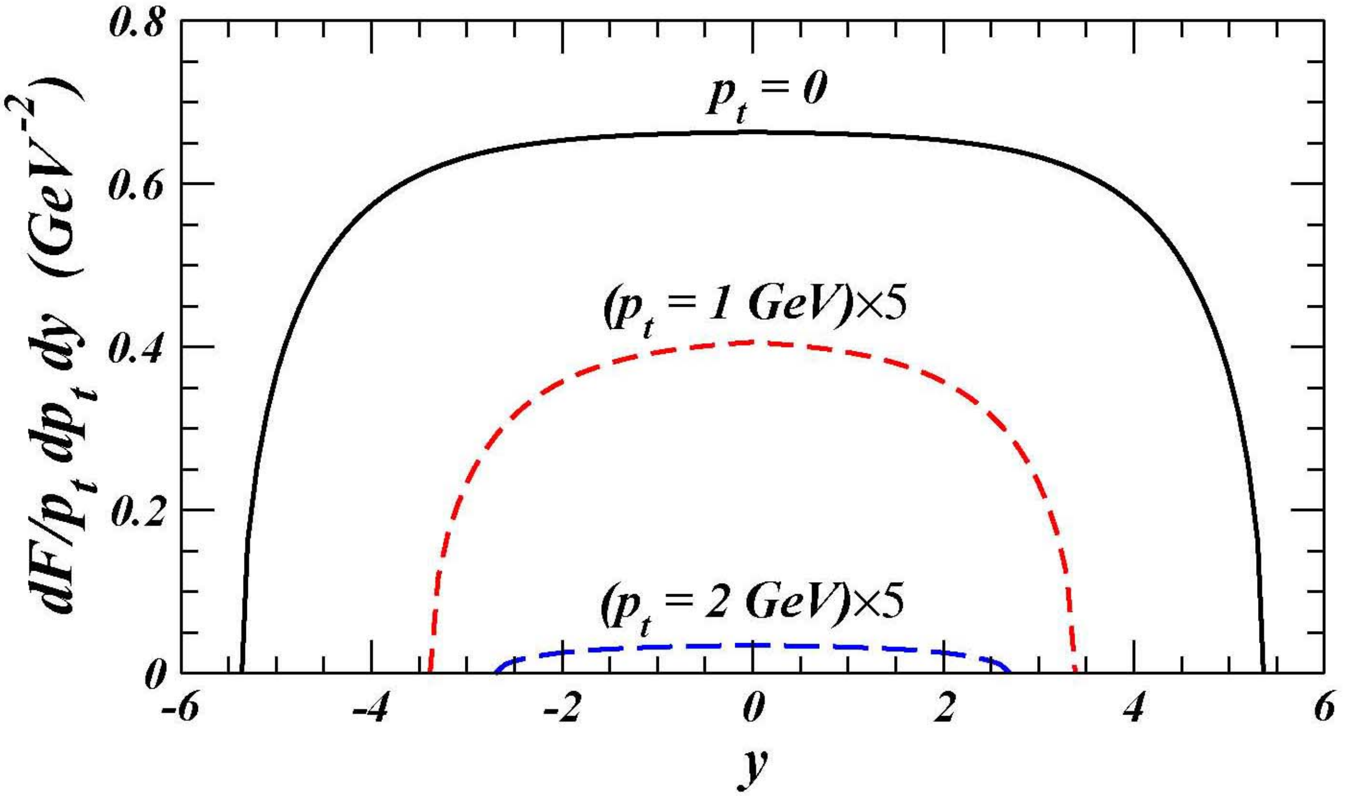


Momentum Kick Model explains PHENIX ridge data

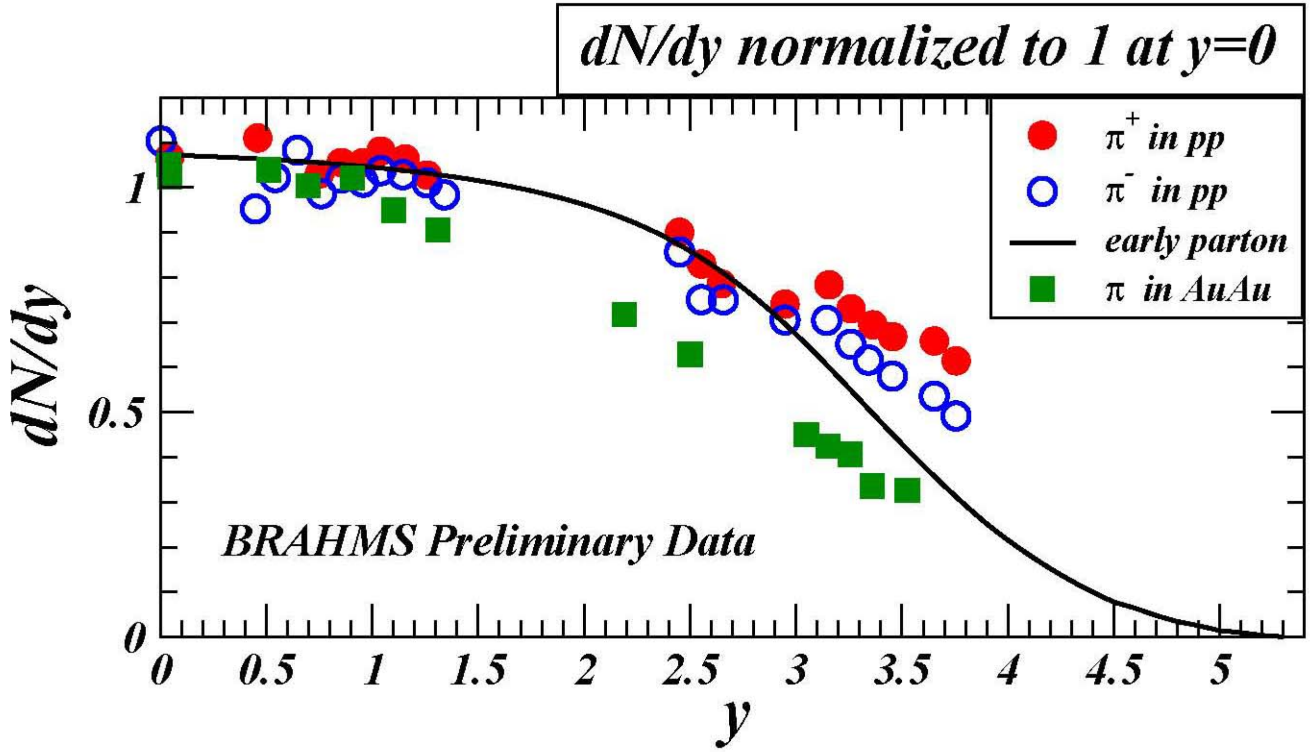
p_t^{trig} p_t^{assoc}



Early parton rapidity distribution has a plateau structure

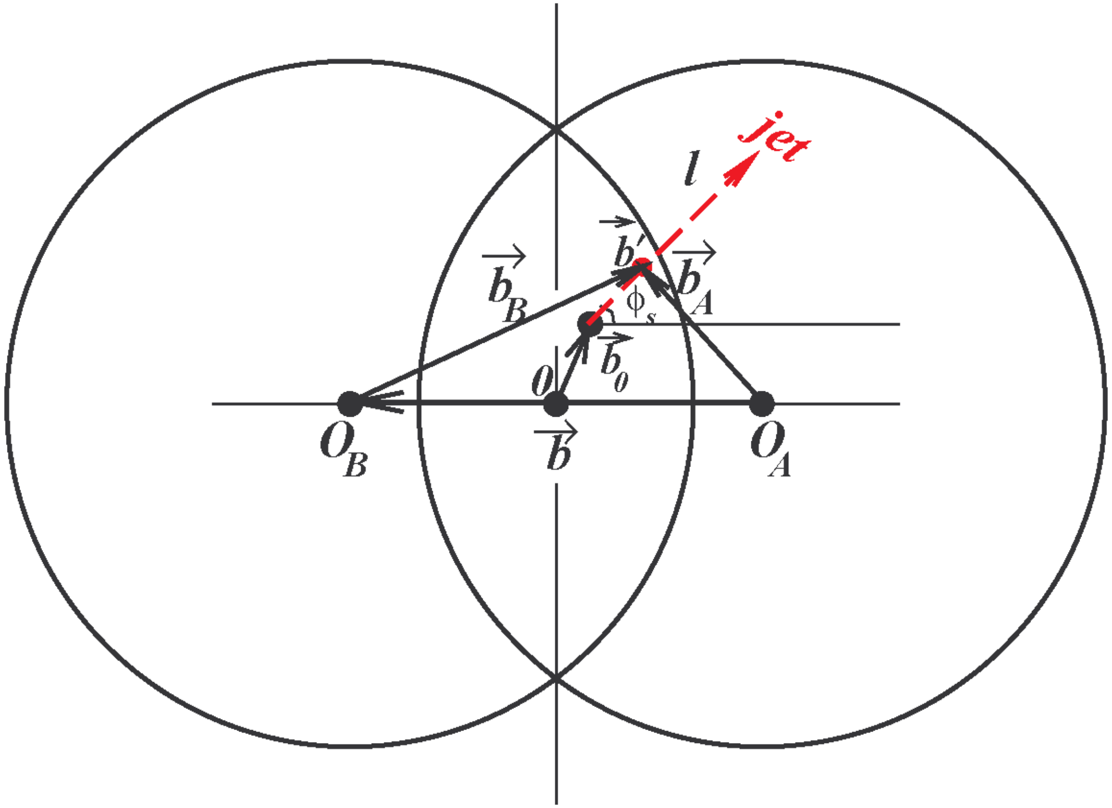


Early parton rapidity distribution is intermediate between those of pp and AA collisions

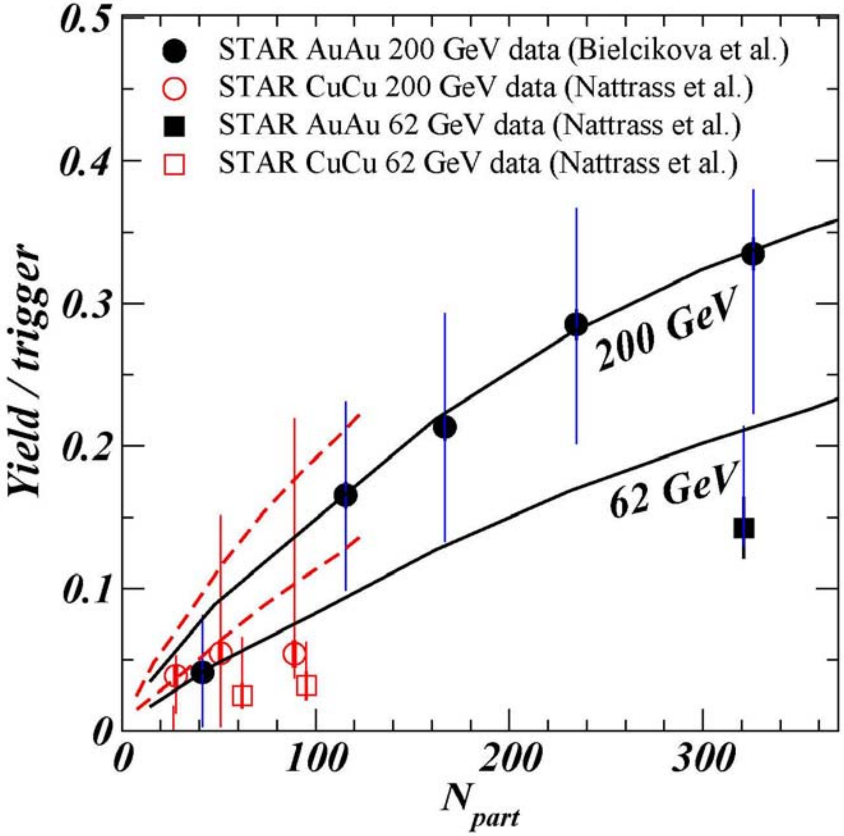


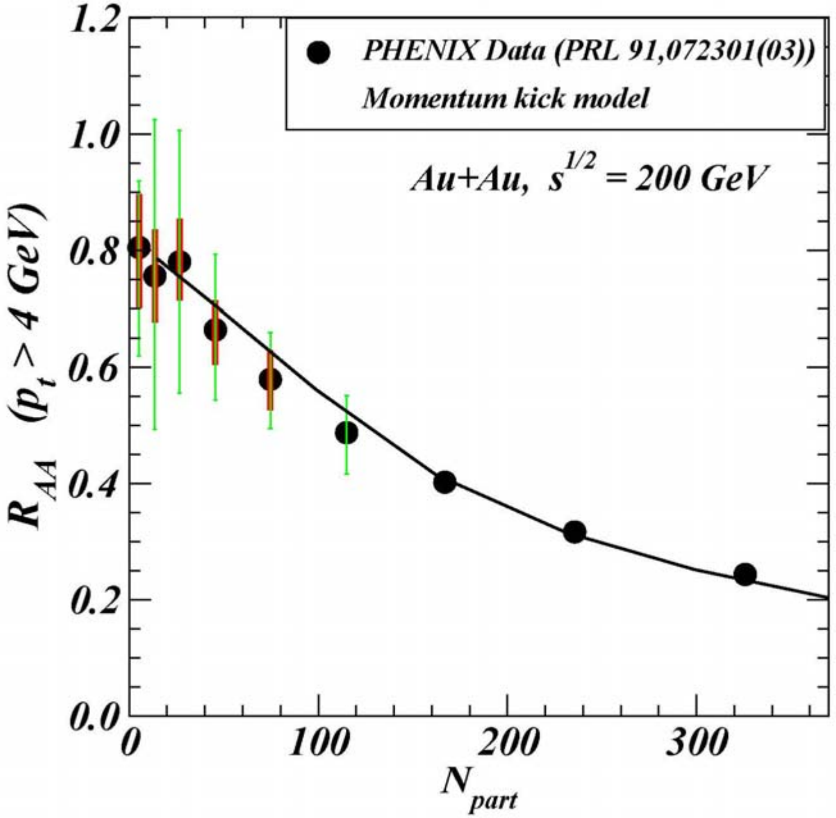
This is consistent with the direction of the evolution of the parton rapidity distributions.

We need jet trajectory calculation to get $<N_k>(b)$.



Energy dependence, mass dependence and RAA are well reproduced in the momentum kick model





We obtain the jet-(medium parton) cross section & rate of absorption

Important information extracted from near-side ridge data at $s^{1/2}$=200 GeV

1 The rapidity distribution of early partons has a plateau structure

2 q_L=0.8-1.0 GeV, longitudinal momentum kick per parton-parton collision

3 $f_R <N_k> =$ 3.0-3.8 for the most central Au+Au collisions

4 The inverse slope T_{MP} for early partons is intermediate between T_{JF} and T_{bulk}

5 The jet-(medium parton) cross section and rate of absorption in jet-(medium parton) collisions

Momentum kick model analysis of CMS pp data

C.Y.Wong arxiv:1105.5871

- We get the size of proton from pp cross sections. We find that R~0.8 fm at 7 TeV
- We get the density of partons from Landau model prediction of average multiplicity N_ch~120 and participant calculations of proton as Chou-Yang droplets.
- We need to extend the longitudinal momentum

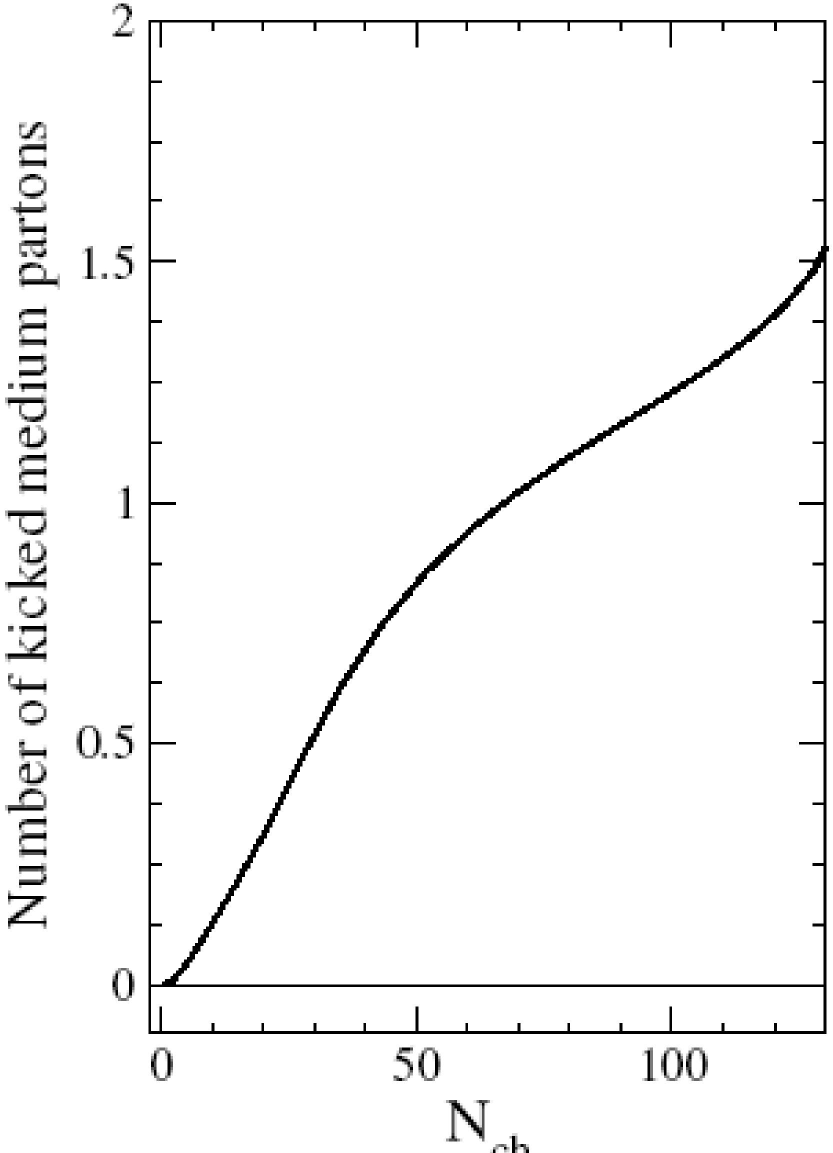
by the beam rapidity, and scale quantities that depend on the transverse momentum by

$$\langle p_T(\mathrm{LHC})\rangle/\langle p_T(\mathrm{RHIC})\rangle \sim 1.4$$

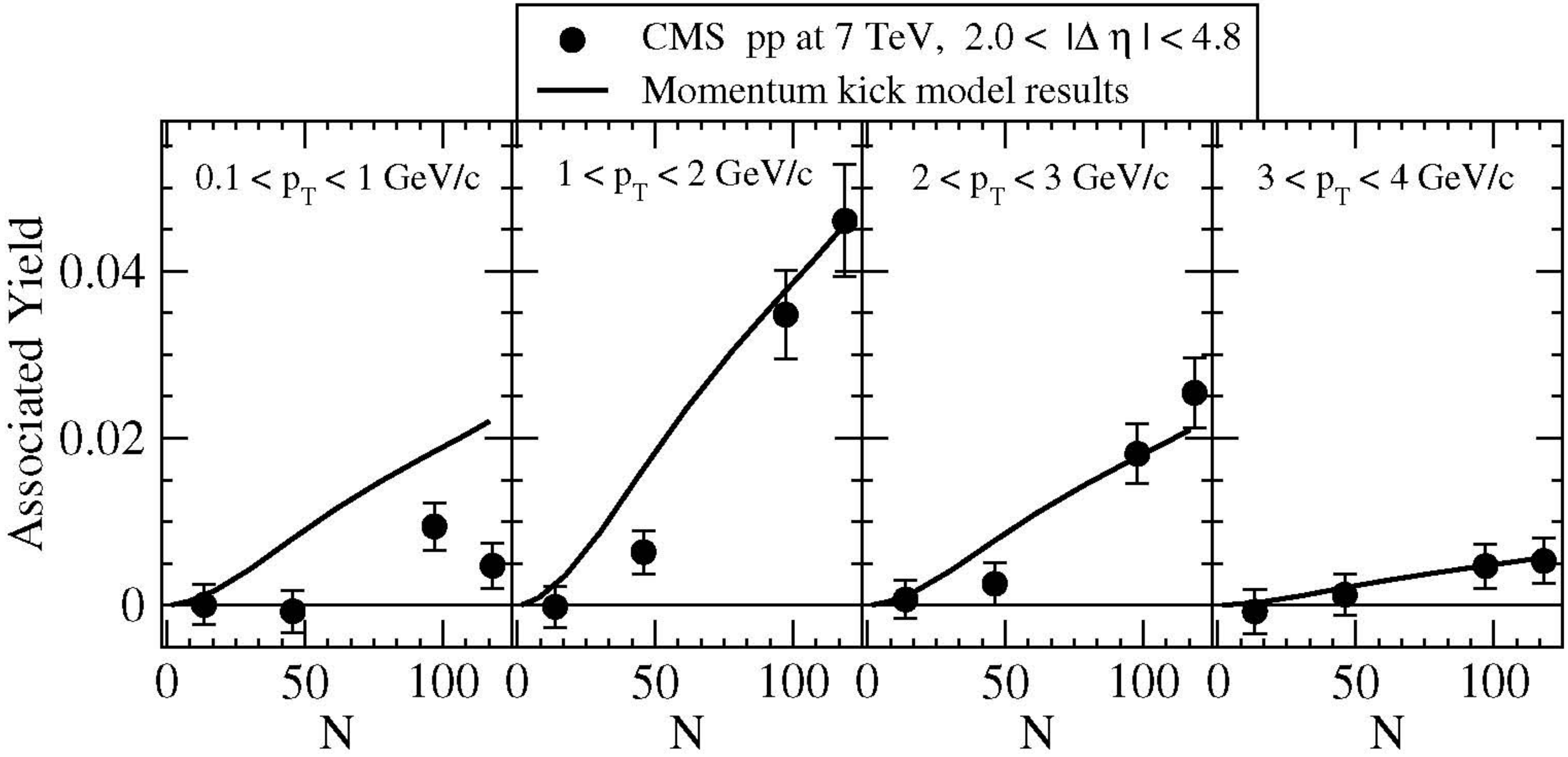
Then there is only one free parameter, q_L=2.0 GeV,

which is greater than q_L=0.8-1.0 GeV for RHIC.

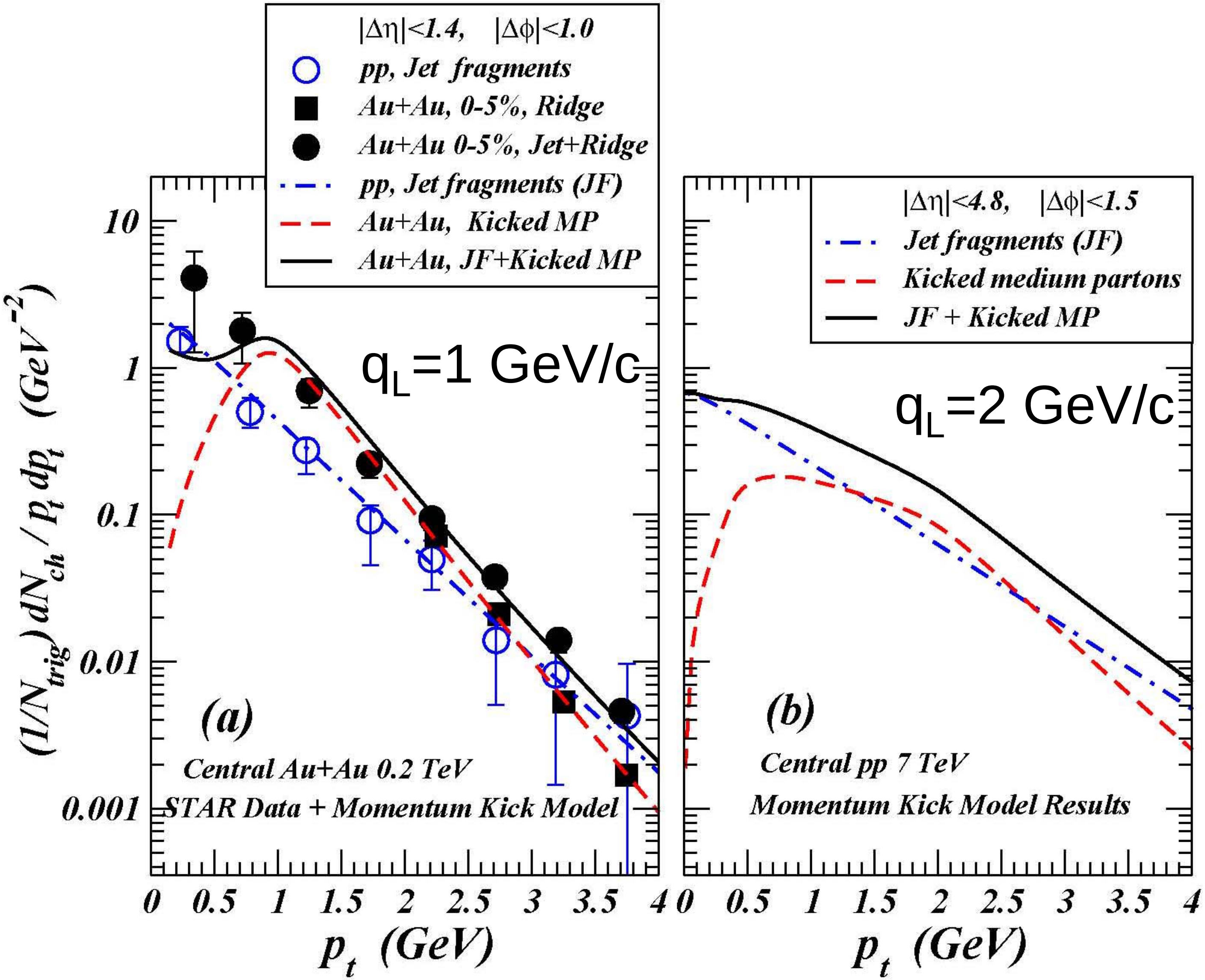
Results of jet trajectory calculation



Momentum kick model results for pp collisions at 7 TeV

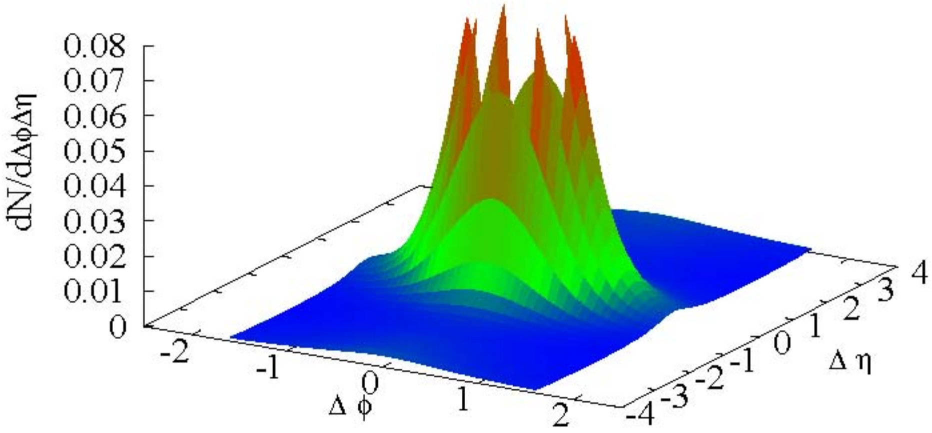


Why is the ridge most prominent between 1<pT<3 GeV/c?

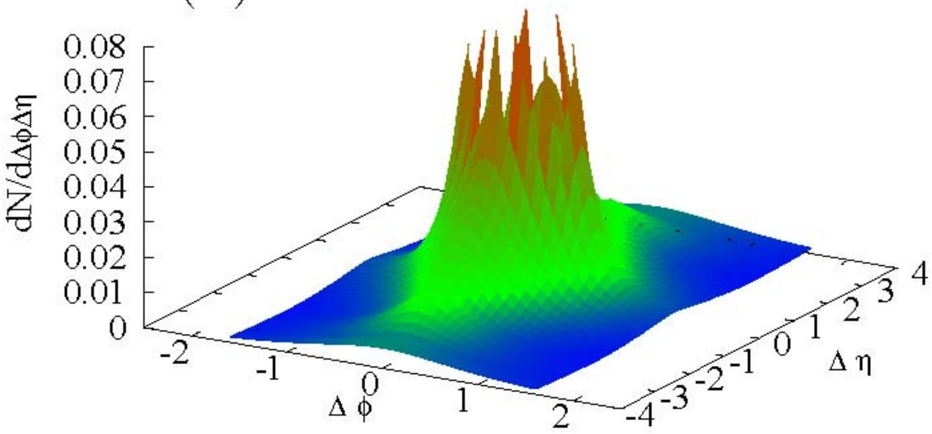


The momentum kick model results for the distribution in (Δφ, Δη) (with the top truncated)

(a) pp at 7 TeV, $0.1 < p_T < 1$ GeV/c



(b) pp at 7 TeV, $1 < p_T < 3$ GeV/c



Conclusions

- Many ridge models and many questions on the extraction of the ridge

In the momentum kick model

- The ridge particles associated with the near-side jet in AA collisions at RHIC and in pp collisions at LHC can be described as medium partons kicked by the jet

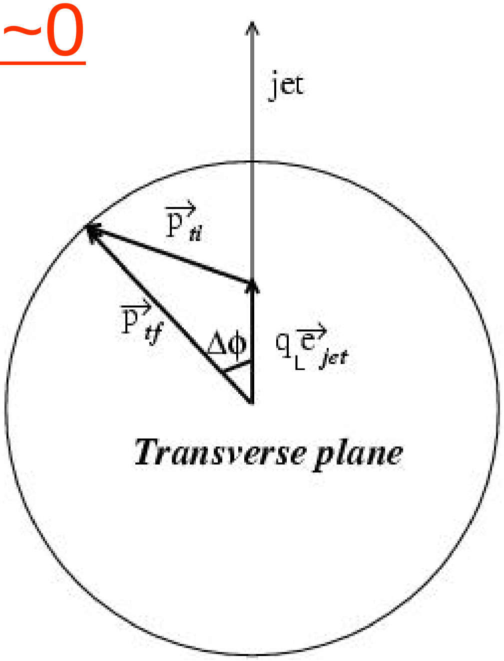
- They carry information on the early parton momentum distribution and the magnitude of the momentum kick.

- The momentum kick model provides a unified description of the ridges in high pT and low pT.

Backup slides

Ridge yield is a maximum at Δ φ ~0

$$\vec{p}_{t\,f} = \vec{p}_{t\,i} + q_L\,\vec{e}_{jet}$$



For the same magnitude of $|\vec{p}_{t\,f}|$ but different $\Delta\phi$, the magnitude of $|\vec{p}_{t\,i}|$ is smallest when $\Delta\phi = 0$.

The probability of initial partons with $\vec{p}_{t\,i}$ is

$$\frac{dN_i}{p_{t\,i}dp_{t\,i}} \propto \frac{\exp\left\{-\left(\sqrt{m^2+p_{t\,i}^2}-m\right)/T\right\}}{\sqrt{m_d^2+p_{t\,i}^2}}.$$

Therefore, the ridge particle yield is a maximum at $\Delta\phi \approx 0$.

There can be systematic errors in the ZYAM ridge yields