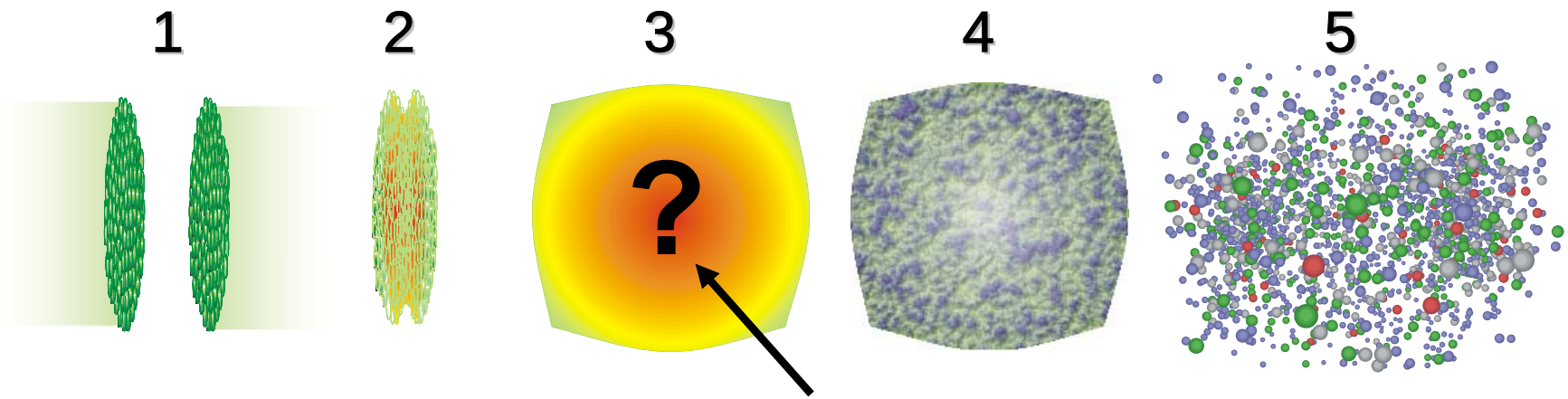
Medium Response Measurements

An experimental overview of interactions with the medium at RHIC

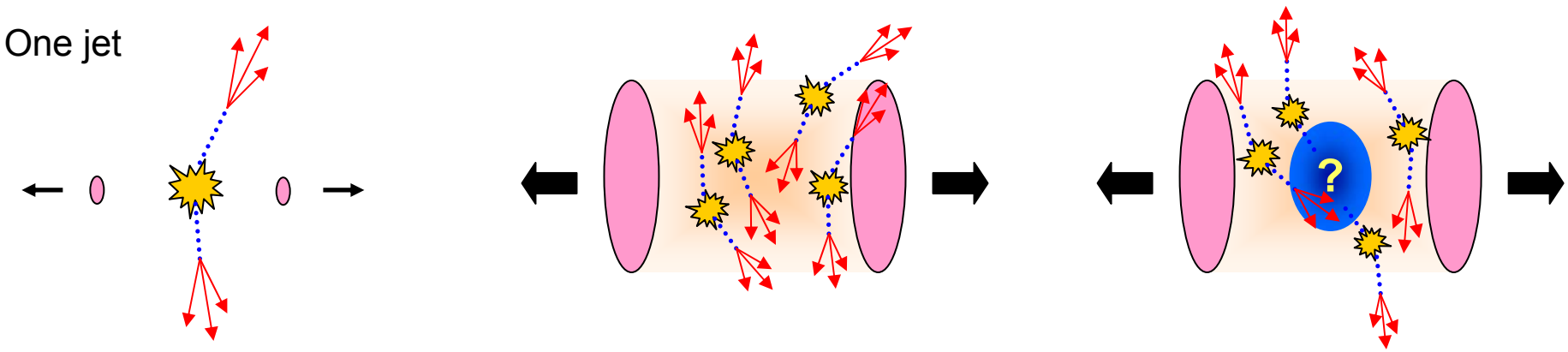
Michael Daugherity – University of Texas

Jet-Medium Interactions



Creation of a nuclear or partonic medium

Use jet interactions to probe the medium



proton-proton

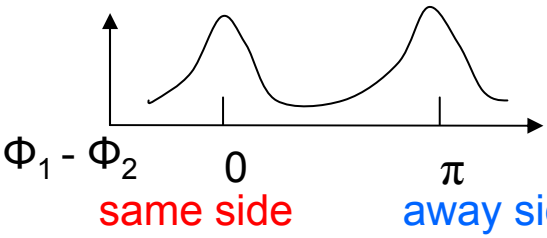
Au-Au as many p-p collisions

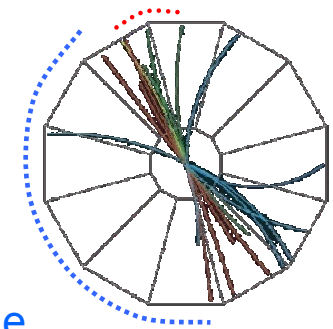
Au-Au with medium

Jet Correlations 101

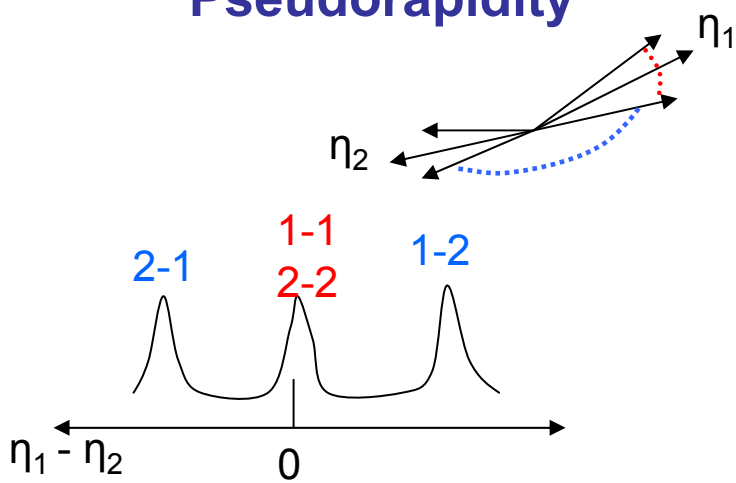
What do jet correlations look like? Use proton-proton as a reference…

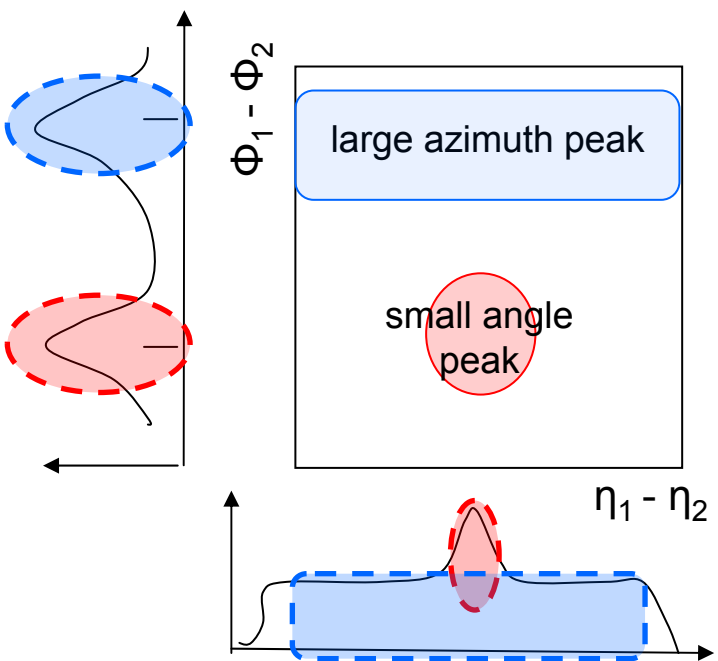
Azimuth



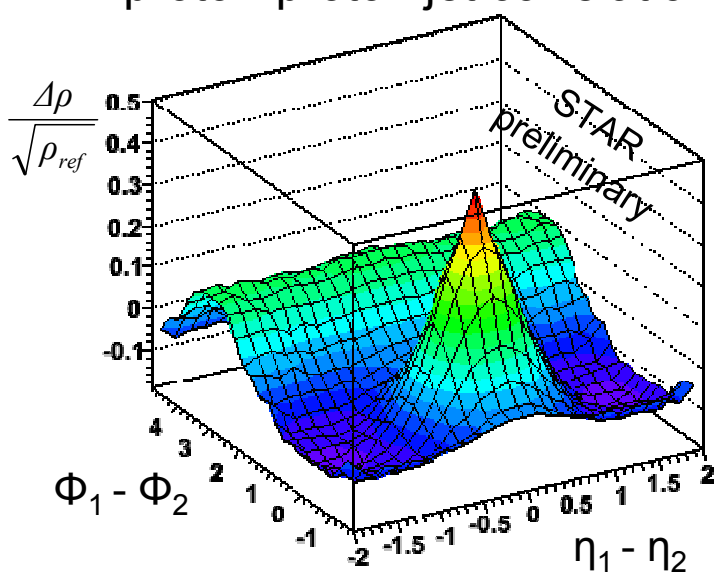


Pseudorapidity



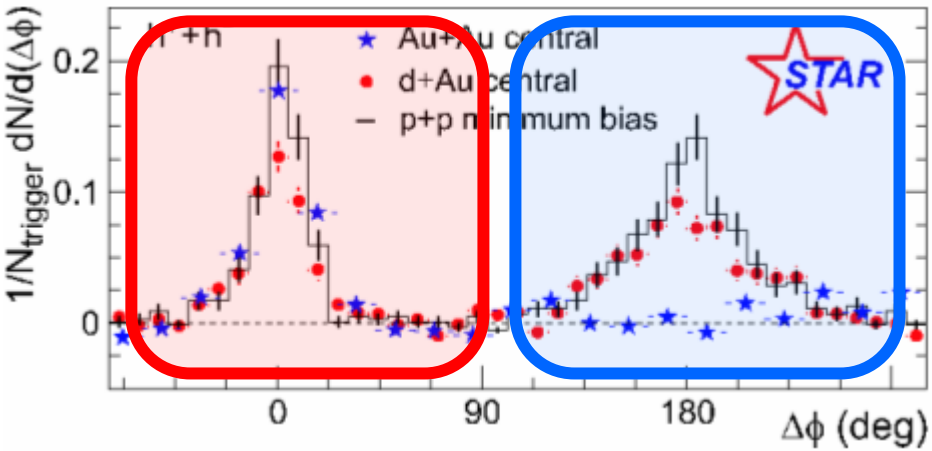


proton-proton jet correlation



Revisiting An Old Story

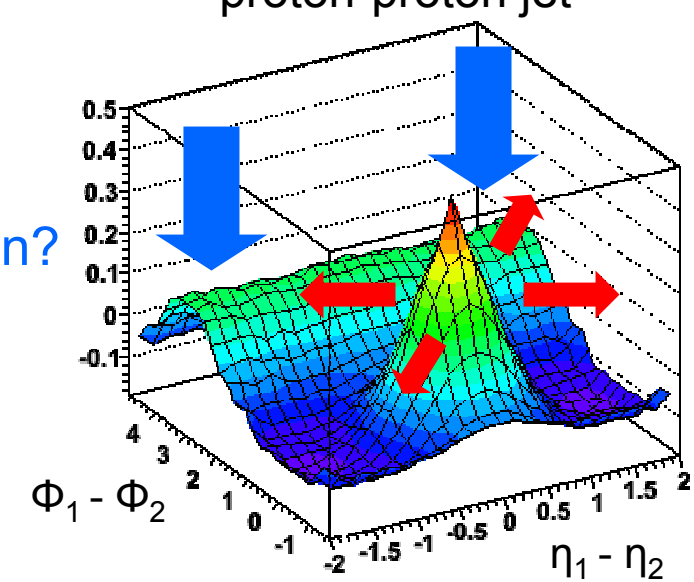
PRL 91 072304



Overview of this talk

- Are the same-side jets really identical?
- What happens to the away-side jets?
- Can we see other effects of the medium?

proton-proton jet



suppression?

interactions?

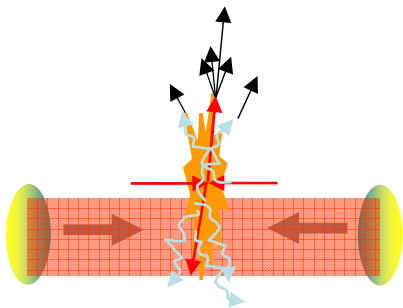
+ anything else?

Act I – Same-Side

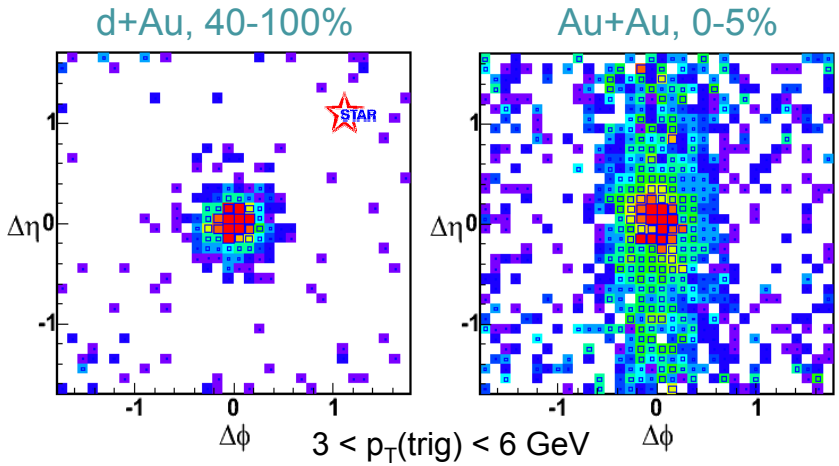
"Ridge" Observation

An Important Discovery

The symmetric jet cone becomes extremely broad along η in central Au-Au forming a ridge-like structure

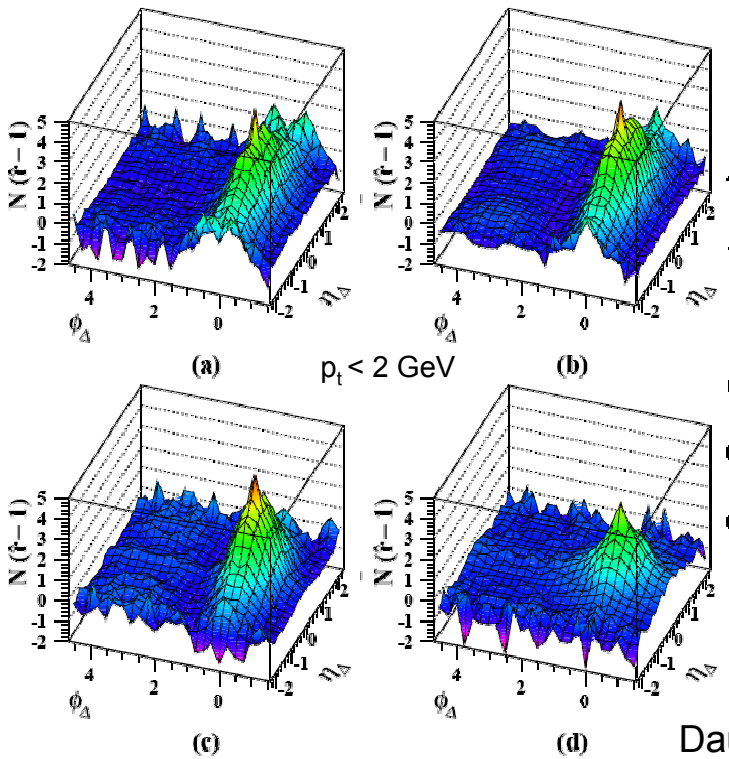


D. Magestro, *Hard Probes 2004*

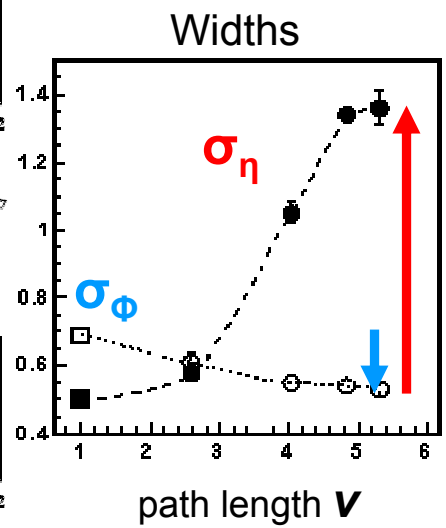


$3 < p_T(\text{trig}) < 6$ GeV
$2 < p_T(\text{assoc}) < p_T(\text{trig})$

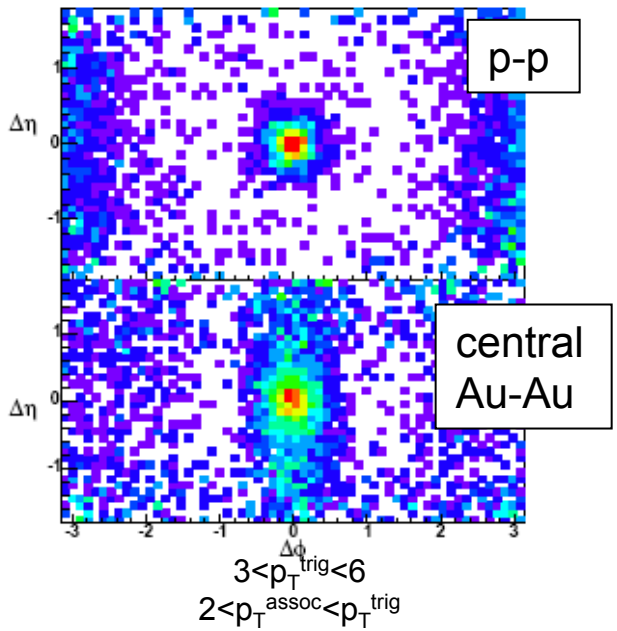
PRC 73 064907



STAR Data



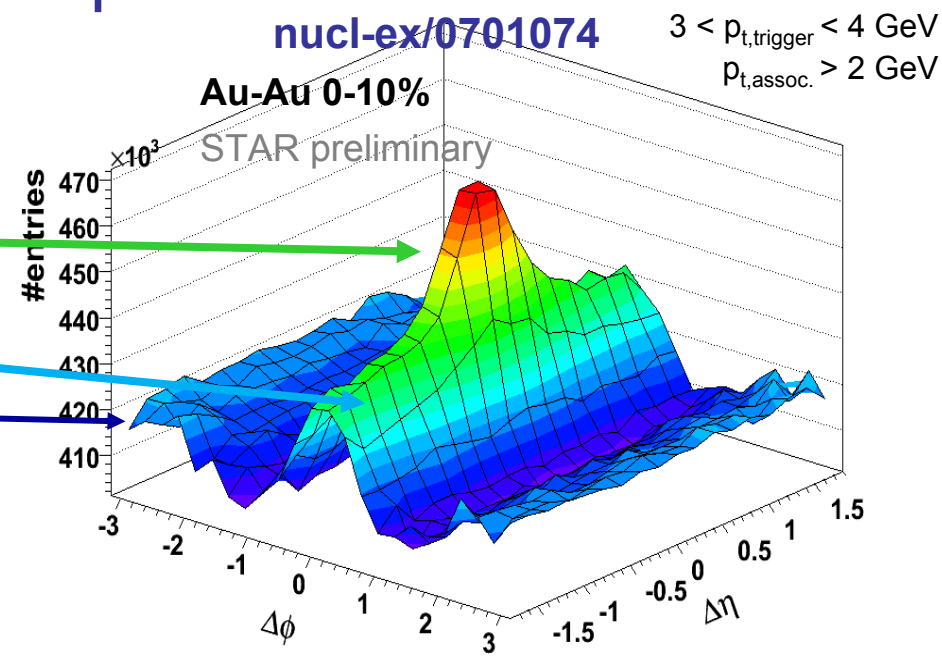
nucl-ex/0503022

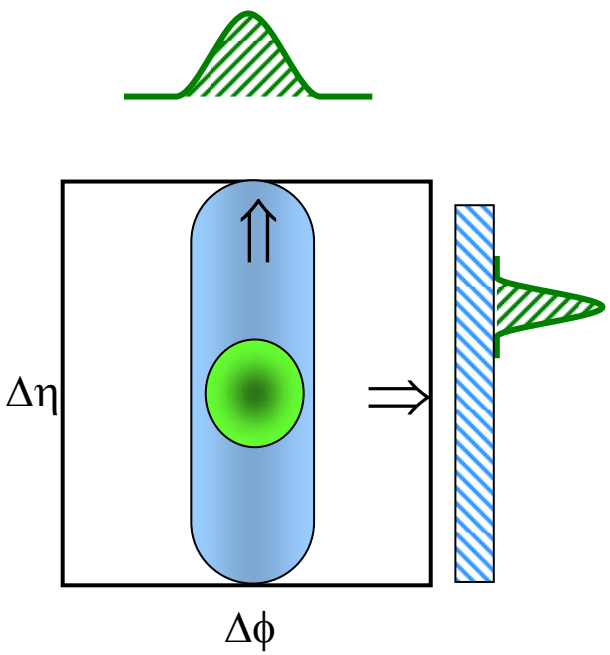


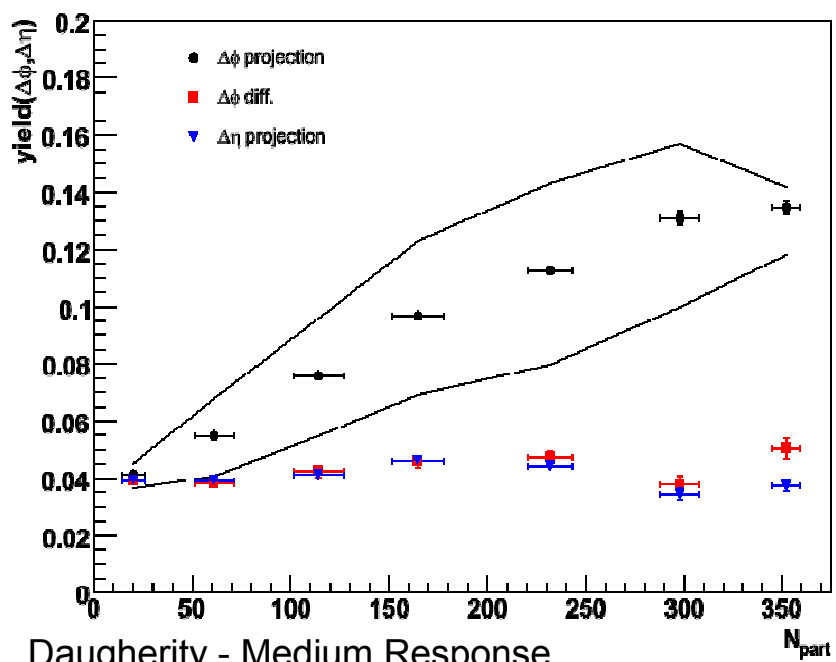
Ridge Components

Components

- Same-side jet peak
- Same-side ridge
- Away-side (and v_2)



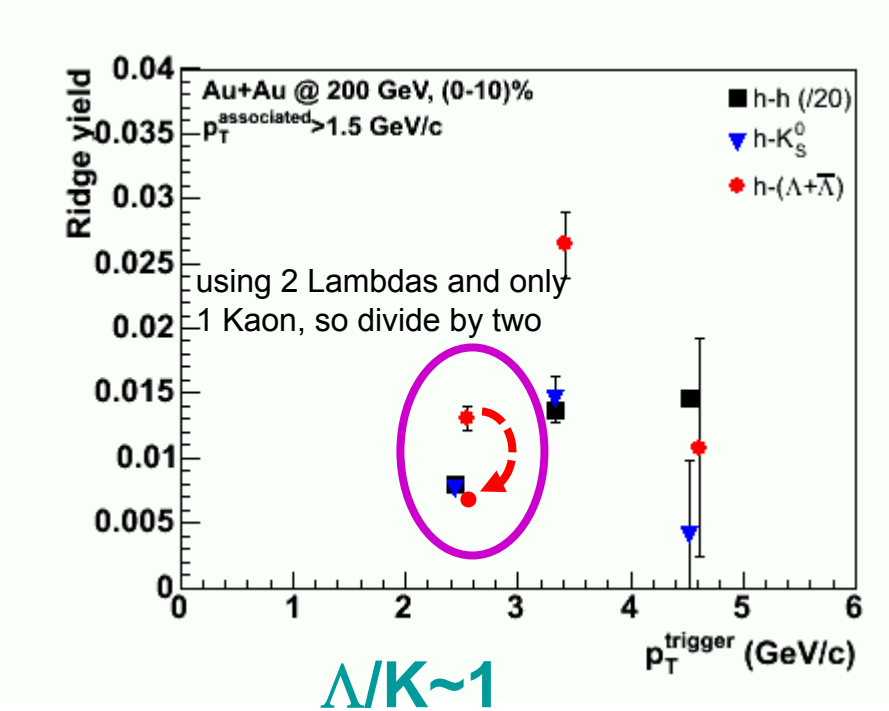


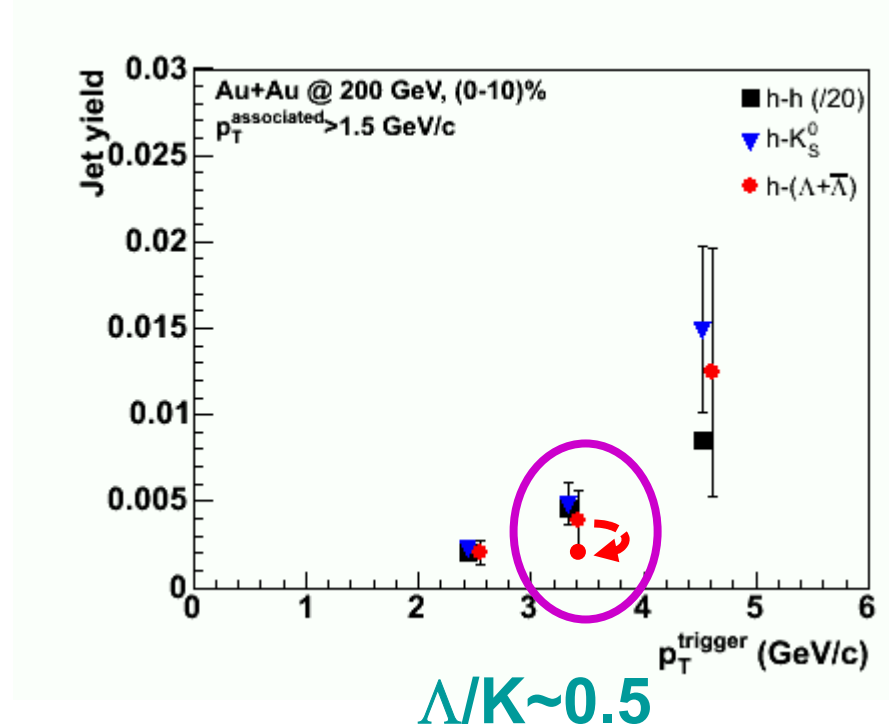


← **Ridge** yield linear with centrality

← **Jet** yield constant

Ridge Properties





Ridge Properties Overview

- Ridge yield increases linearly with centrality
  - same-side yield dominated by ridge in central collisions
- Ridge persists at very high pt
- Ridge spectra and composition much more like bulk medium than jets
- Relative ridge yield comparable at same N_{part} in Au+Au and Cu+Cu

Minimum-bias Correlations

All results so far have used a high-pt triggered jet analysis, but:

- we need to search lower momentum range for more jet-medium interactions and medium response
- we may be missing effects due to high-pt trigger

Solution: remove the trigger particle to make minimum-bias correlations

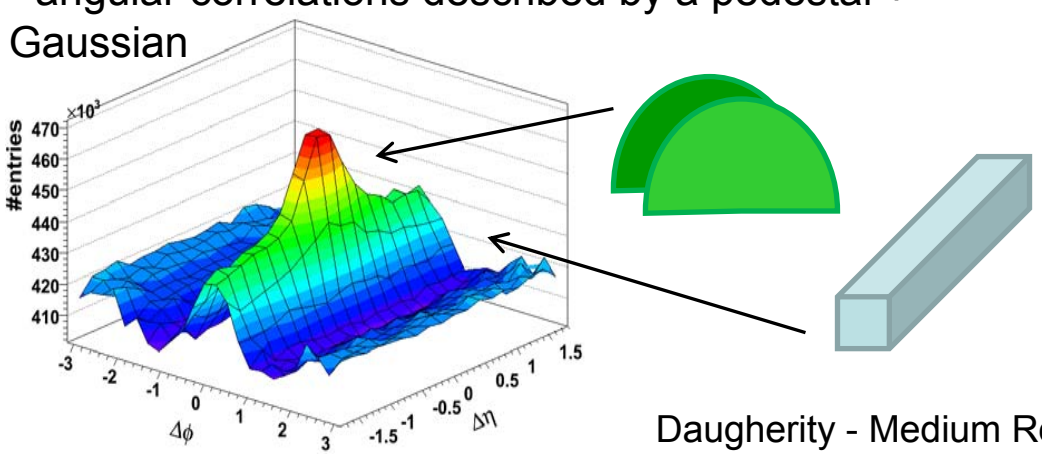
- or, if you prefer, trigger on *every* particle

High-pt Triggered Jet Analysis

• clean separation of jets from other correlations (except flow)

• jets in vacuum above ~2 GeV are well described theoretically with pQCD

• angular correlations described by a pedestal + Gaussian



Minimum-bias Analysis

• will see all correlation sources on equal footing, can use maximal information to isolate one from another

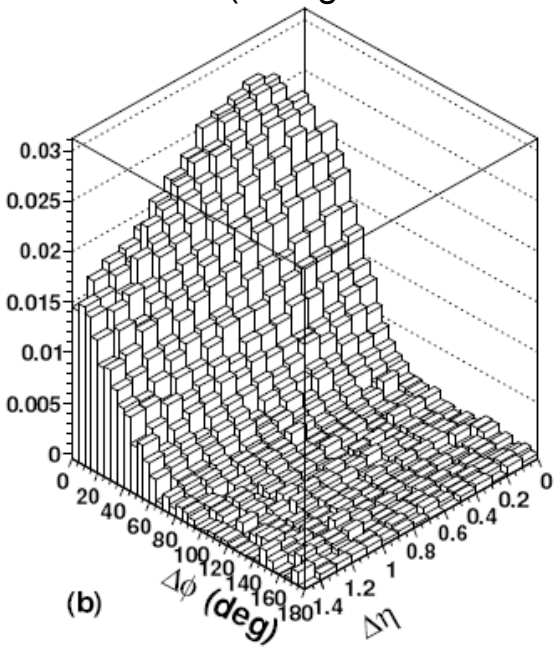
• dominated by soft particles, *nonperturbivate* regime of QCD

• will have to fit data with simplest model functions possible

Minbias – Intermediate p_t

$0.8 < p_t < 4.0$

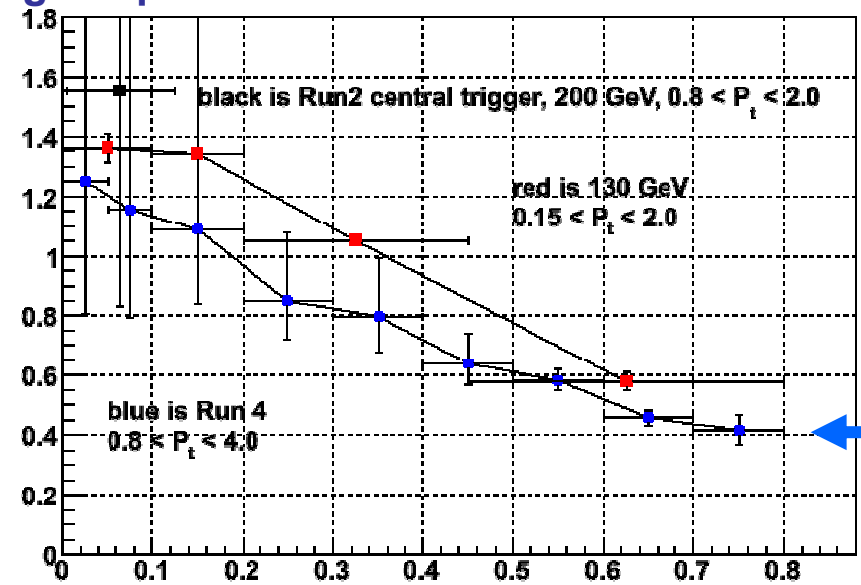
Au-Au 0-5% (background subtracted)



PRC 75 (2007) 034901, nucl-ex/0702008

- Dominant feature is a jet-like peak at the origin
- Other structures are flow and instrumental effects removed with high-precision fit

Signal η Width



η width

- η width increases by 3x
- Φ width ~ constant

Similar η broadening seen in minbias as in trigger particle correlations.

Next we study inclusive pt range

Minbias – Inclusive p_t

All pt > 0.15, no trigger

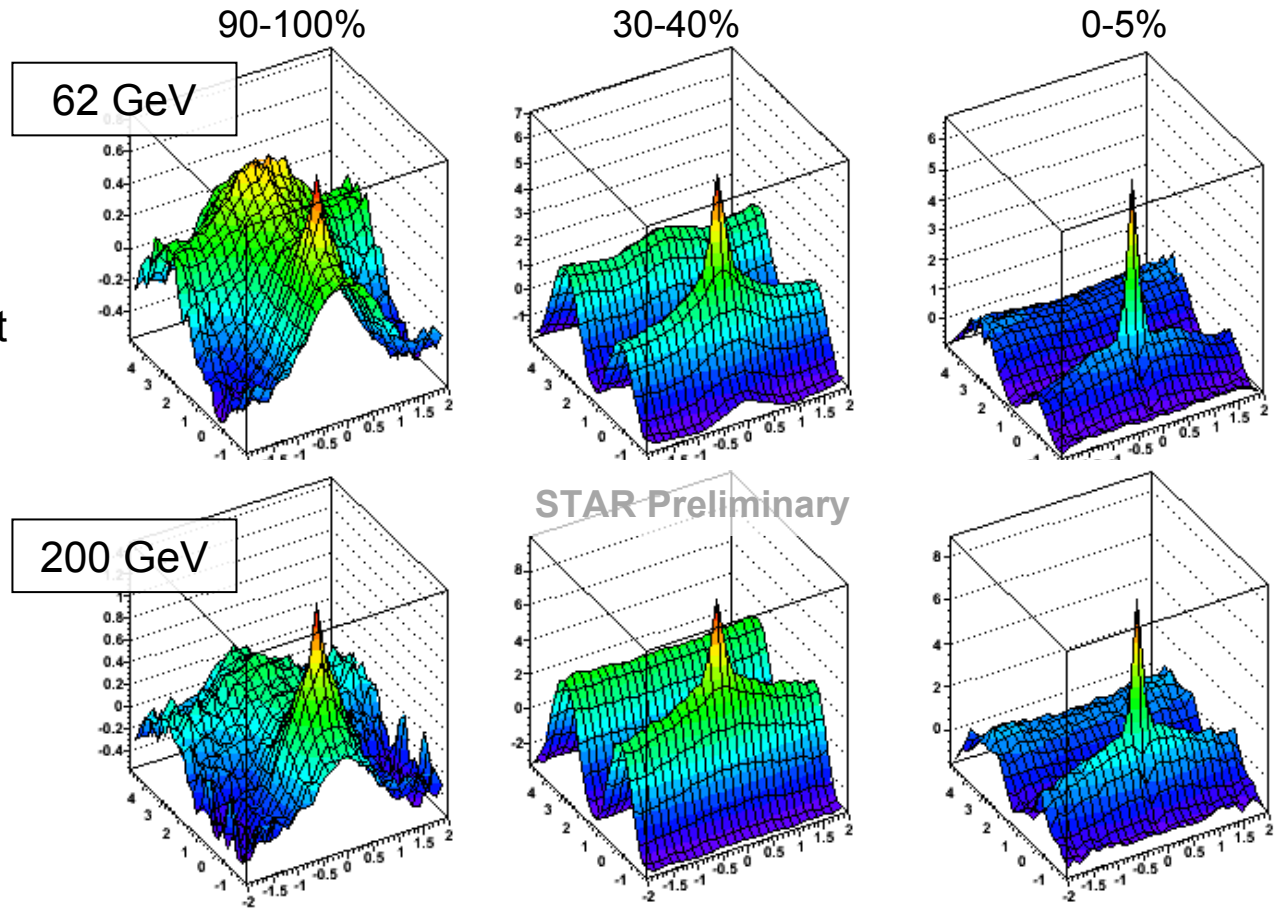
Most jet analyses used a mixed event reference to remove background and report the ratio

same / mixed

This correlation measure uses

(same-mixed) / √mixed

to achieve **per-particle** normalization



- no backgrounds removed: large spike from HBT and e+e- pairs, flow signal evident
- new structure observed: correlation on η in peripheral events, more prominent at low energies; *what is it?*
- 90-100% Au-Au is very similar to proton-proton, let's look for answers there…

Two-component Model

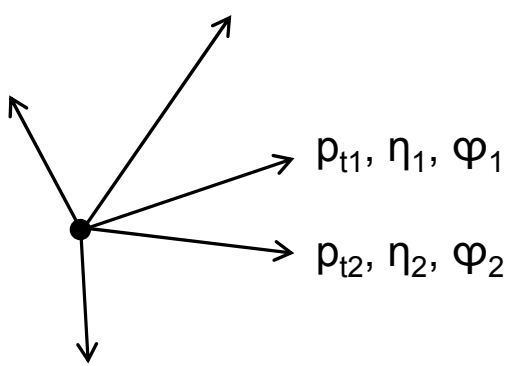
proton-proton collisions

With high-precision STAR p-p data, we can test power-law fit and improve upon it with two-component soft + (semi)hard model

PRD 74, 032006 (nucl-ex/0606028)

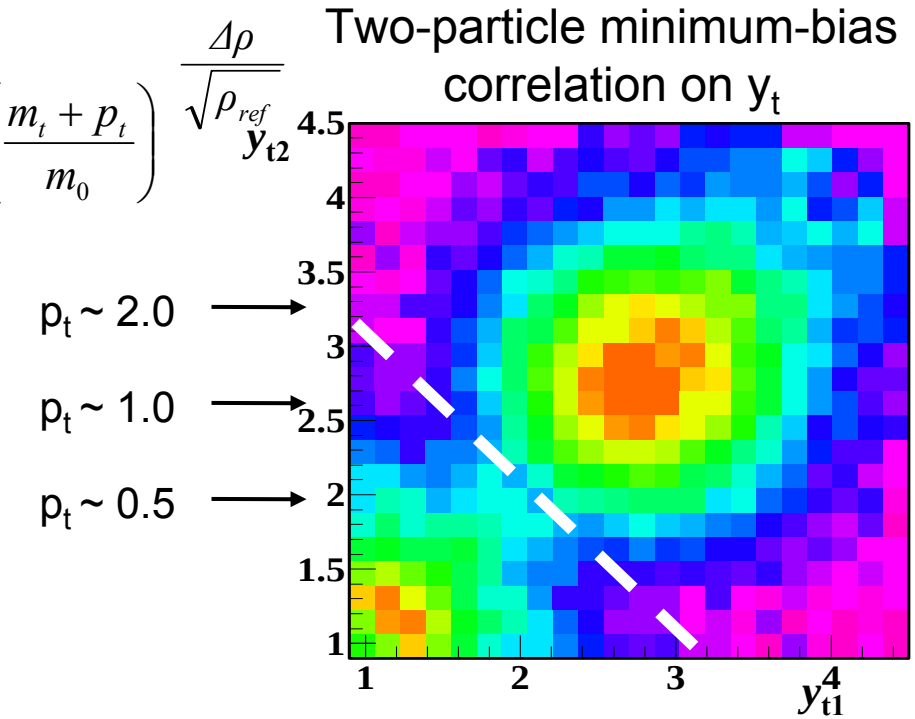
First use correlations on transverse momentum to isolate these components

Next see what the η-φ correlations look like



$$y_t = \ln\left(\frac{m_t + p_t}{m_0}\right)$$

Two-particle minimum-bias correlation on y_t



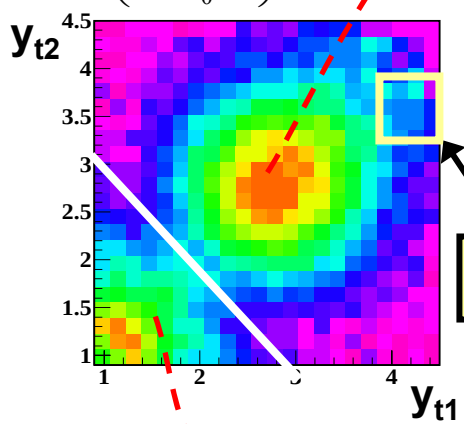
Proton-Proton Correlations

hep-ph/0506172

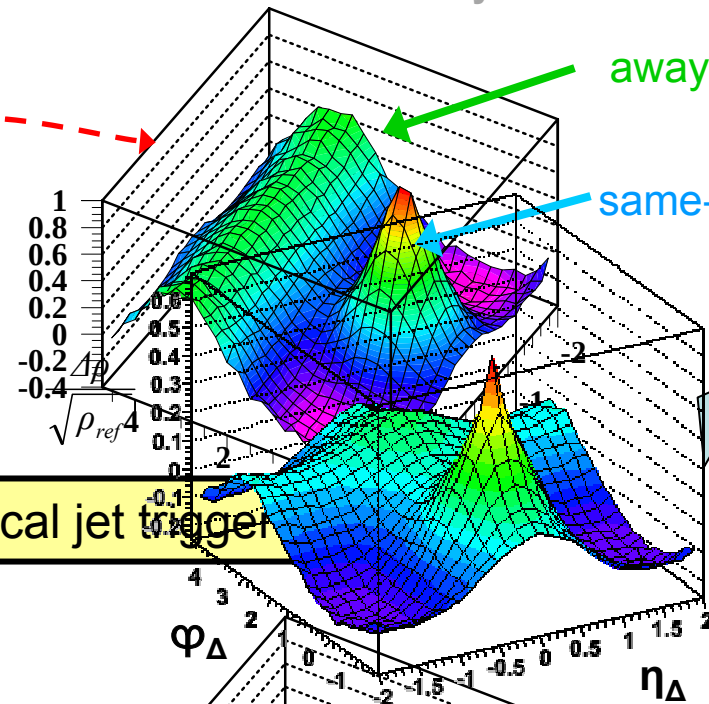
STAR Preliminary

MINIJETS

$$y_t = \ln\left(\frac{m_t + p_t}{m_0}\right)$$



typical jet trigger



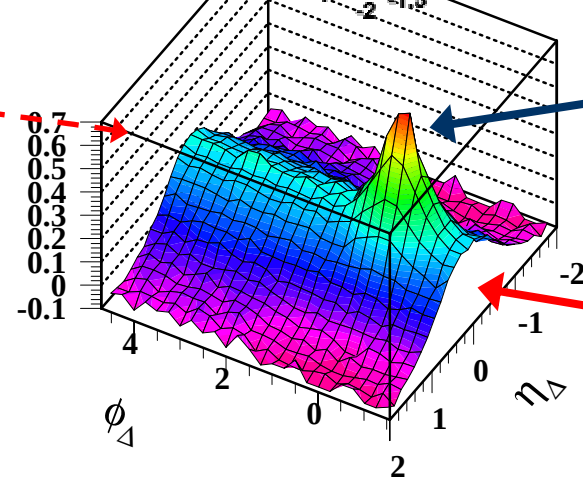
away-side – $\Phi_\Delta \sim \pi$

same-side – small opening angle minijet + HBT

well studied at RHIC

?

STRINGS



HBT

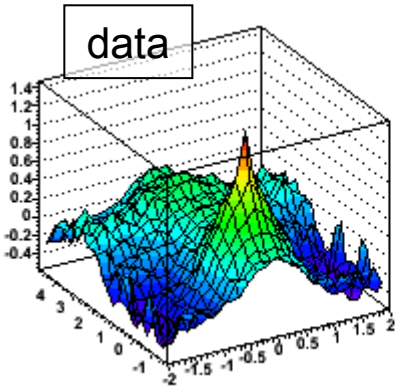
string fragments – 1D Gaussian on η_Δ

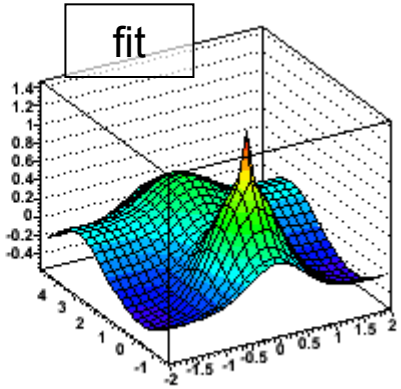
What happens in Au-Au collisions?

Isolating the Components

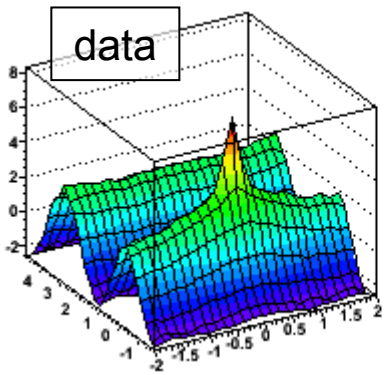
STAR Preliminary

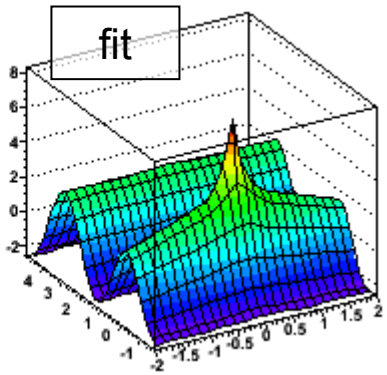
Au-Au 90-100%

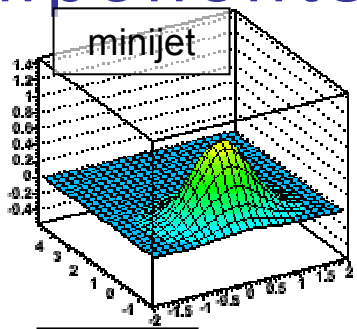


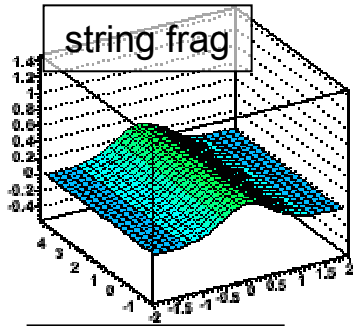


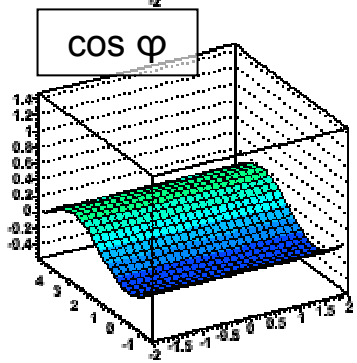
Au-Au 40-50%

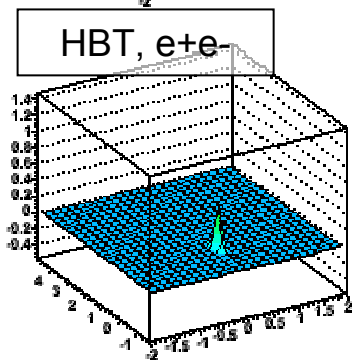


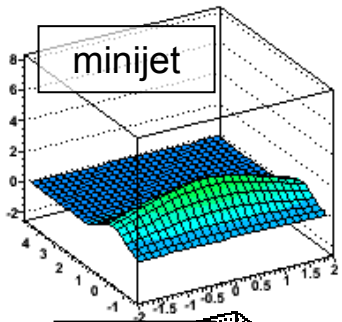


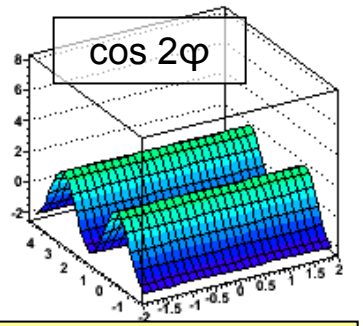


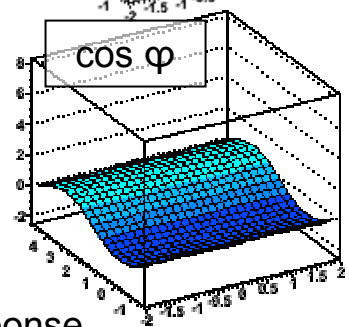


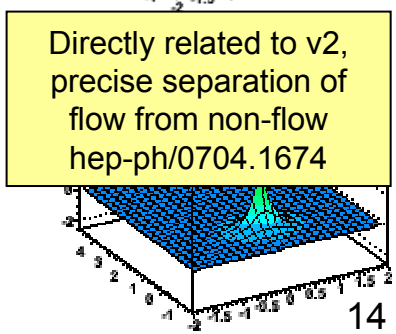










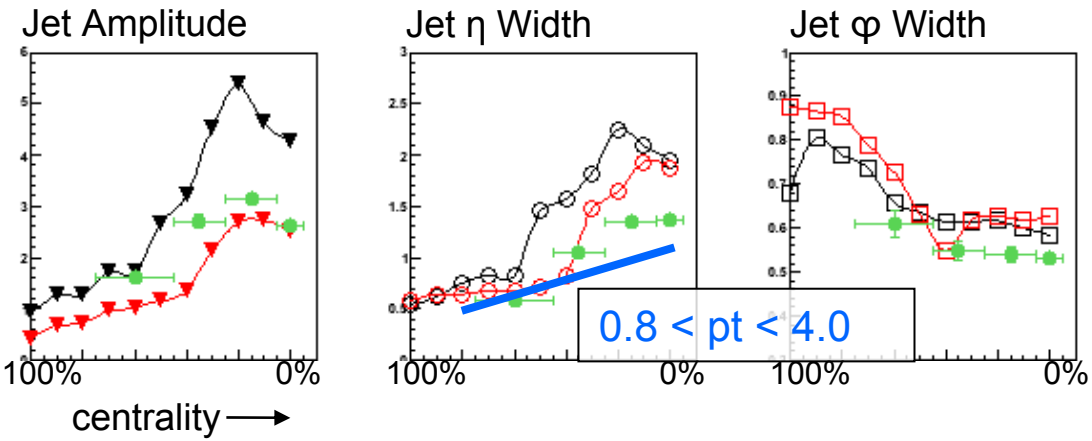


Directly related to v2, precise separation of flow from non-flow hep-ph/0704.1674

- minijet peak becomes extremely large and broad
- string fragmentation correlation disappears
- flow correlation measured

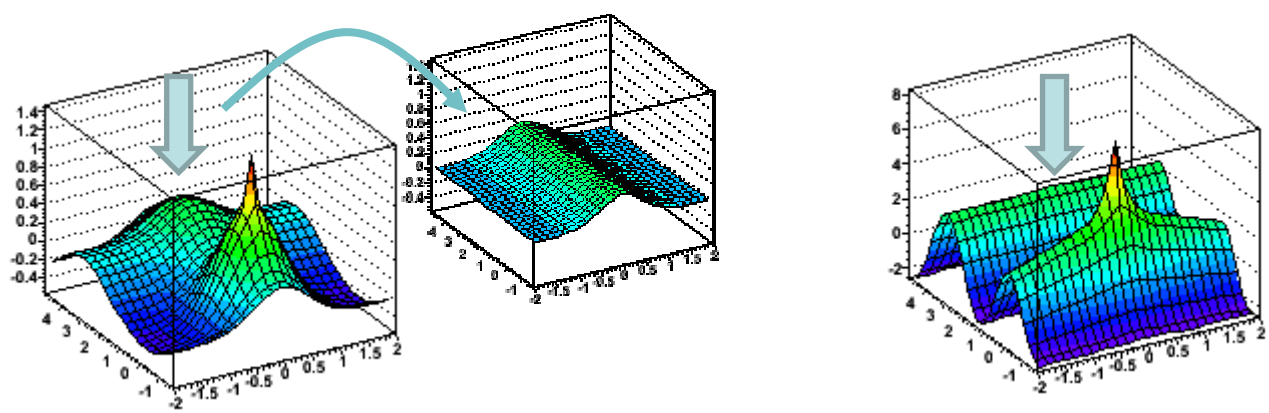
Energy and Centrality Dependence

STAR Preliminary **Au-Au 200, 130, 62** with PRC 73 (2006) 064907



Minbias – dominated by low p_t

- width on η increases 4x
- width on Φ *decreases*
- *width is broader at lower p_t*



- correlation from string fragmentation in low pt particles
- well-described in p-p by Lund string fragmentation model
- evidence that soft strings disappear in central Au-Au, with more rapid disappearance at higher energies
- **We've been studying how jets respond to the medium, here we see effect on strings**

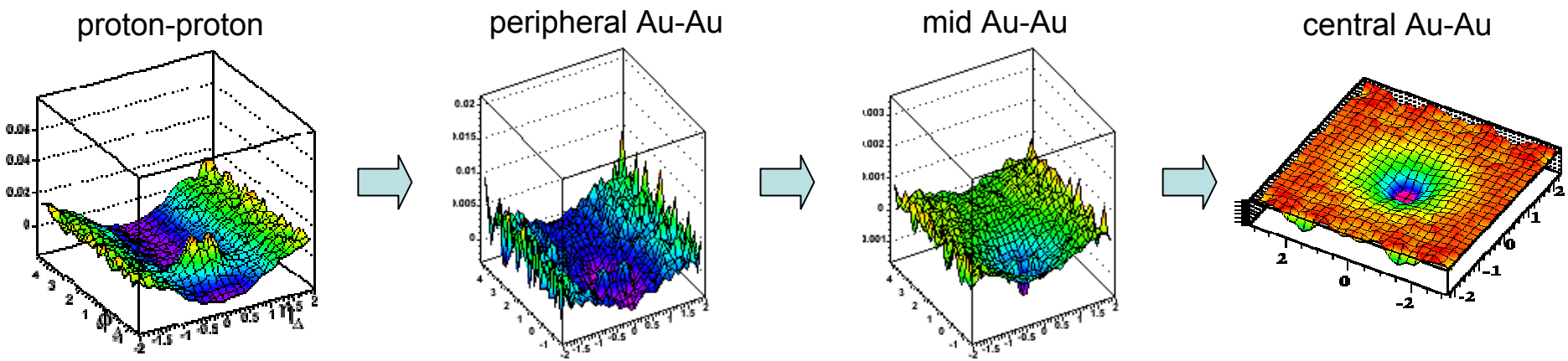
Charge-Dependent Correlations

Charge-ordering: a particle produced from fragmentation tends to have the *opposite electric charge* as its neighbors

In the Lund model, one-dimensional strings fragment on η, should produce charge-ordering signal.

Look for Charge-Dependent correlation = (Like sign pairs) – (Unlike sign pairs)

see PLB 634, 347

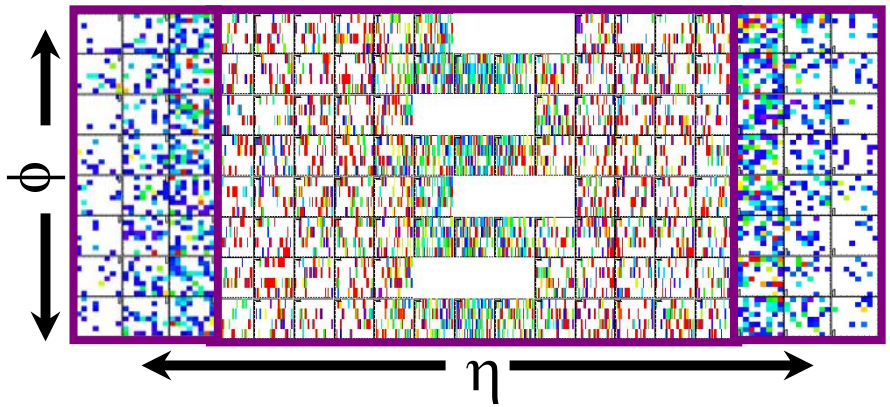


Evidence for charge-ordering moving from one-dimensional string to a surface

- The 1-D signal becomes ***symmetric*** on η_Δ and Φ_Δ in central Au-Au
- Suggests a new geometry of hadronization in RHIC collisions

PHOBOS

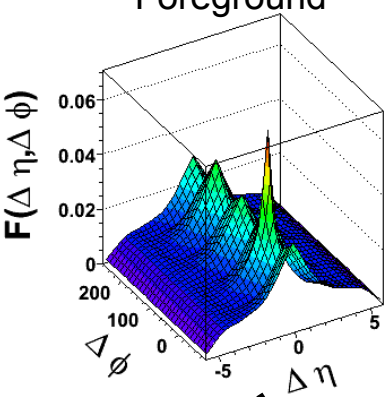
acceptance of octagon detector



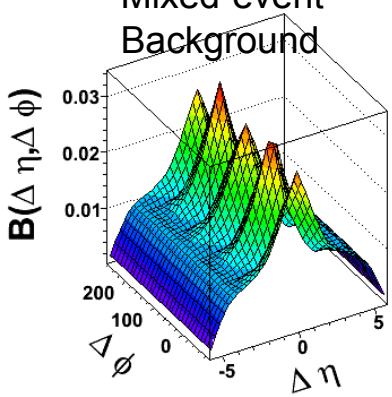
- Minbias correlations by necessity
- Exciting prospect of ridge measurements at large pseudorapidities

proton-proton

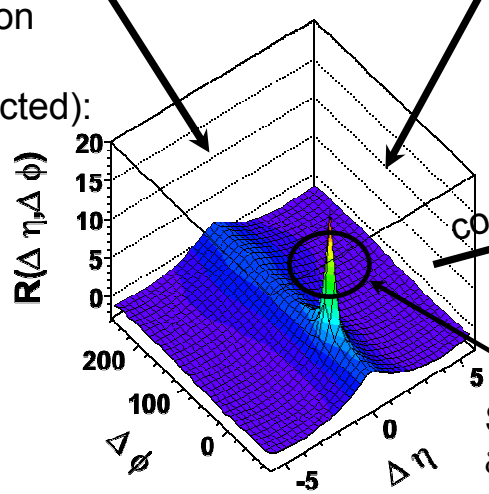
Foreground



Mixed-event Background



correlation function (uncorrected):

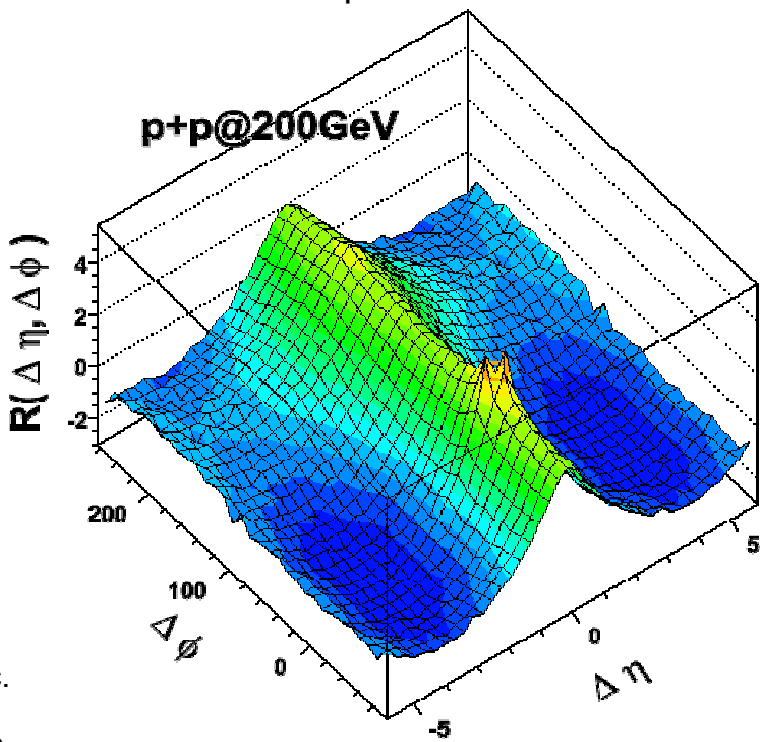


corrections by MC

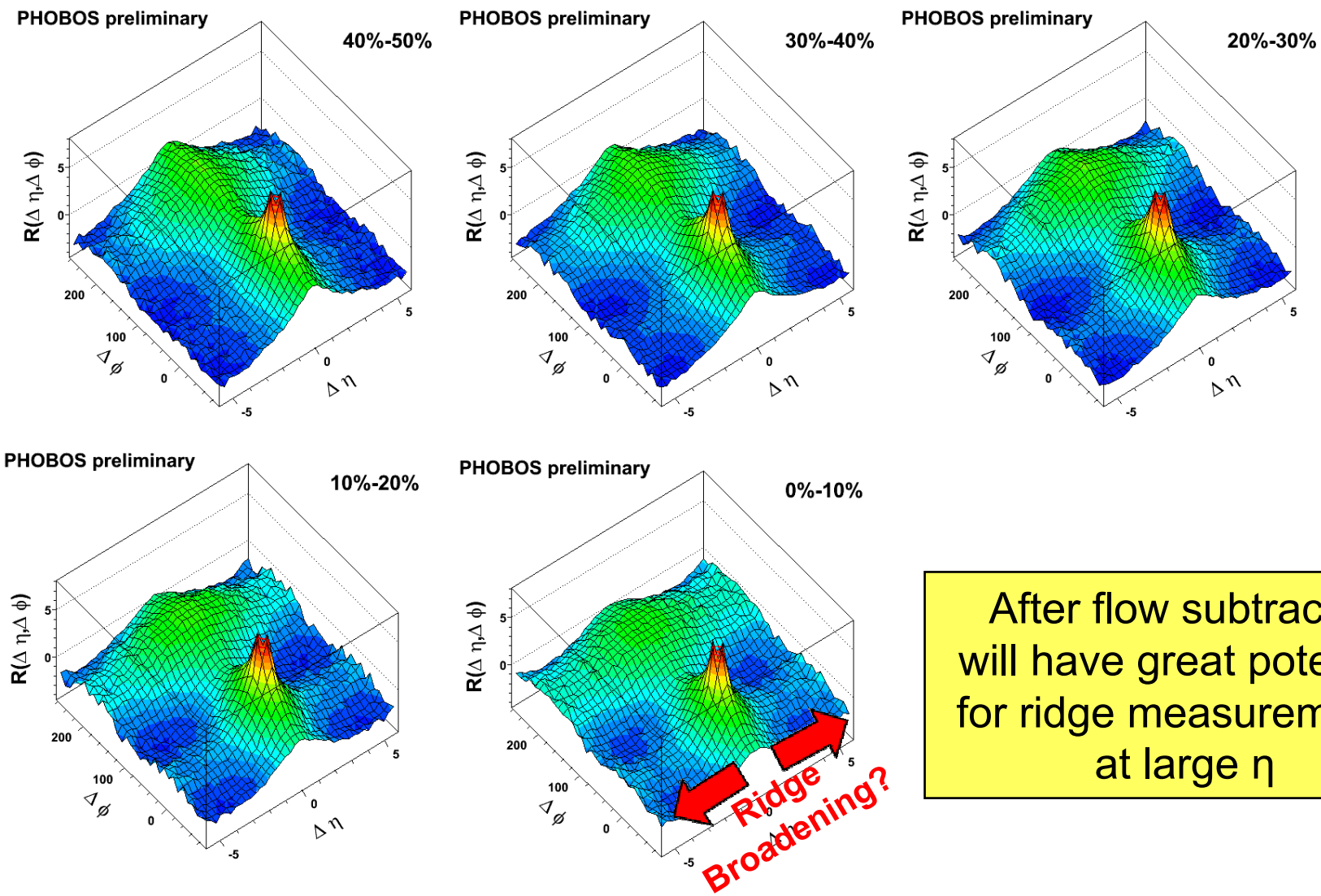
Secondary effects:
δ-electron, γ conversion etc.

Two particle correlation function:

PHOBOS – accepted to PRC



PHOBOS Cu-Cu



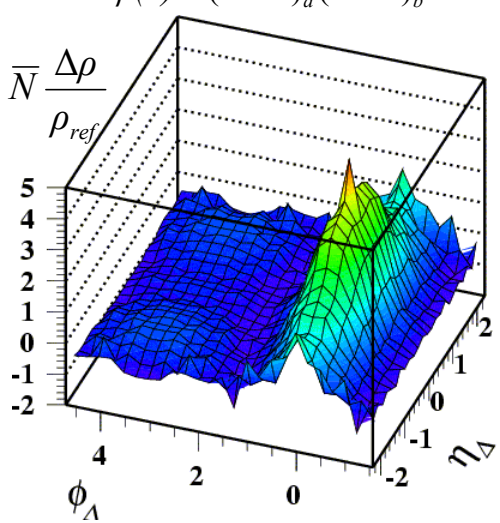
After flow subtraction will have great potential for ridge measurements at large η

A New Correlation

Instead of asking *how many pairs* in a bin, we can count *how much p_t* and find momentum correlations

Number Correlation

$$\Delta\rho(n) = \overline{(n-\bar{n})_a (n-\bar{n})_b}$$

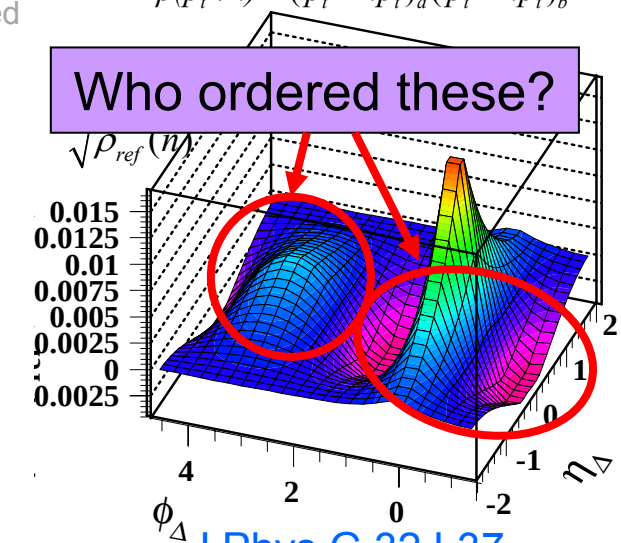


PRC 73 064907

backgrounds subtracted

***Momentum* Correlation**

$$\Delta\rho(p_t : n) = \overline{(p_t - n\hat{p}_t)_a (p_t - n\hat{p}_t)_b}$$



J Phys G 32 L37

Paper named one of the ***Highlights of 2006*** by Journal of Physics G

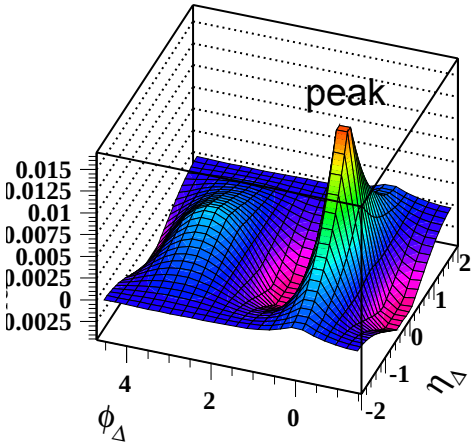
Momentum Correlation shows jet peak with two new structures

$\hat{p}_t$ = inclusive mean pt

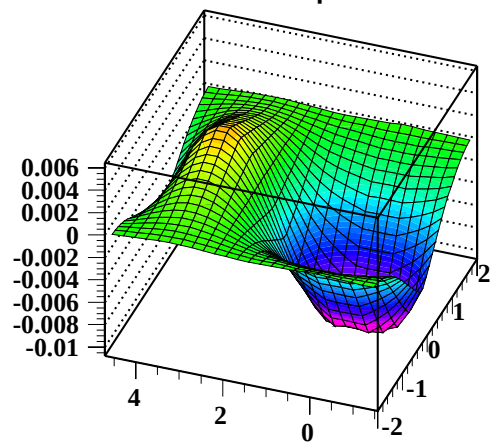
J Phys G 32 L37

Momentum Correlations

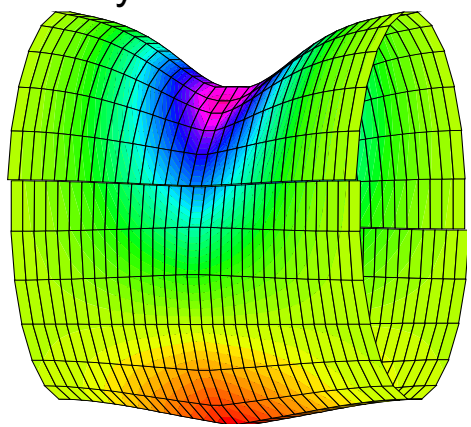
Au-Au 20-30%



data - fit peak



plotted in cylindrical coordinates

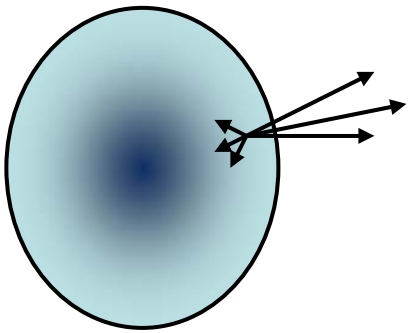


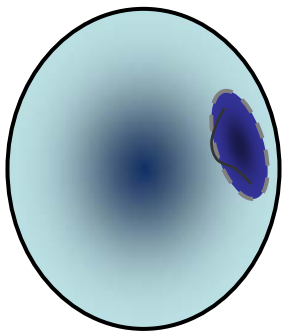
Why does the jet peak sit inside a valley?

When the away-side jet is absorbed, where does the momentum go?

Medium recoil? Momentum red-shift?

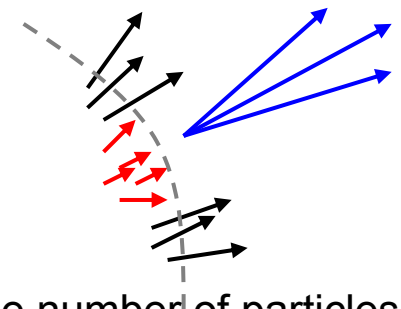
The jet punches the medium





The medium responds

freeze-out



The number of particles doesn't change, but their momenta do

The story so far...

- Same-side correlations reveal *broad structures on η* that evolve dramatically with pt, centrality and energy.

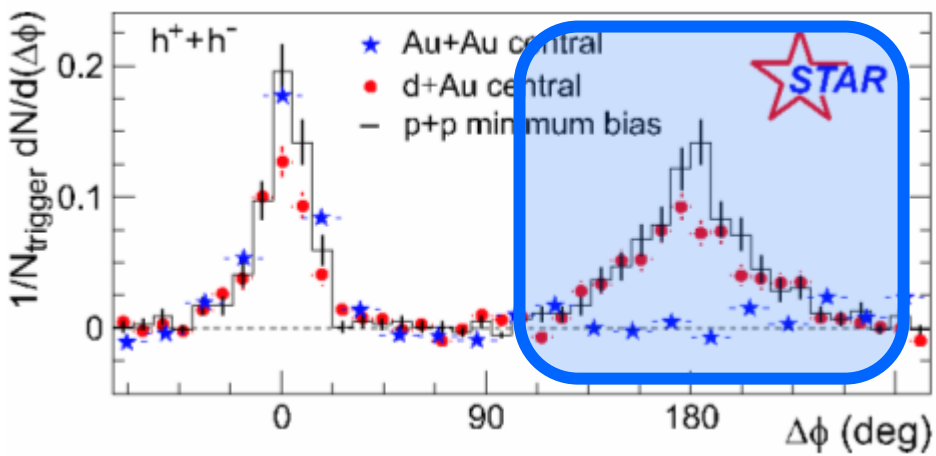
  High pt: "bulk-like" ridge + p-p-like jet
  Minbias: minijet broadening
  Can a single theoretical model describe both of these regimes?

- Low pt studies revealed string fragmentation correlations

  Why is the dominant hadronization mechanism in p-p not present in central Au-Au?
  Related to change in charge-ordering geometry?

- Momentum correlations reveal qualitatively new information about the medium response to minijets

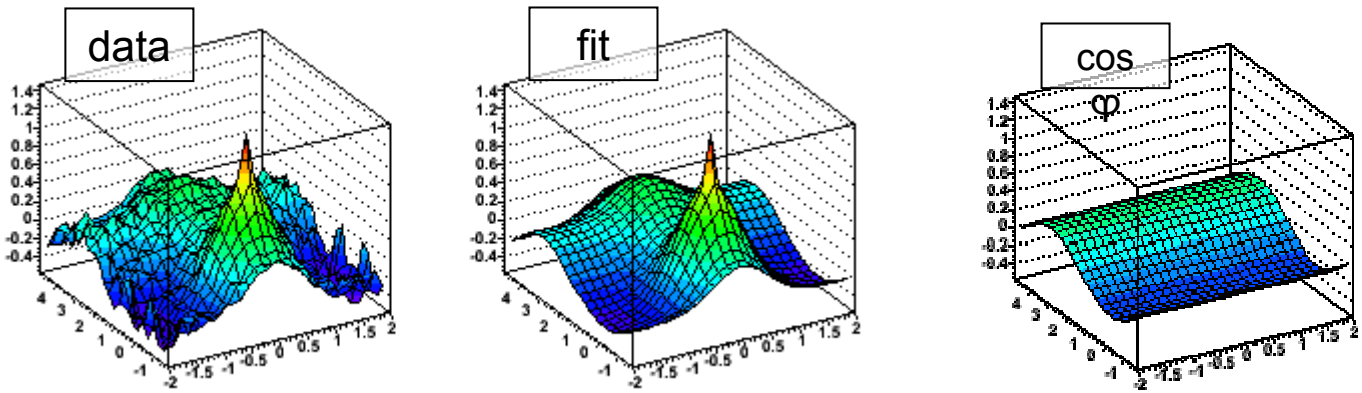
Act II – Away-Side



Away-Side Minbias

Explore the away-side from low to high p_t

- In minbias analyses, we expect a global momentum conservation term of cos(φ)
- Surprisingly, the structure from away-side jets is *indistinguishable* from this term



- Measured amplitude of cosine increases ~ linearly with multiplicity, whereas momentum conservation alone scales as 1/N

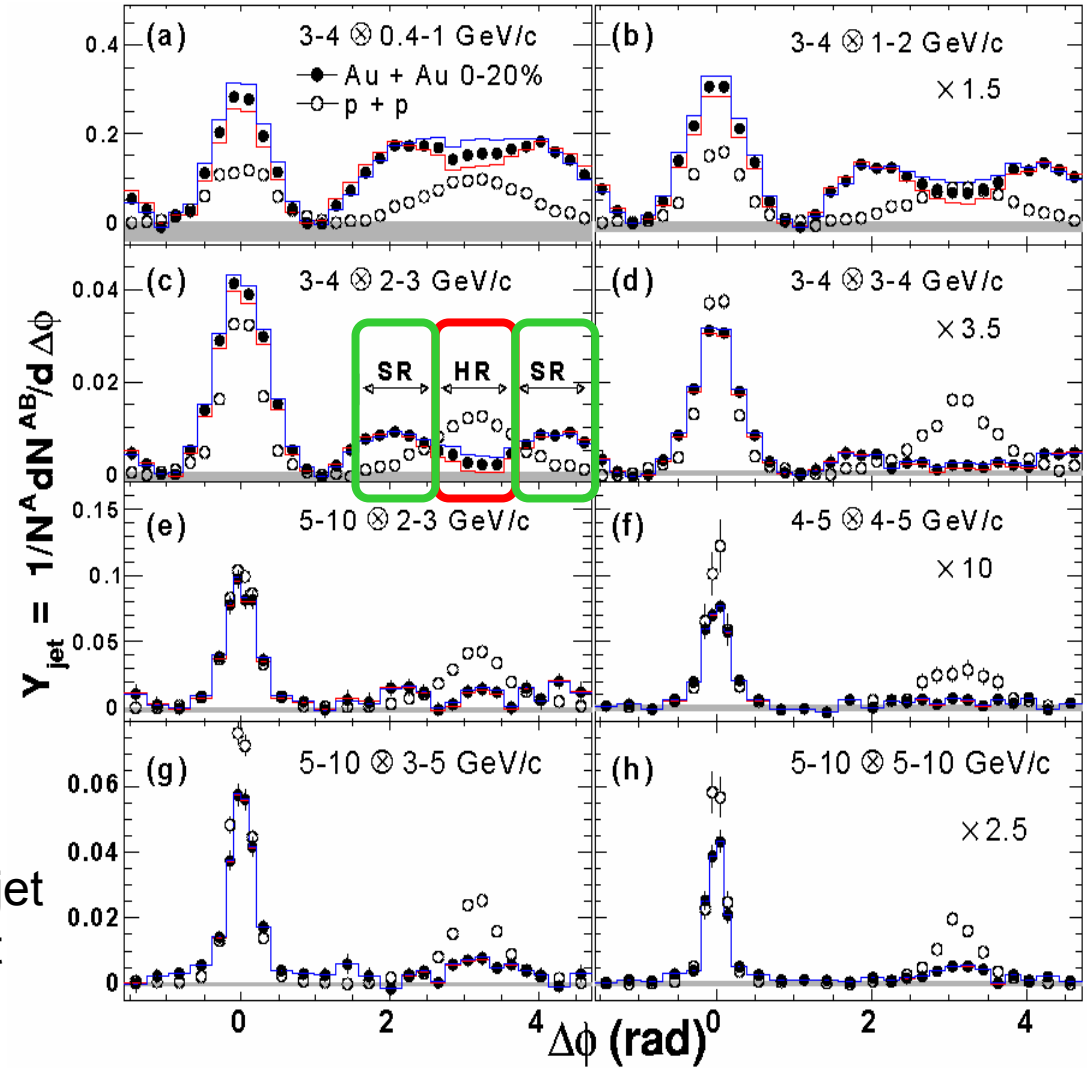
Away-Side Shapes - PHENIX

nucl-ex/0705.3238
submitted to PRL

Empirical observation:

Minbias analyses fit away-side jet with cosine, high-pt triggered analyses use a Gaussian. Here there is a smooth evolution between the two…

- In proton-proton we see a clear away-side jet ("head" region)
- In Au-Au we see a dip after flow subtraction at π defining the "shoulder" regions
- The dip grows as the away-side jet is suppressed, finally reappears at very high momentum

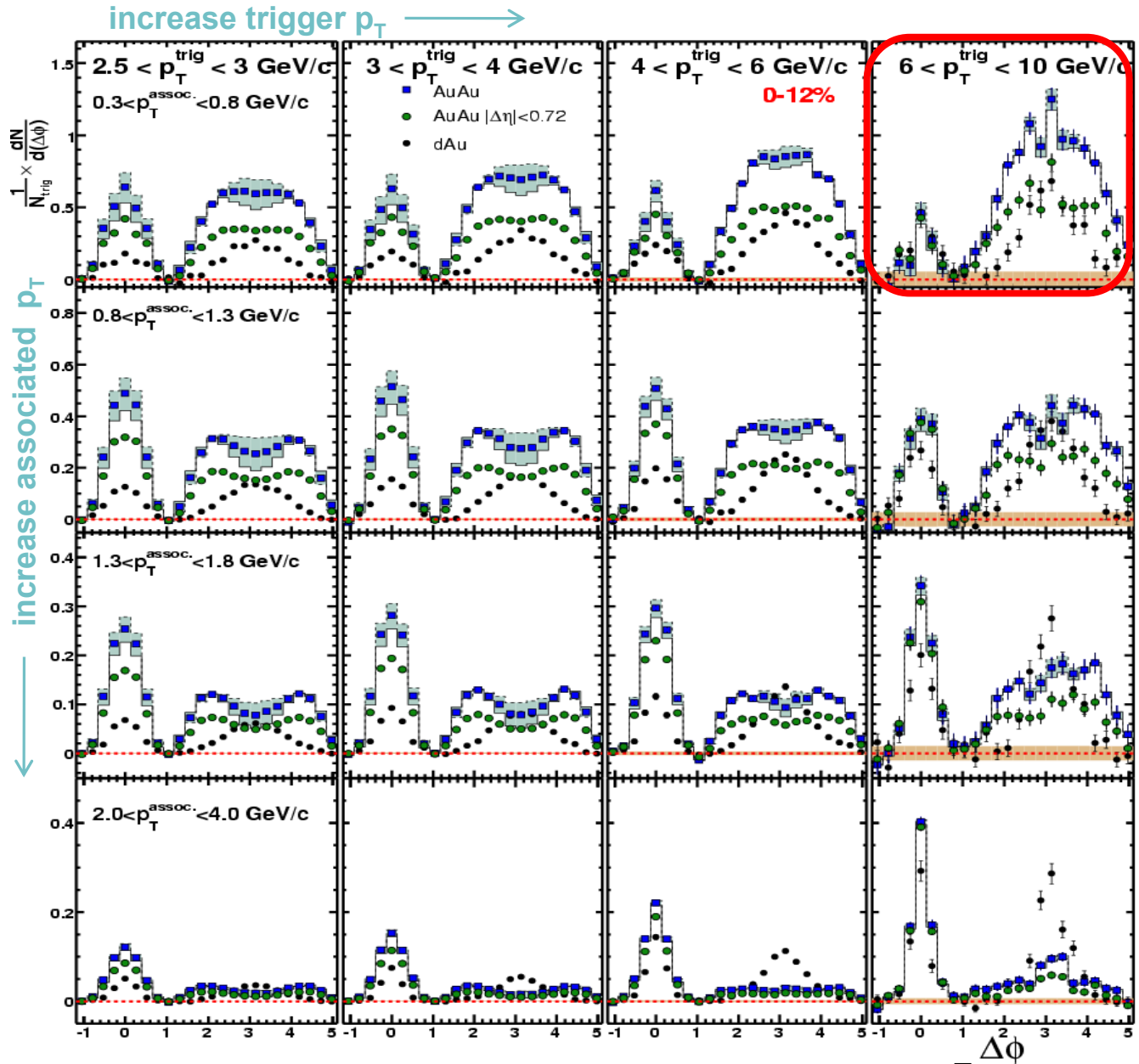


Away-Side Shapes - STAR

STAR Preliminary

Similar story from STAR:
- dip increases
- jet suppressed
- high pt punch-through

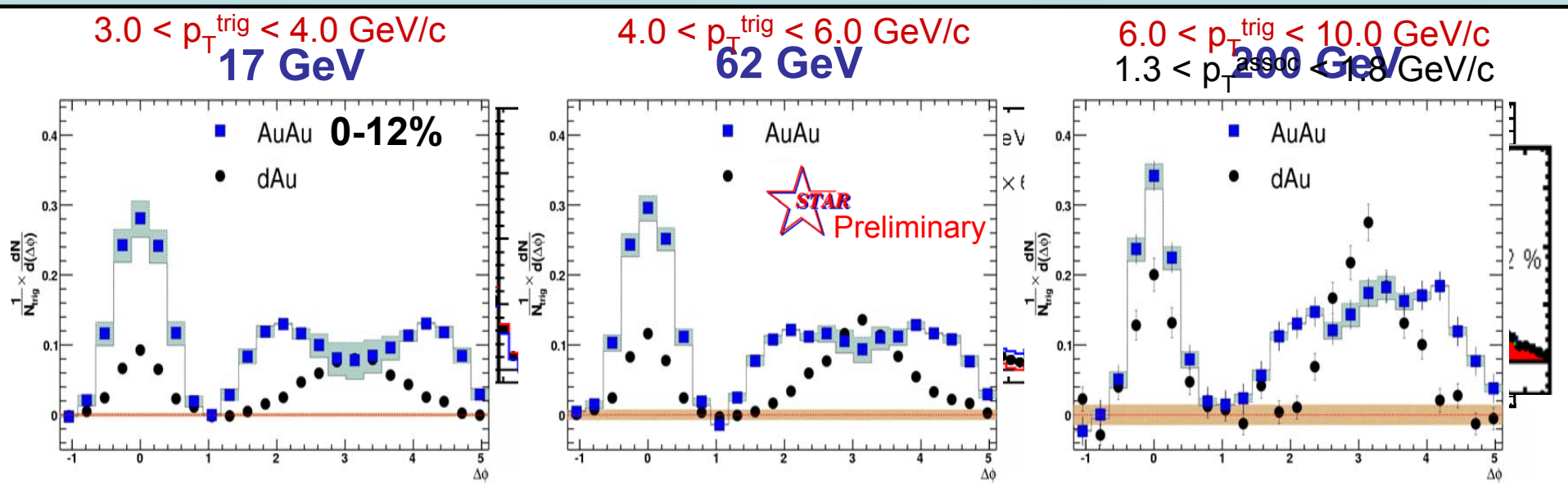
Unique results:
- Same shape in jet region as in ridge region (blue vs green points)
- Large away-side yield for high trigger pt



Away-Side Dependencies

The away-side dip:

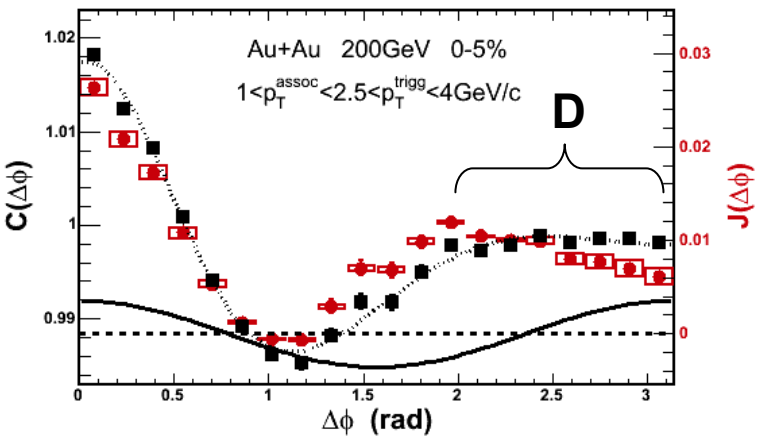
- increases with energy
- increases with centrality
- disappears at high trigger pt
- increases with associated pt

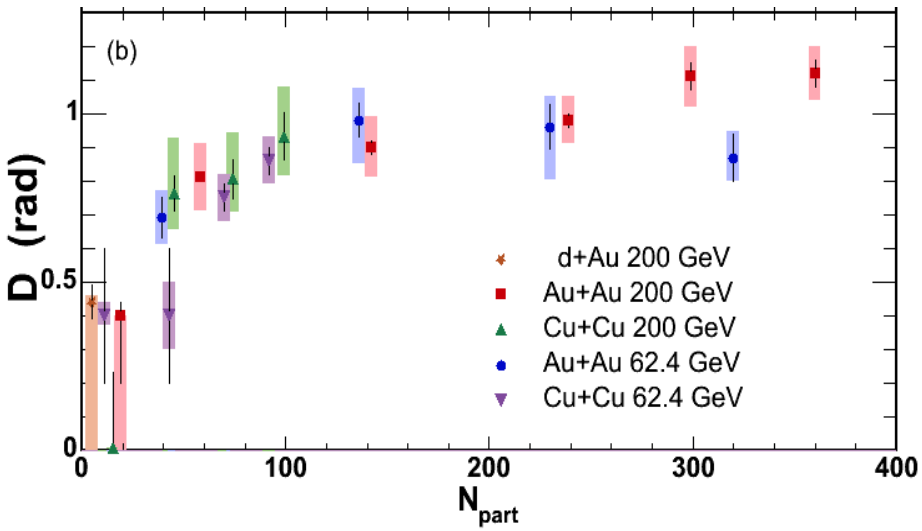


Modeling the Shape

PHENIX
nucl-ex/0611019
submitted to PRL

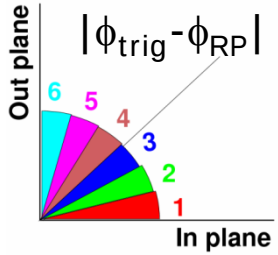
Model away-side jet as two symmetric Gaussians equally displaced from π





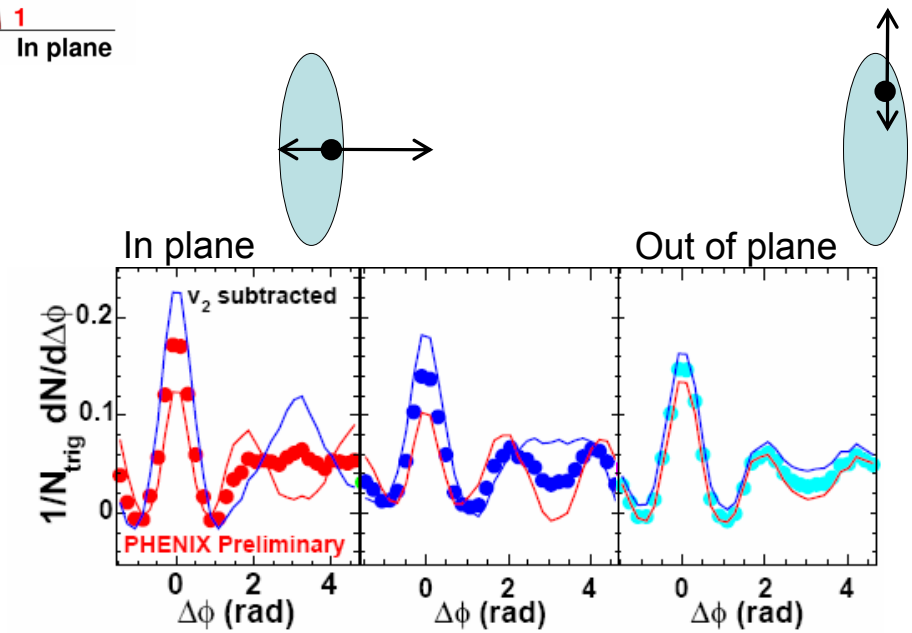
Find displacement for many different systems and energies

- Parameters scale with N_{part} only, not energy or momentum
- Disfavors Cherenkov models where the opening angle depends on the velocity of the particle through the medium

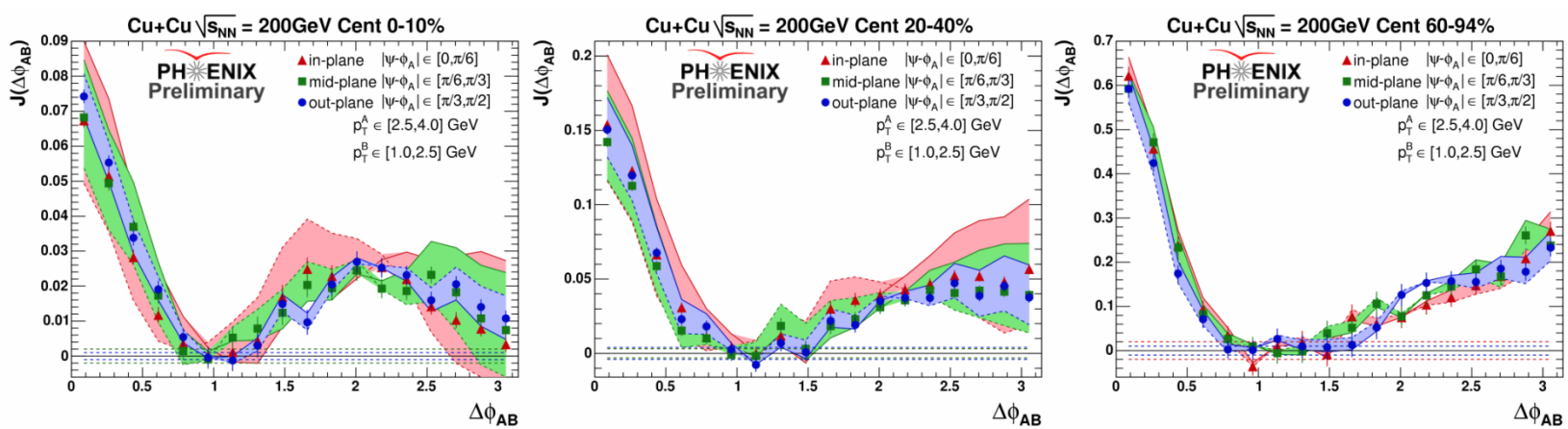


Path Length Dependence

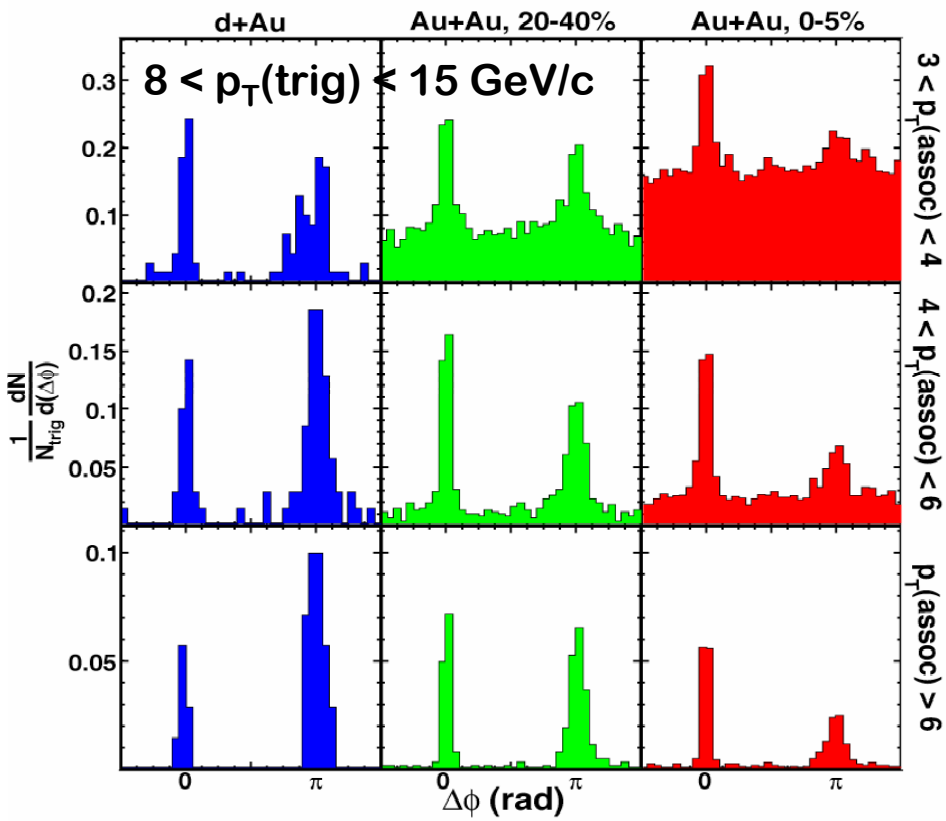
J. Jia (PHENIX), nucl-ex/0510019.



- Hint of stronger suppression out-of-plane than in-plane, consistent with energy loss picture.
- Hint of stronger double-peak structure out-of-plane than in-plane.
- New Cu-Cu results show no path-length dependence within errors
- Need precise determination of flow background



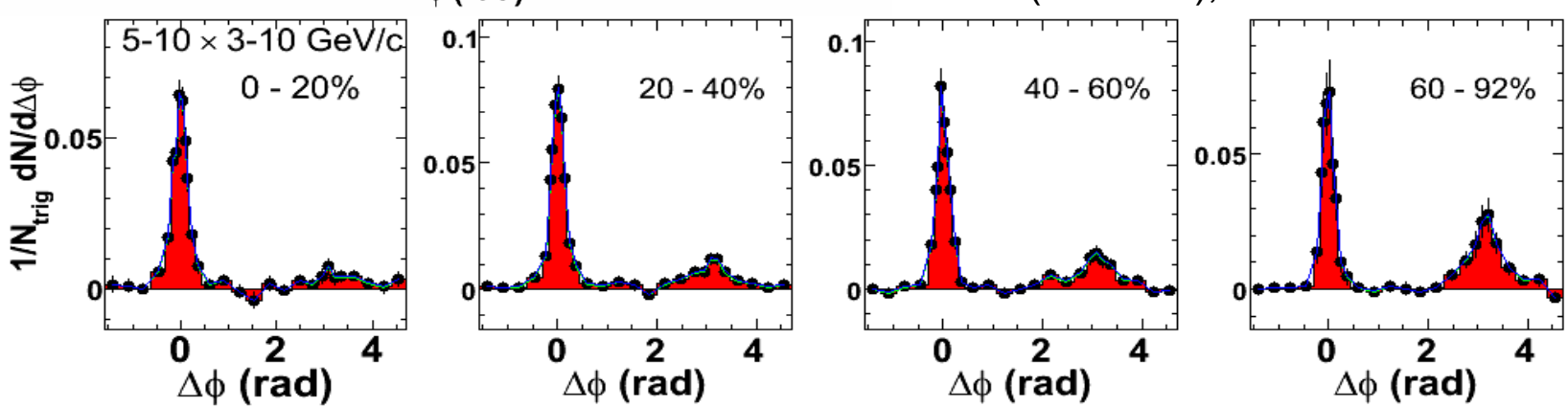
Reappearance at High p_t



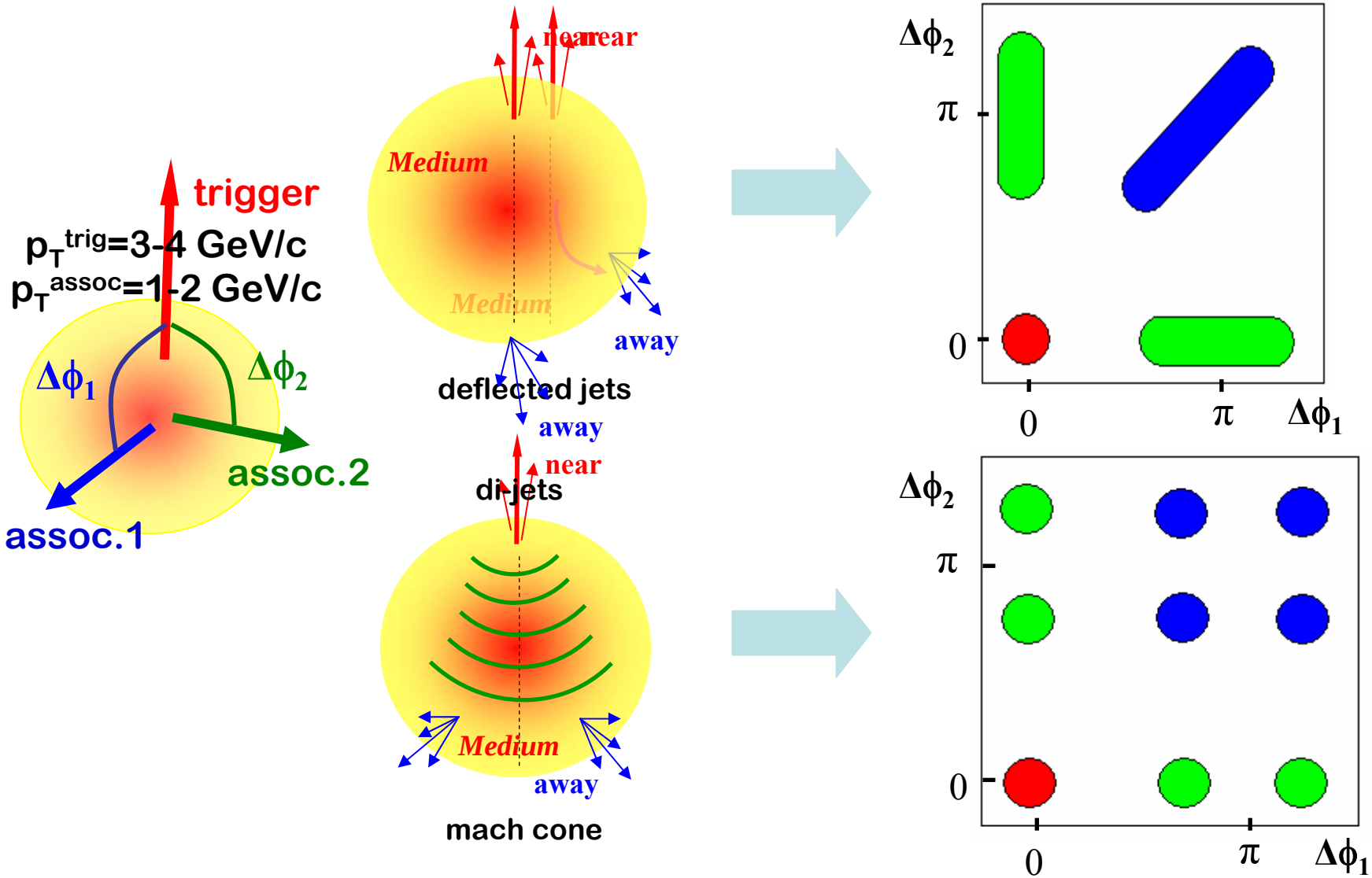
STAR, PRL 97 (2006) 162301.

- clear away-side peak – dijets
- away-side yield suppressed, but shape is unchanged
- likely contributions from tangential jets

J. Jia (PHENIX), nucl-ex/0510019.

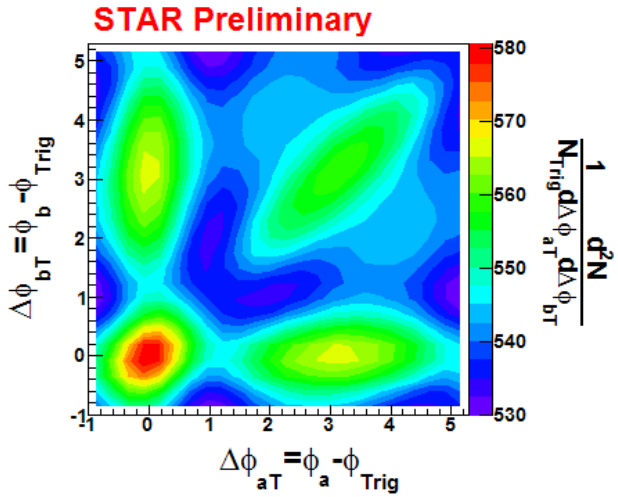


Conditional 2-Particle Distributions

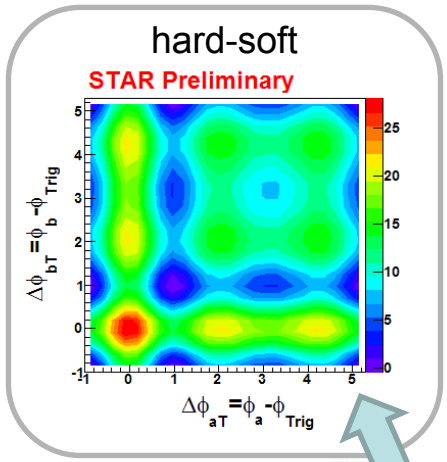


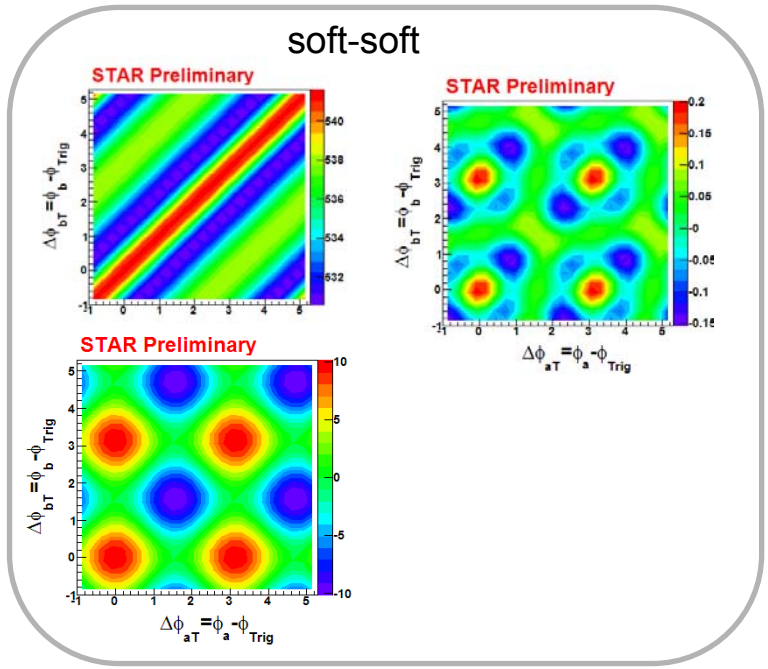
Conditional 2-Particle Distributions

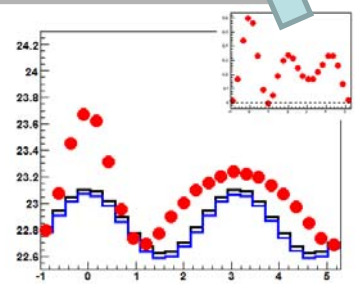
Au-Au 200 GeV
raw data
trigger $3<p_T<4$, associated $1<p_T<2$



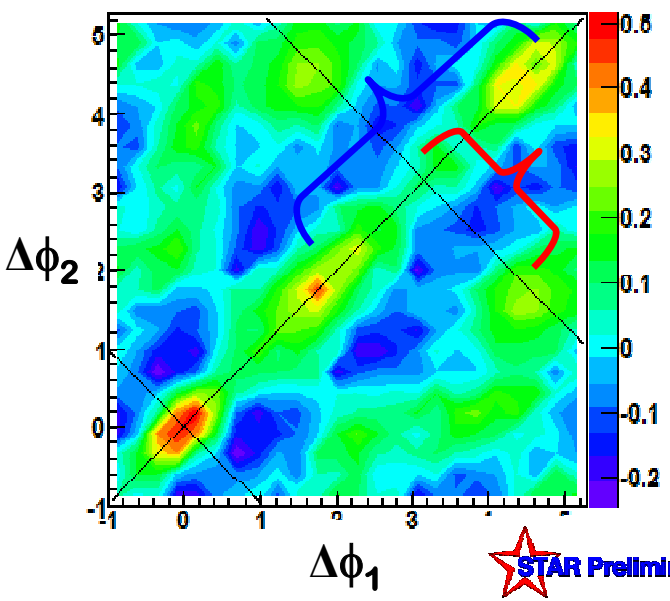
Model background as having hard (jets) and soft (flow) components, need to remove all possible cominbations







Final signal
Au+Au 0-12% ZDC



Subtract all backgrounds

Cone angle = 1.45 radians (~83°) much larger than expected

"True" 3-particle correlations

Conditional analysis is more intuitive and easier to interpret, but requires model-dependent background subtraction

We can also find the true 3-particle correlation which is model-independent, but more difficult to interpret

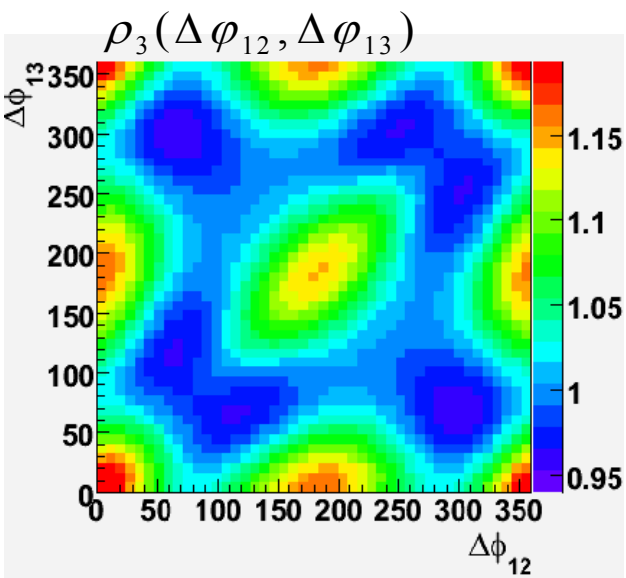
- Particles are labeled 1, 2, 3.
- In this analysis
  - Particle 1: Used as a jet tag/trigger, $3 < p_t < 4$ GeV/c.
  - Particles 2 & 3: associated $1 < p_t < 2$ GeV/c.
- Measure 1-, 2-, 3- particle densities normalized per event
- Calculate

2-Cumulant $C_2 \equiv \rho_2(\varphi_i,\varphi_j) - \rho_1(\varphi_i)\rho_1(\varphi_j)$

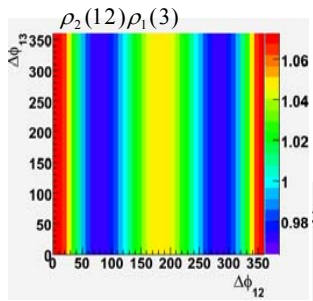
3-Cumulant

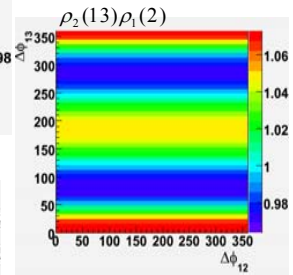
$$C_3 \equiv \rho_3(\varphi_i,\varphi_j,\varphi_k) - \rho_2(\varphi_i,\varphi_j)\rho_1(\varphi_k) - \rho_2(\varphi_i,\varphi_k)\rho_1(\varphi_j) - \rho_2(\varphi_j,\varphi_k)\rho_1(\varphi_i) + 2\rho_1(\varphi_i)\rho_1(\varphi_j)\rho_1(\varphi_k)$$

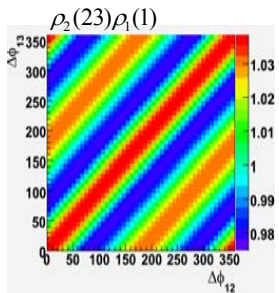
Au+Au 0-10%



As before, subtract two-particle correlations

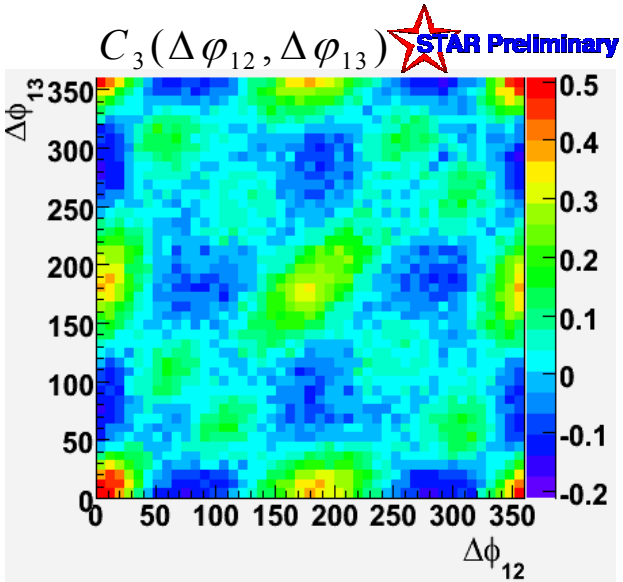




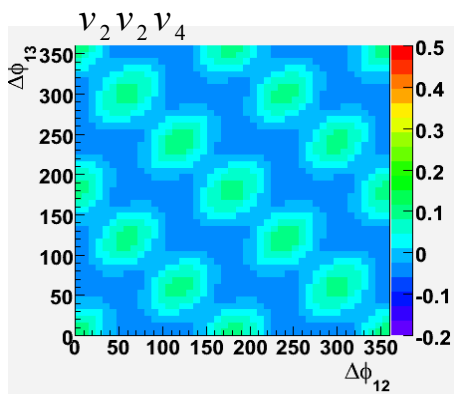


3-particle Correlations

Subtract backgrounds



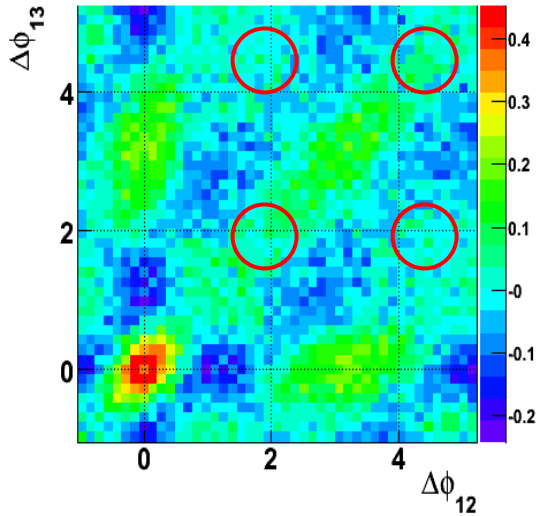
Subtract additional v2v2v4 flow term:

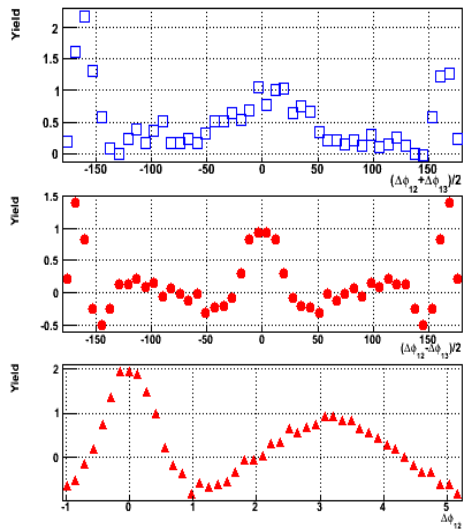


Final Nominal Cumulant

Au+Au 0-10%

v_2 and v_4 from Yutin Bai





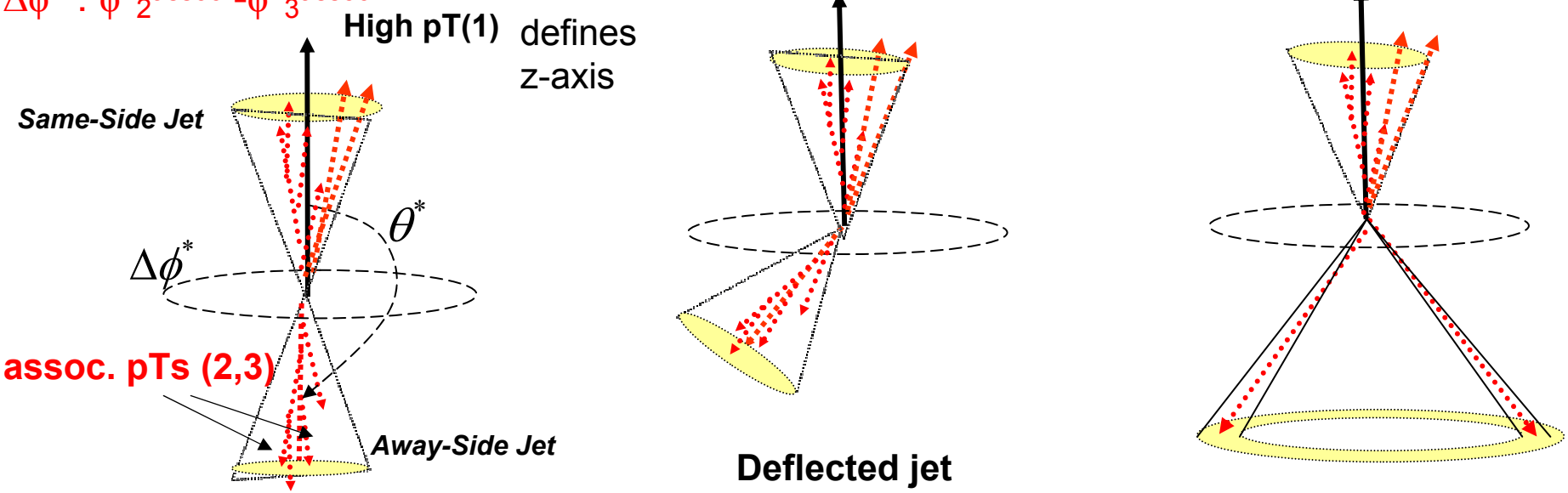
- Clear evidence for *finite 3-Particle Correlations*
- Observation of flow like and jet like structures.
- Finite Sensitivity: No evidence for Mach cone

PHENIX Two-particle Conditional Distributions

θ^* : trigger-associated particle polar angle

$\Delta\phi^*$: $\phi^*_2{}^{assoc} - \phi^*_3{}^{assoc}$

polar coordinates



Back-to-back Jet

$$\left|\phi_{trig,2} - \phi_{trig,3}\right|$$

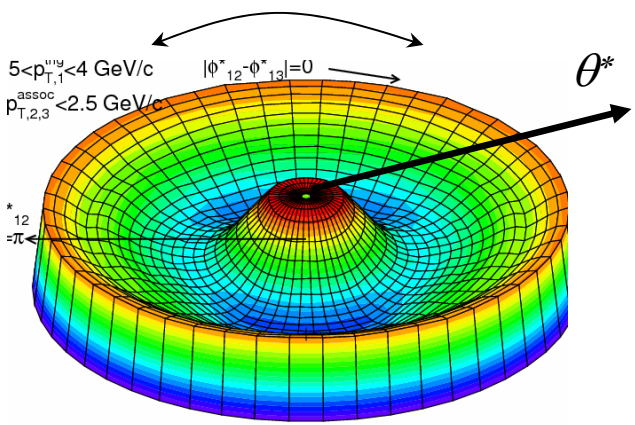
Deflected jet

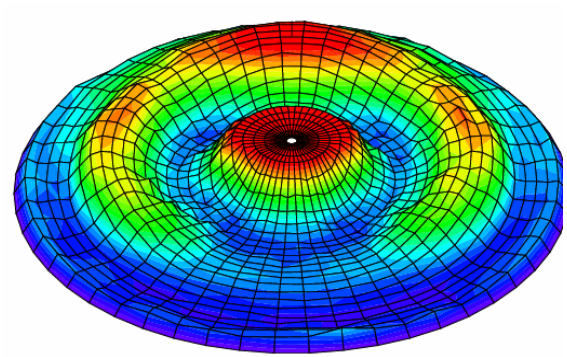
$\Delta\phi^* \sim 0$

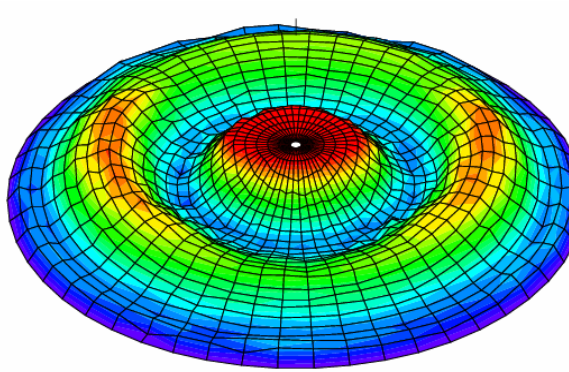
$\theta^* \sim \theta^D$

Mach Cone

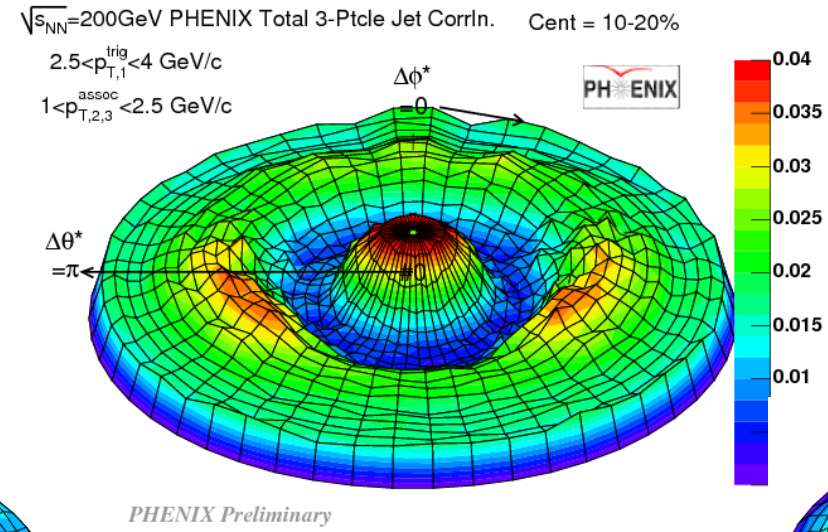
$\theta^* \sim \theta^R$



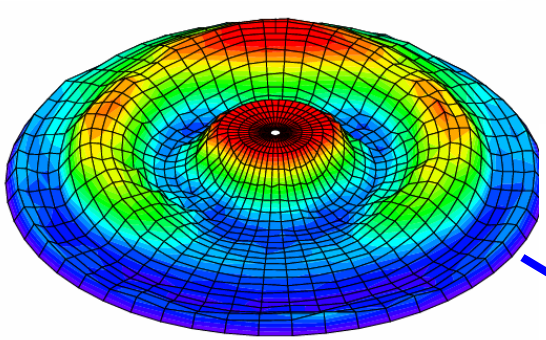




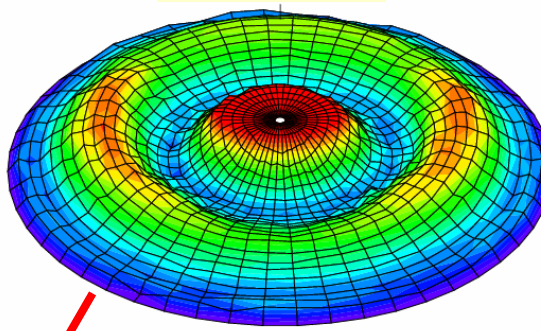
PHENIX Data With harmonic subtraction

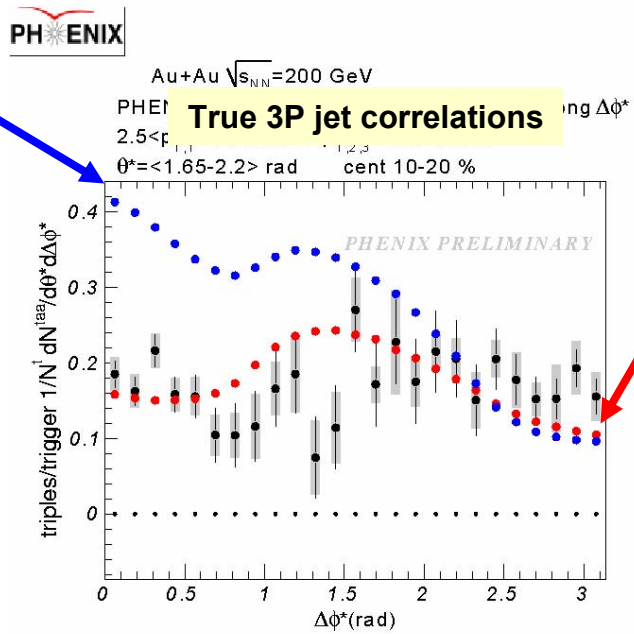


Simulated Deflected jet



Simulated Mach Cone





Evidence for Mach Cone signal, but does not rule out contributions from other topologies.

Away-Side Summary

- At lower p_t, minbias analysis suggests jet momentum dissipation
- For high-p_t trigger analysis a dip appears at $\Delta\varphi=\pi$ (after v2 subtraction) which motivates studies of cone emission.
- Three-particle correlation analyses are complex, requiring meticulous background subtractions.
- Consensus has not yet been reached among the three analyses on the question of cone emission.

Conclusions

Detailed and differential correlation analyses access many areas of RHIC physics

- Same-side jet evolution:
  - momentum dissipation of medium
  - parton-medium interaction and/or modification of fragmentation
  - evolution of hadronization geometry.

- Away-side:
  - energy loss and momentum dissipation
  - possible collective modes of the bulk.

The challenge ahead is to describe these interactions with the medium into a single theoretical framework