The Ridge(s) in STAR

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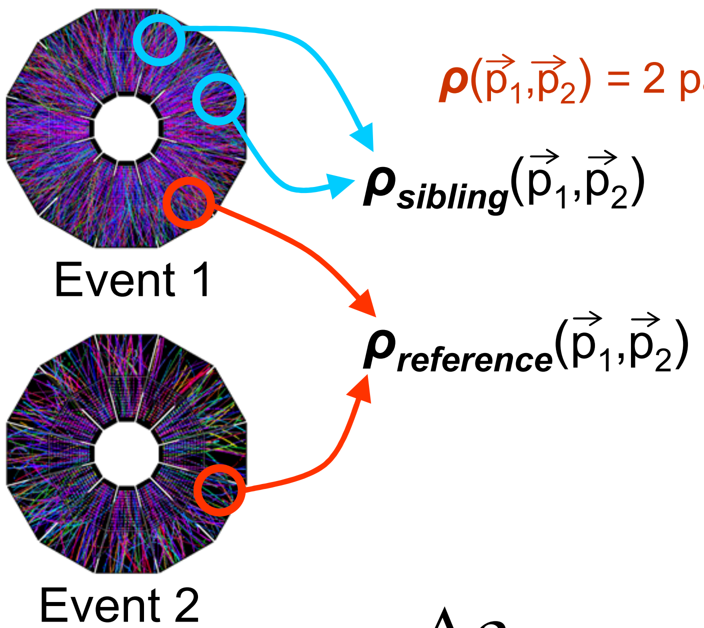
Outline:

- Introduction
- Transverse momentum space
- Au-Au, Cu-Cu results
- Ridge evolution with p_t
- Constraints on models
- Conclusions

RIKEN-BNL Glasma Workshop – May 10-12, 2010

STAR's correlation measure

$\boldsymbol{\rho}(\vec{p}_1,\vec{p}_2)$ = 2 particle density



Fill 2D histograms (a,b), e.g. (ϕ_1,ϕ_2), (η_1,η_2), $(\phi_1-\phi_2,\eta_1-\eta_2)$, (p_{t1},p_{t2}), etc.

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \frac{dN_{ch}}{d\eta d\phi}\left[\frac{\rho_{sib}(a,b)}{\rho_{ref}(a,b)} - 1\right]$$

measures number of correlated pairs *per final state particle*

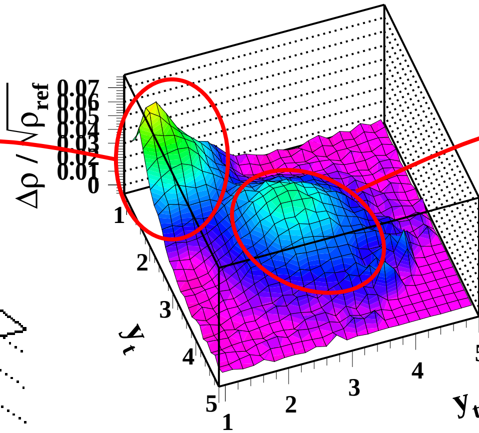
square-root of $\rho_{ref}(a,b)$; (for η,ϕ space)

normalized ratio of 2D binned histograms; acceptance cancellation; two-track ineff. corrections

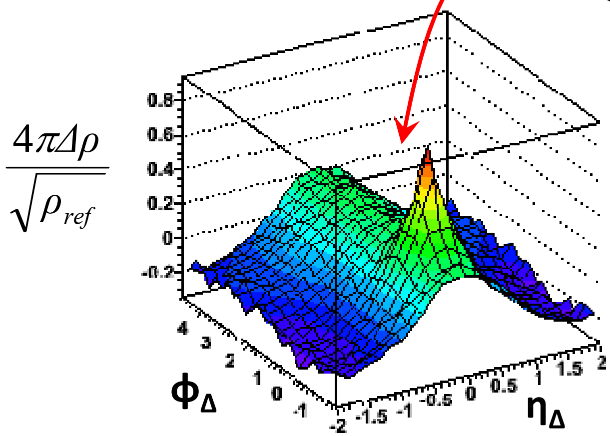
Motivated by p-p superposition null hypothesis

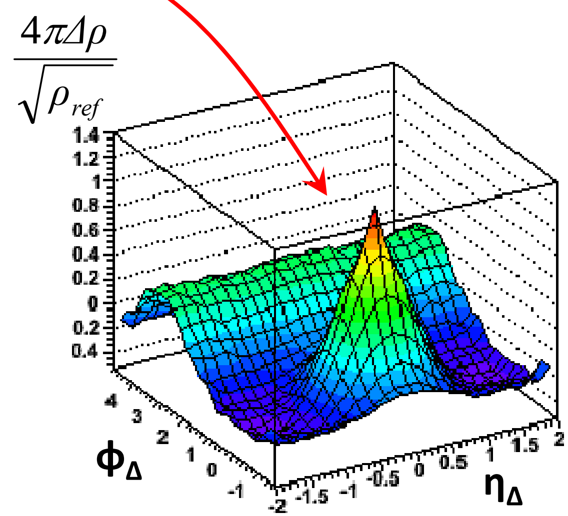
Angular correlations for p-p

cut low y_t pairs and project onto relative η,ϕ:

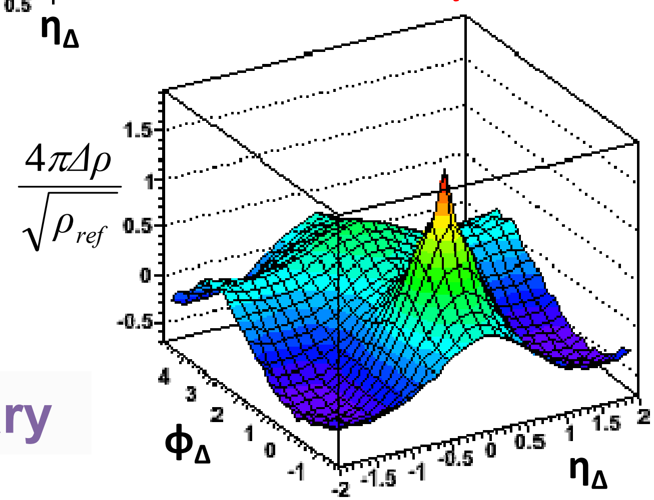


cut larger y_t pairs and project onto relative η,ϕ:





include all y_t pairs



Longitudinal fragmentation (charge ordering) plus HBT for like-sign

Same-side 2D Gaussian plus away-side ridge – *classic back-to-back jet-like structure*

$$\eta_\Delta = \eta_1 - \eta_2$$

$$\varphi_\Delta = \varphi_1 - \varphi_2$$

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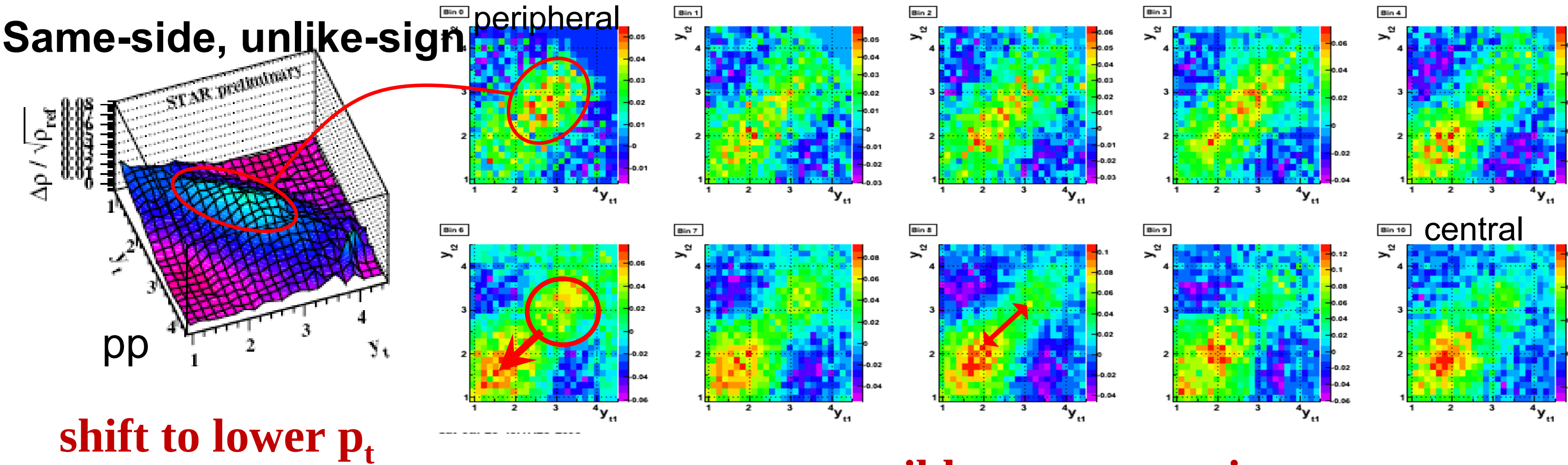
transverse rapidity: $y_t = \ln\left(\frac{m_t + p_t}{m_{pion}}\right)$

(y_{t1},y_{t2}) correlations for same-side, away-side pairs

$y_t = \ln[(m_t + p_t)/m_{pion}]$

Au-Au 200 GeV

Same-side, unlike-sign



possible π–p separation

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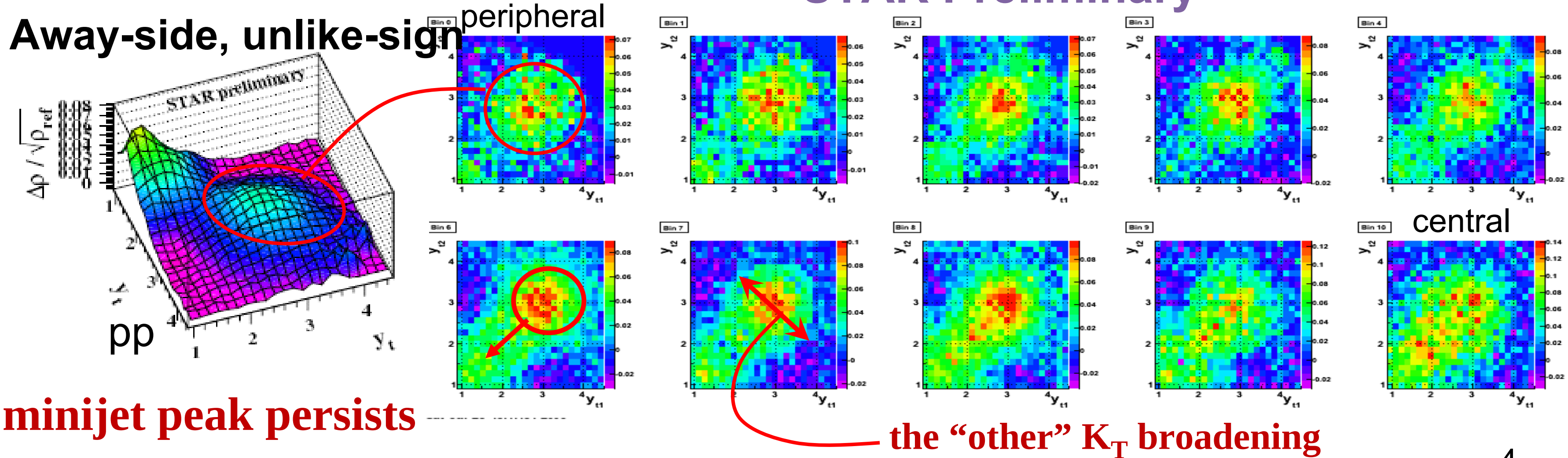
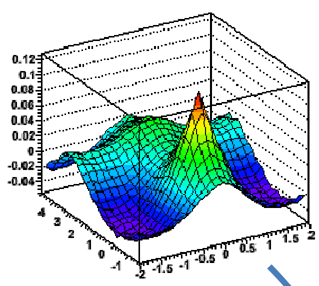
Away-side, unlike-sign

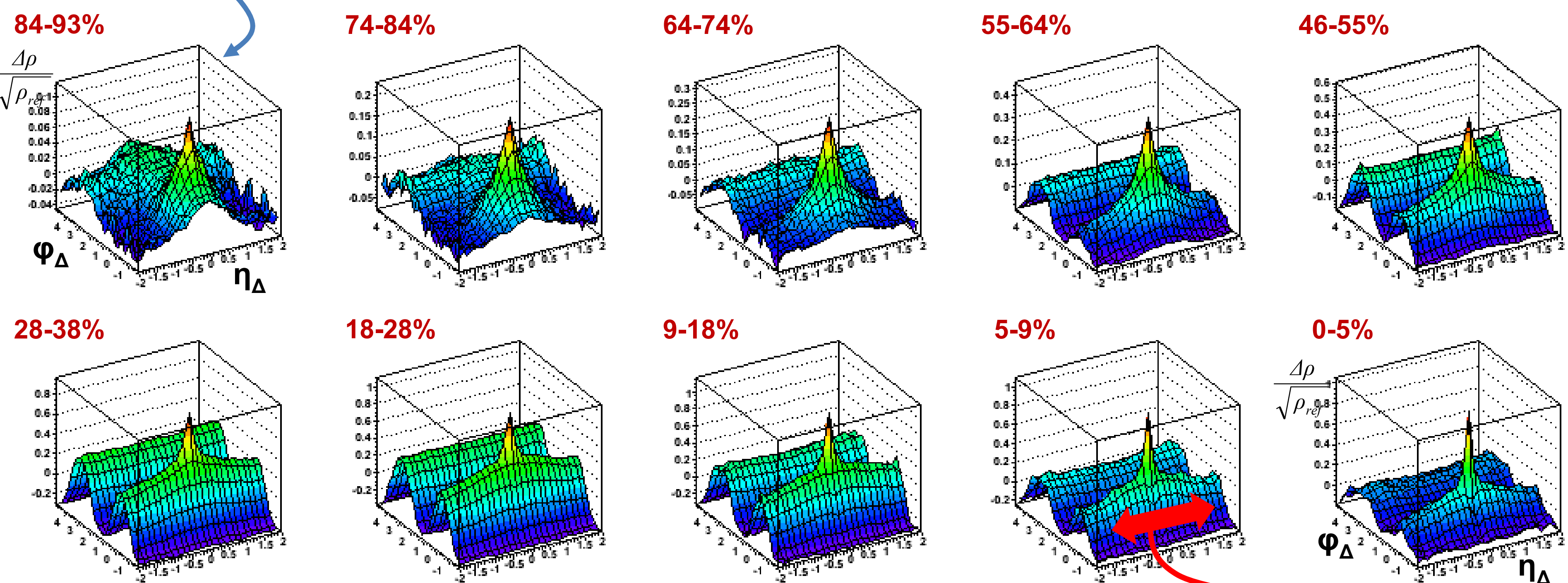


From M. Daugherity's Ph.D Thesis (2008)



200 GeV Au-Au data

Analyzed 1.2M minbias 200 GeV Au+Au events;
included all tracks with p_t > 0.15 GeV/c, $|\eta|$ < 1, full φ



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We observe the evolution of several correlation structures including the same-side low p_t ridge

Similar analysis was done for minbias Au-Au at 62 GeV and Cu-Cu at 62 and 200 GeV

From M. Daugherity's Ph.D Thesis (2008)

Fit function – compact characterization of correl. evolution

Proton-Proton fit function

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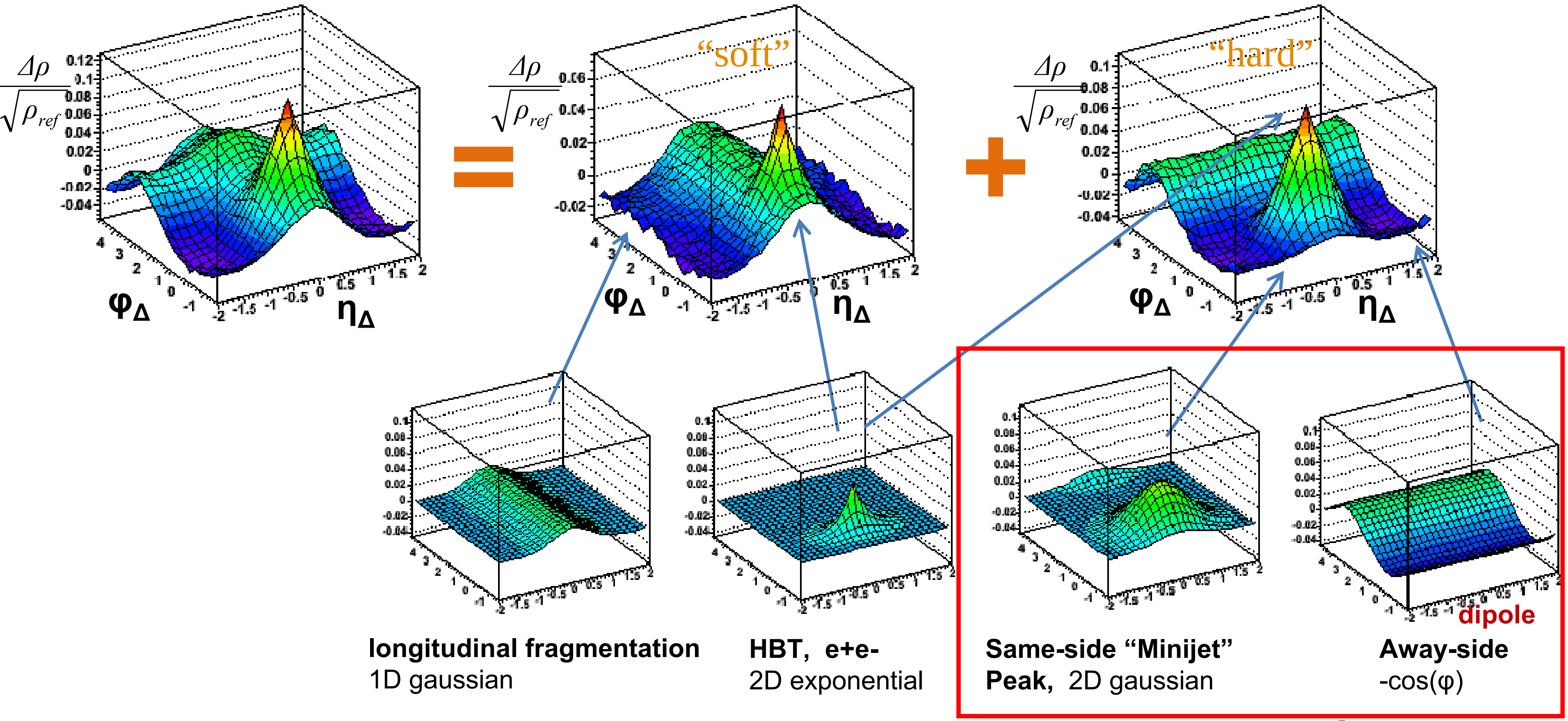
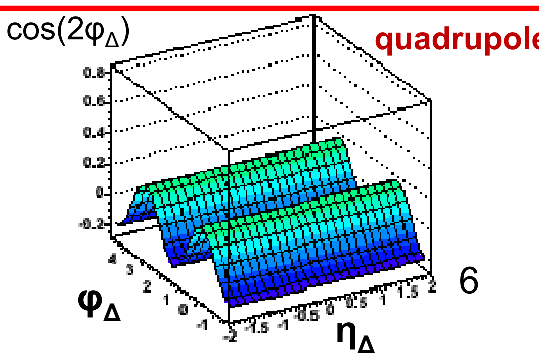


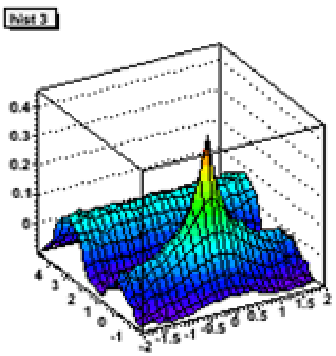
Au-Au fit function

Use proton-proton fit function plus $\cos(2\varphi_\Delta)$ quadrupole term (~ elliptic flow).

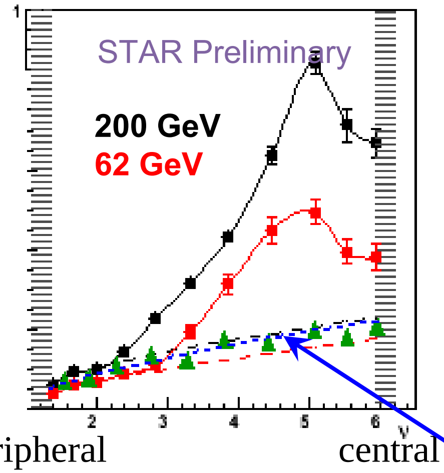


Fits to 62 & 200 GeV Au-Au data

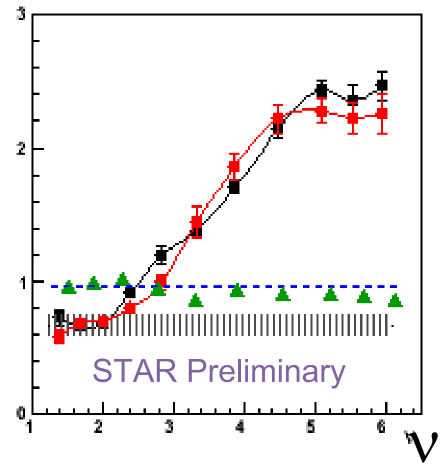
$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}}$$



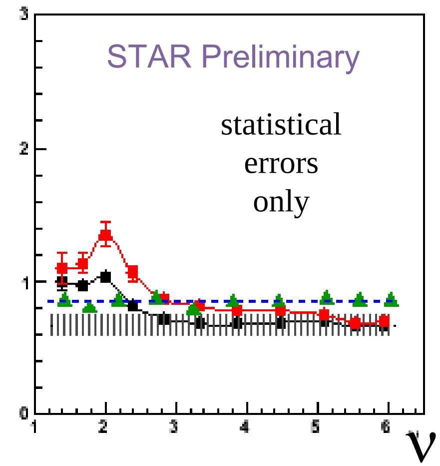
SS Peak Amplitude



Peak η Width

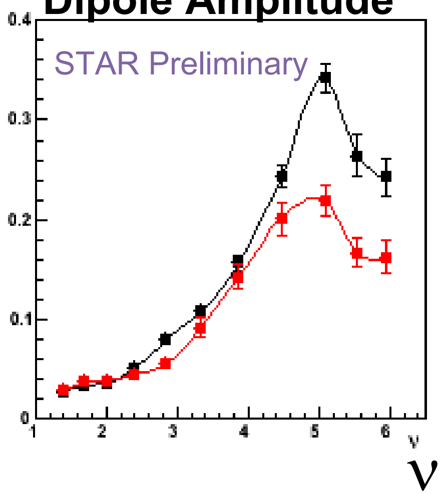


Peak φ Width



$$\nu \equiv \frac{\langle N_{bin} \rangle_{200GeV}}{\langle N_{part}/2 \rangle}$$

Dipole Amplitude

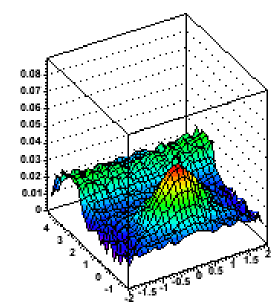


Up to 1/3 of multiplicity in central Au-Au associated with jet angular correlations

Binary scaling: Kharzeev and Nardi

$$\text{Amplitude} = A_{AA} \propto \frac{N_{bin}}{N_{chrg}}$$

HIJING 1.382 default parameters, 200 GeV, quench off



pQCD HIJING jets

Deviations from binary scaling represent new physics unique to heavy ion collisions; the departure from N-N superposition is referred to as a *transition* in the trends.

Observing the transition directly – no fit model

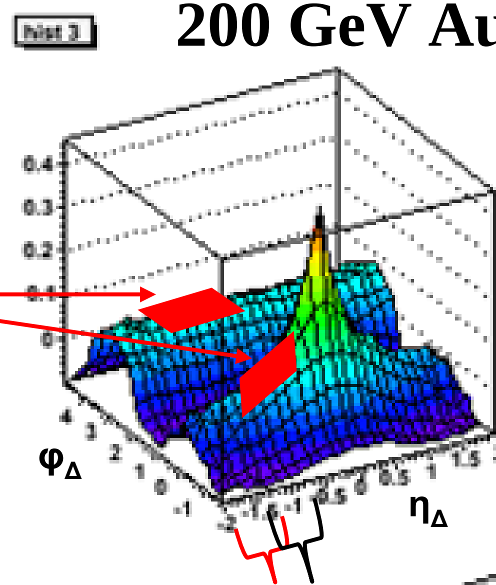
Construct differences:

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}}(\eta_\Delta,\phi_\Delta)-\frac{\Delta\rho}{\sqrt{\rho_{ref}}}(\eta_\Delta,\phi_\Delta+\pi)$$

average over several bin pairs -- the offset, quadrupole (v_2), 1D Gaussian components cancel.

200 GeV Au-Au

$\frac{\Delta\rho}{\sqrt{\rho_{ref}}}$



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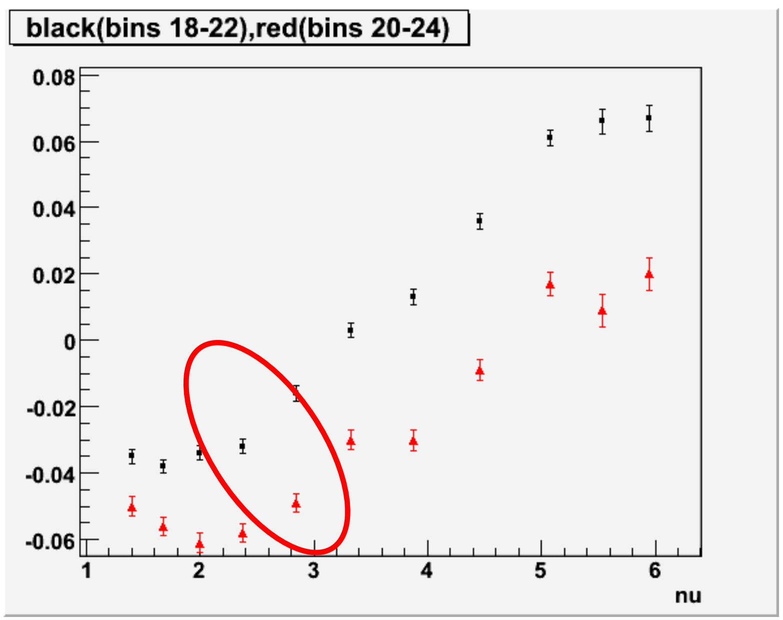
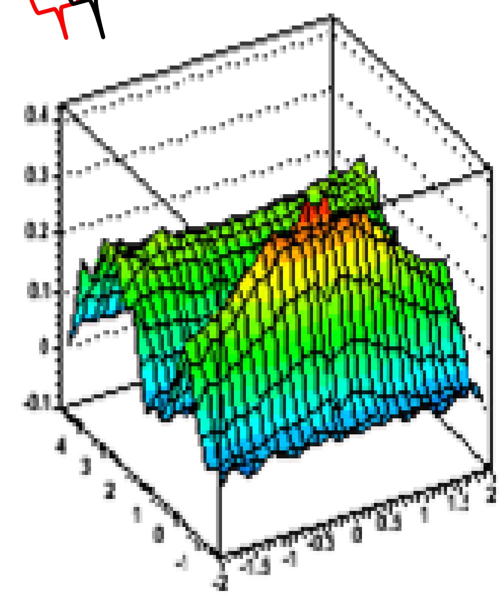


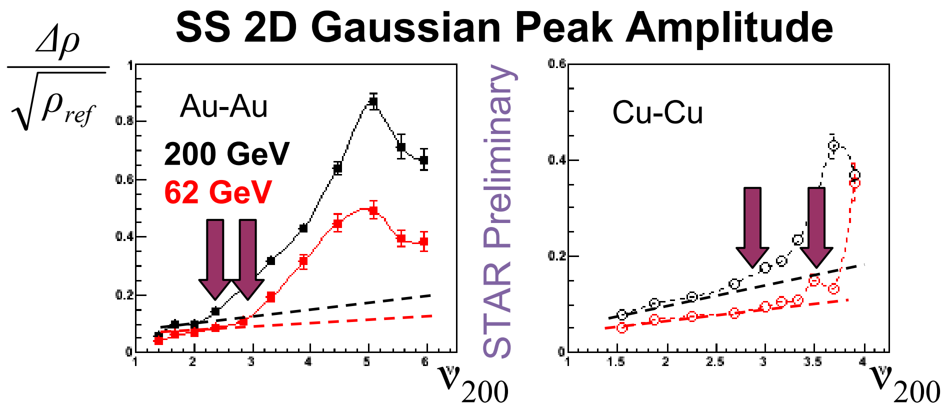
transition observed directly in data

ν



Growth of the "soft-ridges"

Scaling of the Transition: final-state density?



Hypothesis: the transition centrality location depends on final-state transverse particle density, as might be expected if *final state effects* dominate.

	ν_{trans}	$\% \sigma_{tot}$	$\tilde{\rho}_{trans}$
Au-Au 200	2.5 – 2.7	60 – 64	2.5 ± 0.1 *
Au-Au 62	2.7 – 2.9	43 – 55	2.5 ± 0.3
Cu-Cu 200	2.8 – 3.0	22 – 30	3.2 ± 0.2
Cu-Cu 62	3.0 – 3.2	7 - 14	2.9 ± 0.1

Approximate scaling with transverse particle density at each energy; but this scaling hypothesis does not work as well for different collision systems.

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*(errors only account for ν_{trans})

$$\tilde{\rho} = \frac{3}{2}\frac{dN_{ch}}{d\eta} / S \ \ (\text{part./fm}^2)$$

S = overlap area
(Monte Carlo Glauber)

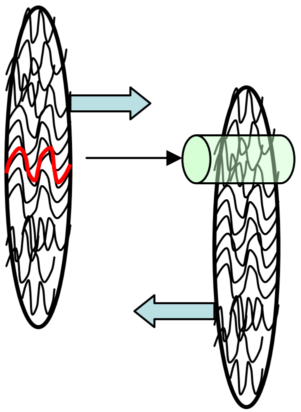
Scaling of the Transition: initial parton overlap?

Consider the low-x gluon overlap in the boosted frame of the beam nucleus in the initial state: [Kopeliovich, Levin et al. *PRC* **79**, 064906 (2009)]

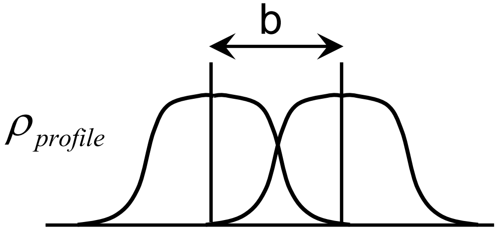
Hypothesis: the transition is due to an *initial-state effect* depending on initial-state overlap of low-x gluons (partons).

Eikonal nuclear profile density – a proxy for low-x gluons: (ignore differences between low-x structure functions in Au and Cu.)

$$\rho_{profile}(x,y) \equiv \int_{-\infty}^{\infty} dz \rho_{matter}(\vec{r})$$

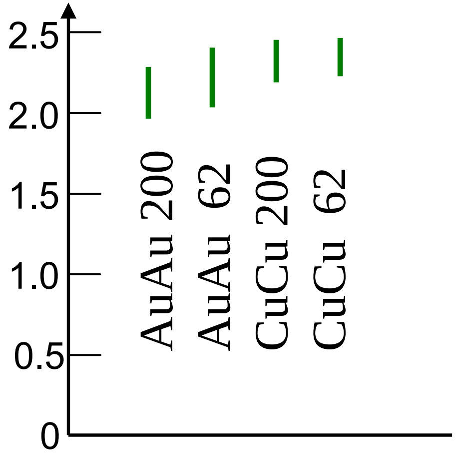


interaction area proxy $\sigma_{NN}(\sqrt{s})$



$$\rho_{profile}(A, b/2)\sigma_{NN}(\sqrt{s})$$

candidate scaling variable for transition



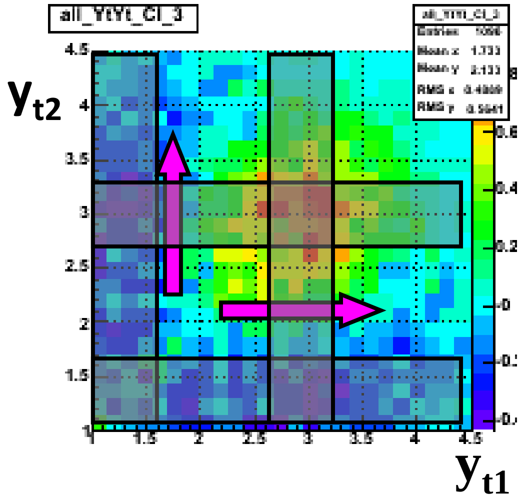
Scaling within errors for both energies and collisions systems.

How do different (y_t,y_t) regions contribute to the ridge?

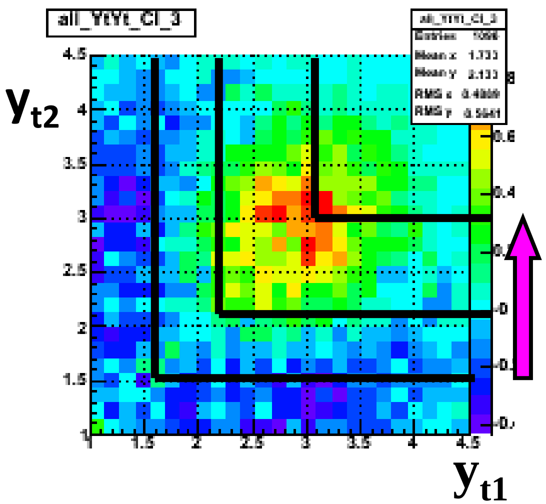
(y_t,y_t) projection schemes

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}}$$

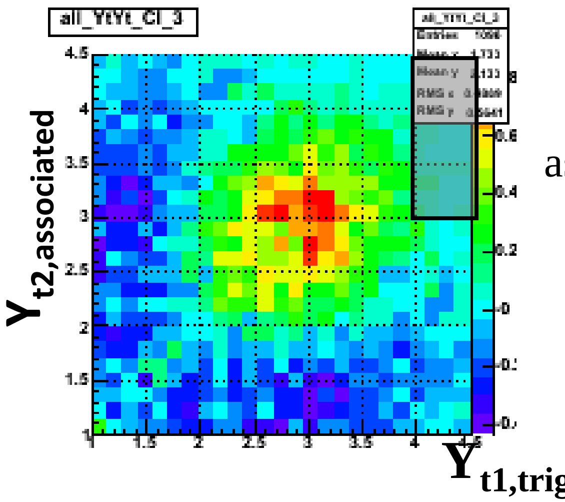
Au-Au 200 GeV
(y_{t1},y_{t2}) for all azimuth
all charged particles
55-64% centrality



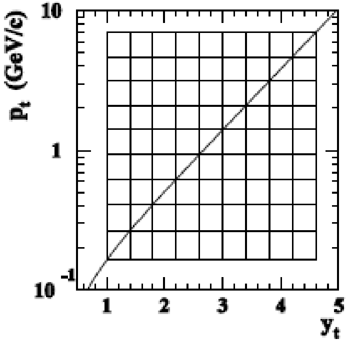
scan p_t dependence



increase $p_{t,min}$



trigger-associated p_t cuts

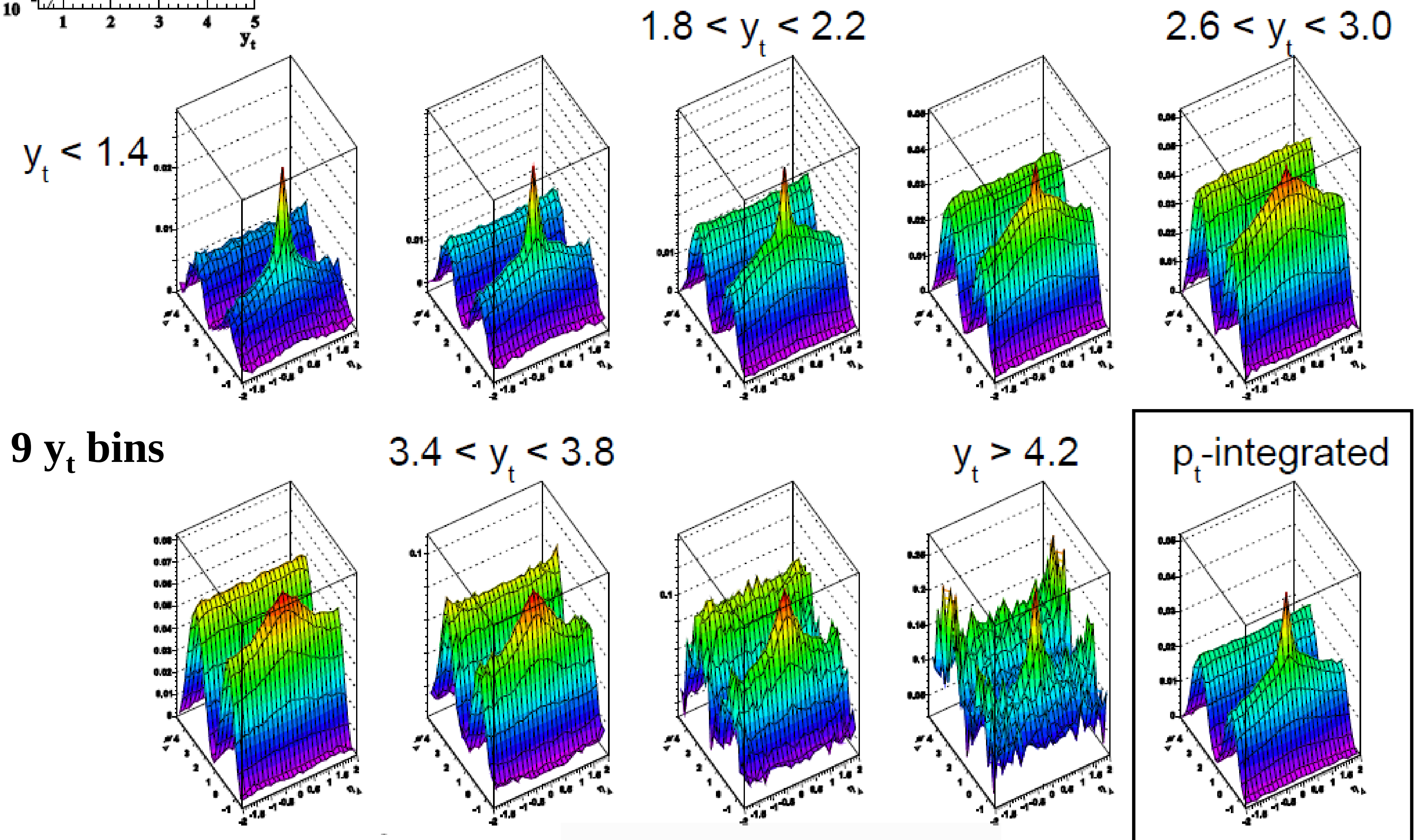


p_t dependence scan: 200 GeV Data

one of 11 centralities

40-50% central

fits to 9×11=99 different 2D histograms



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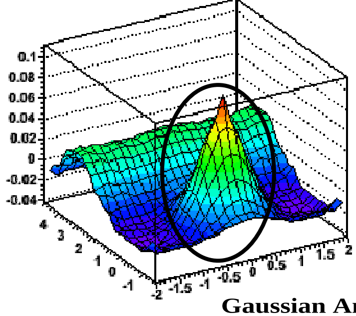
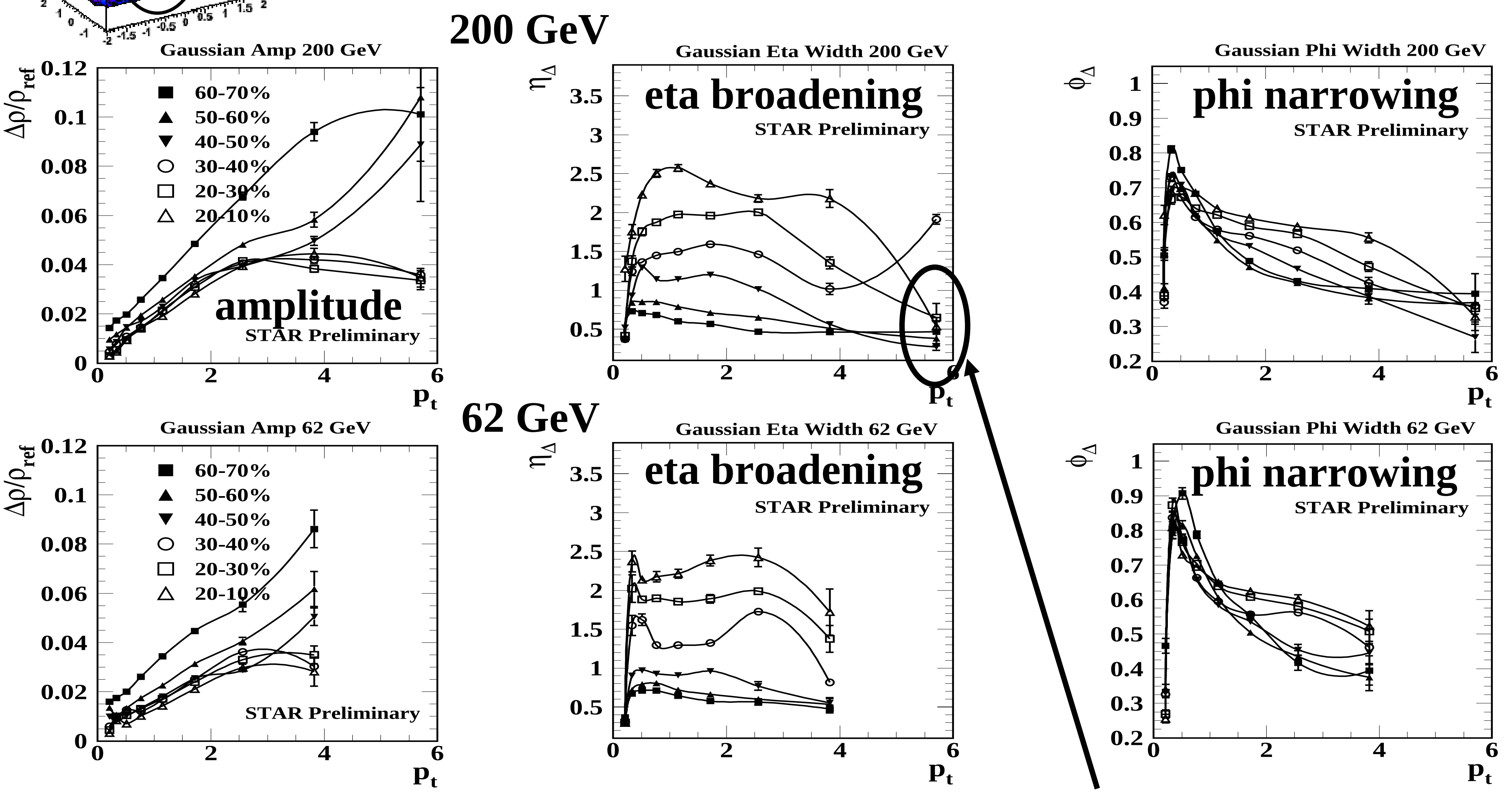
2D fit parameter evolution



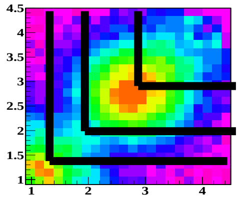
same-side jet peak parameters



angular correlations: marginal on p_t or y_t

unexpected width evolution with centrality, p_t

return to in-vacuum jets above 4 GeV/c



200 GeV Cu-Cu $p_{t,min}$ dependence

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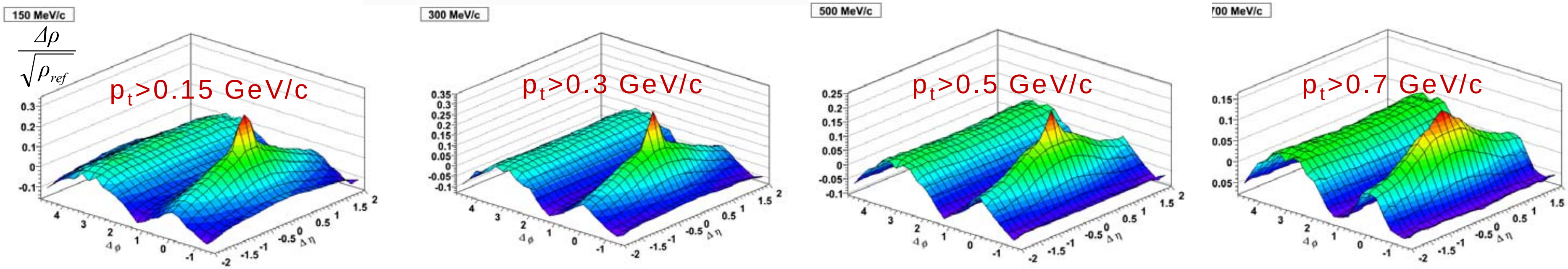
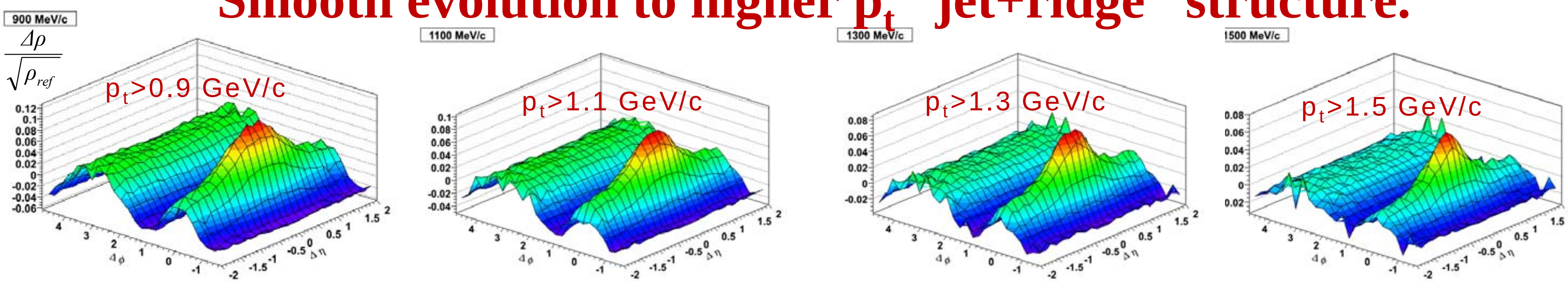
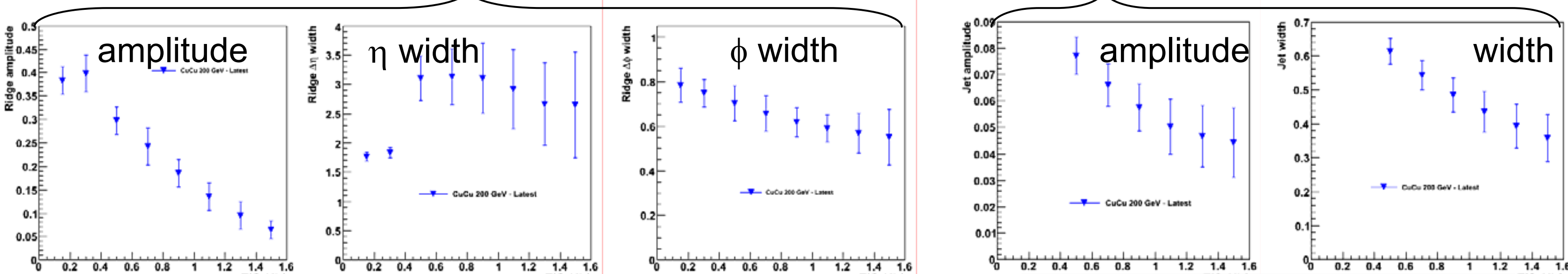
0 - 10%



Smooth evolution to higher p_t "jet+ridge" structure.



Fit same-side with asymmetric 2D Gaussian + symmetric (narrower) 2D Gaussian



Consistent with p_t scan widths

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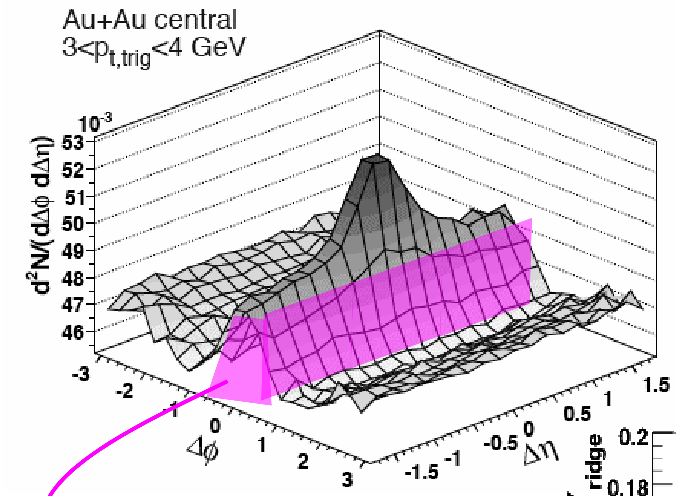
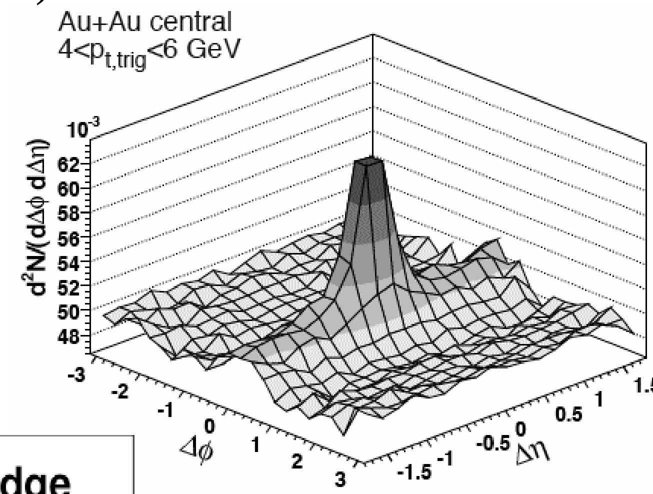
Ridge yield vs. $p_{t,trig}$ in central Au-Au

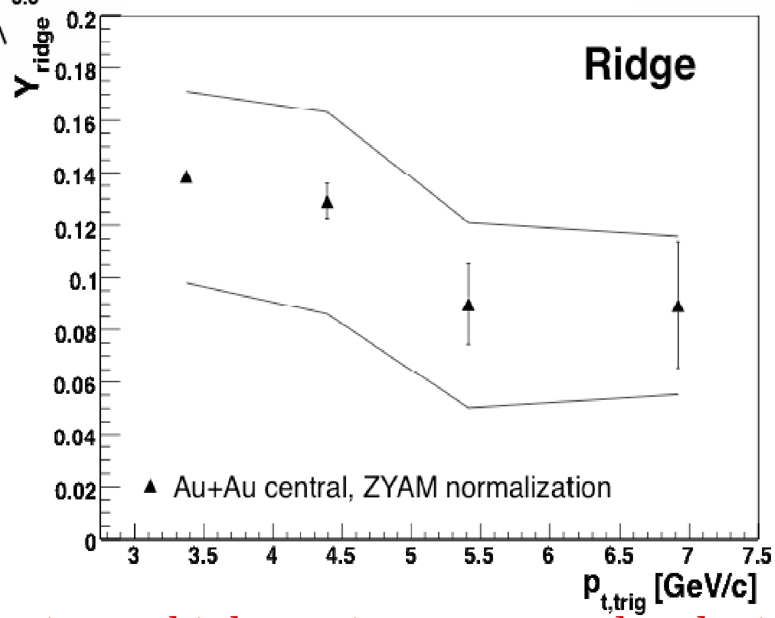
Abelev et al., (STAR) Phys. Rev. C **80** (2009) 064912





$p_{t,assoc.} > 2$ GeV

Integrated ridge yield per trigger; approximately Δη independent

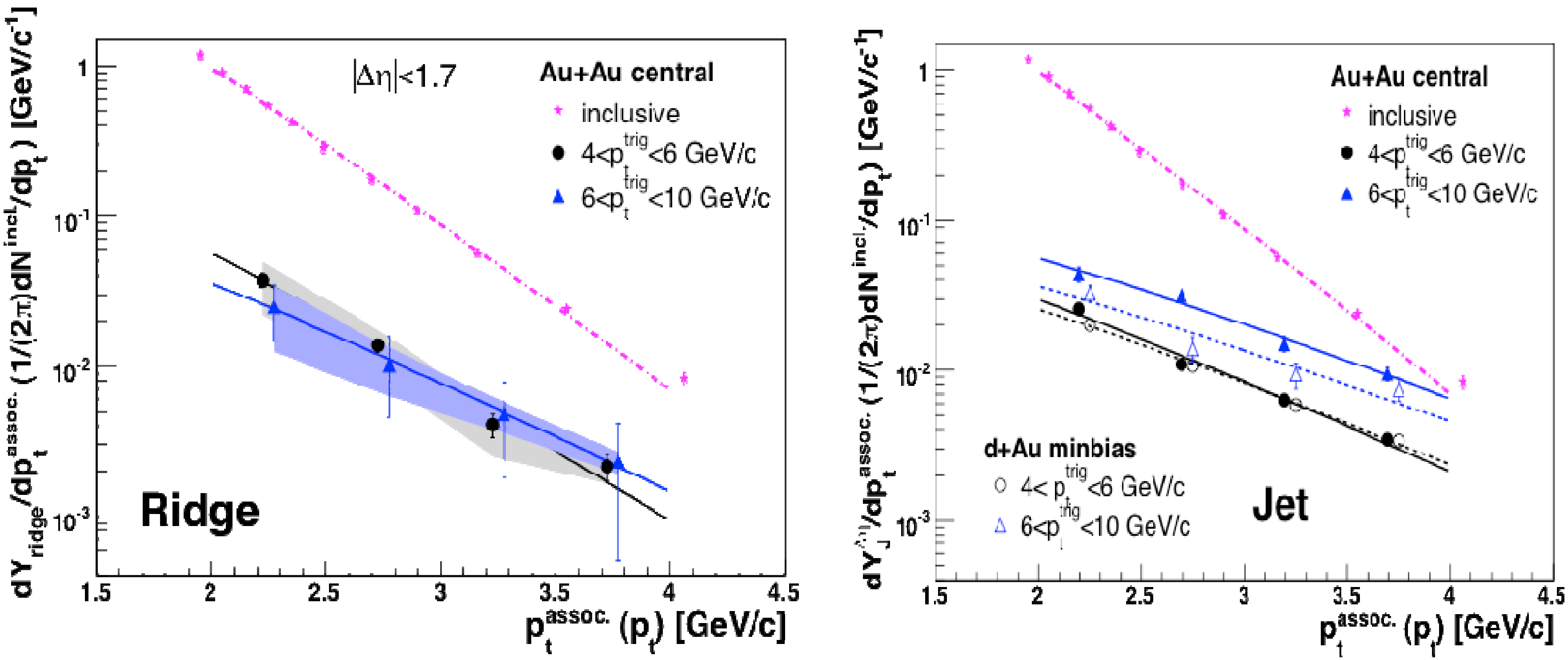


• Ridge yield persists to highest trigger p_t, correlated with jet direction

• Ridge observed only in Au+Au (not present in p+p or d+Au or peripheral Au+Au)

Ridge/Jet $p_{t,assoc}$ spectra in central Au-Au

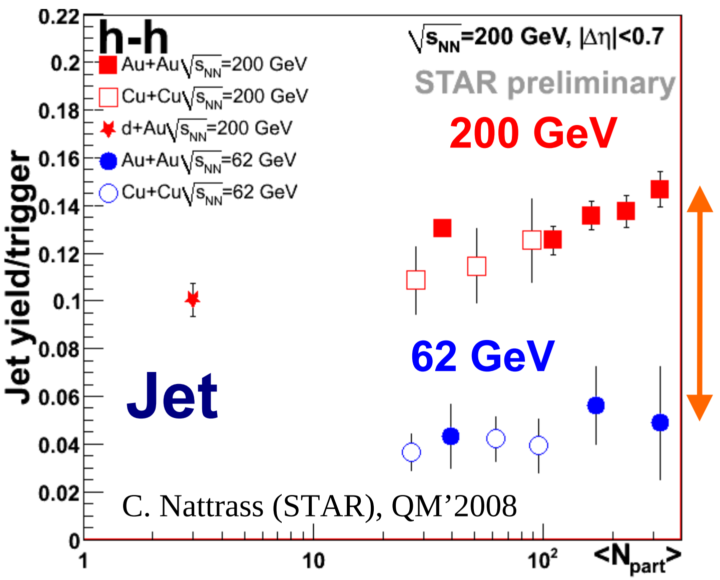
Abelev et al., (STAR) Phys. Rev. C **80** (2009) 064912

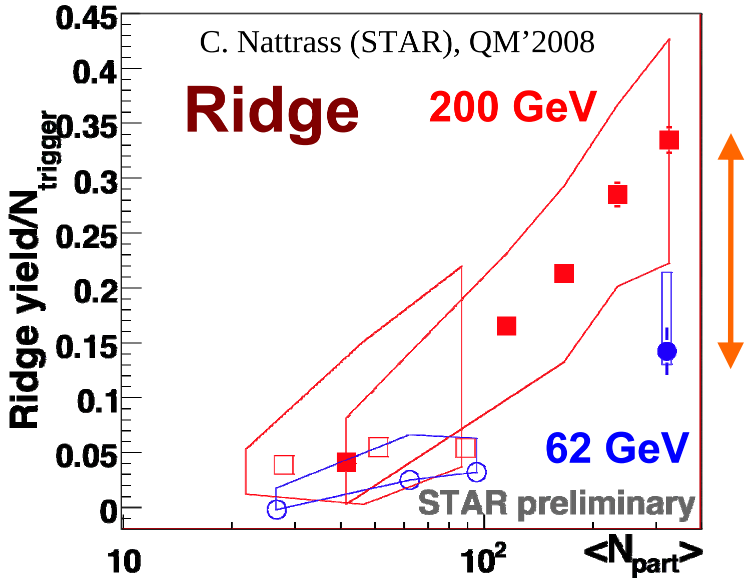


- Jet p_t-spectra harder and increasing with $p_{t,trig}$, as expected from jet fragmentation
- Ridge p_t-spectra are 'bulk-like' and approx. independent of $p_{t,trig}$

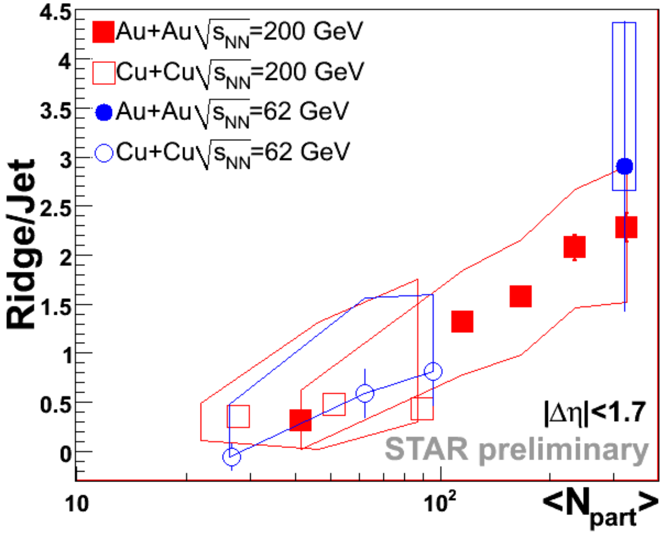
Jet/Ridge 62 vs. 200 GeV in Au-Au, Cu-Cu

3.0 GeV/c < $p_T^{trigger}$ 6.0 GeV/c; 1.5 GeV/c < $p_T^{associated}$ < $p_T^{trigger}$

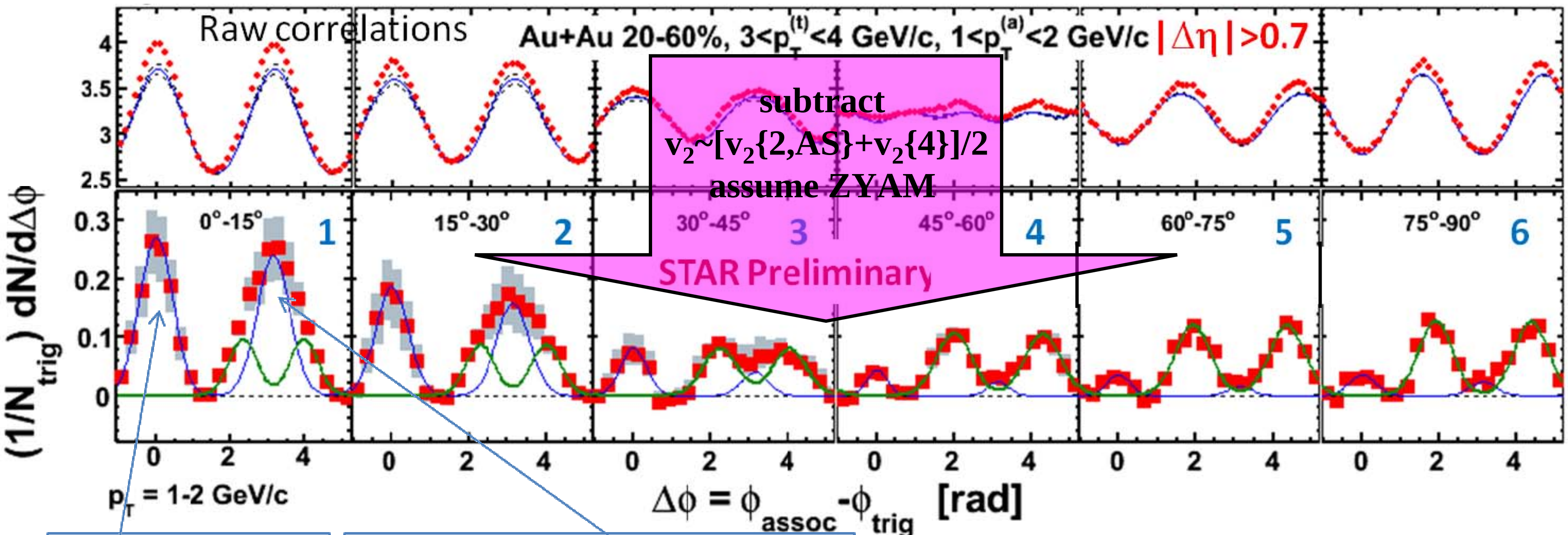




- Jet yield smaller at 62 GeV, consistent with pQCD
- Ridge/Jet ratio comparable in 62 and 200 GeV
  - ridge properties related to jet/pQCD?
- Are we seeing vacuum fragmentation after energy loss on the same-side in central Au-Au with the lost energy deposited in the ridge?

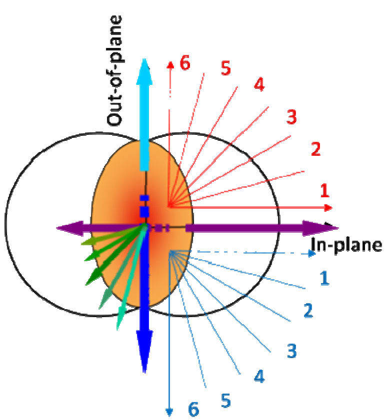


Large-Δη azimuth correlation vs Event Plane

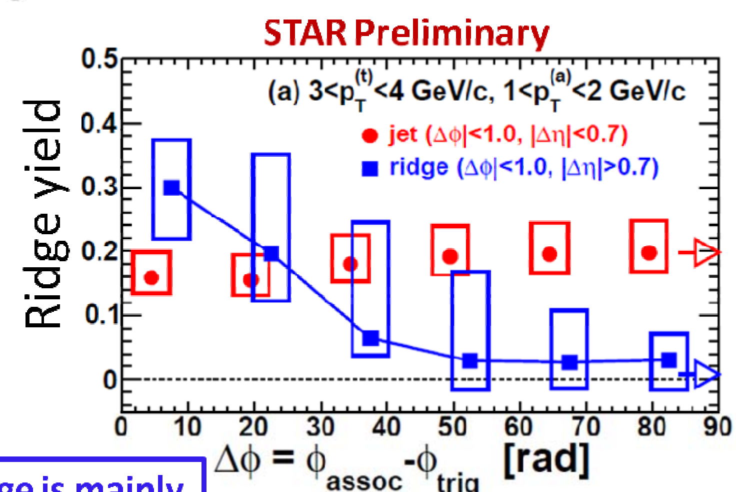


Near-side ridge

Away-side back-to-back ridge

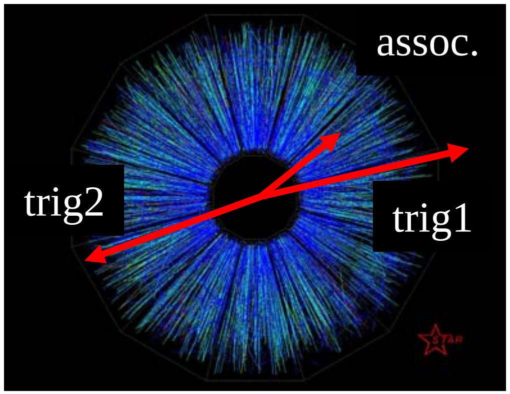


Event plane estimated using $p_T < 2$ GeV/c charged particles



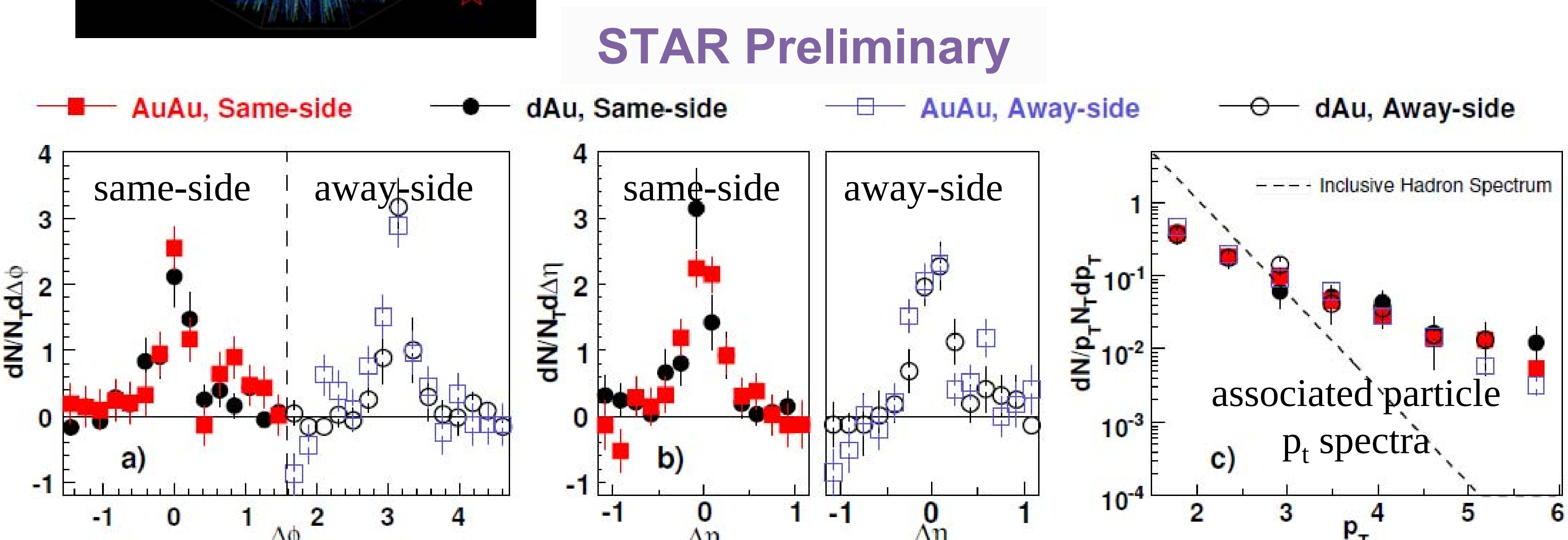
Ridge is mainly in-plane.

Di-trigger – associated particle correlations – *no ridge*



200 GeV Au-Au and d-Au

Trigger 1 is highest p_t particle in event with 5-10 GeV/c
Trigger 2 has p_t > 4 GeV/c and back-to-back within 0.2 rad
Associated particle p_t > 1.5 GeV/c; $\Delta\eta$ < 0.5, $\Delta\phi$ < 0.5
$|\eta|$ < 1 for all particles



- No evidence of medium modifications
- No ridge
- No Mach cones
- Tangential di-jet production suggested

Constraints on Theoretical Models – "soft ridges"

Features of correlations in (y_t, y_t) and $(\eta_\Delta, \phi_\Delta)$ which theory must comprehensively address, i.e. not piecemeal:

- Smooth evolution down to the p-p limit
- Transverse rapidity structure (peak at 1 – 1.5 GeV/*c*)
- Transition - increased yield beyond binary scaling
- Elongation on η_Δ – "soft ridge"
- Azimuth narrowing of small angle structure
- Away-side ridge amplitude growth
- Charge-ordering along η_Δ, ϕ_Δ, and $y_{t\Delta}$
- Away-side K_T broadening on both ϕ_Δ and $y_{t\Delta}$

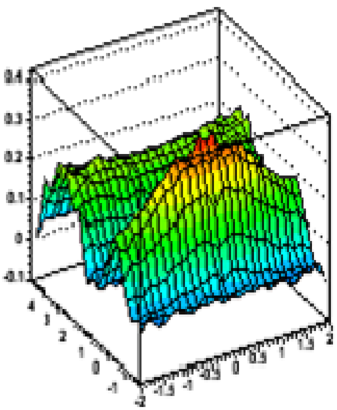
Away-side ridge (dipole): centrality dependence

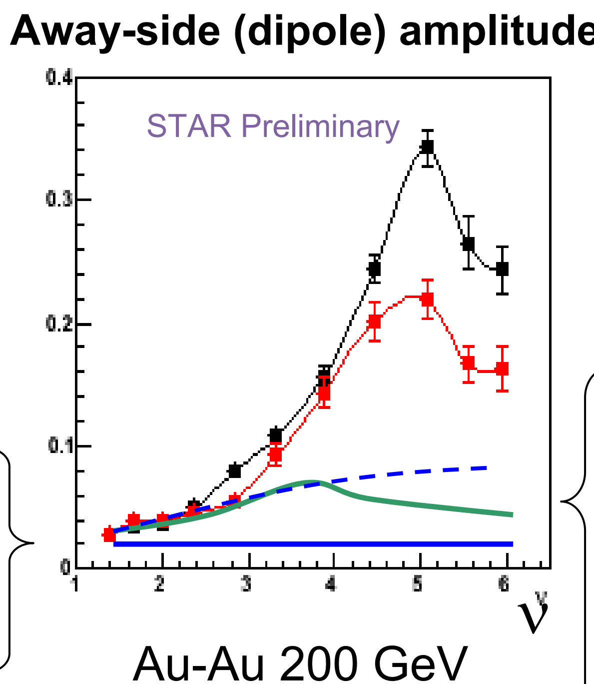
Hypotheses:

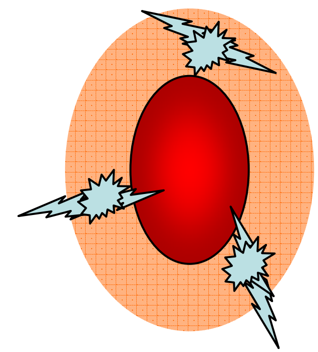
(1) The away-side ridge (other than the quadrupole) <u>is caused</u> by global momentum conservation, where the correlation amplitude ~ $\vec{p}_{t1} \bullet \vec{p}_{t2} / N_{ch}$

(2) The away-side ridge is caused by back-to-back minijets, but only those emitted tangentially from the surface due to strong QGP attenuation; away-side pt escapes, but is dispersed among many more pairs.

opaque core + corona with minijets







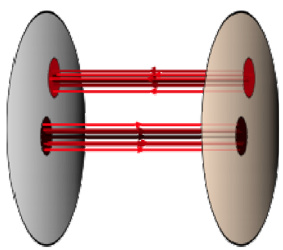
For $\Delta\rho/\mathrm{sqrt}\{\rho_{ref}\}$ global p_t conservation is approximately constant with centrality

Tangential jets: initially follow binary, reduces to surface area scaling when opaque core develops (qualitative trend suggested)

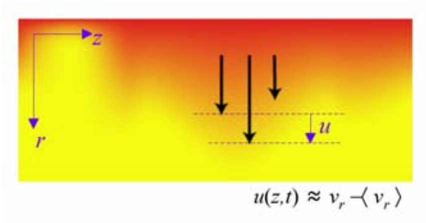
Theoretical models of same-side ridge
- initial fluctuations + radial flow

- ***Voloshin***, Nucl. Phys. A**749**, 287c (2005);
  Shuryak, Phys. Rev. C**76**, 047901 (2007) –
  beam-jet fragments pushed out by radial flow.

- ***Dumitru, Gelis, McLerran, Venugopalan***,
  arXiv:0804.3858[hep-ph] -
  glasma flux tubes pushed out by radial flow.



- ***S. Gavin***, Phys. Rev. Lett. **97**, 162302 (2006) –
  initial state energy fluctuations spread along η
  by shear viscosity; pushed out by radial flow.



These fail to predict the growth of the away-side ridge.

Can they describe the two-particle (yt1,yt2) correlations on <u>both</u> the same and away-sides?

Initial state low-x parton overlap – coherent scattering? *a personal speculation*

incoherent vs. coherent

$$F^2 \xrightarrow{incoh} \sum_n |f|^2 = n|f|^2$$

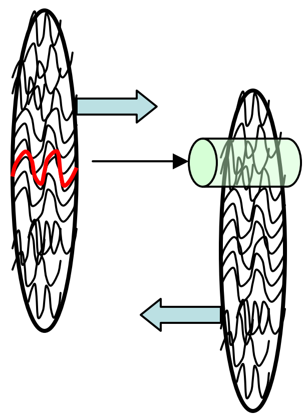
$$F^2 \xrightarrow{coh} \left|\sum_n f\right|^2 = |nf|^2 = nF^2_{incoh}$$

(fixed phase)

$$F^2 \propto |\nu f \nu|^2$$

$$F^2_{coh} \propto N_{part}\nu^4|f|^2 \approx N_{part}N_{bin}|f|^2$$

$$\cong \nu^3 F^2_{incoh}\ ,\ \ N_{part} \propto \nu^3, N_{bin} \propto \nu^4$$



Incoherent (binary) and coherent scaling for semi-hard partonic scattering

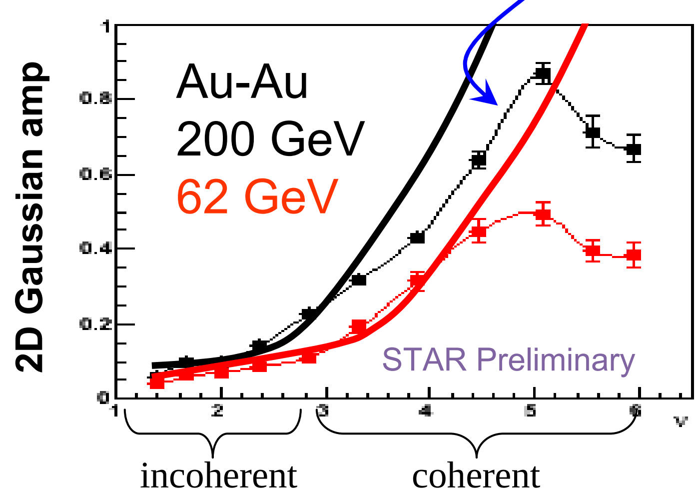
$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} \xrightarrow{binary} a\frac{N_{bin}}{N_{ch}} = \frac{a}{n_{pp}}\frac{\nu}{1+x(\nu-1)}$$

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} \xrightarrow{coherent} a'\frac{N_{bin}\nu^3}{N_{ch}} = \frac{a'}{n_{pp}}\frac{\nu^4}{1+x(\nu-1)}$$

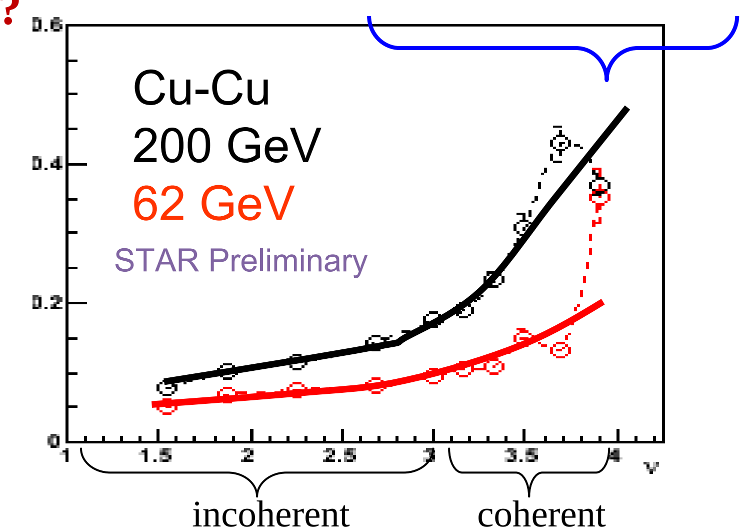
If the transition is from incoherent to coherent partonic scattering, then:

$\rho_{profile} \approx 0.9\ \text{nucleons/fm}^2$

gluon saturation?



$\rho^{Cu,\max}_{profile} \approx 0.72\ \text{nucl/fm}^2 < 0.9$



Summary and Conclusions

- The ridge is observed in Au-Au, Cu-Cu using all pairs and high p_t tagged "trigger" particles
- Transition in centrality trend beyond binary scaling consistent with a common initial condition, $\rho_{profile}\sigma_{NN}$
- The ridge's elongation diminishes above 4 GeV/c while typical jet-like peak returns
- At higher p_t the ridge/jet yield ratios are comparable at 62 and 200 GeV, while jet yields follow pQCD
- An away-side ridge is observed which exceeds global p_t conservation estimates
- Perturbative QCD offers a natural explanation for the two-particle correlations presented here up to the transition, above which one may speculate, e.g. coherent scattering, medium modified fragmentation, etc.
- Above this transition the same- and away-side number correlations increase and away-side (y_t,y_t) correlations persist in the minijet region – not expected for opaque systems
- The 2D correlation data provide an opportunity to learn something new about QCD in dense environments, e.g. secondary interactions, gluon saturation, coherent parton-parton scattering