Physics implications of correlation data from the RHIC and LHC heavy-ion programs

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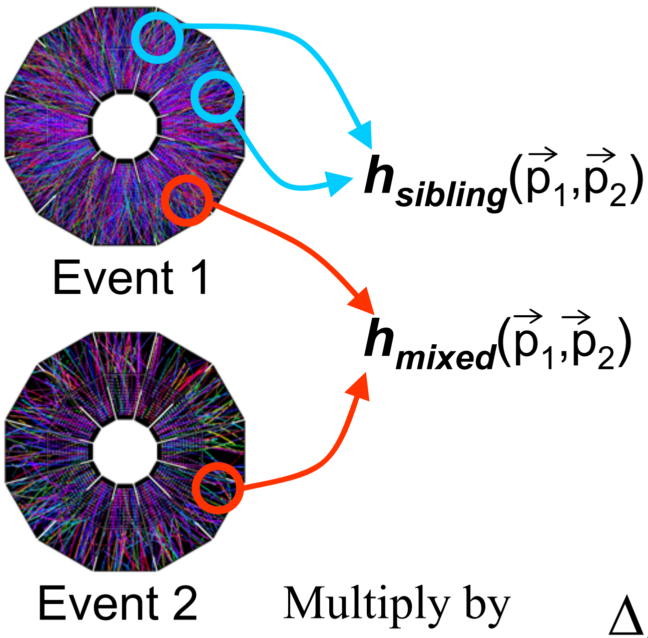
ISMD-2013 Chicago 9/19/2013

Outline

- Two-particle correlations – (η,ϕ) and (p_t,p_t)
- Higher-order harmonics ?
- The view in 4-dimensions
- Minjets and v_2
- pQCD diagrams
- On to the LHC
- Summary and Conclusions

Correlation measure: all charged particles in the acceptance



No trigger particle

$$\text{Ratio}: \left[\frac{h_{sib}}{h_{mix}} - 1\right] \rightarrow \frac{\#\,\text{correl. pairs}}{\#\,\text{final pairs}}$$

Multiply by single particle Density:

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \frac{d^3N_{ch}}{dp^3}\left[\frac{h_{sib}}{h_{mix}} - 1\right]$$

Number of correlated pairs per final-state particle

Fill 2D histograms on: $(\phi_1-\phi_2, \eta_1-\eta_2)$, (p_{t1}, p_{t2}) ; 4D total

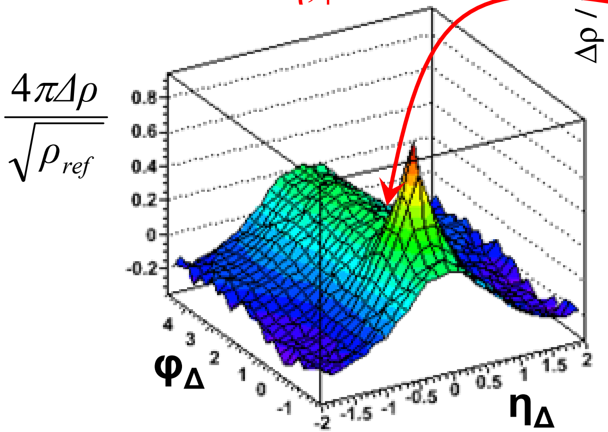
$$\eta_\Delta \equiv \eta_1 - \eta_2$$
$$\phi_\Delta \equiv \phi_1 - \phi_2$$

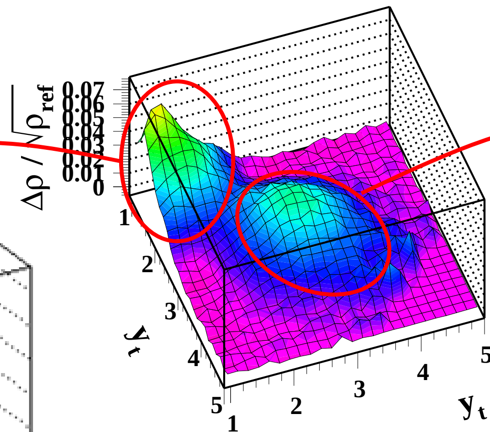
$$y_t = \ln\left(\frac{m_t + p_t}{m_\pi}\right) \approx \ln(p_t)$$

transverse rapidity

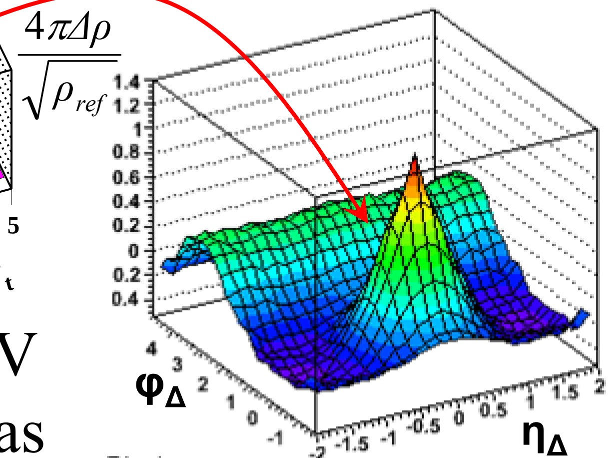
Model element decomposition (η_Δ,ϕ_Δ)

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

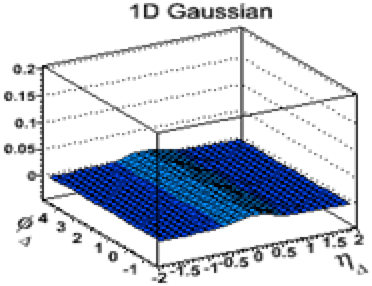


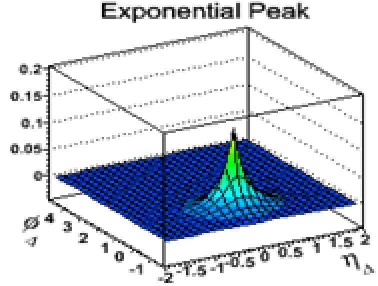


cut larger y_t pairs and project onto relative η,ϕ:

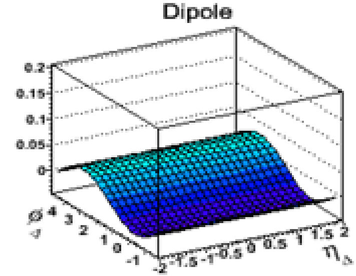


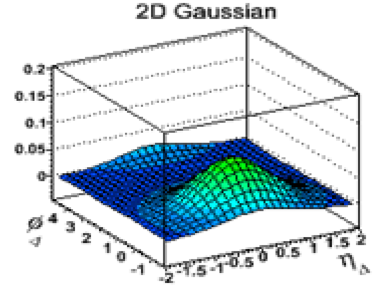
p+p 200 GeV
NSD, minbias



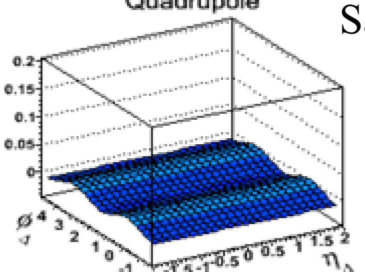


Soft fragmentation plus HBT, $e^{\pm}$ bkgs

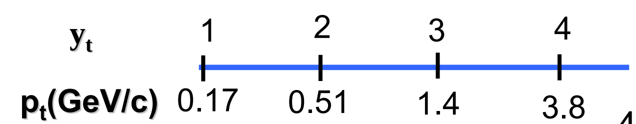




Same-side 2D Gaussian plus away-side ridge – <u>*classic jet structure*</u>



- **For A+A the data require an additional quadrupole: $2A_Q\cos(2\phi_\Delta)$ $A_Q \sim v_2^2$, "elliptical flow"**



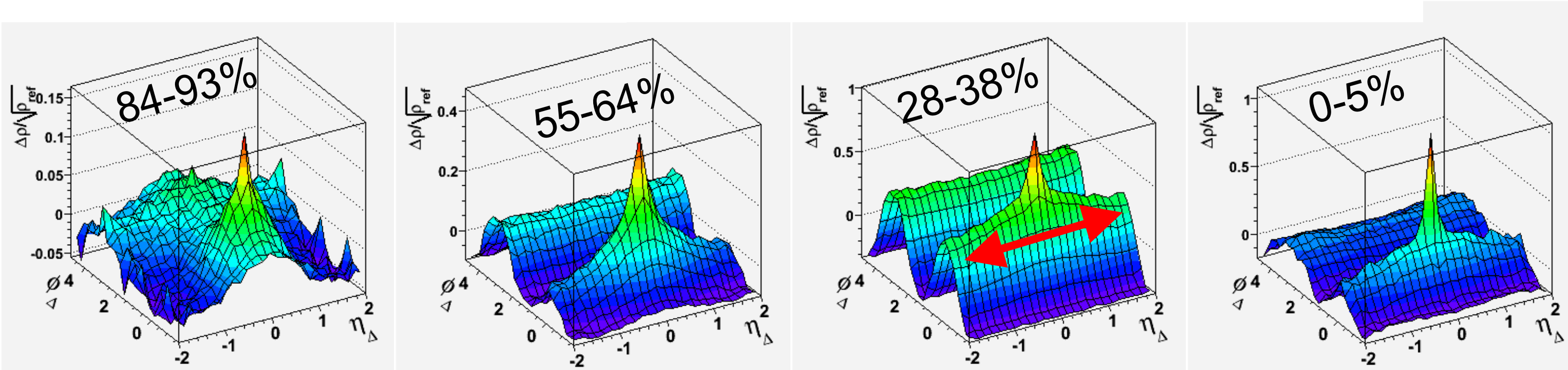
Correlations:

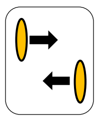
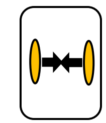
Au-Au 200 GeV minbias collisions

(M. Daugherity) STAR, Phys. Rev. C **86**, 064902 (2012)

- **Data:**

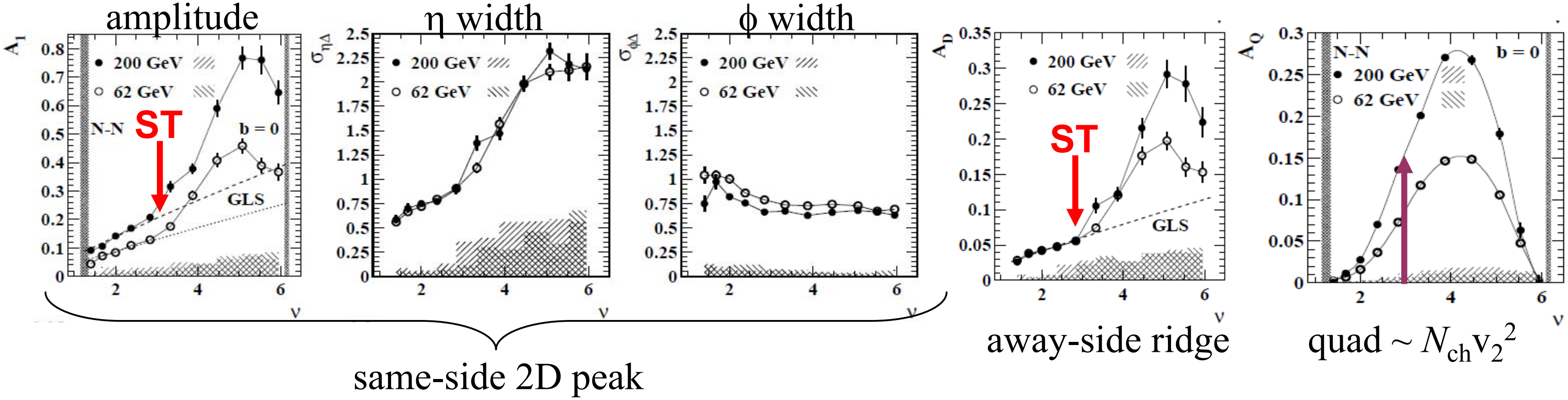
$$\frac{\Delta\rho}{\sqrt{\rho_{mixed}}}$$



peripheral  centrality : # NN - coll/incoming part. N → central 

$$\nu = 2N_{bin} / N_{part}$$

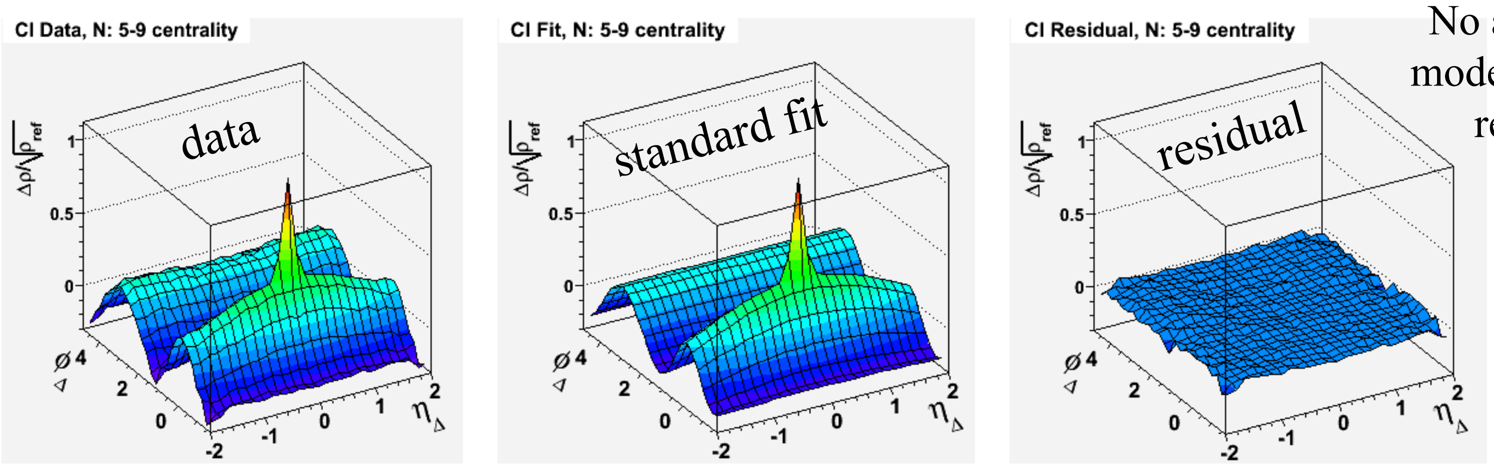
- **Fit Parameters vs. centrality:**



- **Glauber Linear Superposition of unbiased (mini)-jets to ν~3, described by pQCD**
- **Large quadrupole ($N_{ch}v_2^2$) in same range; conventional hydro interpretation**

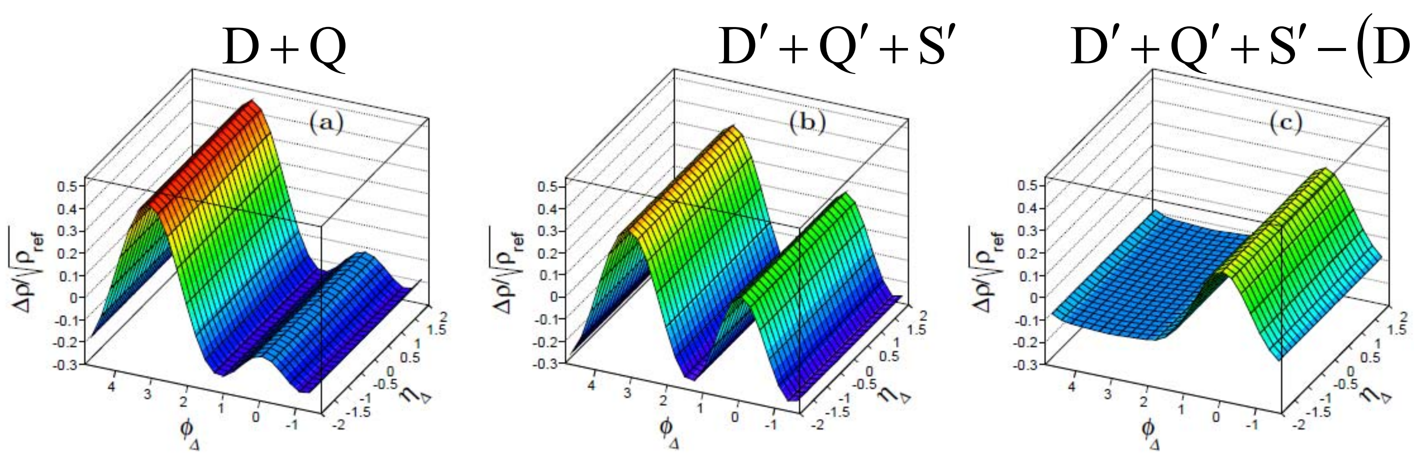
What about higher harmonics, v_n?

- Example: 200 GeV Au+Au 5-9%



No additional model elements required

- Introduce a sextupole $2A_S\cos(3\phi_\Delta)$; maintain away-side fit:



net sextupole contribution

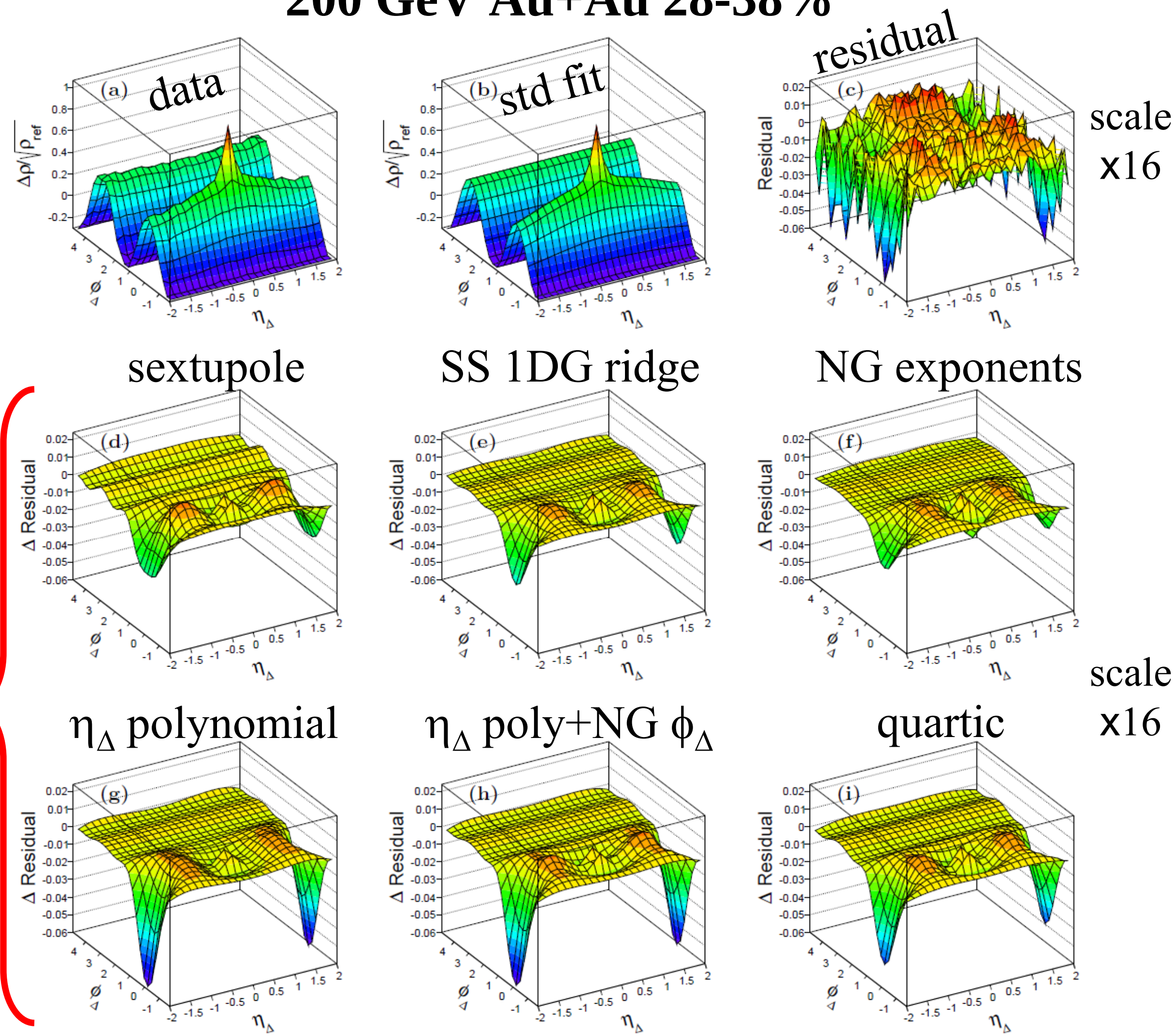
Same-side 2D peak = 1D ridge + reduced 2D Gaussian = *Non-Gaussian* 2D peak

(*LR, Prindle, Trainor, arXiv:1308.4367*)

Non-Gaussian models of same-side 2D peak

$$\begin{pmatrix} \text{Standard} \\ \text{fit model} \end{pmatrix} - \begin{pmatrix} \text{Non-Gaussian} \\ \text{SS 2D peak model} \end{pmatrix}$$

200 GeV Au+Au 28-38%



Non-Gaussian models

Same-Side 1D Gaussian ridge:

$$A_{SSG} \sum_{k=\pm even} e^{-(\phi_\Delta - k\pi)^2/2\sigma_s^2}$$

Non-Gaussian exponents:

$$A_{2D} \exp\left\{-\frac{1}{2}\left[\left(\frac{\eta_\Delta}{\sigma_{\eta_\Delta}}\right)^{2\gamma} + \left(\frac{\phi_\Delta}{\sigma_{\phi_\Delta}}\right)^{2\delta}\right]\right\}$$

η_Δ polynomial with or without NG ϕ_Δ exponent:

$$A_{2D}\left(1 + \alpha\frac{\eta_\Delta^2}{\Delta\eta^2} + \beta\frac{\eta_\Delta^4}{\Delta\eta^4}\right)\exp\left[-\frac{1}{2}\left(\frac{\phi_\Delta}{\sigma_{\phi_\Delta}}\right)^{2\delta}\right]$$

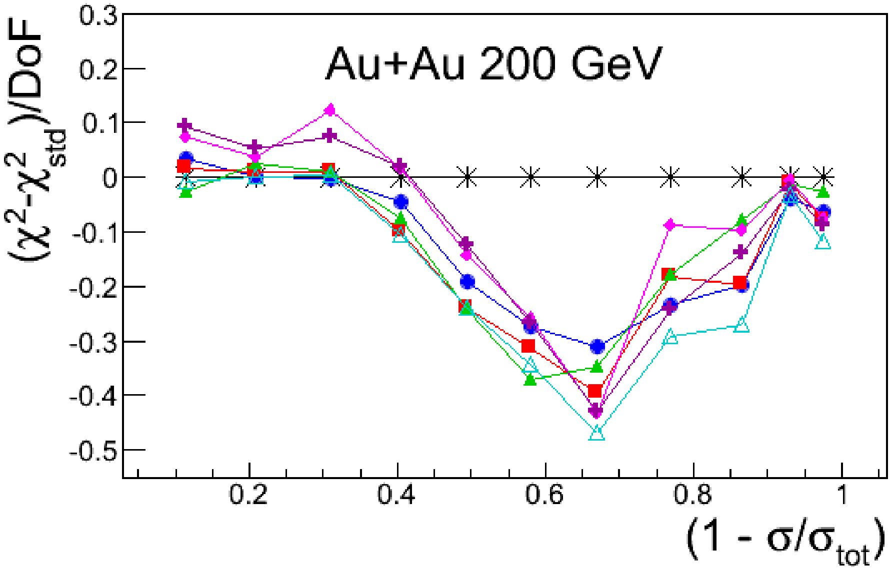
Quartic:

$$A_{2D} \exp\left\{-\frac{1}{2}\left[\left(\frac{\eta_\Delta}{\sigma_{\eta_\Delta}}\right)^2 + \lambda\eta_\Delta^4 + \left(\frac{\phi_\Delta}{\sigma_{\phi_\Delta}}\right)^2 + \varsigma\phi_\Delta^4\right]\right\}$$

- **Slight leptokurtic shape at 2-3σ significance.**

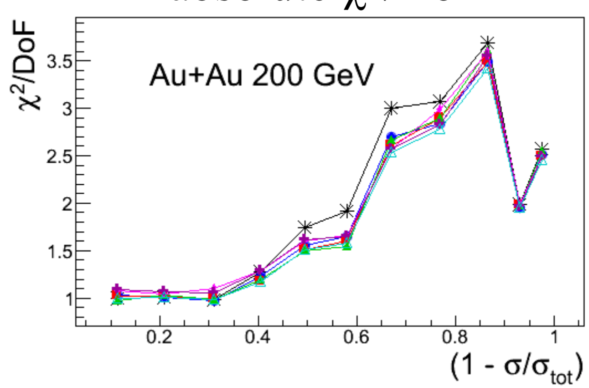
(*LR, Prindle, Trainor, arXiv:1308.4367*)

Sextupole (v_3) – one example of a NG peak



Reduction in χ^2/DoF using **sextupole** and using the other NG models

absolute χ^2/DoF



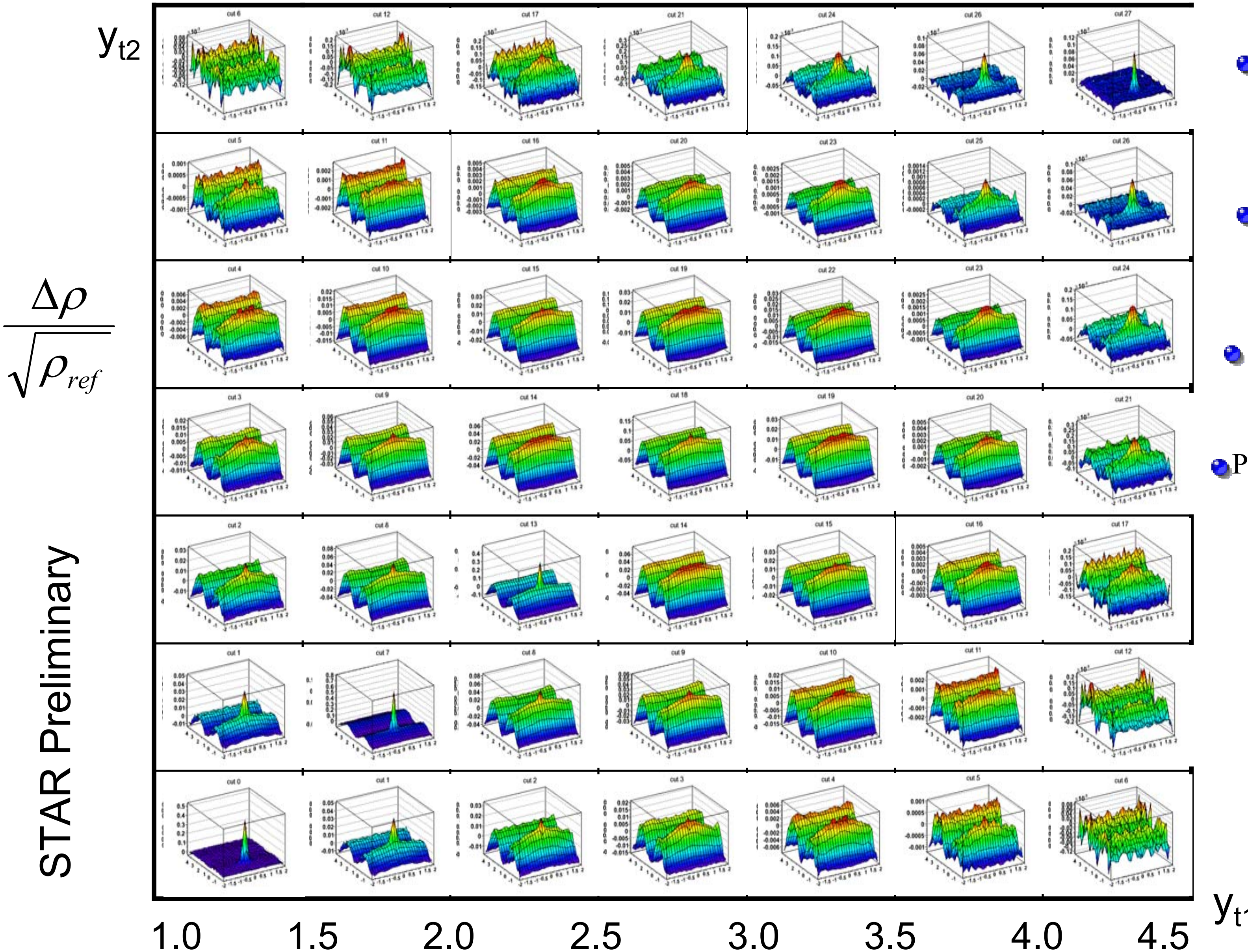
The net effect of the sextupole (v_3) is to allow a small non-Gaussian shape for the same-side 2D peak. It is not unique in that regard; other NG models work as well or better. The only issue here is the small NG shape of the SS 2D peak.

(*LR, Prindle, Trainor, arXiv:1308.4367)*

Returning to 4D correlations…

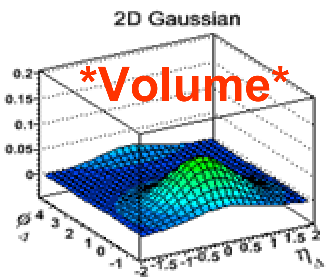
E. Oldag
UT Austin
Ph.D. thesis

Au-Au 200 GeV 18-28%



- Define y_t cut bins
- Project 2D angular correlations
- Fit each with 2D model
- Plot amplitudes, volumes, etc. for each angular correlation feature

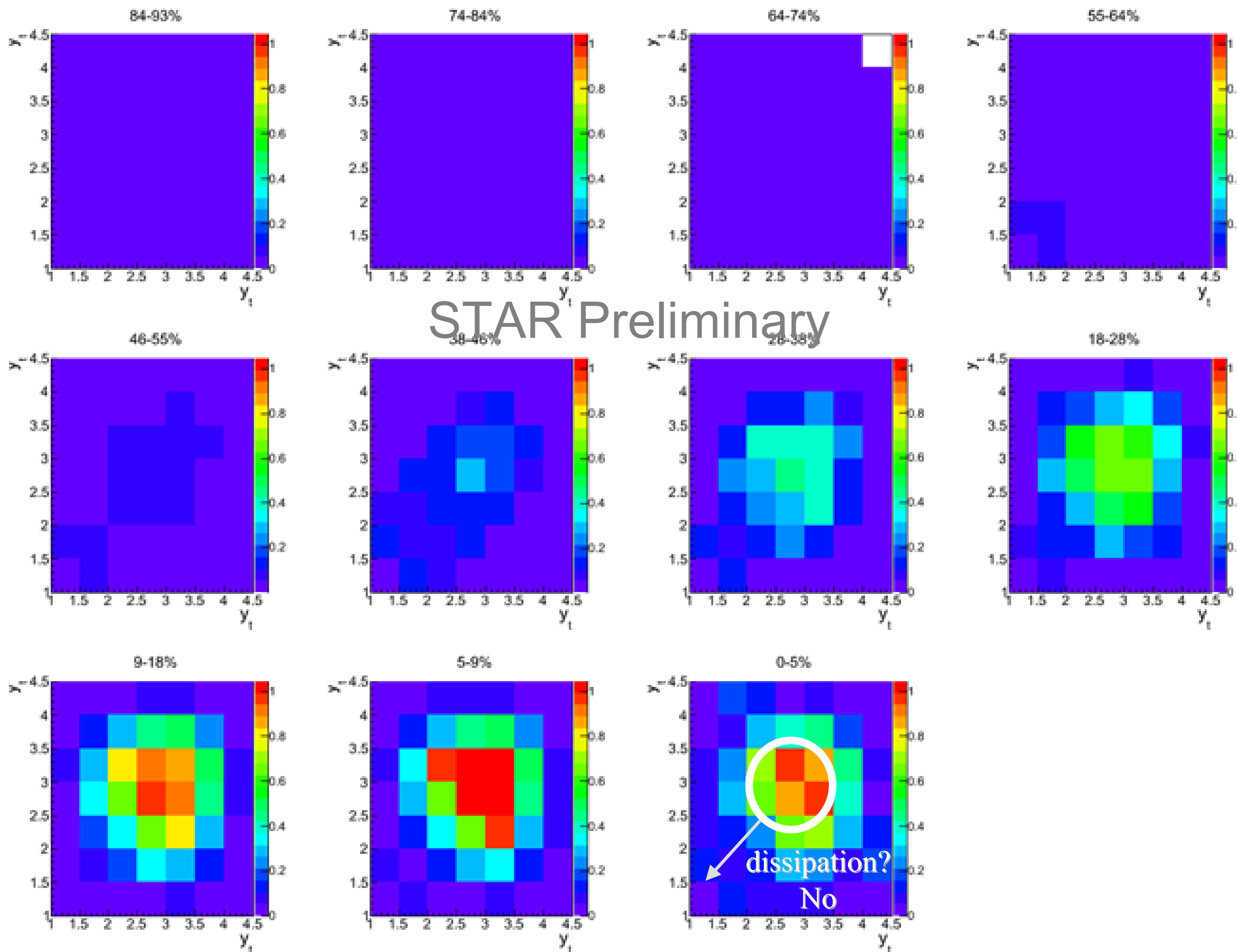
Momentum dependence of SS 2D peak volume



$$\times \frac{1}{\sqrt{\frac{dN_{soft}}{dy_{t,1}}\frac{dN_{soft}}{dy_{t,2}}}} =$$

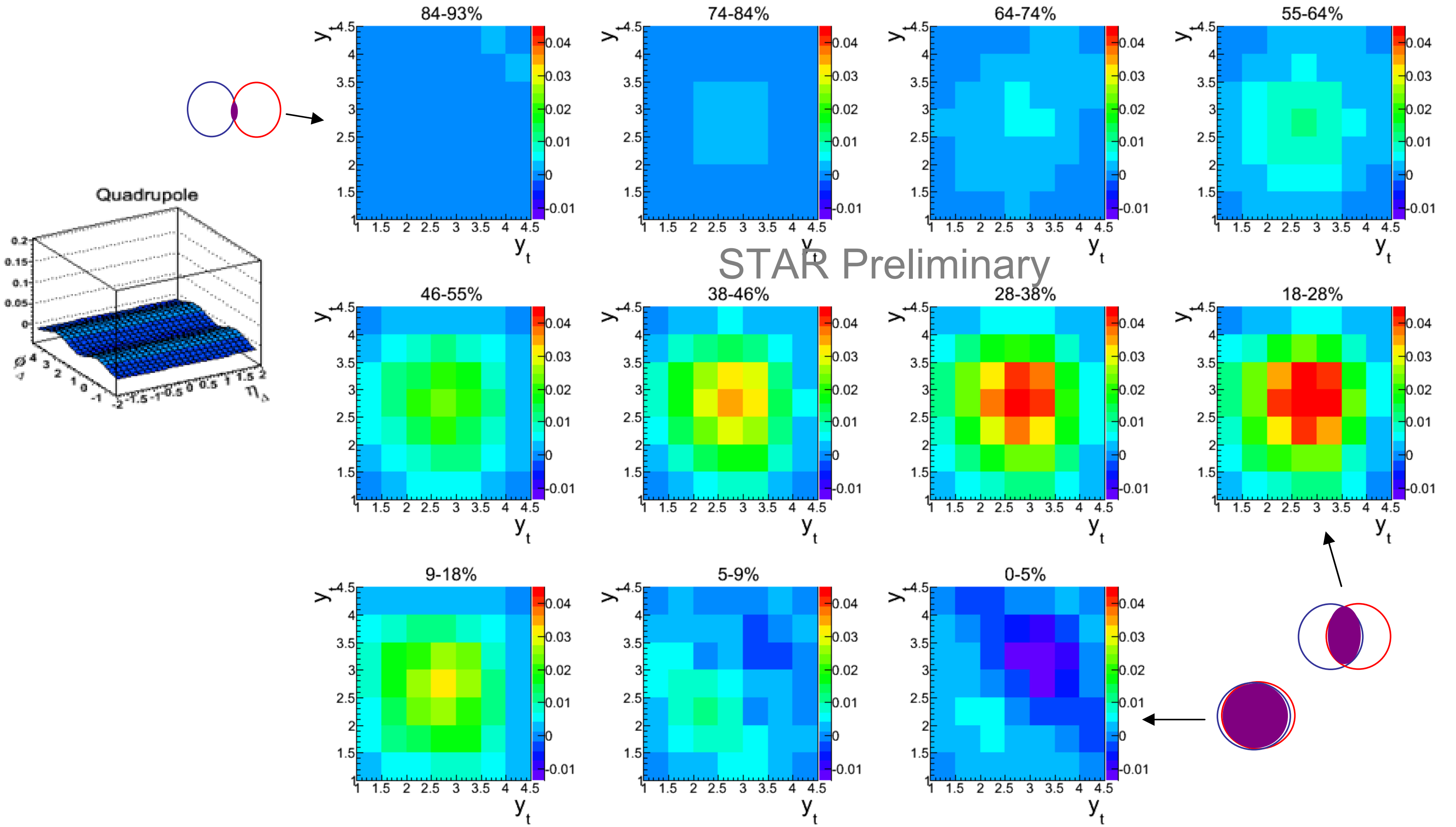
Number of correlated pairs in the 2D Gaussian, among pairs in each (y_{t1},y_{t2}) bin, per final state particle on y_t.

Au-Au 200 GeV



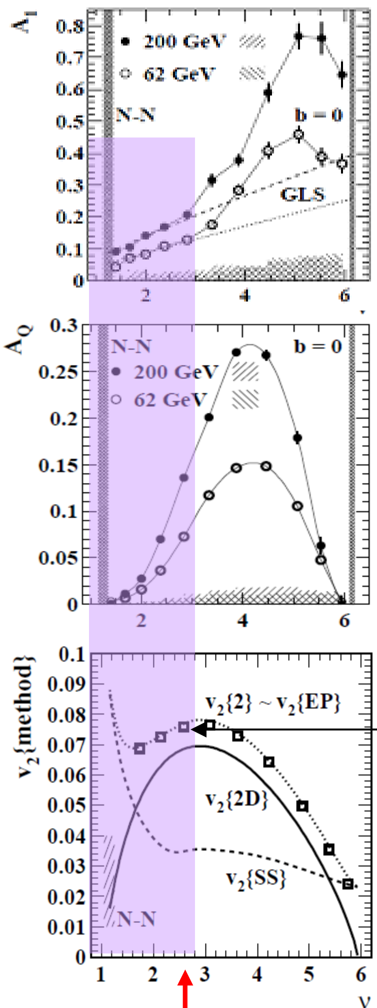
- **Pairs forming the SS 2D peak are distributed about (y_t,y_t) = (3,3) [~1.4 GeV/c]**
- **No p_t dissipation observed for more central; counter-intuitive for sQGP**

Momentum dependence of the Quadrupole – v_2



- **Pairs forming the quadrupole are also distributed about $(y_t,y_t) = (3,3)$ [~1.4 GeV/c] with similar shape to minijet y_t dist.; reduction to smaller y_t in more central**

Is there a similar (pQCD) origin for both structures?

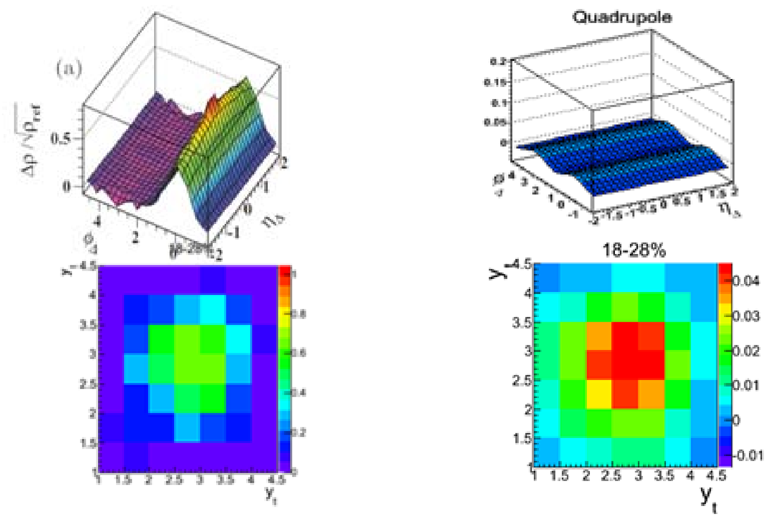


minijets - pQCD transparent system ν<3?

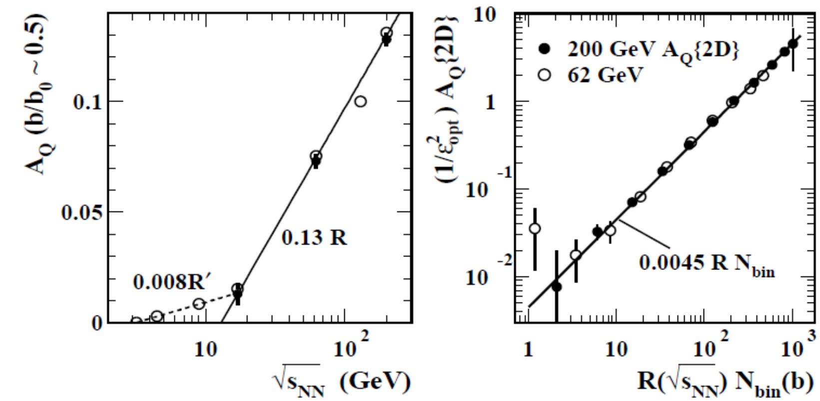
strong rescattering; hydro?

maximum v_2

ST



- Yet both are formed from particles with the same p_t
- Both have similar (y_t, y_t) distributions

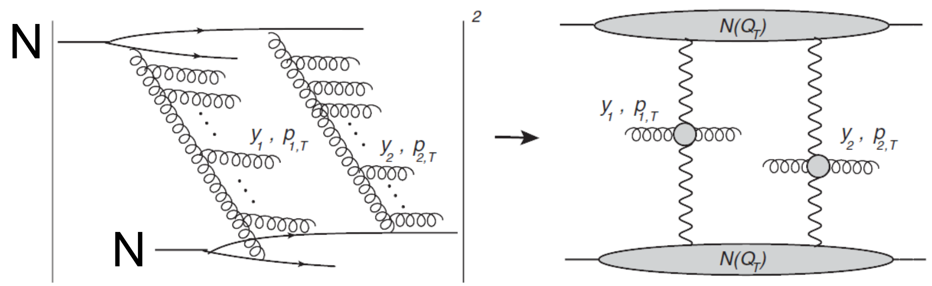


- Both Quad and minijets ~ $\log(s) N_{bin}$

Does all this point to a (p)QCD origin for the quadrupole (v_2)?

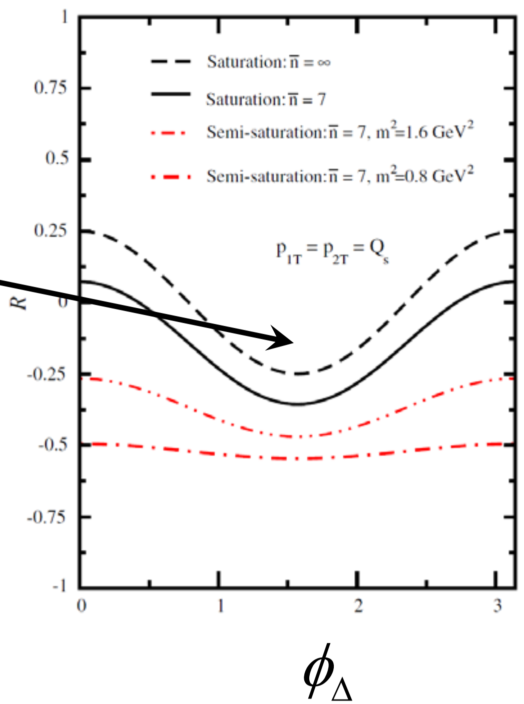
BFKL Pomerons - gluon interference

E. Levin and A. H. Rezaeian, Phys. Rev. D **84**, 034031 (2011)



Two-BFKL Pomeron Exchange with two-gluon emission & interference

- Multiple gluon emission from 2 or more Pomerons interfere producing azimuth anisotropy wrt momentum transfer $\vec{Q}_T$
- Resulting correlation: $\propto \cos(2\phi_\Delta)$
- Random emission results in uniform η_Δ dependence.
- This mechanism was proposed to explain the same-side ridge. However, it is a pQCD prediction for a **quadrupole** correlation, or $\mathbf{v_2}$.



(Balitsky, Fadin, Kuraev, Lipatov); see also Kopeliovich et al. Phys. Rev D**78**, 114009 (2008).

Application to 200 GeV p-p

Two-gluon density for 2-Pomeron exchange: N_{IPh}^2 is the prob. for two parton showers in a N-N collision.

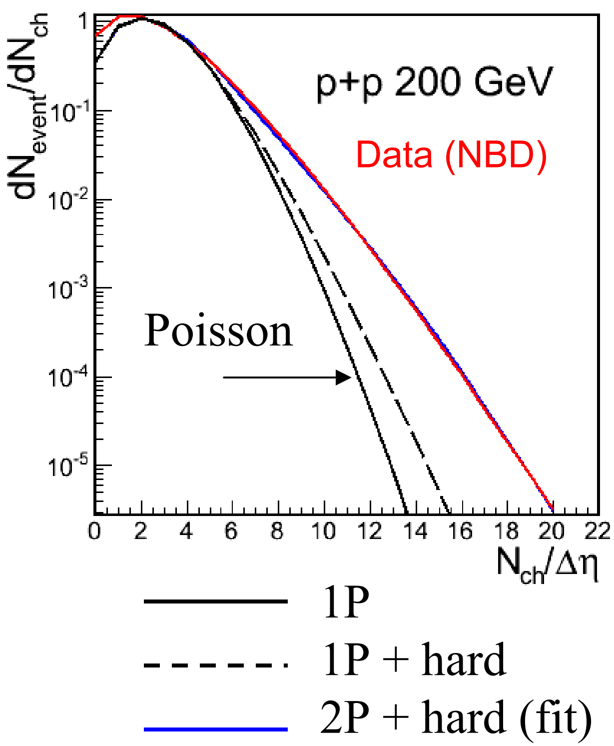
$$\frac{d\sigma}{dy_1 dy_2 d^2\vec{p}_{1,T} d^2\vec{p}_{2,T}} = \pi \int dQ_T^2 N_{IPh}^2(Q_T^2) \frac{d\sigma}{dy_1 d^2 p_{1,T}}(Q_T=0) \frac{d\sigma}{dy_2 d^2 p_{2,T}}(Q_T=0) \times \left\{1 + \frac{1}{2} p_{1,T}^2 p_{2,T}^2 Q_T^4 \left\langle \frac{1}{q^4} \right\rangle^2 (2+\cos(2\Delta\varphi))\right\}, \quad (22)$$

- Fit 200 GeV p+p frequency distribution assuming 1, 2, … parton showers with probabilities P_1, P_2, …

  Mean N_{ch} per parton shower equals the minbias mean $\overline{N}_{ch} = 2.5/\Delta\eta$

  Each shower produces a Poisson distribution.

$P_1 = 0.91,\ P_2 = 0.09,\ P_3 = P_4 \sim 0$



Application to 200 GeV p-p

- Probability weighted sum over 1 & 2 Pomeron diagrams, p_t-integral.

$$\frac{\Delta\rho}{\sqrt{\rho_{\rm ref}}}\Big|_{Quad} = \bar{N}_{ch}\,\frac{4P_2}{P_1+4P_2}\,\tfrac{1}{2}\left\langle p_t^2\right\rangle^2 \left\langle\left\langle Q_T^4\right\rangle\right\rangle \left\langle\frac{1}{q^4}\right\rangle^2 \cos 2\phi_\Delta$$

Minimum-bias average:

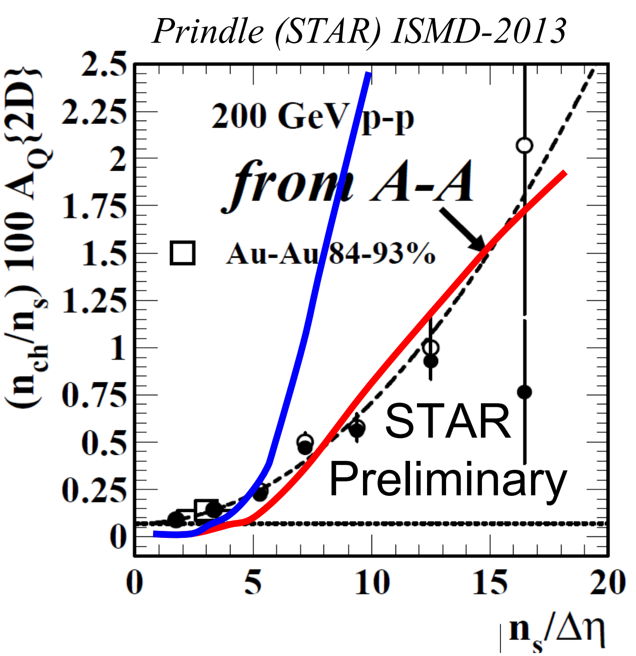
A_Q = 0.002 – 0.02; [semi-sat – saturated]

From D. Prindle (STAR) ISMD-2013 poster:
$\mathbf{A_Q}$ **= 0.002** for 200 GeV p-p NSD minbias

- N_{ch} dependent quadrupole:

$$\frac{\Delta\rho}{\sqrt{\rho_{\rm ref}}} = n_{ch}\,\frac{\#\,\text{correl. 2P pairs}}{\text{total}\,\#\,\text{pairs}}$$

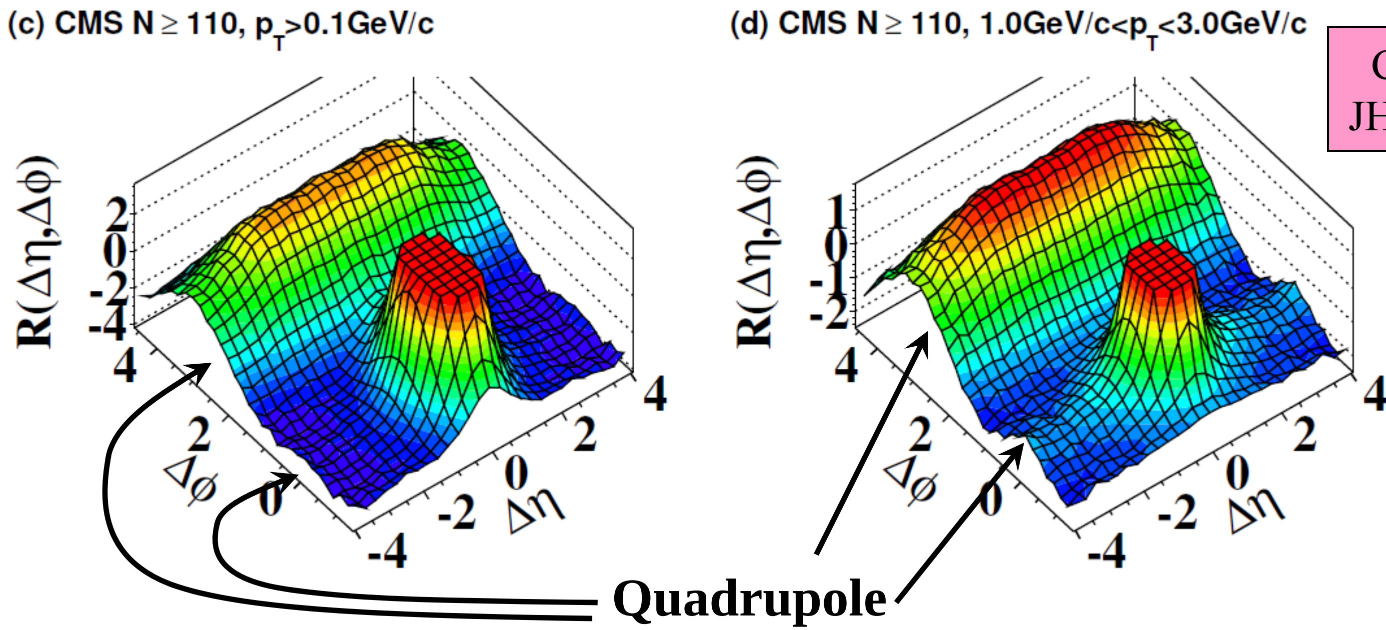
$$= n_{ch}\,\frac{P_2(n_{ch})\,n_{ch}(n_{ch}-1)\,\tfrac{1}{2}\left\langle p_t^2\right\rangle^2 \dfrac{m^4}{15Q_S^8}}{n_{ch}^2}\cos 2\phi_\Delta$$



Q_S^2=0.6 GeV^2

Q_S^2=0.8 GeV^2

7 TeV p+p from CMS



CMS Collaboration, JHEP **1009**,091(2010).

Fits [Phys. Rev. D 84, 034020] obtain :

$$A_{Q,N>110,p_t>0.1} = 0.059 \quad \text{at } \frac{dN_{ch}}{d\eta} = 28 \text{ at 7 TeV}$$

Compared to 200 GeV p + p

$$A_Q \approx 0.025 \text{ at } \frac{dN_{ch}}{d\eta} = 20$$

5.02 TeV p+Pb at the LHC

Fit with quadrupole:

$$A_Q = (< 0.008), 0.19 \text{ at } \frac{dN_{ch}}{d\eta} = 5,\ 30$$

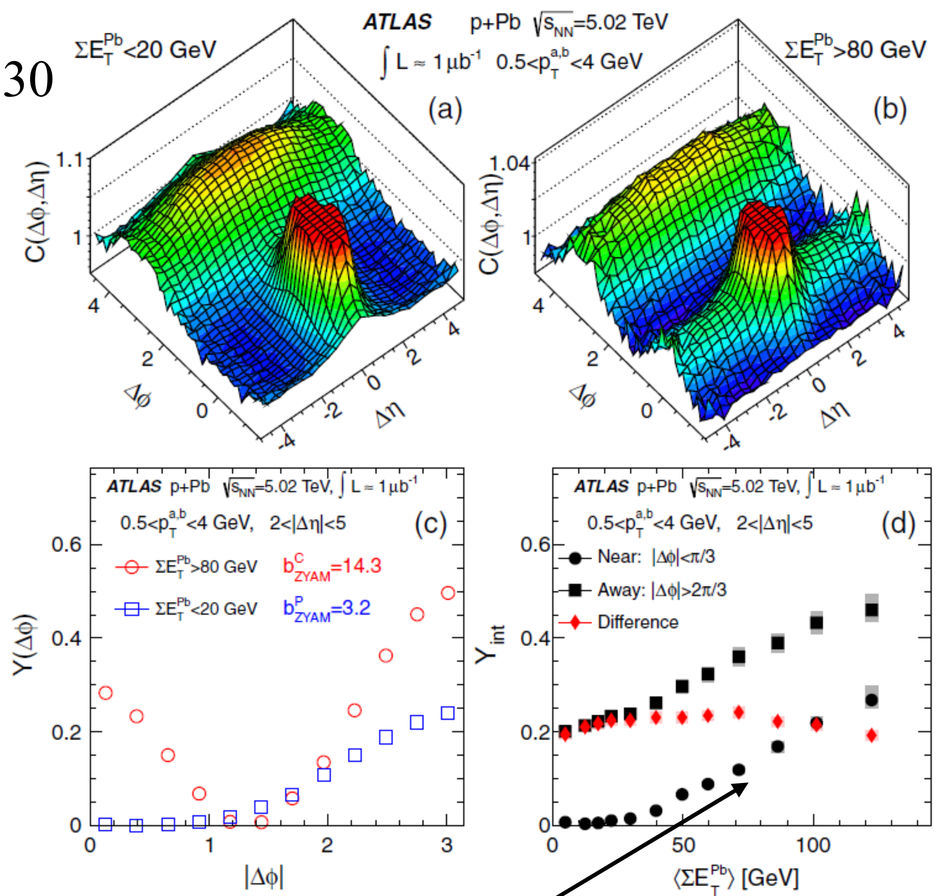
Larger than the 7 TeV p + p quadrupole (0.059) at similar N_{ch}.

$N_{\text{part}} \in [2,20]$ at LHC

In the BFKL-Pomeron model typical high multiplicity p+Pb collisions will have a couple of 2-Pomeron events.

Anisotropy should be ~ additive causing A_Q to increase with N_{ch}.

ATLAS, PRL **110**, 182302 (2013)



Monotonic increase in same-side η-extension, ~ quadrupole amplitude

Summary & Conclusions

- Higher-order harmonic (sextupole - v_3) descriptions of 2D angular correlations are actually describing small, non-Gaussian structure in the same-side 2D (minijet) peak. The detailed structure of this peak is the real issue.

- 4D correlations show that the correlated particles forming the SS 2D peak and the quadrupole (v_2) are similarly distributed in transverse momentum space.

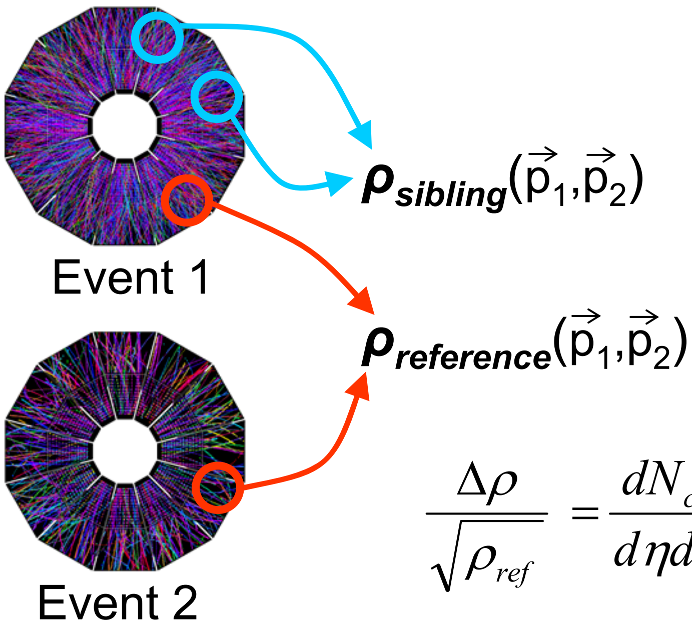
- Given this and other properties of the quadrupole we may ask if there is a pQCD explanation for v_2.

- The BFKL-Pomeron model of Levin and Rezaeian was applied to 200 GeV p+p; quadrupole predictions, though uncertain (Q_S), are consistent with recent data.

- Further study and application of pQCD (Pomeron, color-dipole) to the quadrupole correlation in p+p, p+A and A+A at RHIC and LHC is warranted.

Extras

Correlation measure



Fill 2D histograms
$(\phi_1-\phi_2,\eta_1-\eta_2)$, (p_{t1},p_{t2})

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \frac{dN_{ch}}{d\eta d\phi}\left[\frac{\rho_{sib}(\eta_\Delta,\phi_\Delta)}{\rho_{mix}(\eta_\Delta,\phi_\Delta)} - 1\right], \qquad \begin{matrix}\eta_\Delta \equiv \eta_1 - \eta_2 \\ \phi_\Delta \equiv \phi_1 - \phi_2\end{matrix}$$

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \sqrt{\frac{dN_{ch}}{dy_{t1}d\eta_1 d\phi_1}\frac{dN_{ch}}{dy_{t2}d\eta_2 d\phi_2}}\left[\frac{\rho_{sib}(y_{t1},y_{t2})}{\rho_{mix}(y_{t1},y_{t2})} - 1\right]$$

Number of correlated pairs per final-state particle

$$y_t = \ln\left(\frac{m_t + p_t}{m_\pi}\right), \approx \ln(p_t)$$

transverse rapidity

Correlations:

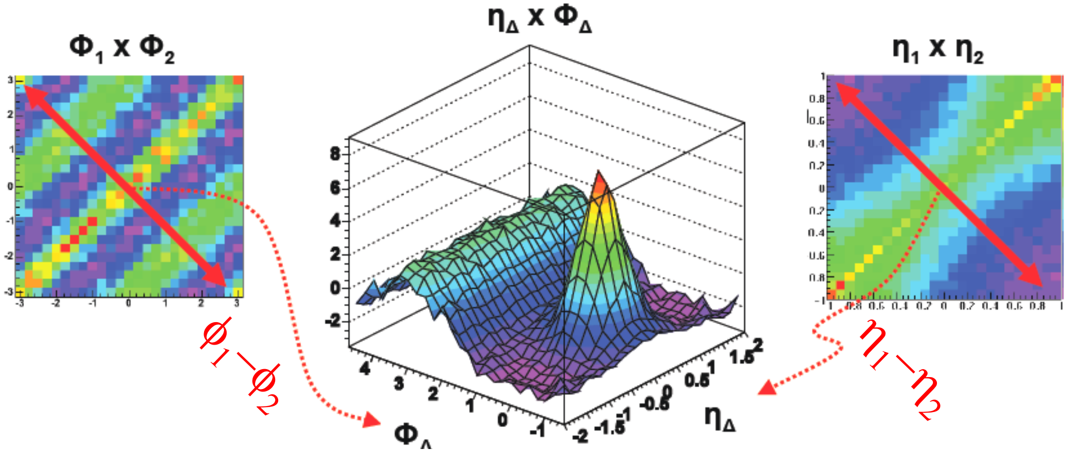
(Main collaborator U. Washington)

- Our goal is to measure <u>6D correlations</u> for $(\vec{p}_1, \vec{p}_2)$ with respect to collision energy, centrality with identified particles using full TPC acceptance
- Study the evolution of correlation structures from p-p to central Au-Au
- Characterize the structures with mathematical models
- Compare with theoretical models based on pQCD, transport and hydrodynamics

- $$\frac{\rho_{sibling} - \rho_{mixed}}{\sqrt{\rho_{mixed}}} \equiv \frac{\Delta\rho}{\sqrt{\rho_{mixed}}}$$
  $$\equiv \frac{\#\,\text{correlated pairs}}{\text{final-state charged particle}}$$

- $6D \rightarrow 4D\,\{\eta_1 - \eta_2, \phi_1 - \phi_2, p_{t1}, p_{t2}\}$
  no dependence on $\eta_1 + \eta_2, \phi_1 + \phi_2$
  define: $\eta_\Delta \equiv \eta_1 - \eta_2, \phi_\Delta \equiv \phi_1 - \phi_2$

- $(p_{t1}, p_{t2}) \rightarrow (y_{t1}, y_{t2})$, where
  $$y_t = \ln\left(\frac{m_t + p_t}{m_\pi}\right) \approx \ln(p_t)$$
  is *transverse rapidity*



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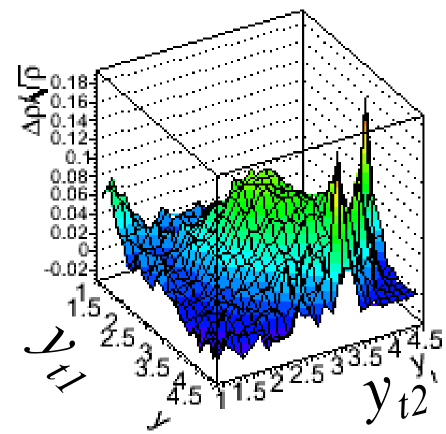


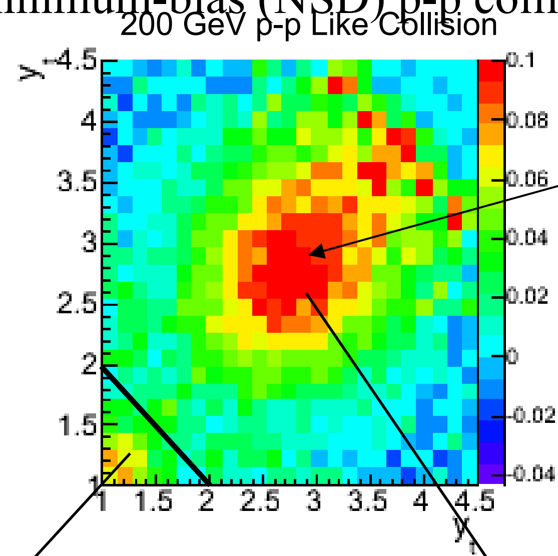
Correlations in Momentum Space

Start with the observed correlations in minimum-bias (NSD) p-p collisions

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}}(y_{t1}, y_{t2})$$

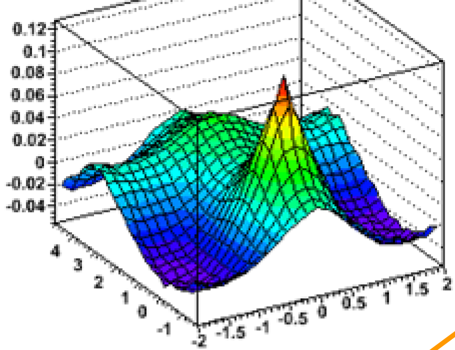
$$y_t \propto \ln(p_t)$$

y_t	1	2	3	4
p_t(GeV/c)	0.17	0.51	1.4	3.8

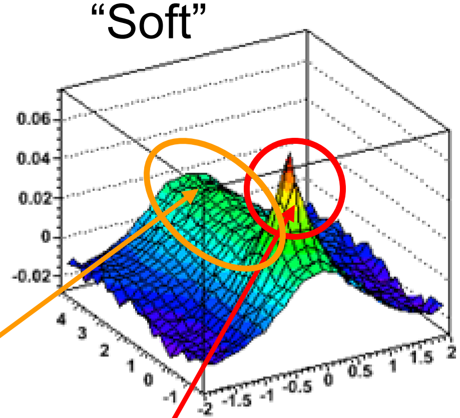


If an event has a particle with a y_t of 3 there is likely other particles with a y_t of 3 compared to a random statistical background, most likely correlated from jets

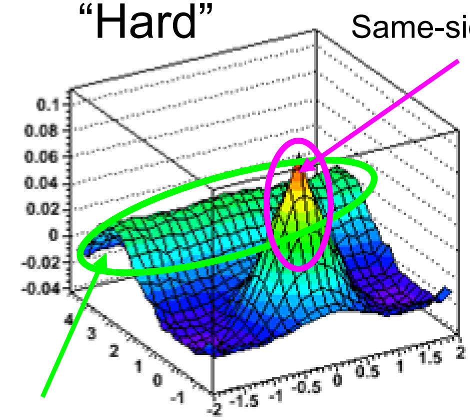
All Particles



“Soft”



“Hard”

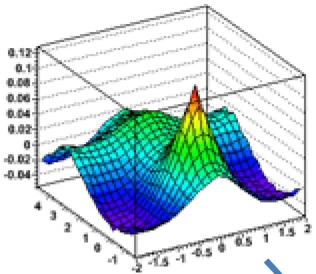


Same-side of the jet

Away-side of the jet, superposition of many overlapping peaks

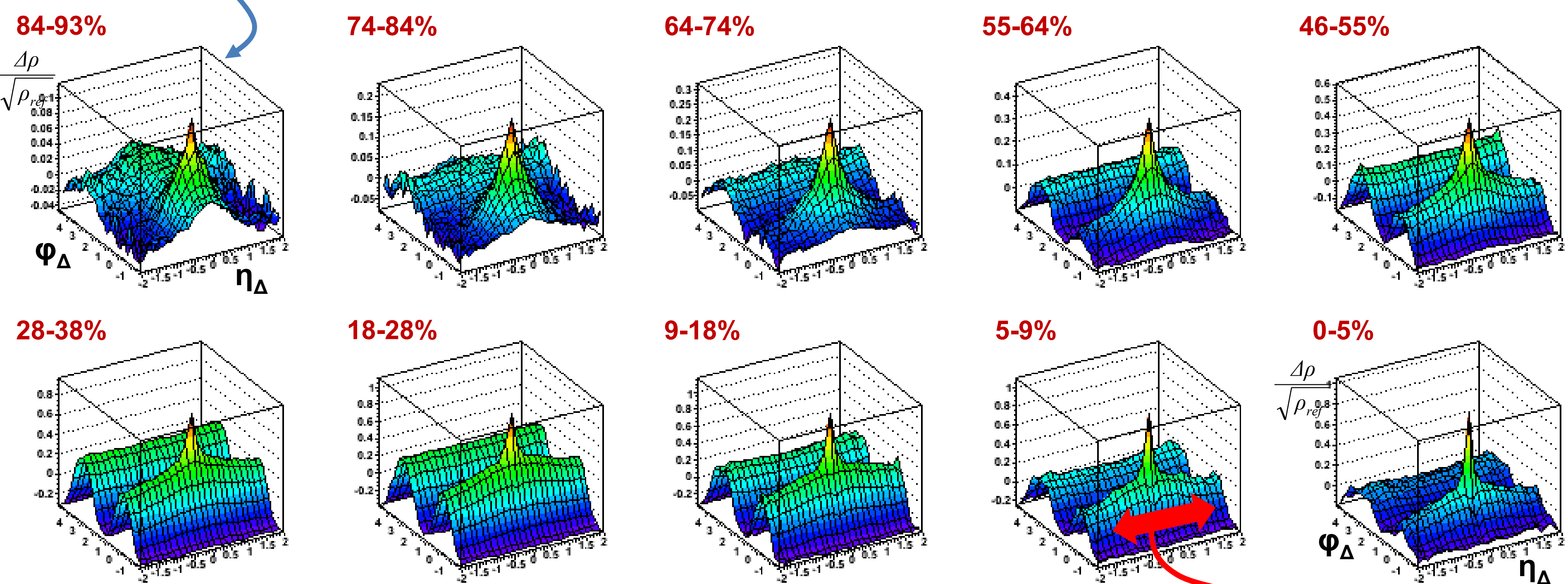
Soft particle production, often modeled as string fragmentation

Background:
- e-/e+ pairs produced by photons interacting with detector material
- quantum interference effects resulting in enhancement at small opening angles



Angular correlations for 200 GeV Au-Au:

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



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

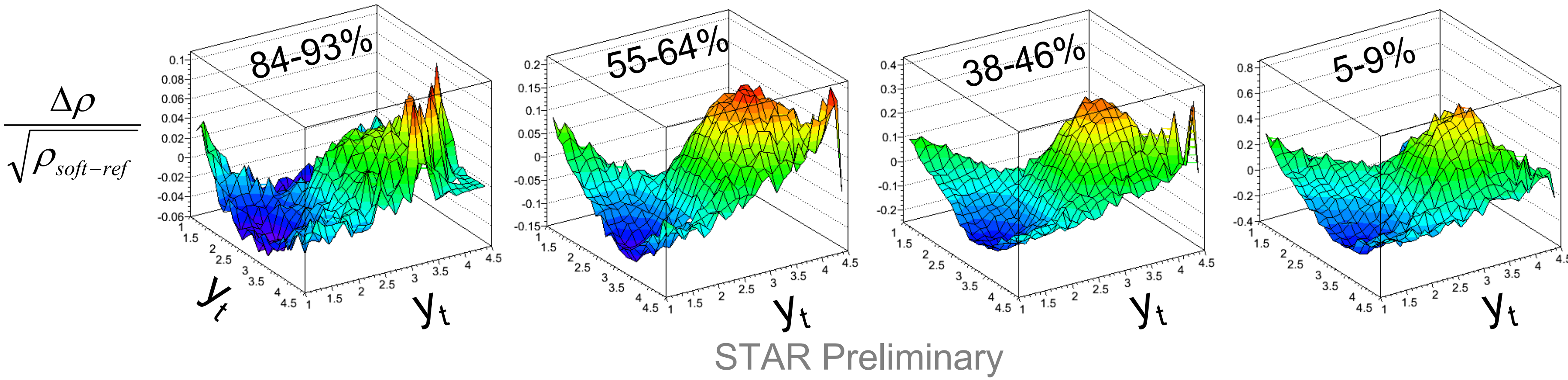
STAR Preliminary

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

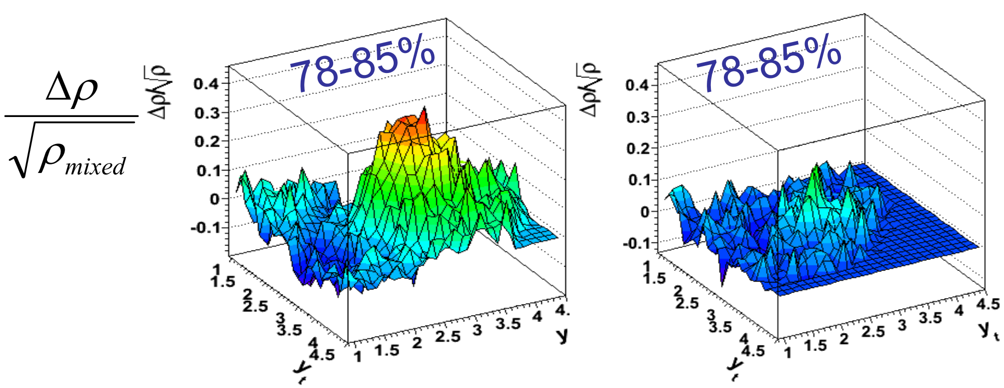
Similar analysis was done for minbias Au-Au at 62 GeV and Cu-Cu at 62 and 200 GeV

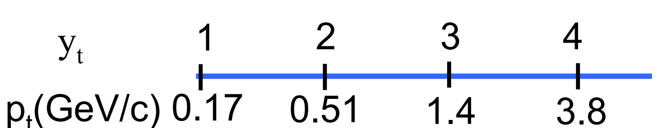
Correlations: Au-Au 200 GeV minbias, all charged particles

(Ph.D. Thesis data of E. Oldag; all charge, full azimuth, $p_t \geq 0.15$ GeV/c)



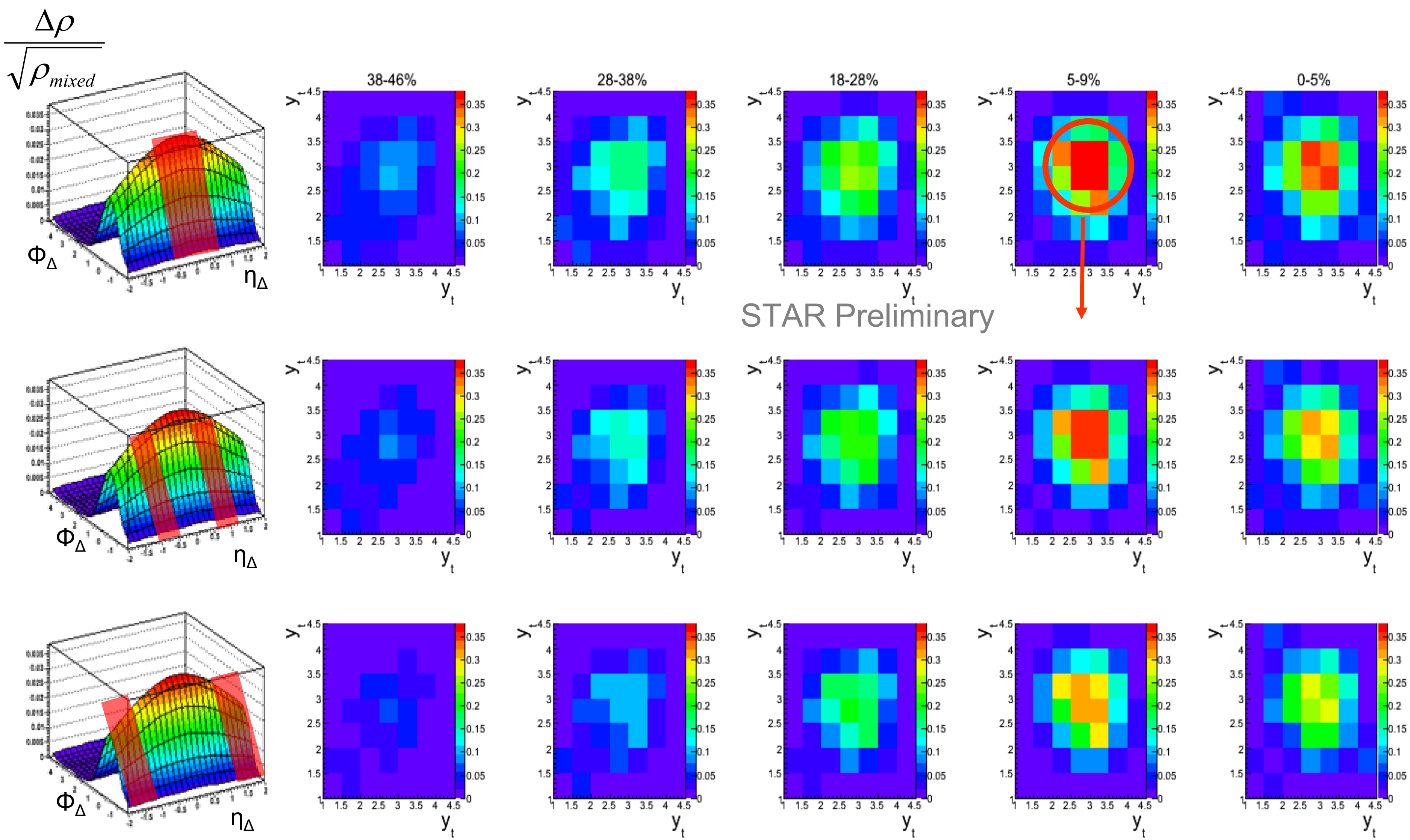
HIJING: with & without jets





- Smooth centrality evolution; no sharp transition as in (η,ϕ)
- Peak at (3,3) (1.4 GeV/c) persists to most-central
- Peak amplitude follows binary scaling
- **HIJING** with jets (no quenching) predicts this peak

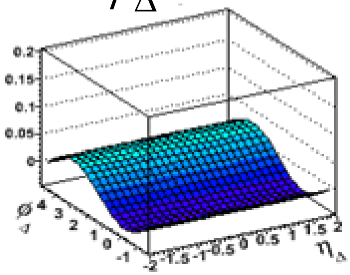
Correlations: y_t dependence of same-side peak with η_Δ, centrality

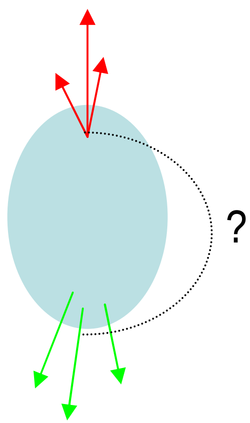


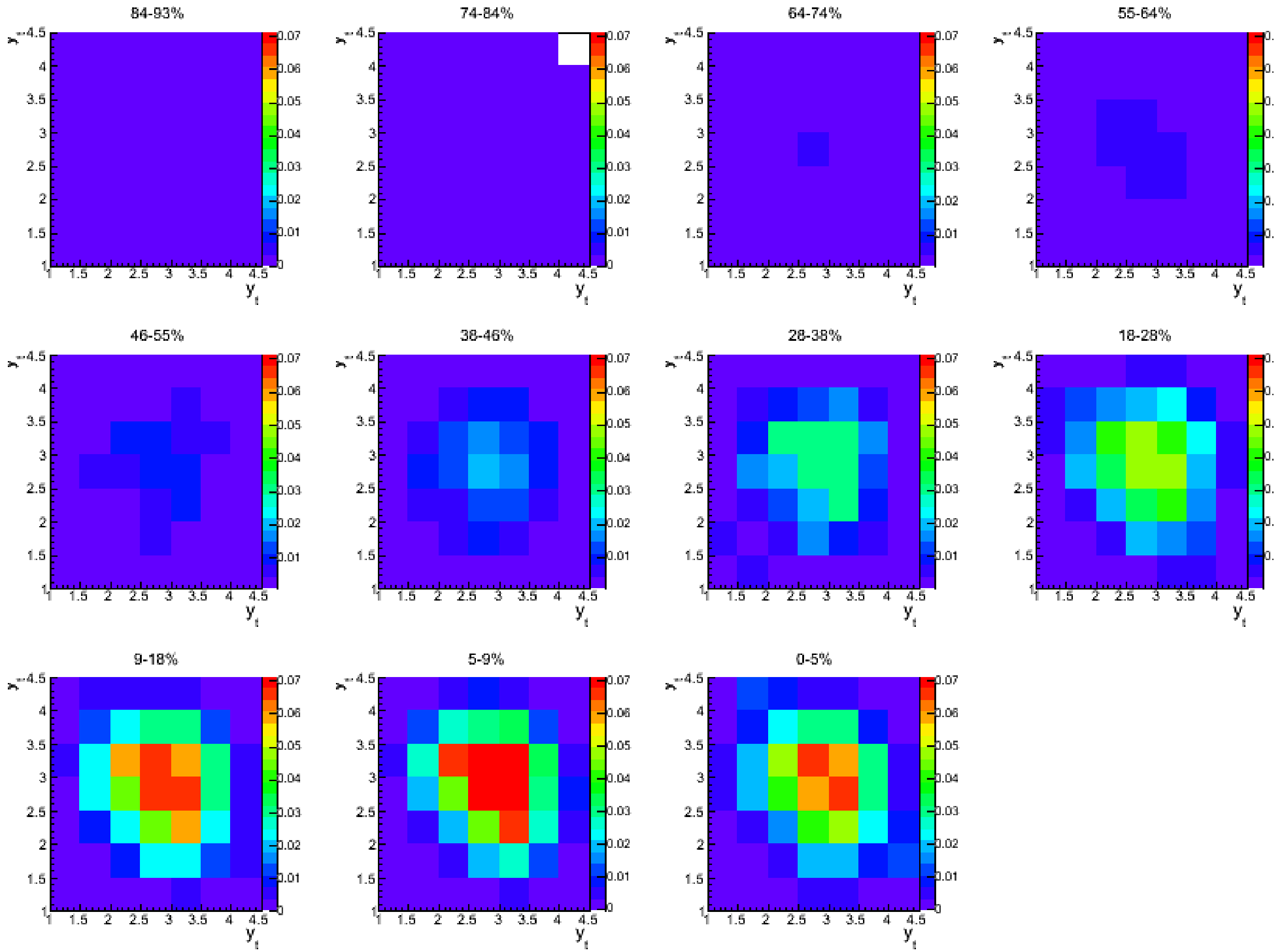
The extended correlation on η_Δ (the "ridge") is not comprised of softer pairs relative to the center.

Momentum Dependence of the Dipole (di-jet awayside)

$\phi_\Delta \approx \pi$





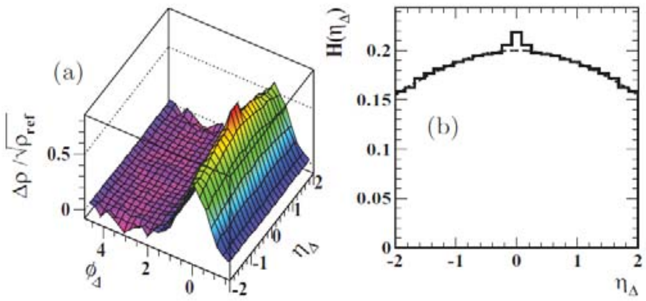


- Dipole represents the di-jet away-side
- Does not soften with increased centrality

Projection of same-side 2D peak

(*LR, Prindle, Trainor, arXiv:1308.4367)*

- Subtract D, Q, 2D-exp from data, project onto η_Δ



- Fit with:

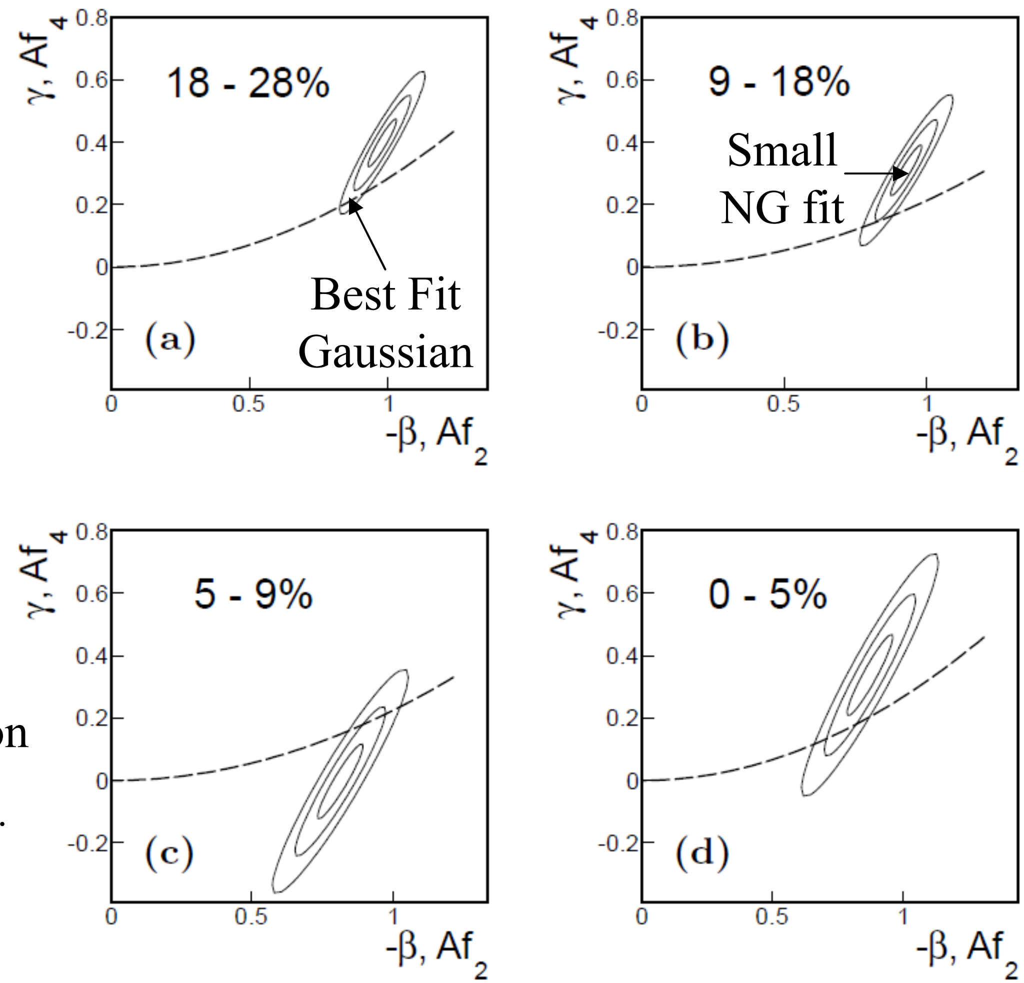
$$F(\eta_\Delta) = \alpha + \beta\frac{\eta_\Delta^2}{\Delta\eta^2} + \gamma\frac{\eta_\Delta^4}{\Delta\eta^4}$$

- Compare with Gaussian expansion

$$F_{\text{Gauss}}(\eta_\Delta) \approx A - Af_2\frac{\eta_\Delta^2}{\Delta\eta^2} + Af_4\frac{\eta_\Delta^4}{\Delta\eta^4} + \cdots$$

where $Af_4 = Af_2^2/2$ (parabola)

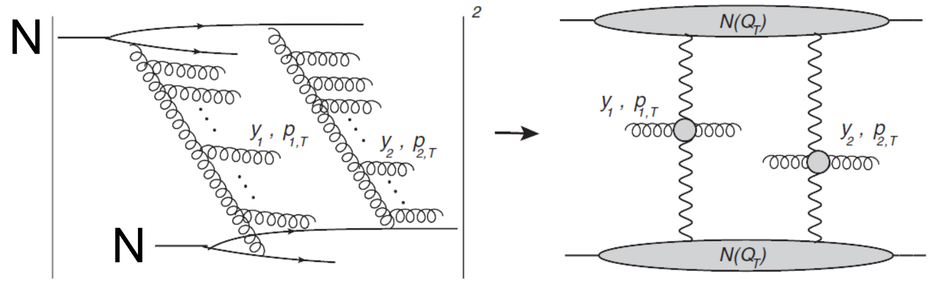
200 GeV Au+Au



- **SS 2D peak consistent (~2σ) with Gaussian, but small NG shape improves χ2**

BFKL Pomeron and gluon interference

E. Levin and A. H. Rezaeian, Phys. Rev. D **84**, 034031 (2011)



Two-BFKL Pomeron Exchange with two-gluon emission & interference

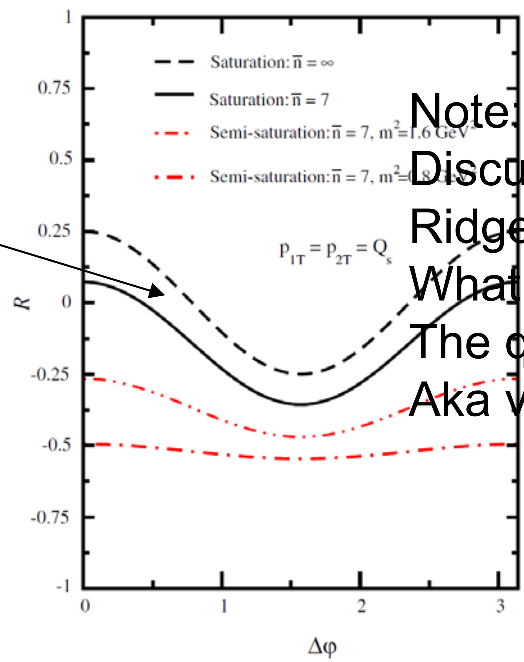
Angular correlation – η_Δ independent peak at $\phi_\Delta = 0$, but also away-side! azimuth ***quadrupole***

$$\mathcal{R}\left(\Delta\varphi; y_1, y_2\right) = \frac{\frac{dN}{dy_1 d^2\vec{p}_{1,T}\, dy_2 d^2\vec{p}_{2,T}}}{\frac{d^2N}{dy_1 d^2\vec{p}_{1,T}}\;\frac{d^2N}{dy_2 d^2\vec{p}_{2,T}}} - 1$$

$$= \frac{\bar{n}(\bar{n}-1)}{2\bar{n}^2}\left\{1 + \frac{1}{2}(2+\cos(2\Delta\varphi))\right\} - 1,$$

$$\mathcal{R}\left(\Delta\varphi; y_1, y_2\right) = \frac{\bar{n}(\bar{n}-1)}{2\bar{n}^2}\left\{1 + \frac{m^4}{30Q_s^4}(2+\cos(2\Delta\varphi))\right\} - 1.$$

$$\mathcal{R}\left(b, \Delta\varphi, y_1, y_2\right) = \tfrac{1}{2} p_{1,T}^2 p_{2,T}^2 (\langle 1/q^4\rangle_{\mathrm{proton}})^2 (\nabla_b^2 \nabla_b^2 T_{AA}^2(b))(2+\cos(2\Delta\varphi)).$$



Note: The paper Discusses the same-side Ridge. However What is predicted is The quadrupole, Aka v22!

Application to 200 GeV p-p

The correlations in L&R are for 2-Pomeron diagrams only. To compare with data We must sum over events with varyiong number of Pomeron exchanges, namely 1 And 2 given by P1=0.91, P2=0.09.

$$\frac{h_{\text{sib}}}{h_{\text{mix}}} = \frac{N_{\text{events}}\left[P_1\overline{N}_{ch}^2 + P_2\left(2\overline{N}_{ch}\right)^2\left(1+C_Q\right)\right]}{N_{\text{events}}\left(N_{\text{events}}-1\right)\left[P_1\overline{N}_{ch} + 2P_2\overline{N}_{ch}\right]^2},\ \overline{N}_{ch} \text{ is the mean p-p NSD minbias multiplicity}/\Delta\eta$$

$$C_Q = \tfrac{1}{2}\, p_{t_1}^2 p_{t_2}^2 \left\langle\left\langle Q_T^4\right\rangle\right\rangle \left\langle\frac{1}{q^4}\right\rangle^2 \left(2+\cos 2\phi_\Delta\right), \text{ is the angular correlation from 2-Pomeron exchange}$$

$$\left\langle\left\langle Q_T^4\right\rangle\right\rangle \left\langle\frac{1}{q^4}\right\rangle^2 \in \left[\frac{m^4}{15Q_S^8}, Q_S^{-4}\right], \text{ where } m^2 = 0.8 \text{ to } 1.6\ \text{GeV}^2,\ Q_S \text{ is the saturation scale (GeV)}$$

Assuming pair normalization (as done for the data) we normalize the ratio of histograms,

$$\text{N}\left[\frac{h_{\text{sib}}}{h_{\text{mix}}} - 1\right] \propto C_Q \rightarrow \frac{4P_2}{P_1+4P_2} C_Q = \frac{\Delta\rho}{\rho_{\text{ref}}}$$

The p_t-integral correlation is

$$\frac{\Delta\rho}{\sqrt{\rho_{\text{ref}}}} = \overline{N}_{ch} \frac{4P_2}{P_1+4P_2} \tfrac{1}{2} \left\langle p_t^2\right\rangle^2 \left\langle\left\langle Q_T^4\right\rangle\right\rangle \left\langle\frac{1}{q^4}\right\rangle^2 \left(2+\cos 2\phi_\Delta\right) \equiv A_0 + 2A_Q \cos 2\phi_\Delta$$

$$A_Q = \overline{N}_{ch} \frac{P_2}{P_1+4P_2} \left\langle p_t^2\right\rangle^2 \left\{\begin{matrix} Q_S^{-4} \\ \dfrac{m^4}{15Q_S^8} \end{matrix}\right\}, \text{ range depends on saturation}$$

Pp quad prediction range
And T&D's data

Pp scaling and T&D's data

Pp and p-Pb LHC extension

Application to 200 GeV p-p

The correlations in L&R are for 2-Pomeron diagrams only. To compare with data a probability weighted sum over 1, 2, etc. Pomeron diagrams is carried out.

sibling/mixed pair ratio:

$$\frac{h_{\text{sib}}}{h_{\text{mix}}} = \frac{\left[P_1 \bar{N}_{ch}^2 + P_2 \left(2\bar{N}_{ch}\right)^2 \left(1 + C_Q\right)\right]}{\left[P_1 \bar{N}_{ch} + 2P_2 \bar{N}_{ch}\right]^2}$$

$$C_Q = \tfrac{1}{2}\, p_{t_1}^2 p_{t_2}^2 \left\langle \left\langle Q_T^4 \right\rangle \right\rangle \left\langle \frac{1}{q^4} \right\rangle^2 \left(2 + \cos 2\phi_\Delta\right), \text{ from 2 - Pomeron exchange}$$

The p_t - integral correlation is

$$\frac{\Delta\rho}{\sqrt{\rho_{\text{ref}}}} = \bar{N}_{ch} \frac{4P_2}{P_1 + 4P_2} \tfrac{1}{2} \left\langle p_t^2 \right\rangle^2 \left\langle \left\langle Q_T^4 \right\rangle \right\rangle \left\langle \frac{1}{q^4} \right\rangle^2 \left(2 + \cos 2\phi_\Delta\right)$$

$$\equiv A_0 + 2A_Q \cos 2\phi_\Delta$$

$$A_Q = \bar{N}_{ch} \frac{P_2}{P_1 + 4P_2} \left\langle p_t^2 \right\rangle^2 \begin{Bmatrix} Q_S^{-4} \\ \dfrac{m^4}{15 Q_S^8} \end{Bmatrix},$$

range depends on gluon saturation scale Q_S

$m \sim 1$ GeV

Application to 200 GeV p+p

- BFKL Pomerons $A_Q = 0.0021 \rightarrow 0.0083 \quad \rightarrow 0.0175$

  $m^2 = \underbrace{0.8 \quad \rightarrow 1.6\,\text{GeV}^2}_{\text{Semi-saturated}}$ Saturated

$P_1 = 0.91, P_2 = 0.09$

$\langle p_t^2 \rangle = 0.188\,(\text{GeV/c})^2$

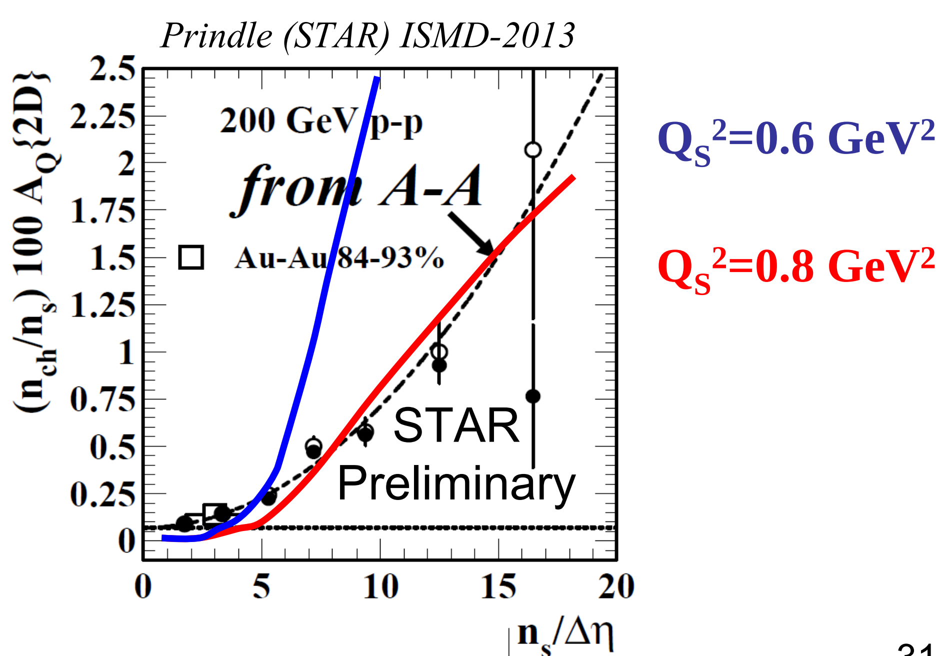
$Q_S^2 = 0.6\,\text{GeV}^2$ (L & R, for LHC)

From D. Prindle (STAR) ISMD-2013 poster:
$\boldsymbol{A_Q}$ **= 0.002** for 200 GeV p-p NSD minbias

- N_{ch} dependent quadrupole:

$$\frac{\Delta\rho}{\sqrt{\rho_{\text{ref}}}} = n_{ch}\frac{\#\,\text{correl. 2P pairs}}{\text{total}\,\#\,\text{pairs}}$$

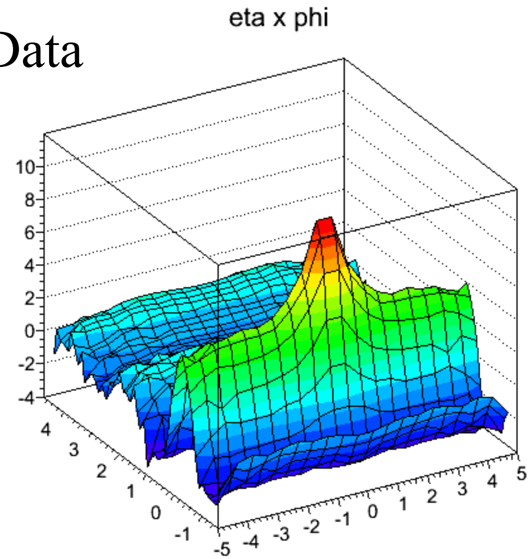
$$= n_{ch}\frac{P_2(n_{ch})n_{ch}(n_{ch}-1)\tfrac{1}{2}\langle p_t^2\rangle^2 \dfrac{m^4}{15Q_S^8}}{n_{ch}^2}\cos 2\phi_\Delta$$

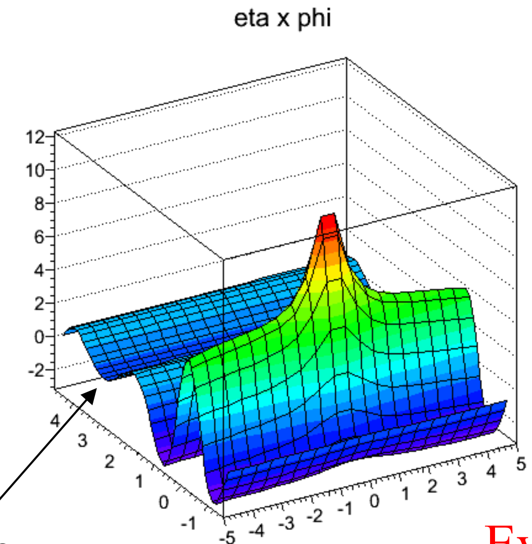


ATLAS 2.76 TeV Pb + Pb, p_t= 2 – 3 GeV/c

0-1% centrality

Data



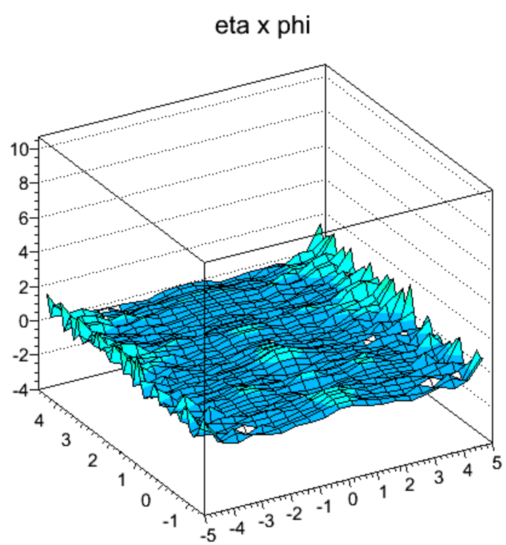


Standard 11-parameter model fit with & without sextupole

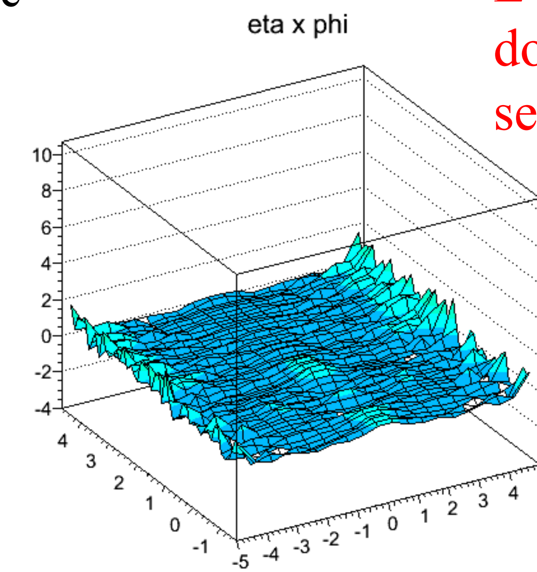
negative quadrupole

Even these data do not ***require*** a sextupole!

Residuals



no sextupole



with sextupole, < 0 in free fit

Model Comparisons: HIJING

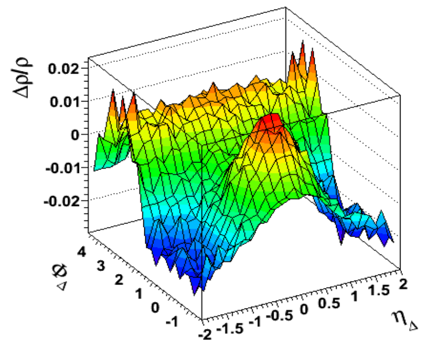
- HIJING is based on the LUND string model and semi-hard jet fragmentation (PYTHIA) and describes peripheral angular correlation data well

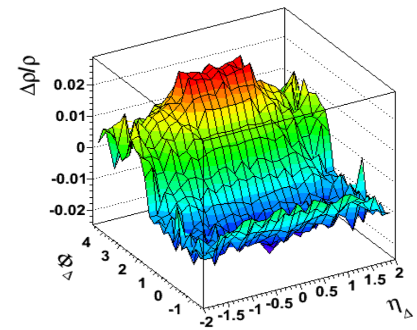
HIJING: With Jets

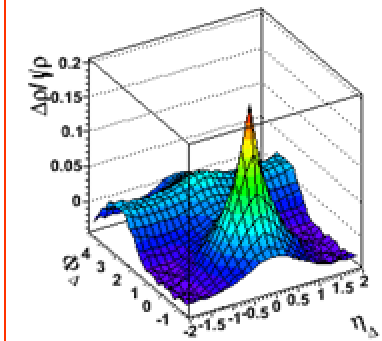
HIJING: No Jets

Data

$(\eta_\Delta,\phi_\Delta)$ space

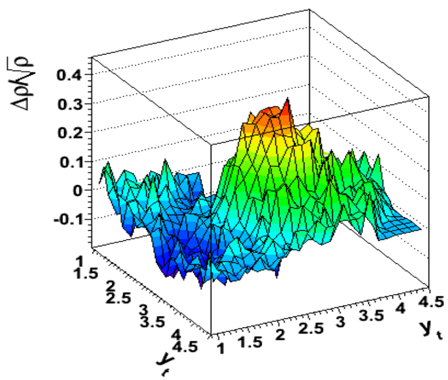


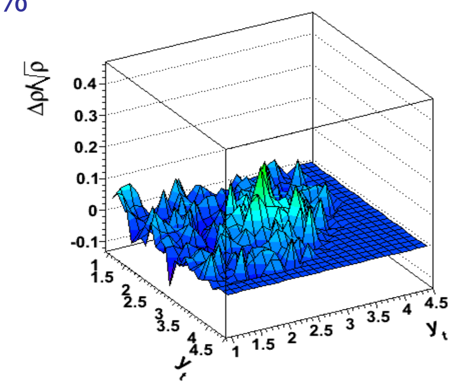


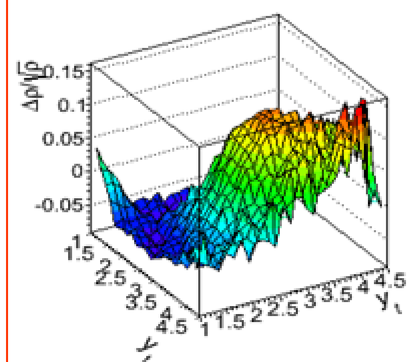


78-85%

(y_t,y_t) space



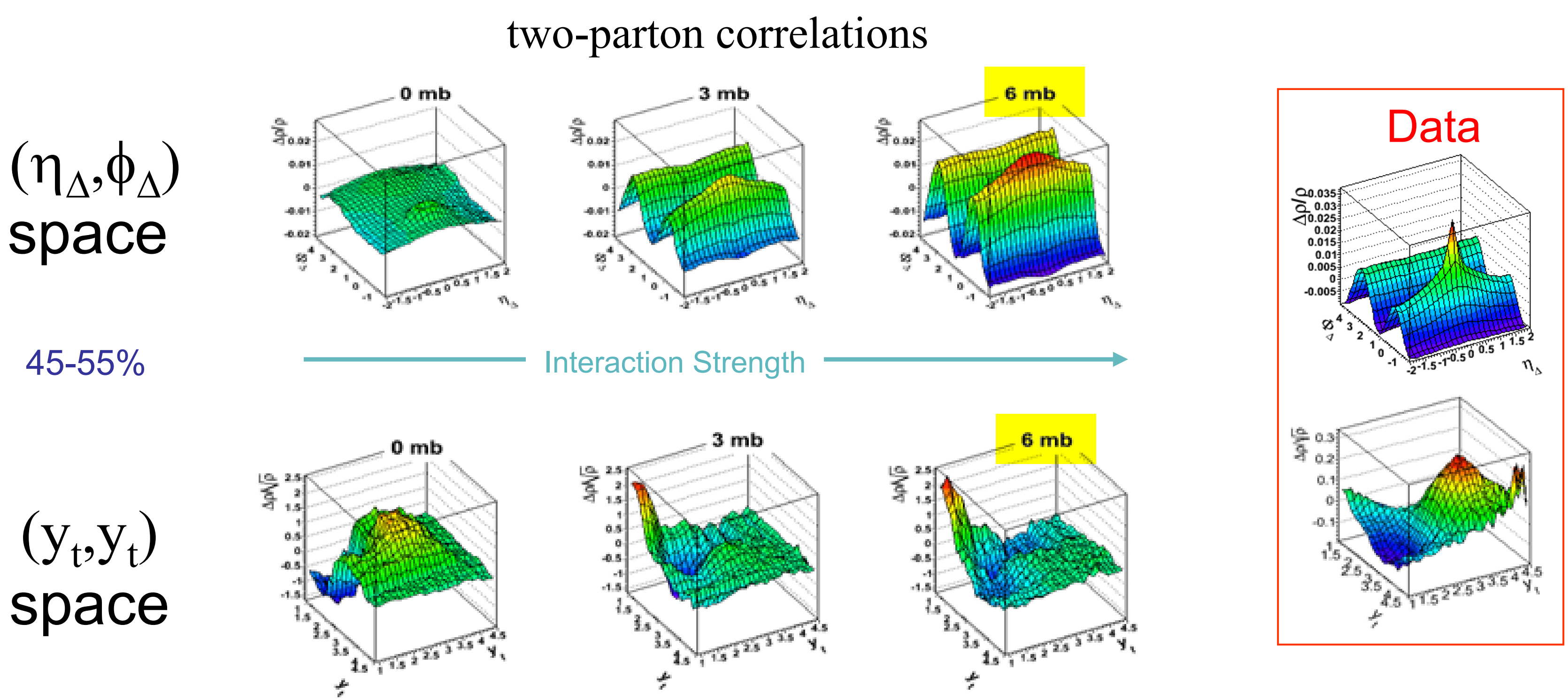




- The peak in (y_t,y_t) space is strongly enhanced by jets.
- If the peak in data is also due to jets then there is little observed dissipation of jet correlations in central collisions.

Model Comparisons: AMPT

- Includes jets and predicts a quadrupole using a hybrid transport model that includes a period of parton-parton rescattering.

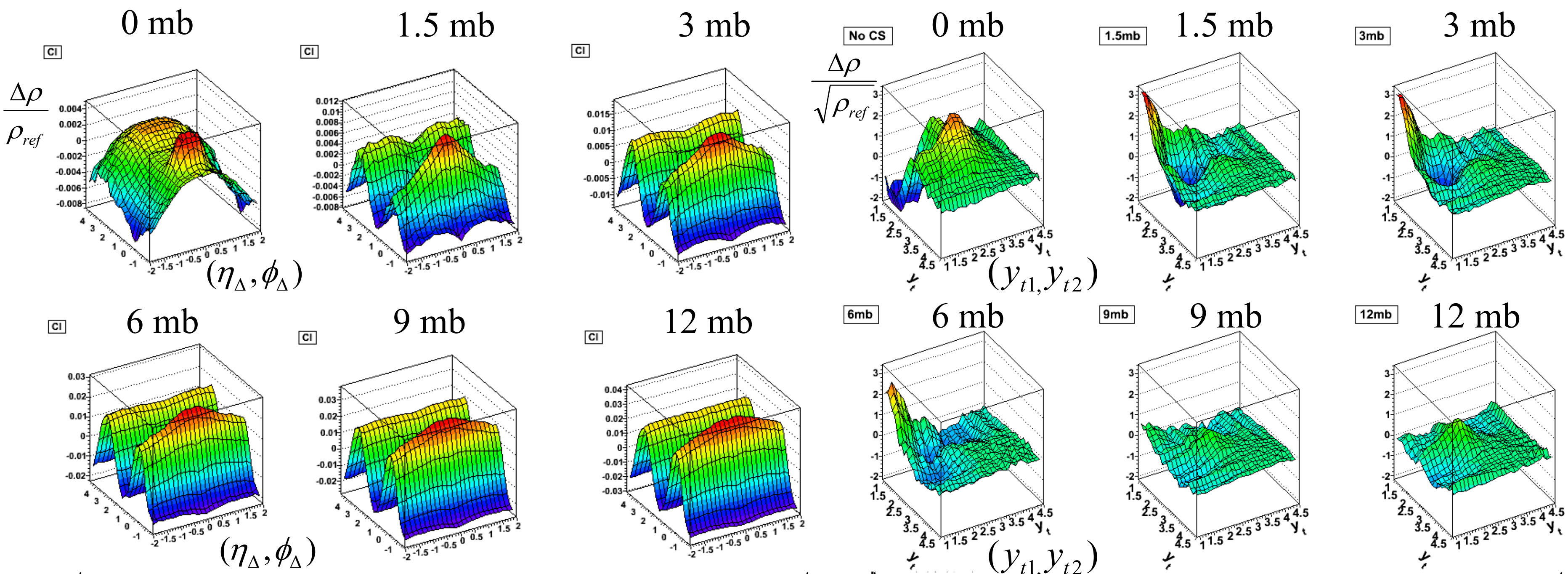


- AMPT can model the quadrupole in angular space but fails in modeling the correlation observed in data in momentum space.

AMPT: parton correlations

The preceding results are counter-intuitive. We therefore studied the predicted parton correlations as a function of parton cross section (0,1.5,3,6,9,12 mb) with ***no coalescence***

200 GeV Au-Au 46-55% - parton correlations



angular (η_Δ,ϕ_Δ) correlations

SS peak: amplitude and widths (η,ϕ) increase
Quadrupole: increases to exp. value at ~6mb

(y_t,y_t) correlations

Jet peak: strong dissipation as expected. <u>What is coalescence doing?</u>

From E. Oldag

Model Comparisons: NexSPHerio

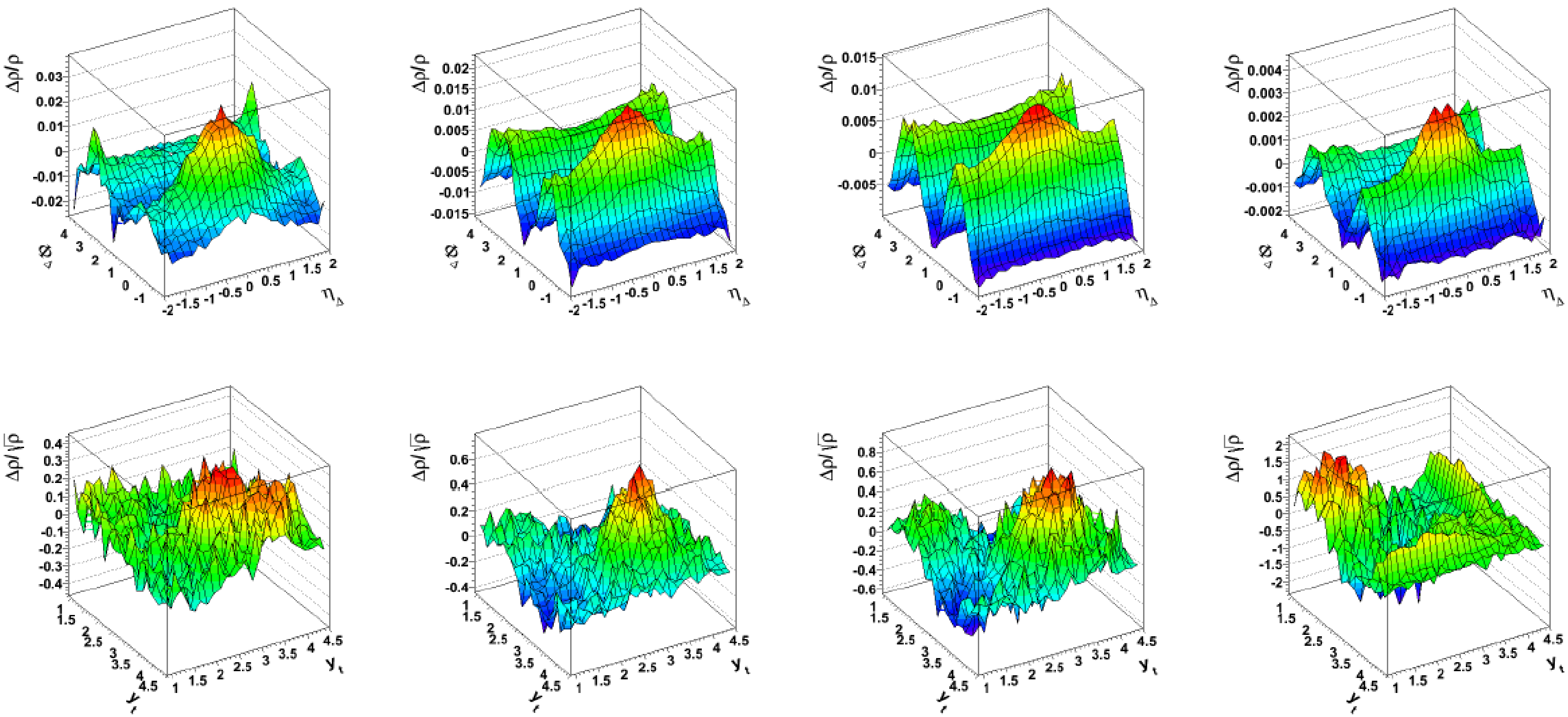


Figure 5.17: Correlations from NexSpheRIO events in angular (upper) and momentum (lower) space for Au+Au 200 GeV collisions in four centralities. The centralities, from left-to-right, are 60-80%, 40-60%, 20-30%, and 0-10%.