Two-particle correlation distributions on transverse momentum in relativistic heavy-ion collisions

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for the STAR Collaboration

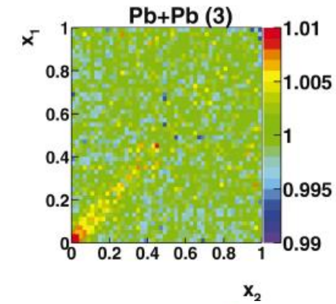
What are these correlations?
What do they look like?
What might we learn from them?

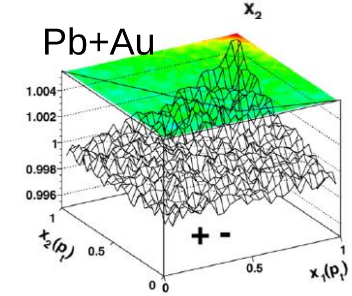
Fall 2019 DNP Meeting – Crystal City, VA

Overview – main points

- Particle pair number correlations on (p_{t1},p_{t2}) have been reported:

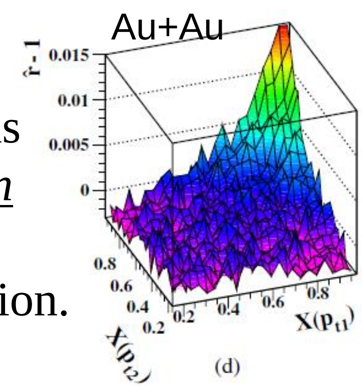
  NA49: J. Reid, Nucl. Phys. A **698**, 611 (2002);
  Nucl. Phys. A **715**, 55 (2003);
  Phys. Rev. C **70**, 034902 (2004).
  CERES: Adamova et al., Nucl. Phys. A **811**, 179 (2008)
  STAR: J. Reid, Ph.D. Thesis (UW), nucl-ex/0302001.
  Adams et al., J.Phys.G Nucl.Part. **34**,799 (2007)
  Trainor, Prindle, Phys. Rev. D **93**, 014031 (2016)
  E. Oldag, Ph.D. Thesis (UT); J.Phys.Conf.Ser. **446**, 012023 (2013)





- However, the physics impact, so far, has been limited.

- These correlations:
  1) allow access to additional properties of the heavy-ion collisions including the *degree of equilibration*; *dynamical fluctuations in soft- and hard QCD processes.*
  2) enable *absolute normalization* of the full, two-particle correlation.



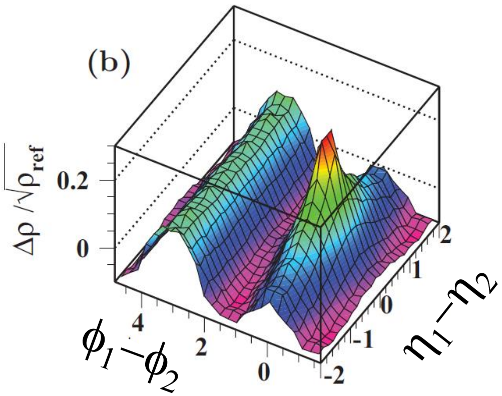
- Supporting details are in:

  Phys. Rev. C **94**, 064902 (2016) – *statistical bias correction, normalization*
  Phys. Rev. C **99**, 024911 (2019) – *phenomenological models developed*

Two-particle correlations – the basics

- Construct ratios $\dfrac{\rho_{same\text{-}event}}{\rho_{mixed\text{-}event}}$ or $\dfrac{\Delta\rho}{\rho_{me}} \equiv \dfrac{\rho_{se} - \rho_{me}}{\rho_{me}}$ to approximately cancel acceptance and inefficiencies.

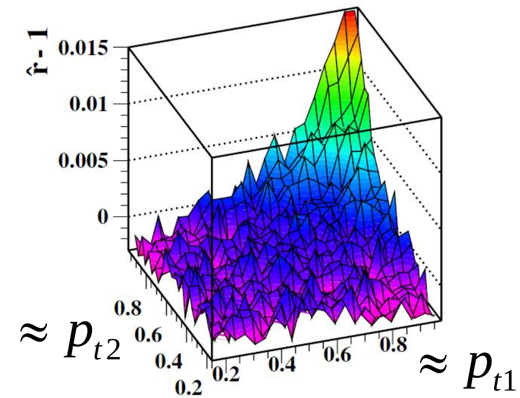
when (p_{t1},p_{t2}) range is fixed:



STAR: PRC **86**, 064902 (2012)

Au+Au 200 GeV

…or when $(\Delta\eta,\Delta\phi)$ range is fixed:



STAR: J.Phys.G **34**, 799 (2007)

- “easily” interpreted *geometrical* structures:
  - quantum interferometry (HBT)
  - v_2 – quadrupole, elliptic flow, gluon-interference
  - jets and dijets, modified fragmentation

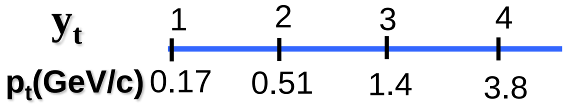
- No visually obvious structures or ready interpretation

- Phenomenology required…

Improving the visual aspects

- Transverse momentum $\Rightarrow$ transverse rapidity:

$$y_t = \ln\left[\left(p_t + m_t\right)/m_0\right] \approx \ln(p_t); \quad m_0 = m_\pi = 0.14\,\mathrm{GeV}/c^2$$



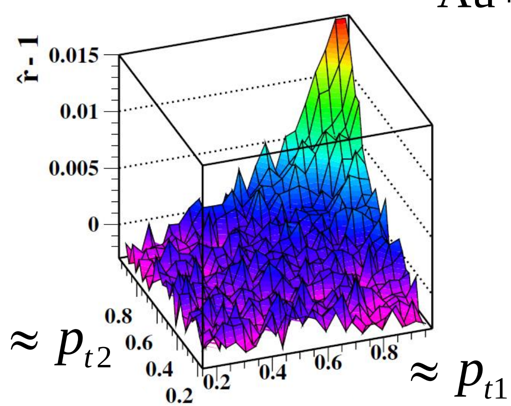
- Multiply $\Delta\rho/\rho_{me}$ by a <u>*pre-factor*</u> (P_{Factor}), giving a <u>*per-particle measure*</u>.

The final quantity used here is:

$$\underbrace{\frac{\Delta\rho}{\sqrt{\rho_{soft}}}}_{\text{(uses single-particle spectra)}} = P_{Factor}(y_{t1}, y_{t2}) \frac{\rho_{se}(y_{t1}, y_{t2}) - \rho_{me}(y_{t1}, y_{t2})}{\rho_{me}(y_{t1}, y_{t2})}$$

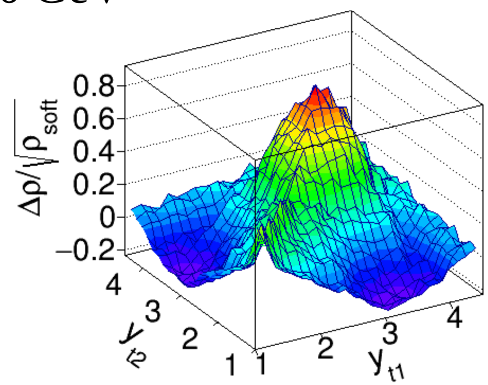
$$P_{Factor} \approx \sqrt{\rho_{me}}\text{, see:}$$

Phys. Rev. C **99**, 024911 (2019).



Au+Au 200 GeV

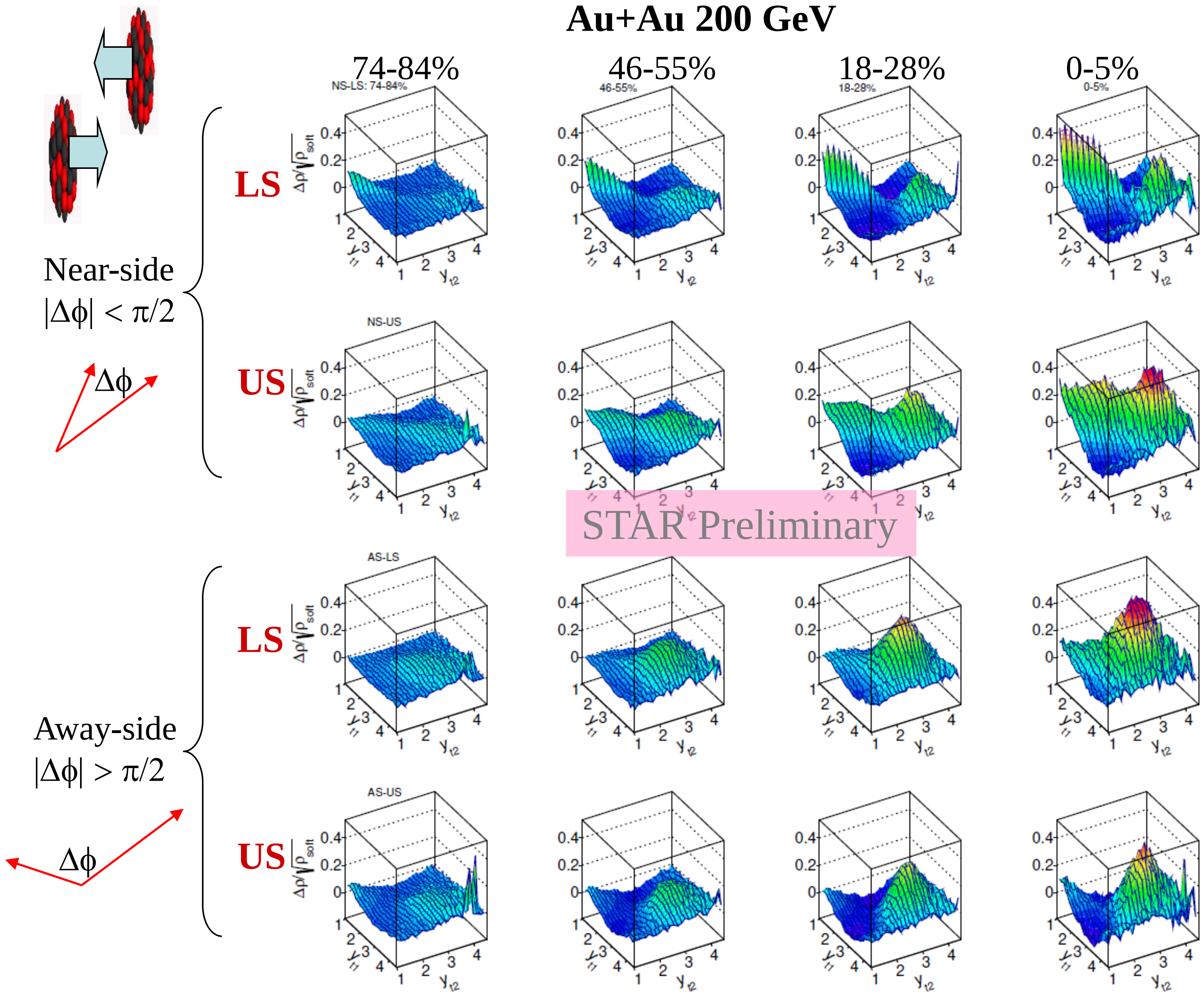
0-5%



STAR Preliminary

- **Analysis of 200 GeV Au+Au from STAR, Run 4**
  - No PID, all charged particles
  - $p_t > 0.15$ GeV/c; $|\eta| < 1$; 2π azimuth
  - Usual primary track quality selection, see PRC **86**, 064902 (2012).

Sample correlations – rich in untapped structure



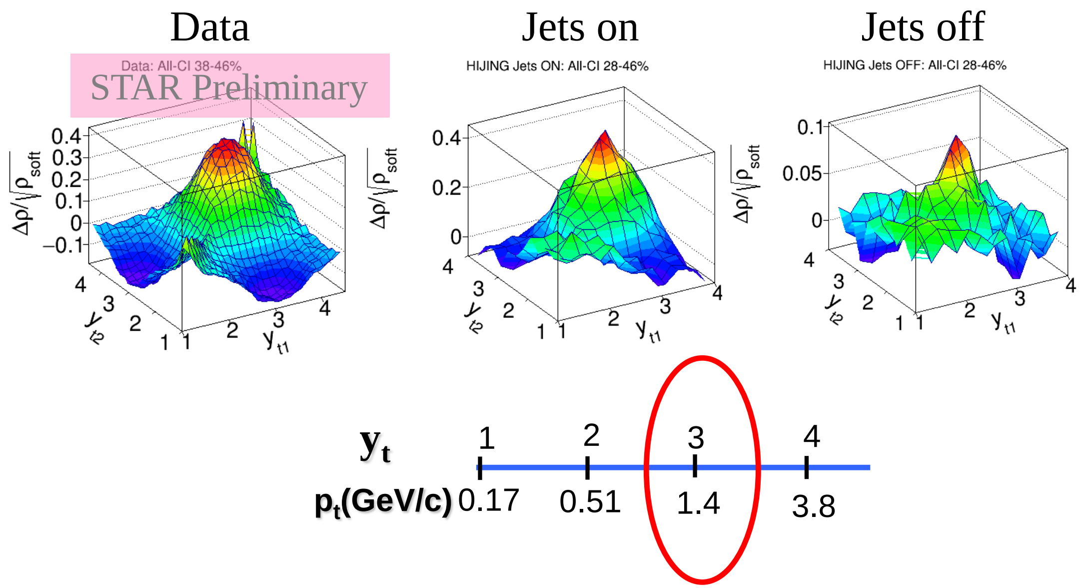
$$LS = \frac{(++)+(--)}{2}$$

$$US = \frac{(+-)+(-+)}{2}$$

HIJING
Jets On & Off

All azimuth, all charge

Au+Au 200 GeV



HIJING
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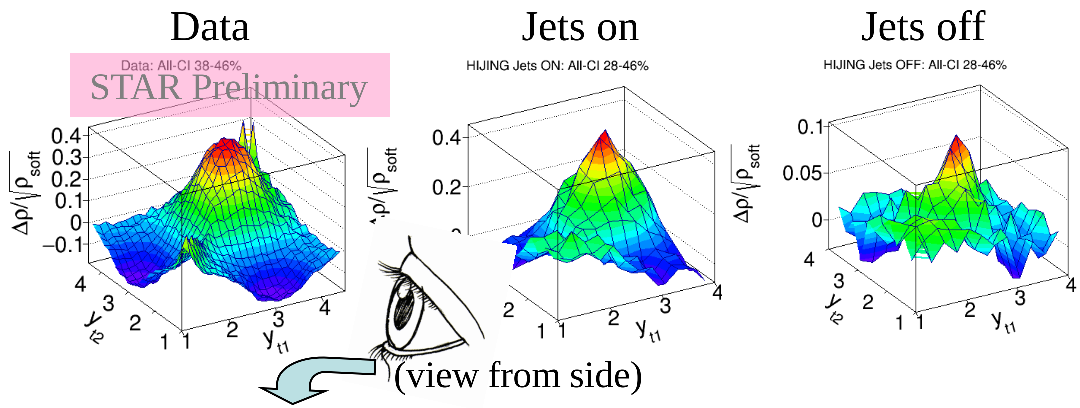
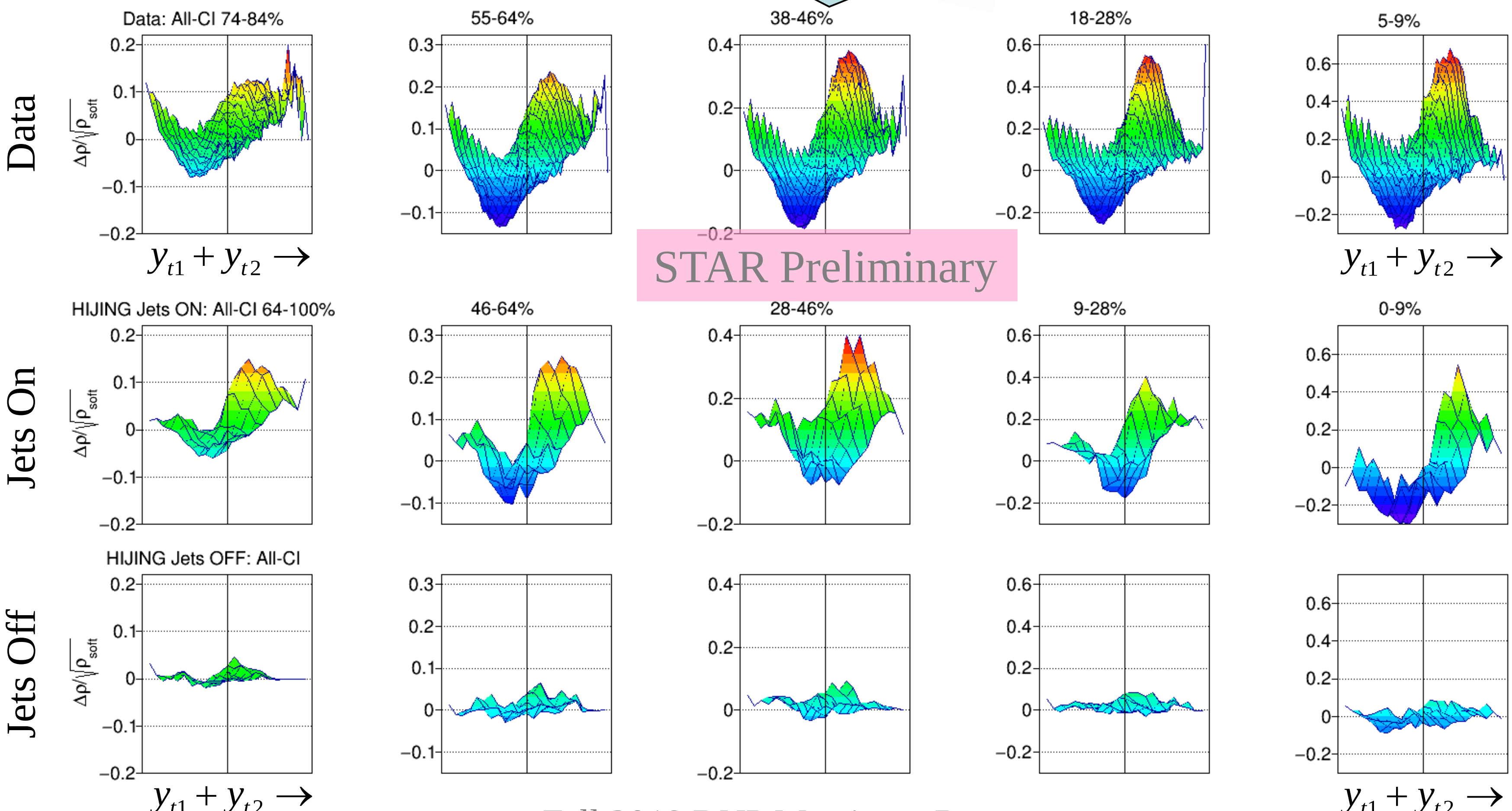
Au+Au 200 GeV





HIJING Jets On & Off

All azimuth, all charge

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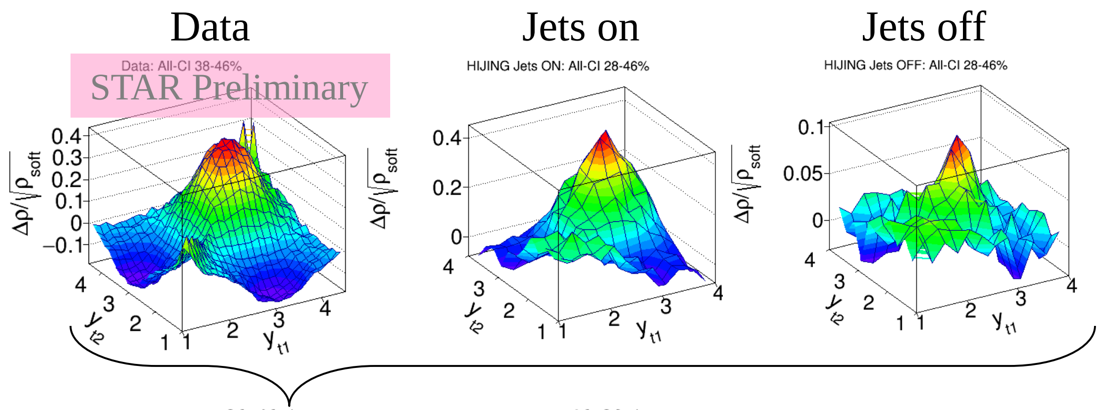
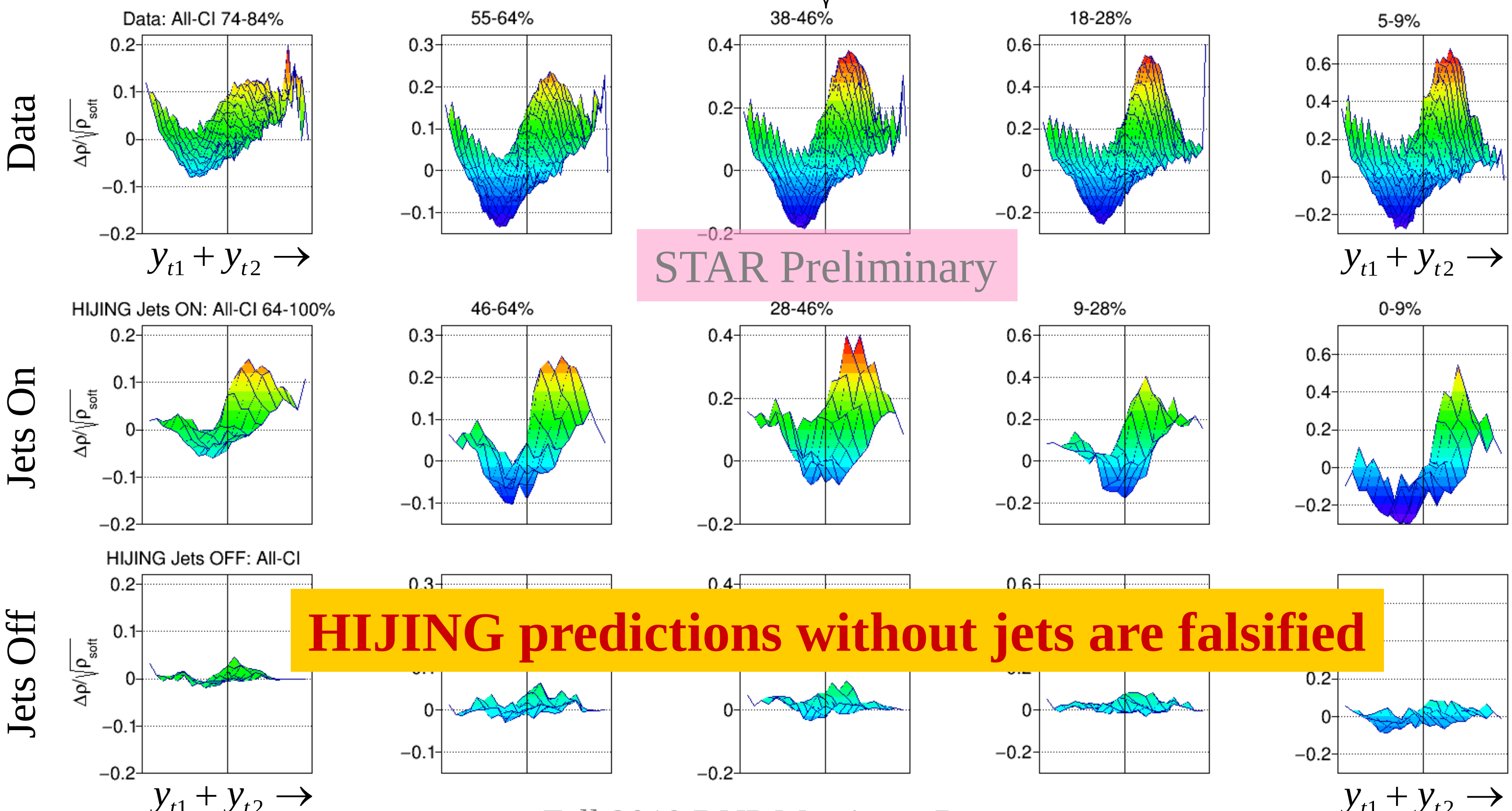


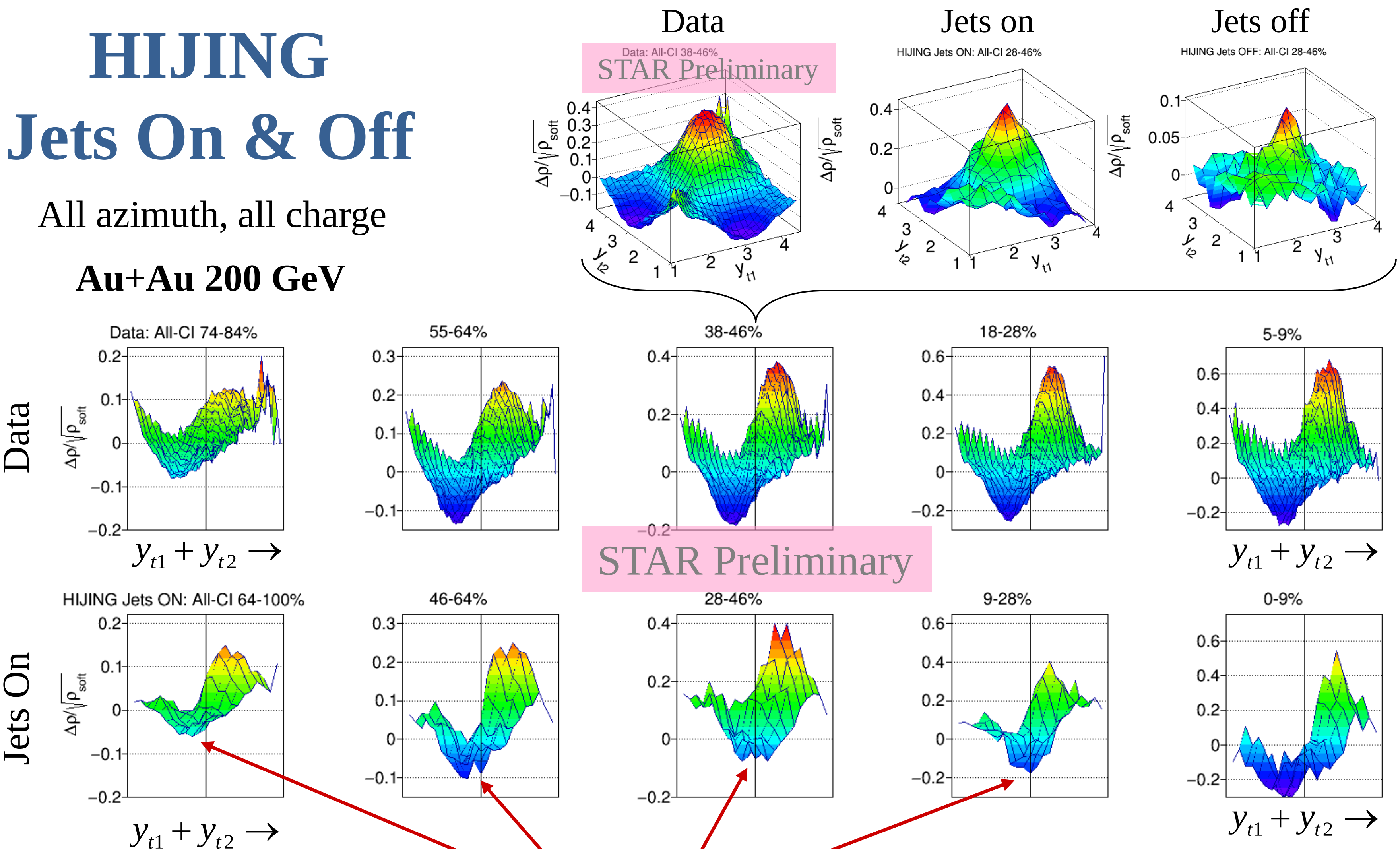


HIJING predictions without jets are falsified

HIJING
Jets On & Off

All azimuth, all charge

Au+Au 200 GeV

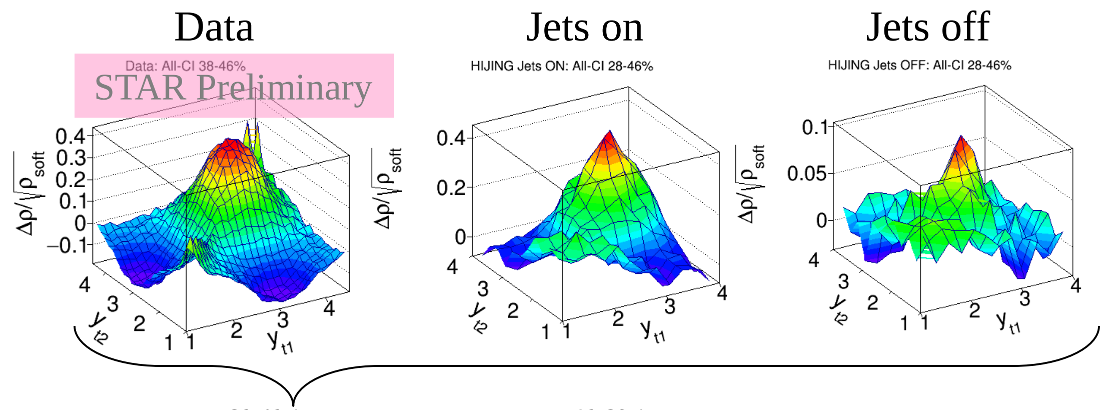


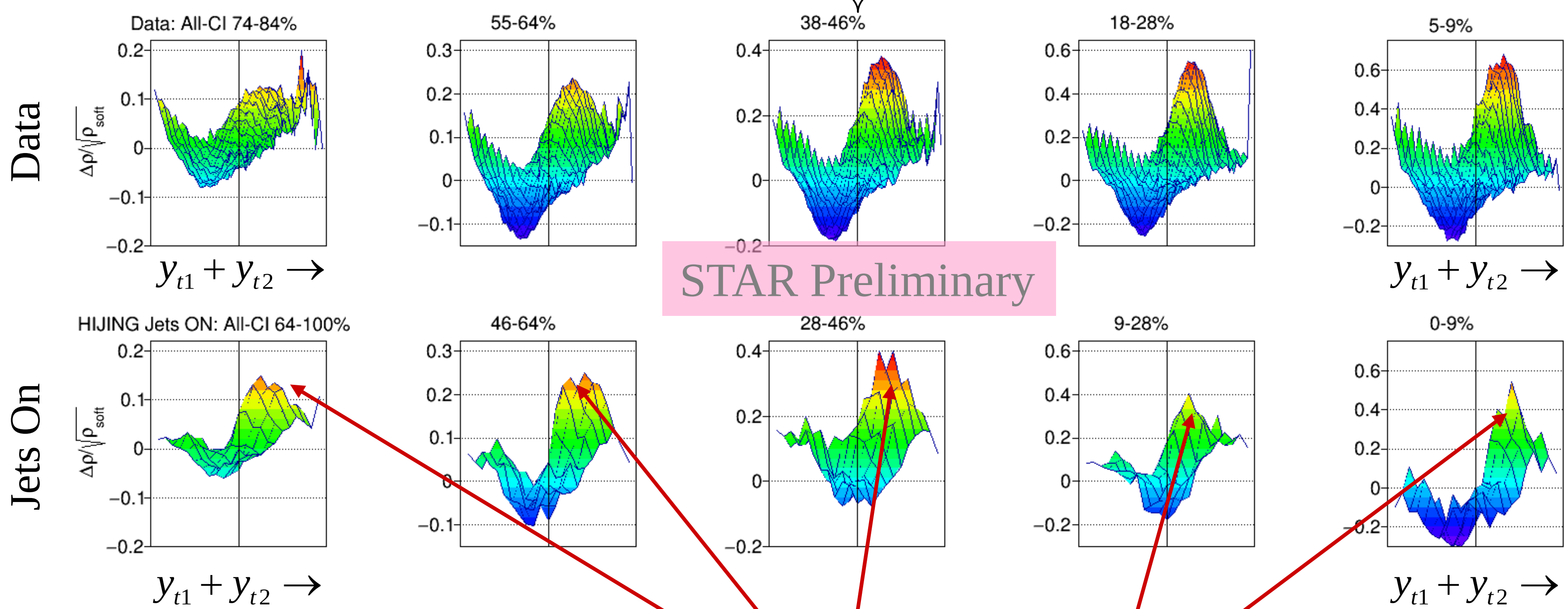
Jets On: Minima are too shallow; phenomenological analysis suggests that this is due to insufficiently correlated color-string fluctuations.

HIJING
Jets On & Off

All azimuth, all charge

Au+Au 200 GeV





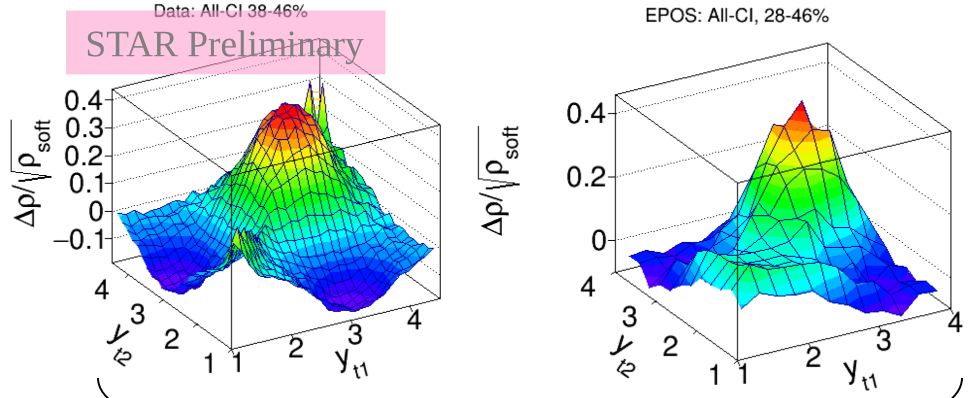
Jet peak amplitudes are OK, but then fall short;
insufficient jet-related correlated fluctuations – medium effects

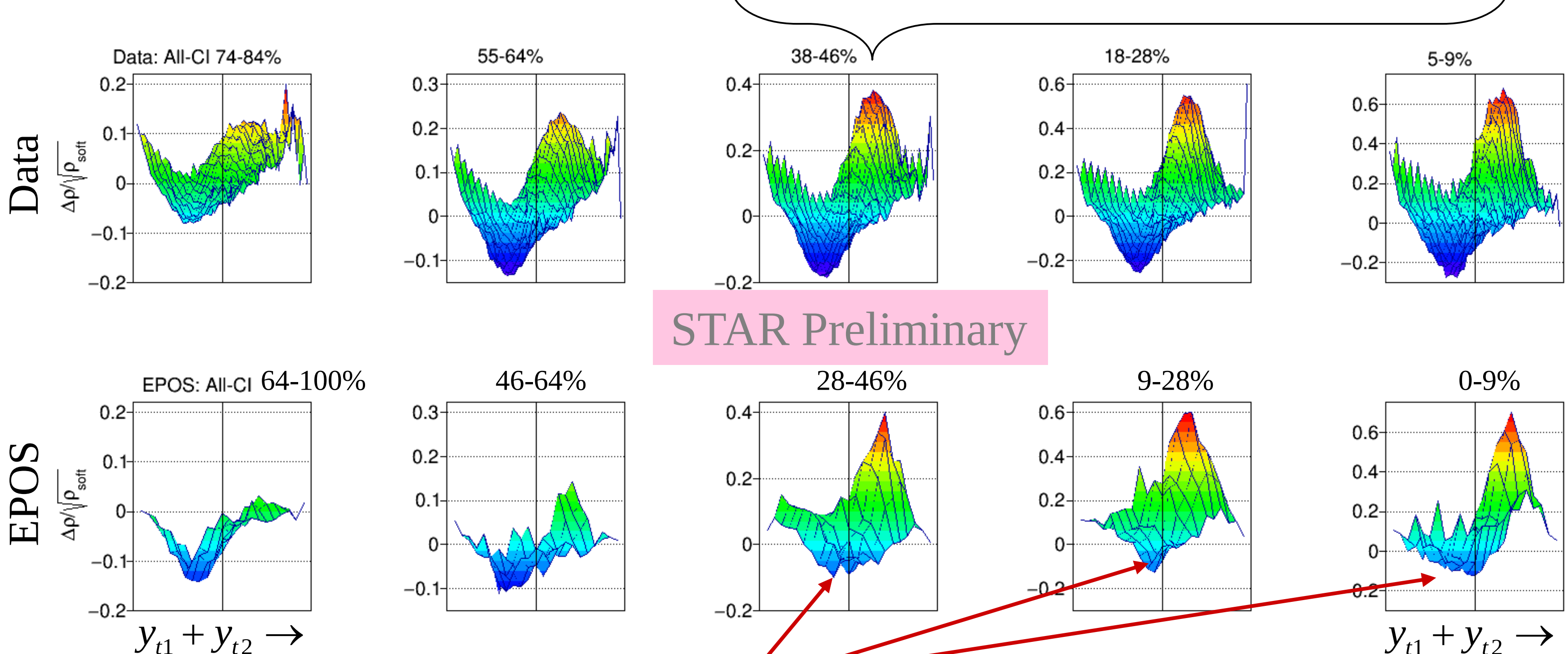
EPOS

(K. Werner*, 3+1 hydro; core+corona; UrQMD)

All azimuth, all charge

Au+Au 200 GeV





Peripheral is poorly described; interactions are too strong (?)

Minima too shallow; insufficient *Temp*-correlations

Peaks in more-central OK; strong medium interactions

*Nucl. Phys. B (Proc. Suppl.) **175-176**, 81 (2008).

Phenomenology

Interpretation of (y_t,y_t) correlations and the implications of the comparisons with theoretical predictions are facilitated by using phenomenology:

Two-component fluctuation model (Kharzeev-Nardi):

- Correlated fluctuations in p_t-slopes of particle emission from color-strings
- Fluctuation in event-wise hard vs. soft particle-production
- Correlated fluctuations in event-wise mini-jet energies
- Tests of binary scaling in hard scattering contributions to (y_t,y_t) data

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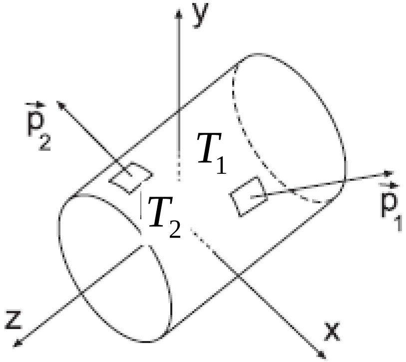
Fluctuating blast-wave model (Schnedermann, Sollfrank, Heinz):

- Correlated fluctuations in global/local freeze-out temperatures
- Correlated transverse flow velocities
- Tests transverse flow contributions
- Tests global vs local equilibration – *an example follows*

[Both are developed in: Phys. Rev. C **99**, 024911 (2019)]

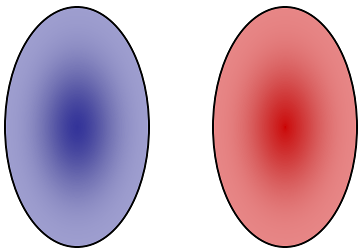
Phenomenology: Blast-Wave

Two-particles:



Particles 1 and 2 *locally* sample distributions of temperature and flow velocity; these may be correlated. [STAR, J. Phys. G: 34, 799 (2007)].

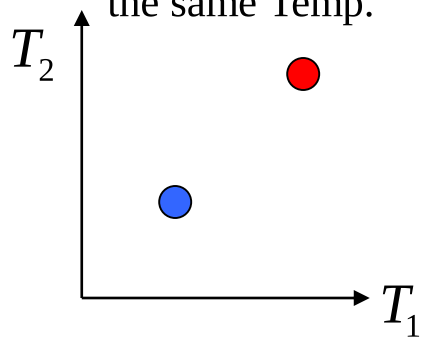
Example: collisions in *Global Equilibrium*



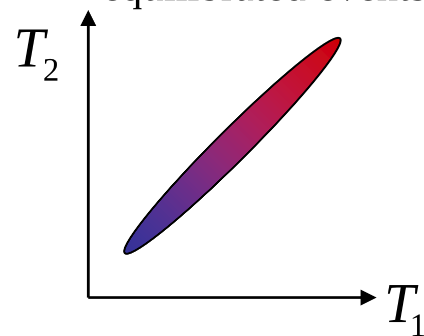
cold event

hot event

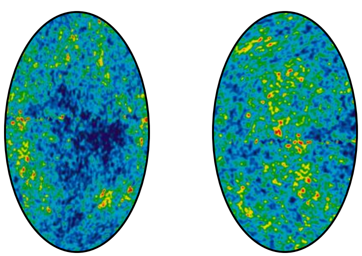
All pairs sample the same Temp.



Ensemble of globally equilibrated events

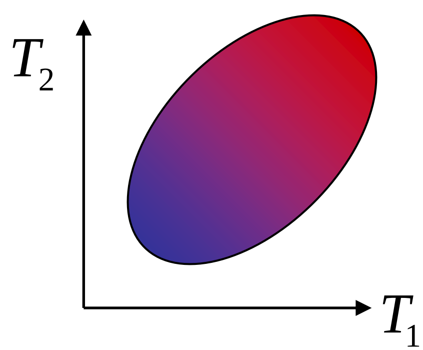


Example: collisions in *Local Equilibrium*



cooler mean

warmer mean



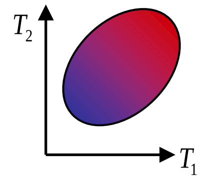
Ensemble of locally equilibrated events

Can data distinguish these?

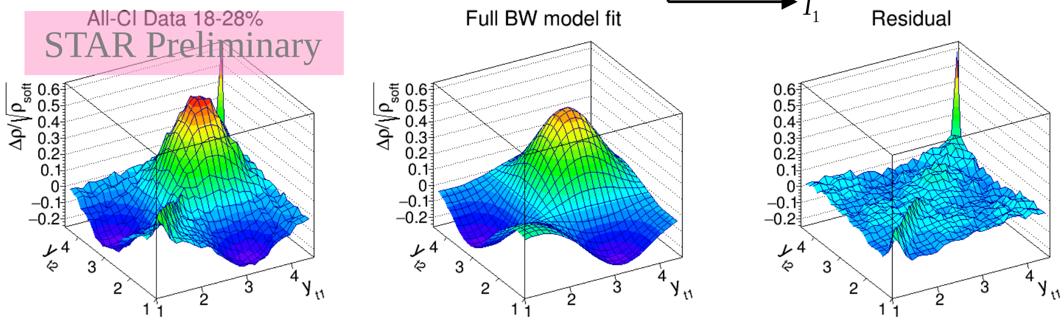
Phenomenology: Blast-Wave

Test global equilibration hypothesis as function of p_t range: **Au+Au 200 GeV, 18-28%**

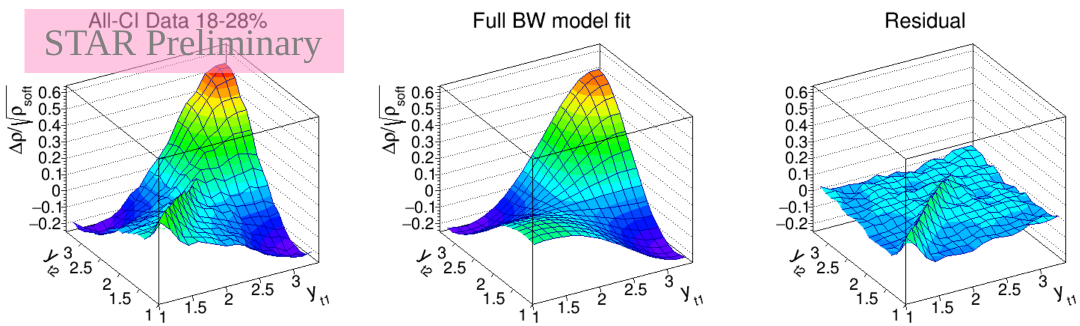
BW fit – *local equilib*.



p_t = 0.15-6.3 GeV/*c*



p_t = 0.15-2.0 GeV/*c*



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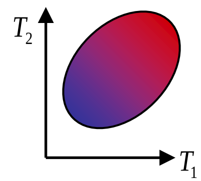
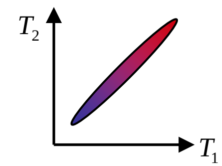
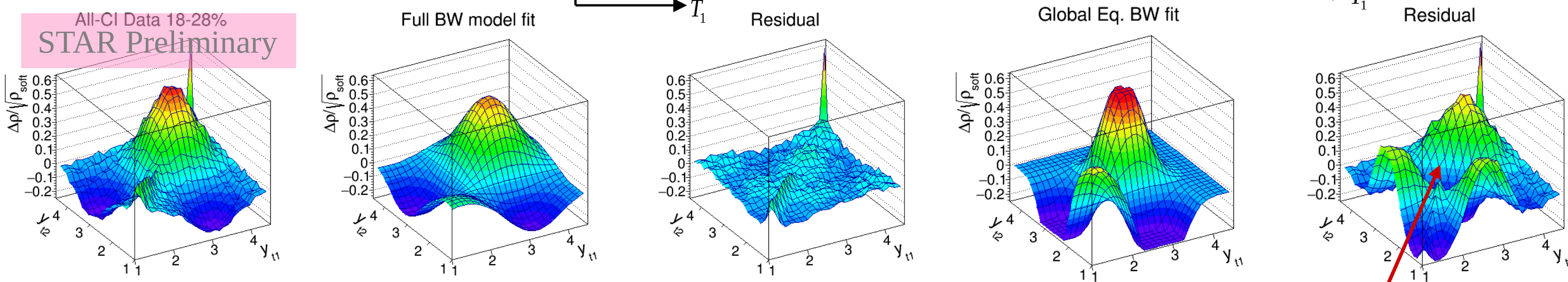


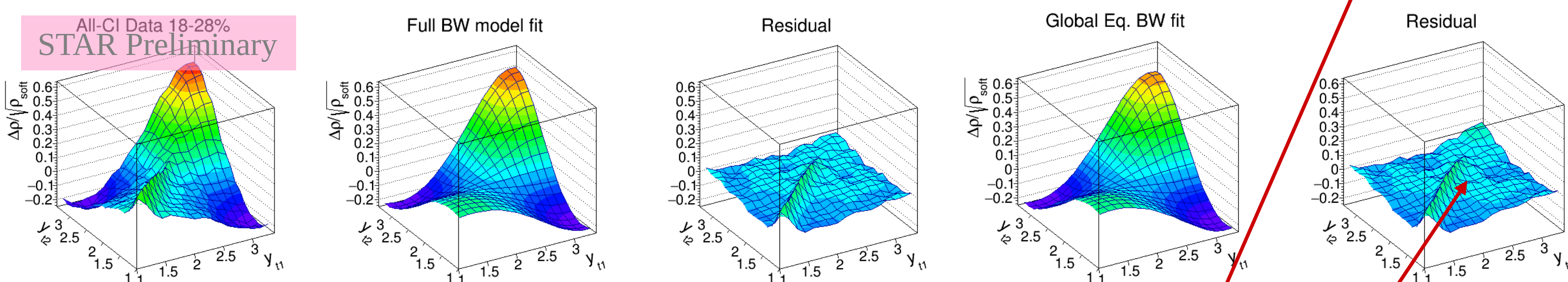
BW fit – *global equilib. required*



p_t = 0.15-6.3 GeV/c



p_t = 0.15-2.0 GeV/c



Global equilibration, as in BW model, falsified for full p_t range of data;
but not for limited p_t range, e.g. 2 GeV/c

Conclusions

- Correlations on (y_{t1},y_{t2}) enable access to *additional properties* of heavy-ion collisions, within a dynamical framework.
- HIJING with jets-on is *similar to data* (peak amplitudes) from peripheral to mid-central; fails for more-central; suggests *importance of interactions with medium*.
- EPOS appears to have *too much medium interaction* in peripheral collisions but *predicted correlations are similar to data* (peak amps.) for mid- to most-central.
- Phenomenology provides a bridge between data and theory.
- Within the BW model, *global equilibration is falsified* for $p_t < 6$ GeV/c, but not when $p_t < 2$ GeV/c.
- These, and many other (y_{t1},y_{t2}) correlation data for 200 GeV Au+Au will be available from STAR next year – *providing new constraints on developing models*.

Backup

Introduction: Two-particle correlations

- Final correlations are displayed with respect to <u>transverse rapidity</u>:

  $$y_t = \ln\left[\left(p_t + m_t\right)/m_0\right] \approx \ln(p_t);\ \text{where}\ m_t = \sqrt{p_t^2 + m_0^2};\ m_0 = m_\pi = 0.14\,\mathrm{GeV}/c^2$$

  to better display the structures at lower and higher momentum;
  natural coordinate for studying fragmentation.

- $\Delta\rho/\rho_{me}$ is multiplied by an analytic <u>*pre-factor*</u> which better displays the correlation structures, gives a per-particle measure, and facilitates tests of <u>*binary scaling*</u>.

- The final quantity used here is:

$$\frac{\Delta\rho}{\sqrt{\rho_{soft}}} = \frac{\dfrac{d^2N_{ch}}{dy_{t1}d\eta_1}\dfrac{d^2N_{ch}}{dy_{t2}d\eta_2}}{\sqrt{\dfrac{d^2N_{soft}}{dy_{t1}d\eta_1}\dfrac{d^2N_{soft}}{dy_{t2}d\eta_2}}}\;\frac{\rho_{se}(y_{t1},y_{t2}) - \rho_{me}(y_{t1},y_{t2})}{\rho_{me}(y_{t1},y_{t2})}$$

where: $d^2N_{ch}/dy_{t1}d\eta_1$ are Levy model fits to charged-particle spectra data for A + A,

$d^2N_{soft}/dy_{t1}d\eta_1$ are Levy model fits to the extrapolated, no-jet N + N limit of the A + A spectra.

Au+Au 200 GeV