Report from

“Correlations and Fluctuations”

workshop at

2005 RHIC/AGS Users Meeting

Gunther Roland

MIT

Correlations and Fluctuations: Talks

1. Event-by-Event Fluctuations from PHENIX (Tomoaki Nakamura)
2. Event-by-event Fluctuations from PHOBOS (Zhengwei Chai)
3. Event-by-Event fluctuations from STAR (Claude Pruneau)
4. Correlations in Transport Models (Denes Molnar)
5. Trigger particle correlations PHENIX (Paul Constantin)
6. Trigger particle correlations STAR (Jason Ulery)
7. Correlations and Recombination (Steffen Bass)
8. Correlation and Fluctuation measures (Tom Trainor)
9. Auto correlations and event structure (Lanny Ray)
10. Correlations/fluctuations from SPS (Georgios Tsiledakis)
11. Correlations and Parton Saturation (Kirill Tuchin)

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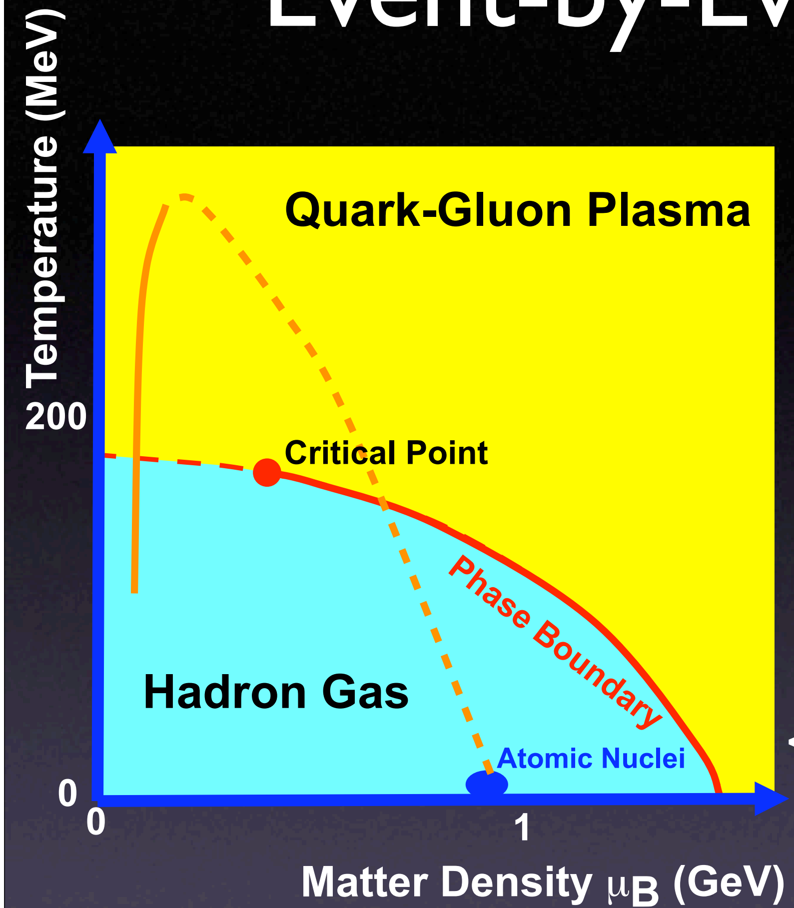
Many new results!

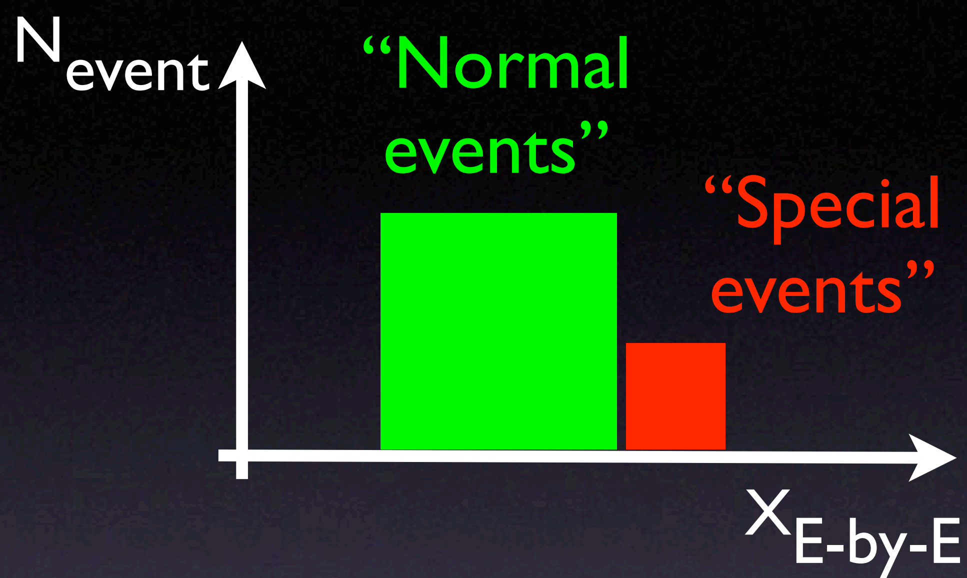
Many new ideas!

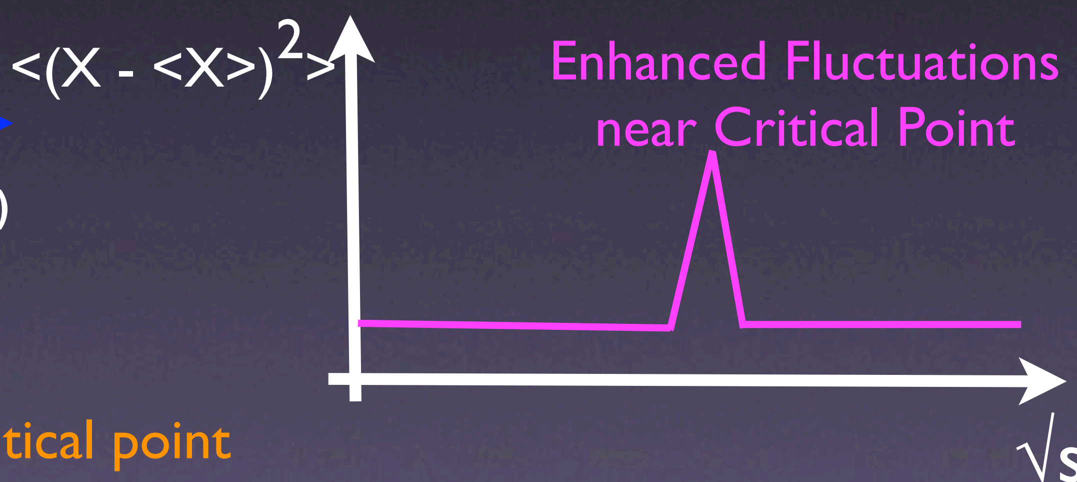
too little time!

Summarize main new directions

Event-by-Event Physics (last century)





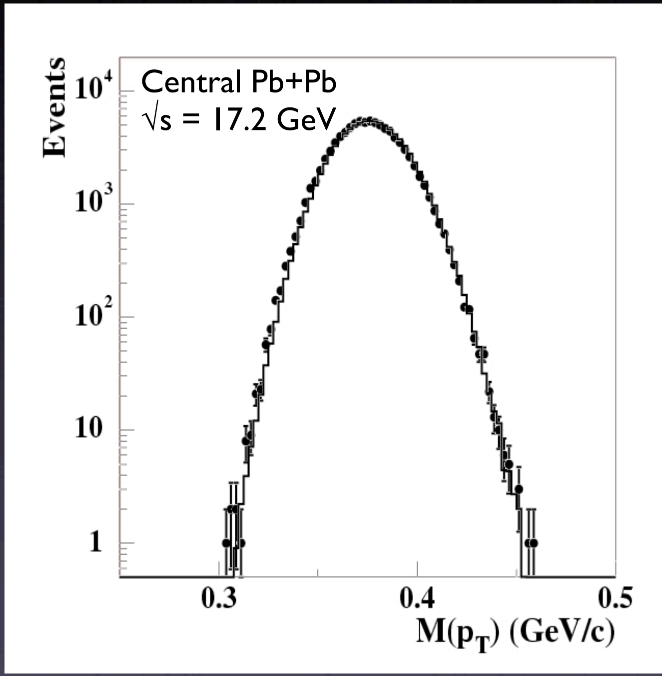


"Event-by-event Physics":
Search for critical phenomena
induced near phase transition/critical point

Classic Example: <p_T> Fluctuations

- p_T - simple observable (supposedly...)
- High statistical precision: $\sigma_{pT}/\langle pT \rangle_{inc} <$ 0.1%
- Sensitive to many interesting scenarios
  - Critical Point
  - DCC production
  - Droplet formation
  - **Any non-statistical, momentum-localized process**

NA49, Phys Lett B459 (1999) 679



Event-by-event <p_T> compared to stochastic reference (mixed events)

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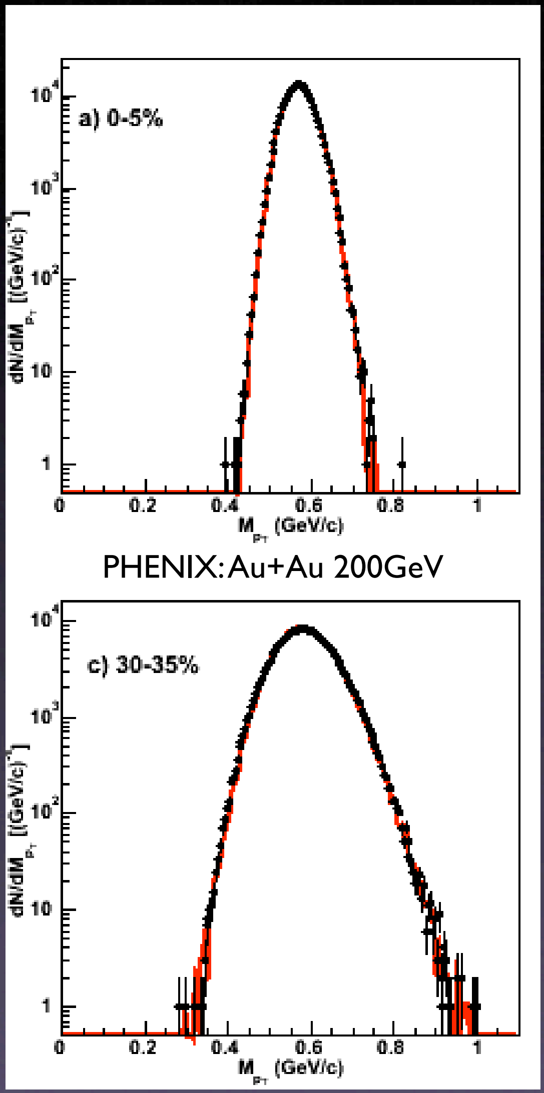
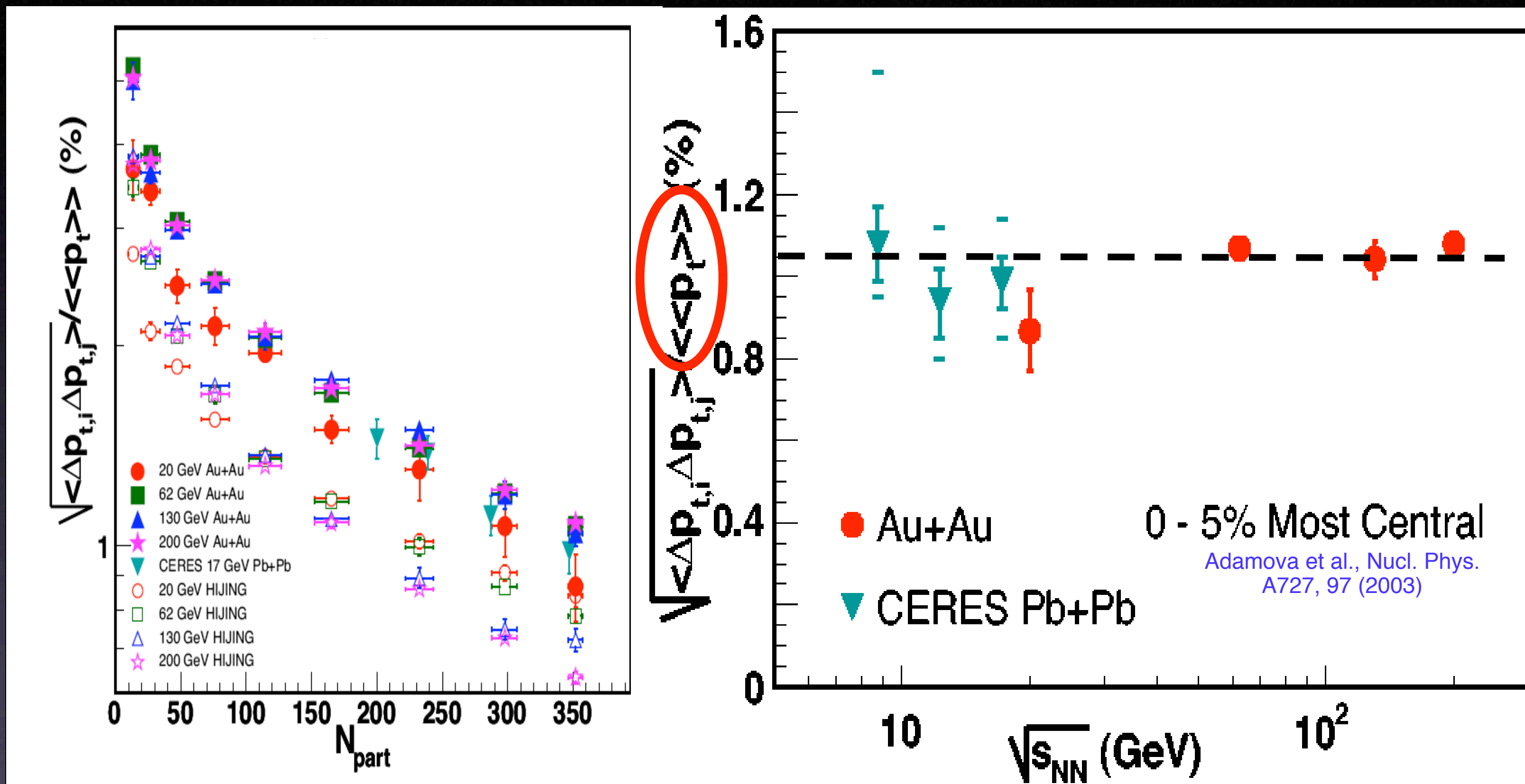


Tomoaki Nakamura (PHENIX)

p_T Fluctuations vs √s

Claude Pruneau (STAR), Georgios Tsiledakis (CERES)

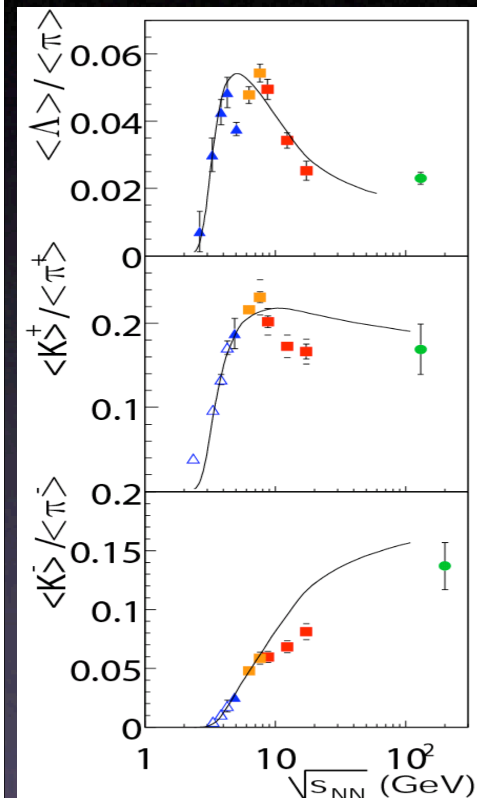


No Structure vs √s

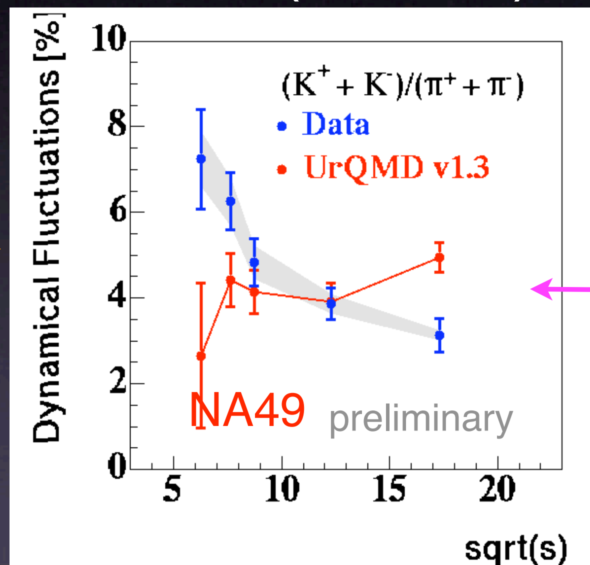
Relative fluctuations (~ ΔT/T) √s - independent

Strangeness Fluctuations vs √s

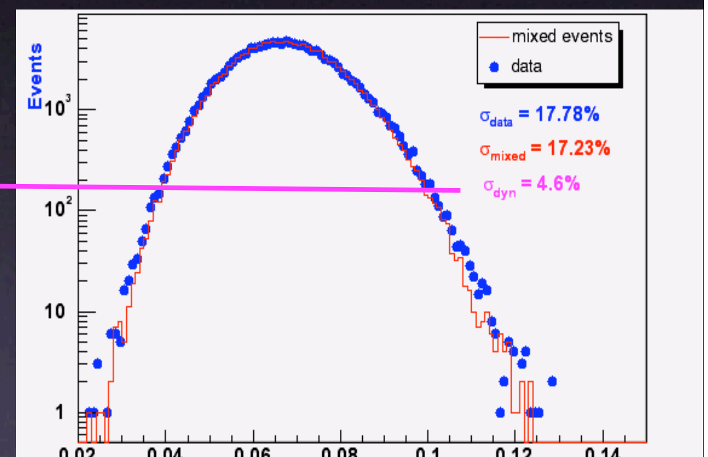
NA49 'Horn'



NA49 (QM'04)



Claude Pruneau (STAR)



Fluctuations in K/pi ratio

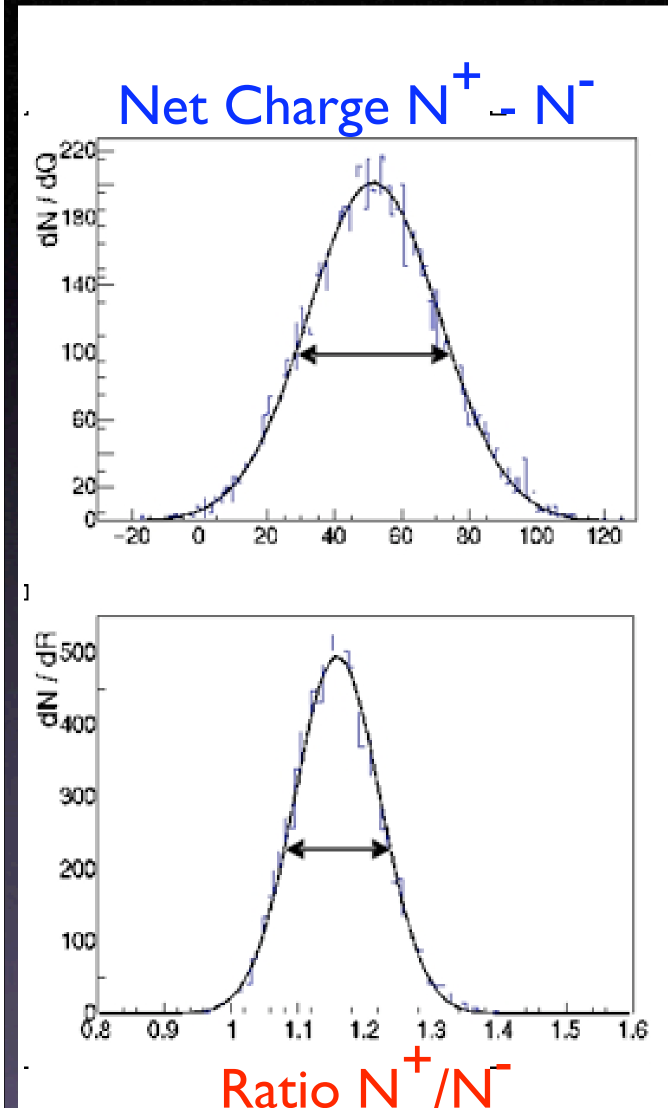
An Evolving Paradigm

- Event-by-Event Physics
  - Critical phenomena?
    - Global ("large scale") fluctuations
    - Small, but measurable
    - No hint of non-monotonic structure (at least between SPS and RHIC)!

An Evolving Paradigm

- Event-by-Event Physics
  - Critical phenomena?
    - Global ("large scale") fluctuations
    - Small, but measurable
    - No hint of non-monotonic structure (at least between SPS and RHIC)!
  - Fluctuations of conserved quantities (2000)
    - Net-charge fluctuations (Jeon, Koch hep-ph/0003168 Asakawa, Heinz, Mueller hep/ph/0003169)

Net Charge Fluctuations - Smoking Gun?



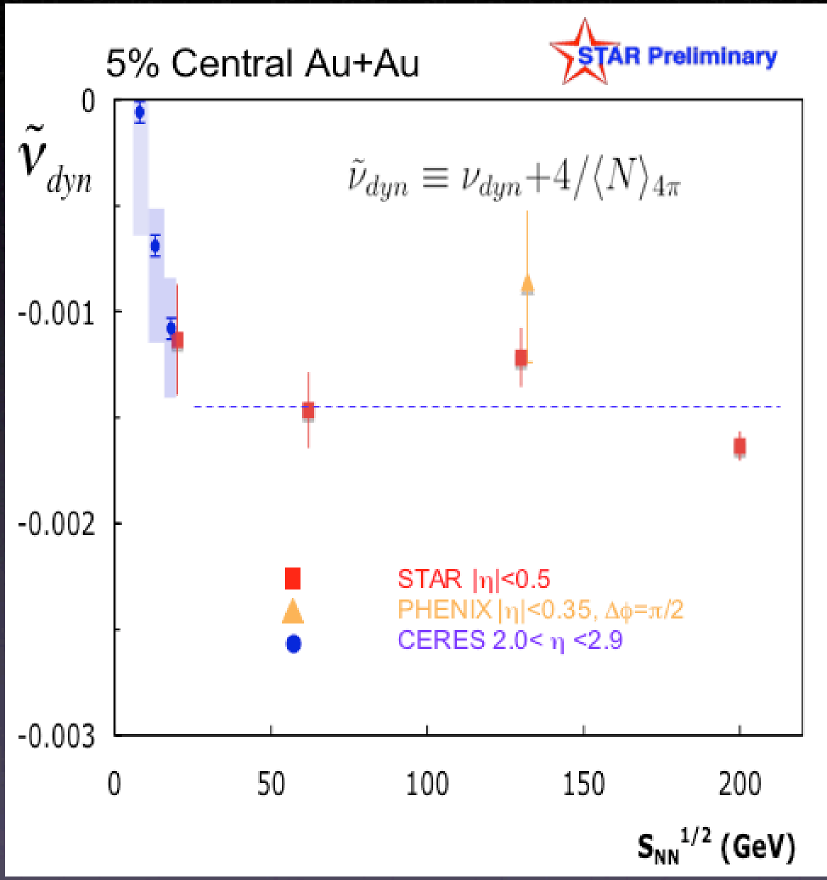
- Net Charge/Δy Fluctuations <-> Charge/DoF
  - Jeon, Koch hep-ph/0003168
  - Asakawa, Heinz, Mueller hep/ph/0003169
  - Change from 1-2 (QGP) to 4 (Pion Gas)

- Fluctuations frozen b/c charge conservation
  - Diffusion vs Expansion timescale

- Fluctuations of N^+/N^- or $N^+ - N^-$ vs statistical reference

Net Charge Fluctuations vs √s

Claude Pruneau (STAR)



← QGP

Is this a Problem?

- Basic argument still appears valid
- Possible Explanations
  - Diffusion in long-lived hadronic phase?
  - Resonances?
  - A feature of hadronization?
  - Quark Coalescence?
  - Bound states?
- Need connection to other data and QCD

Karsch et al

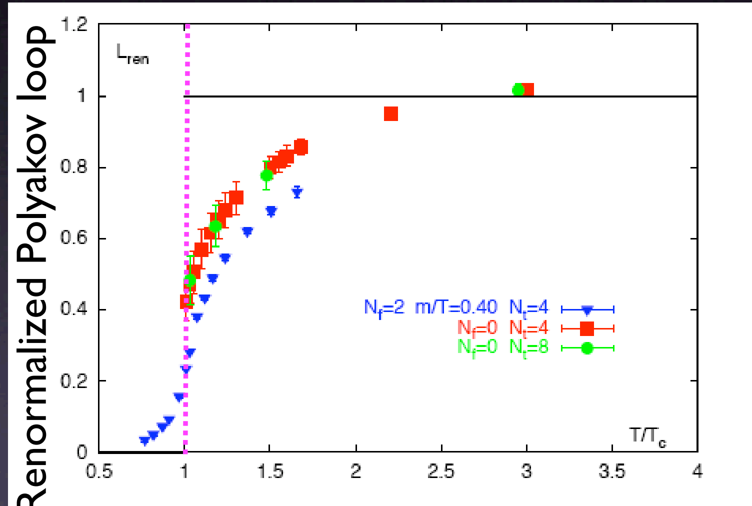


Fig. 6. The renormalized Polyakov loop in full QCD compared to the quenched results[1].

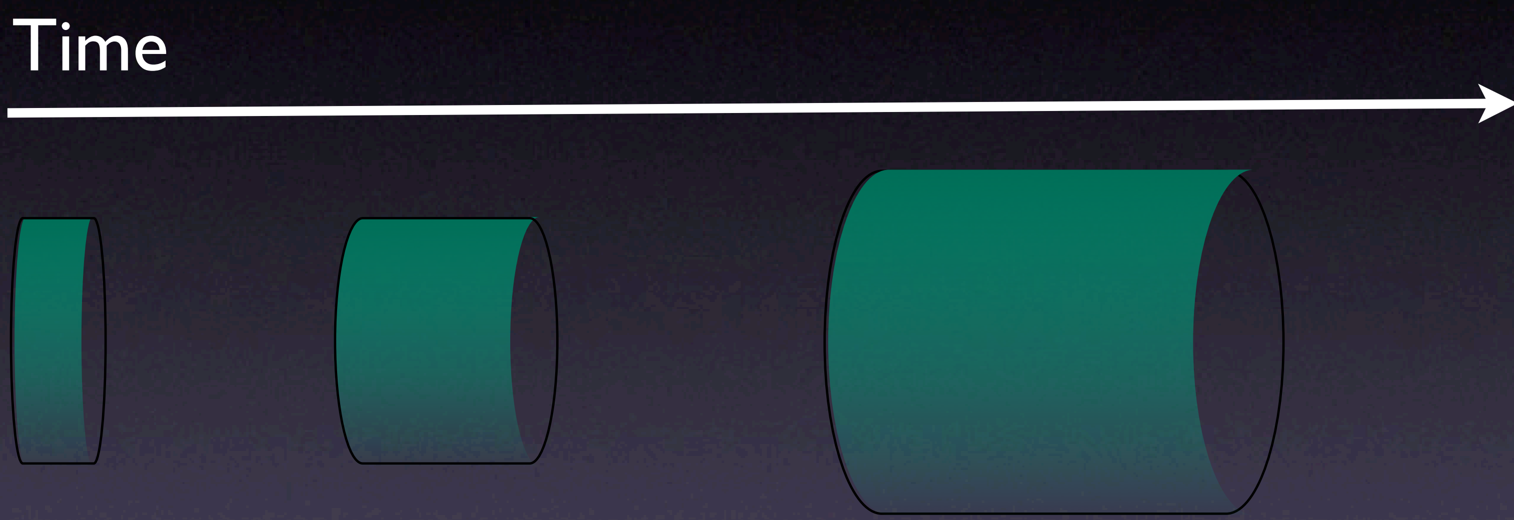
An Evolving Paradigm

- Event-by-Event Physics
  - Critical phenomena
  - Fluctuations of conserved quantities (2000)

An Evolving Paradigm

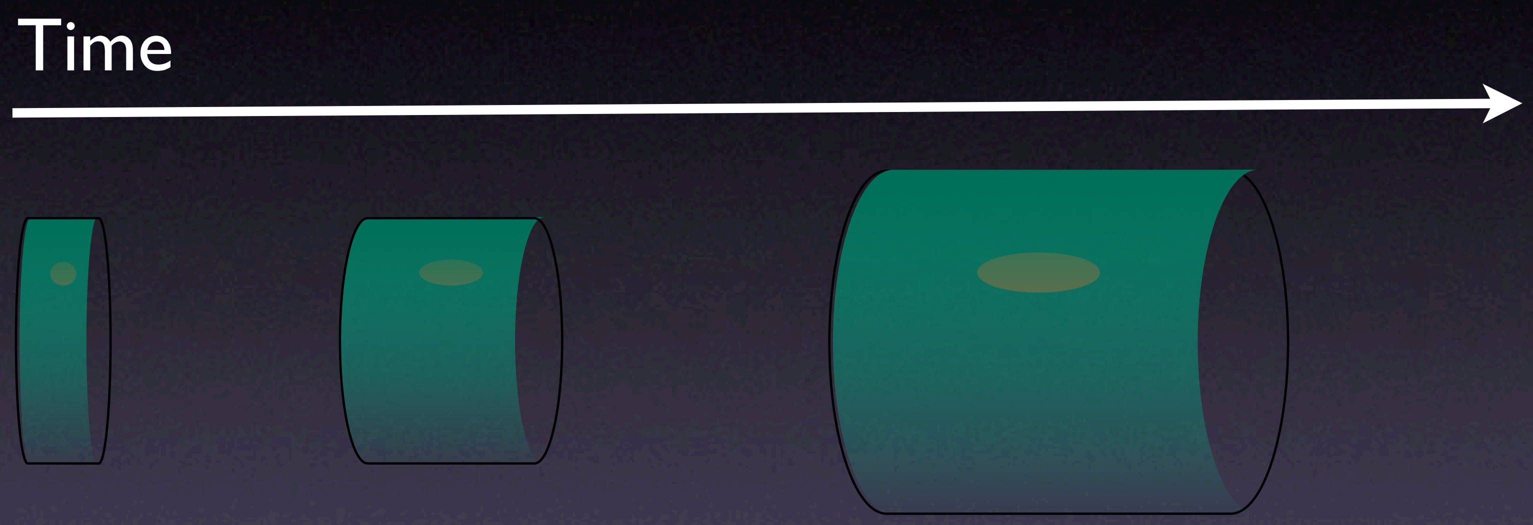
- Event-by-Event Physics
  - Critical phenomena
  - Fluctuations of conserved quantities (2000)
- Fluctuations and Correlations
  - Use correlations to study transport properties of the medium

Correlation Probes of the Medium

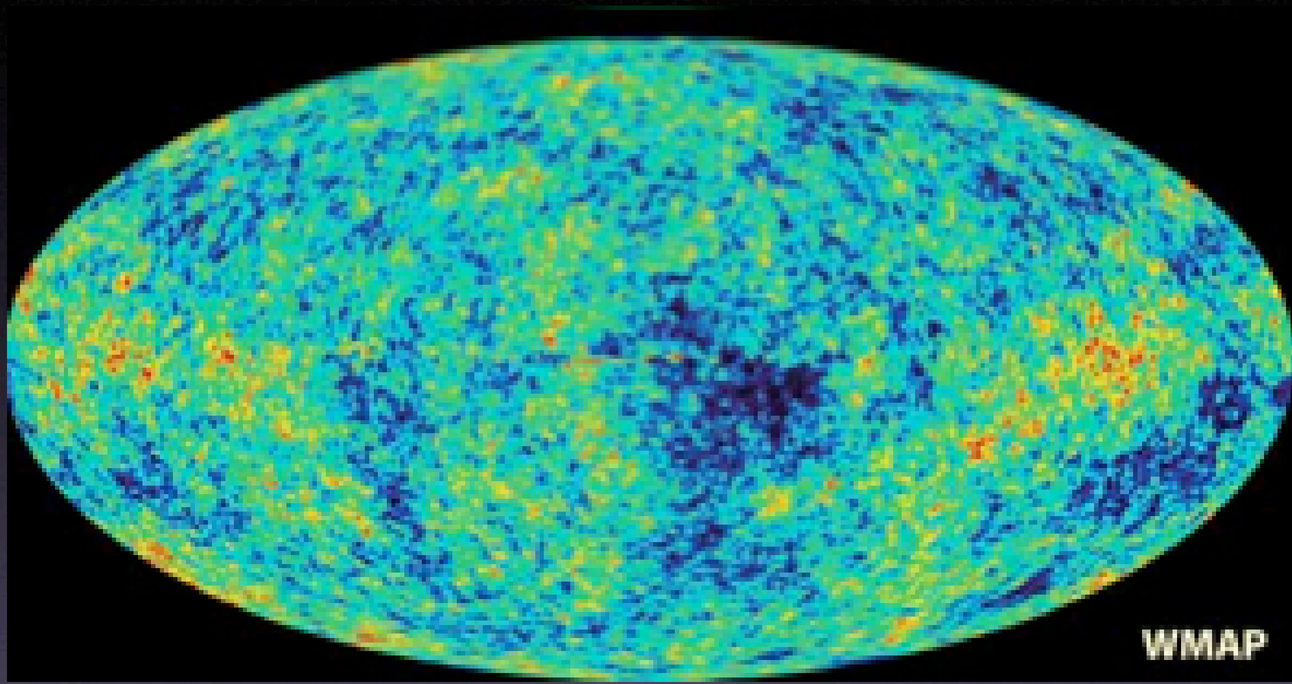


- Probe

Correlation Probes of the Medium

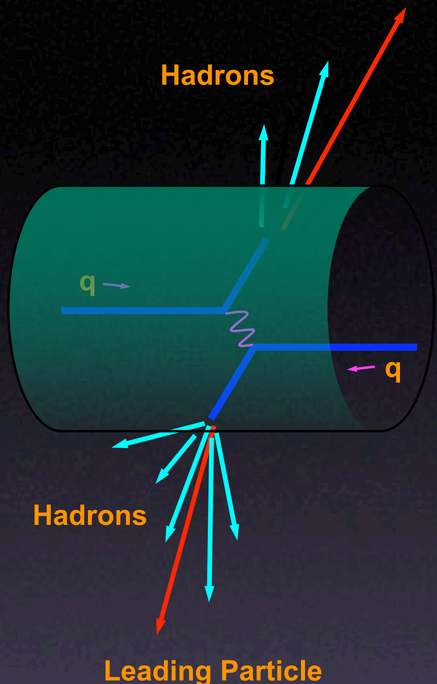


Analogy: Cosmic Microwave Background



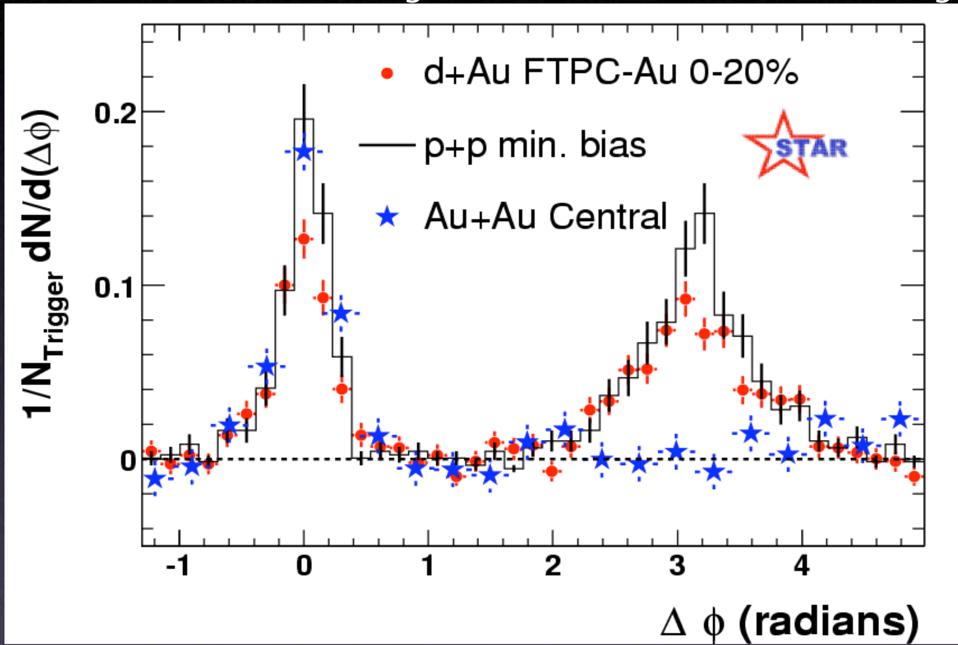
Use scale-dependent analysis of correlations in frozen-out final state to constrain dynamics of early stage expansion

Correlations at 'high' p_T



Jason Ulery (STAR)

$|\eta| < 0.7$, 4 GeV/c $< p_{Ttrig} <$ 6 GeV/c, $2 < p_{TAsso} < p_{Ttrig}$



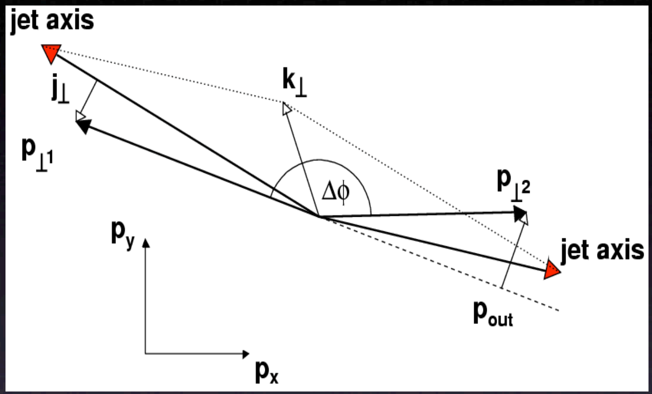
STAR PRL (2003)

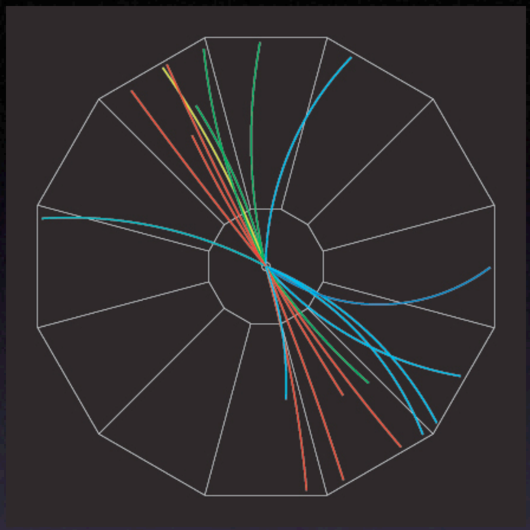
Relative to trigger particle:

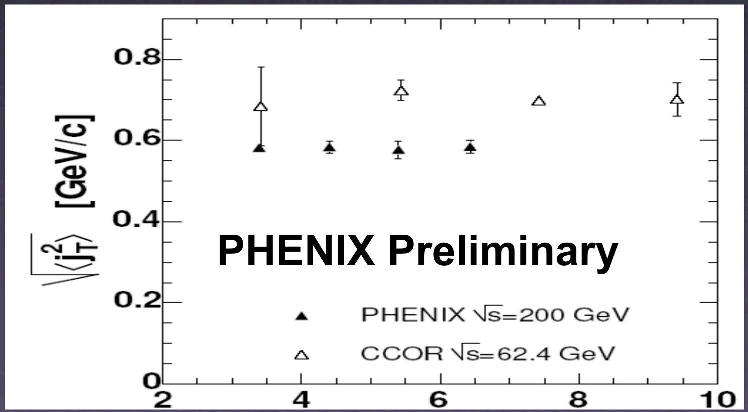
- Jet-like near-side correlations visible in Au+Au
- Away-side correlations disappear for central Au+Au

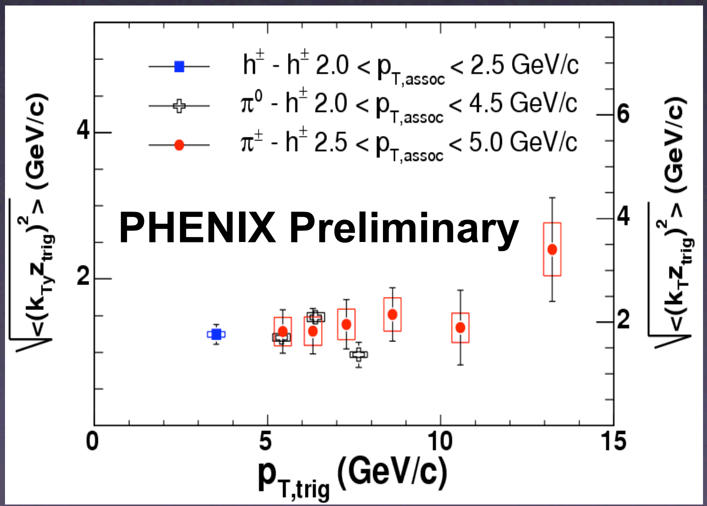
Jet-like Correlations in p+p

Paul Constantin (PHENIX)





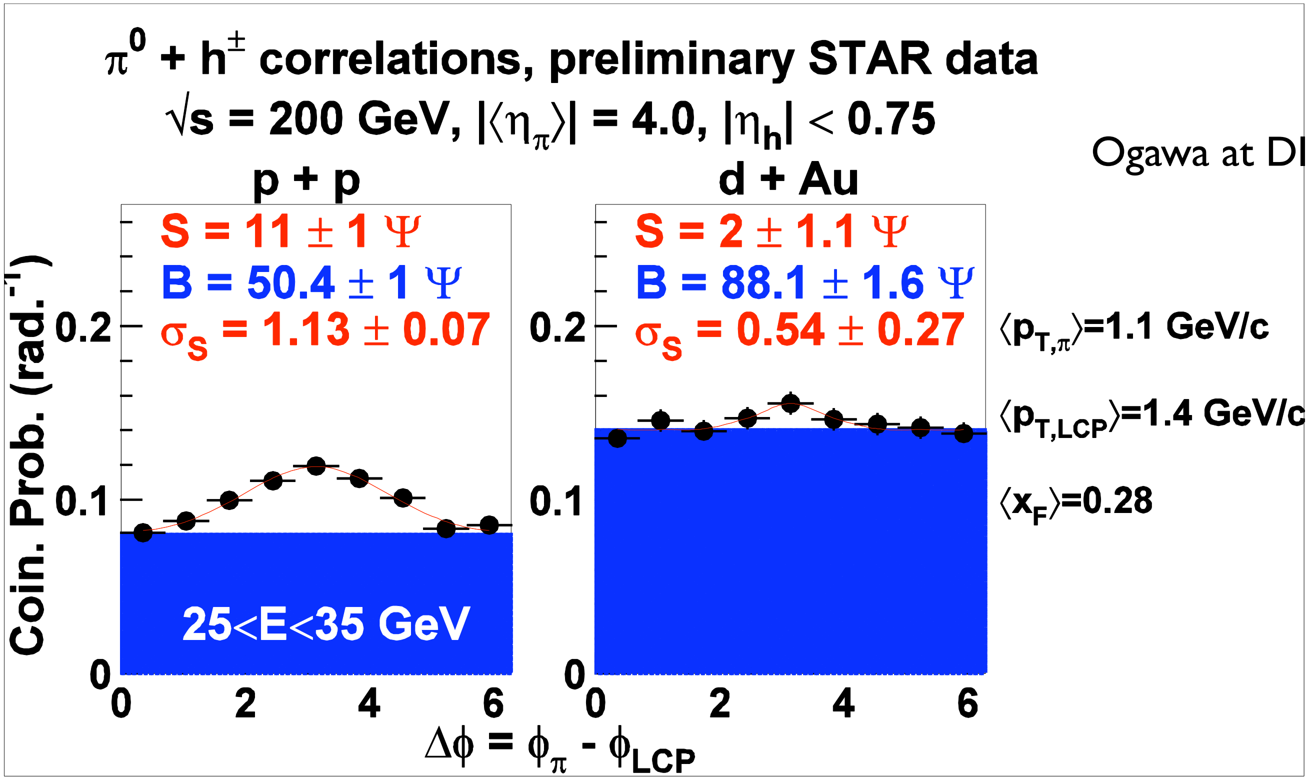




d+Au Back-to-back Correlations

- Disappearance of back-to-back correlations in dAu collisions predicted by KLM seems to be observed in preliminary STAR data.

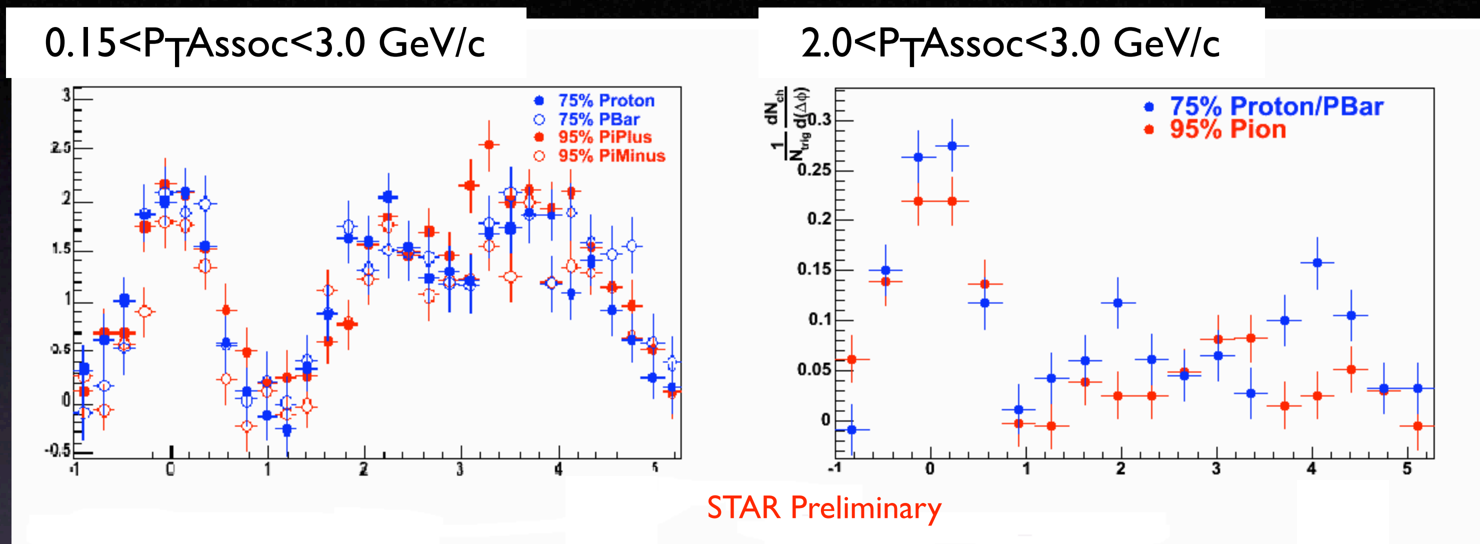
Ogawa at DIS2004



Kirill Tuchin

Identified Trigger Particles

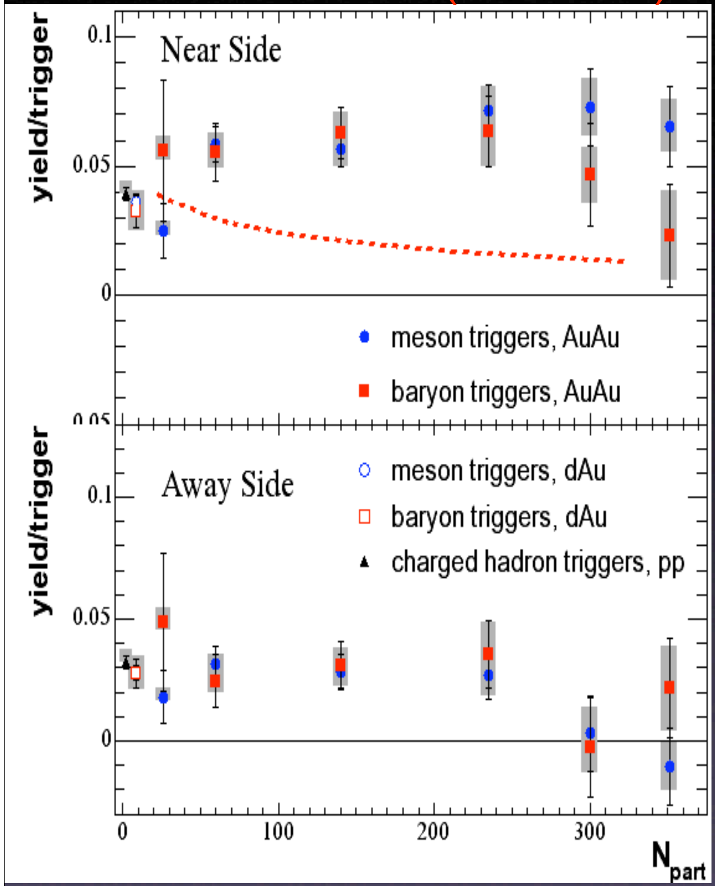
Jason Ulery (STAR)



- **3<P$_T$Trig<4** GeV/c Au+Au Central Year 2
- Trigger particle v2 is obtained by
  - $v2_{baryon}/v2_{meson}=3/2$
  - $v2_{baryon}{}^*yield_{baryon} + v2_{meson}{}^*yield_{meson} = v2_{charged}{}^*yield_{charged}$
- Correlation functions look similar between different trigger particle species.

Identified Trigger Particles

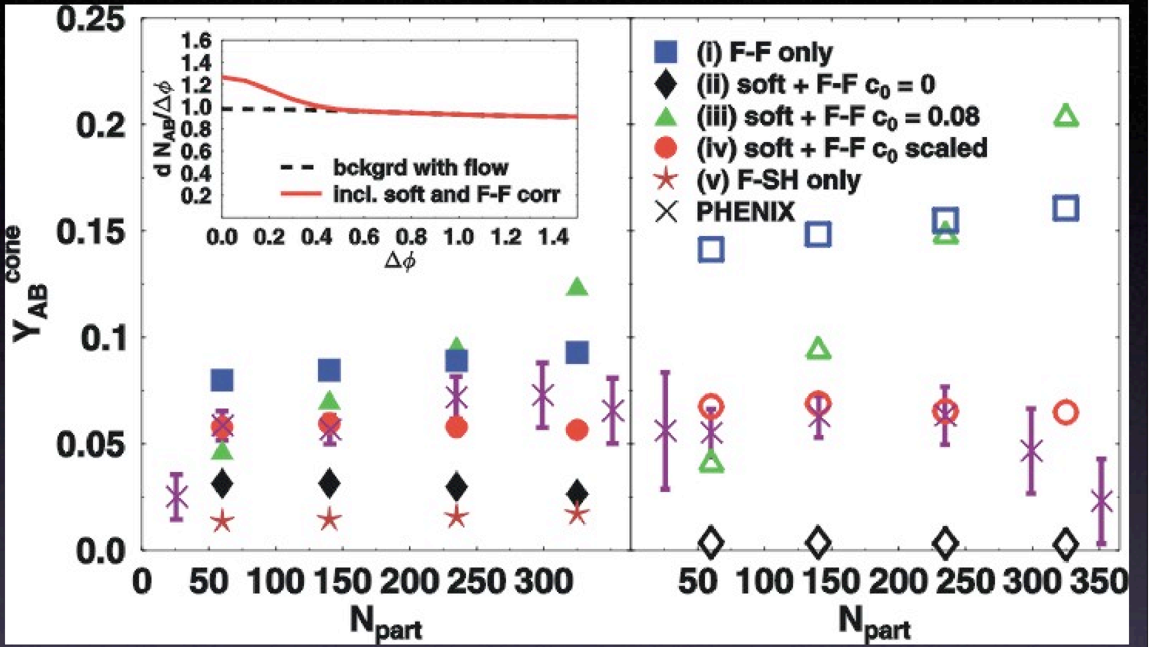
Paul Constantin (PHENIX)



"Away side: partner rate as in pp/dAu confirms jet source of baryons!"

nucl-ex/0408007

Steffen Bass

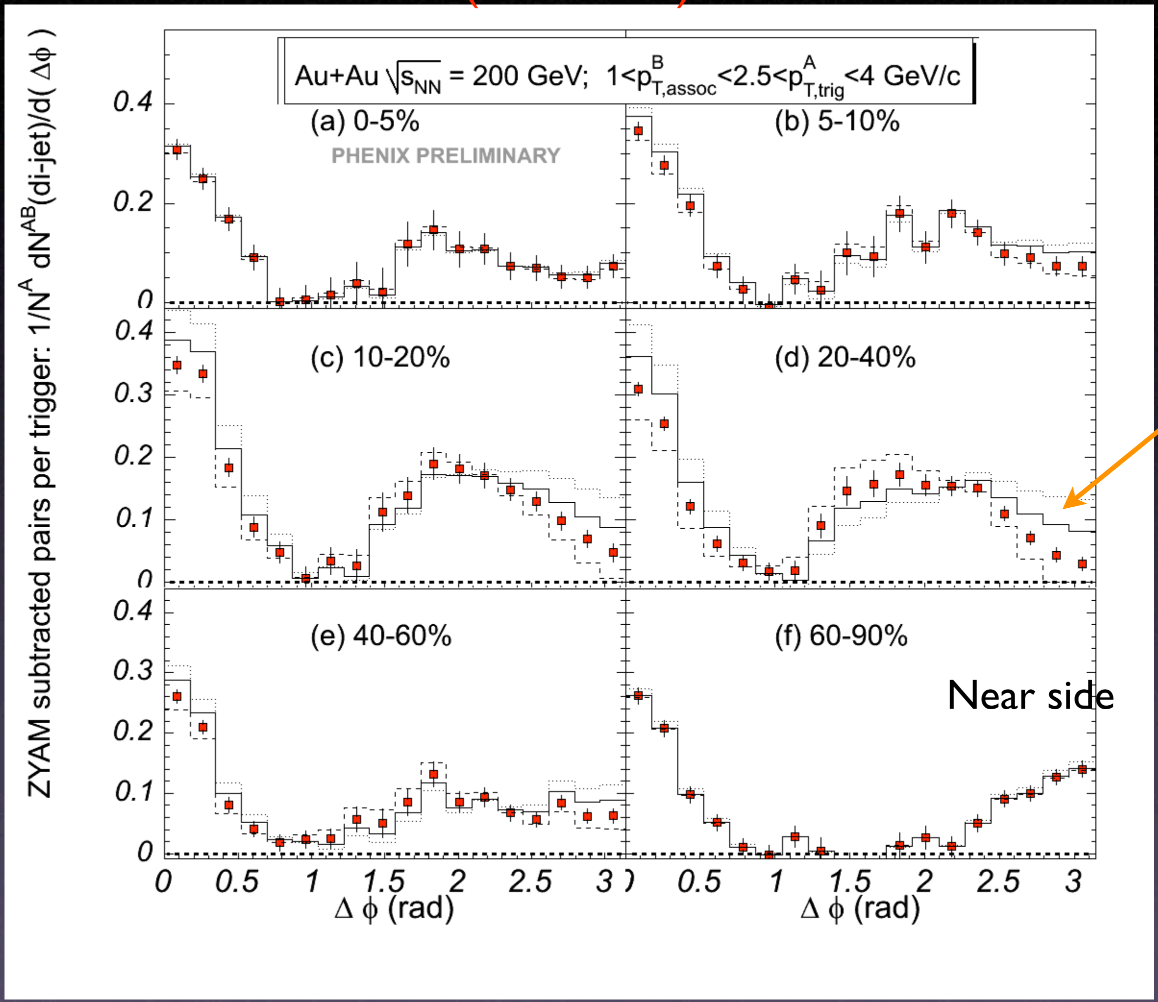


"Recombination can accommodate correlations, given the 'right' input"

Predictive power?

Correlations at not-so-high pT

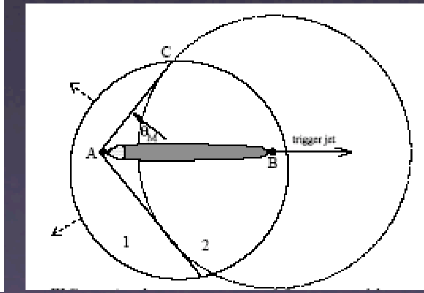
Paul Constantin (PHENIX)



Near side

Cone-Structure?

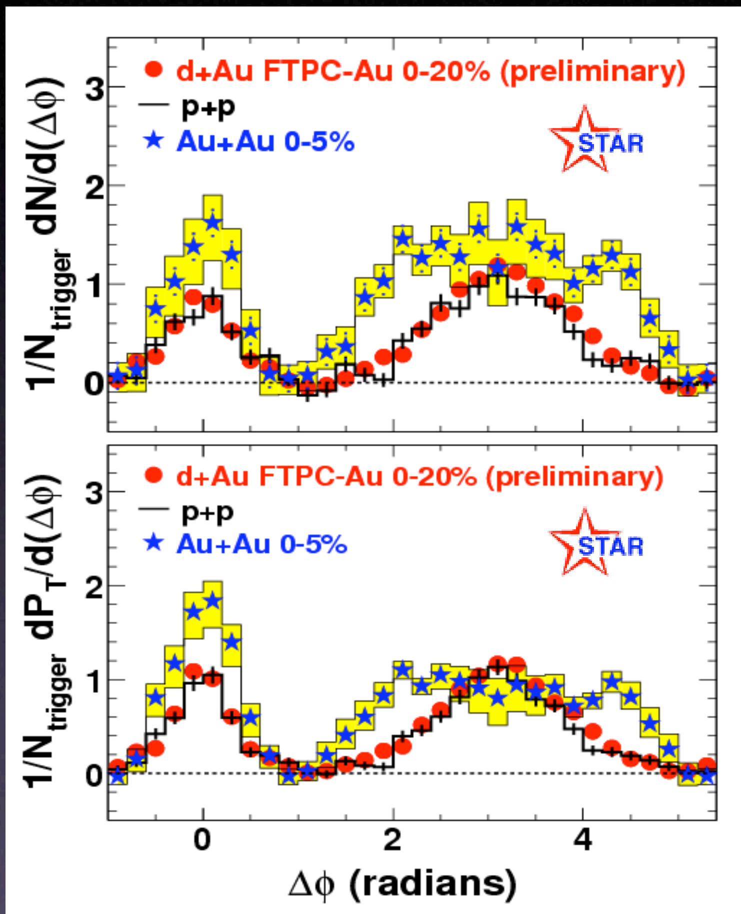
Sonic shock waves
Stoecker, nucl-th0406018
Casalderrey, Shuryak, Teaney, hep-ph/0411315

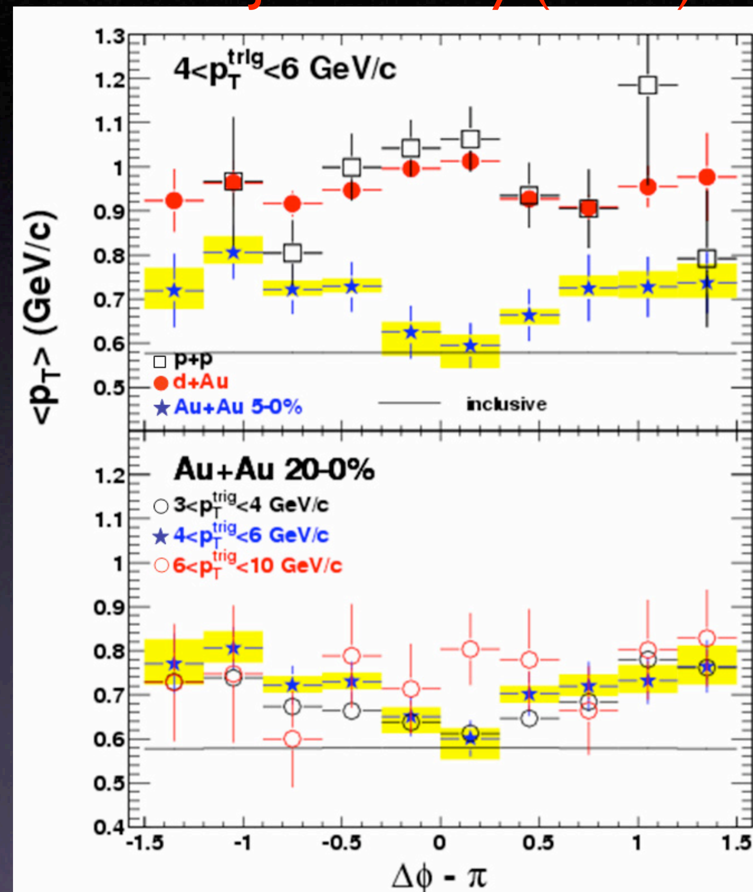


$\cos(\theta)=c_S$

Conical Flow

Jason Ulery (STAR)



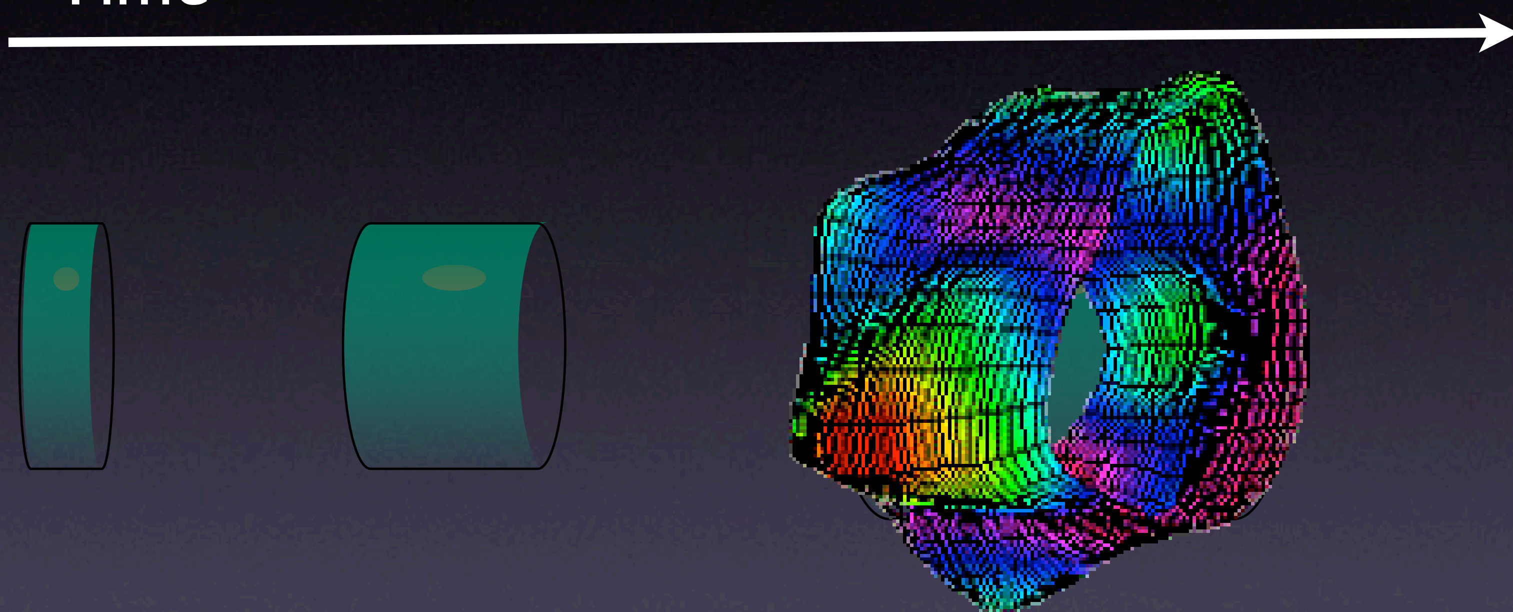


$4 < P_T$Trig< 6 GeV/c
$0.15 < P_T$Assoc< 4 GeV/c

p_T - Dependence?

Correlation Probes of the Medium

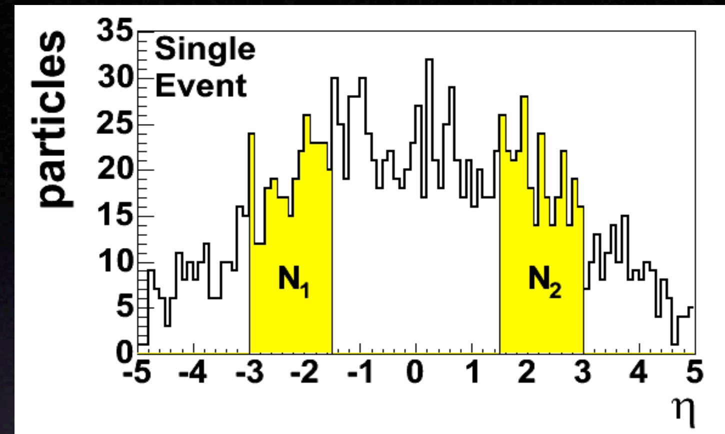
Time



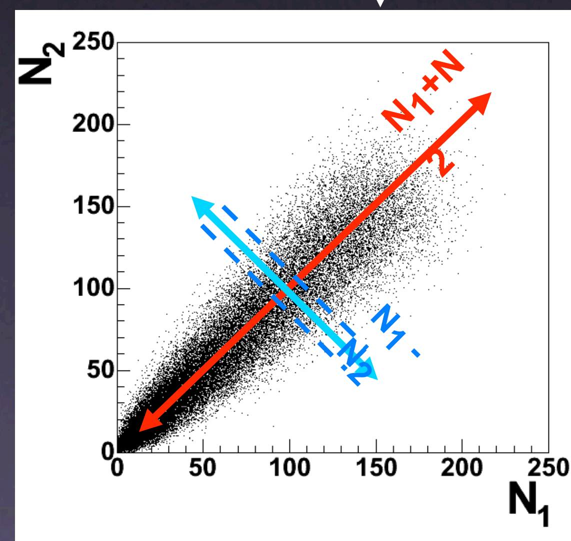
Lanny Ray, Tom Trainor
(STAR)

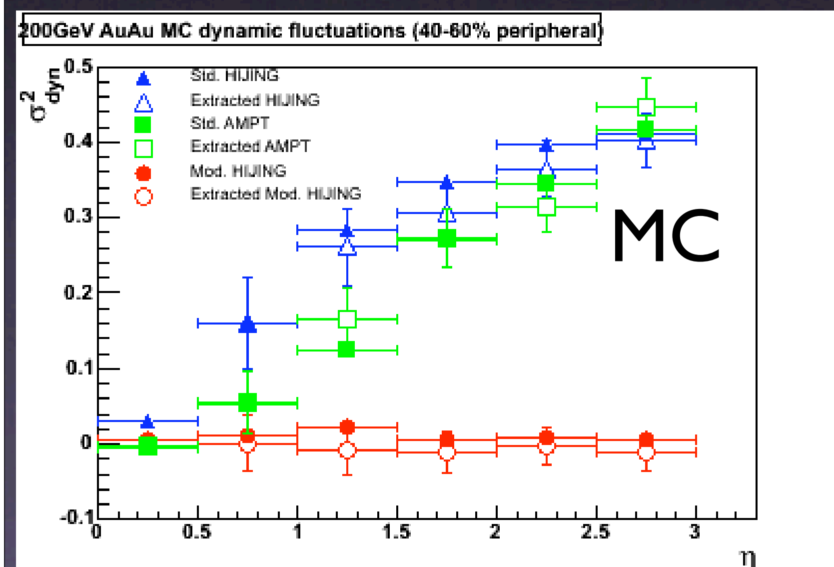
Multiplicity Fluctuations

Zhengwei Chai (PHOBOS)



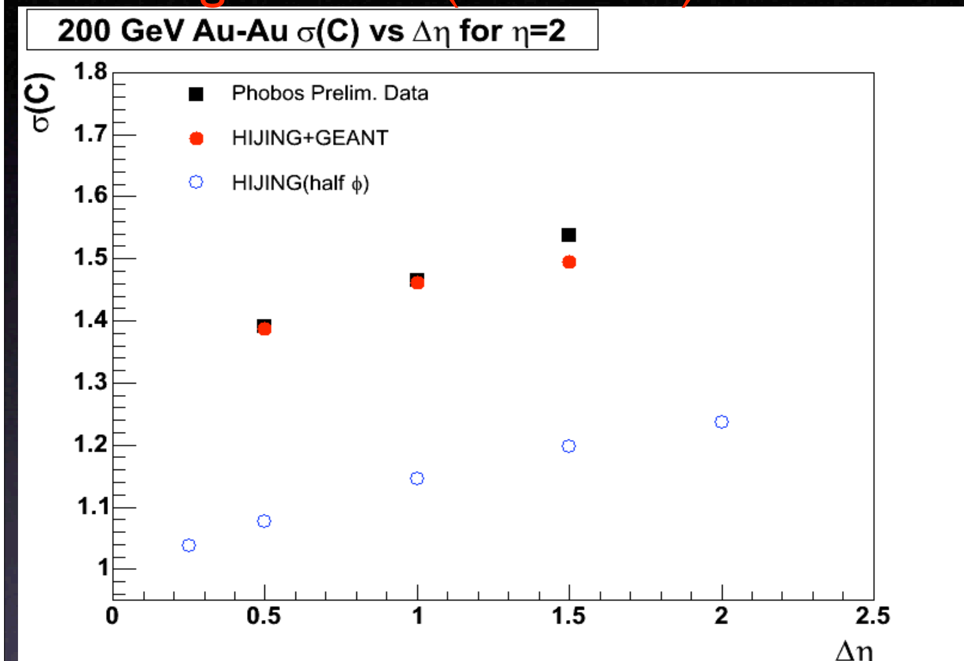
Multiplicity Fluctuations from forward/backward correlations



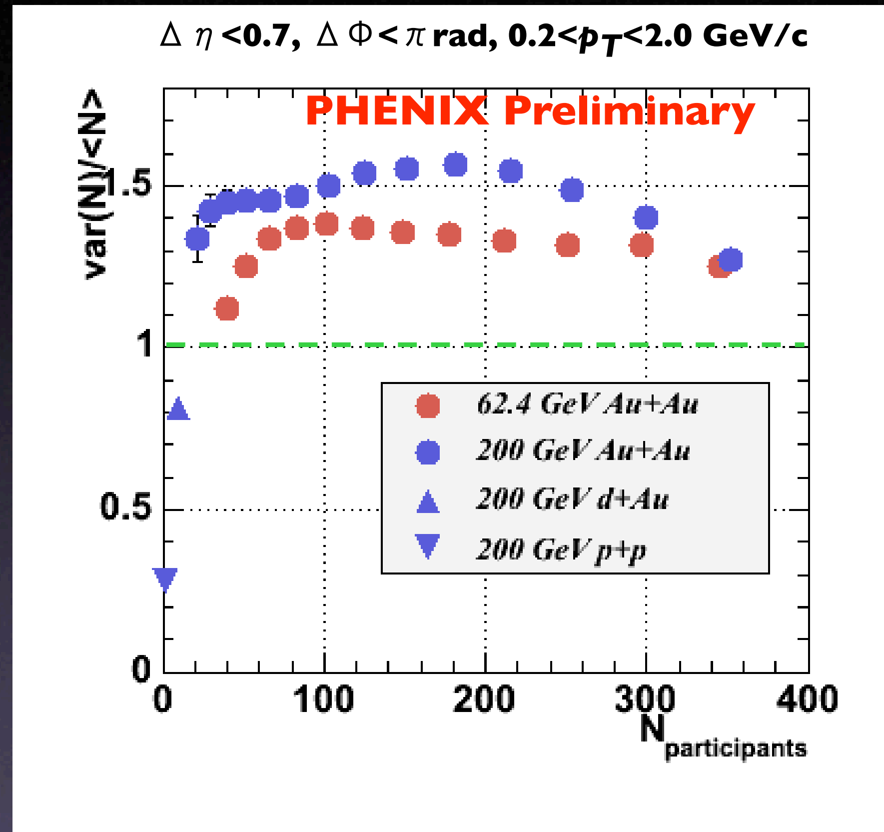


Multiplicity Fluctuations

Zhengwei Chai (PHOBOS)



Tomoaki Nakamura (PHENIX)

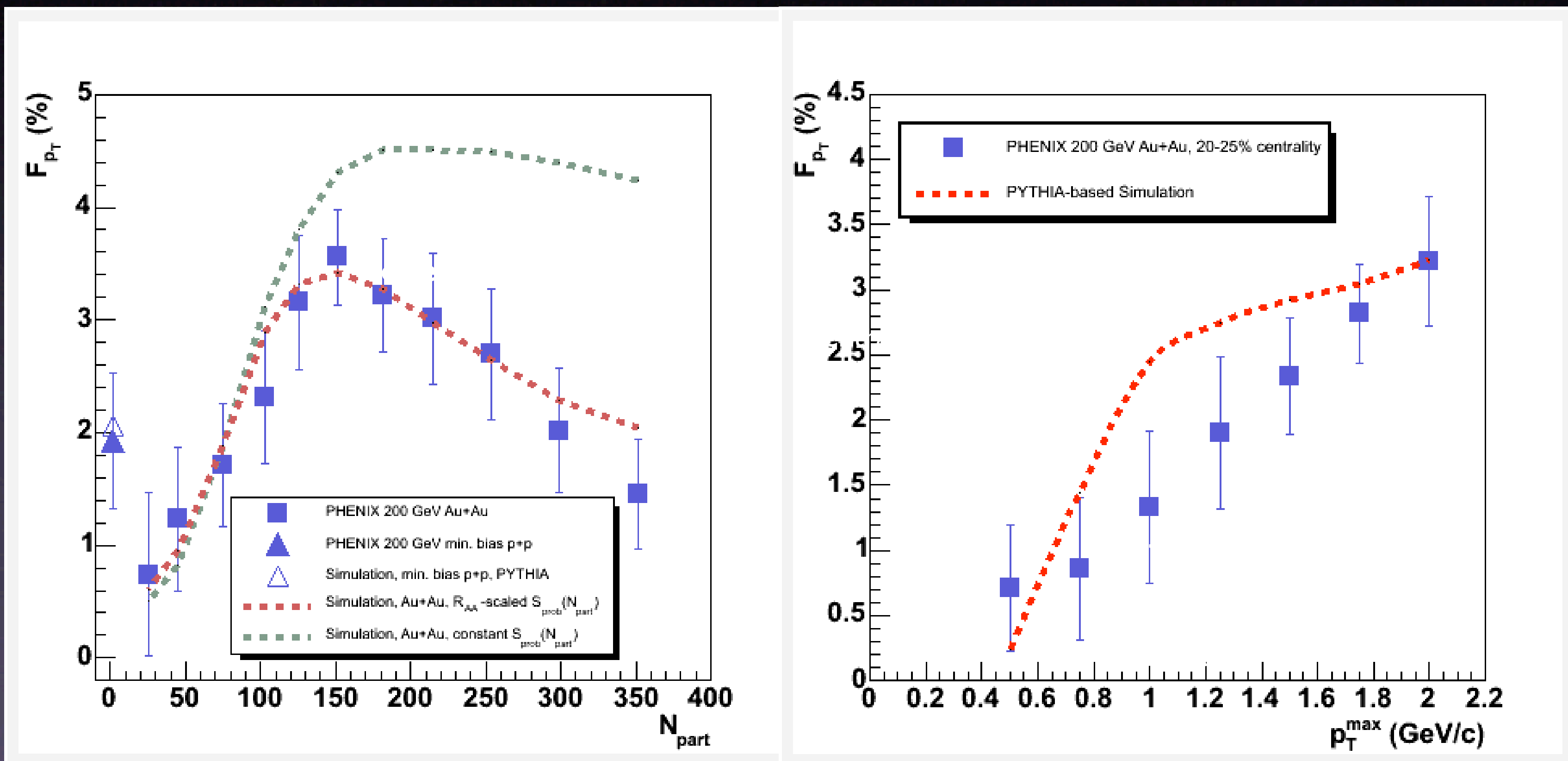


Large non-statistical Multiplicity Fluctuations

Many detailed studies by PHENIX

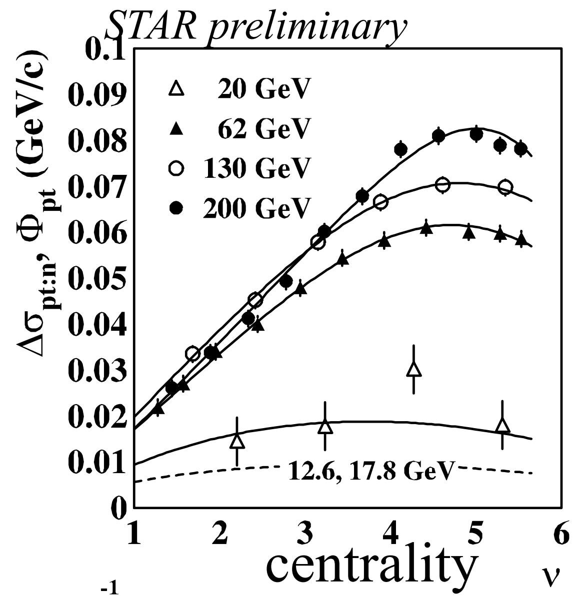
Jets and $\langle p_T \rangle$ Fluctuations

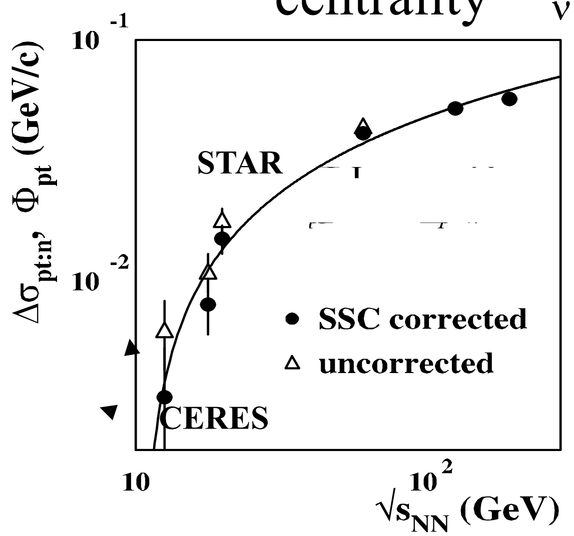
"PYTHIA based simulation, which contains scaled hard-scattering probability factor (S_{prob}) by the nuclear modification factor (R_{AA}), well agree with the measured F_{pT}. It might indicate that jet suppression might contribute to the average p_T fluctuation."



Tomoaki Nakamura (PHENIX)

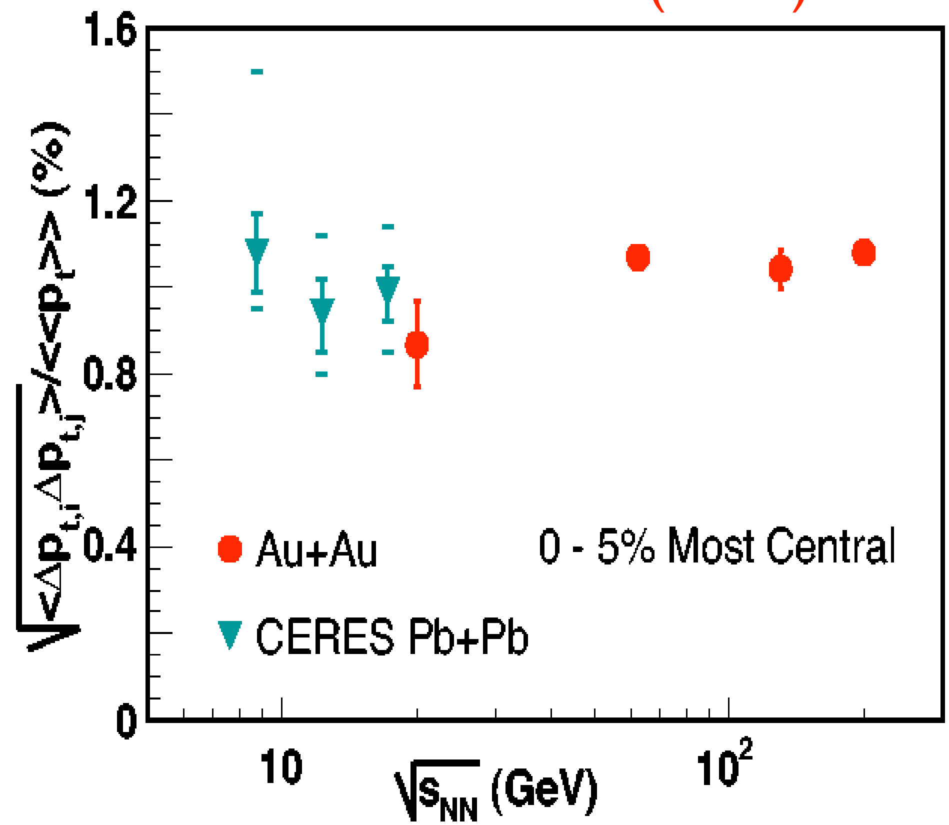
Energy Dependence?





Lanny Ray (STAR)

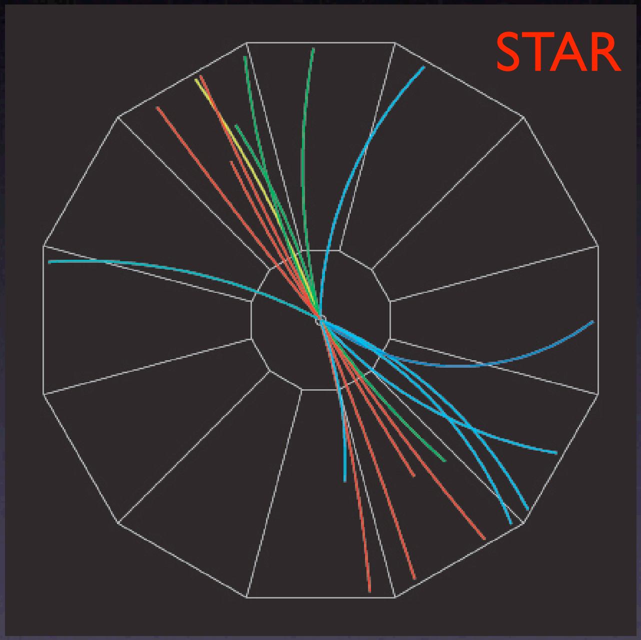
Claude Pruneau (STAR)



Normalization to <pT>?
Different sensitivity to large momentum scales

Correlations in p+p

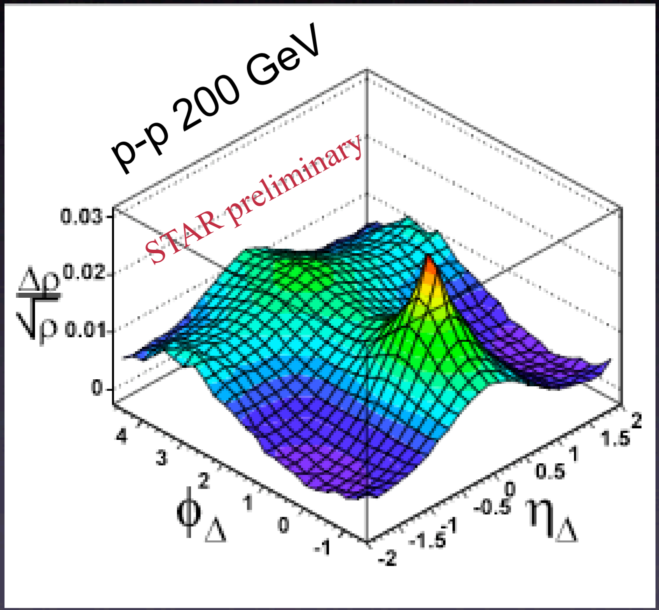
Seeing partons at high pT



Correlations in p+p

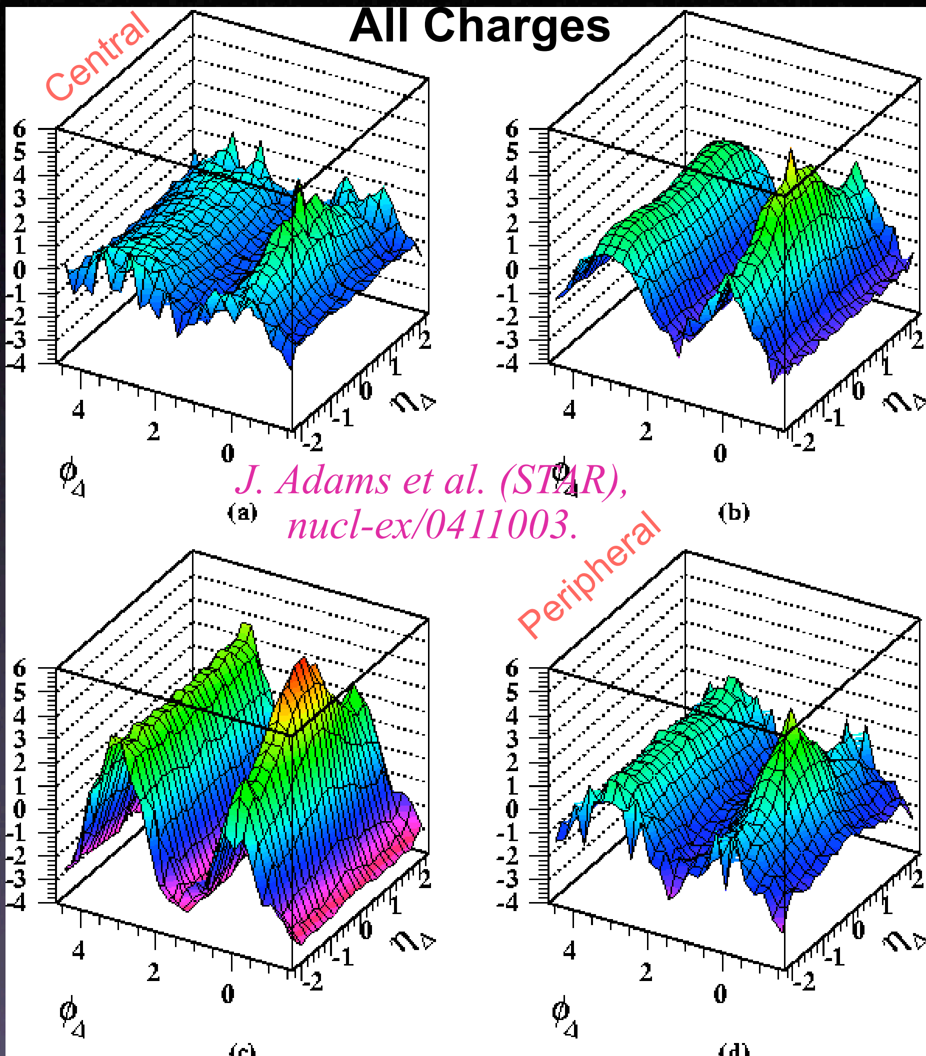
Soft Look at Partons

Lanny Ray (STAR)

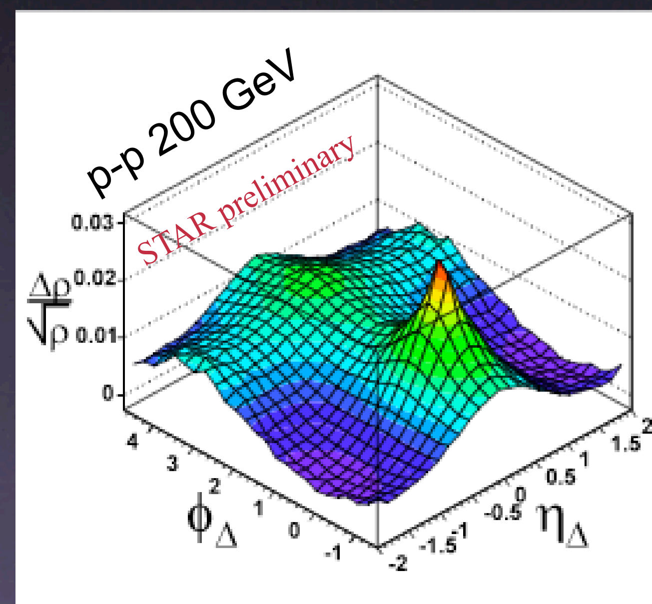


Two-particle angular correlations show rich structure at low to moderate p_T (~GeV/c)

From p+p to Au+Au

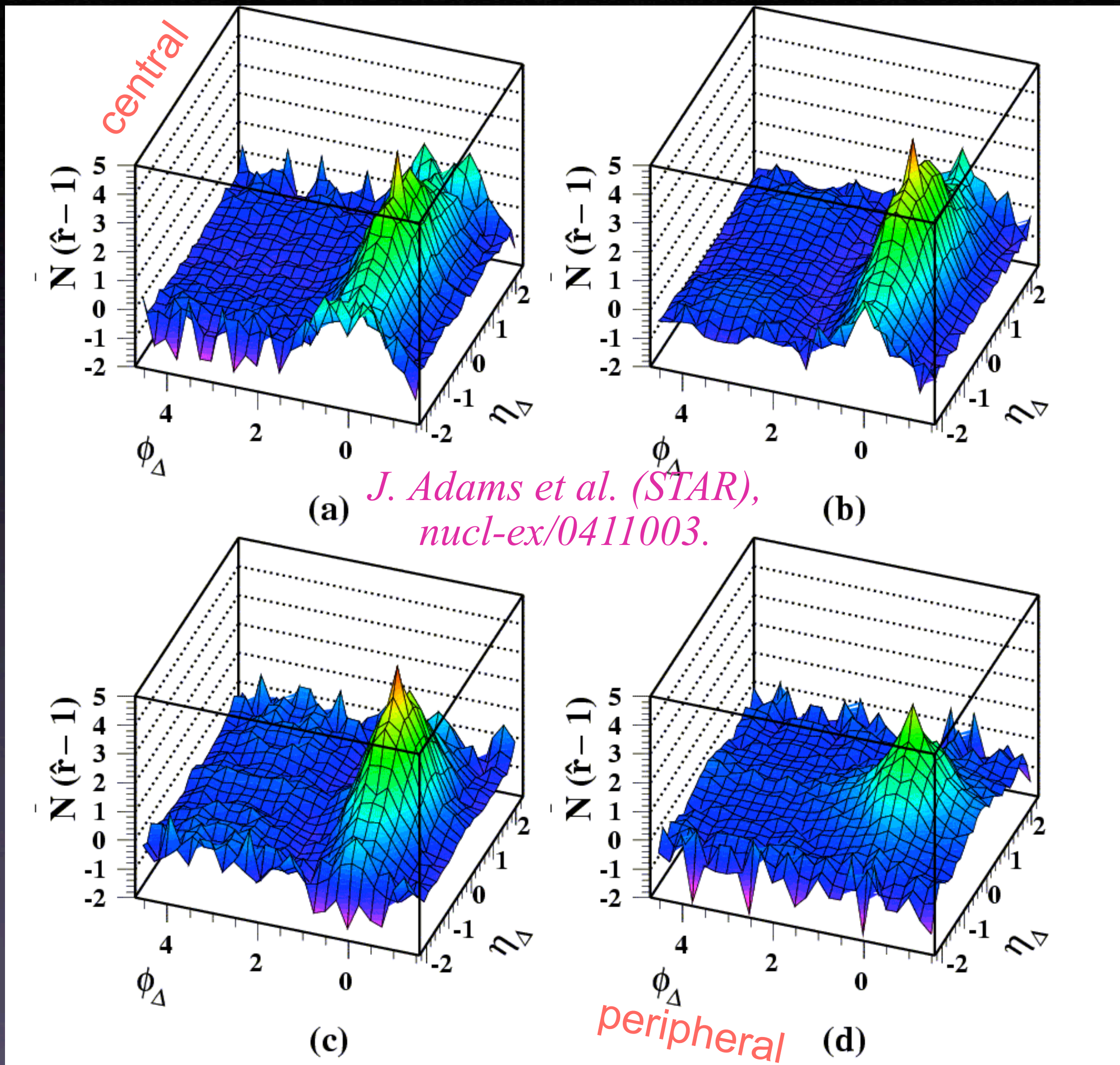


Evolution of Structure from p+p to central Au+Au



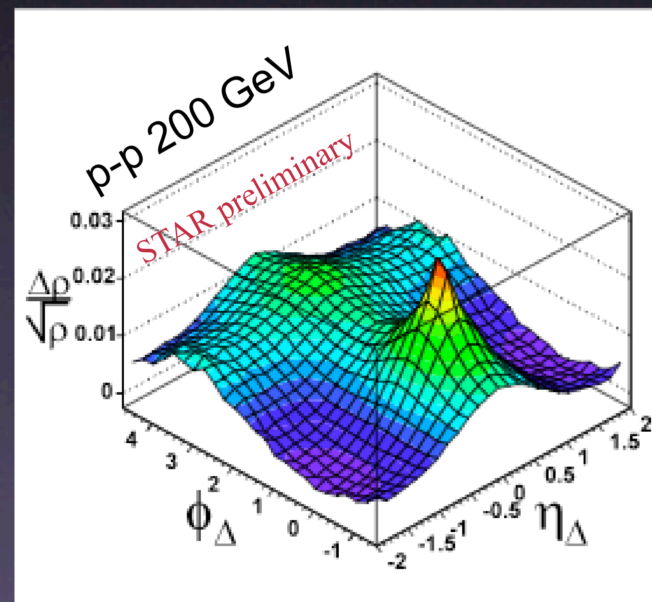
Lanny Ray (STAR)

From p+p to Au+Au



J. Adams et al. (STAR), nucl-ex/0411003.

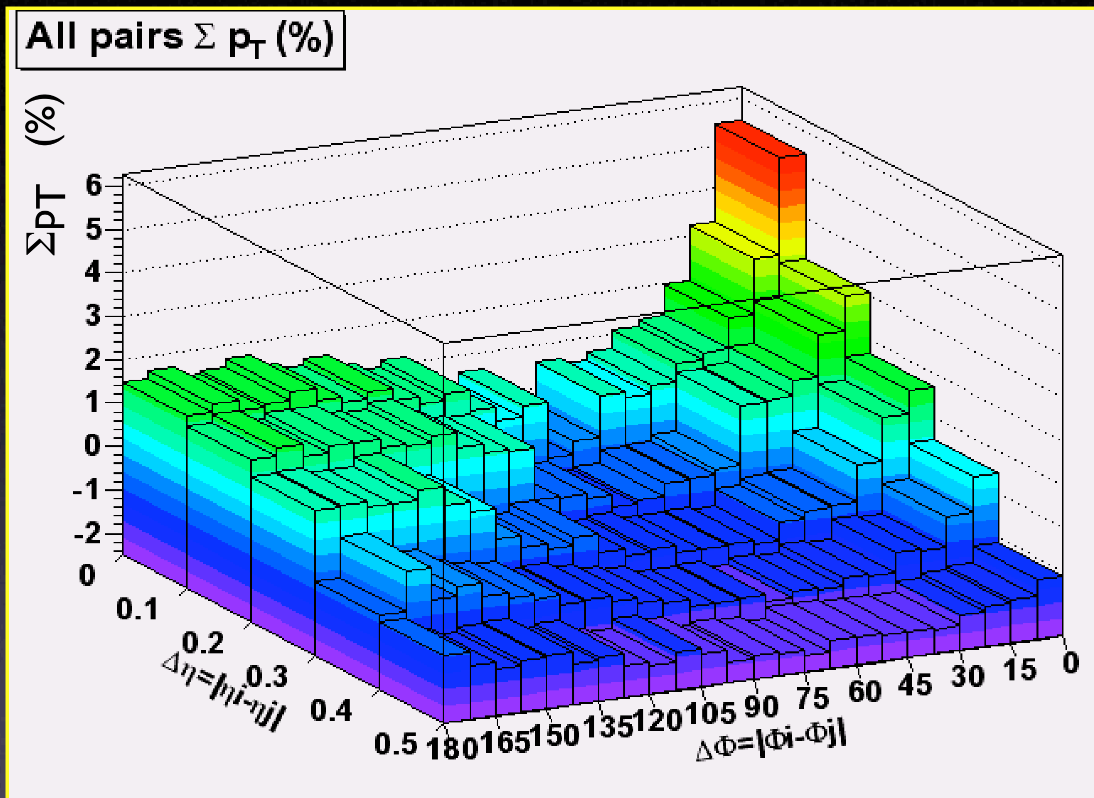
Evolution of Structure from p+p to central Au+Au



Lanny Ray (STAR)

Momentum Correlations at SPS

Georgios Tsiledakis (CERES)

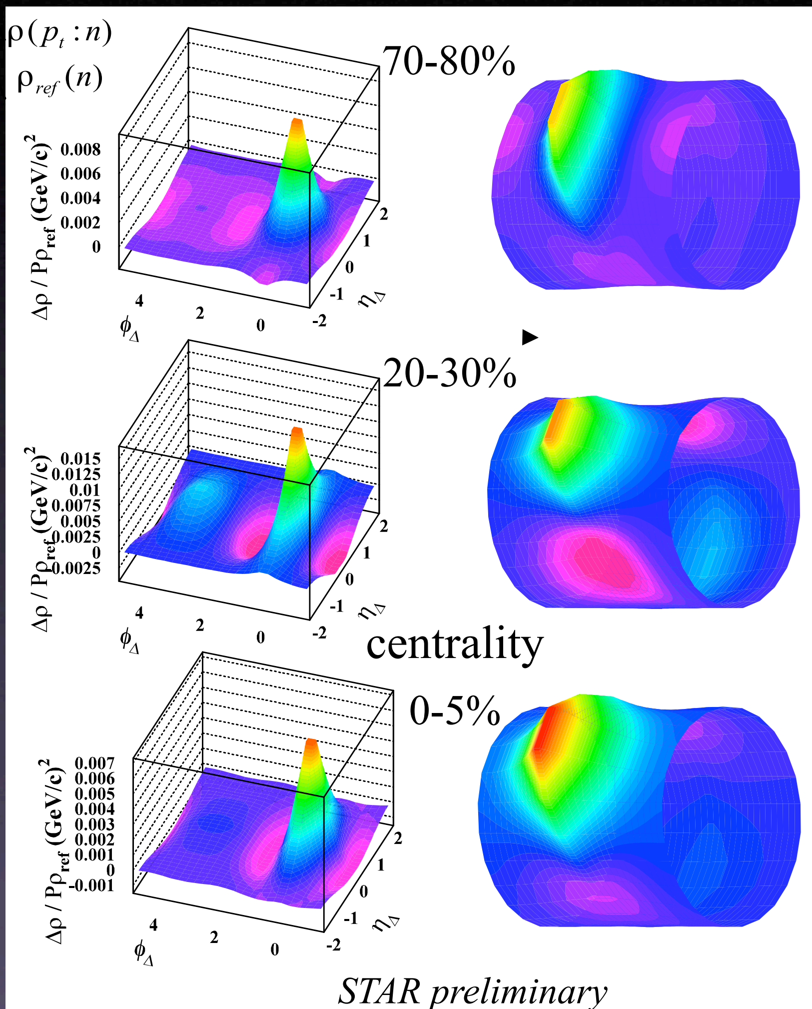


CERES
158 AGeV/c Pb-Au
Preliminary

$\Sigma p_T = 100 * (<\Delta p_{t,i}\, \Delta p_{t,j}>)^{1/2} / p_T<incl>$ (%)

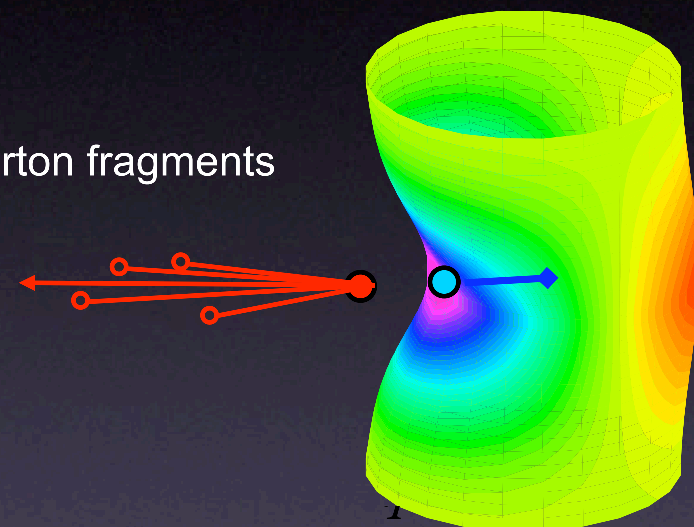
Angular Structure of Momentum Correlations seen at SPS

Momentum Correlations at RHIC



Subtract fragmentation peak to look at medium

parton fragments



bulk medium

"Minijets: *velocity/temperature* correlation structures on (η,φ)"

Lanny Ray (STAR)

Correlations in Transport Models

Molnar's Parton Cascade (MPC)

Elementary processes: elastic $2 \to 2$ processes + $gg \leftrightarrow q\bar{q}$, $q\bar{q} \to q'\bar{q}'$ + $ggg \leftrightarrow gg$

Equation for $f^i(x,\vec{p})$: $i = \{g, d, \bar{d}, u, \bar{u}, \ldots\}$

$$
\begin{aligned}
p_1^\mu \partial_\mu \tilde{f}^i(x,\vec{p}_1) = \; & \frac{\pi^4}{2} \sum_{jkl} \int_2\!\!\int_3\!\!\int_4 \left(\tilde{f}_3^k \tilde{f}_4^l - \tilde{f}_1^i \tilde{f}_2^j \right) \left| \bar{\mathcal{M}}_{12\to34}^{i+j\to k+l} \right|^2 \delta^4(12-34) \quad \swarrow 2\to2 \\
& + \frac{\pi^4}{12} \int_2\!\!\int_3\!\!\int_4\!\!\int_5 \left(\frac{\tilde{f}_3^i \tilde{f}_4^i \tilde{f}_5^i}{g_i} - \tilde{f}_1^i \tilde{f}_2^i \right) \left| \bar{\mathcal{M}}_{12\to345}^{i+i\to i+i+i} \right|^2 \delta^4(12-345) \quad \swarrow 2\leftrightarrow3 \\
& + \frac{\pi^4}{8} \int_2\!\!\int_3\!\!\int_4\!\!\int_5 \left(\tilde{f}_4^i \tilde{f}_5^i - \frac{\tilde{f}_1^i \tilde{f}_2^i \tilde{f}_3^i}{g_i} \right) \left| \bar{\mathcal{M}}_{45\to123}^{i+i\to i+i+i} \right|^2 \delta^4(123-45) \quad \swarrow 3\leftrightarrow2 \\
& + \tilde{S}^i(x,\vec{p}_1) \quad \leftarrow \text{initial conditions}
\end{aligned}
$$

with shorthands:

$$\tilde{f}_i^q \equiv (2\pi)^3 f_q(x,\vec{p}_i), \quad \int_i \equiv \int \frac{d^3p_i}{(2\pi)^3 E_i}, \quad \delta^4(p_1+p_2-p_3-p_4) \equiv \delta^4(12-34)$$

advantage of transport approach :

bulk dynamics (v_2) and jets in same framework

HERE: study jet correlations on parton level (before hadronization)

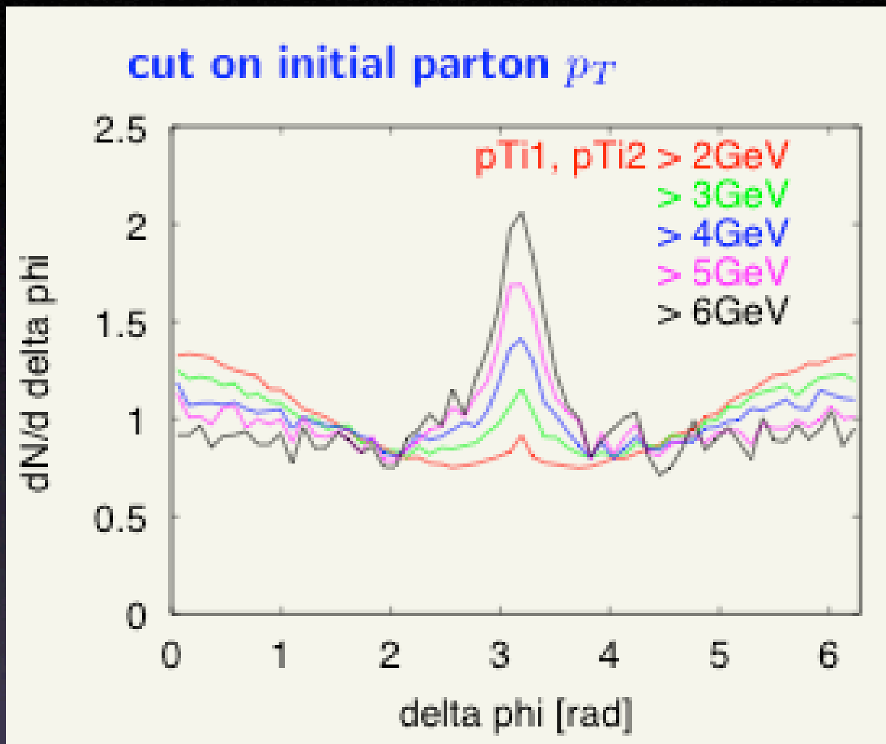
initial conditions: back-to-back dijets above $p_T > 2$ GeV
uncorrelated soft partons below $p_T < 2$ GeV

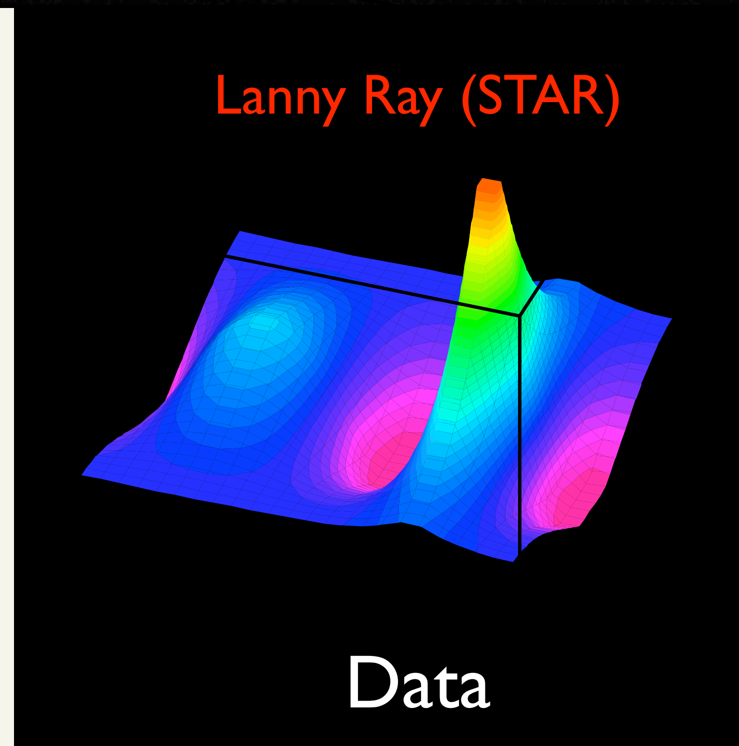
Au+Au @ 200 GeV, $b = 8$ fm - same as for charm study DM '04

Denes Molnar

RHIC AGS users' group

Correlations in Transport Models





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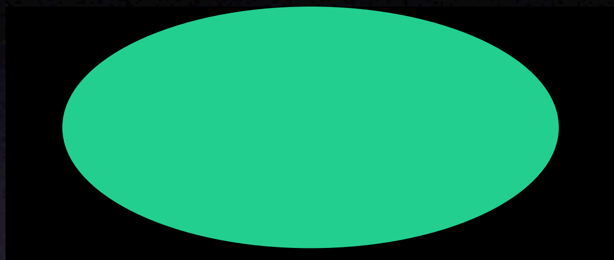
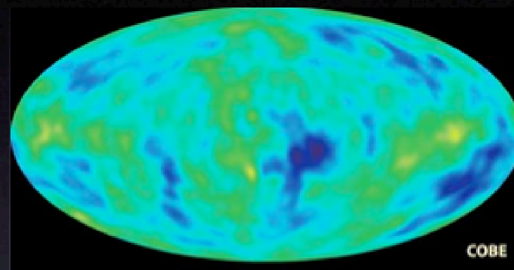
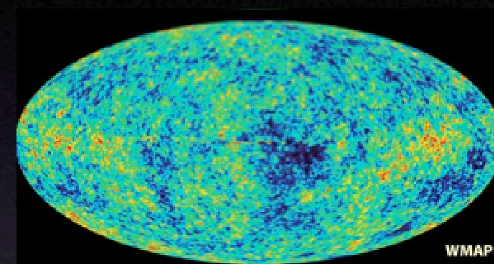
- This is the first study of jet correlations that treats the bulk sector and jets in the same framework. The results are encouraging but need several improvements:
  - add soft partons ("push" effect will contribute)
  - study centrality, particle type dependence (higher statistics)
  - include hadronization (coalescence, fragmentation)
  - extend to radiative processes, coherence
  - could also study other correlations, e.g., Mach cone ...

Analogy: Cosmic Microwave Background

Cosmic microwave background







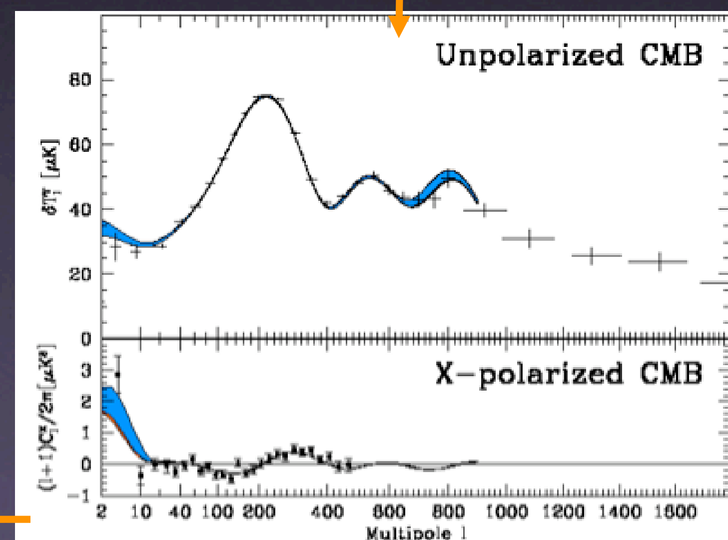
Penzias, Wilson 1964

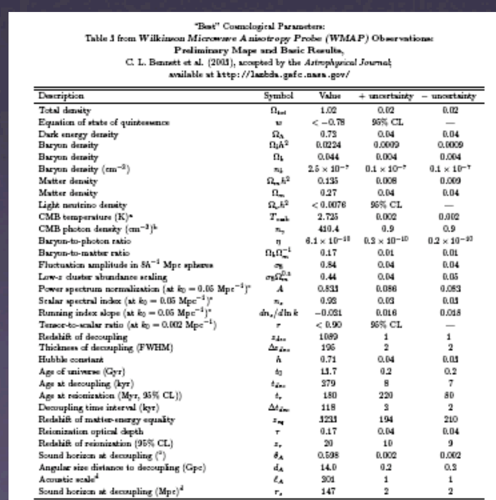
$<T>=3K$

COBE 1992

$\Delta T/T \sim 10^{-5}$

WMAP et al. 2003



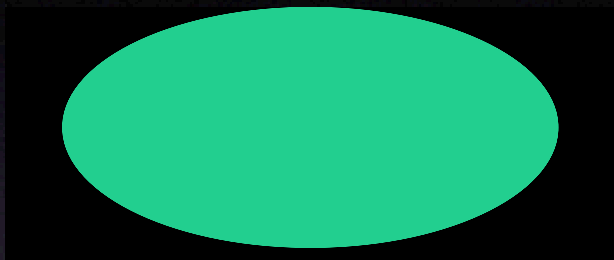


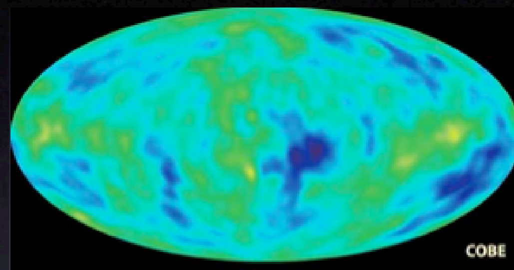
"Best" Cosmological Parameters:
Table 1 from *Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results*,
C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*;
available at http://lambda.gsfc.nasa.gov/

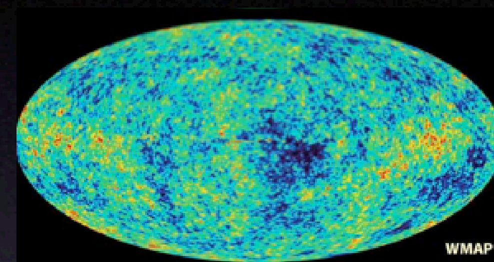
Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05$ Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05$ Mpc^{-1})[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05$ Mpc^{-1})[c]	$dn_s/d\ln k$	−0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc^{-1})	r	< 0.90	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL))	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular size distance to decoupling (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2

Analogy: Cosmic Microwave Background

Cosmic microwave background







Penzias, Wilson 1964

COBE 1992

WMAP et al. 2003

We are about here -
a long way to go!