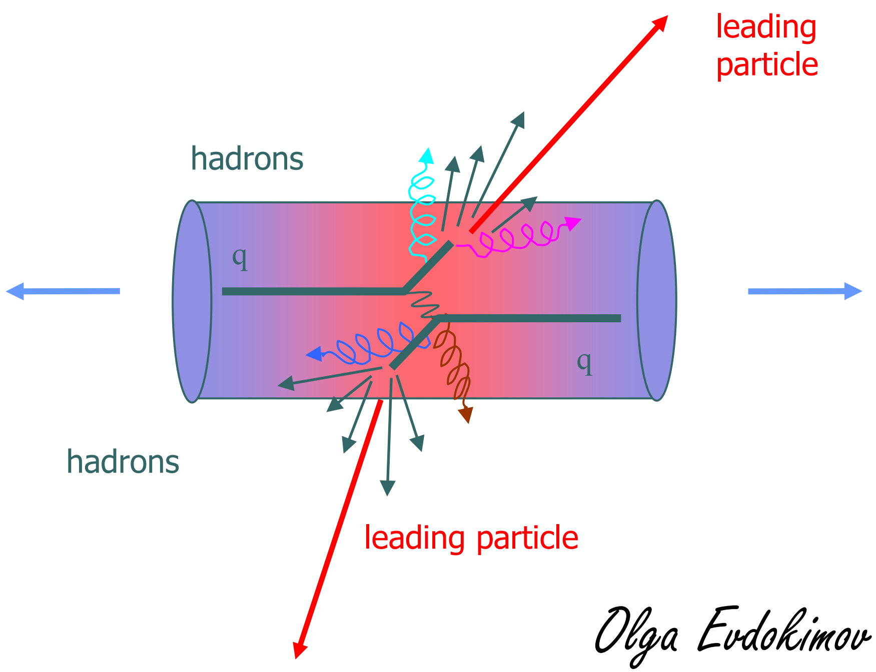
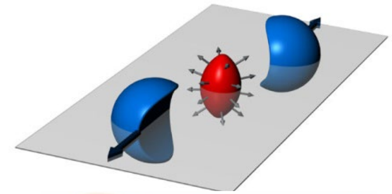
Correlations for Jet Probes of Quark-Gluon Plasma

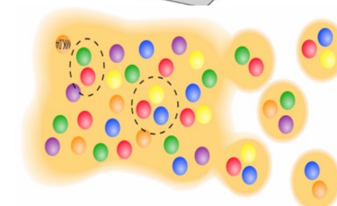


Olga Evdokimov

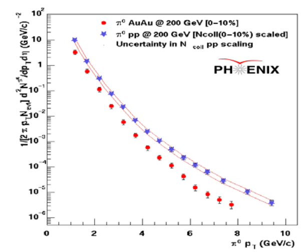
University of Illinois at Chicago

(some) RHIC Discoveries

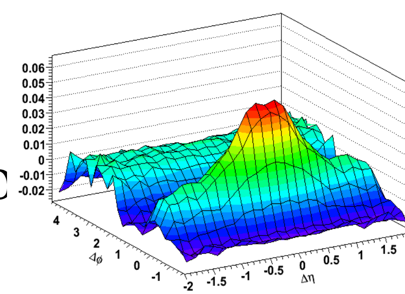




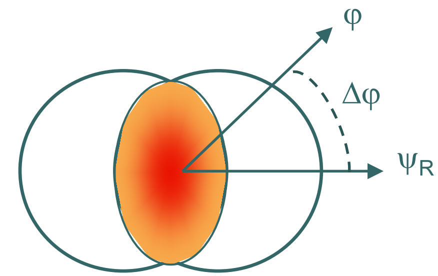
- Strongly interacting medium with partonic degrees of freedom
  - Strong collective flow
  - Constituent number scaling



- Jet quenching
  - “Missing” high-p_T hadrons
  - Novel “landscape” in hadron correlatic



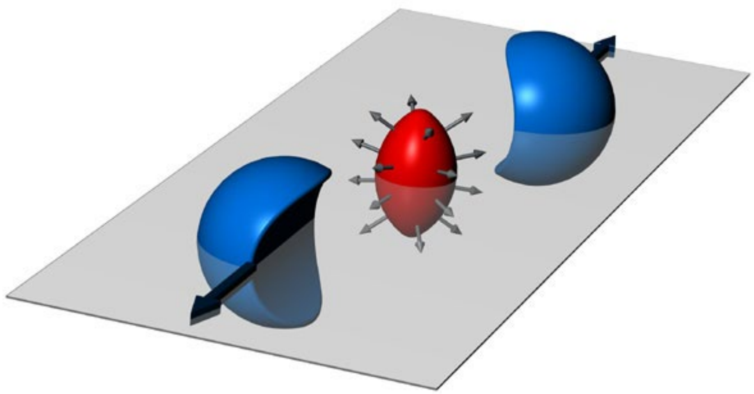
Elliptic Flow

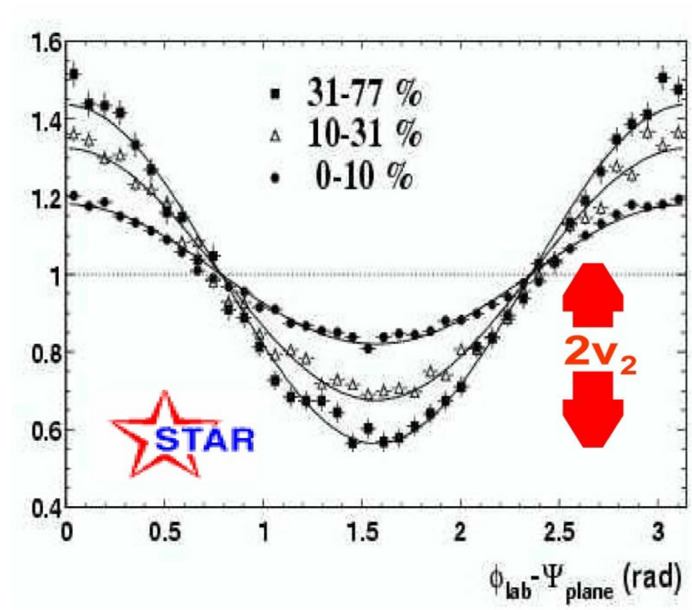


Fourier expansion for angular distributions:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos(n\Delta\varphi)\right)$$

v_2 - elliptic flow



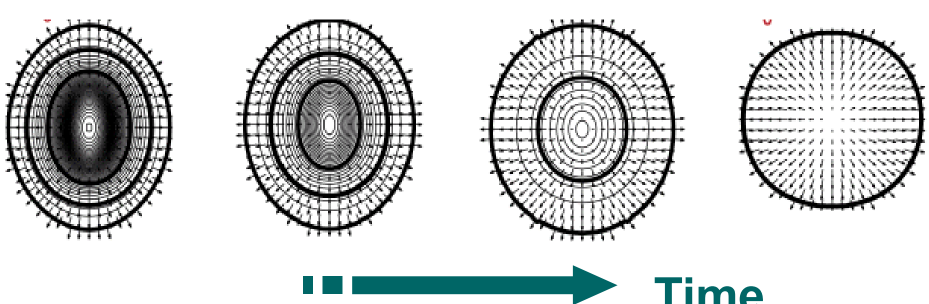


Initial state spatial anisotropy

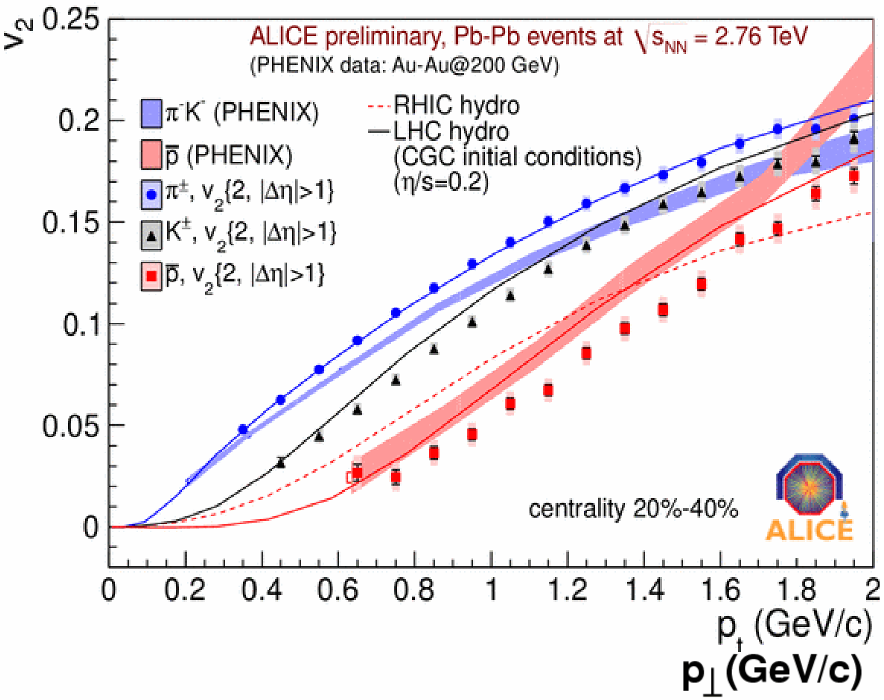
→ Pressure gradient anisotropy

→ Final state momentum anisotropy

Elliptic flow is developed at early stage



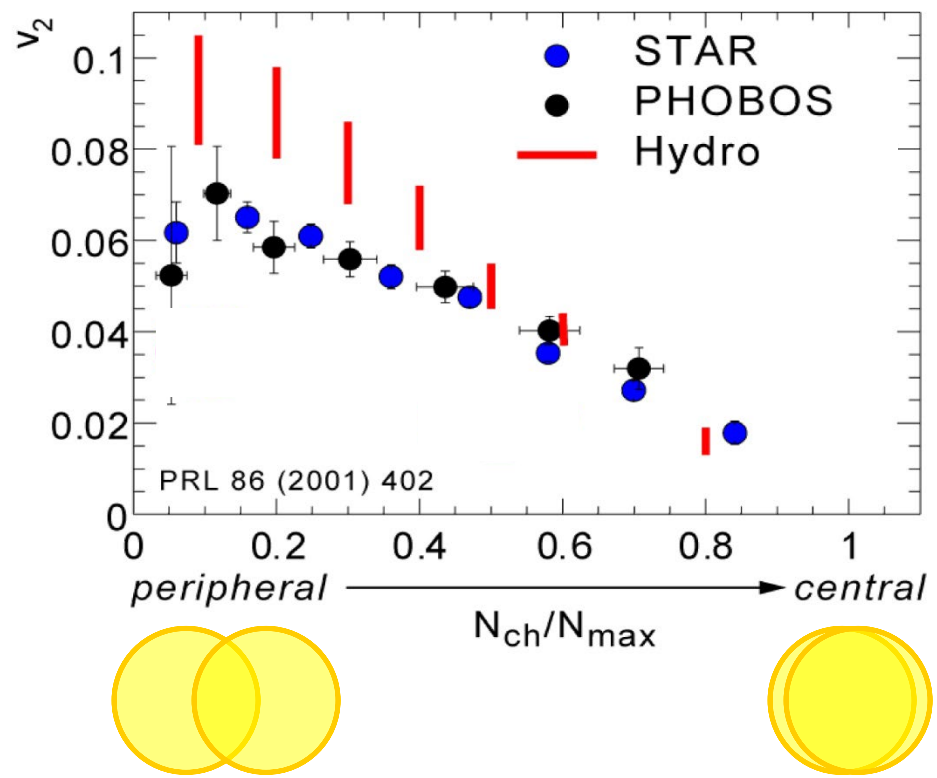
Perfect Fluid



$v_2(p_t)$ and mass dependence - best described by **ideal** hydrodynamics!

Ideal hydro → "Perfect" liquid:

equilibrium, zero mean free path, low viscosity

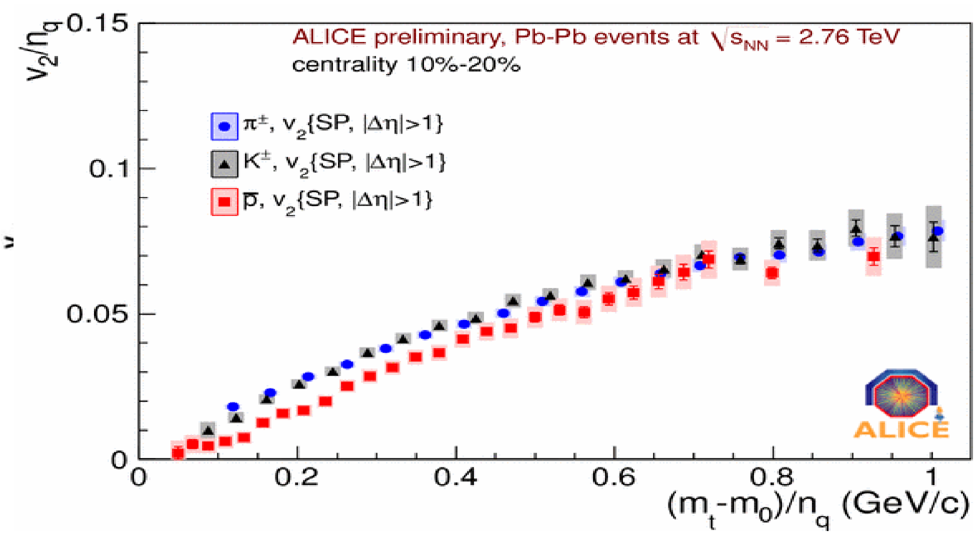


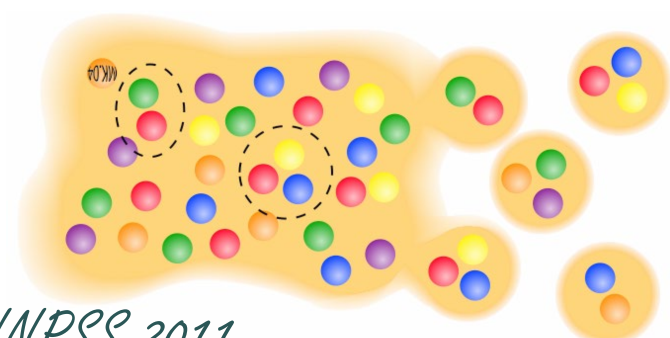
Note: strange, multi-strange, charm hadrons -- flow!

Partonic Degrees of Freedom

Pressure gradients converting work into kinetic energy

$$KE_T = m(\gamma_T - 1) = m_T - m$$



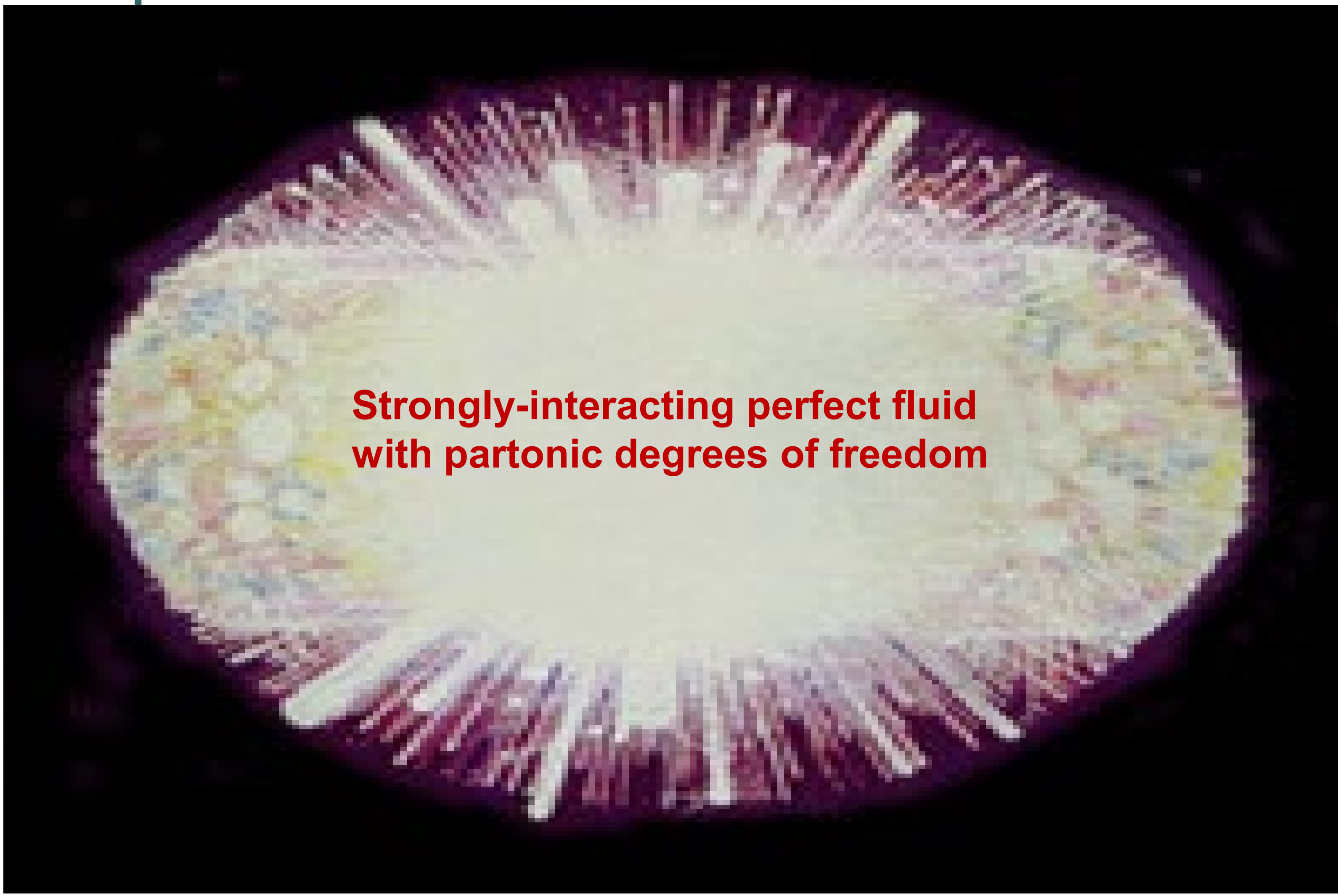


v2 appears to scale with the number of constituent quarks.

→

Quark coalescence

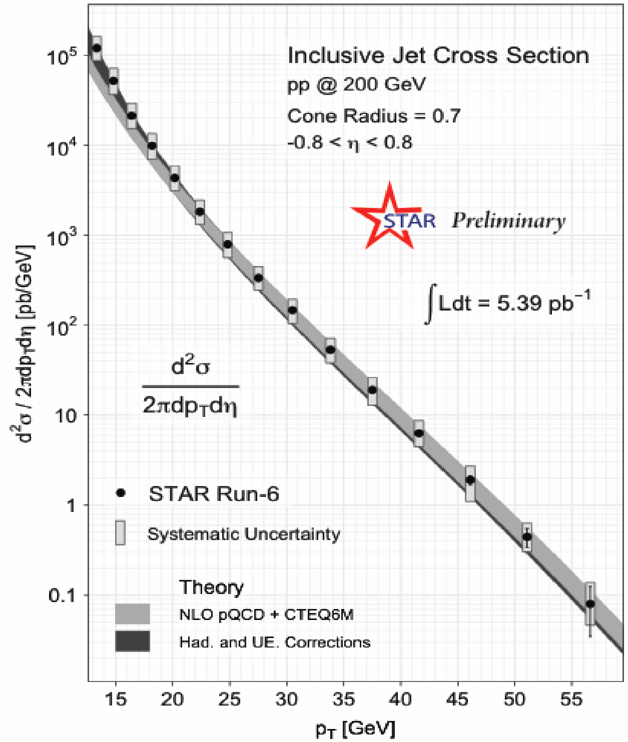
Hard Probes for QGP



ts)!

Hard Probes

“Hard” == large scale → suitable for perturbative QCD



high momentum transfer Q^2

high transverse momentum p_T

high mass m

– **Hard probes = PDF ⊗ pQCD ⊗ FF**

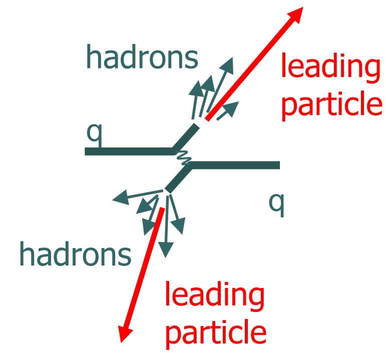
(PDF: non-perturbative; pQCD: perturbative; FF: non-perturbative)

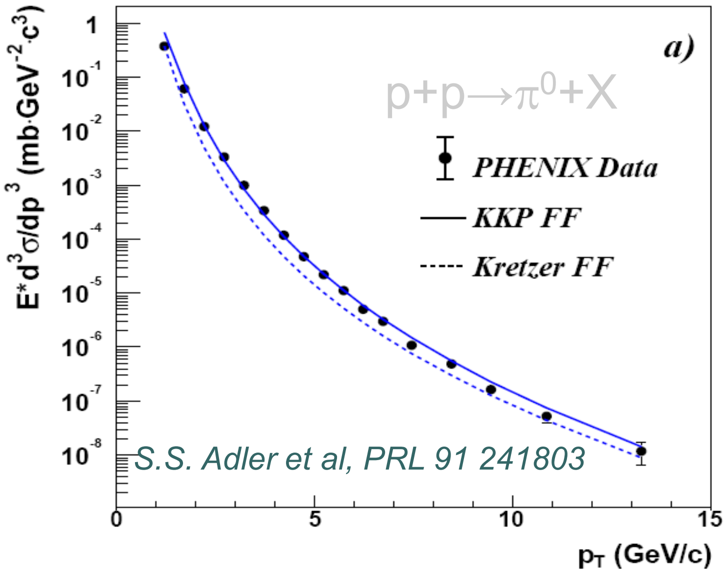
Assumptions:

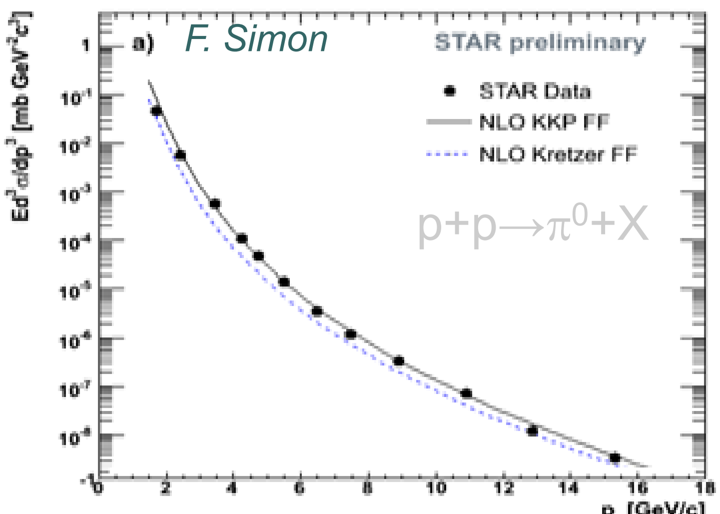
Factorization assumed between the perturbative and non-perturbative parts

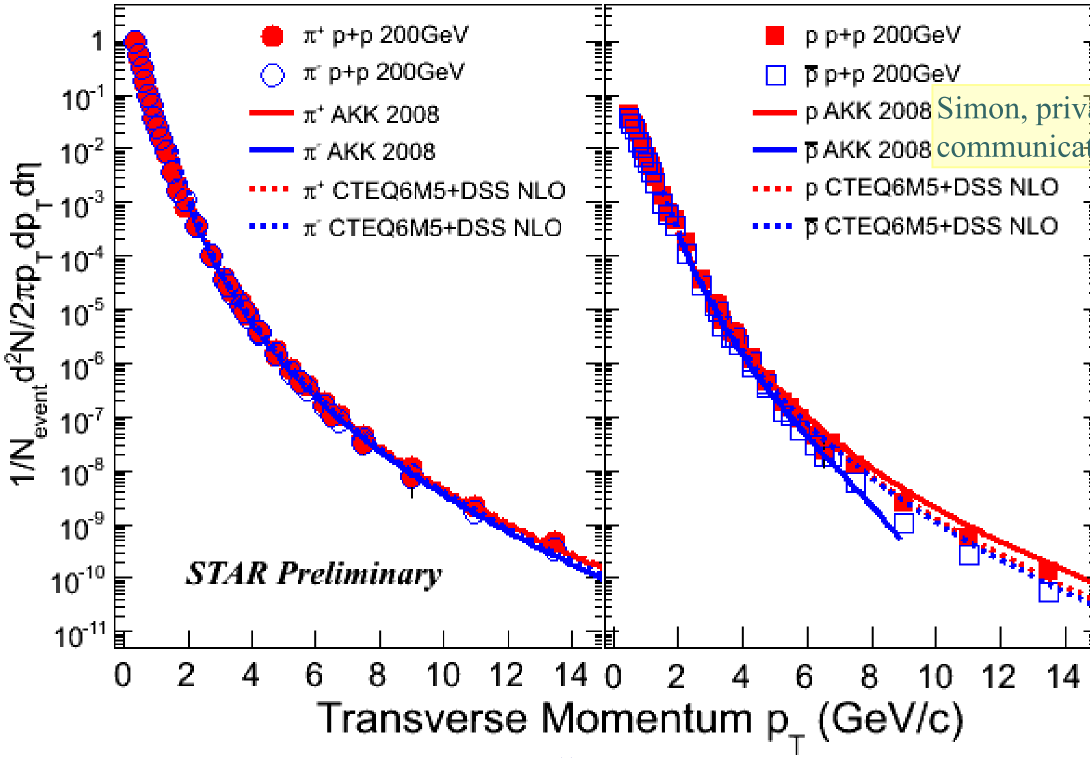
Universal fragmentation and parton distribution functions

The reference









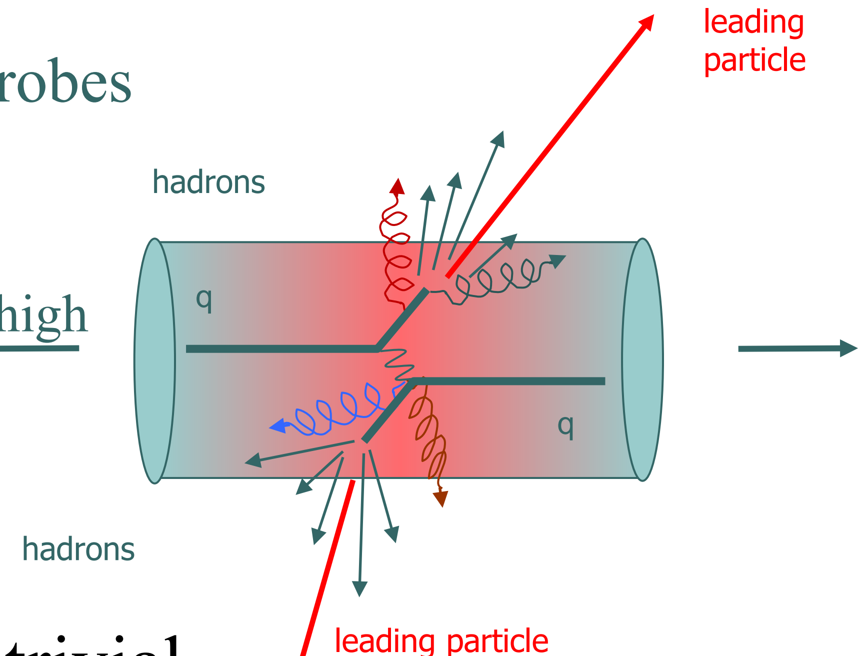
Simon, private communication

KKP: B. Kniehl, G. Kramer, P ¨ otter, Nucl. Phys. **B597**, 337 (2001)
AKK: S. Albino, B Kniehl, G. Kramer, **arXiv: 0803.2768v2**
DSS: D. de Florian, W. Vogelsang, F. Wagner, **arXiv: 0708.3060v3**

Medium properties via jets

Jet Tomography: calibrated (?) probes

What happens if partons traverse a high energy density colored medium?

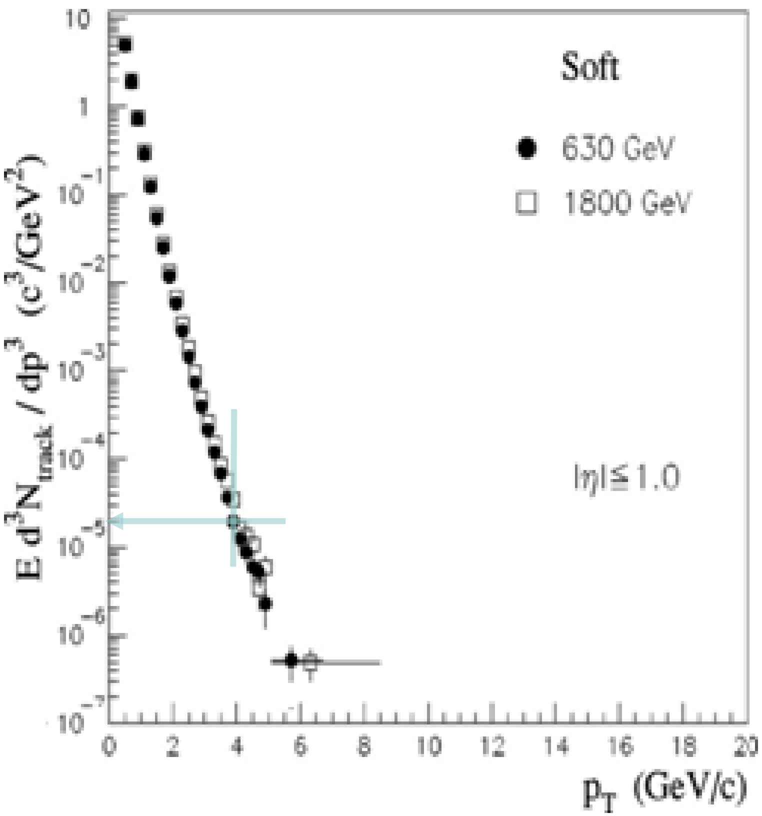


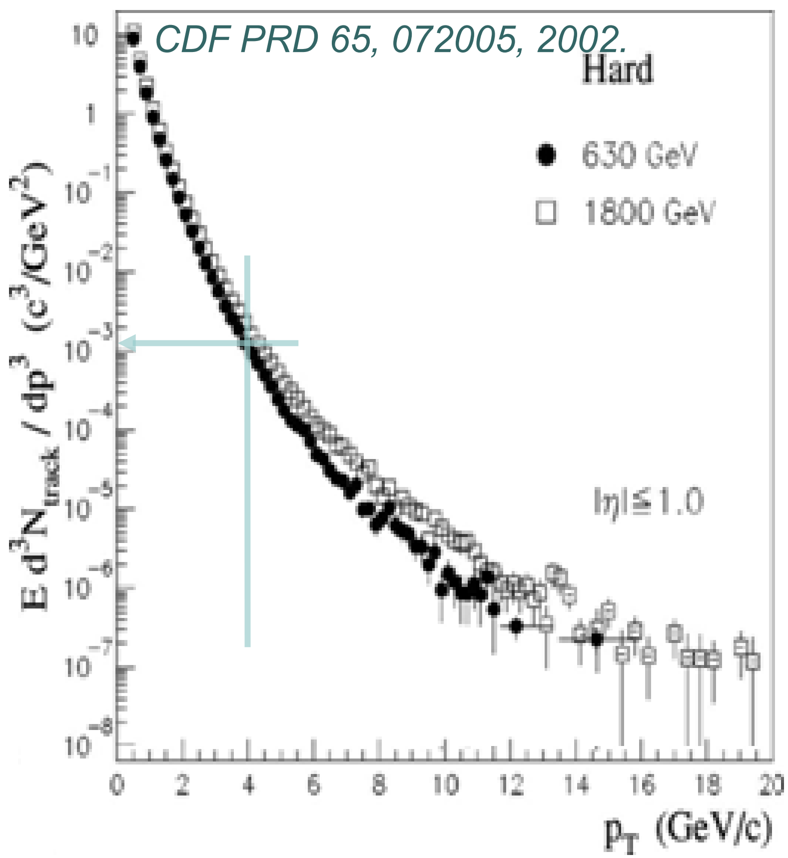
- Energy loss mechanisms
- Path length effects → non-trivial:
- Flavor/color-charge dependence of parton-medium coupling
- In-medium fragmentation/ hadronization

→Hard probes!

Define "hard"

In *pp*: inclusive cross-section is dominated by jet production above ~4 GeV/*c*



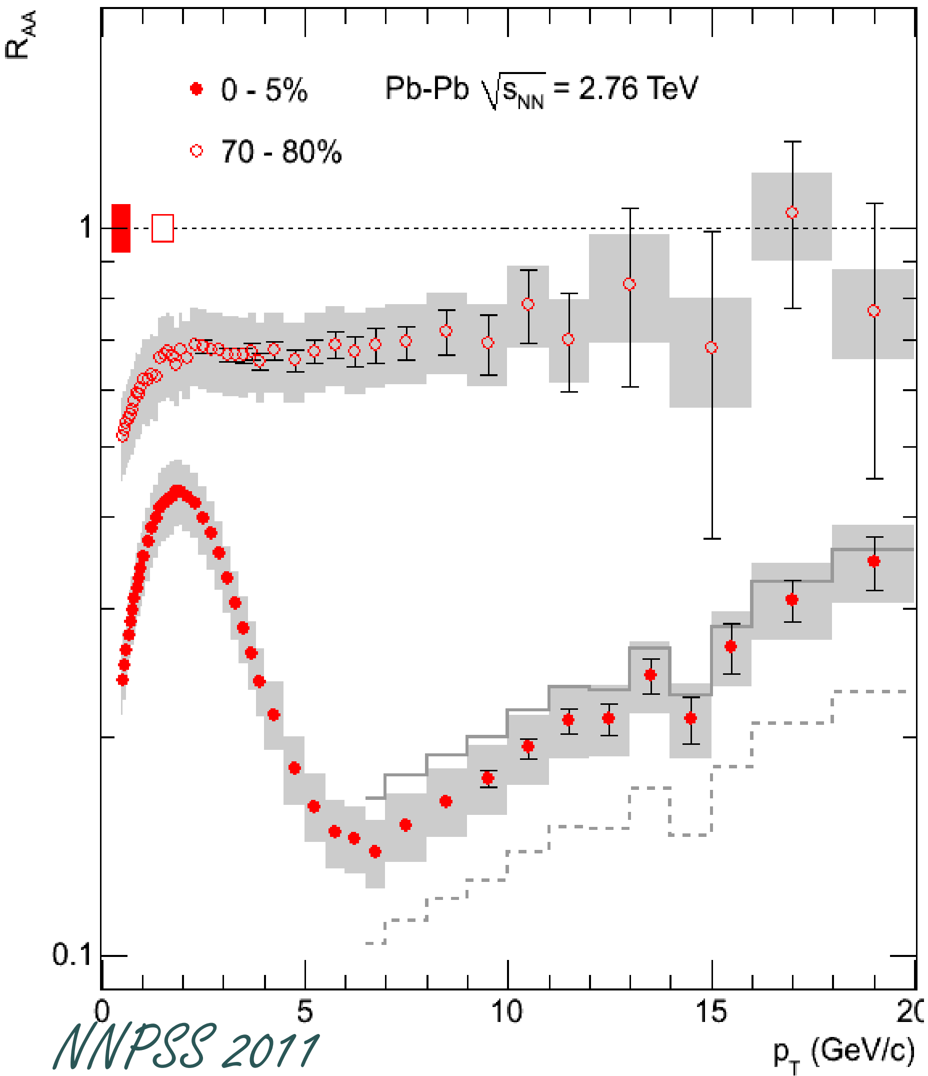


What about RHIC/LHC matter? Probably, > 6GeV/c

(but soft part cannot be dropped)

QGP101-Jets are quenched

ALICE PLB 696 (2011) 30-39



Nuclear Modification Factors

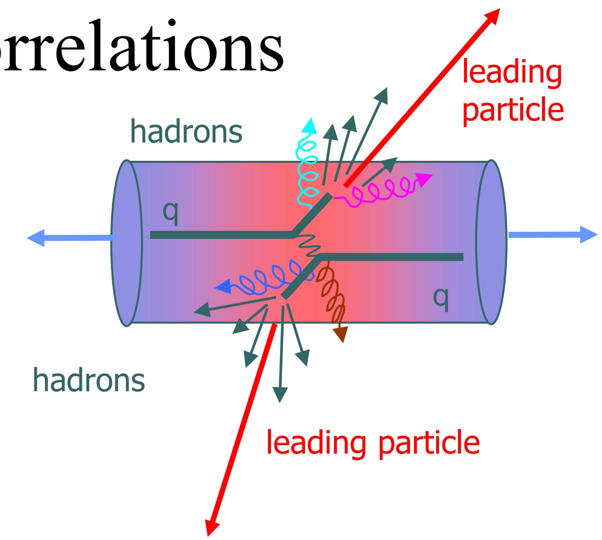
$$R_{AA} = \frac{\mathrm{Yield}_{AA} / \langle N_{binary} \rangle_{AA}}{\mathrm{Yield}_{pp}}$$

- Jet quenching evident in strong suppression of high p_T hadrons
- Multiple models provide a successful descriptions of the suppression levels
- Most include radiative and collisional energy loss

Jets are quenched! How?

More differential measurements:

- Angular di- and multi-hadron correlations
- Reconstructed jets
- Jet-jet, jet-hadron correlations

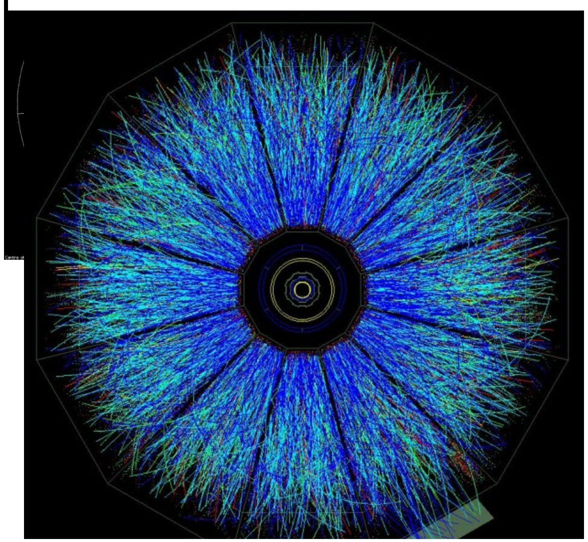


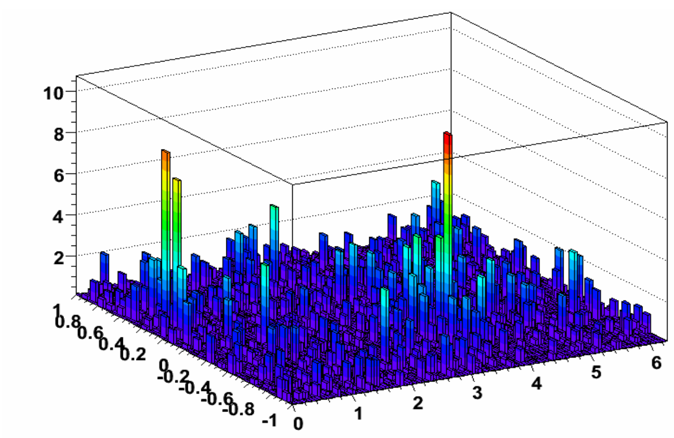
Outline:

- Early di-hadron correlation results
- Landscape details: “peaks”, “humps” and “ridges”
- Multi-particle correlations

HI collisions: the environment

Jet event in Au+Au?





Data:

High multiplicities

→ background levels

→ new techniques for jet studies

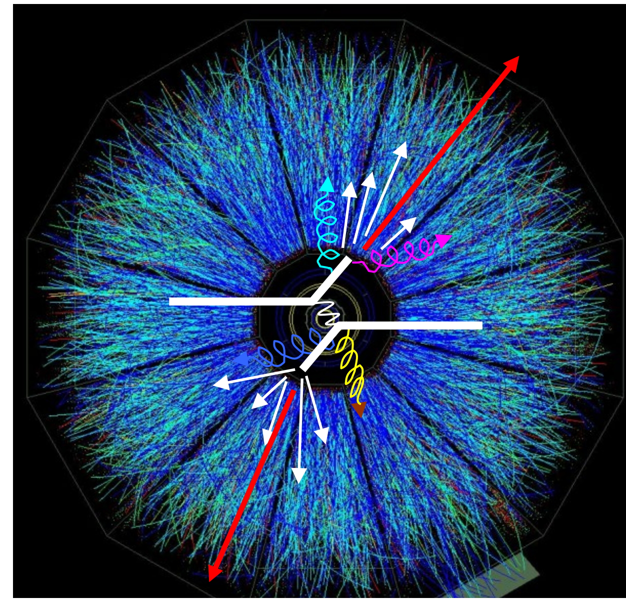
Physics:

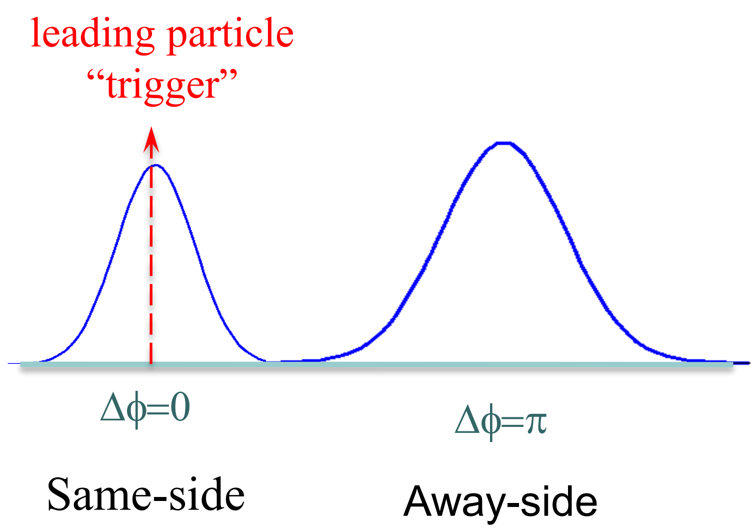
Strongly-interacting partonic medium

→ modified jets

Jets via angular correlations

Jet produces high p_T particles →
Select a high p_T particle to locate jet,
look for correlated hadrons.





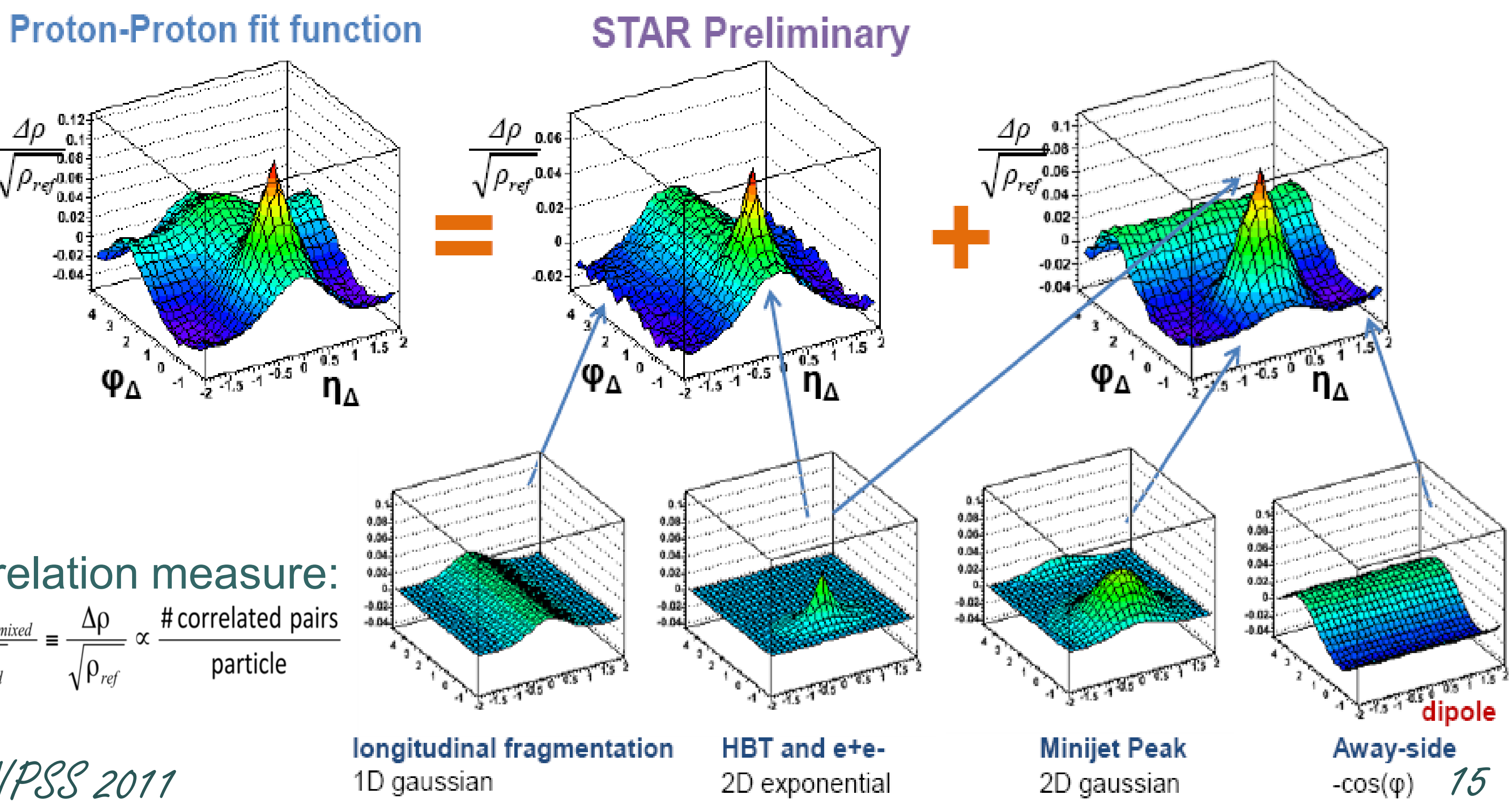
Measure reference, look for changes:

- Correlation strength
- Correlated shapes
- Associated spectral distributions

But…

A fly in the ointment – “backgrounds”:

many processes would lead to some sort of angular correlations



Correlation measure:

$$\frac{\rho_{same}-\rho_{mixed}}{\sqrt{\rho_{mixed}}} \equiv \frac{\Delta\rho}{\sqrt{\rho_{ref}}} \propto \frac{\#\,\text{correlated pairs}}{\text{particle}}$$

Signal decomposition

Triggered di-hadron correlations:

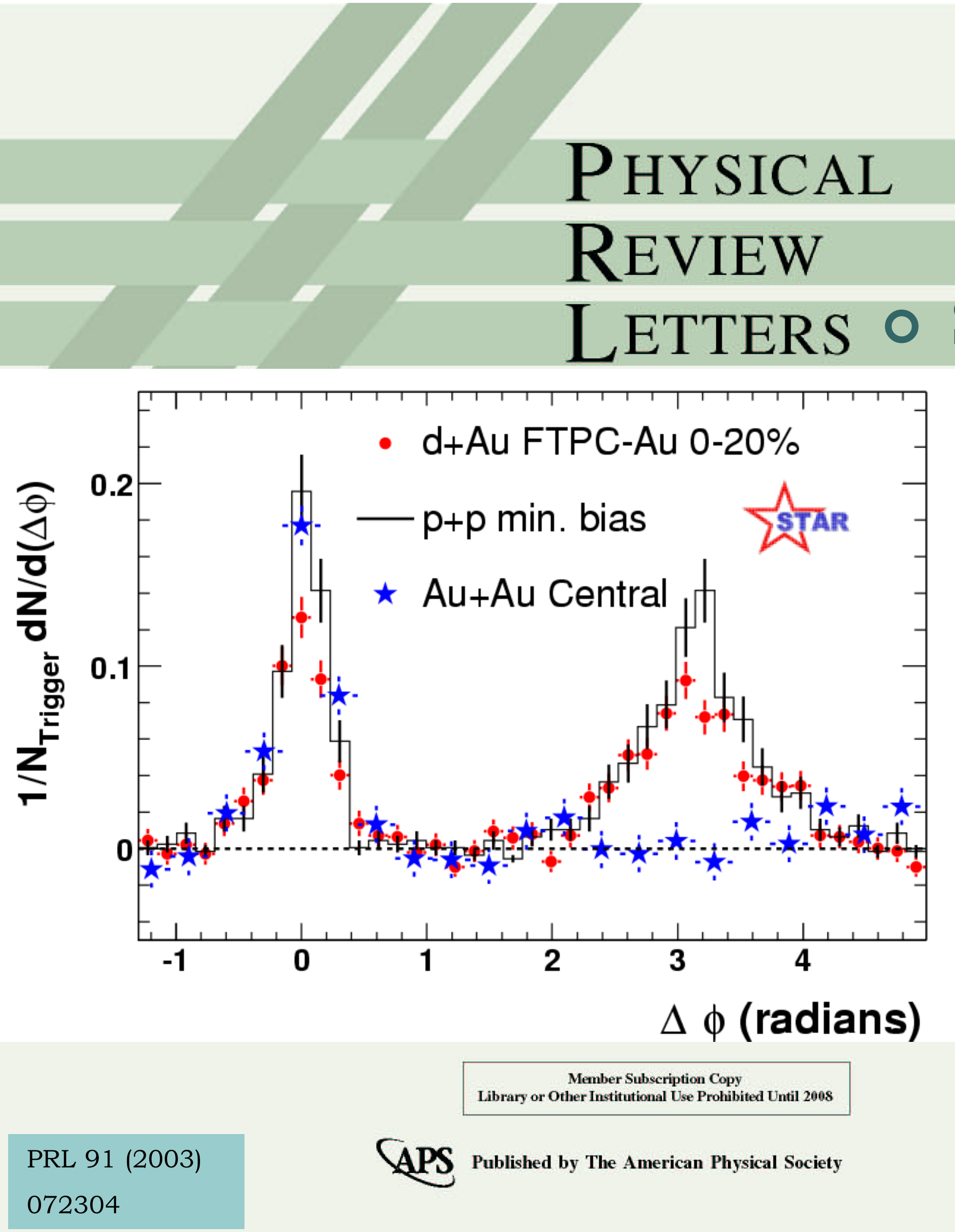
Azimuthal pair distribution per trigger: $$C(\Delta\phi) = \frac{1}{N_{trigger}}\frac{1}{\epsilon}\int d\Delta\eta N(\Delta\phi,\Delta\eta)$$

Two-component model: all hadrons come from jet fragmentation + "soft" processes

$$C(\Delta\varphi) = \underbrace{C^{pp}}_{\text{common partonic hard-scattering}} + \underbrace{B(1+2\langle v_2^T v_2^A\rangle\cos(2\Delta\varphi))}_{\text{pairs from all other sources}}$$

In two-component approach one needs to know only B, and $v_2(p_T)$ and assume $\langle v_2^T v_2^A\rangle \approx \langle v_2^T\rangle\langle v_2^A\rangle$

First results



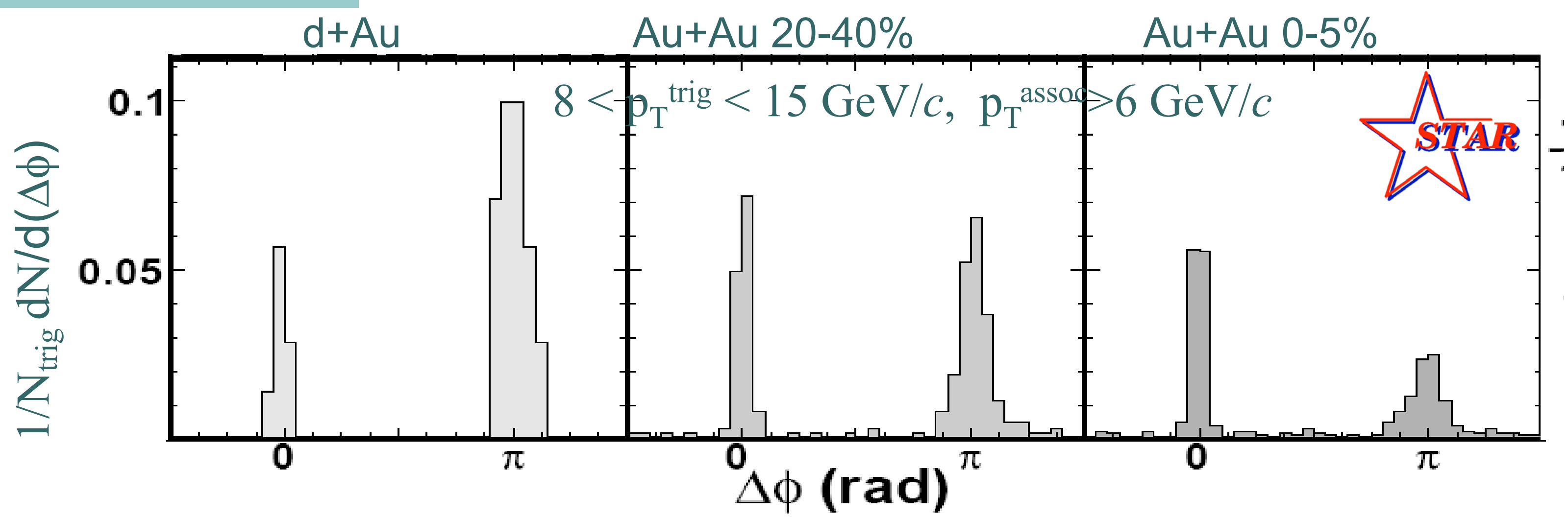
PRL 91 (2003) 072304

- Signature two-particle correlation result:
  - "Disappearance" of the away-side jet in central Au+Au collisions (for associated hadrons $p_T^{\,assoc}>2$)
  - Effect vanishes in peripheral/d+Au collisions

Significant Energy Loss in the Medium

Are there jets?

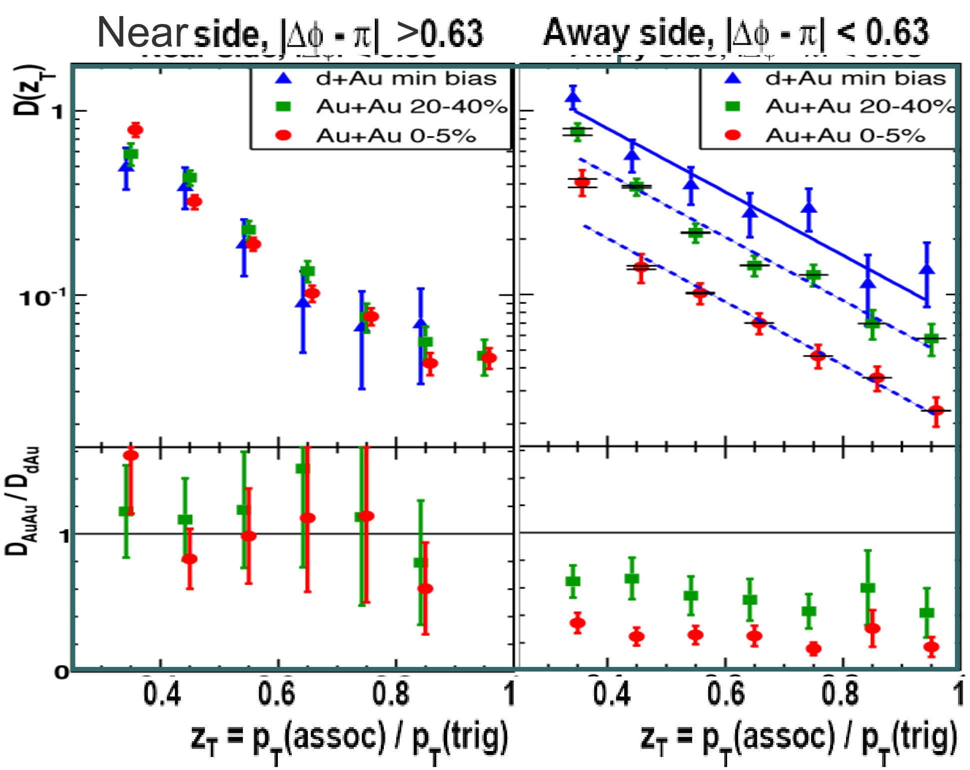
STAR PRL 97 (2006) 162301



- Recovering the away side:
  - Away-side yield suppression
  - Little modification of the Near-side yields
  - No broadening on Near- or Away-sides

High-p_T – vacuum fragmentation?

STAR PRL 97 (2006) 162301

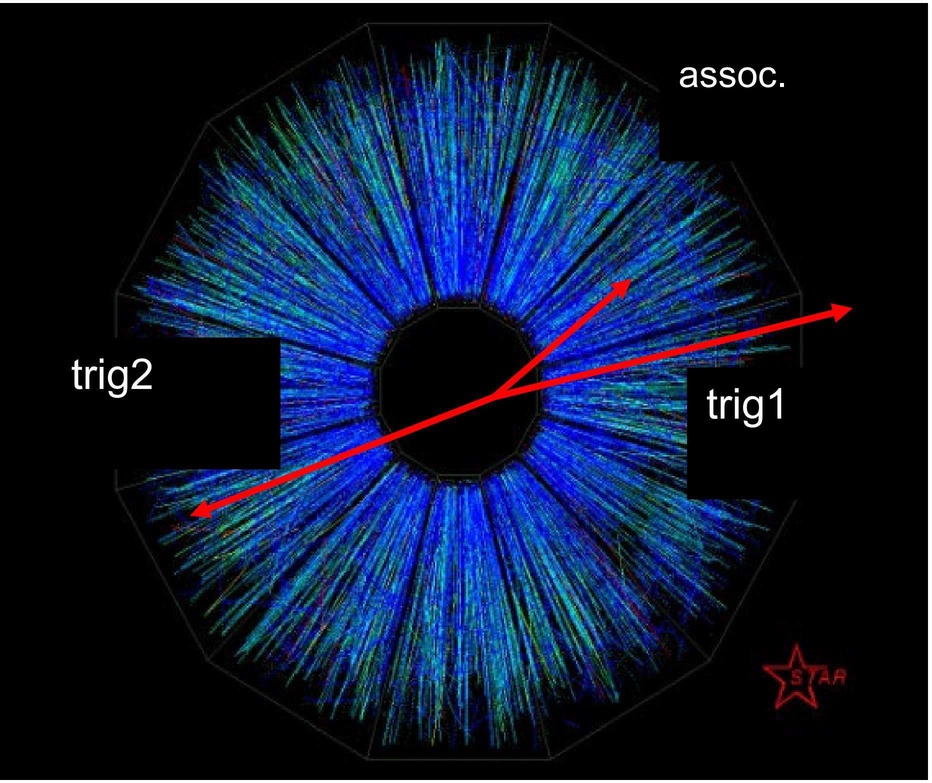


$$D^{h_1h_2}\left(z_T, p_T^{trig}\right) = p_T^{trig}\,\frac{d\sigma_{AA}^{h_1h_2}/dp_T^{trig}dp_T}{d\sigma_{AA}^{h_1}/dp_T^{trig}}$$

$$z_T \equiv \frac{p_T^{assoc}}{p_T^{trig}}$$

- Near-side:
  - No dependence on z_T in the measured range – no modification
- Away side:
  - Suppression ~ level of R_{AA}
  - No dependence on z_T in the measured range – no modification

Di-jets through correlations



Use back-to-back (correlated) trigger pairs
to pick both sides of a di-jet

"2+1" correlations:

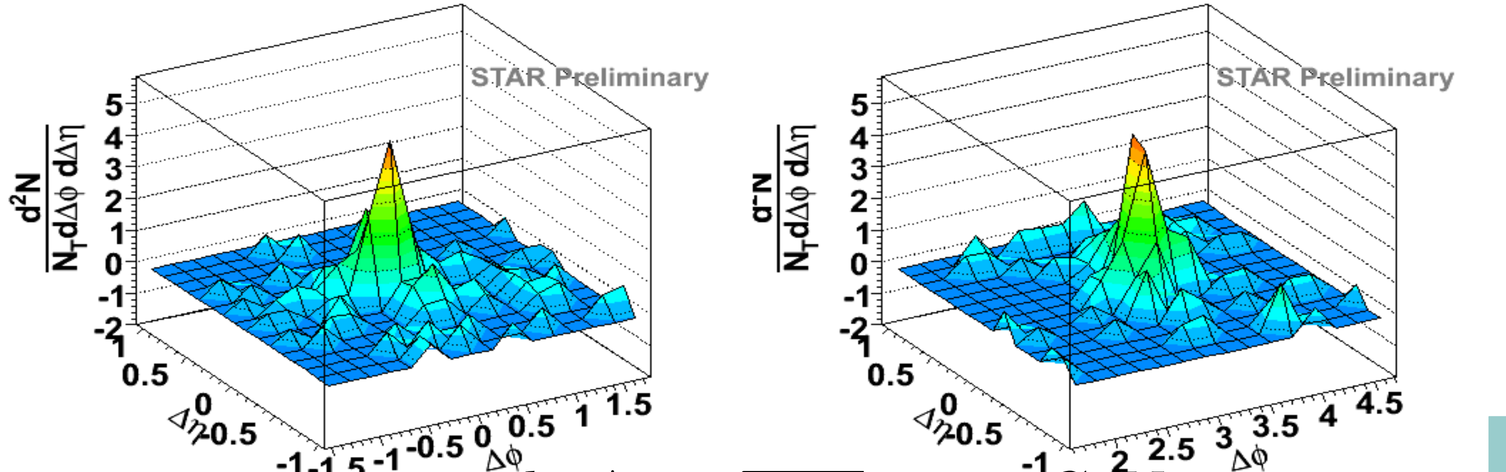
Trig1 - highest p_T in event, 5-10 GeV/c
Trig2 - back-to-back with Trig1 $p_T > 4$ GeV/c
Associated particles $p_T > 1.5$ GeV/c

Di-jet correlations

$5 < p_T^{Trig1} < 10$ GeV/c

$4 < p_T^{Trig2} < p_T^{Trig1}$

$1.5 < p_T^{Assoc} < 10$GeV/c



$$2003 \text{ d+Au } \sqrt{s_{NN}} = 200 GeV$$

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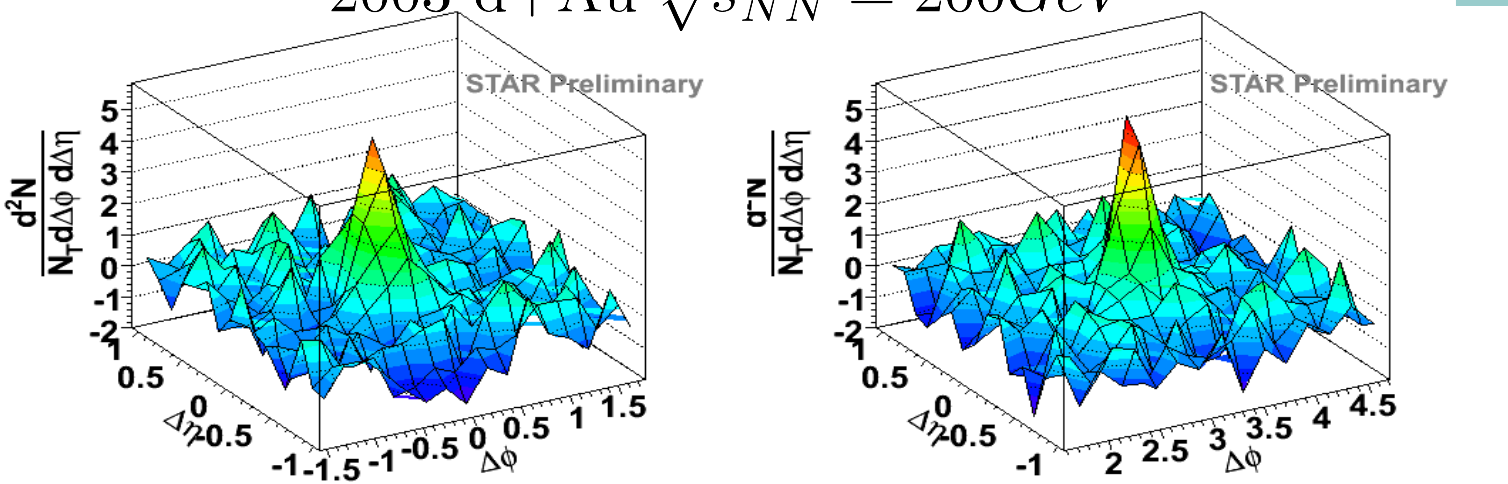
K. Kauder QM'09



$$2004 \text{ Au+Au } \sqrt{s_{NN}} = 200 GeV$$

Surface effects in di-jets

200 GeV Au+Au and d+Au

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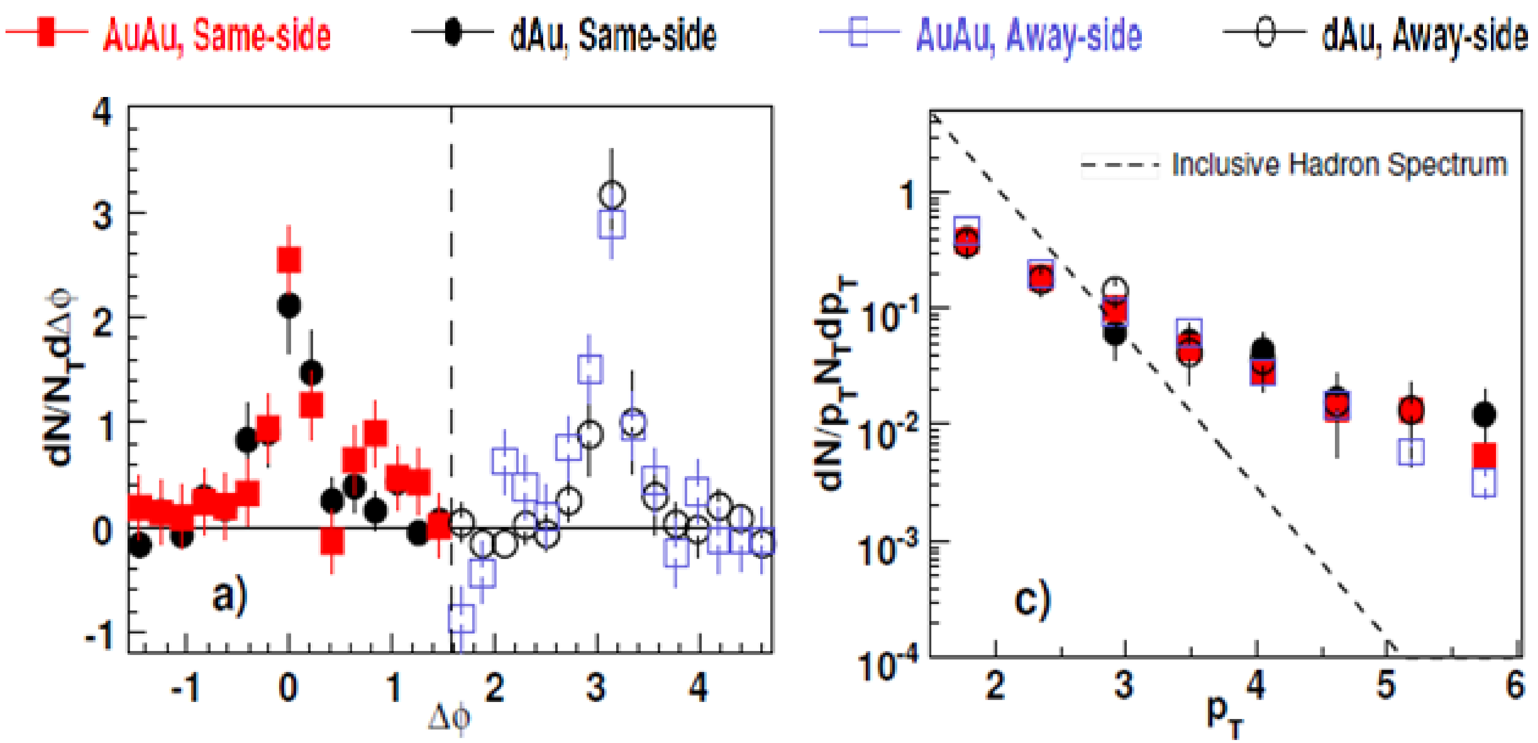
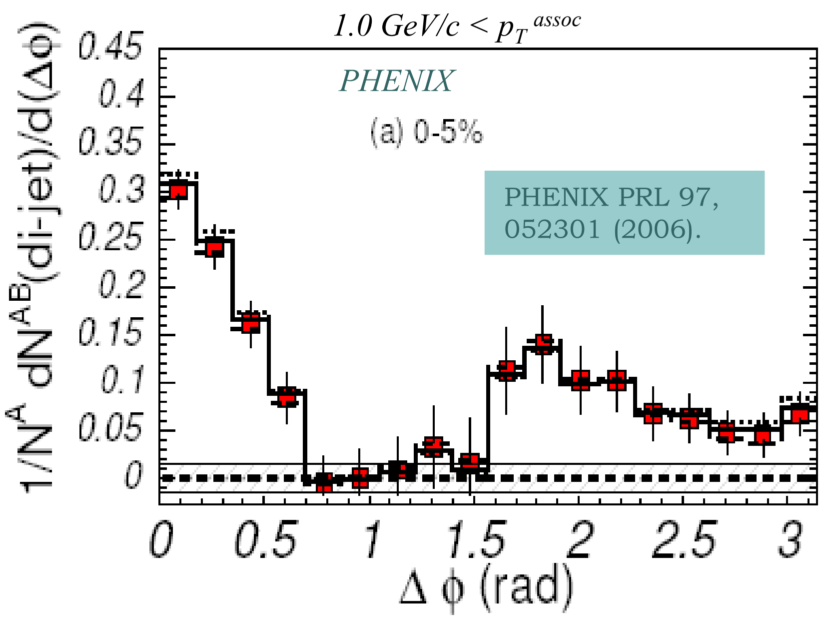
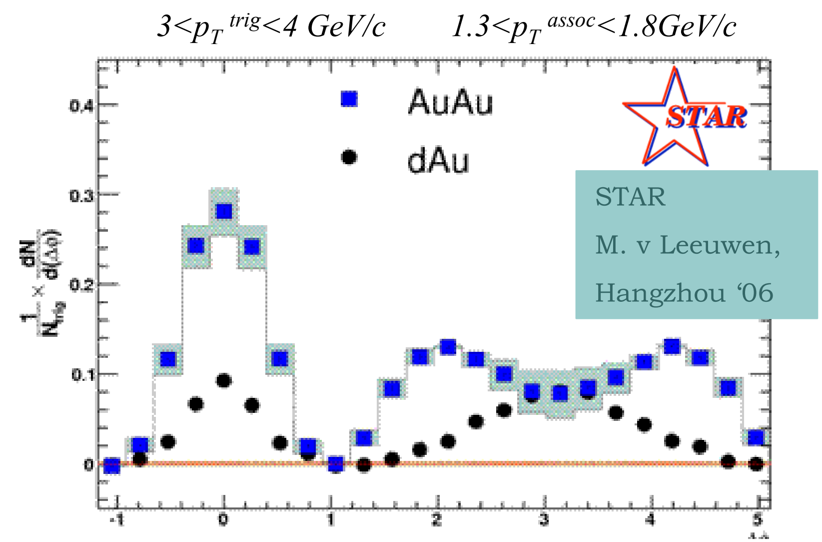


- No evidence of medium modifications

Di-jets observed - all tangential?

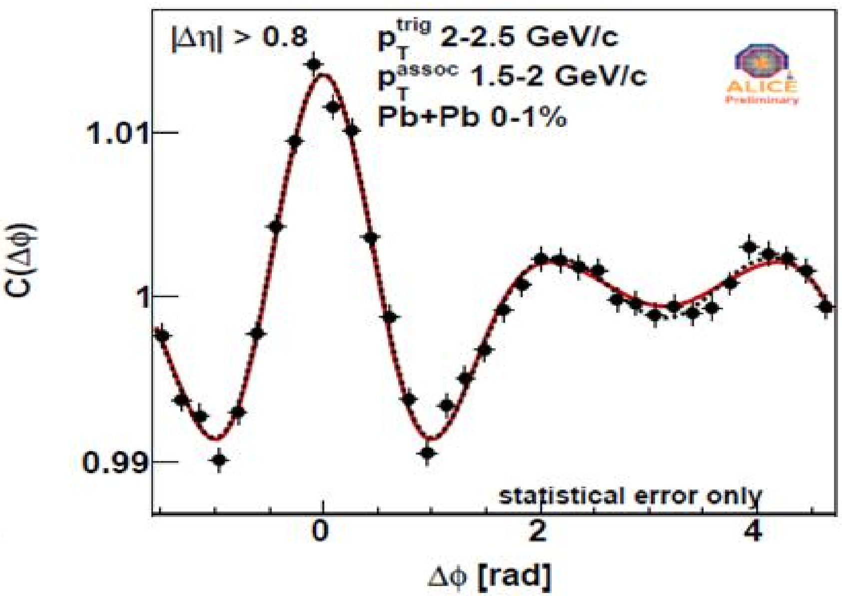
Jet modifications: $p_T \downarrow$



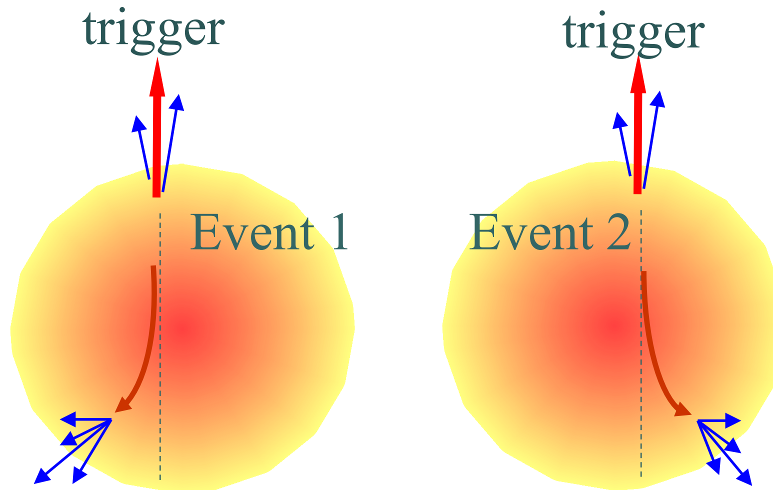


- One high-p_T, one low-p_T trigger
  - Reappearance of the away-side jet
  - Double-hump structure hints at additional physics phenomena

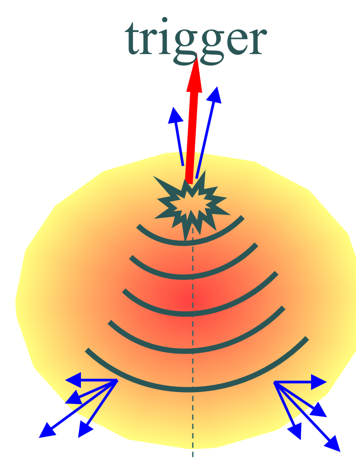
Away side: double-humps



Double-humps
or shoulders



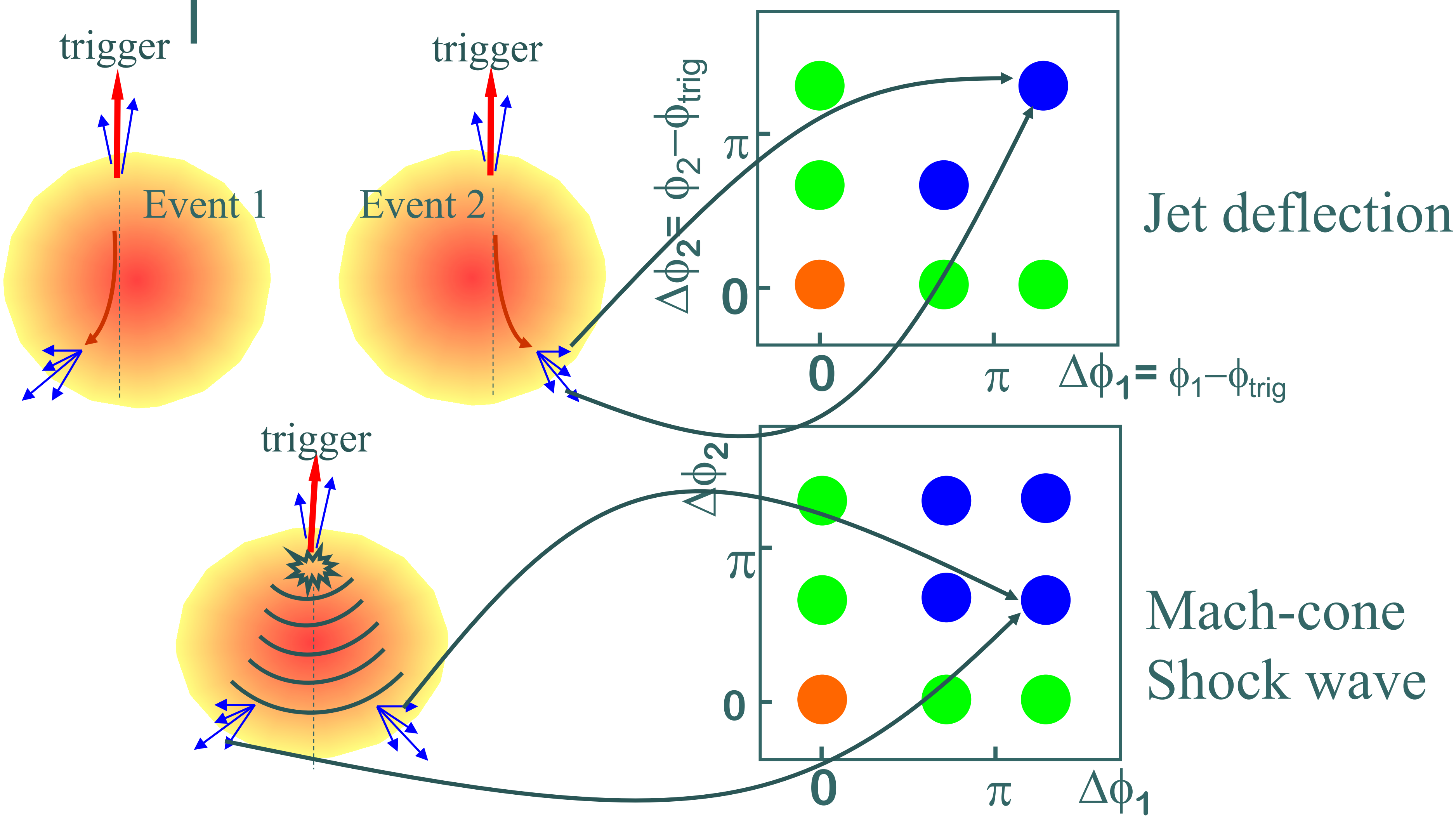
Jet deflection



Mach-cone
Shock wave

Are these features “real”, e.g. jet-related?

3-particle correlation in $\Delta\phi$



3-particle Δφ-Δφ correlations

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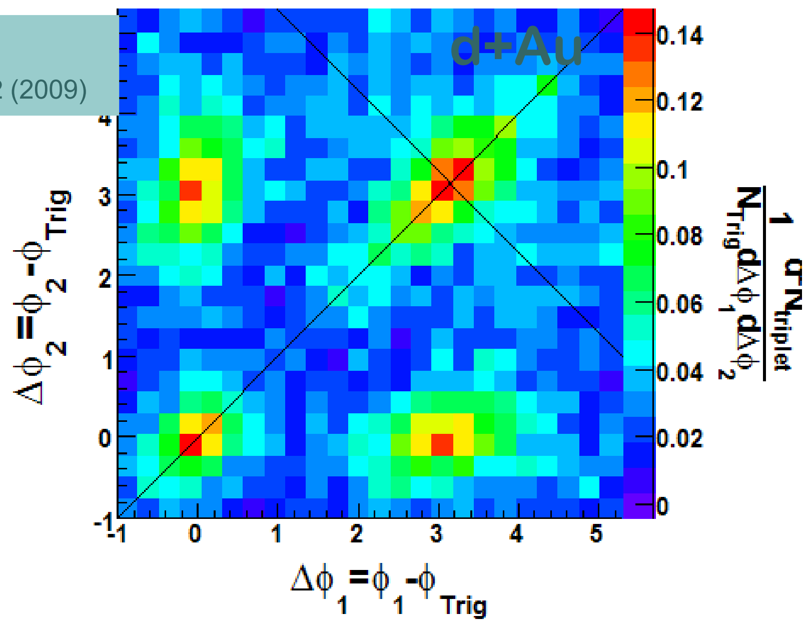
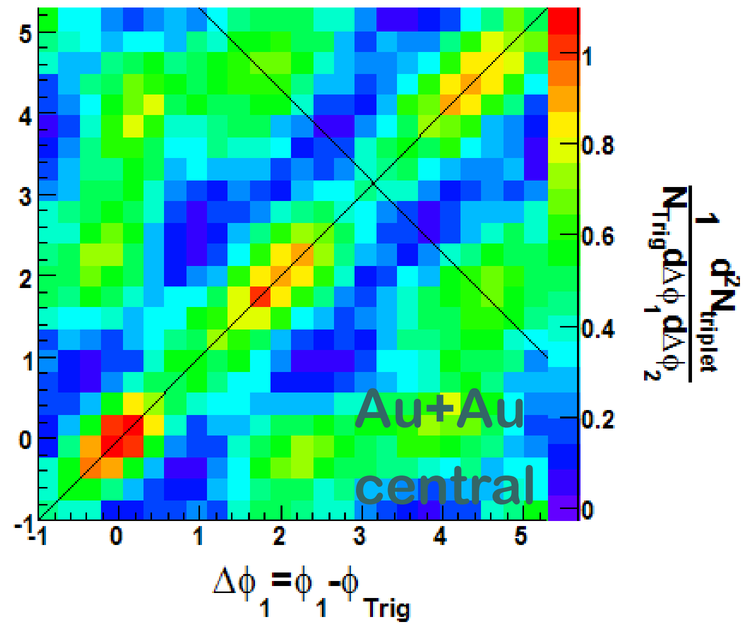
PRL 102 52302 (2009)

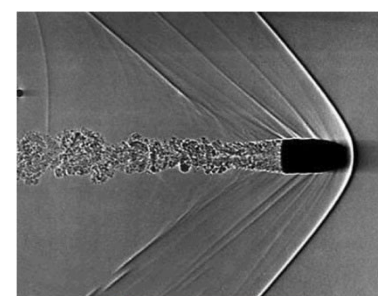




Experimental observations consistent with

- jet deflection
- conical emission (Constrains the speed of sound:

$\theta_M = 1.37 \pm 0.02 \pm 0.06 \rightarrow c_S \sim 0.2$)

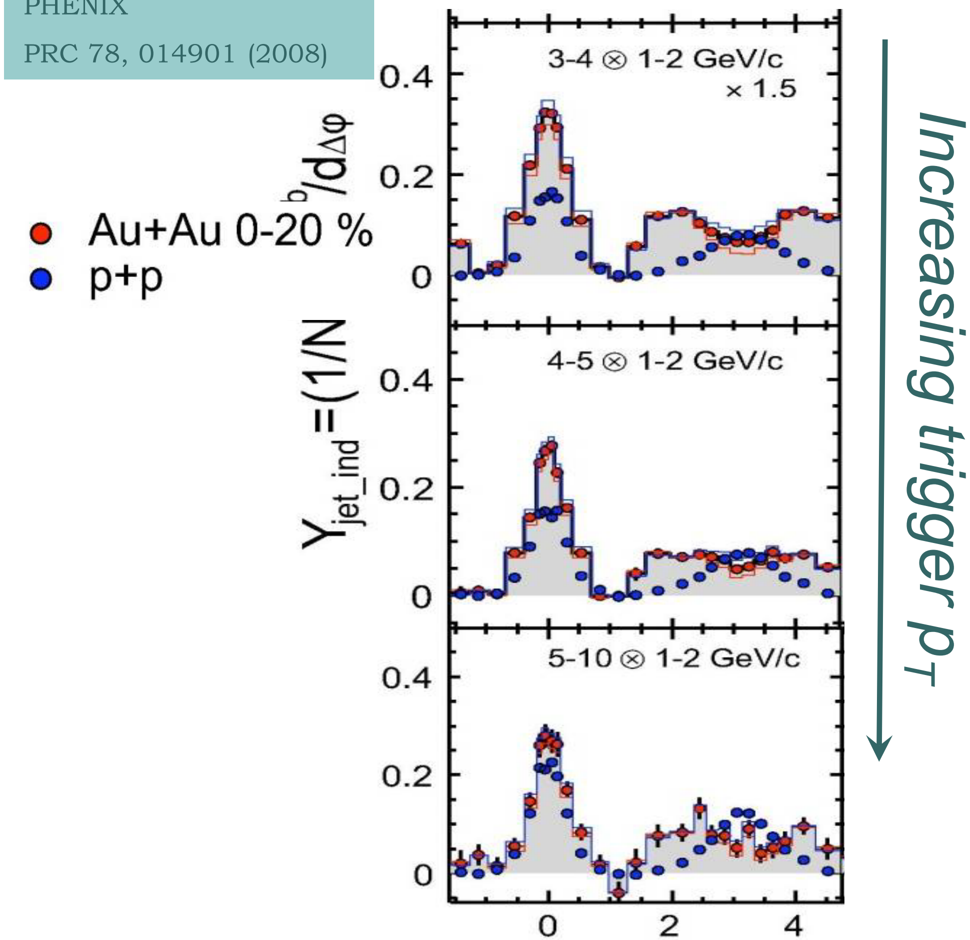


$\cos(\theta_M) = c_s$

Closing the chapter?

Same-side excess yield

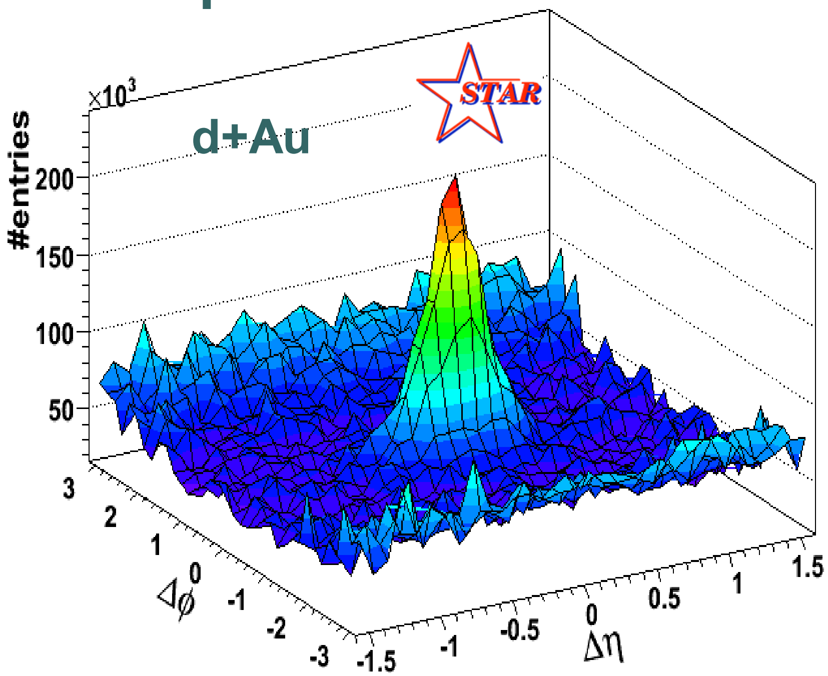
PHENIX
PRC 78, 014901 (2008)

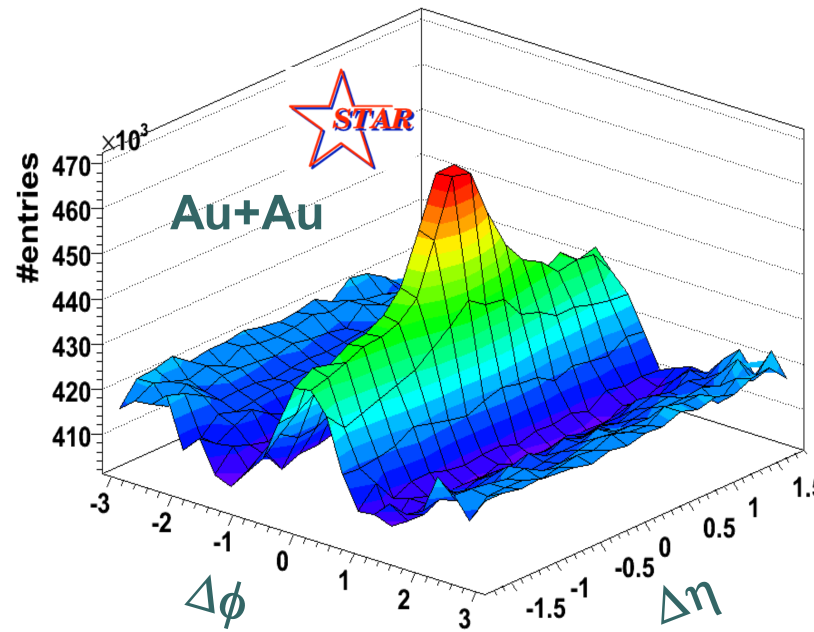


- Excess yield on the same-side
- Away-side “shoulders” magnitude ↓
  - Is it related to energy loss?
  - Correlated with same-side excess?

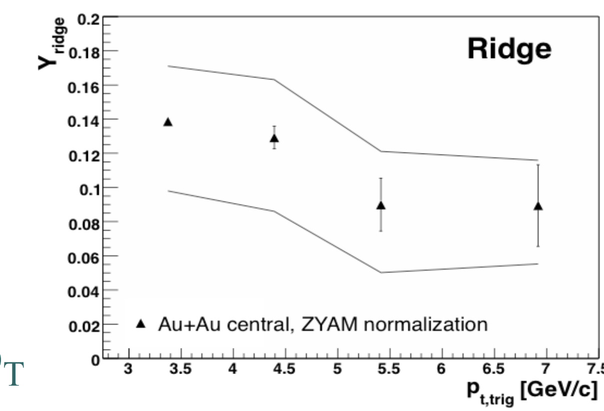
→ Zooming in on the same side

RHIC Signature Result: the Ridge





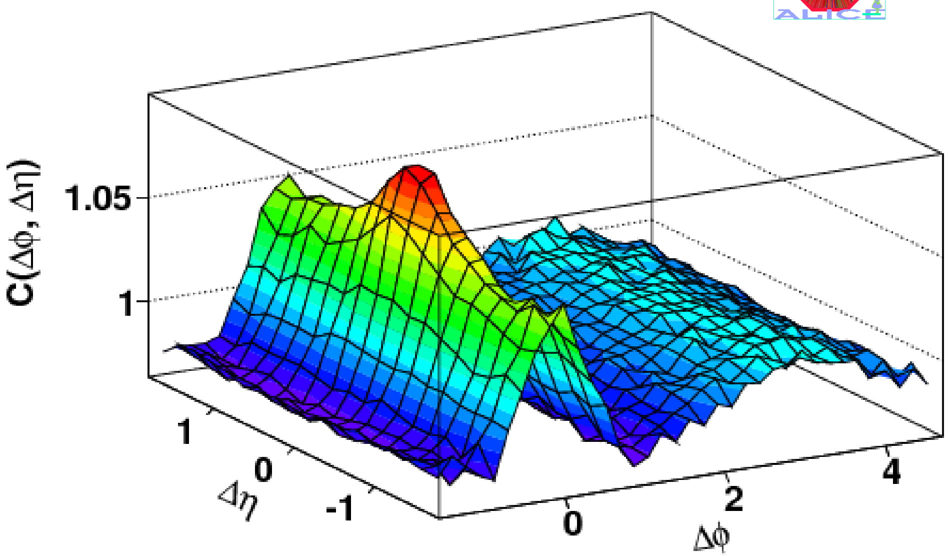
- Near-side correlation structure:
  - Central Au+Au: cone-like + ridge-like
  - Ridge correlated with jet direction
  - Approximately independent of $\Delta\eta$ and trigger p_T



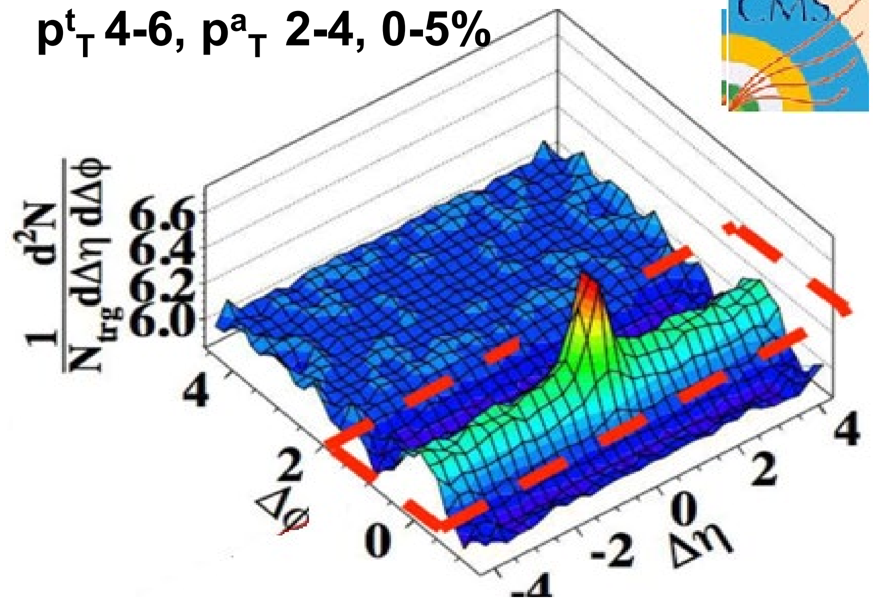
Ridge in AA collisions at LHC

Pb+Pb @ 2.76 TeV

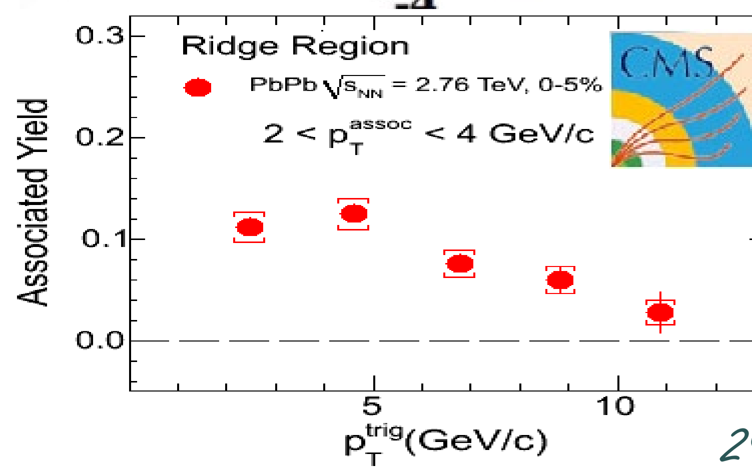
p^t_T 3-4, p^a_T 2-2.5, 0-10%



p^t_T 4-6, p^a_T 2-4, 0-5%



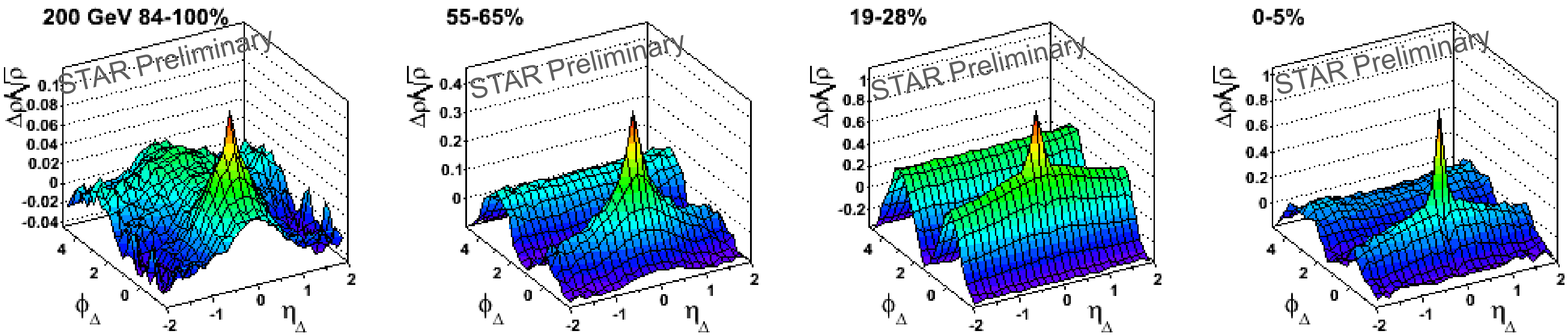
- Long-range near-side correlation:
  - ☑ Cone-like + ridge-like
  - ☑ Ridge correlated with jet direction
  - ☑ Approximately independent of $\Delta\eta$
    - ☒ and trigger p_T



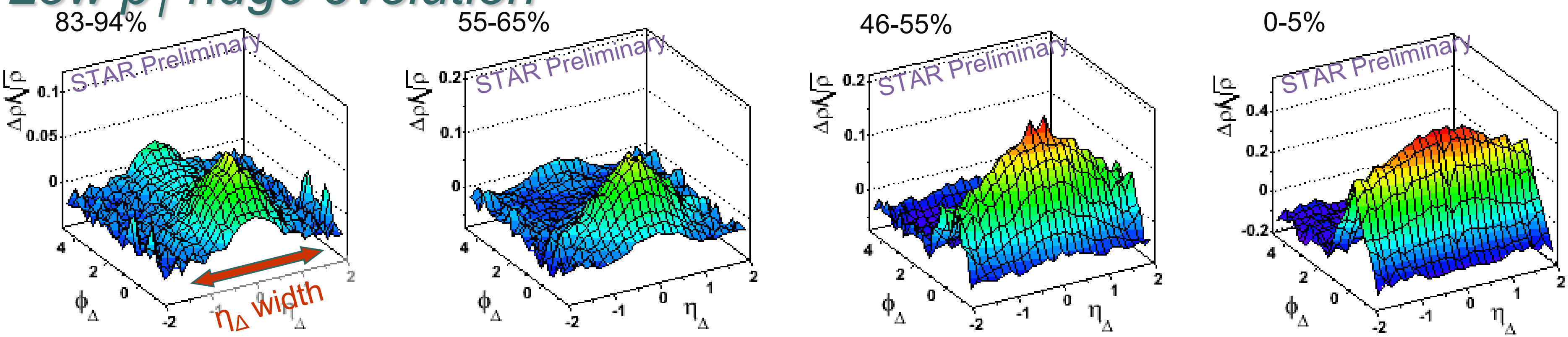
Ridge in pair correlations

Au+Au 200 GeV

M Daugherity, QM08



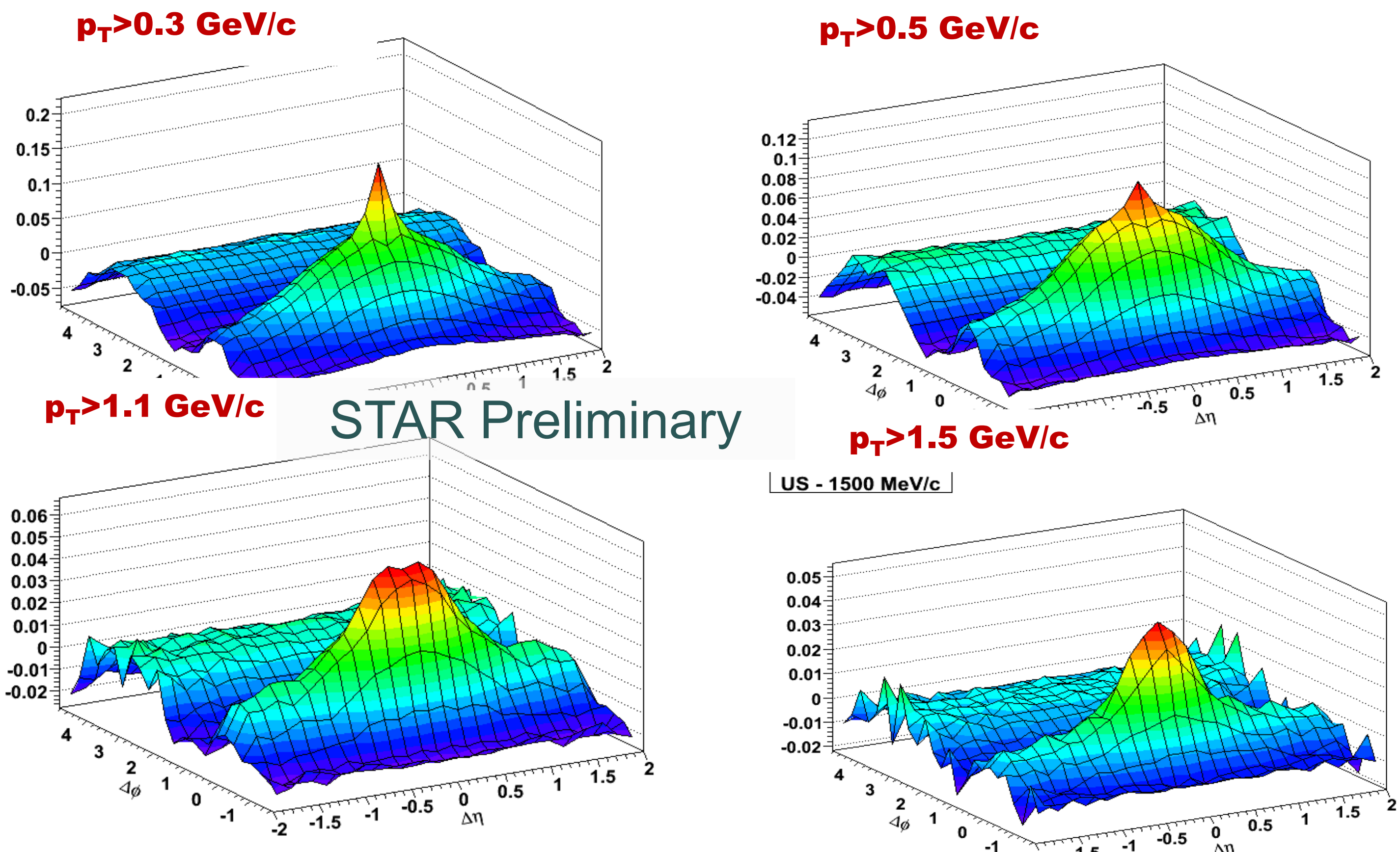
Low p_T ridge evolution



Long-range near-side correlation in inclusive events

Transverse momentum scan

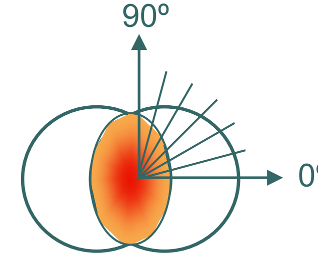
Zoom in on jets: follow p_T evolution



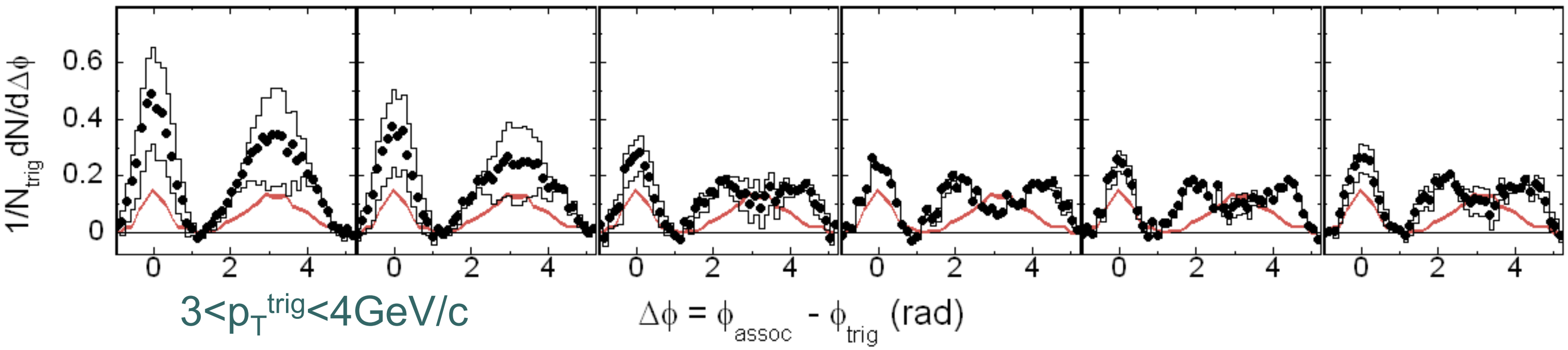
Unlike-charge-sign pairs from 10% most central 200 GeV Cu+Cu data

Low p_T elongation evolves into high p_T ridge

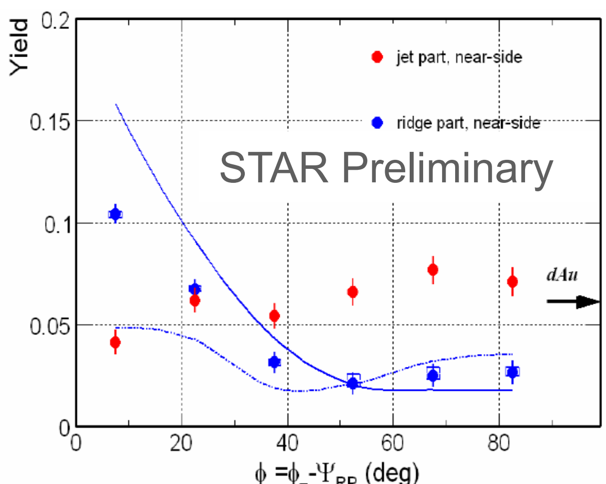
Path-length effects



in-plane $\phi_S=0$ → out-of-plane $\phi_S=90^o$



$3<p_T^{trig}<4$GeV/c



- Same-side yield
  - Jet: d+Au ~ Au+Au
- Ridge decreases from in-plane to out-of-plane

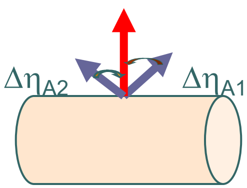
Flow effects?

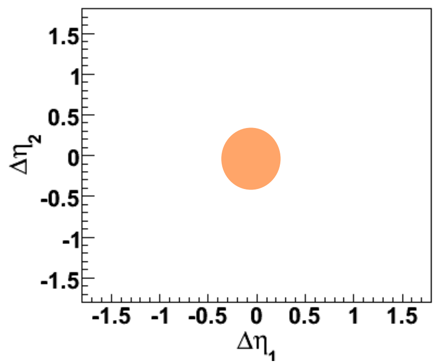
3-particle correlation in $\Delta\eta$

T : Trigger particle
A1: First Associated particle
A2: Second Associated particle

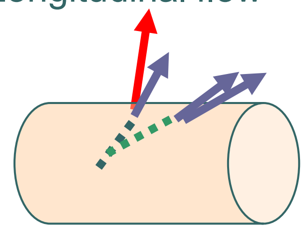
$\Delta\eta_1=\eta_{A1}-\eta_T$
$\Delta\eta_2=\eta_{A2}-\eta_T$

Jet fragmentation in vacuum

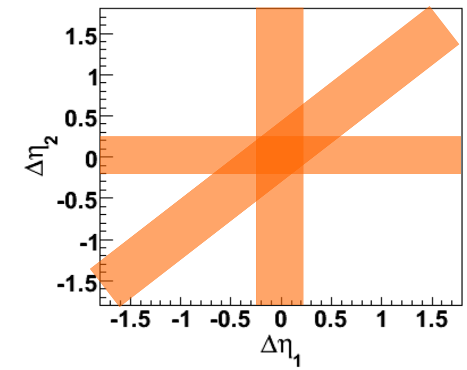




In medium radiation + Longitudinal flow

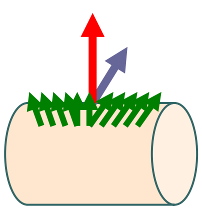


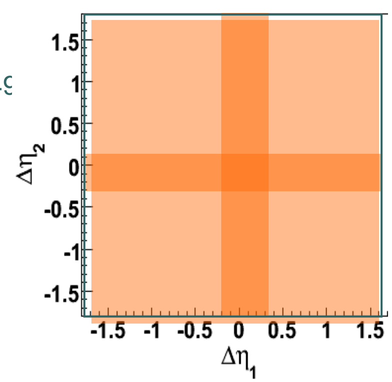
N.Armesto et.al Phys.Rev.Lett. 93(2004) 242301



Transverse flow boost

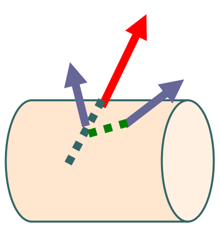
S.A.Voloshin, Phys.Lett.B. 632(2006)49
E.Shuryak, hep-ph:0706.3531

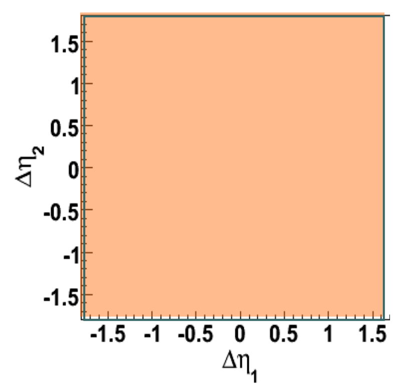




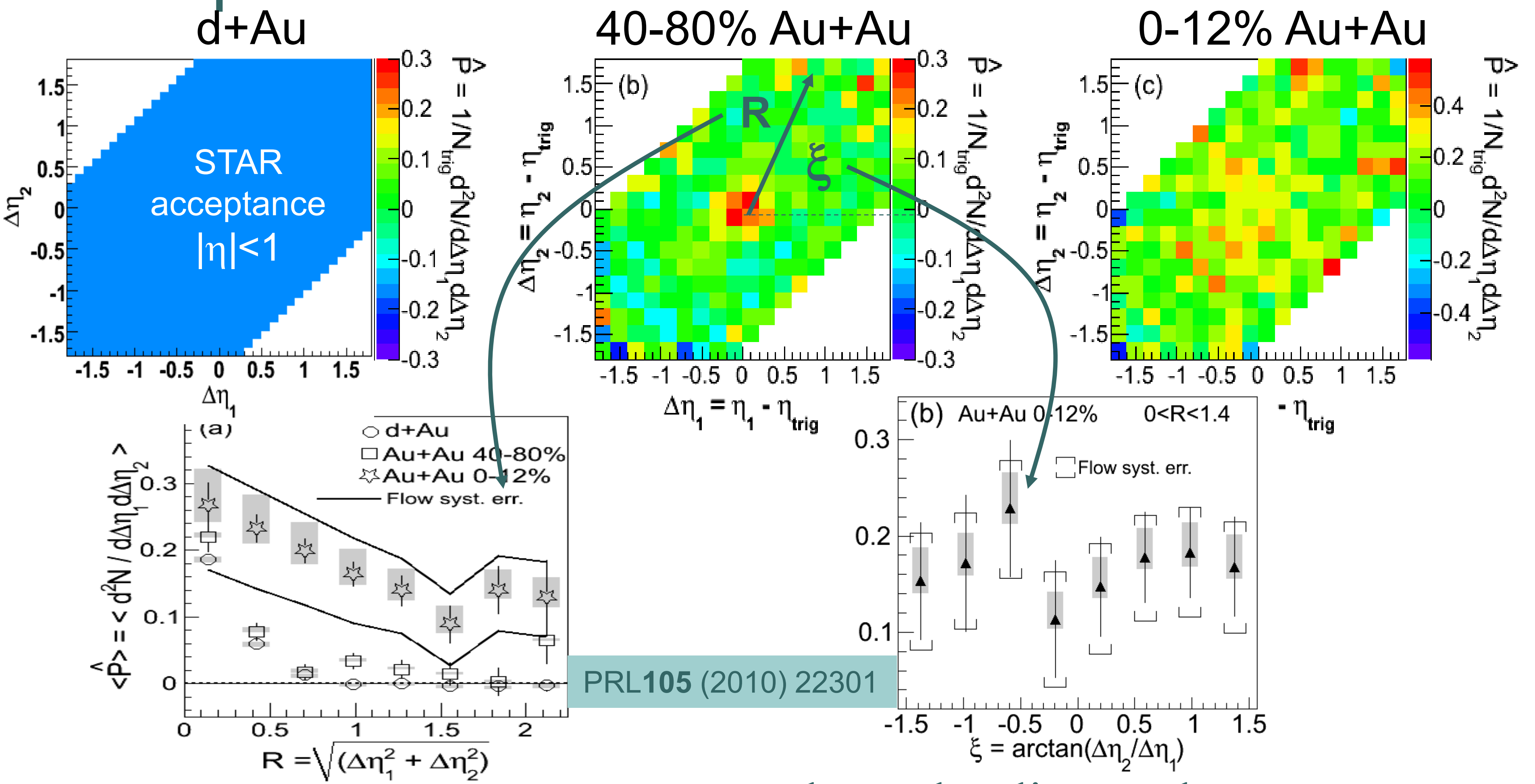
Turbulent color field.

A.Majumder et.al
Phys. Rev. Lett.99(2004)042301



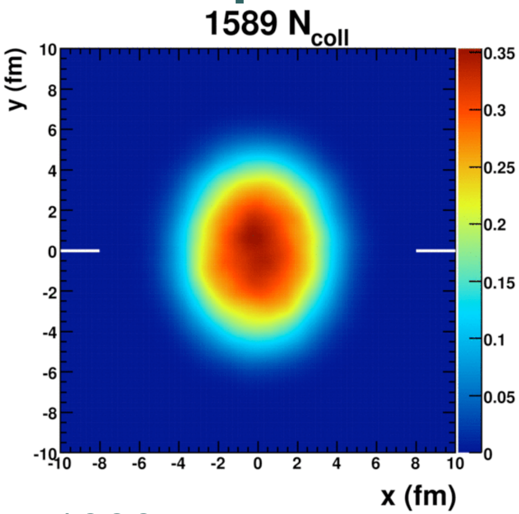


3-particle Δη-Δη correlation

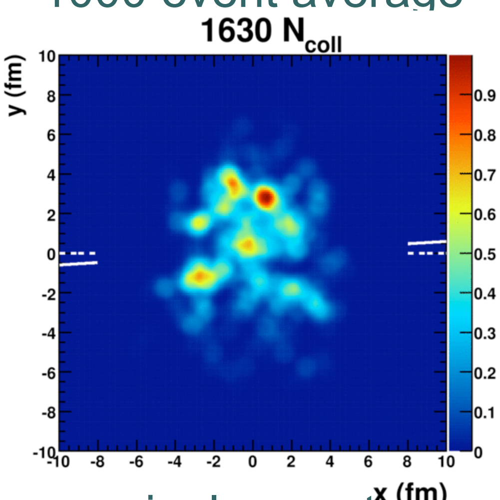


- No significant structures along the diagonals or axes
- The ridge is uniform in every event

Medium response = Energy loss?



1000 event average

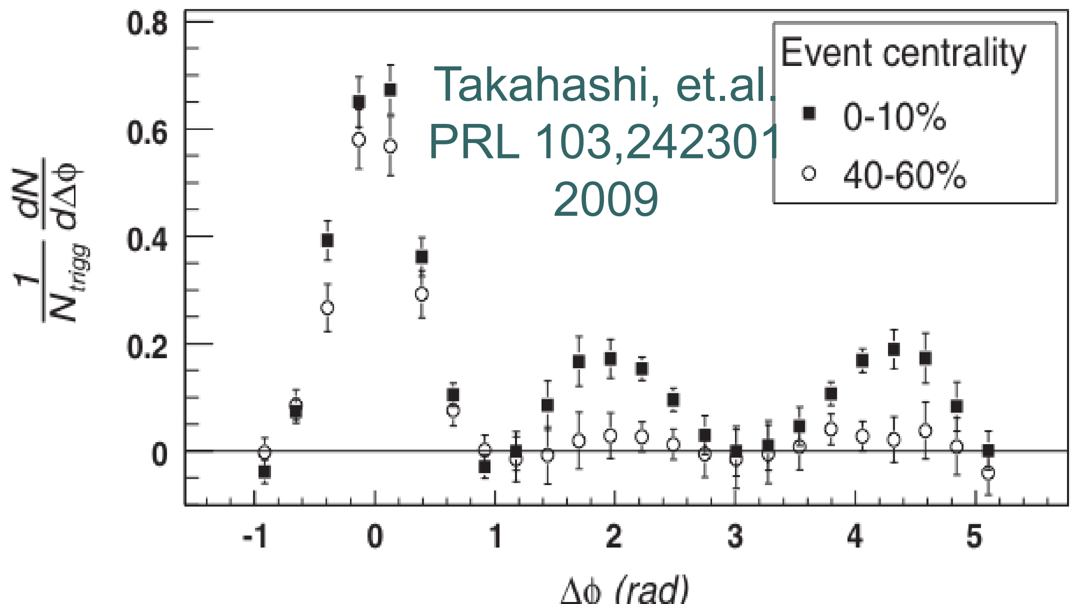


single event

"Lumpy" initial conditions in individual events, breaks the symmetry

NEXSPHERIO

Hydrodynamics

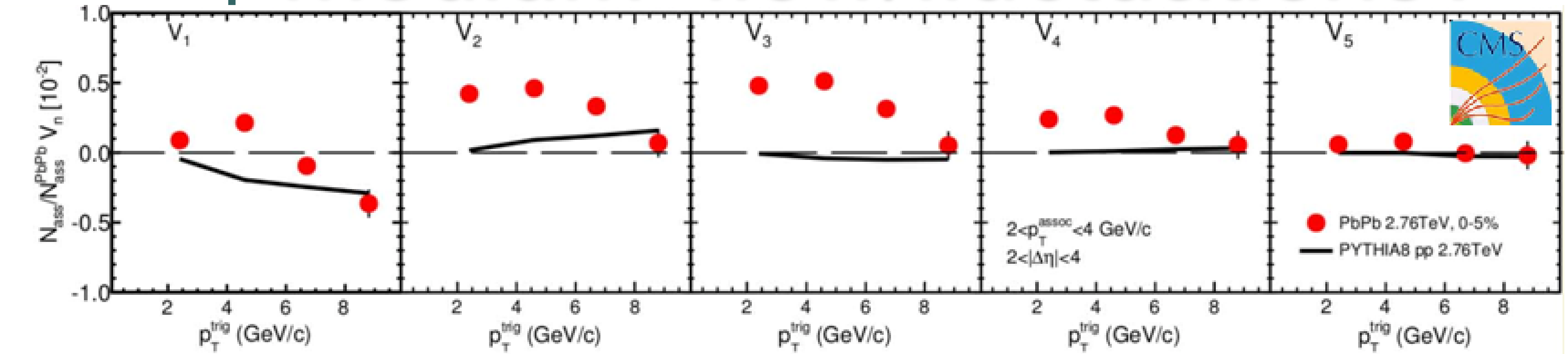


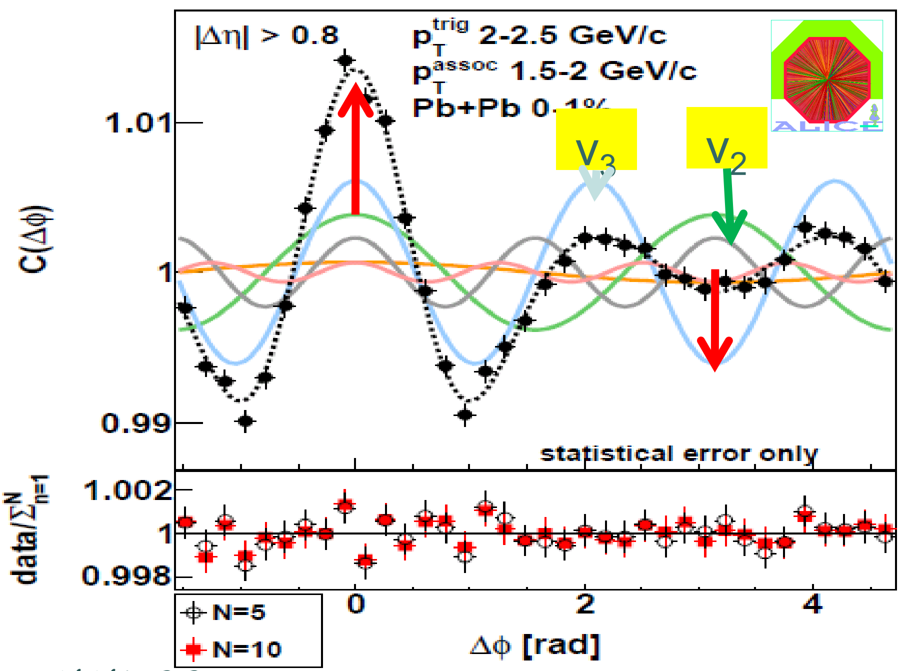
Takahashi, et.al. PRL 103,242301 2009

No parton-medium coupling required

Could explain both double-humps (and ridge)

Jet-medium interactions or medium flow/fluctuations?





Full correlation structure described by Fourier Coefficients $\mathbf{v_1}, \mathbf{v_2}, \mathbf{v_3}, \mathbf{v_4}, \mathbf{v_5}$ *

Central events:

$\mathbf{v_2}$ and $\mathbf{v_3}$, are comparable, sizable $\mathbf{v_4}$

😐 Can describe anything with enough terms

☺ v_n factorization (?)

Summary:

- Hard probes are essential for understanding of QGP properties
- Angular correlations are powerful experimental tools for such studies

High p_T

Disappearance of away-side peak in central Au+Au, but not in d+Au
- jet quenching discovery
- establishing "final" state effect

Re-emerging of di-jet signal at higher p_T
- punch through ?
- tangential jets ?

Low p_T

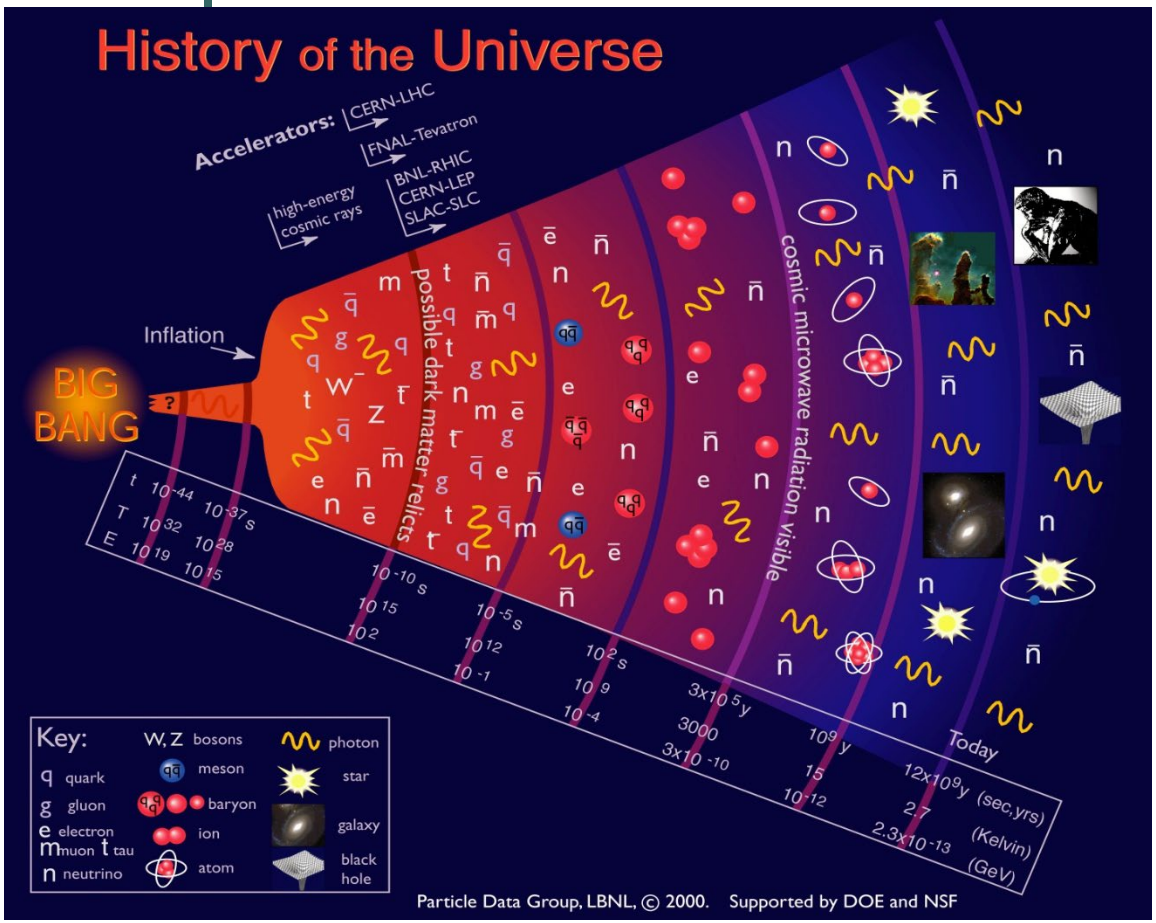
Away-side double-hump structure -
- mach cone ?
- deflected jets ?
- medium response/medium?

Near-side ridge -
- manifestation of energy loss?
- medium response/medium ?

How to control biases?
How to decompose observed structures?

Back Up

Why QGP?



To test and understand QCD:

Strong interaction,

Confinement,

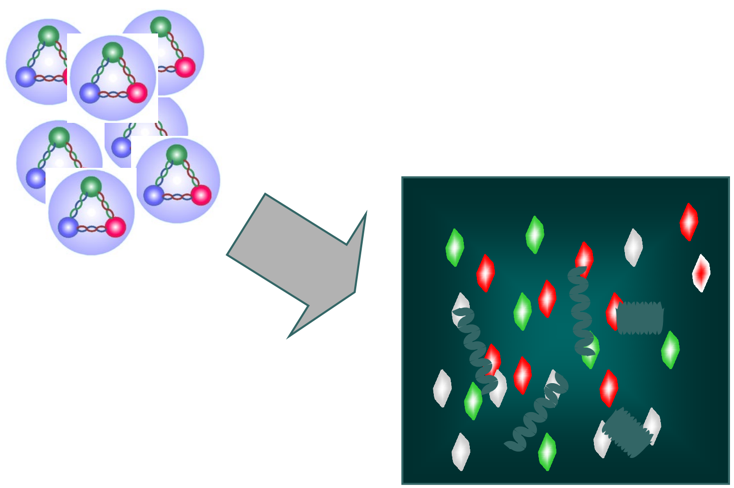
Mass,

Chiral symmetry.

Few microseconds after the Big Bang the entire Universe was in a QGP state.

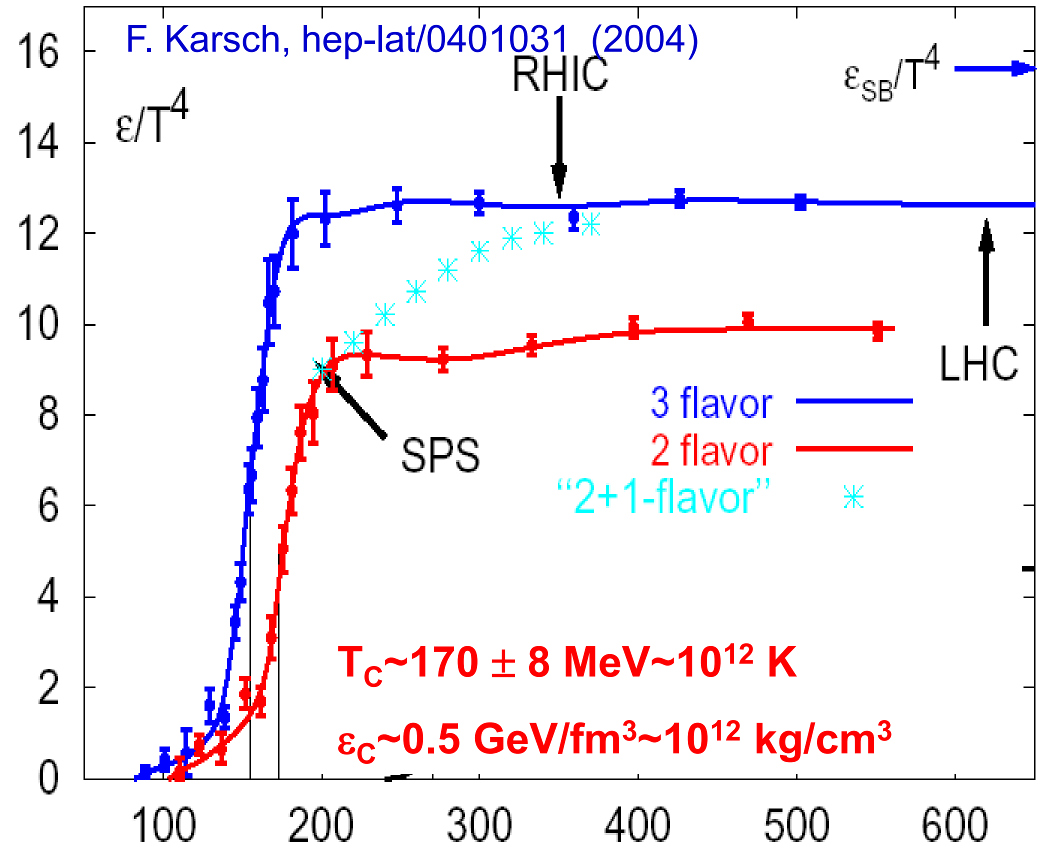
What is QGP?

Nuclear Matter



QGP

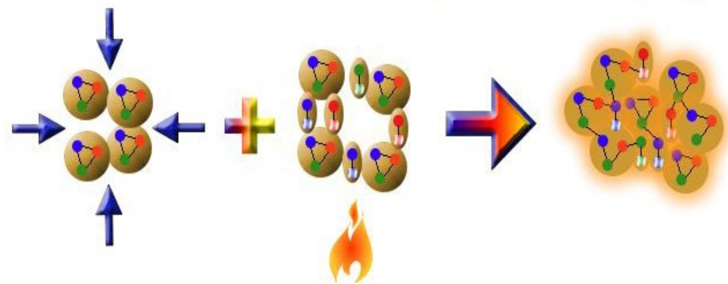
Lattice QCD prediction

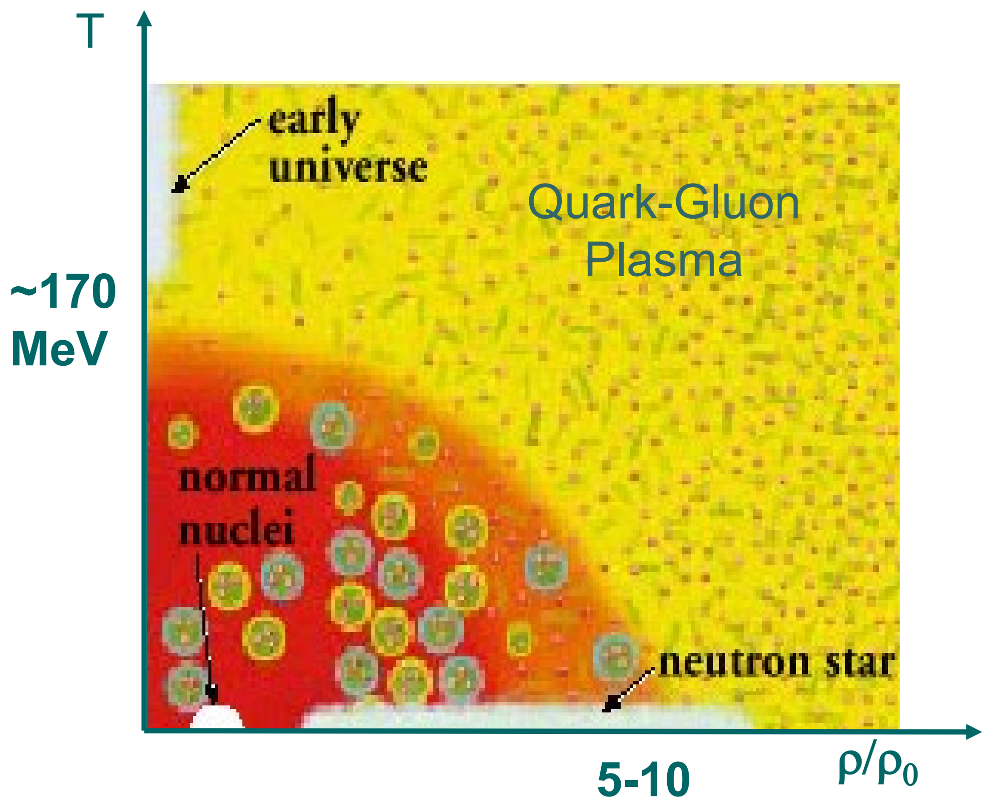


QGP ≡ **a thermally equilibrated deconfined quarks and gluons, where color degrees of freedom become manifest over nuclear, rather than nucleonic, volumes.**

Making a Big Bang

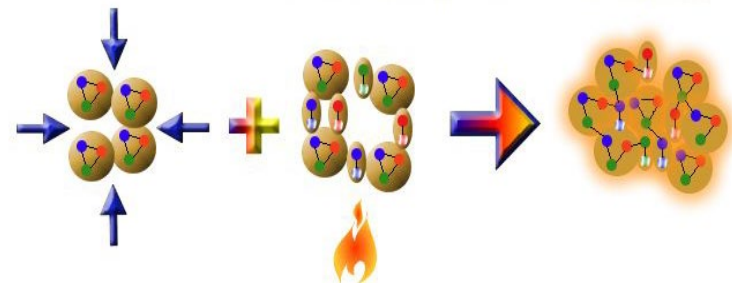
How to create Quark Gluon Plasma?

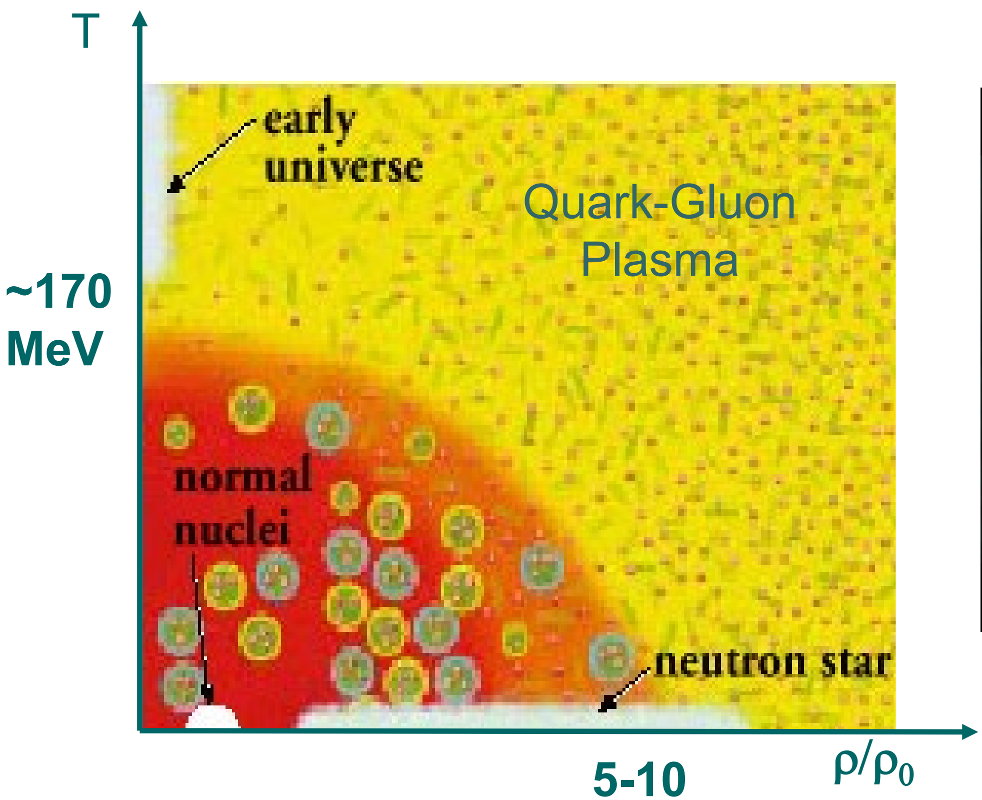


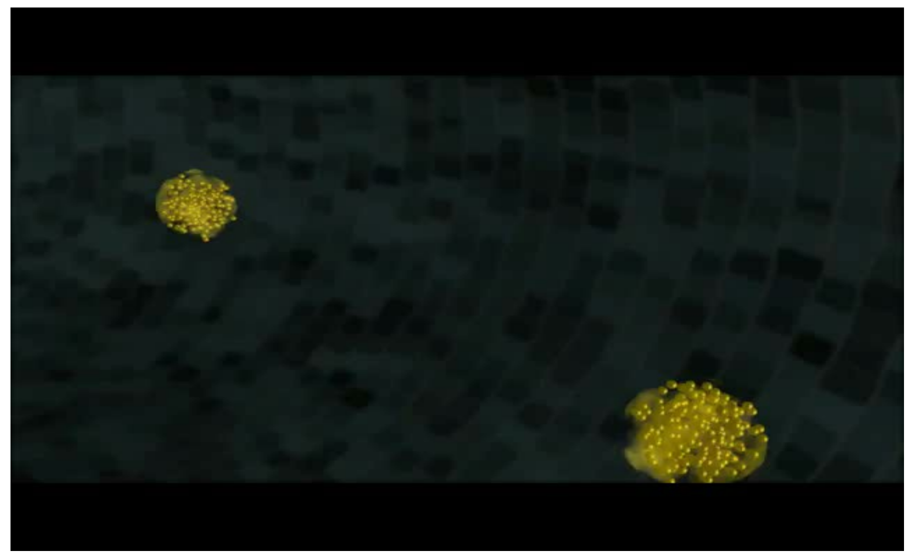


Making a Big Bang

to create Quark Gluon Plasma (QGP) –
a deconfined state of quarks and gluons

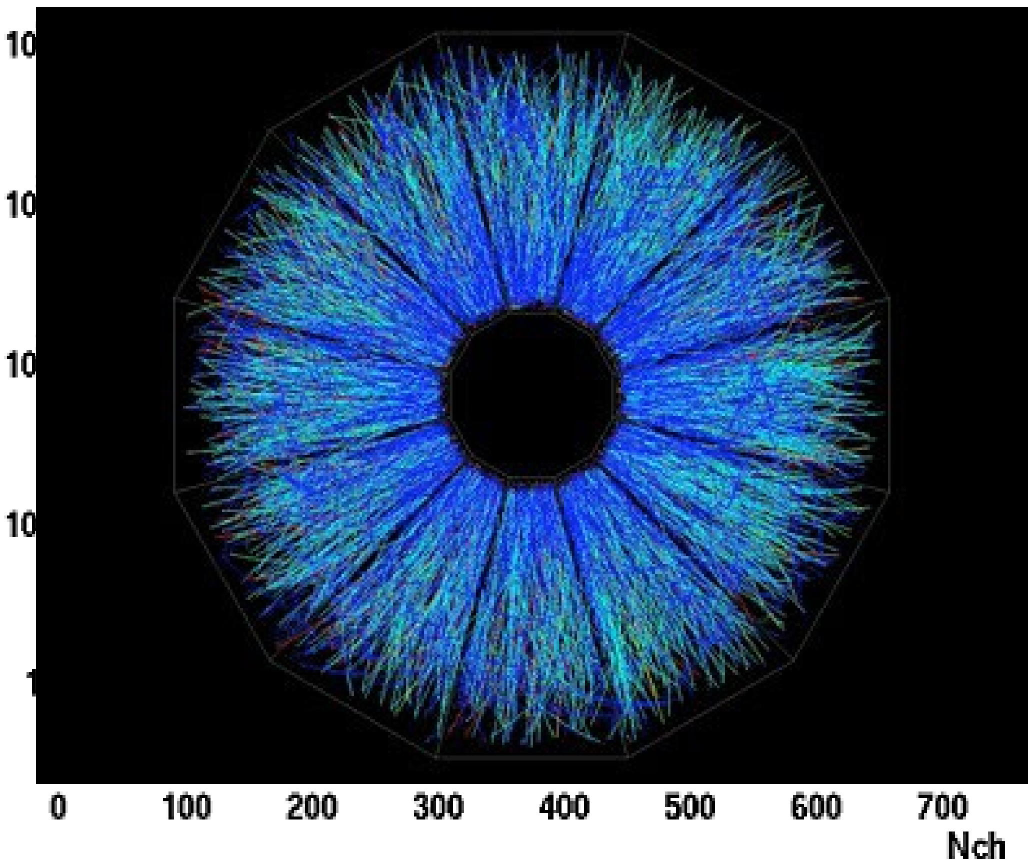




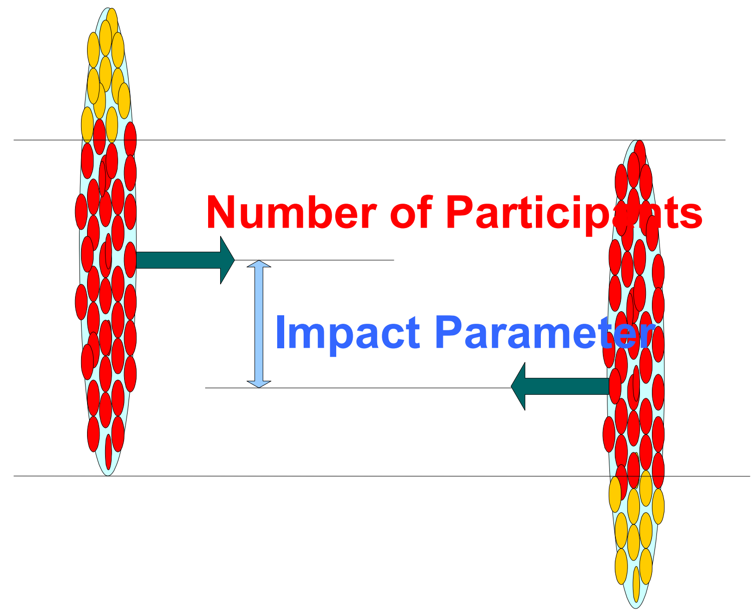


Heavy Ion Collisions

Collision Centrality



centrality

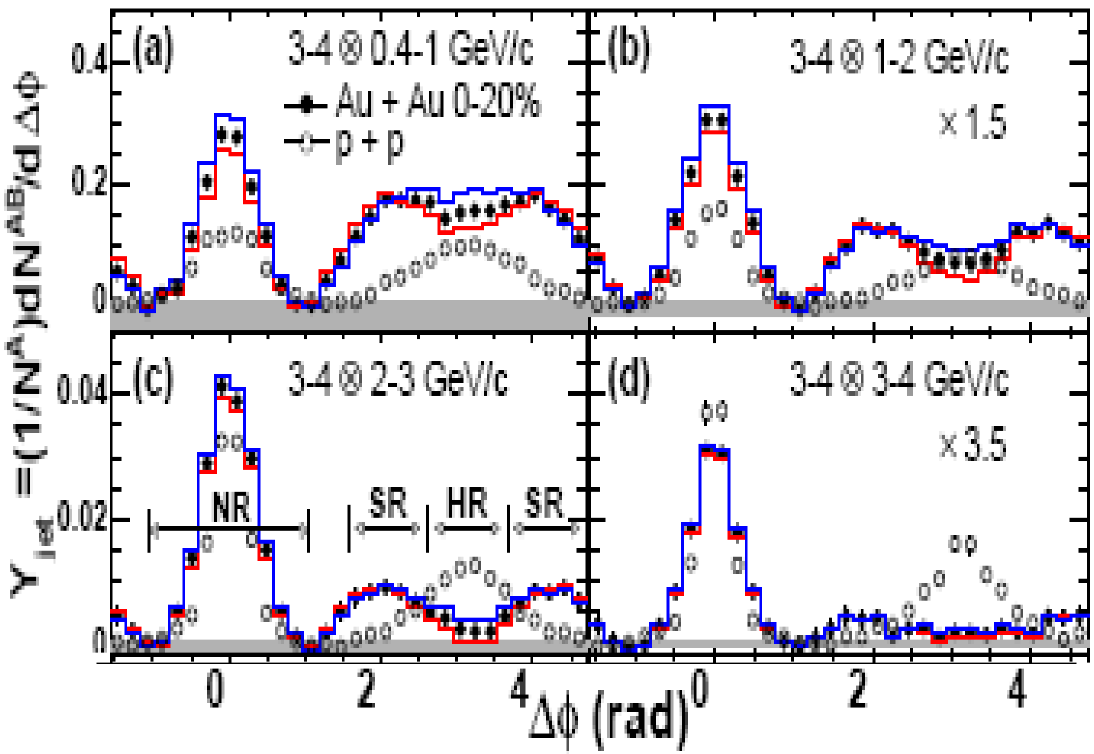


N_{part} = # of participant nucleons
N_{bin}= # of binary collisions

(Estimated by Glauber Model)

Away-side scan

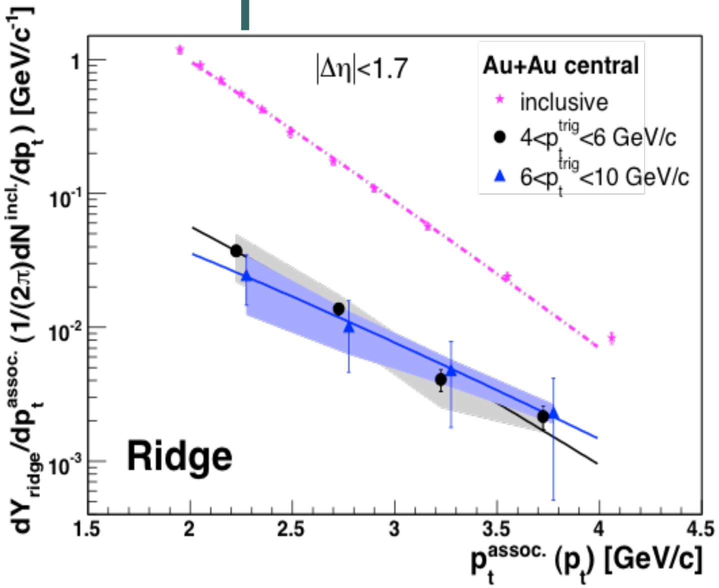
PHENIX
PRC 78, 014901 (2008)

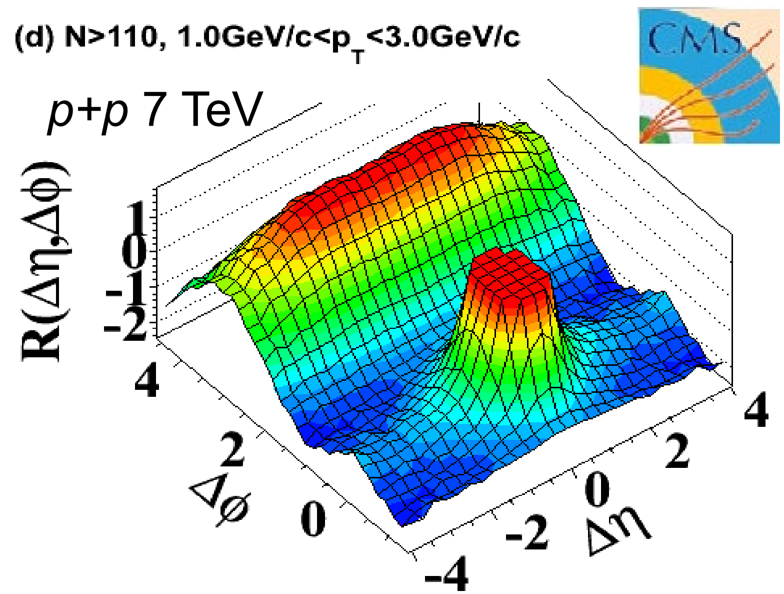


Associated p_T dependence:

- Recovering the away side
- Development of "double-humps" or "shoulders"

What is same-side ridge?





Ridge in high multiplicity p+p at LHC!

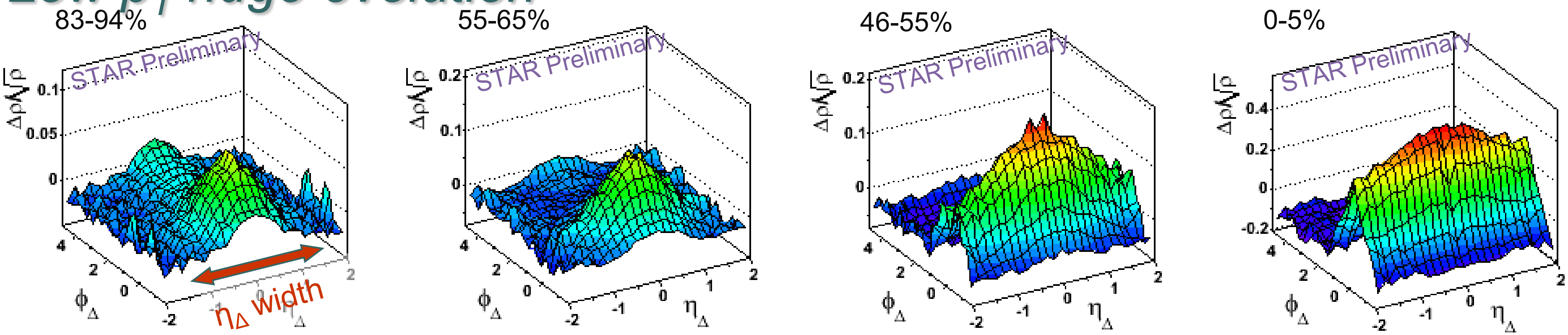
- Jet modified medium?
  - Ridge p_T-spectra and particle ratios are 'bulk-like'
  - Ridge diminishes(?) with p_T^{trig}

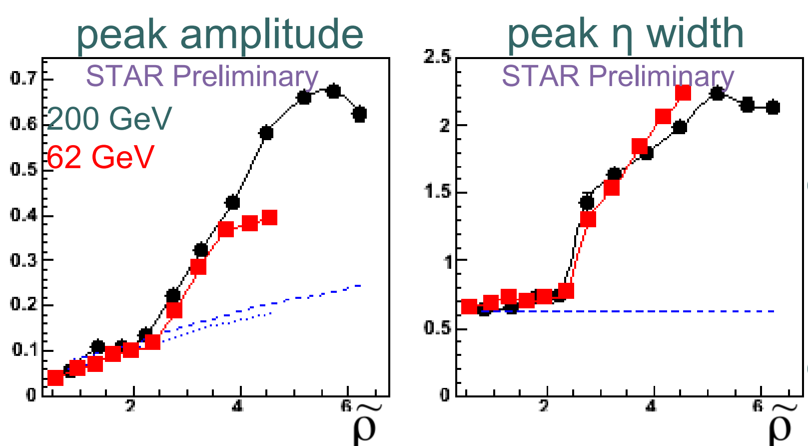
How is it related to jets?

Low p_T ridge

M Daugherity, QM08

Low p_T ridge evolution





Transverse particle density

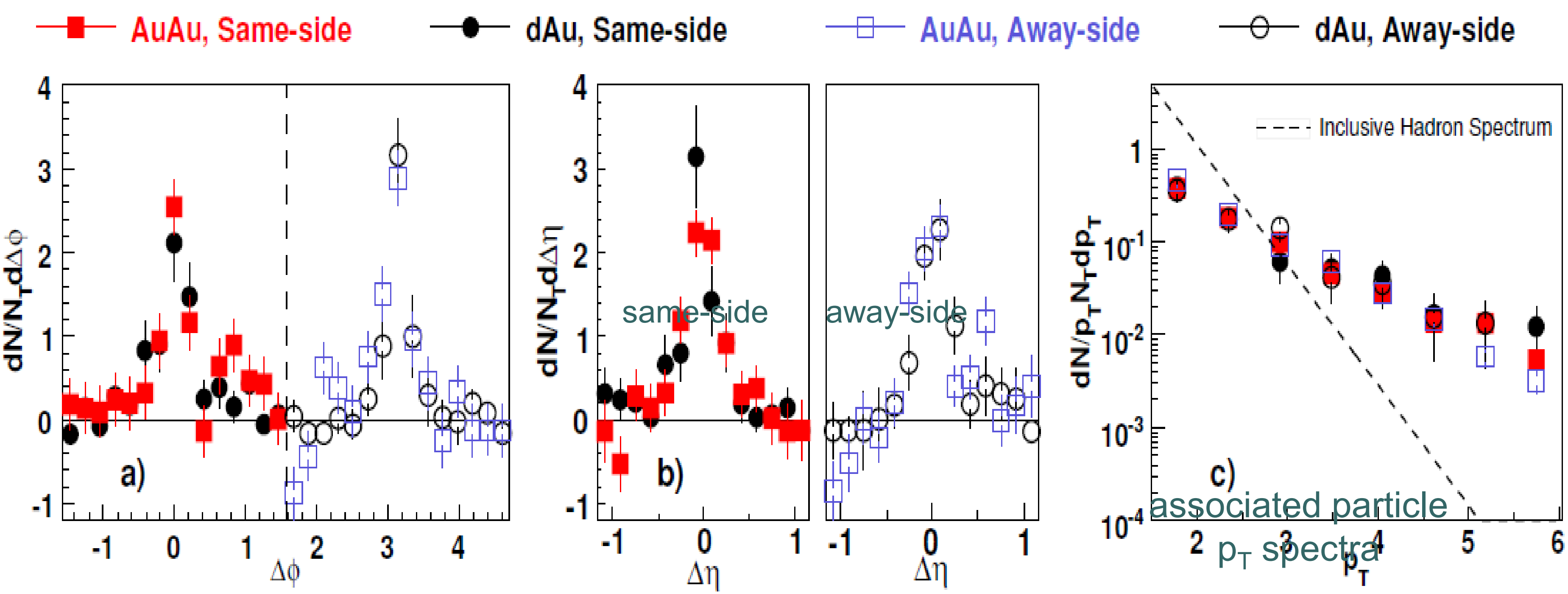
$$\frac{3}{2}\frac{dN_{ch}}{d\eta}/S$$

- Low pT "ridge" – part of "minijet" peak evolution
- Sharp transition in both amplitude and width at ρ ~ 2.5

Surface effects in di-jets

200 GeV Au+Au and d+Au

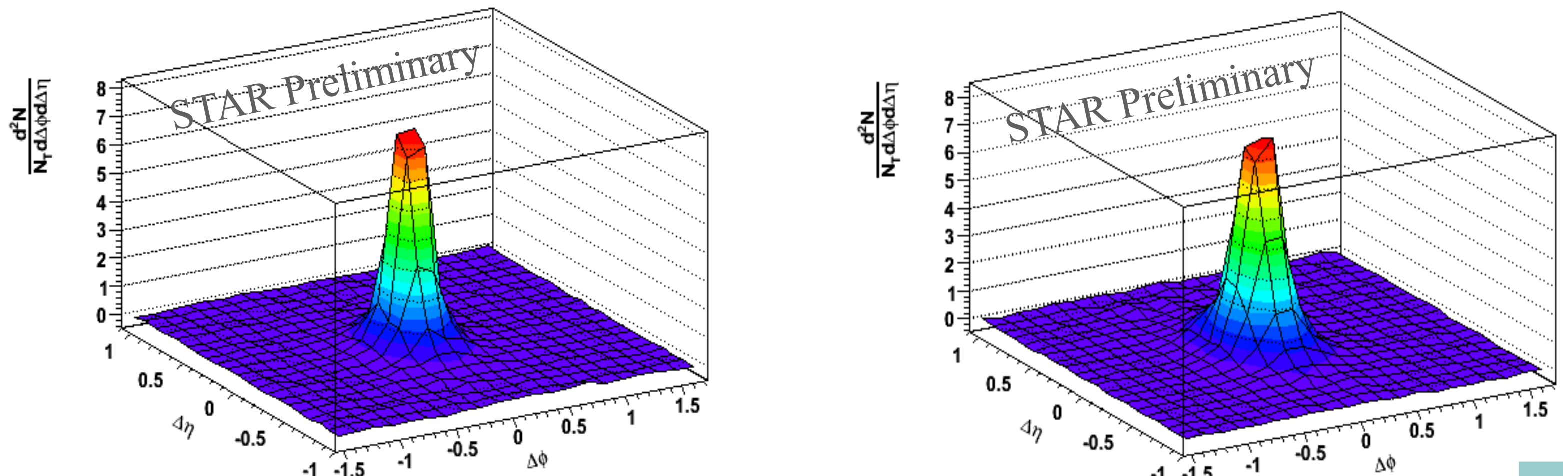
STAR PRC (2011)



- No evidence of medium modifications   Di-jets observed - all tangential?

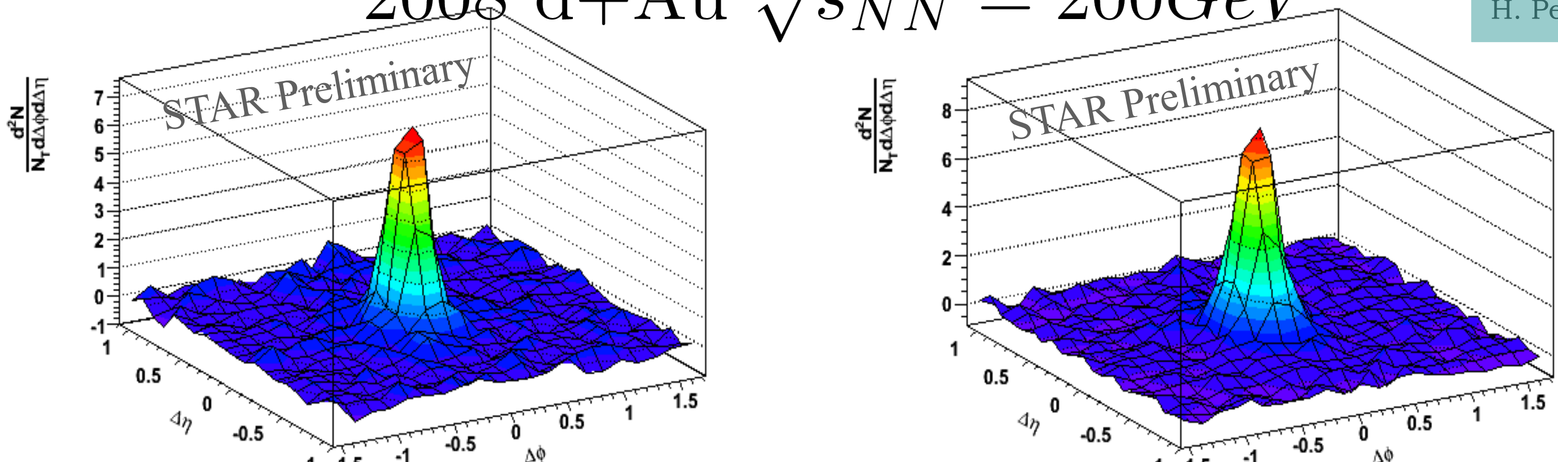
Misbalanced triggers

$8 < E_T^{Trig1} < 15$ GeV/c
$4 < p_T^{Trig2} < 10$ GeV/c
$1.5 < p_T^{Assoc} < 10$GeV/c



$$2008 \text{ d+Au } \sqrt{s_{NN}} = 200GeV$$

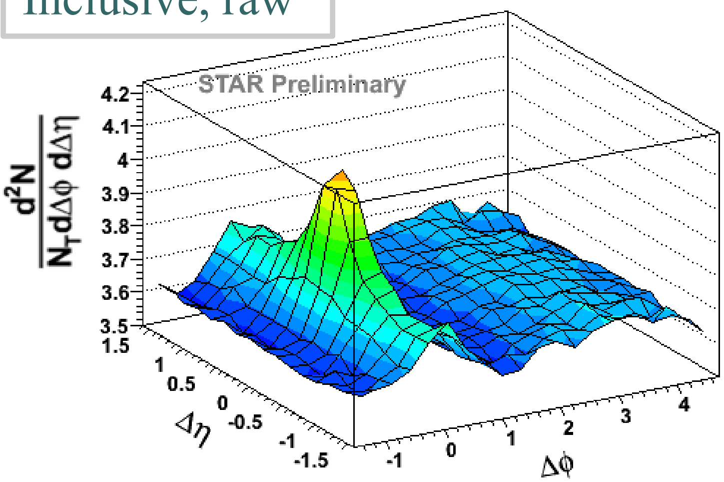
STAR
H. Pei DNP'09

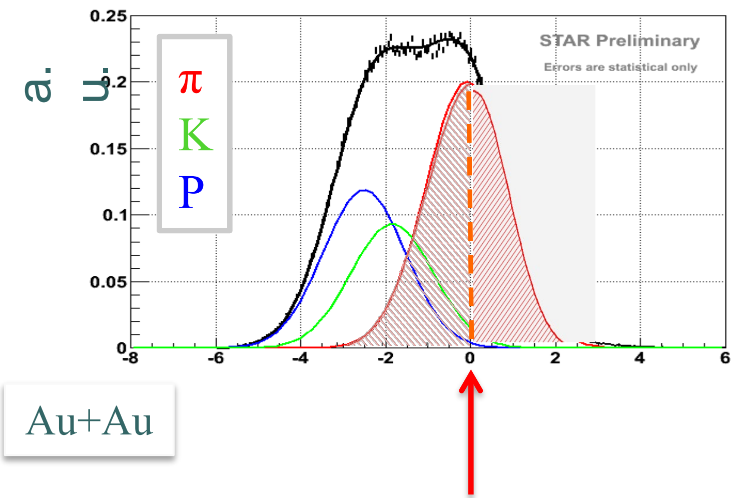


$$2007 \text{ Au+Au } \sqrt{s_{NN}} = 200GeV$$

PID for Trigger hadrons

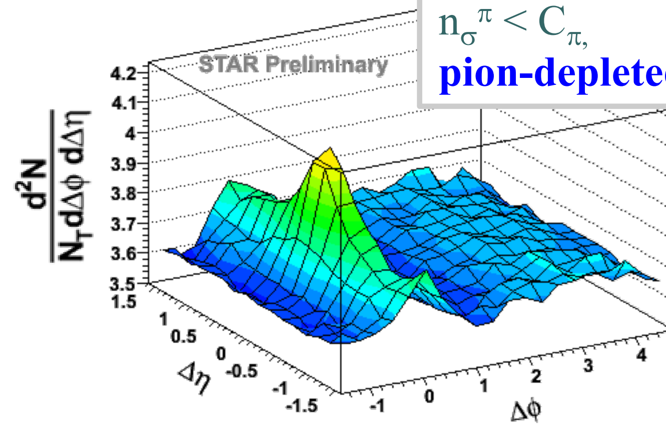
Inclusive, raw



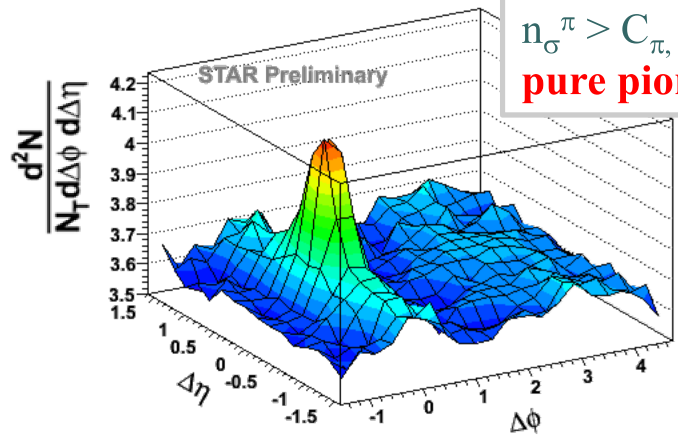


Au+Au

$n_{\sigma}^{\pi} < C_{\pi}$,
pion-depleted sample



$n_{\sigma}^{\pi} > C_{\pi}$, 95%
pure pion sample

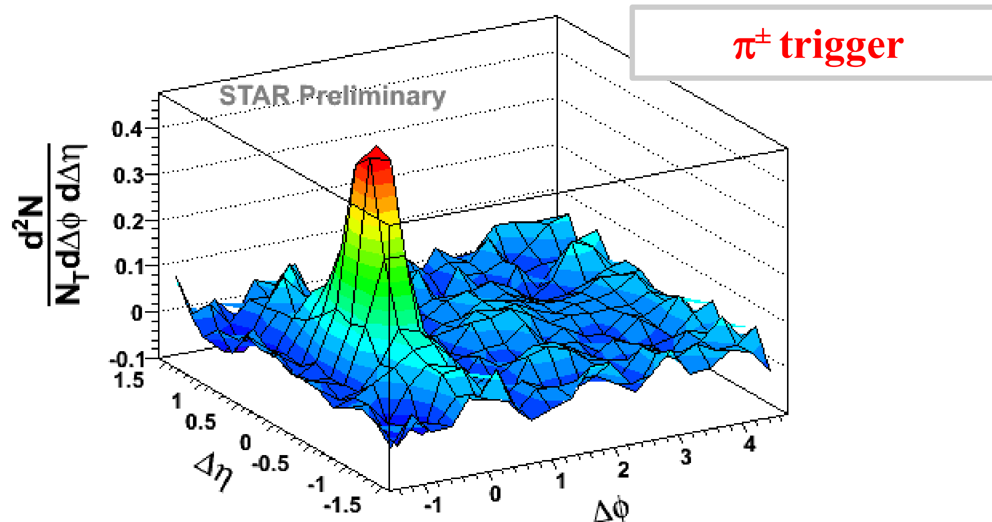


0-10% central, Trigger is highest p_T track

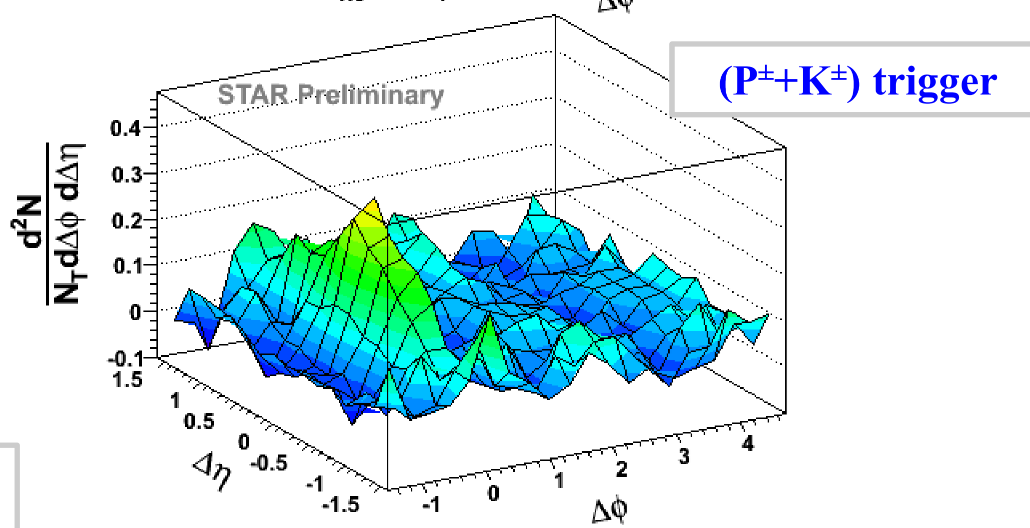
$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c

PID-dependent correlations

- Large jet-like cone, small ridge from pion triggers



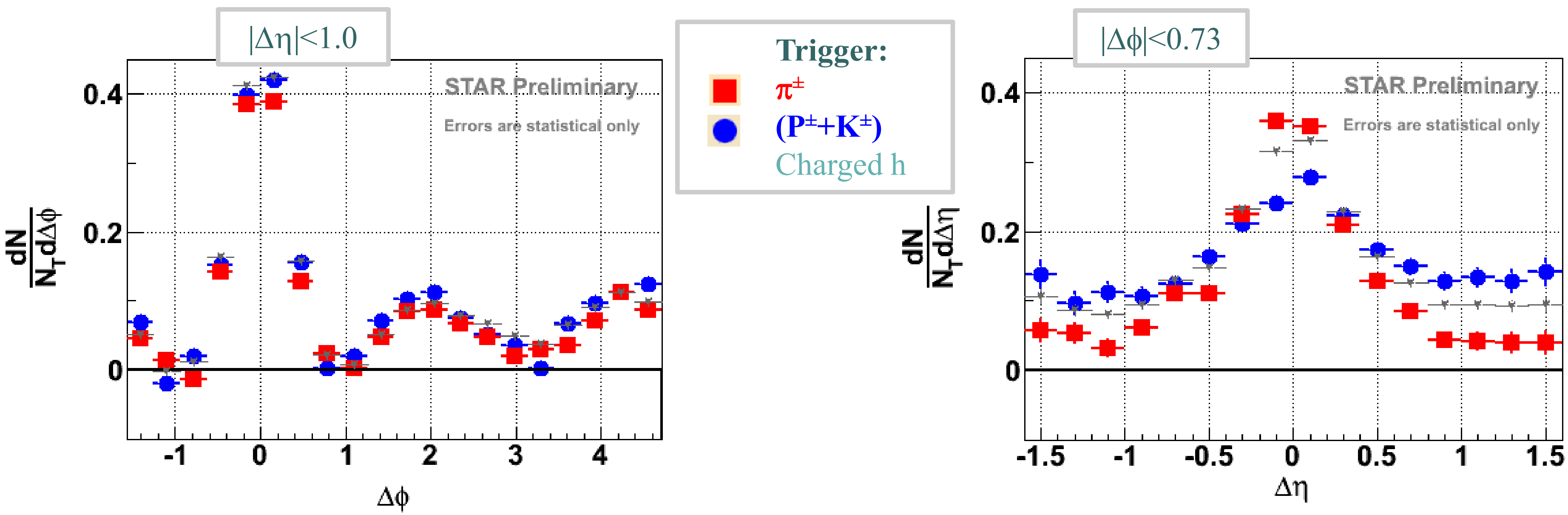
- Smaller cone, large ridge from P+K triggers



Au+Au

$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c

Projections – Au+Au



- Consistent with previous results – but that is a function of projection range!
- Does not reveal entire structure

- Δη reveals rich trigger PID dependent structure:
  - Higher jet-like amplitude for pions
  - Ridge predominantly contributed by non-pion-triggered events

Au+Au

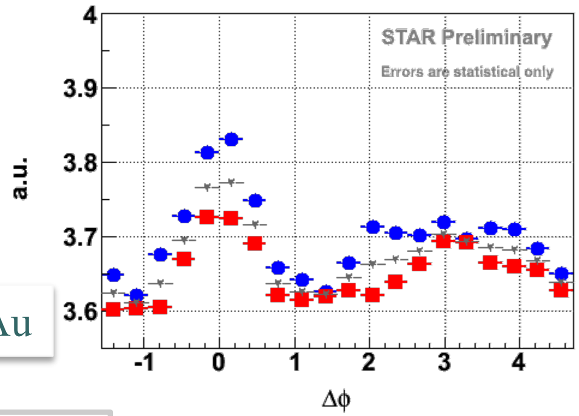
$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c

Raw PID Correlations

$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c

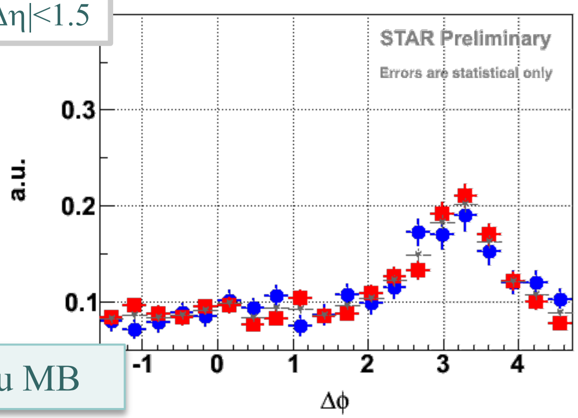
Before background subtraction

- Large $\Delta\eta$: Ridge difference evident in raw correlations.
- Not reconcilable with **symmetric** backgrounds.



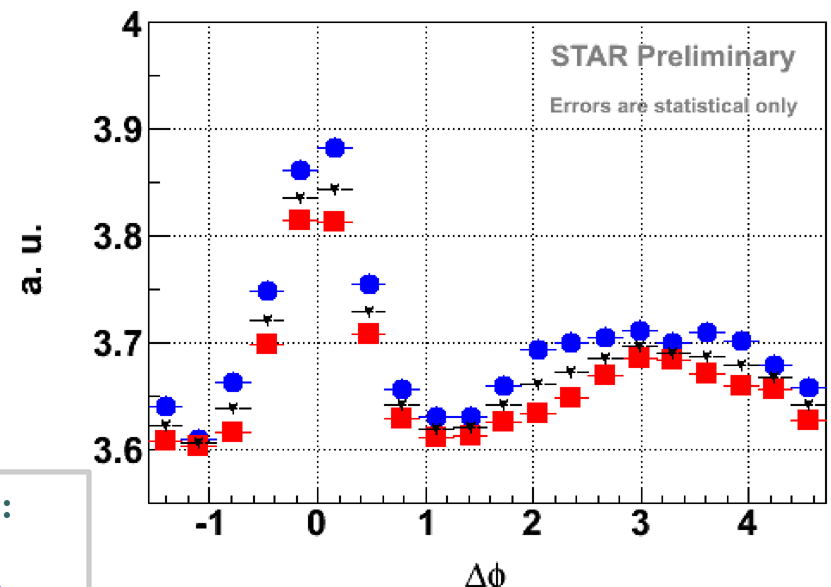
Au+Au

0.7<|Δη|<1.5



d+Au MB

- Full $\Delta\eta$ range: Difference in **away-side** structures.



Au+Au

0 <|Δη|<1.5

Trigger:
$\pi^{\pm}$
($P^{\pm}$+$K^{\pm}$)
Charged h