STAR Recent Results

and perspective

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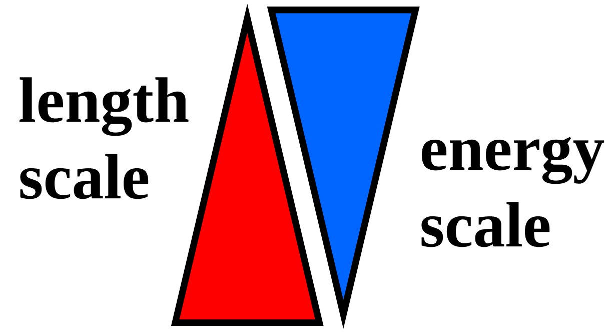
(for the STAR Collaboration)

RHIC-AGS Users Meeting

May 29, 2008

Agenda



Elementary Processes

spin structure of the proton

ultra-peripheral collisions

Parton energy loss – pQCD

light- and heavy-flavor parton energy loss

Fragmentation and the medium – non-pQCD

modified fragmentation and medium properties

Hydro *vs* QCD

dynamical processes at small energy scales

Spin Structure of the Proton

polarized DIS: 0.2~0.3

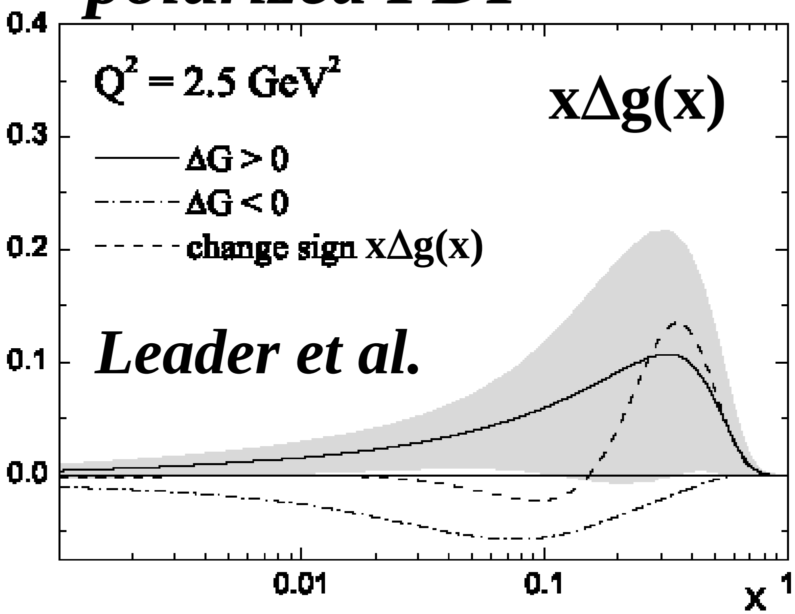
poorly constrained

$$\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

A_{LL} (ΔG)

A_N ($\langle L_z^q \rangle + \langle L_z^g \rangle$)

polarized PDF



RHIC Spin

three recent DIS fits of equal quality:

- ***$\Delta G = 0.13 \pm 0.16$***
- ***$\Delta G \sim 0.006$***
- ***$\Delta G = -0.20 \pm 0.41$***

all at Q^2 = 1 GeV²

[-0.6,0.3]

1σ

Leader et al., PRD 75, 074027 (2007)

first goal of the RHIC Spin program:

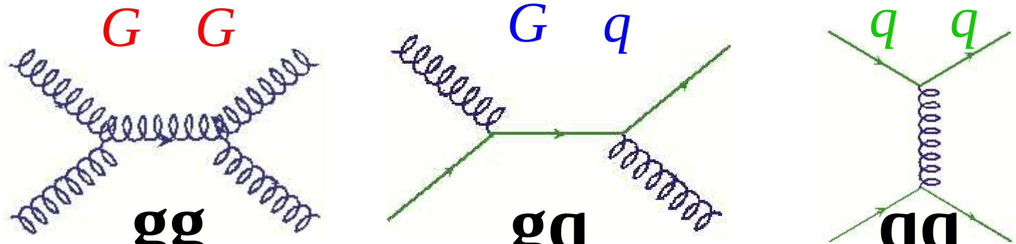
determine the gluon polarization distribution

Polarized p-p Collisions at RHIC

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a}{f_a} \frac{\Delta f_b}{f_b} \hat{a}_{LL} \quad f = g, q$$

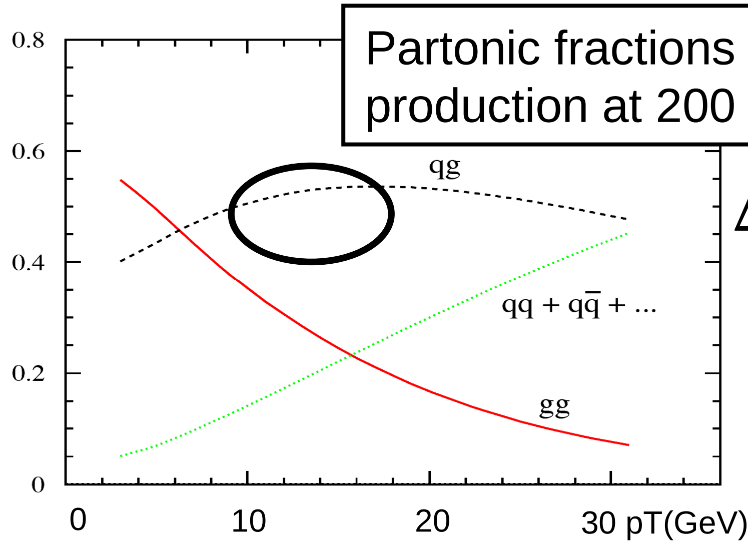
Δf: polarized parton distribution functions

$\frac{\Delta G}{G} \frac{\Delta G}{G}$ $\frac{\Delta G}{G} \frac{\Delta q}{q}$ $\frac{\Delta q}{q} \frac{\Delta q}{q}$

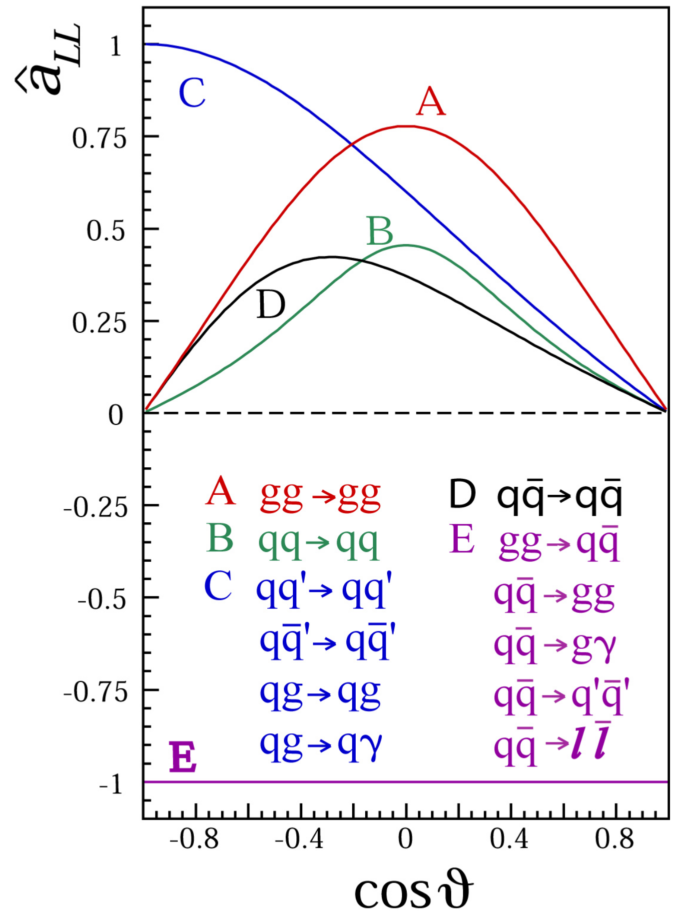


gg **gq** **qq**

Partonic fractions in jet production at 200 GeV



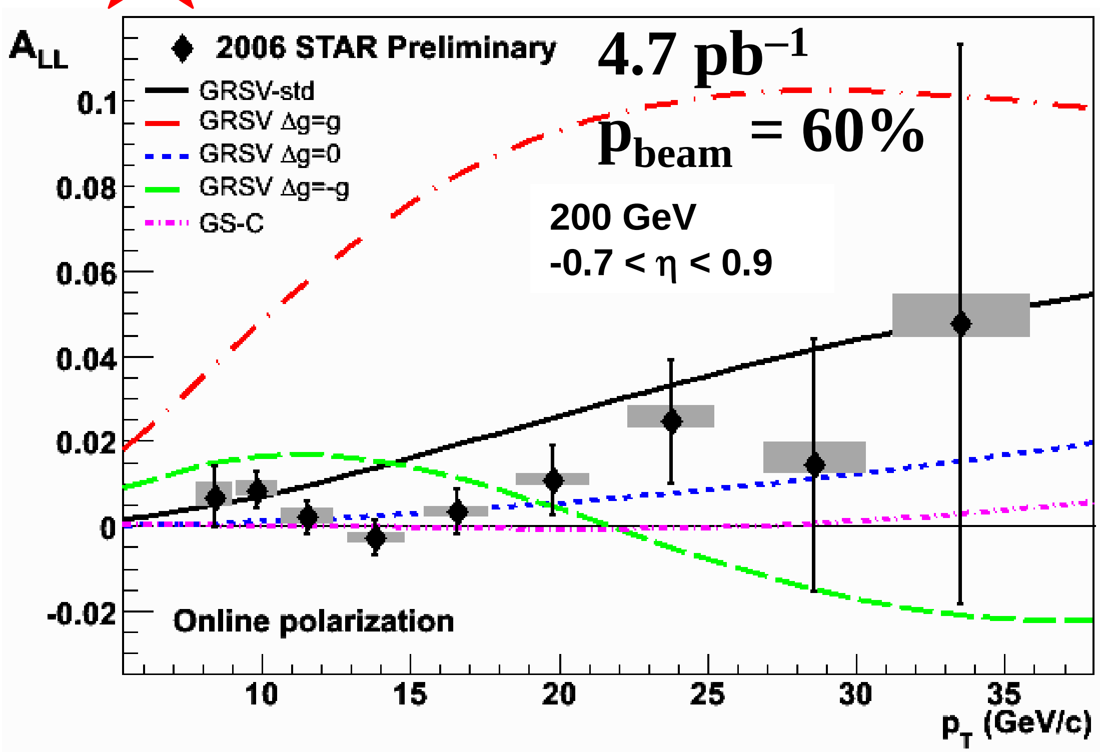
Δg(x) sign

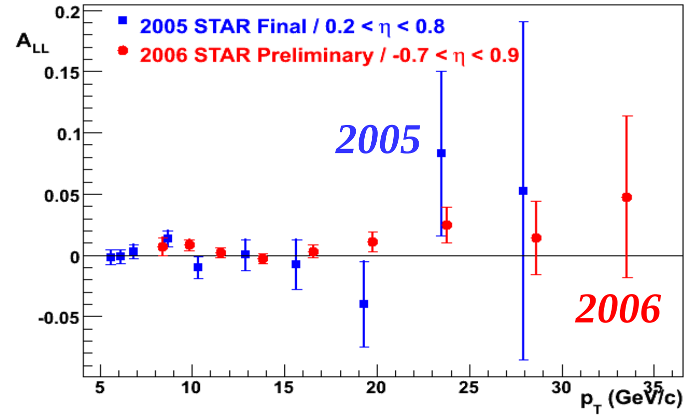


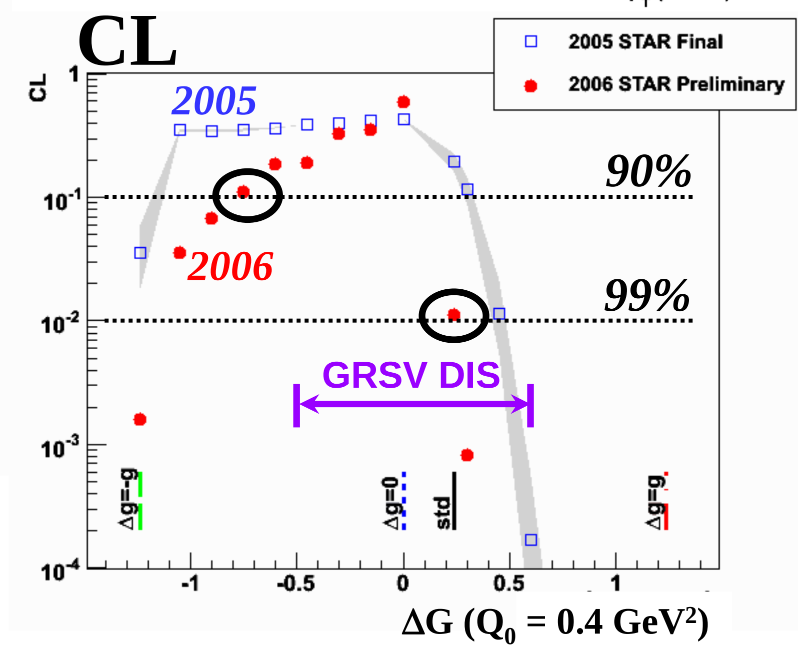
for most RHIC kinematics ***gg*** and ***gq*** dominate – A_{LL} for jets is sensitive to **gluon polarization**

2006 Inclusive-jets A_{LL}

model curves calculated with cone radius 0.7 and $-0.7 < \eta < 0.9$





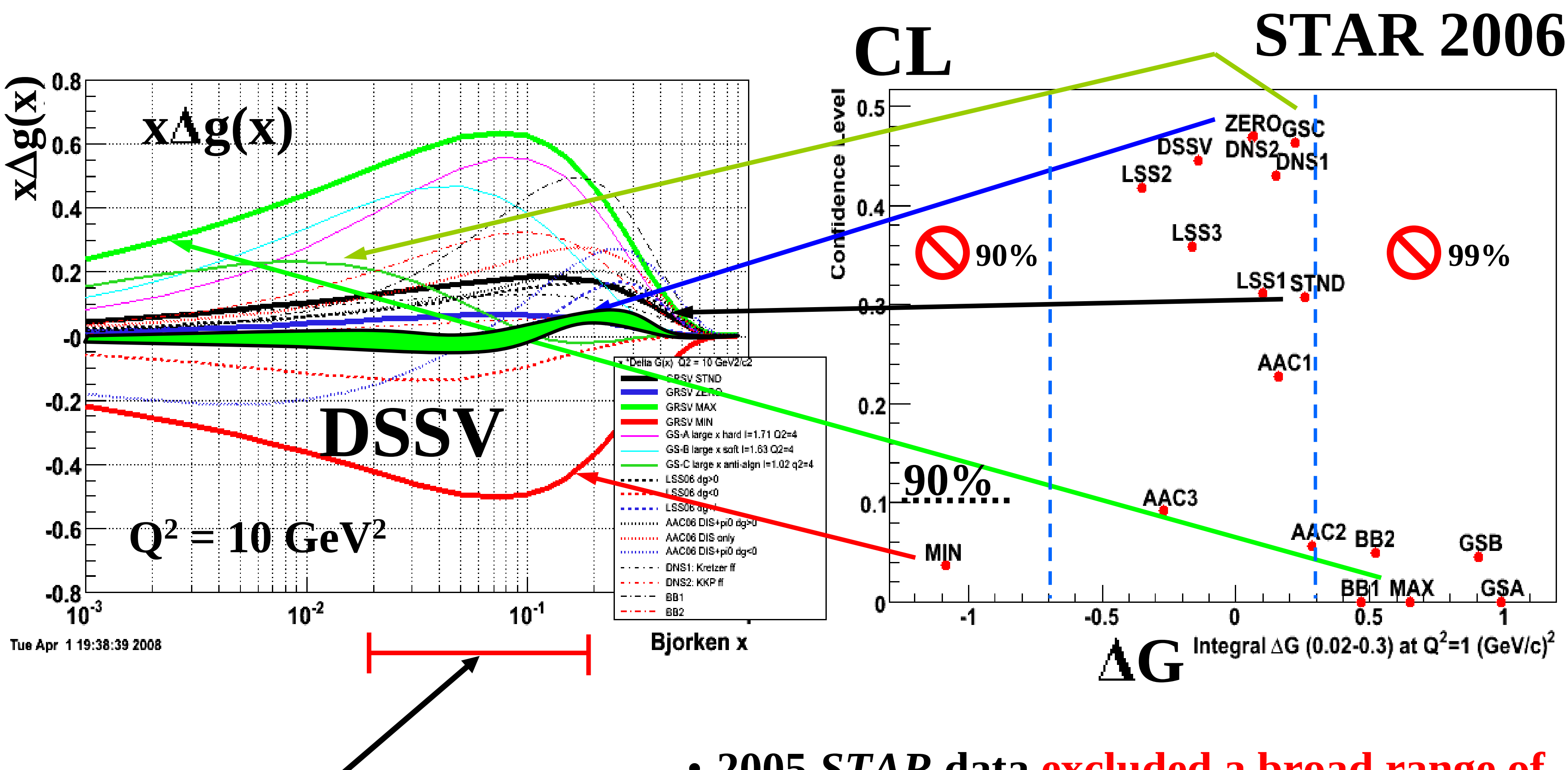


statistical uncertainties 3-4 times smaller than 2005 data for $p_T > 13$ GeV/c

In the GRSV framework: GRSV-std excluded with 99% CL

$\Delta G < -0.7$ excluded with 90% CL

Other Global DIS Analyses



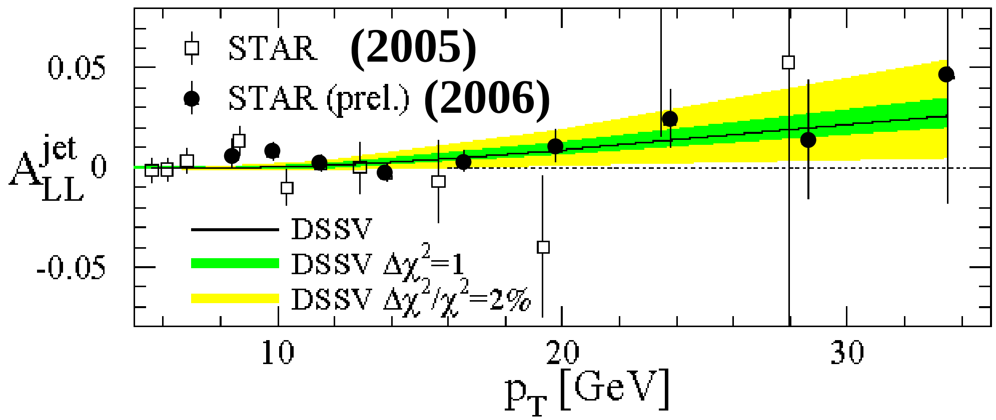
measurements sensitive over this range of x_{gluon}

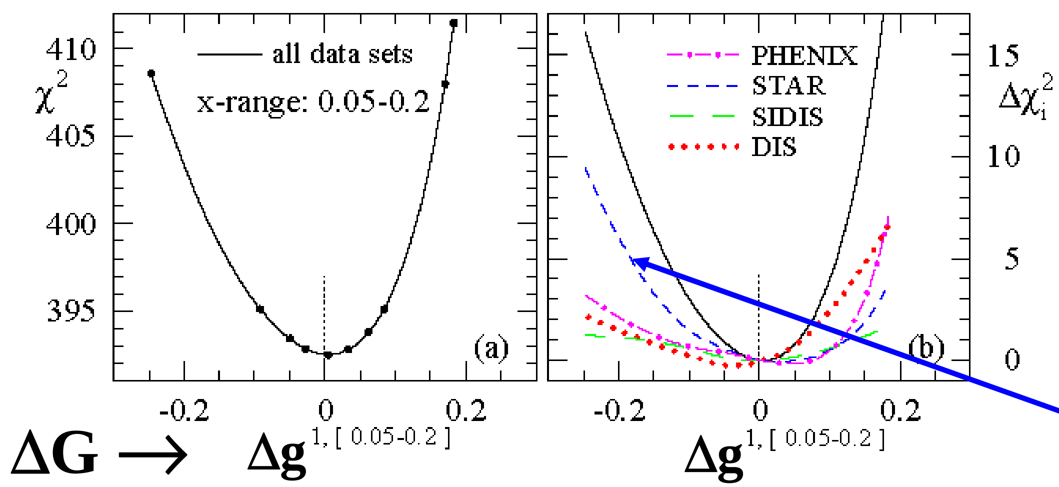
- **2005 *STAR* data excluded a broad range of models with ΔG larger than GRSV-std**
- **Counter-example: GS-C – <u>node</u> near $x \sim 0.1$, large <u>positive</u> integral at small x**

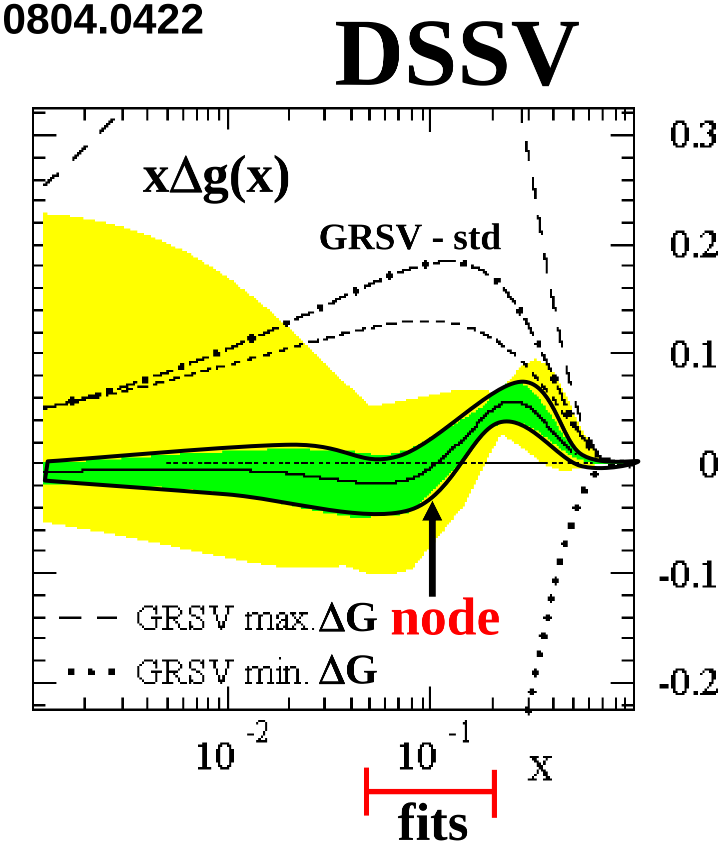
GS-C: Gehrmann & Stirling

First Global Analysis with Polarized Jets

de Florian et al., arXiv:0804.0422







STAR contribution – prevailing limit for ΔG < 0

- **First global NLO analysis to incorporate inclusive DIS, SIDIS, and RHIC pp data on an equal footing**
- **<u>Node</u> in gluon distribution near *x* ~ 0.1 – <u>opposite phase</u> from GS-C**

Near Future: Di-jets and $\Delta g(x)$

jet cuts:

$0.2 < \eta < 0.8$

$\Delta\phi > 2$

$p_T > 5$ GeV/c

$M > 20$ GeV/c^2

$$x_1 = \frac{1}{\sqrt{s}}\left(p_3 e^{\eta_3} + p_4 e^{\eta_4}\right)$$

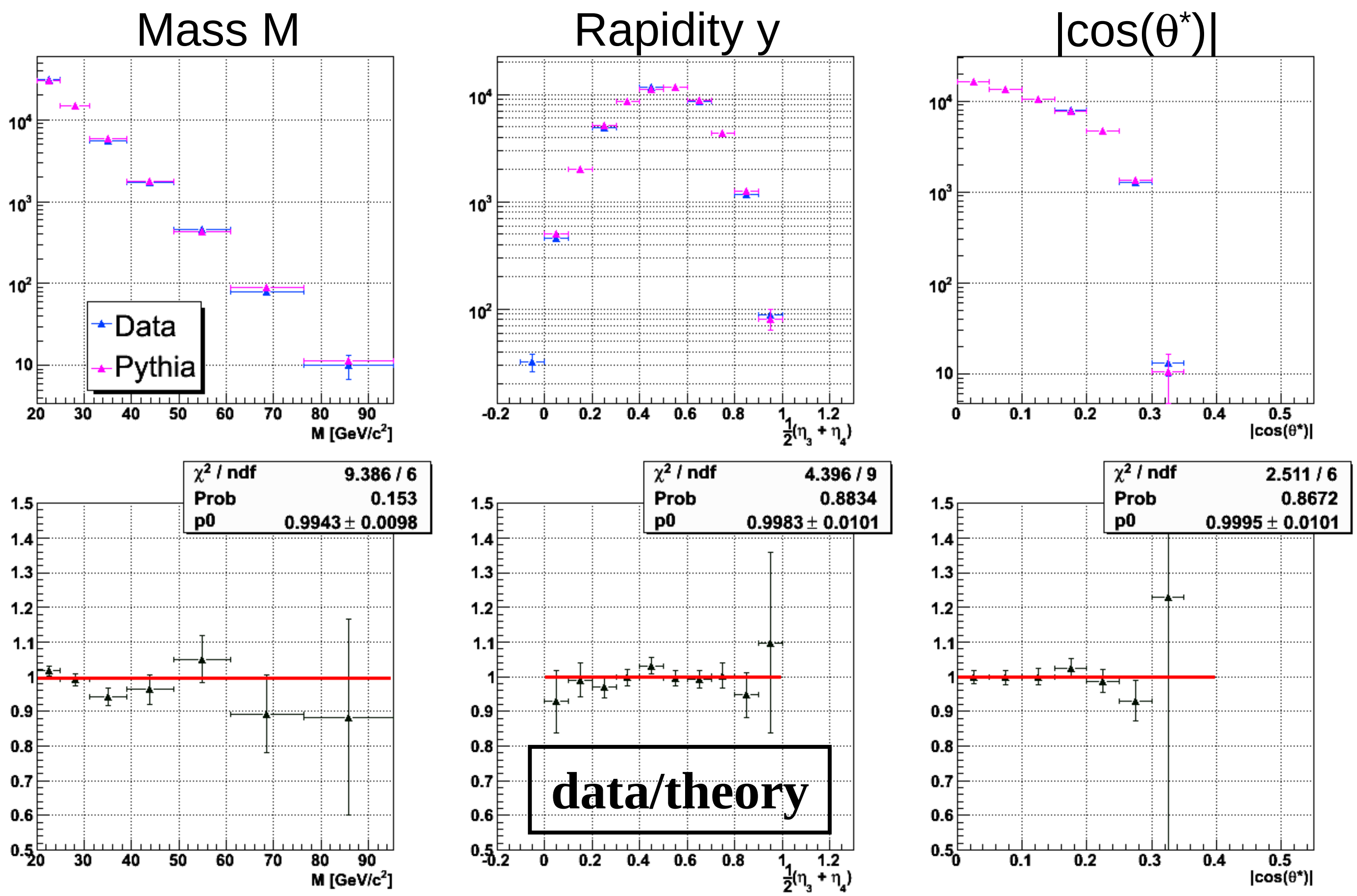
$$x_2 = \frac{1}{\sqrt{s}}\left(p_3 e^{-\eta_3} + p_4 e^{-\eta_4}\right)$$

$$M = \sqrt{x_1 x_2 s}$$

$$y = \frac{1}{2}\ln\frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2}$$

$$|\cos\theta^*| = \tanh\frac{|\eta_3 - \eta_4|}{2}$$

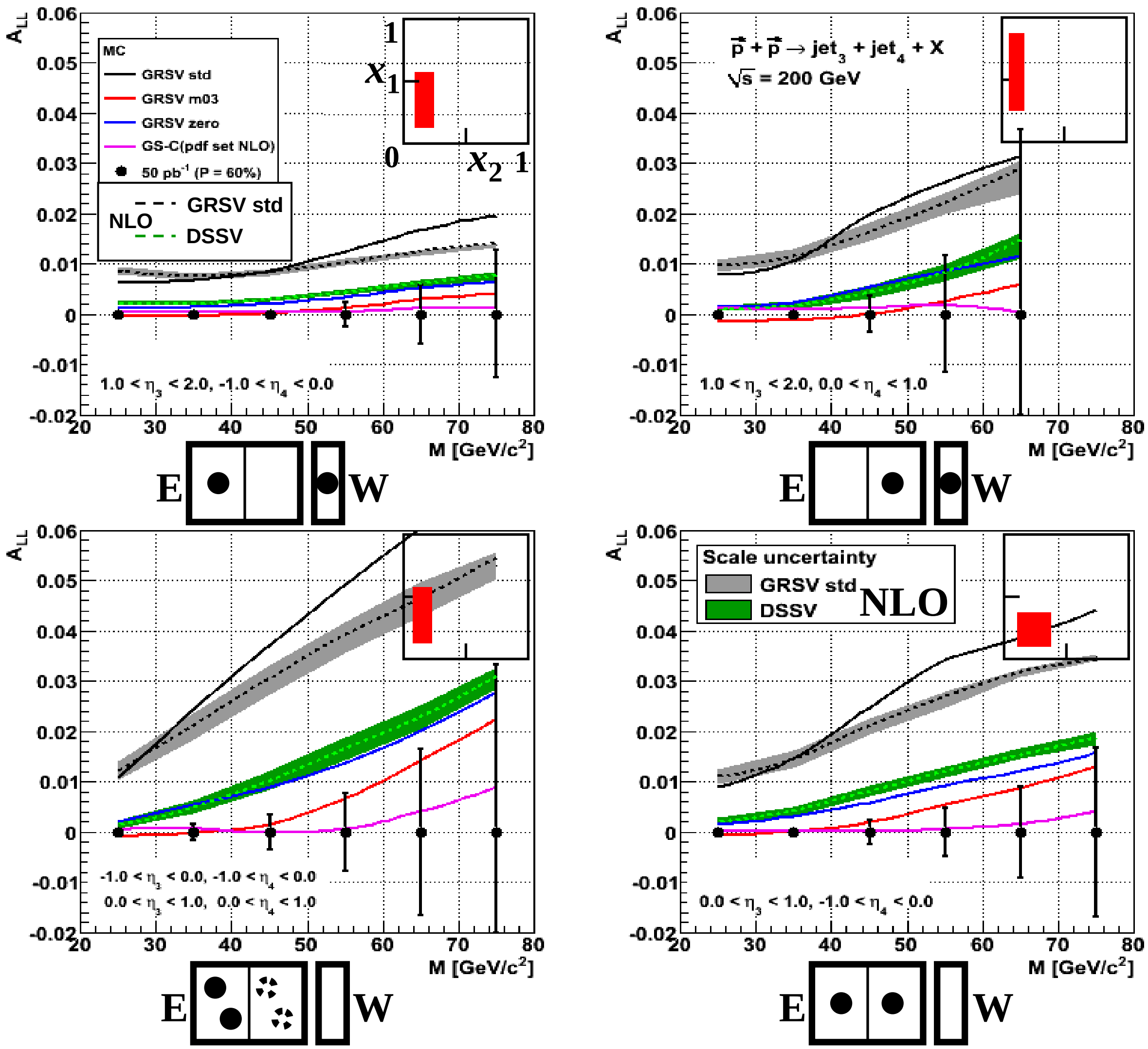
STAR **2005 preliminary di-jet distributions**



di-jets: direct access to parton kinematics at LO

Di-jet Sensitivity in Run 9

EMCal acceptance combinations



Direct access to $\Delta g(x)$ in LO

Full NLO for di-jets ~ LO

Good model discrimination

$x \in [0.05, 0.85]$

200 GeV di-jets dominated by q-g scattering

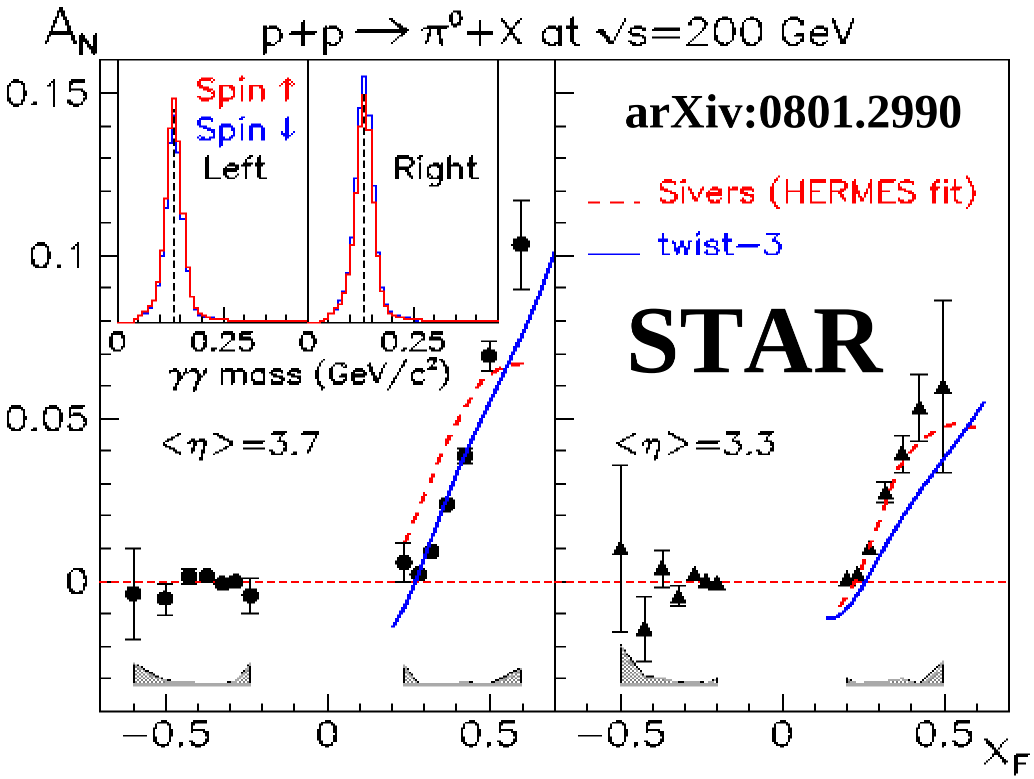
q polarizations large

FoM = P^4L = 6.5 pb^{-1}

data: 50 pb^{-1} of 200 GeV p-p collisions with 60% polarization

A_N 2006 Final Results – FPD

x_f dependence of A_N for forward π production



L_z orbital angular momentum

some aspects of A_N seem well-understood

C. Kouvaris, J. Qiu, W. Vogelsang, F. Yuan, PRD 74 (2006) 114013

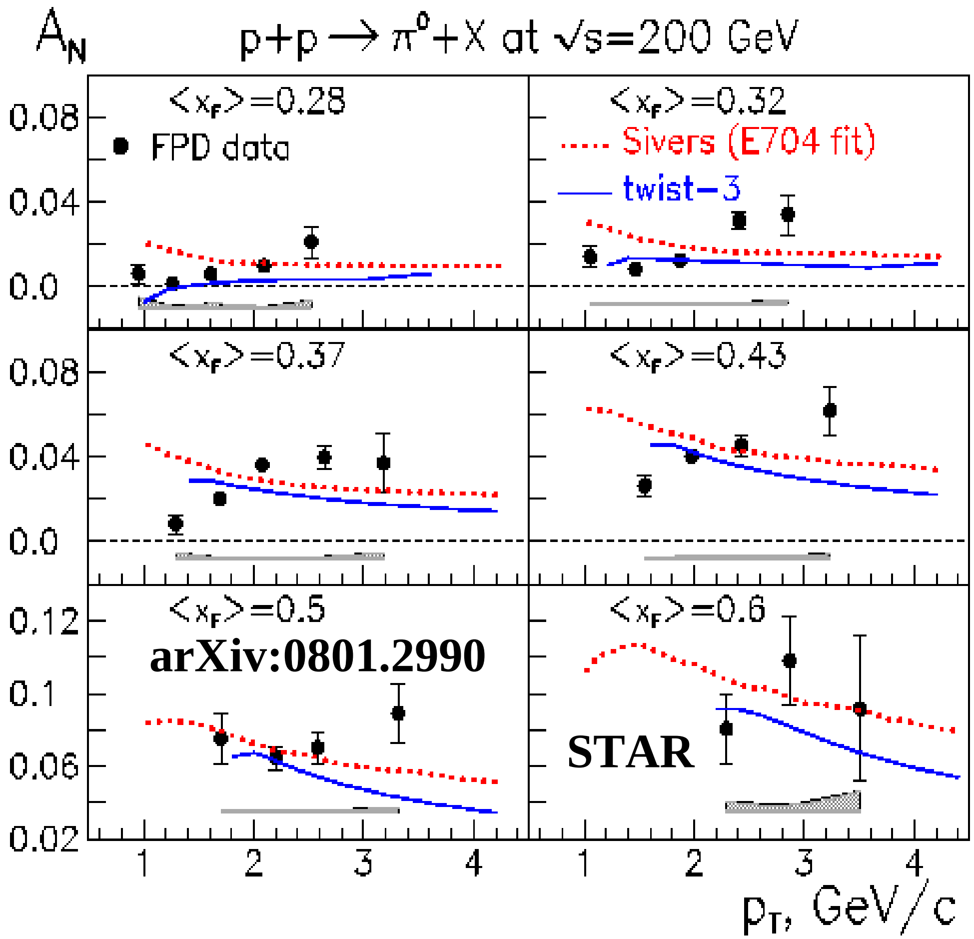
M. Boglione, U. D'Alesio, F. Murgia arXiv:0712.4240

SIDIS measurements and forward π^0, $\pi^\pm$ data have small kine overlap, but…

most features of RHIC $A_N(x_F)$ data described by phenomenology from SIDIS

A_N 2006 Final Results – FPD

first $\boldsymbol{p_T}$ ***dependence of*** $\boldsymbol{A_N}$ ***for forward*** $\boldsymbol{\pi}$ ***production***



while some do not

data-driven problem

FMS and RHIC II

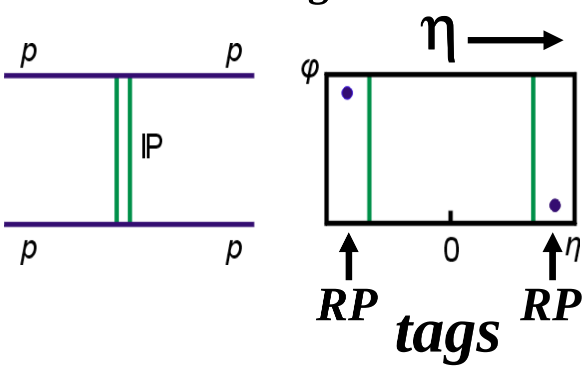
p_T dependence of A_N at fixed x_F <u>not</u> explained

Sivers: A_N should <u>decrease</u> with increasing p_T

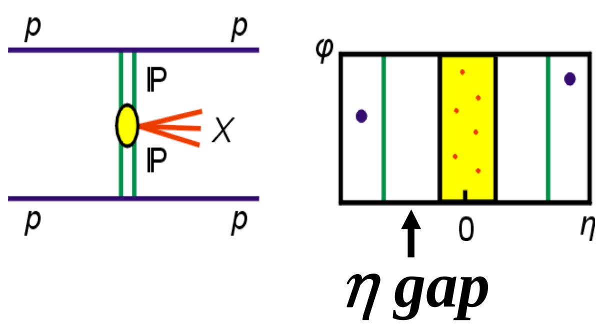
pp2pp: Tagged Forward Protons

- **Elastic and inelastic hadron diffraction and its spin dependence in unexplored *t* and *s* ranges**
- **Structure of color-singlet exchange in non-perturbative regime of QCD**
- **Central production of light and massive systems**
  - **Particle production**
  - **Exotics: glueballs, hybrids, …**

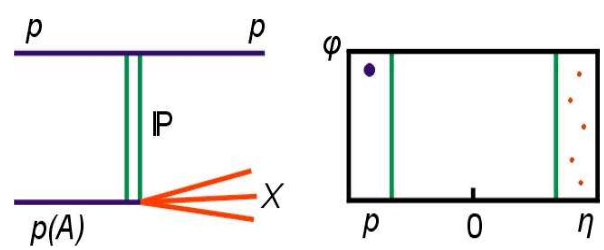
Elastic Scattering



Central Production



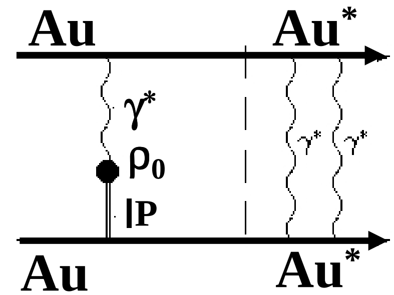
Single Diffraction



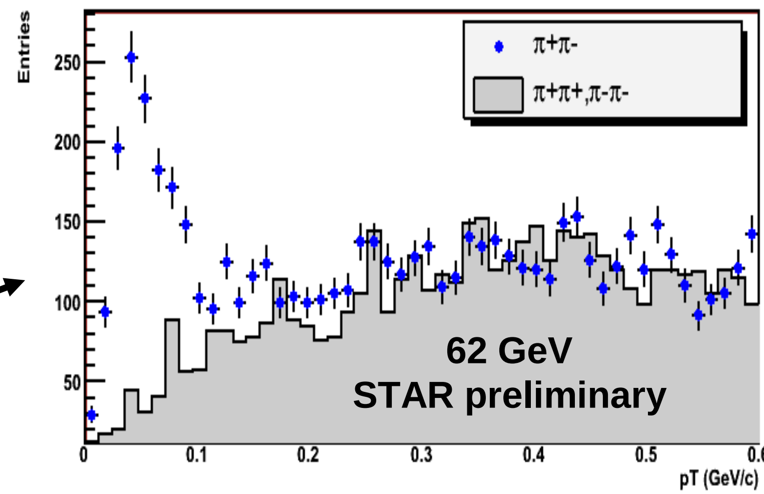
- **Roman Pots (RPs) measure momentum transfer from diffracted protons**
- **STAR RPs installed (Phase I, 2008) (Phase II, additional RPs – Run 11)**
  - **No impact on backgrounds in STAR mid-rapidity detectors**
- **pp2pp integrated into STAR Trigger and DAQ systems**

UPC Processes

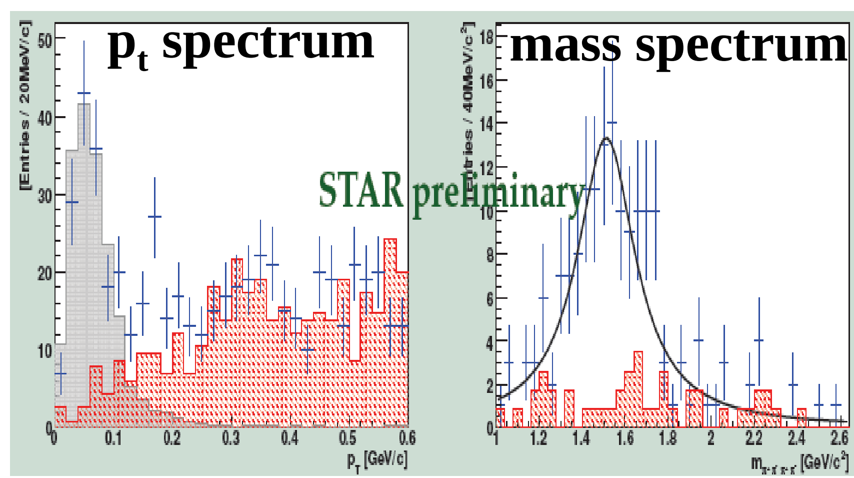
ultra-peripheral collisions



- **Coherent/incoherent photo-production of ρ^0 ($\sqrt{s_{NN}}$ = 130, 200 GeV)**
  - **Excludes several models: PRL 89 272302 (2002); PRC 77, 034910 (2008)**
- **ρ^0 photo-production in dAu $\sqrt{s_{NN}}$ = 200 GeV and AuAu $\sqrt{s_{NN}}$ = 62 GeV**



- **Observation of two-source interference in the photo-production reaction AuAu→AuAuρ^0 (EPR paradox)**
- **Resonant $\pi^+\pi^-\pi^+\pi^-$ photo-production in AuAu collisions at $\sqrt{s_{NN}}$ = 200 GeV**
  - **Test of the coupling to the nucleus, ρ(1450) and ρ(1700) candidates**

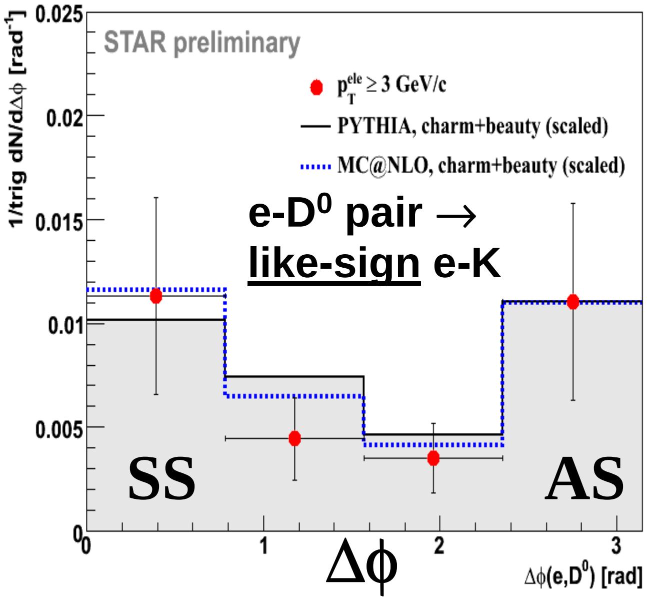


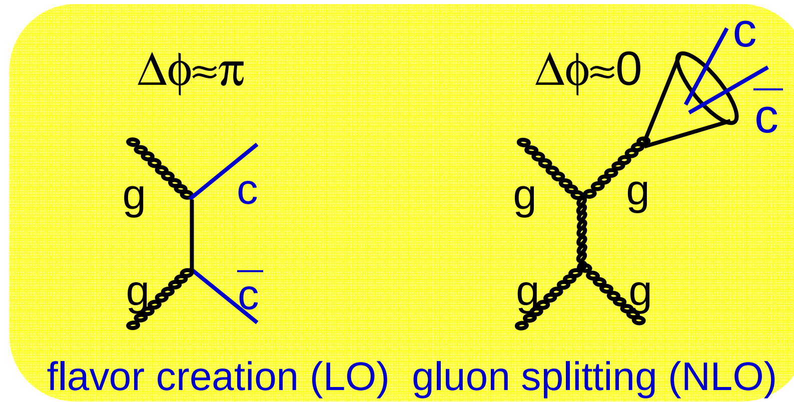
e-h Azimuth Correlations

p-p 200 GeV
reference system

charm, bottom, NLO processes (splitting)

e-D⁰ correlations

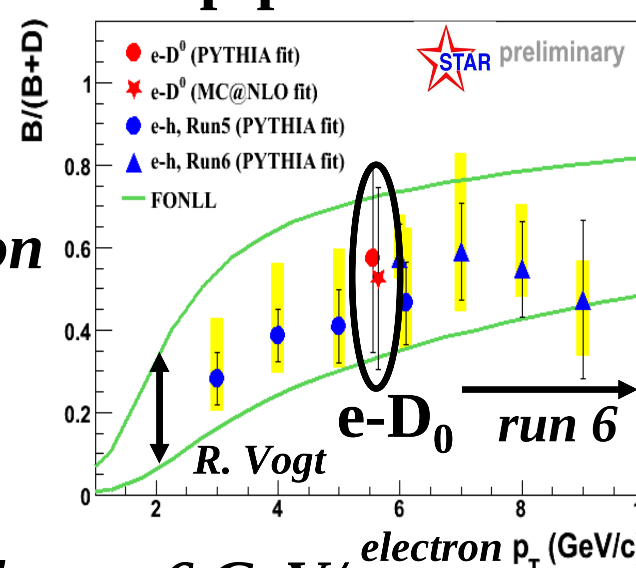




comparisons to Pythia and MC@NLO

p-p 200 GeV

B fraction



mainly b, NLO c	*c, b contribute*

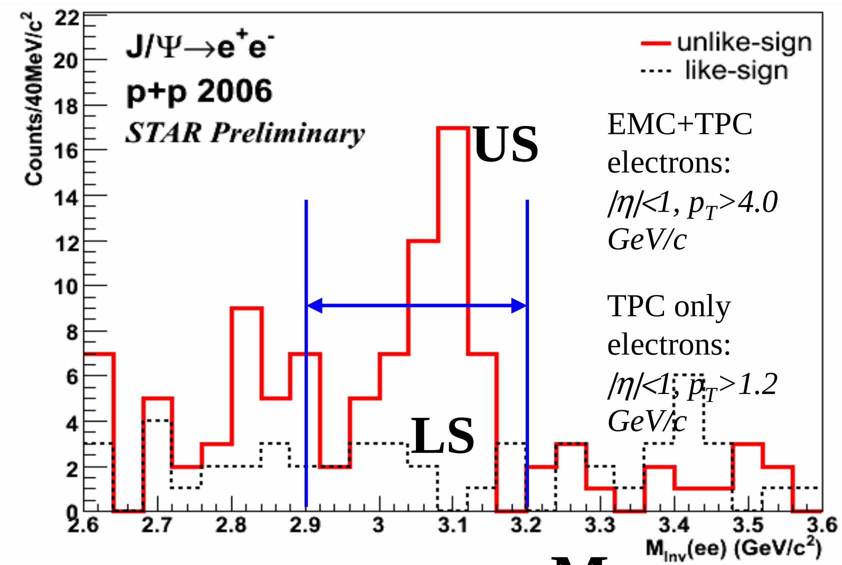
clear same-side signal

consistent with Pythia, MC@NLO

10× improvement with RHIC II

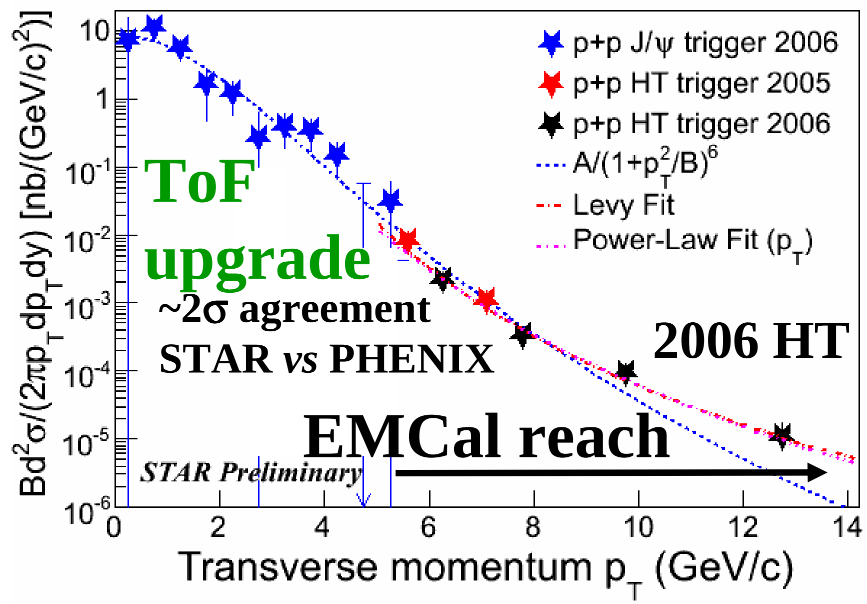
significant (~50%) b contribution to NP-e above ~6 GeV/c

J/ψ Production in p-p



M_{inv}

e-e mass spectrum

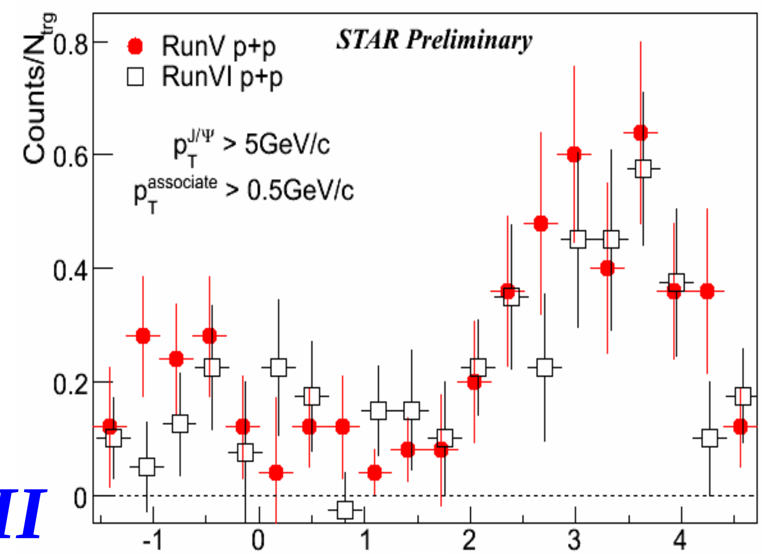


J/ψ – h correlations in p-p

weak same-side signal

constrains B contribution to J/ψ yield

10-40× improvement with RHIC II

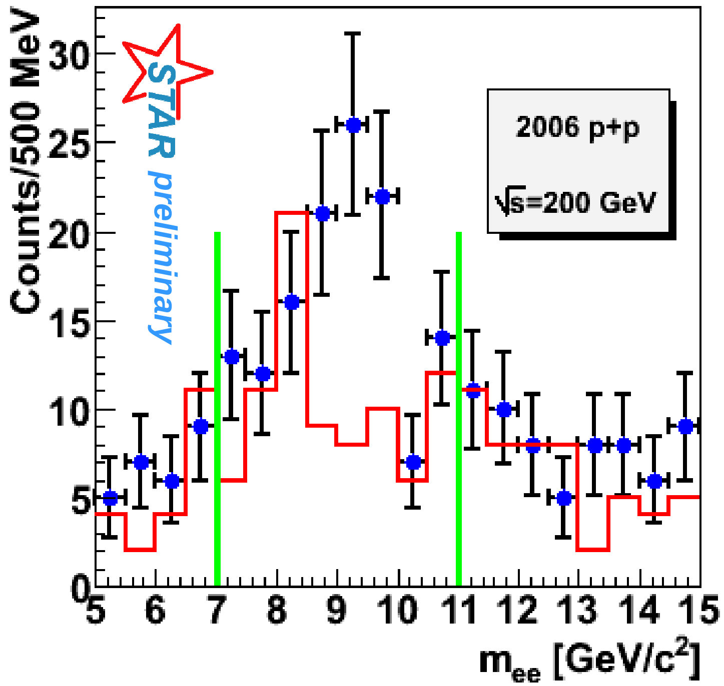


0 Δϕ π

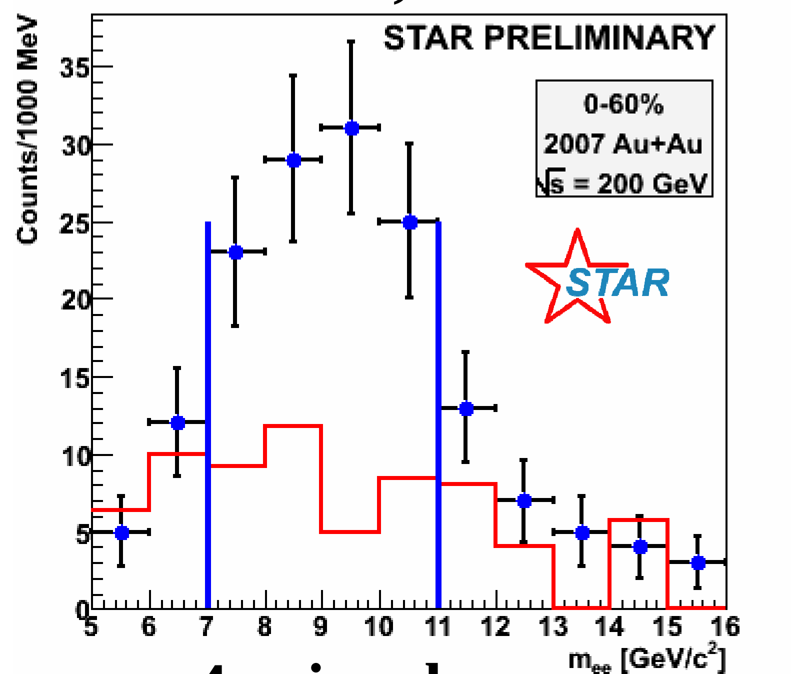
ϒ Production in p-p and Au-Au

e-e mass spectra

p-p



Au-Au, 0-60%



4σ signal

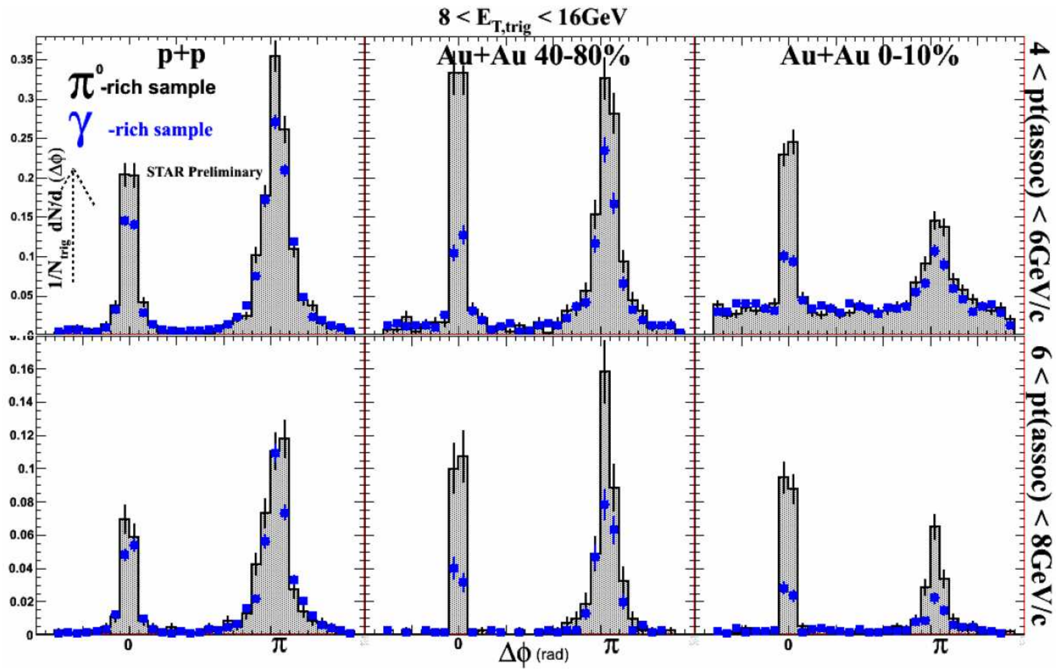
cross section measured
consistent with pQCD

first measurement of ϒ in A-A

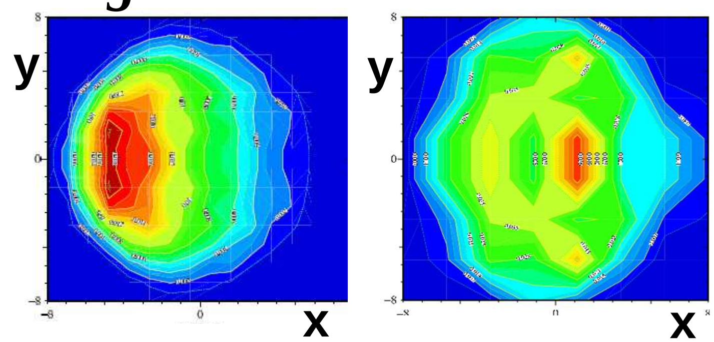
on-going analysis: first look at ϒ R_{AA}

10-70× improvement with RHIC II

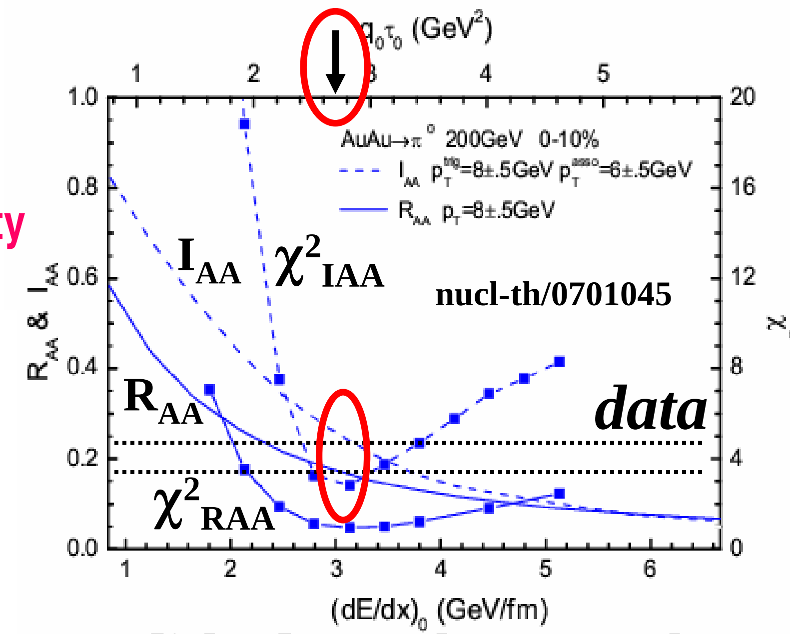
Di-hadron,γ-hadron Correlations



single-hadron *di-hadron*

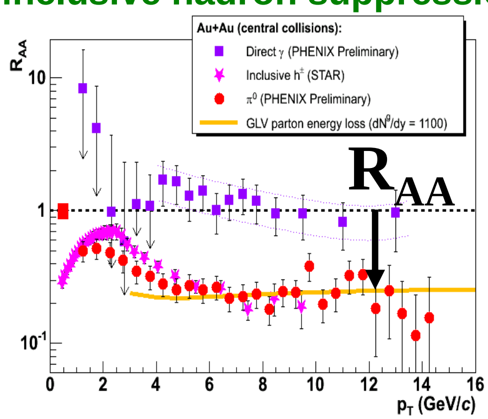


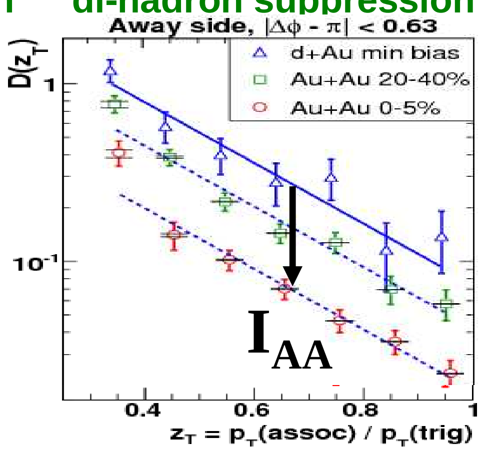
less surface bias



First steps to precision study with RHIC-II high luminosity

inclusive hadron suppression **di-hadron suppression**

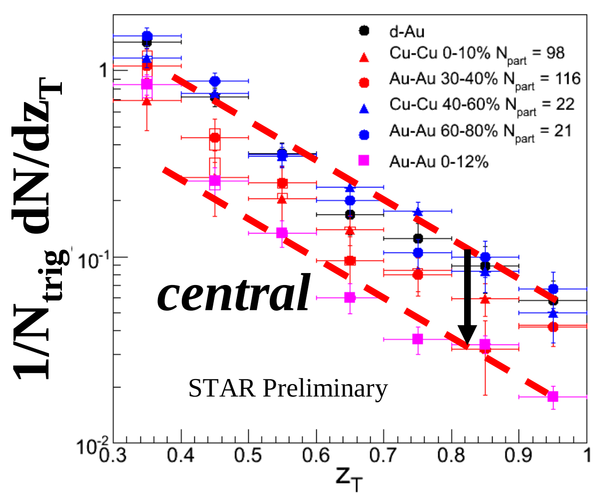


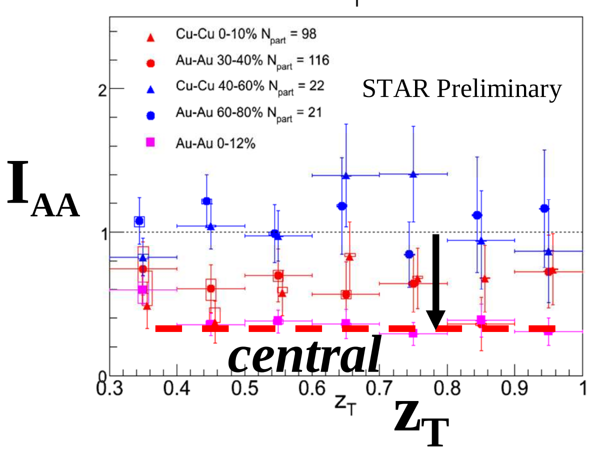


di-hadrons: better probes of initial density

Away-side Di-hadron FFs

$z_T = p_T^{assoc} / p_T^{trig}$





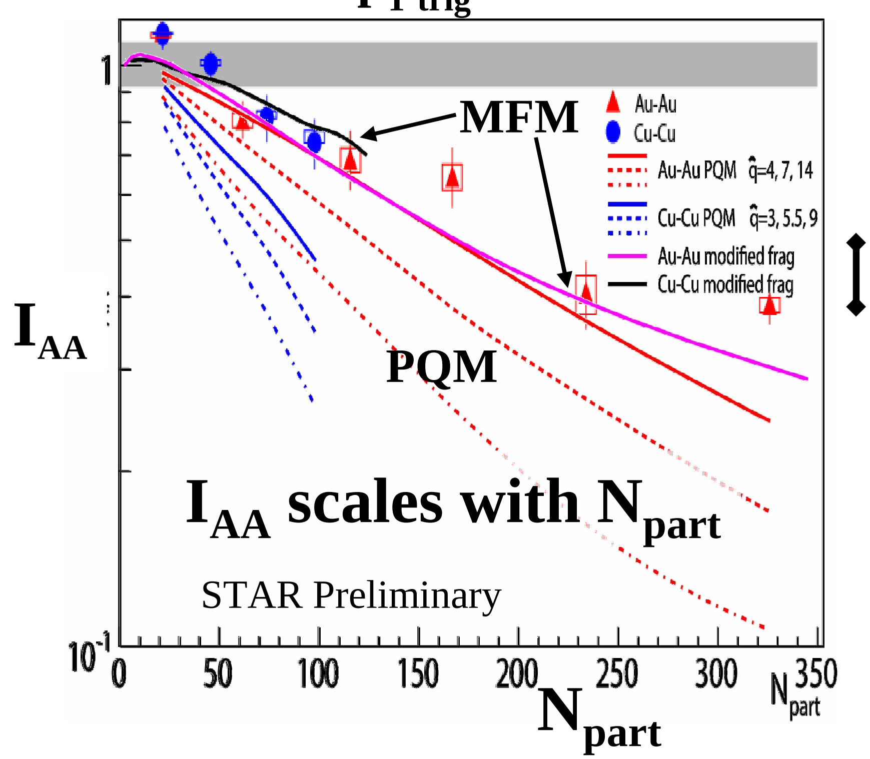
Au-Au

vs

Cu-Cu

$$I_{AA} = \frac{D_{AA}(z_T, p_T^{trig})}{D_{pp}(z_T, p_T^{trig})}$$

6 < $p_{T\ trig}$ < 10 GeV



denser medium in central Au-Au compared to central Cu-Cu

inconsistent with Parton Quenching Model

PQM: C. Loizides, Eur. Phys. J. C 49, 339 (2007)

→ Modified Fragmentation Model

MFM: H. Zhang et al., PRL 98, 212301 (2007)

γ-hadron Correlations, Clusters

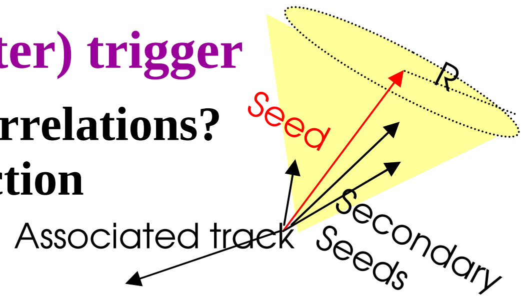
γ-jet events are rare → large luminosity

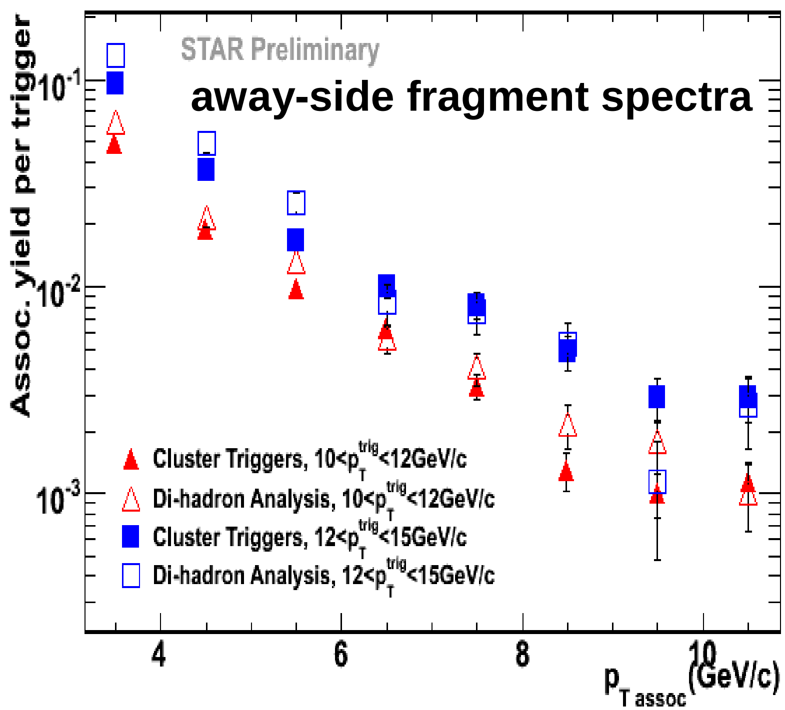
first measurements… RHIC run-7

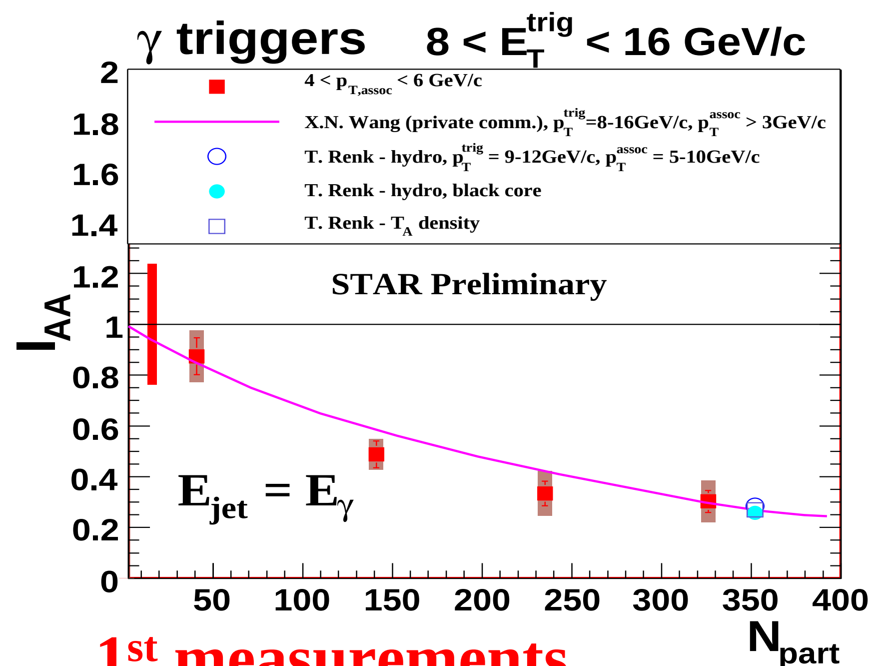
10-40× improvement with RHIC II

multi-hadron (cluster) trigger

biased di-hadron correlations?
→ HI jet reconstruction







1st measurements…
away-side γ-h correlations

X.-N. Wang, et al. PRL 77, 231 (1996)

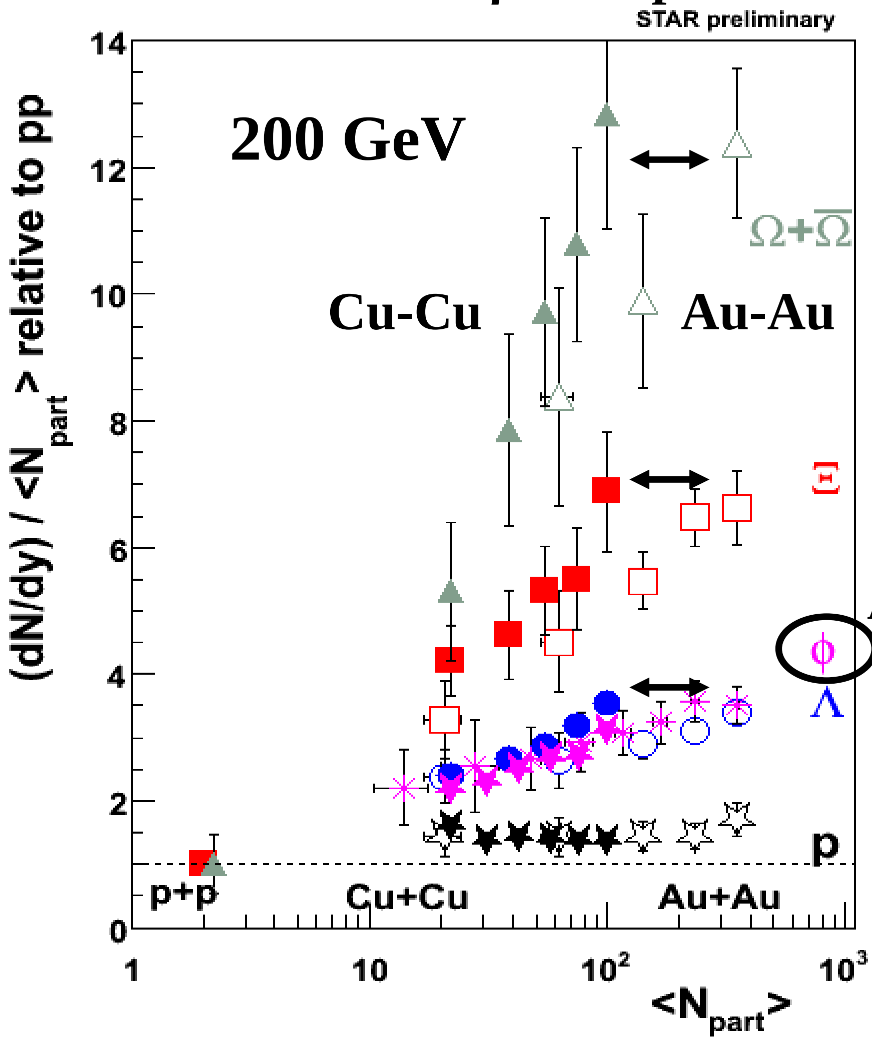
single-hadron and multi-hadron triggers give similar results

suppression similar to inclusives in central collisions

Strangeness Enhancement

strange baryons vs ϕ – yield systematics

similar trends for antiparticles



Au-Au *vs* Cu-Cu

enhancement measure $\frac{2}{N_{part}} \frac{dn/dy_{AA}}{dn/dy_{pp}}$

strangeness enhancement does not follow a simple N_{part} power-law scaling

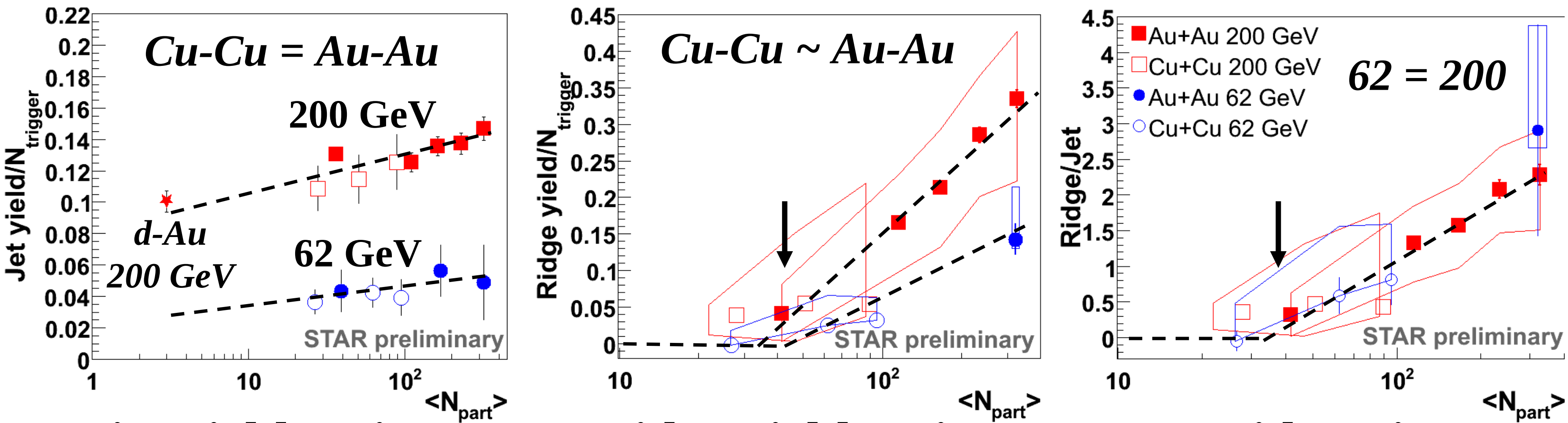
similar effects seen in Ω/ϕ, Λ/K p_t spectrum ratios for Cu-Cu vs Au-Au

Energy and System Dependence

dashed lines guide the eye

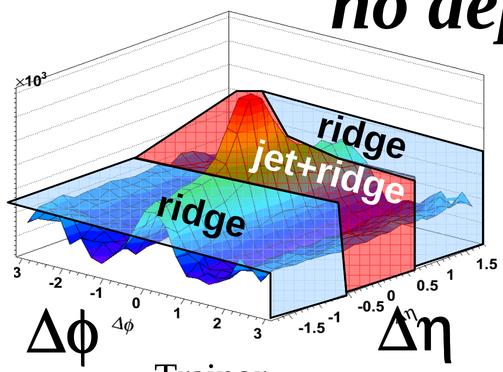
angular correlation systematics

common jet/ridge trends for different collision systems



jet yield / trigger **ridge yield / trigger** **ridge / jet**

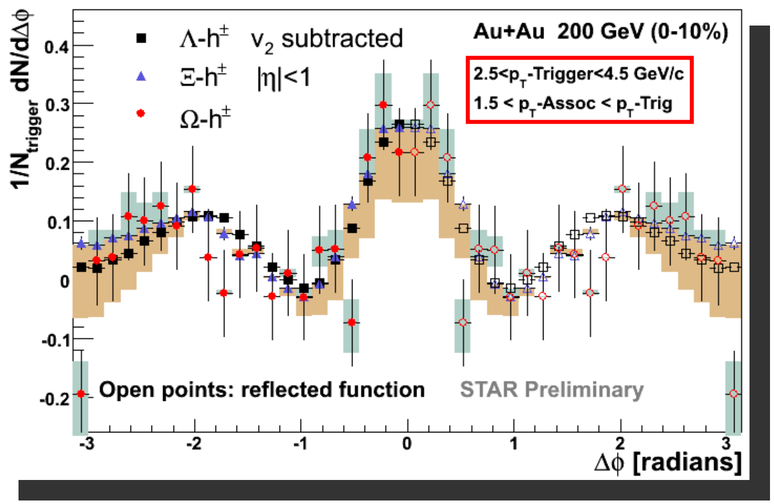
no dependence on A ***no dependence on $\sqrt{s_{NN}}$***



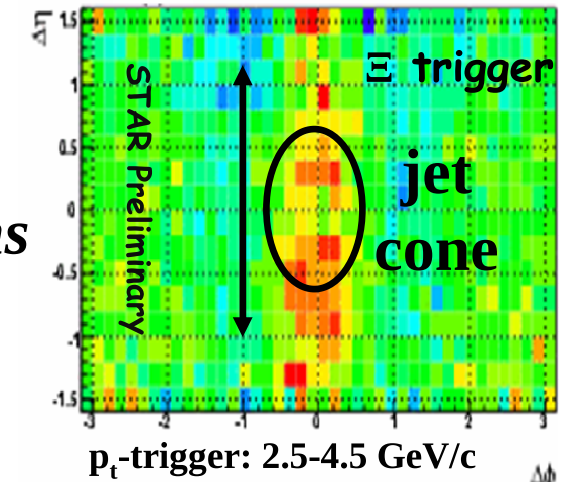
stringent tests of jet/ridge formation scenarios

Particle Type Dependence

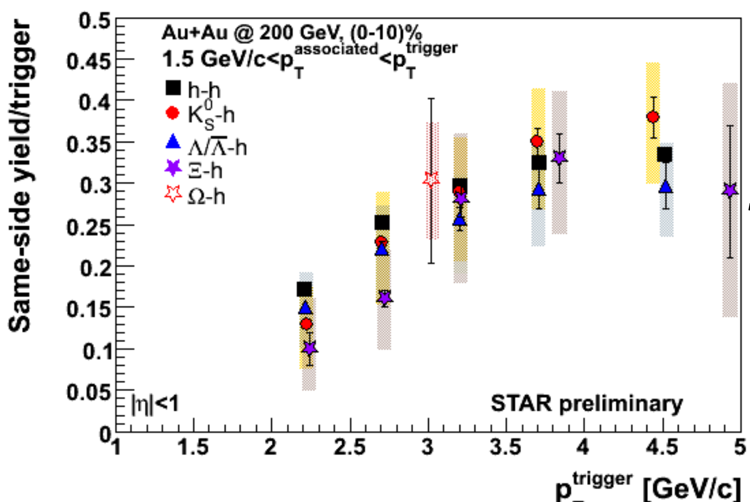
angular correlation systematics



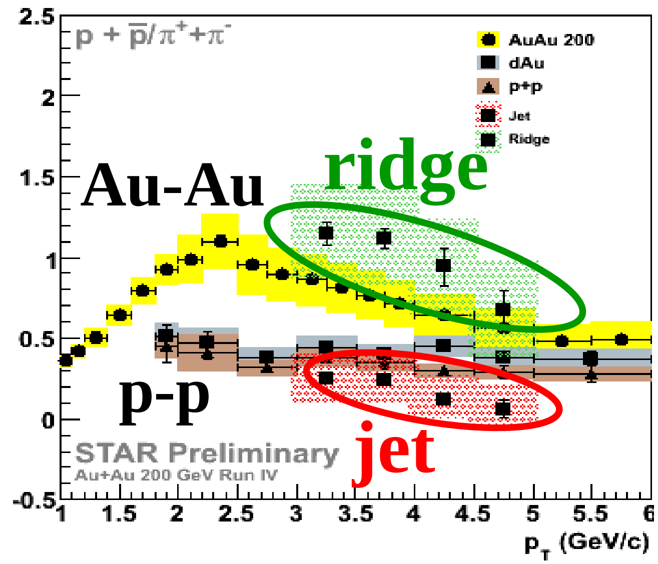
azimuth correlations similar for all trigger species



common η broadening



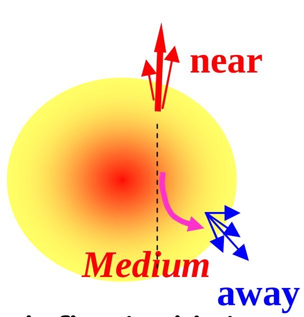
jet + ridge yield similar on p_t for all trigger species



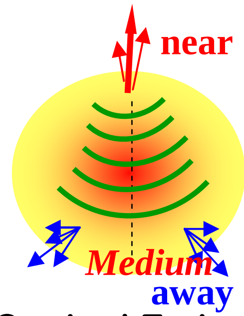
jet/ridge phenomenology independent of leading flavor

Conical Emission Studies

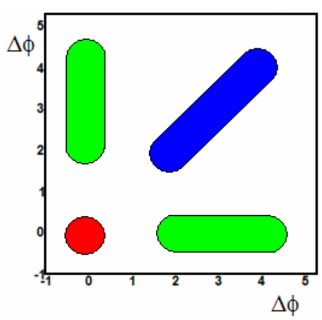
Δϕ–Δϕ correlations

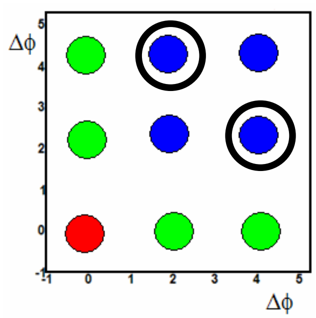


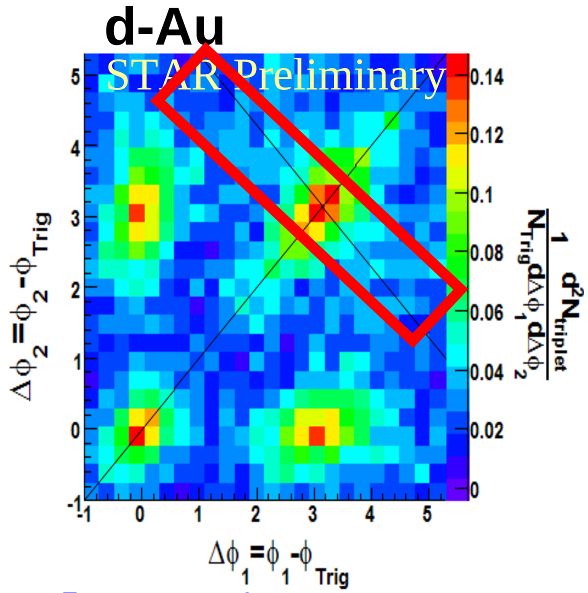
deflected jets

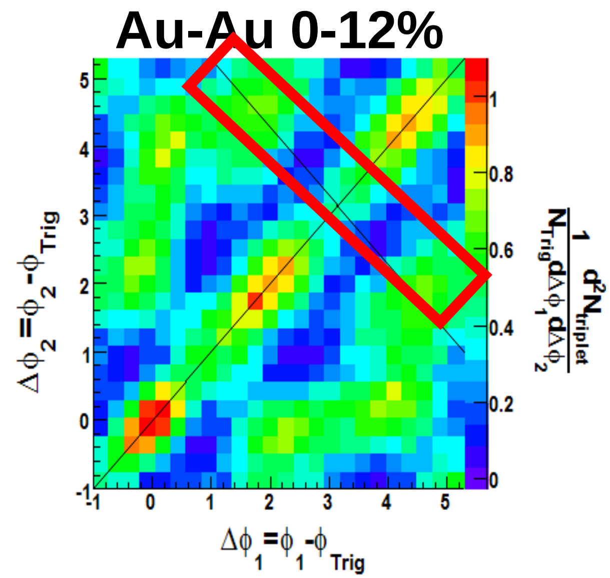


Conical Emission





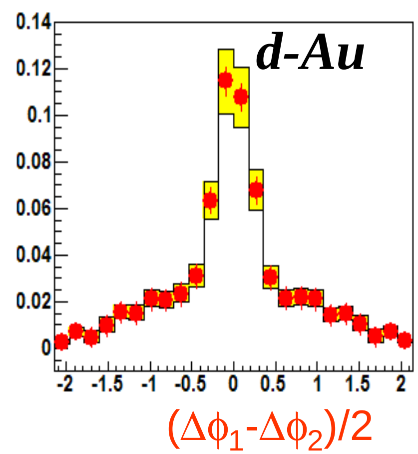


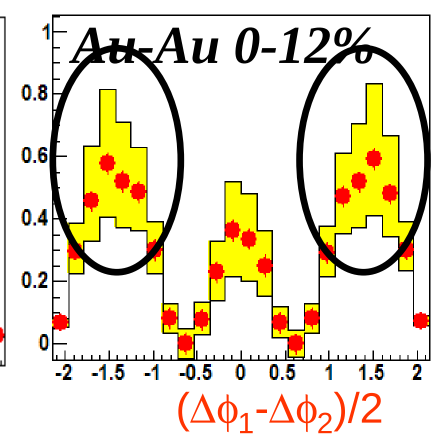


large improvements with STAR ToF

three-particle analysis within a two-component context

$3 < p_{T\text{-}trig} < 4$ GeV/c $1 < p_{T\text{-}assoc} < 2$ GeV/c

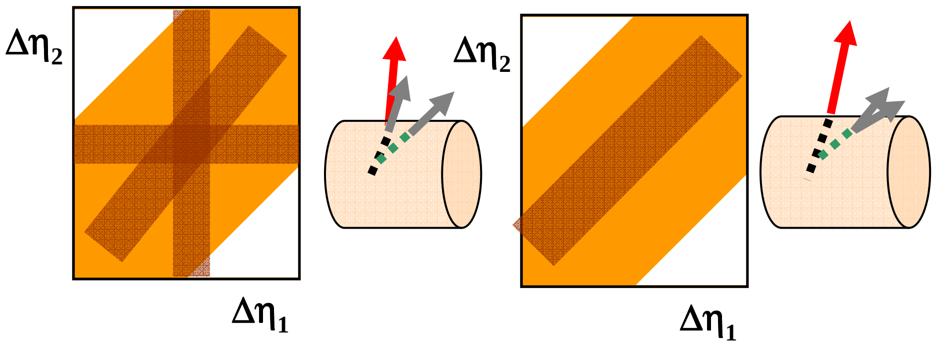




structures provide evidence for conical emission

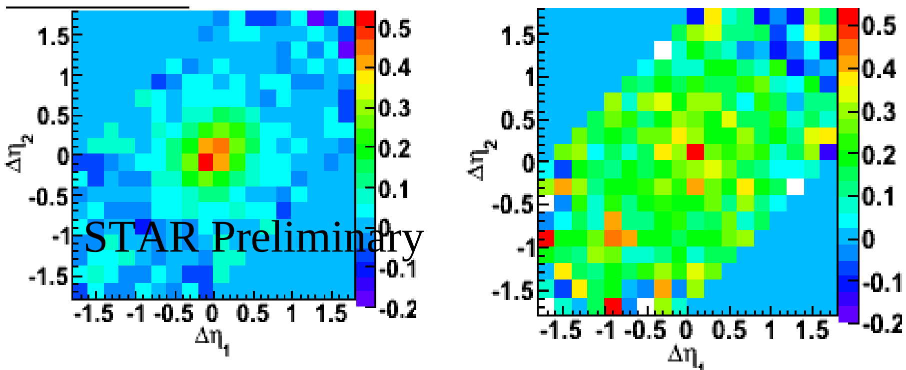
Other Three-hadron Correlations

Δη–Δη correlations

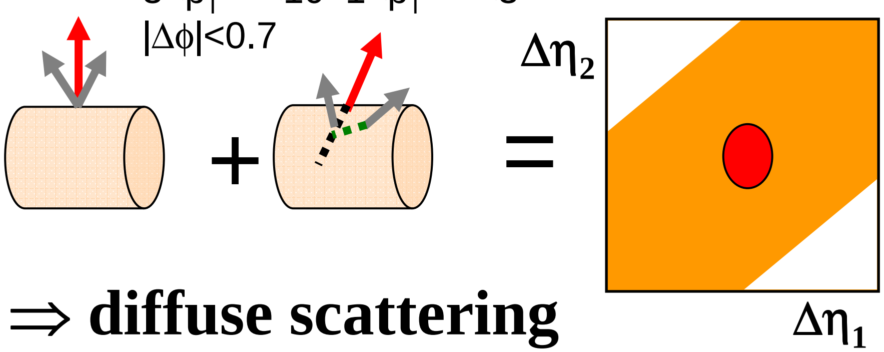


dAu : Jets

AuAu : 200 GeV



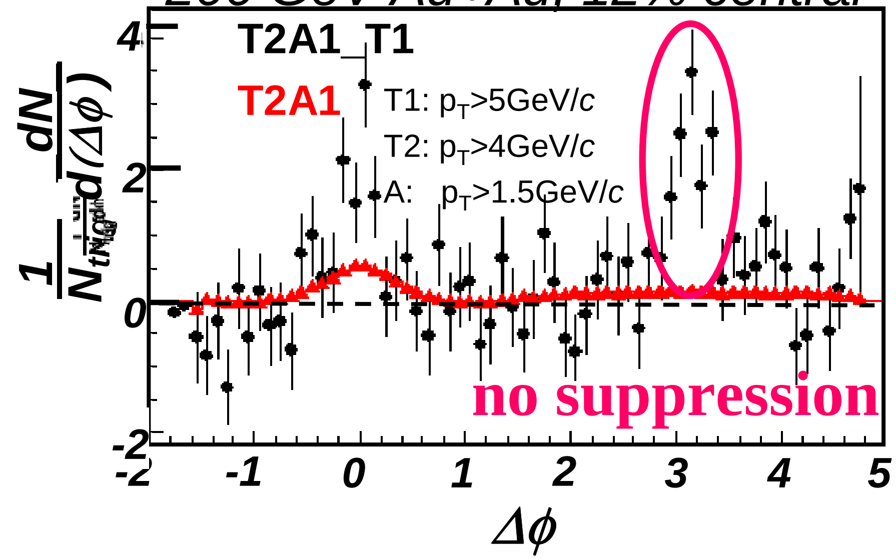
$3<p_T^{Trig}<10$ $1<p_T^{Asso}<3$
$|\Delta\phi|<0.7$



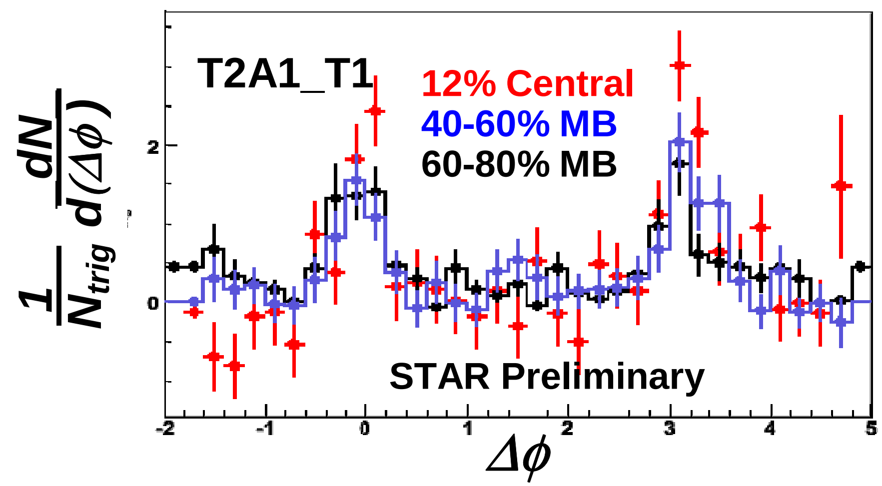
⇒ diffuse scattering

di-hadron triggers

200 GeV Au+Au, 12% central



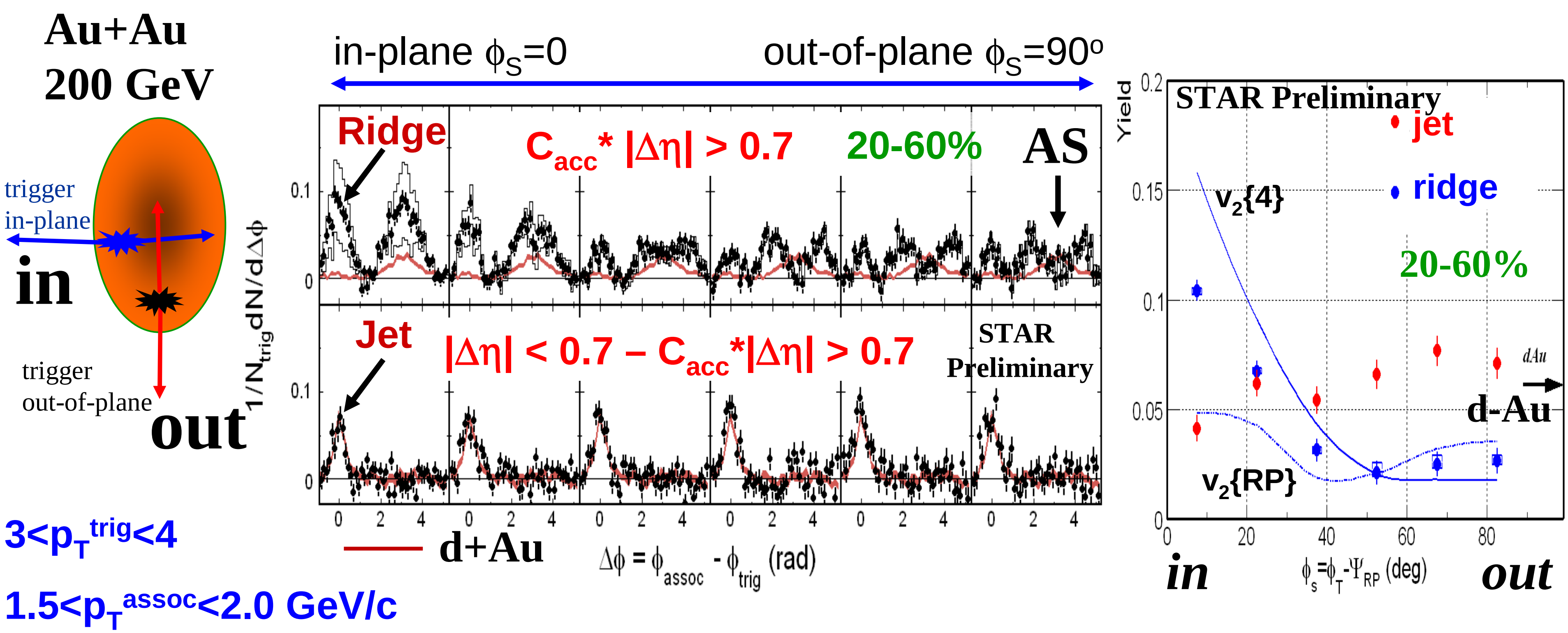
no “ridge” on η



Di-hadron Correlations w.r.t. ℞

path-length increases with ϕ_s (in → out of plane)

→ increasing away-side modification

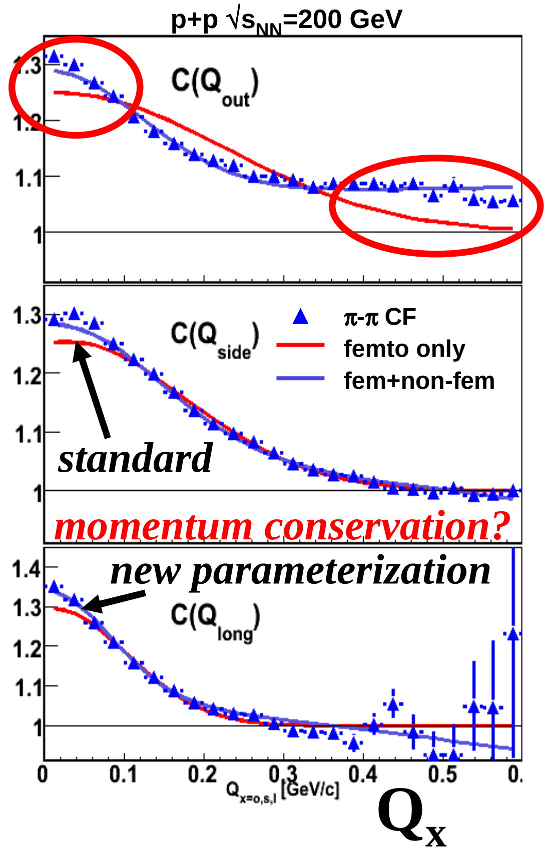


di-hadrons relative to the reaction plane

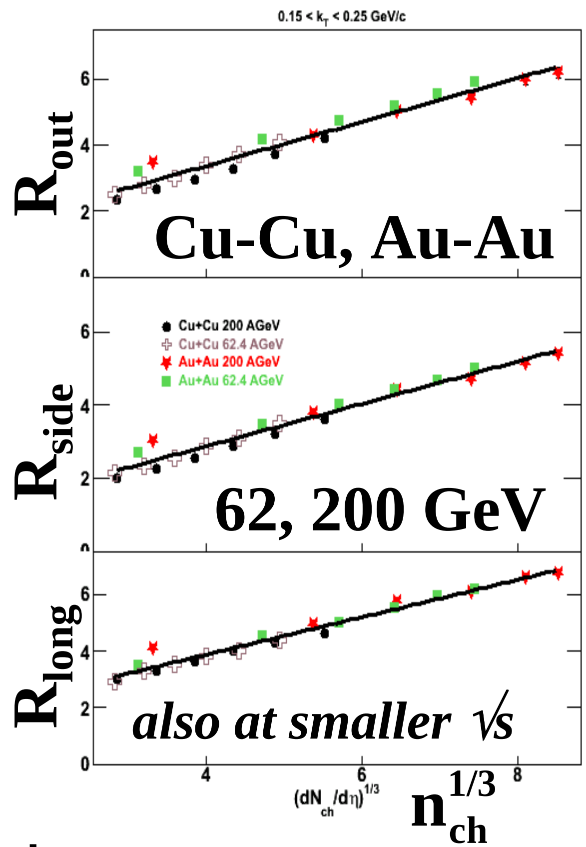
- **Ridge drops from in-plane to out-of-plane**
- **Jet peak stays consistent with d-Au**

Femtoscopy Systematics

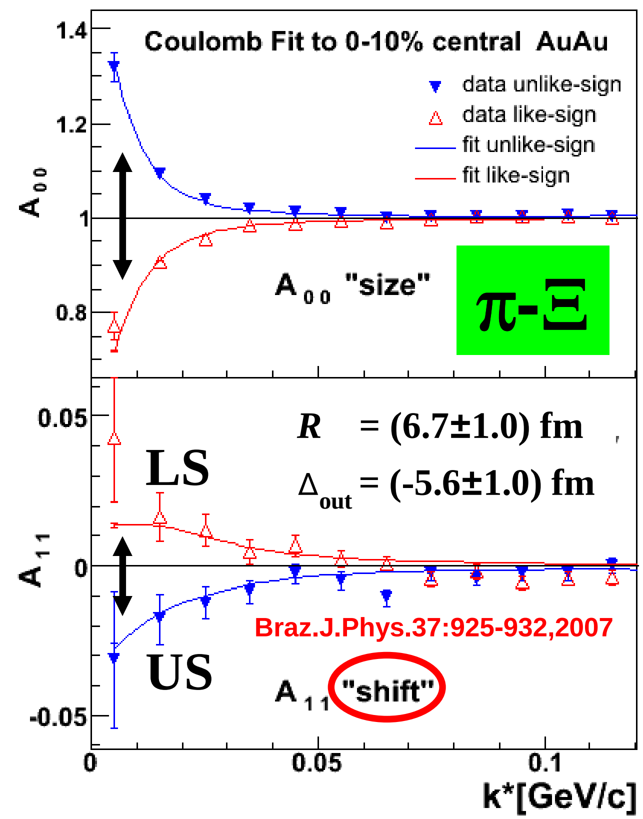
correlation sources



radii related to n_{ch}



heavy/light emission



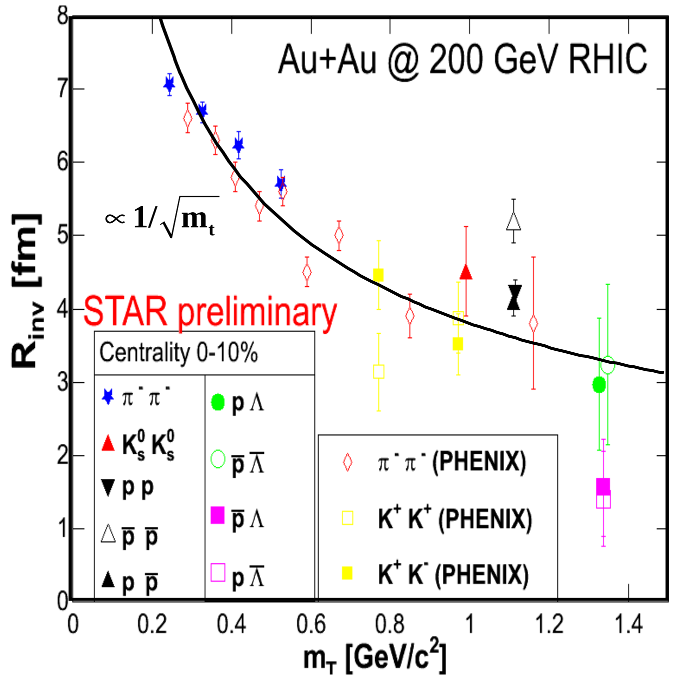
multiple correlation sources
important for small n_{ch}

same for all systems
and <u>lower energies</u>
not b or N_{part}

shift due to radial flow

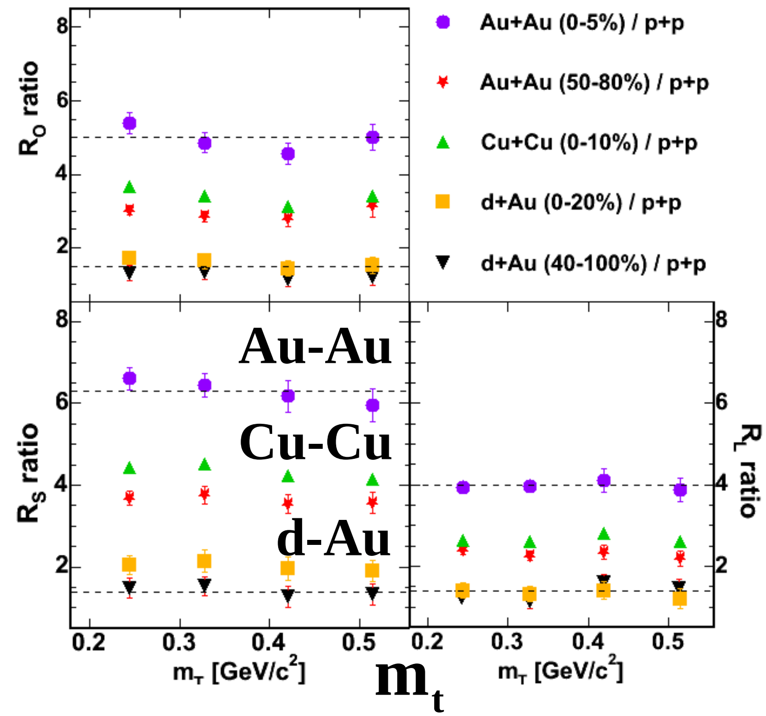
more flow effects

Radial Flow Effects

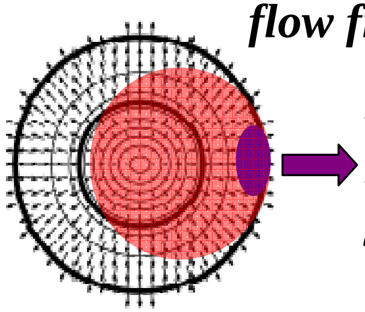


m_t dependence: evidence for radial flow

AA / pp radius ratios



m_t trends the same in A-A, p-p



flow field

homogeneity region shrinks

as m_t increases

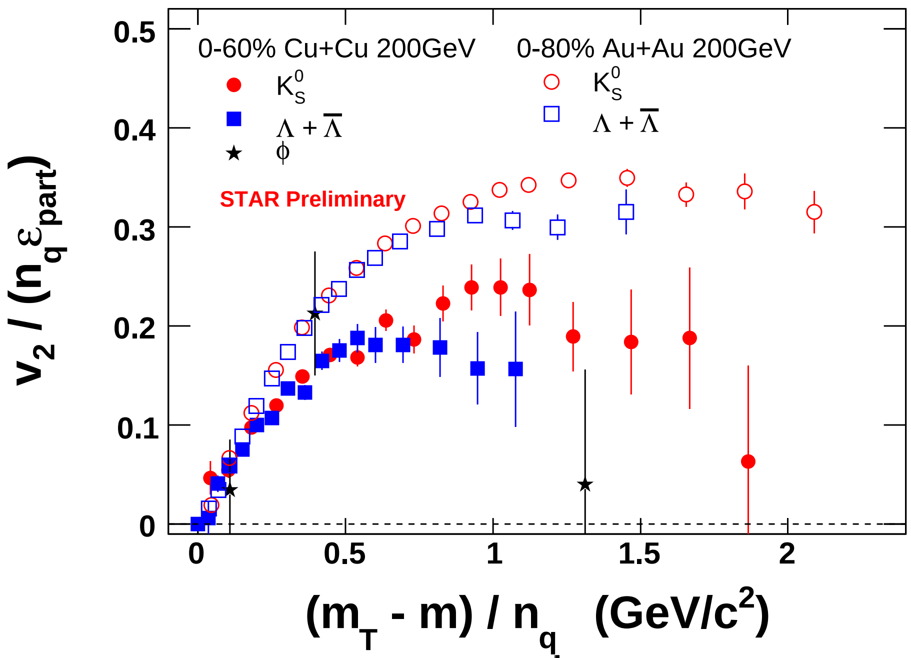
$\rightarrow$ evidence for strong radial flow in A-A

<u>but</u>, does that imply radial flow in p-p?

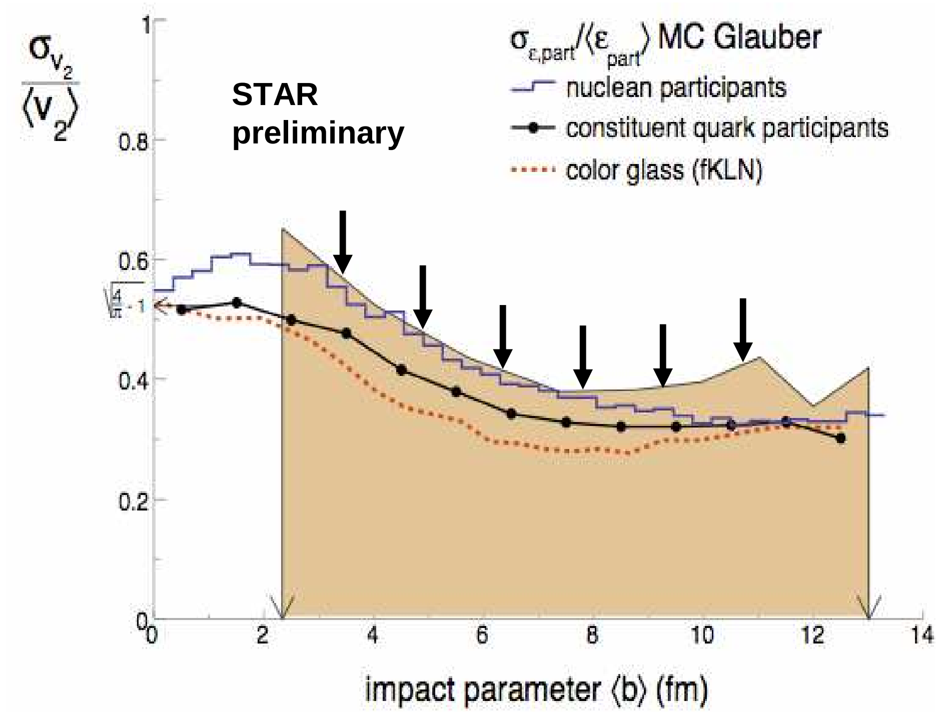
what relation to QCD processes?

v_2: elliptic flow studies

Differential v_2 Studies



compare: PHENIX PRL 98, 162301 (2007)
STAR PRC 77, 54901 (2008)



No participant-eccentricity scaling

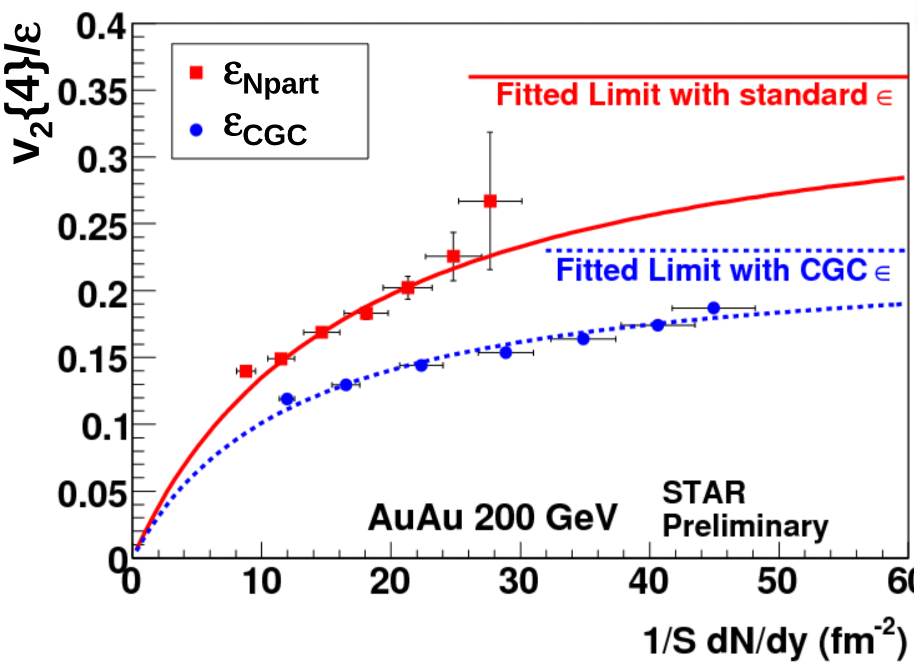
Sizeable v_2 for ϕ mesons (sparse hadronic interactions) $\Rightarrow$ partons

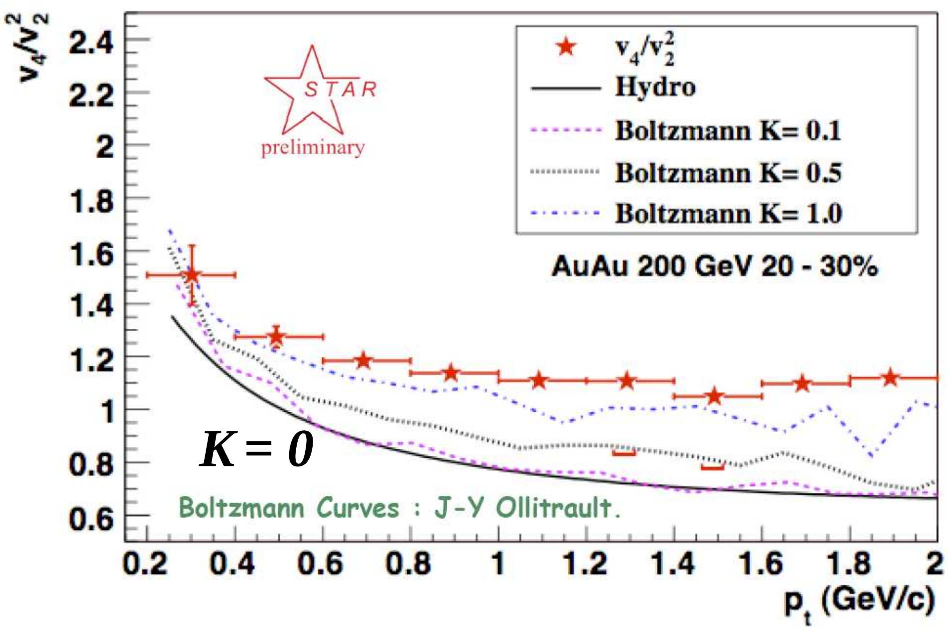
Upper limit on v_2 fluctuations

Challenges models of initial-state eccentricity fluctuations

v_2 and its fluctuations probe dynamics at different time scales

Incomplete Thermalization?





Fitting function: H-J Drescher et al. PRC 76, 024905 (2007)
CGC ε: A.Adil et al. PRC 74, 044905 (2006)

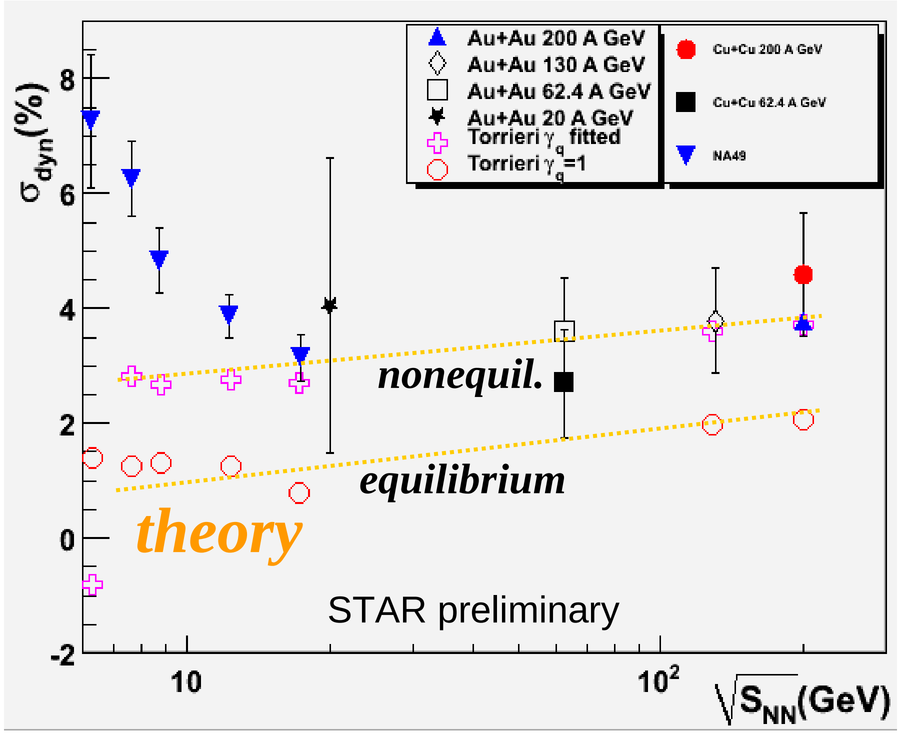
v_2 / ε ~ 30% below ideal Hydro, even for central collisions

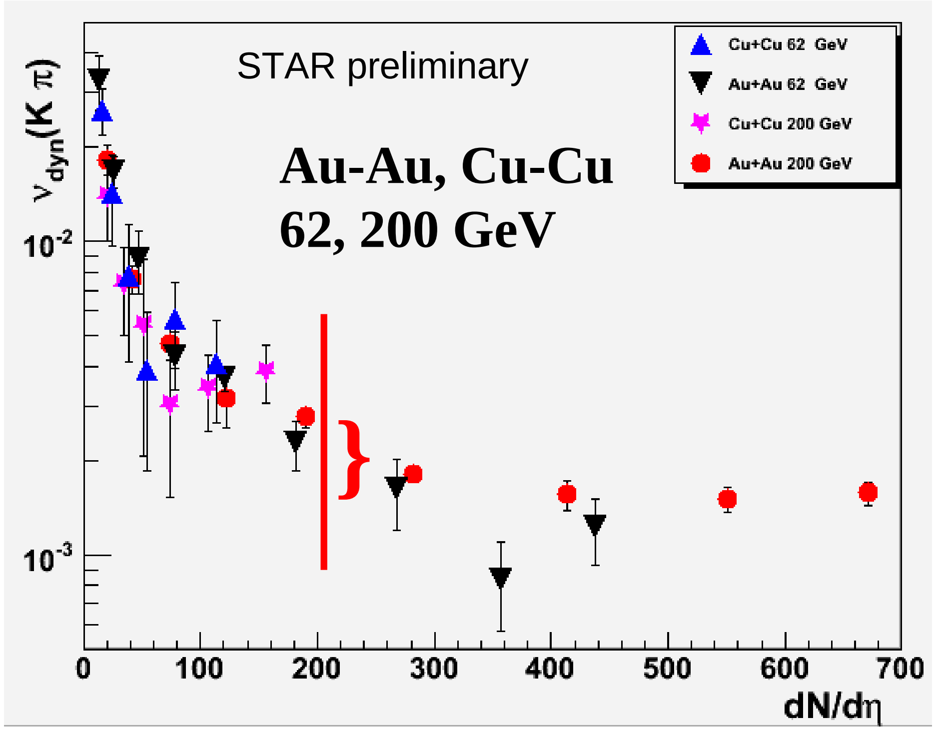
Knudsen number K is not ~ 0 as for ideal hydro, must be > 0.5 to explain v_4/v_2^2

some features inconsistent with complete thermalization

not easily dismissed

K/π Fluctuations





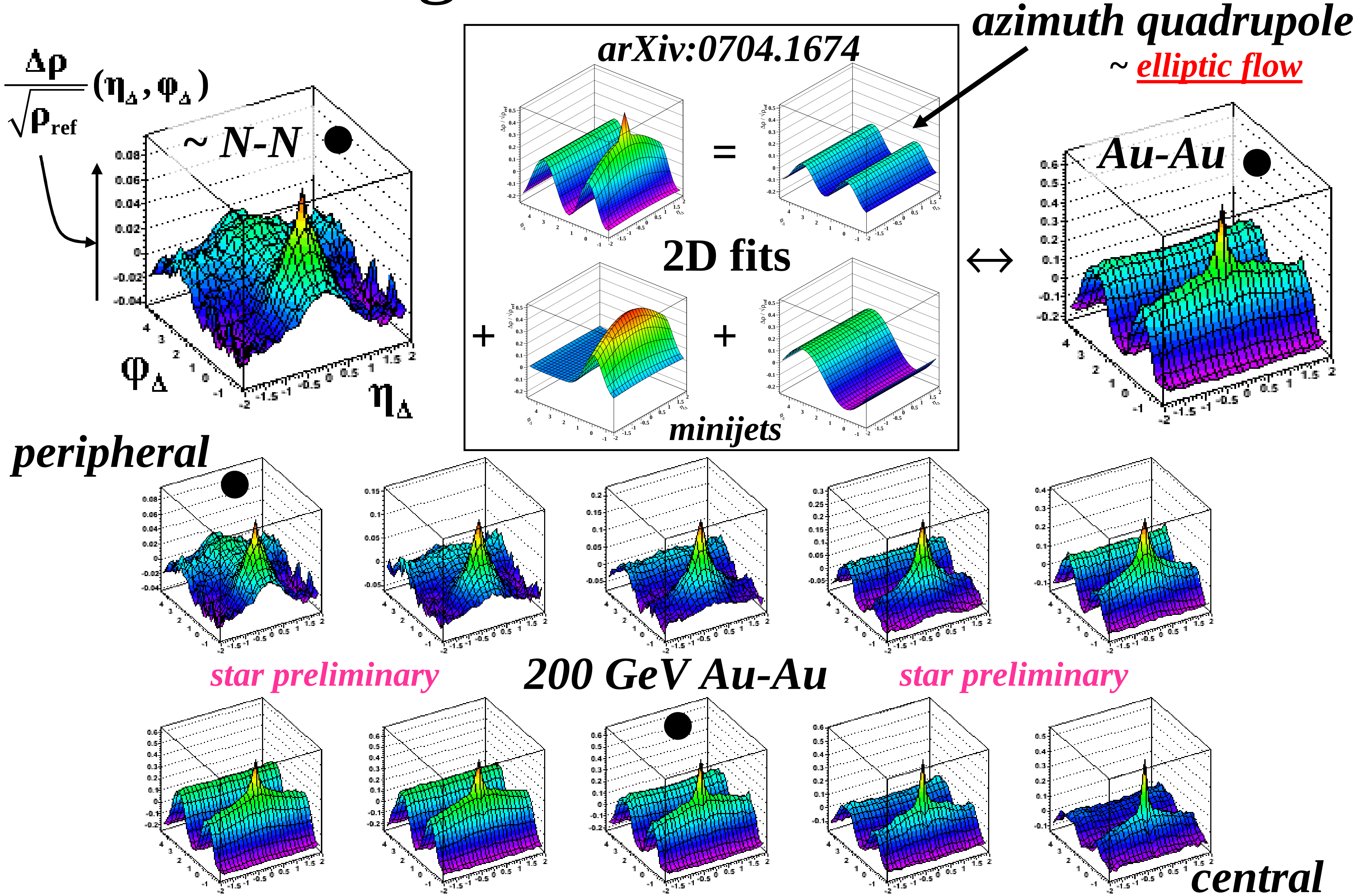
K/π fluctuations appear consistent with NA49 at highest SPS energy

K/π fluctuations at same dN/dη: little variation with energy or system size

Higher RHIC luminosity and STAR ToF should greatly improve this analysis

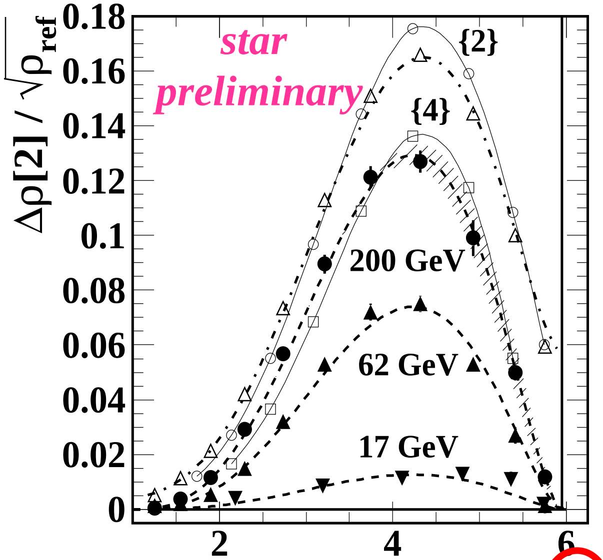
featured element of low-energy scan program

2D Angular Autocorrelations



Model-Fit Parameters

quadrupole amplitude



$$\frac{\Delta\rho[2]}{\sqrt{\rho_{ref}}} \equiv \frac{\bar{n}\, v_2^2\{2D\}}{2\pi}$$

quadrupole $v_2\{2D\}$

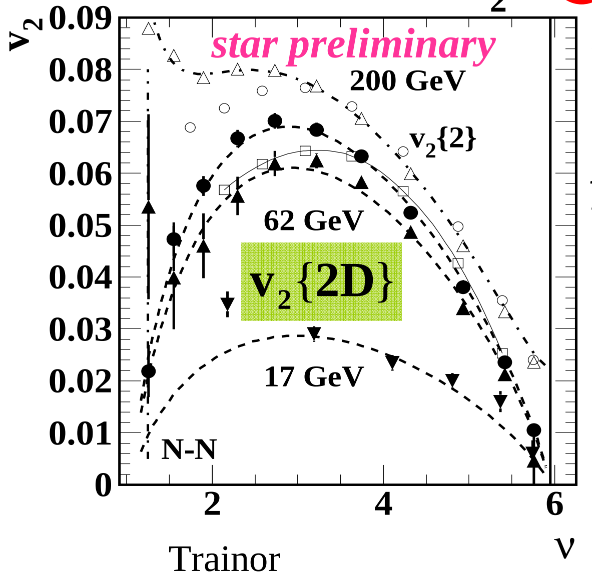
$\in \{v_2\{2\}, v_2\{4\}, \ldots\}$

~ "elliptic flow"

centrality measure

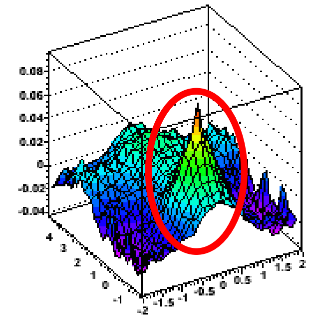
$\nu \equiv 2n_{binary}/n_{participant}$

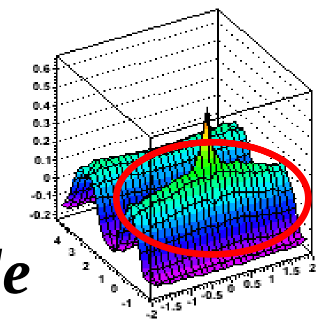
conventional v_2

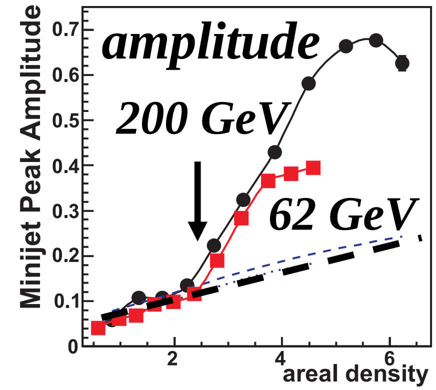


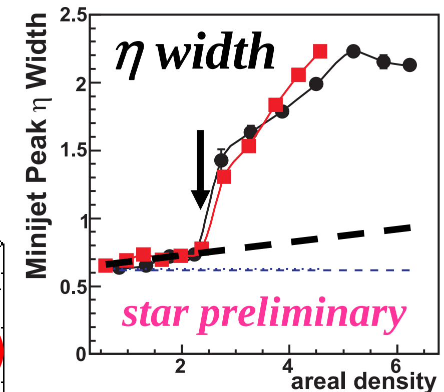
accurate separation of *azimuth quadrupole* from other structure

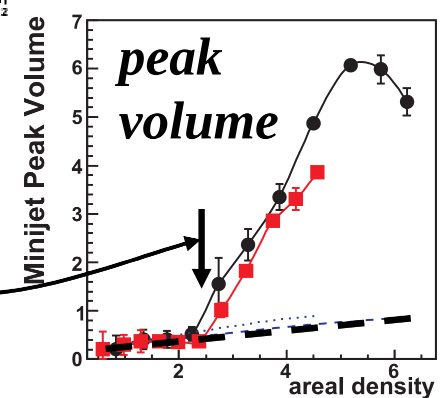
minijet same-side peak







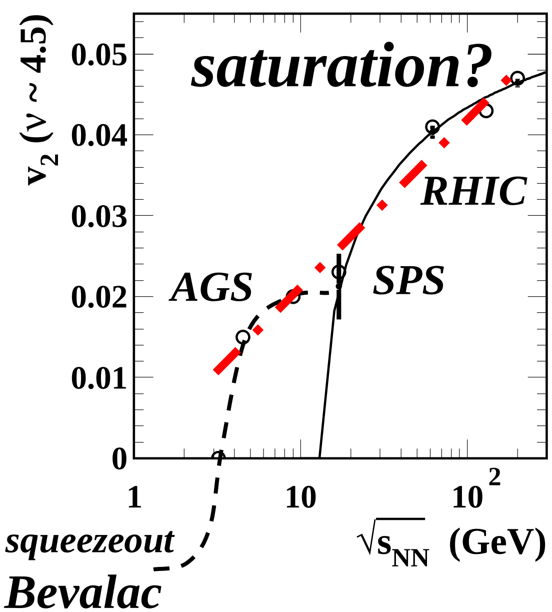




medium?

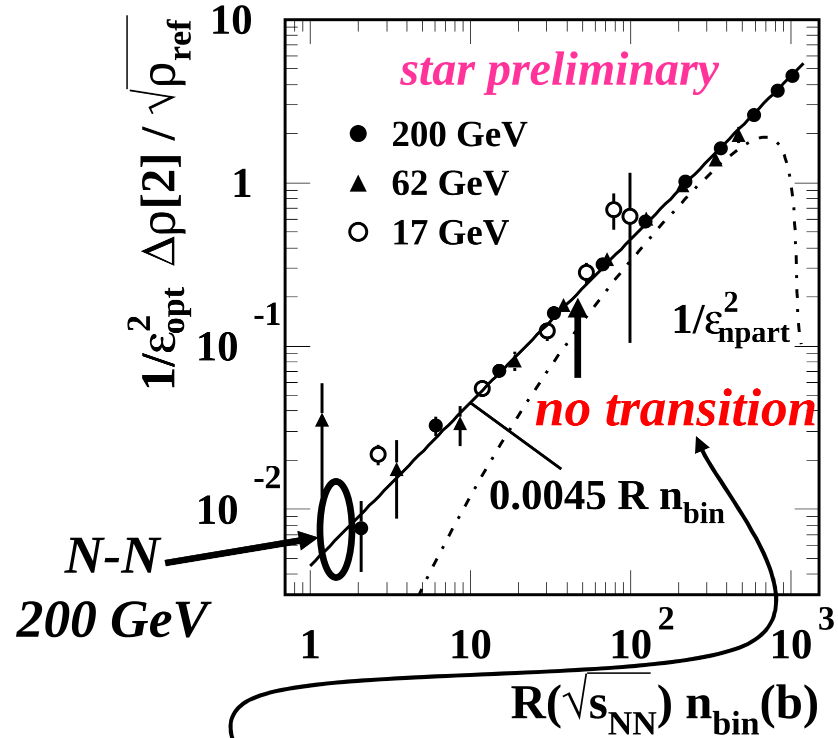
sharp transitions in minijet properties

Energy and Centrality Trends



$\sqrt{\textit{per-pair}}$

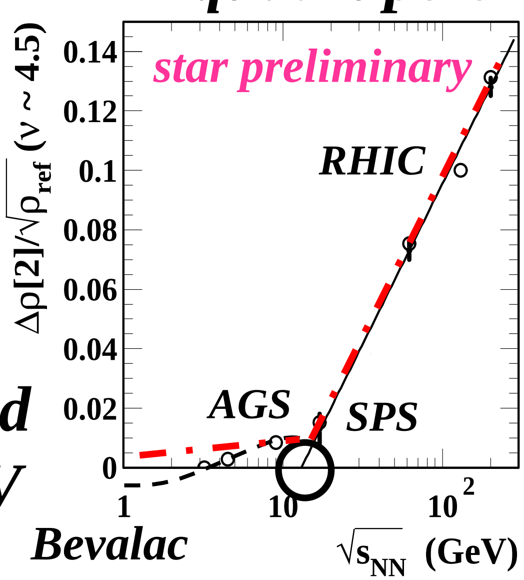
$$v_2\{2D\} \equiv \sqrt{\frac{2\pi}{\bar{n}} \cdot \frac{\Delta\rho[2]}{\sqrt{\rho_{ref}}}}$$



$$R\left(\sqrt{s_{NN}}\right) \propto \log\left(\sqrt{s_{NN}}/13\text{GeV}\right)$$

quadrupole

per-particle



universal trend above 13 GeV

no medium sensitivity?

$$\frac{\Delta\rho[2]}{\sqrt{\rho_{ref}}} = 0.0045\ R\left(\sqrt{s_{NN}}\right)\varepsilon^2_{opt}(b)\, n_{bin}(b)$$

no EoS, medium properties (viscosity)

Summary

- **2006 inclusive-jet A_{LL} data restrict $|\Delta G|$ to small values, inclusive-π A_N data consistent with DIS on x_F, puzzling on p_T**
- **Di-jet, γ-jet A_{LL} data should provide direct access to differential $\Delta g(x)$ $\rightarrow$ gluon spin structure fully revealed**
- **Heavy-flavor E-loss probes coming on line, strong pQCD tests**
- **Accurate parton E-loss through di-hadron, γ-hadron studies**
- **Fragmentation strongly modified, insensitive to leading flavor**
- **Complex medium dynamics strongly coupled to parton E-loss**
- **Evidence for strong transverse flow, but paradoxical aspects**
- **Conventional hydro picture, viscosity challenged by minijets**

STAR:

Unprecedented access to QCD in p-p and A-A

RHIC II and STAR ToF: essential upgrades