STAR Recent Results and perspective

Tom Trainor
(for the STAR Collaboration)

RHIC-AGS Users Meeting
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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

\[
\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_q^z \rangle + \langle L_g^z \rangle
\]

three recent DIS fits of equal quality:
- \( \Delta G = 0.13 \pm 0.16 \)
- \( \Delta G \approx 0.006 \)
- \( \Delta G = -0.20 \pm 0.41 \)
all at \( Q^2 = 1 \text{ GeV}^2 \)

first goal of the RHIC Spin program:
determine the gluon polarization distribution

Leader et al., PRD 75, 074027 (2007)
Polarized p-p Collisions at RHIC

\[ A_{LL} = \frac{\sigma^{++} - \sigma^{-+}}{\sigma^{++} + \sigma^{-+}} \propto \frac{\Delta f_a}{f_a} \frac{\Delta f_b}{f_b} \hat{\alpha}_{LL} \]

\( \Delta f \): polarized parton distribution functions

\[ \frac{\Delta G}{G} \quad \frac{\Delta G}{G} \quad \frac{\Delta G}{G} \quad \frac{\Delta q}{q} \quad \frac{\Delta q}{q} \]

Partonic fractions in jet production at 200 GeV

\[ \Delta g(x) \] sign

for most RHIC kinematics \( gg \) and \( gq \) dominate – \( A_{LL} \) for jets is sensitive to gluon polarization
2006 Inclusive-jets $A_{LL}$

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

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

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Statistical uncertainties 3-4 times smaller than 2005 data for $p_T > 13$ GeV/c
Other Global DIS Analyses

- 2005 STAR data excluded a broad range of models with $\Delta G$ larger than GRSV-std
- Counter-example: GS-C node near $x \sim 0.1$, large positive integral at small $x$

GS-C: Gehrmann & Stirling

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First Global Analysis with Polarized Jets

de Florian et al., arXiv:0804.0422

- First global NLO analysis to incorporate inclusive DIS, SIDIS, and RHIC pp data on an equal footing
- Node in gluon distribution near $x \sim 0.1$ – opposite phase from GS-C

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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$^2$

\[ x_1 = \frac{1}{\sqrt{s}} \left( p_3 e^{\eta_3} + p_4 e^{\eta_4} \right) \]
\[ x_2 = \frac{1}{\sqrt{s}} \left( p_3 e^{-\eta_3} + p_4 e^{-\eta_4} \right) \]
\[ M = \sqrt{x_1 x_2 s} \]
\[ y = \frac{1}{2} \ln \left( \frac{x_1}{x_2} \right) = \frac{\eta_3 + \eta_4}{2} \]
\[ |\cos(\theta^*)| = \tanh \left( \frac{\eta_3 - \eta_4}{2} \right) \]

$\Delta$-jets: direct access to parton kinematics at LO

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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

$\mathbf{x} \in [0.05, 0.85]$  

200 GeV di-jets dominated by $q$-$g$ scattering 
$q$ polarizations large

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

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

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$A_N$ 2006 Final Results – FPD

$x_f$ dependence of $A_N$ for forward $\pi$ production

$L_z$ orbital angular momentum

some aspects of $A_N$ seem well-understood

SIDIS measurements and forward $\pi^0$, $\pi^\pm$ 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 $p_T$ dependence of $A_N$ for forward $\pi$ production

$p_T$ dependence of $A_N$ at fixed $x_F$ not explained

Sivers: $A_N$ should decrease 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, …

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 $\rho^0$ ($\sqrt{s_{NN}} = 130, 200\ \text{GeV}$)
  - Excludes several models: PRL 89 272302 (2002); PRC 77, 034910 (2008)

- $\rho^0$ photo-production in dAu $\sqrt{s_{NN}} = 200\ \text{GeV}$ and AuAu $\sqrt{s_{NN}} = 62\ \text{GeV}$

- Observation of two-source interference in the photo-production reaction AuAu → AuAu$\rho^0$ (EPR paradox)

- Resonant $\pi^+\pi^-\pi^+\pi^-$ photo-production in AuAu collisions at $\sqrt{s_{NN}} = 200\ \text{GeV}$
  - Test of the coupling to the nucleus, $\rho(1450)$ and $\rho(1700)$ candidates
**e-h Azimuth Correlations**

**p-p 200 GeV**

Reference system

**e-D⁰ correlations**

- **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

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**charm, bottom, NLO processes (splitting)**

Flavor creation (LO) gluon splitting (NLO)

Comparisons to Pythia and MC@NLO

**p-p 200 GeV**

**B fraction**

R. Vogt

**e-D⁰ run 6**
J/ψ Production in p-p

J/ψ → e⁺e⁻
p+p 2006

**STAR Preliminary**

EMC+TPC electrons:
|η|<1, p_T>4.0 GeV/c

TPC only electrons:
|η|<1, p_T>1.2 GeV/c

**US**

**LS**

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

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$\gamma$ Production in p-p and Au-Au

e-e mass spectra

p-p

Au-Au, 0-60%

Cross section measured consistent with pQCD

First measurement of $\gamma$ in A-A

On-going analysis: first look at $\gamma R_{AA}$

10-70x improvement with RHIC II
Di-hadron, γ-hadron Correlations

First steps to precision study with RHIC-II high luminosity

inclusive hadron suppression
di-hadron suppression

\[ R_{AA} \]

\[ I_{AA} \]

\[ \chi^2_{IAA} \]

\[ \chi^2_{RAA} \]

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nucl-th/0701045

data

di-hadrons: better probes of initial density

\[ q_0^\gamma (GeV^2) \]
Away-side Di-hadron FFs

\[ z_T = p_T^{\text{assoc}} / p_T^{\text{trig}} \]

**Au-Au vs Cu-Cu**

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

- \( z_T \) = \( p_T \) of associated over \( p_T \) of trigger

- **Density of medium**
  - denser medium in central Au-Au compared to central Cu-Cu

- **Inconsistent with Parton Quenching Model**
  - Modified Fragmentation Model
**γ-hadron Correlations, Clusters**

**multi-hadron (cluster) trigger**

biased di-hadron correlations?  
→ HI jet reconstruction

**γ-jet events are rare → large luminosity**

first measurements… RHIC run-7

10-40× improvement with RHIC II

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**away-side fragment spectra**

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**single-hadron and multi-hadron triggers give similar results**

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**suppression similar to inclusives in central collisions**

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Strangeness Enhancement

*strange baryons vs $\phi$ – yield systematics*

**similar trends for antiparticles**

**Au-Au vs Cu-Cu**

**enhancement measure**

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

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

similar effects seen in $\Omega/\phi$, $\Lambda/K$ $p_t$ spectrum ratios for Cu-Cu vs Au-Au

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Energy and System Dependence

Angular correlation systematics

Common jet/ridge trends for different collision systems

\[ \text{Cu-Cu} = \text{Au-Au} \]

\[ \text{Cu-Cu} \sim \text{Au-Au} \]

\[ 62 = 200 \]

No dependence on \( A \)

No dependence on \( \sqrt{s_{NN}} \)

Stringent tests of jet/ridge formation scenarios

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Particle Type Dependence

angular correlation systematics

azimuth correlations similar for all trigger species

jet + ridge yield similar on $p_T$ for all trigger species

jet/ridge phenomenology independent of leading flavor

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Conical Emission Studies

$\Delta \phi - \Delta \phi$ correlations

deflected jets

near

Medium

away

Conical Emission

$d$-Au

Au-Au 0-12%

STAR Preliminary

large improvements with STAR ToF

three-particle analysis within a two-component context

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

structures provide evidence for conical emission

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Other Three-hadron Correlations

$\Delta \eta - \Delta \eta$ correlations

dAu : Jets

AuAu : 200 GeV

$3 < p_T^{\text{Trig}} < 10$  $1 < p_T^{\text{Asso}} < 3$

$|\Delta \phi| < 0.7$

$\Rightarrow$ diffuse scattering

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\[ \frac{1}{N_{\text{trig}}} \frac{dN}{d(\Delta \phi)} \]

200 GeV Au+Au, 12% central

T2A1

T1: $p_T > 5$ GeV/c
T2: $p_T > 4$ GeV/c
A: $p_T > 1.5$ GeV/c

no suppression

no “ridge” on $\eta$

\[ \frac{1}{N_{\text{trig}}} \frac{dN}{d(\Delta \phi)} \]

12% Central
40-60% MB
60-80% MB

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Di-hadron Correlations w.r.t. $R$

path-length increases with $\phi_s$ \(\text{(in} \rightarrow \text{out of plane)}\)
\[\rightarrow\] increasing away-side modification

Au+Au
200 GeV

\[\text{in-plane } \phi_s=0 \quad \text{out-of-plane } \phi_s=90^\circ\]

Ridge $C_{\text{acc}}\,|\Delta \eta| > 0.7 \quad 20-60\% \quad \text{AS}$

Jet $|\Delta \eta| < 0.7 - C_{\text{acc}}\,|\Delta \eta| > 0.7$

\[\text{d-Au} \quad \text{d+Au}\]

$\Delta \phi = \phi_{\text{assoc}} - \phi_{\text{trig}} \text{ (rad)}$

\[3<p_T^{\text{trig}}<4 \quad 1.5<p_T^{\text{assoc}}<2.0 \text{ GeV/c}\]

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

**Radii related to $n_{ch}$**

- Cu-Cu, Au-Au
- 62, 200 GeV
- also at smaller $\sqrt{s}$

**Heavy/light emission**

- Coulomb Fit to 0-10% central AuAu
- $R = (6.7 \pm 1.0)$ fm
- $\Delta_{out} = (-5.6 \pm 1.0)$ fm

**Correlation sources**

- $p+p \sqrt{s_{NN}}=200$ GeV
- $C(Q_{out})$
- $C(Q_{side})$ standard
- $C(Q_{long})$ new parameterization
- multiple correlation sources important for small $n_{ch}$
- momentum conservation?

**Important for small $n_{ch}$ and lower energies**

- not $b$ or $N_{part}$

**Shift due to radial flow**

- more flow effects

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pp pp - $R = (6.7 \pm 1.0)$ fm

LS US

Radial Flow Effects

$m_t$ dependence: evidence for radial flow

flow field

homogeneity

region shrinks as $m_t$ increases

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

→ evidence for strong radial flow in A-A

but, does that imply radial flow in p-p?

what relation to QCD processes?

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**$v_2$: elliptic flow studies**

**Differential $v_2$ Studies**

![Graph showing $v_2$ vs. $(m_T - m) / n_q$](image)

**Upper limit on $v_2$ fluctuations**

**Challenges models of initial-state eccentricity fluctuations**

- No participant-eccentricity scaling
- Sizeable $v_2$ for $\phi$ mesons (sparse hadronic interactions) $\Rightarrow$ partons

**$v_2$ and its fluctuations probe dynamics at different time scales**

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Incomplete Thermalization?

$\epsilon_{\text{Npart}}$ vs $\epsilon_{\text{CGC}}$ for AuAu 200 GeV collisions. Fitted limit with standard $\epsilon$ and CGC $\epsilon$.

$K = 0$

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

$\frac{v_2}{\epsilon} \sim 30\%$ below ideal Hydro, even for central collisions

Knudsen number $K$ is not $\sim 0$ as for ideal hydro, must be $> 0.5$ to explain $\frac{v_4}{v_2^2}$

Some features inconsistent with complete thermalization not easily dismissed

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K/π Fluctuations

**STAR preliminary**

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**

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2D Angular Autocorrelations

\[
\frac{\Delta \rho}{\sqrt{\rho_{\text{ref}}}}(\eta_{\Delta}, \phi_{\Delta}) \sim N-N
\]

\[2D \text{ fits} \quad \text{minijets} \]

\[\text{azimuth quadrupole} \quad \text{elliptic flow}\]

\[\text{peripheral} \quad \text{star preliminary} \quad 200 \text{ GeV Au-Au} \quad \text{star preliminary} \quad \text{central}\]

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arXiv:0704.1674

\[\leftrightarrow \]
Model-Fit Parameters

\[ \frac{\Delta p[2]}{\sqrt{p_{\text{ref}}}} \equiv \bar{n} v_2^{2\{2D\}} \]

\[ v_2^{2\{2\}} \in \{v_2^2, v_2^4, \ldots\} \]

\(~\text{“elliptic flow”}\)

\[ v \equiv 2n_{\text{binary}} / n_{\text{participant}} \]

accurate separation of azimuth quadrupole from other structure

\[ \text{minijet same-side peak} \]

\[ \text{amplitude} \]

200 GeV

62 GeV

\[ \text{amplitude} \]

200 GeV

62 GeV

\[ \text{minijet peak volume} \]

\[ \eta \text{ width} \]

\[ \text{minijet peak \( \eta \) width} \]

\[ \text{star preliminary} \]

\[ \text{peak volume} \]

\[ \text{medium?} \]

\[ \text{sharp transitions in minijet properties} \]
Energy and Centrality Trends

$$v_2\{2D\} = \frac{2\pi \Delta\rho[2]}{\sqrt{n} \rho_{\text{ref}}}$$

- **saturation?**
- **per-pair**
- **squeezeout**
- **Bevalac**
- **per-particle**
- **quadrupole**

**universal trend**
- above 13 GeV

**no transition**

**no medium sensitivity?**

**no EoS, medium properties (viscosity)**
Summary

- 2006 inclusive-jet $A_{LL}$ data restrict $|\Delta G|$ to small values, inclusive-$\pi$ $A_N$ data consistent with DIS on $x_F$, puzzling on $p_T$
- Di-jet, $\gamma$-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, $\gamma$-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