Overview of recent results for p+p, d+A, and flow from the PHENIX detector at RHIC

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Outline

- Physics motivation for RHIC experiments
- Overview of the PHENIX experiment
- \( p+p \) and \( d+A \):
  - Neutral mesons
  - Heavy quarkonia
  - \( J/\Psi \) polarization
- Flow
- Summary
Relativistic heavy ion collisions

Quark-gluon plasma

History of the Universe

PHENIX
Relativistic Heavy Ion Collider:

- $p+p$, $d+A$, and $A+A$ collisions at energies up to $\sqrt{s}=200\text{GeV}/c^2$ ($500\text{GeV}/c^2$ for $p$);
- polarized protons

Very versatile machine!
The PHENIX detector

Central arm acceptance: $|\eta| < 0.35 \quad \Delta \phi = 2 \times \pi/2$

Global Detectors: BBC/ZDC

Tracking System: Drift Chamber/Pad Chamber

Pattern recognition: Drift Chamber/Pad Chamber/Em Calorimeter

Calorimetry: Pb Scintillator/PbGlass

PID: Time of flight/PbSc/Rich
Studying p+p and d+Au collisions is an essential component of A+A program

- Why p+p?
  - Precise measurements of hadron production mechanisms in p+p collisions are important for understanding QCD phenomena such as parton dynamics and hadronization.
  - To form a baseline for particle and jet production in heavy ion collisions.

- Why d + Au?
  - To understand the effects of cold nuclear matter as distinct from hot nuclear matter.
Neutral mesons in p+p and d+A

neutral meson invariant mass distributions
Invariant differential cross sections for neutral mesons in p+p collisions at $\sqrt{s} = 200$ GeV

Spectral shapes are exponential at low pt (<3 GeV/c) suggesting a thermal distribution. Spectra follow a power law at high pt.

Spectra are fit with Tsallis function which has two parameters, $T$ and $n$, and explicit $m_0$ dependence.

Fit describes spectra well across a wide pt range

$T$ describes lower pt range and $n$ describes power-law.

$T$ is harder to interpret for p+p collisions.
Dependence of the fit parameters on particle mass

Fit parameters $T$ and $n$ are approximately the same across all measured mesons, slight mass dependence

$$T = 117.4 \pm 2.5 \text{ GeV/c}^2$$

Similarity of parameters suggests similar production mechanisms for all mesons for $p+p @ 200$ GeV
Heavy Quarkonia in p+p and d+A collisions

$p+p$ at 200 GeV/c$^2$

PHENIX preliminary

$\sqrt{s_{NN}} = 200$ GeV p+p

$B \frac{dN}{dy}$

- PRL98:232002
- RHIC 2006 $y \in [-0.35, 0.35]$
- RHIC 2006 $y \in [-2.2, -1.2]$
- RHIC 2006 $y \in [1.2, 2.2]$

$\pm 10.1\%$ Global Scale Uncertainty

Higher statistics and better control over systematics
Excellent agreement with published results

⇒ Better constraints on models
Production model comparisons for p+p

Production models:

- COM or NRQCD – ccbar pair produced in octet state
- CSM – to LO, ccbar pair neutralized by 3rd gluon

CSM (LO)+S channel cut, reproduces PHENIX data fairly well.

Models have absolute normalization; they are not scaled.
Note agreement between data at positive and negative rapidity.

Harder spectra observed at mid-rapidity.

CSM + SC Model also works well for pt distributions.
J/ψ production in d+Au

d+Au at 200 GeV/c²

2008 data sample

\[ R_{CP}^{0-20\%} = \frac{N_{inv}^{0-20\%}}{N_{coll}^{0-20\%}} \bigg/ \langle \frac{N_{inv}^{60-88\%}}{N_{coll}^{60-88\%}} \rangle \]

\( R_{CP} \) is ratio of particle yield in central collisions to the particle yield in peripheral collisions.

Systematic errors largely cancel in \( R_{CP} \).

\( R_{cp} \sim 1 \) at negative rapidity
\( R_{cp} < 1 \) and decreases with centrality at positive rapidity
Take a npdf prescription (here EKS)

add a $J/\psi$ (or precursors) breakup cross-section $\sigma_{\text{breakup}}$

Fit the best $\sigma_{\text{breakup}}$ to the data, properly accounting for correlated and uncorrelated errors.

Small and moderate shadowing fail to reproduce the high rapidity data
At low enough $x_2$ (in the target nuclei), the gluon wave functions overlap. The $cc$ pair from the projectile parton interacts with all nucleons from the target in a coherent way, resulting in the $J/\psi$ formation.

This is applicable at low $x_2$ (forward rapidity) only; makes the use of $\sigma_{\text{breakup}}$ irrelevant in this regime.
J/Ψ production in d+Au II: gluon saturation, using 2008 data

Geometrical description of the collision is oversimplified in both plots. Right plots are an early comparison of the same calculation to 2008 $R_{CP}$ data.

Good job at forward rapidity
Doesn’t do backward rapidity (high x)
How to connect to previous picture

J/Ψ Polarization

Need angular distribution of decay leptons to fully understand bound state formation

$$\lambda = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$$

Amplitude and sign of $\lambda$ depends on frame:
- HX – helicity
- GJ – Gottfried-Jackson
- CS Collins-Soper

$\lambda < 0$ longitudinal polarization
$\lambda > 0$ transverse polarization
J/Ψ Production in p+p

Invariant mass of dielectrons in the J/Ψ mass range. Dashed lines represents the mass range used in the polarization analysis.

Fit to J/Ψ yield times dielectron branching ratio (B)

$$p+p \rightarrow J/\psi + X \quad |y|<0.35 \quad \sqrt{s} = 200 \text{ GeV}$$

$$\frac{d\sigma}{dydp_T} = \frac{A p_T}{\left[1+\left(\frac{p_T}{b}\right)^2\right]^n}$$
The observed $p_T$-dependent $J/\Psi$ polarization parameter in the HX frame is consistent with no polarization within current uncertainties. Also consistent with the s-channel cut CSM and COM.
The azimuthal distribution of particles emitted in high energy heavy ion collisions is a sensitive tool for understanding bulk properties of the matter produced in these collisions.

Written as a Fourier series:

\[ \frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi + 2v_4 \cos 4\phi + \cdots \]
Agreement between measurements from different detectors spanning $1.0<\eta<3.9$ suggest flow measurements are free of significant $\Delta \eta$ and $p_t$ dependent nonflow contributions.
Universal scaling of harmonic flow at RHIC

**v_2 scaling**

**v_4 scaling**

**Universal scaling**

KE_T & n_q (n_q^2) scaling validated for v_2 (v_4) → Partonic flow

Slide from Arkadij Taranenko
Higher harmonics important for determination of transport properties

Calculations: C. Gombeaud, J-Y Ollitrault

Estimate $4\pi(\eta/s) \approx 1\text{-}2$

Low energy scan coming next!
Summary

- **Neutral mesons in p+p and d+A:**
  - Systematic study of neutral meson production in p+p collisions at 200 GeV/c2. Spectra described well over entire momentum range by 2-parameter Tsallis fit. Parameters approximately the same for all mesons with weak mass dependence.

- **J/Ψ in p+p and d+A:**
  - CSM (LO)+S channel cut describes rapidity distribution and p_t spectrum fairly well.
  - npdf + σ_breakup describes R_{cp} at low rapidity with small, moderate shadowing but fails to reproduce the high rapidity data.
  - Gluon saturation describes R_{cp} at forward rapidity well but doesn’t address backward rapidity (high x).
  - J/Ψ polarization parameter in the HX frame consistent with no polarization within current uncertainties. Also consistent with the s-channel cut CSM and COM. For more d+A in PHENIX, see talk by O. Eyser, this session.

- **Flow:**
  - No evidence for strong Δη-dependent non-flow contribution.
  - Measurements compatible with a small value of η/s.
  - Universal scaling of v_2 and higher harmonics below pT~ 3 GeV/c implies partonic flow.
  - Low energy scan under analysis.

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