Jets and Heavy Flavor from STAR

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• High $p_T$ hadron and Jets

• Quarkonium

• Open Heavy Flavor
Single Hadron High $p_T$ Suppression

High $p_T$ hadron suppression at RHIC and LHC energies
Single Hadron High $p_T$ Suppression @ BES

Meson and Baryon: different $R_{cp}$ trends
At high $p_T$, pion suppressed for $\sqrt{s_{NN}} > 27$ GeV
proton enhanced at all BES energies
Semi-inclusive Jet Measurements

Spectrum shift -> Energy transport out-of-cone

<table>
<thead>
<tr>
<th>System</th>
<th>R</th>
<th>Jet $p_T$ (GeV/c)</th>
<th>Spectrum $p_T$ shift (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au @ 200 GeV</td>
<td>0.5</td>
<td>10-20</td>
<td>-2.8 ± 0.2 ± 1.5</td>
</tr>
<tr>
<td>Pb+Pb @ 2.76 TeV</td>
<td>0.5</td>
<td>60-100</td>
<td>-8 ± 2</td>
</tr>
<tr>
<td>p+Pb @ 5.02 TeV</td>
<td>0.4</td>
<td>15-50</td>
<td>abs shift &lt; -0.4</td>
</tr>
</tbody>
</table>

Smaller shift at RHIC than LHC

→ lower energy loss at RHIC
but larger $\Delta p_T/p_T^{jet}$ at RHIC

★ No Glauber/N_{coll} needed

p+Au h-jet coming

Au+Au $\gamma$-jet coming
Inter-jet Broadening: Scattering off the QGP

Conjecture for weak coupling:
dominated by single hard Molière scattering at “sufficiently large” $\Delta \phi$

No significant evidence for large-angle scattering in central Au+Au

d’Eramo et al., JHEP 1305 (2013) 031
STAR, PRC 96, 024905 (2017)
Photon-hadron Correlations

Calibrate initial parton energy
Avoid surface bias
Select more quark recoil jets

Absolute $p_T$ rather than particle $p_T$ fraction more relevant
Photon Triggered Recoil Jet

Jet-Hadron

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

- $10 < p_T^{jet} < 15$ GeV/c
- $20 < p_T^{jet} < 40$ GeV/c
- $\xi = \ln(p_T^\gamma/p_T^{assoc})$

$p_T^{assoc} \sim 2$ GeV/c

Absolute $p_T$ rather than particle $p_T$ fraction more relevant
‘Hard Core’ Dijets

Au+Au w/o soft particles

Au+Au w/soft particles

locate hard core dijets

reconstruct matched dijets

\[ p_T, \text{cut} = 2 \text{ GeV/c} \]
\[ p_T, \text{Lead} > 20 \text{ GeV/c} \]
\[ p_T, \text{SubLead} > 10 \text{ GeV/c} \]
\[ |\Delta\phi - \pi| < 0.4 \]
Dijets Restore Balance with Low $p_T$

STAR, PRL 119, 062301 (2017)

\[
A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}}
\]

Momentum balance restored to pp baseline for $R = 0.4$, after adding particle $< 2\text{GeV/c}$

For hard core matched dijets

credit: K. Jung
Dijet-Hadron Correlations

for **hard core** matched dijets

Background subtracted with Gaussian+constant fit

\[ \Delta \phi < 0.71 \]

STAR Preliminary

\[ \Delta \phi < 0.71 \]

STAR Preliminary

\[ p_T^{assoc} > 2 \text{ GeV/c}: \text{No significant difference for jet constituent multiplicity} \]

But jet energy changed — \( A_J \) different

\[ HT: E_T > 4.5 \text{ GeV} \]
Dijet-Hadron Correlations

for **hard core** matched dijets

Background subtracted with Gaussian+constant fit

\[ \Delta \phi | < 0.71 \]

STAR Preliminary

\[ \Delta \phi | < 0.71 \]

STAR Preliminary

HT: \( E_T > 4.5 \text{ GeV} \)

\[ A_J \] sensitive to modification in few events

Effect diluted in ensemble measurements (dijet-hadron)

\( \rightarrow \) Dijet-Hadron \( A_J \) dependence
Jet Substructure: Soft Drop $z_g$

Goal: to search for modification of hardest jet splitting

$z_g = \min\left(\frac{p_{T1}}{p_{T1} + p_{T2}}, \frac{p_{T2}}{p_{T1} + p_{T2}}\right)$

$z_g$ in **hard core** matched dijets with $p_{T,\text{cut}} > 0.2$ GeV/$c$

**Credit:** Marta Verweij

No significant splitting modification

Larkoski, *et al.*, JHEP05(2014)146
• High $p_T$ hadron and Jets

• Quarkonium

• Open Heavy Flavor
Quarkonium Productions

• The goal: Evidence for deconfinement; Thermometer

• Formation:
  • Mechanisms not fully understood even in p+p
  • Feed down contribution

• Modification:
  • Cold nuclear effects
  • Hot medium effects

• J/ψ photoproduction
J/ψ Spectra in p+p Collisions

- CGC+NRQCD and NLO NRQCD (prompt) consistent with data (inclusive) at p+p @ 200 and 500 GeV

\[ p+p @ 200 \text{ GeV} \]

\[ p+p @ 500 \text{ GeV} \]

NLO NRQCD: Ma et al., PRL106 (2011) 042002
CGC+NRQCD: Ma, Venugopalan, PRL113 (2014) 192301
J/ψ vs. Event Activity in p+p

Stronger-than-linear growth for high $p_T$ J/ψ

- Feed-down fraction depends on $p_T$
- $\chi_c$, $\psi(2s)$, B-hadrons

- Prompt J/ψ in jet populated at low $z$
- Less isolated than expected at LHC

Discussions on MPI effect: ALICE, arXiv 1202.2816, 1505.00664

< TofMult > J/ψ event $\approx 2.6$

< TofMult > MB event

LHCb, PRL 118, 192001 (2017)
Ψ(2S) to J/ψ Double Ratio in p+Au Collisions

Muon Telescope Detector (MTD) enables STAR’s first Ψ(2S) to J/ψ double ratio measurement in p+p and p+Au collisions:

\[ 1.37 \pm 0.42{\text{(stat.)}} \pm 0.19{\text{(syst.)}}. \]
J/ψ Suppression in Au+Au Collisions

Low $p_T$ J/ψ in central collisions:

- PHENIX: PRL 98 (2007) 232301
- ALICE: PLB 734 (2014) 314
- ALI-PREL-121481

High $p_T$ J/ψ in all centralities:

- STAR preliminary

$R_{AA}(200 \text{ GeV}) < R_{AA}(2.76 \text{ TeV}) \sim R_{AA}(5.02 \text{ TeV})$

Less regeneration at RHIC

$R_{AA}(200 \text{ GeV}) > R_{AA}(2.76 \text{ TeV}) \sim R_{AA}(5.02 \text{ TeV})$

Less color screening at RHIC
Production in p+p and p+Au Collisions

• Yields consistent with NLO model

• $R_{pA}$ quantifies CNM effects
Suppression in Au+Au Collisions

Sequential melting observed at both RHIC and LHC energies

CMS, PLB 770 (2017) 357
Excess of J/ψ at Very Low p_T

- J/ψ $R_{AA} \sim 30$ at $p_T < 0.05$ GeV/c in 60-80% collisions

- No significant centrality dependence of the excess yield in 30-80% collisions, while hadronic production is small and expected to strongly depend on $N_{part}$
Photoproduction Model Comparison

Large flux of quasi-real photons makes a hadron collider also a photon collider

- Consistent with coherent photoproduction
- Central collisions have a larger discriminating power
- A novel probe to study the medium?
  - potential to discriminate dissociation and regeneration

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Zha, et al., arXiv: 1705.01460
PHENIX, PLB 679 (2009) 321
Klein and Nystrand, PRL84 2330 (2000)
• High $p_T$ hadron and Jets

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Open Heavy Flavor Probes

Produced early and probe the full QGP history:

- Flavor-dependence of in-medium energy loss
  Nature of heavy quark-medium interaction

- Heavy quark collective behavior
  Degree of thermalization, spatial diffusion coefficient

- Heavy quark hadronization
  QGP dynamics
B vs D Mass Hierarchy of Energy Loss

Made possible by excellent Heavy Flavor Tracker (HFT) tracking resolution

Smaller suppression for electrons from B than D

★ High precision measurements coming
D⁰ Anisotropic Flow

Strong collectivity of D⁰ mesons
Consistent with charm quark achieving local equilibrium with the medium

★ D⁰ direct flow coming

STAR, PRL 118 (2017) 212301
Theory refs cited in paper
Heavy Quark Hadronization

Enhanced $D_s/D^0$ and $\Lambda_c/D^0$ ratios compared to Pythia
Charmed quarks may participate in coalescence hadronization

★★ Detailed measurements coming
Summary

• Significantly enhanced understanding of jet modifications at RHIC
  • total jet energy loss less than at LHC
  • lost energy re-emerges at low $p_T$
  • $z_g$ unmodified for hard core jets

• Explore heavy-flavor interaction with medium
  • mass hierarchy of c/b-quark energy loss observed
  • c-quark ‘thermalized’
  • Quarkonium sequential melting, smaller regeneration than LHC

• Quarkonium formation and cold nuclear effect investigated

• Excess of J/$\psi$ at very low $p_T$ consistent with coherent photoproduction
Probing the jet modification at RHIC

- High $p_T$ hadron suppression at BES (arXiv:1707.01988)
- pp in very good agreement with theory (Di-jets, PRD 95 (2017) 71103 (R))
- Unbiased recoil jets highly suppressed due to medium induced broadening
- Total $E_{\text{loss}}$ less than at LHC (Hadron-jet correlations, PRC 96 (2017) 24905)
- Lost energy re-emerges at low $p_T$ not $z_T$ ($\gamma$-hadron correlations, PLB 760 (2016) 689)
- Di-jet energy imbalance largely recovered within $R=0.4$ when low $p_T$ hadrons included (Di-jet $A_J$, PRL 119 (2017) 062301 - Editor's suggestion)
- $z_g$ unmodified for hard core jets (preliminary release)
- $\gamma$-jet, jet in small systems, flavor jet ... (stay tuned)

Significantly enhanced understanding of jet modifications at RHIC
B/D -> e Mass Hierarchy of Energy Loss

Excellent Heavy Flavor Tracker (HFT) resolution
Distinguish different electron sources by DCA

\[ R_{AA}^{B/D\rightarrow e} = \frac{1 - f_{AA}^{B/D\rightarrow e} (Data)}{1 - f_{pp}^{B/D\rightarrow e} (Data)} R_{AA}^{HF_e} (Data) \]

\[ R_{AA}^{B\rightarrow e} > R_{AA}^{D\rightarrow e} \]

Consistent with mass hierarchy of energy loss
Non-prompt J/ψ $R_{AA}$ in Au+Au Collisions

Fit pseudo proper decay length
Extract non-prompt J/ψ fraction

$$R_{AA}^{B \rightarrow J/\psi} = \frac{f_{Au+Au}^{B \rightarrow J/\psi}(Data)}{f_{p+p}^{B \rightarrow J/\psi}(Theory)} \times R_{AA}^{inc. J/\psi}(Data)$$

Strong suppression of $B \rightarrow J/\psi$ at high $p_T$ (> 5 GeV/c)
Comparable with $D^0$
Non-prompt $D^0$ Suppression

Template fit on DCA distribution to extract $B \to D^0$ contribution

Less suppression for non-prompt $D^0$ than for inclusive $D^0$
Excess of $J/\psi$ at Very Low $p_T$

- Significant $J/\psi$ enhancement at $p_T < 0.2$ GeV/c in peripheral collisions
- No significant centrality dependence of the excess yield, while hadronic production is expected to strongly depend on $N_{\text{part}}$
Low pT J/ψ excess from coherence photoproduction

W. Zha, et al., arXiv: 1705.01460

Calculations from coherence photoproduction describe data
Suppression in Au+Au Collisions

- SBS (Strongly Binding Scenario): fast dissociation—potential based on internal energy.
- WBS (Weakly Binding Scenario): slow dissociation—potential based on free energy.
- Data seem to favor the SBS model

Strickland, Bazov, NPA 879 (2012) 25
No CNM, no regeneration
Emerick, Zhao, Rapp, EPJ A48 (2012) 72,
Includes CNM, SBS case
Liu, Chen, Xu, Zhuang, PLB 697 (2011) 32
Dissociation only for excited states, suppression of ground state due to feed-down, SBS