STAR measurements sensitive to hadronization and underlying event/multiple parton interactions

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MPI@LHC 20.11.2023
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6 Summary
STAR is a well suited machine for high multiplicity studies thanks to its large TPC.
Soft vs. hard production mechanisms

Studied with quarkonium production vs. multiplicity

- What is the collision energy dependence?
- How the scale of the hard process ($p_T, m$) affects the production?
\[ J/\psi \sqrt{s} = 200 \text{ GeV} \text{ vs. } \sqrt{s} = 500 \text{ GeV} \] production vs. event activity

\[ p+p \sqrt{s} = 200, 500 \text{ GeV} \] 2012, 2011 datasets, \( J/\psi \rightarrow e^+ e^- \)

\begin{itemize}
  
  \item Strong increase of \( J/\psi \) production with \( N_{ch} \), a measure of "event activity"
  
  \item Percolation model: [E. G. Ferreiro, C. Pajares, Phys.Rev.C, 86, 034903(2012)]
    \begin{itemize}
      \item Low-\( p_T \) data are well described
      \item High-\( p_T \) data are above the model at high \( N_{ch} \). Note that the calculation is for \( p_T > 0 \text{ GeV}/c \)
    \end{itemize}
  
  \item CGC/Saturation model: [E. Levin et al., EPJC 97(5), 376(2019)], [E. Levin et al., EPJC 80(6), 560(2020)]
    \begin{itemize}
      \item Describes the data, however uncertainties are large
      \item Data are slightly above the model at high \( p_T \). Note that the calculation is for \( p_T > 0 \text{ GeV}/c \)
    \end{itemize}
  
  \item Possible effects of parton saturation
\end{itemize}
Cross section ratios: $\Upsilon(nS)/\Upsilon(1S)$

$p+p \sqrt{s} = 500$ GeV 2011 dataset, $\Upsilon \to e^+ e^-$


- Ratios vs. TofMult - no strong multiplicity dependence observed.
- TofMult: number of tracks matched to TOF within $|\eta| < 1$, $p_T > 0.2$ GeV/c (uncorrected)
- Linear fits (solid line) and $1\sigma$ uncertainty (dashed line)
\( \gamma \) production vs. event activity

\( p+p \sqrt{s} = 500 \text{ GeV} \) 2011 dataset, \( \gamma \rightarrow e^+e^- \)

- Self-normalized yield vs. self-normalized multiplicity in \( p+p \sqrt{s} = 500 \text{ GeV} \) measured for \( \gamma(1S + 2S + 3S) \) and \( \gamma(1S) \)

- Data consistent with a linear rise (black line), with a hint for stronger-than-linear rise for \( \gamma(1S) \) above \( p_T > 4 \text{ GeV}/c \)

- Percolation model predicts quadratic dependence

\[
\frac{N_{\text{hard}}}{\langle N_{\text{hard}} \rangle} = \langle \rho \rangle \left( \frac{\frac{dN_{\text{ch}}}{d\eta}}{\langle \frac{dN_{\text{ch}}}{d\eta} \rangle} \right)^2
\]


- Quadratic fit \( y = ax^2 \) describes the data, suggest quenching due to overlapping strings
$p+p \sqrt{s} = 500\,\text{GeV}$ 2011 dataset, $\Upsilon \rightarrow e^+e^-$

- PYTHIA8 and Percolation models reproduce the trend in the data
  - MPI or string quenching effects

- CGC/Saturation model describes the data within large uncertainties
  - [E. Levin M. Siddikov, EPJC, 97(5), 376(2019)], [EPJC 80(6), 560(2020)]
  - Hint of saturation effects
Compare $J/\psi$ and $\Upsilon$ production vs. event activity - mass dependence

$p+p \sqrt{s} = 500$ GeV 2011 dataset, $\Upsilon \rightarrow e^+ e^-$

Similar trend at RHIC and LHC for $\Upsilon$ and $J/\psi$

- Seems to be independent of mass or collision energy

Effect of jets on underlying event

- Study jets and correlations vs. underlying event
- Underlying event can be studied in the transverse direction relative to jet

[V. Verkest, DNP 2022]
Studies of UE in jets in 3 regions:
- toward, away, transverse

The $\langle \frac{dN_{ch}}{d\eta d\phi} \rangle$ increases with leading jet $p_T$ in the toward and away directions.

Strong dependence of $\langle p_T \rangle$ on leading jet $p_T$ in the toward and away directions.

Weak dependence of $\langle \frac{dN_{ch}}{d\eta d\phi} \rangle$ and $\langle p_T \rangle$ in the transverse direction.

Hint of small contributions to UE from initial (ISR) and final state radiation (FSR). 

STAR: [Phys. Rev. D 101, 052004]

[J. Fiete G-O, Joliot-Curie International School 2018]
Jets vs. underlying event in $p + Au$

- Underlying event UE is defined as charged particles within $1 < |\phi_{lead} - \phi_{UE}| < \pi - 1$
- Higher UE $N_{ch}$ in events with large event activity measured by the BBC in Au-going direction
- Larger UE in the Au-going direction
  - No significant dependence on leading jet $p_T$
Evidence of non-linear gluon dynamics

Opportunity to test CGC with jets
Back-to-back azimuthal correlations of \( \text{d}i\pi_0 \) at forward pseudorapidity
(2.6 < \( \eta \) < 4.0)
  - measured in \( p + p, p + Al, \) and \( p + Au \)
Relative area: area of away-side peak of the correlation function with respect to \( p + p \)
Clear \( A \)-dependent suppression of back-to-back yields in \( p + A \) compared to \( p + p \)
for small-\( x \) (and \( Q^2 \)) pairs with low \( p_T \)
STAR Pythia8 "‘Detroit’’ Tune

Towards comprehensive description of $p + p$ collisions at RHIC energy (not only!)

[Aguilar et al., Phys. Rev. D 105, 016011]
Detroit Pythia8 Tune - input data and procedure

Interpolate
Minimize $\chi^2$

Tuned using Professor tool: [EPJC 65 (2010) 331-357]

- Interpolate
- Minimize $\chi^2$

Used a wide data sample from STAR and Tevatron

- Combines soft and hard processes
  - Cross sections, multiplicity distributions, jet characteristics
- Included in Rivet

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Detroit Tune - tuned parameters

ColourReconnection:range
1.8 → 5.4

Global $\chi^2/\text{ndf} = 611/493$

MultipartonInteractions:ecmPow
0.215 → 0.135

MultipartonInteractions:coreRadius
0.4 → 0.56

MultipartonInteractions:coreFraction
0.5 → 0.78

MultipartonInteractions:pT0Ref
2.28 → 1.40 GeV

[Aguilar et al., Phys. Rev. D 105, 016011]

$$p_{T,0} = p_{T,0}^{\text{ref}} \left( \frac{\sqrt{s}}{\sqrt{s}_{\text{ref}}} \right)^{\text{ecmPow}}$$
Better description of STAR data with Detroit than Monash tune
Better description of STAR data with Detroit than Monash tune
Simultaneous description of underlying event and jet substructure
High $p_T$ - better description with Detroit than Monash
Low $p_T$ - larger variation due to the proton shape used
In general better performance when extrapolating from RHIC energy to LHC
  - This opens a possibility of more tuning at lower energies
  - Will be important for upcoming Electron Ion Collider
Prospects for $J/\psi$ and $\Upsilon$

High precision measurement of $J/\psi$ and $\Upsilon$ dependence on normalized $N_{ch}$

Very high integrated luminosity:
- $\mathcal{L}_{int} \sim 750 \text{ pb}^{-1}$ for Barrel High Tower triggered $e$ - high energy electrons
- $\mathcal{L}_{int} \sim 375 \text{ pb}^{-1}$ for $\mu \mu$ triggers

Possible to discriminate different models

2017 data is already $10 \times$ more than 2011
Future plans for STAR

- Forward upgrade $2.5 < y < 4$ - already installed and running
  - Silicon detectors (FST) - tracking
  - Small-strip Thin Gap Chambers (sTGC) - tracking
  - Electromagnetic and hadronic calorimeters - jet energy measurements

- High integrated luminosity for precision quarkonium production studies both at mid and forward rapidity

- Collect $p + p$, $p + A$, $Au + Au$ data at 200 GeV for comprehensive studies

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*https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648*
**Summary**

### Multiplicity dependence of quarkonium production
- Similar trend observed for $J/\psi$ and $\Upsilon$ at RHIC and LHC
  - Same effects at different energies and mass scales
- Percolation Model, PYTHIA and CGC/Sat models qualitatively describe the data
  - Indication of quarkonium production in MPI
  - Possible effect of parton saturation
- More data coming as well as opportunity to study it at forward vs. mid-rapidity

### Studies of UE with jets and correlations
- UE measured in the transverse region shows very weak dependence on leading jet $p_T$
  - Hint of small contributions of ISR and FSR to UE
- $\text{di}-\pi_0$ correlations at forward $\eta$ show indication of non-linear gluon effects

### STAR Pythia8 Detroit tune
- Optimized Underlying Event and MPI parameters as well as PDFs
- Better performance than Monash tune at RHIC and Tevatoron energies
- Good performance at LHC suggests its better to extrapolate from low to high energies
  - More opportunities of tuning at low energies
  - Important for future EIC
Thank you for your attention!
BACKUP
Detroit - energy extrapolation

\[ p_{T,0} = p_{T,0}^{\text{ref}} \left( \frac{\sqrt{s}}{\sqrt{s_{\text{ref}}}} \right)^{\text{ecmPow}} \]