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Quarkonium Energy Correlator for Heavy Quark Hadronization

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Chen, et al., PRL. 133 (2024) 19, 2405.10056

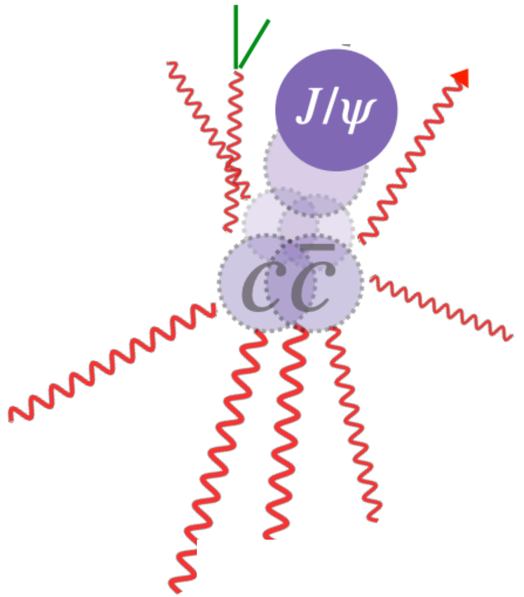
Outline

- The idea of the quarkonium energy correlator
- Connection to energy distribution during heavy quark hadronization
- Conclusion

Quarkonium Energy Correlator and hadronization

Quarkonium Physics

- regarded as an excellent place to study non-pert phenomenon
- How $c\bar{c} \to J/\psi$?
  - NRQCD Bodwin et al., PRD 1995
    - Power counting in $v \ll 1$, e.g., $E_{g_s} \sim Mv$
    - encoded in $\langle \mathcal{O}_{\mathbf{1}} \rangle$, $\langle \mathcal{O}_{\mathbf{8}} \rangle$
  - remains largely unknown: amount of energy released? Energy Distribution?



Quarkonium Energy Correlator and hadronization

Quarkonium Physics

Probing Quarkonium Production Mechanisms with Jet Substructure

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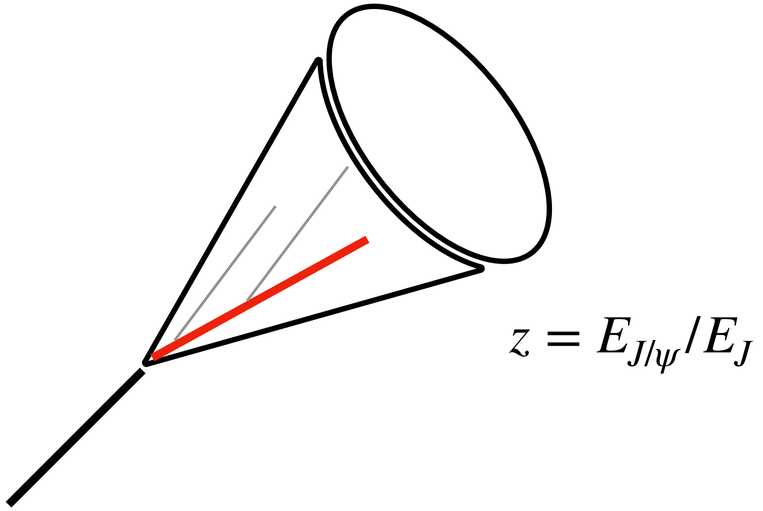
(Dated: June 27, 2018)



Unlike light hadron fragmentation, $D_{q\to J/\psi}(z)$ dominated by perturbative radiation from E_J to $2m_c$

$$D_{q\to J/\psi}(z) \sim C_i(z)\langle \mathcal{O}_i \rangle$$

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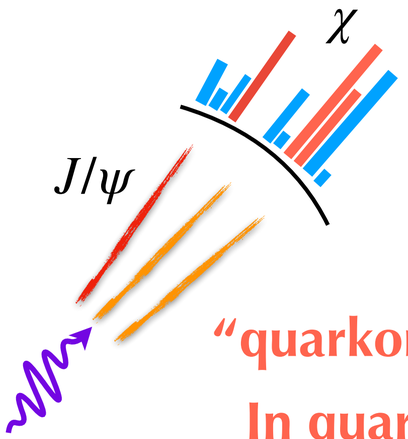
Quarkonium Energy Correlator Chen et al., 2405.10056



"quarkonim-Jet correlation"

In quarkonium rest frame

$$\Sigma_{\mathrm{QEC}}(\chi) = \frac{1}{\sigma_{J/\psi}} \int d\sigma_{J/\psi} \frac{E_i}{M} \delta(\chi - \chi_i)$$

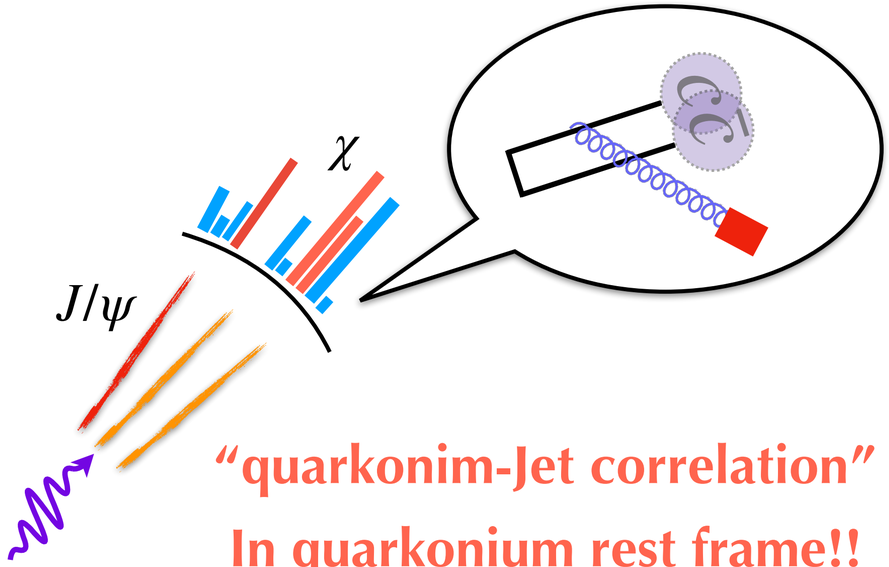
~ average energy at the angle χ

Quarkonium Energy Correlator and hadronization

Quarkonium Energy Correlator

Chen et al., 2405.10056

- $\Sigma_{@EC} = \Sigma_{@EC,P.T.} + \Sigma_{@EC,had.}$
  - Hadronization enters as an additive correction, not in the form of convolution
  - $\Sigma_{@EC,had.}$ can be extracted from "Measured - pQCD", If $\Sigma_{@EC,had.}$ is not too small



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Quarkonium Energy Correlator

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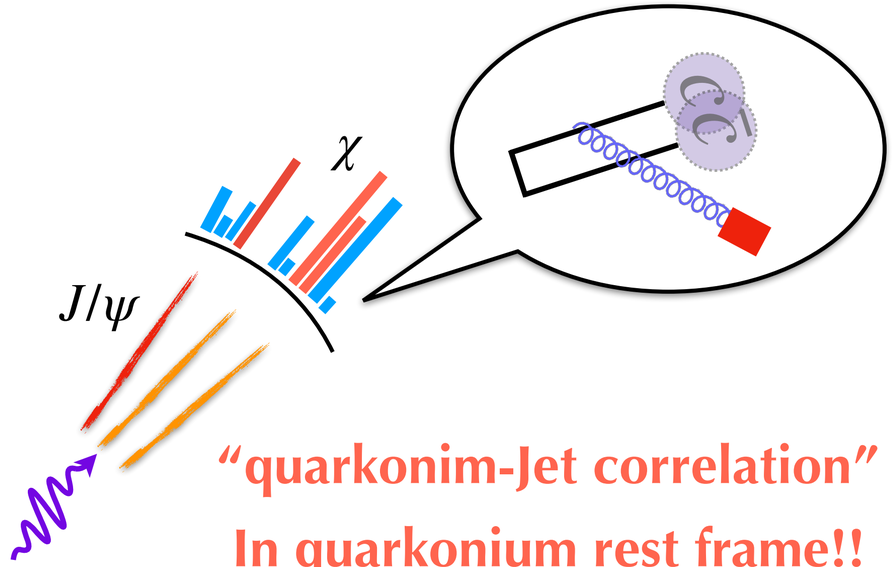
  - Hadronization enters as an additive correction, not in the form of convolution

$$\Sigma_{@EC,P.T.} \sim \alpha_s(M)\frac{E(\chi)}{M}E^2(\chi),$$

$$\Sigma_{@EC,had.} \sim \frac{Mv}{M}M^2v^2$$



"quarkonim-Jet correlation"

In quarkonium rest frame!!

$$\Sigma_{@EC}(\chi) = \frac{1}{\sigma_{J/\psi}}\int d\sigma_{J/\psi}\frac{E_i}{M}\delta(\chi-\chi_i)$$

$$\sim \int_{Mv}^{E_{\max}} \frac{E^2dE}{2E}\frac{E}{M}\langle\mathcal{O}_{\mathbf{1,8}}\rangle + \int^{Mv} \frac{E^2dE}{2E}\frac{E}{M}$$

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Quarkonium Energy Correlator

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$$\Sigma_{@EC,P.T.} \sim \alpha_s(M)\frac{E(\chi)}{M}E^2(\chi),$$

$$\Sigma_{@EC,had.} \sim \frac{Mv}{M}M^2v^2$$

  - Hadronization contribution could be large

for J/ψ $\alpha_s(M) \sim v^2, v \sim 0.5$

$$\Sigma_{@EC,had.}/\Sigma_{@EC,P.T.} \sim \frac{Mv}{\alpha_s E}\frac{M^2v^2}{E^2} \sim v \times \frac{v^2}{\alpha_s}\frac{M^3}{E(\chi)^3}$$

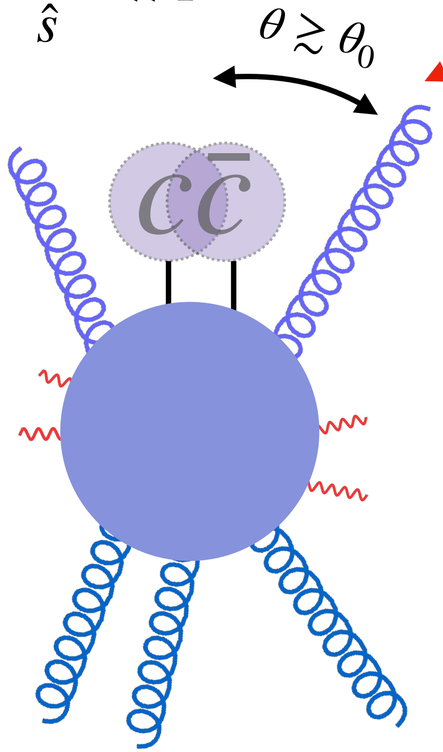
If $E(\chi)/M \sim 1$

$$\Sigma_{@EC,had.}/\Sigma_{@EC,P.T.} \sim 50\%!$$

Quarkonium Energy Correlator and hadronization

Generic configuration of boost J/ψ production in pQCD

COM frame $r \equiv \frac{M^2}{\hat{s}} \ll 1$



$E_s \sim \mathcal{O}(M), E_{J_{near}} \sim E_{J_{away}} \sim \mathcal{O}\left(\frac{\sqrt{\hat{s}}}{2}\right)$

dead-cone effects Dokshitzer et al., J. Phys. G

$$d\sigma_{Q\to Qg} \sim \frac{\alpha_s C_F}{\pi}\frac{dE_g}{E_g}\frac{\theta^2 d\theta^2}{[\theta^2+\theta_0^2]^2}$$

$$\theta_0 \sim \frac{M}{E_{\bar{J}/\psi}} \sim \frac{2M}{\sqrt{\hat{s}}} = 2\sqrt{r}$$

Near-side radiations:

$E_J \sim \sqrt{\hat{s}}/2\,, p_t \sim M$

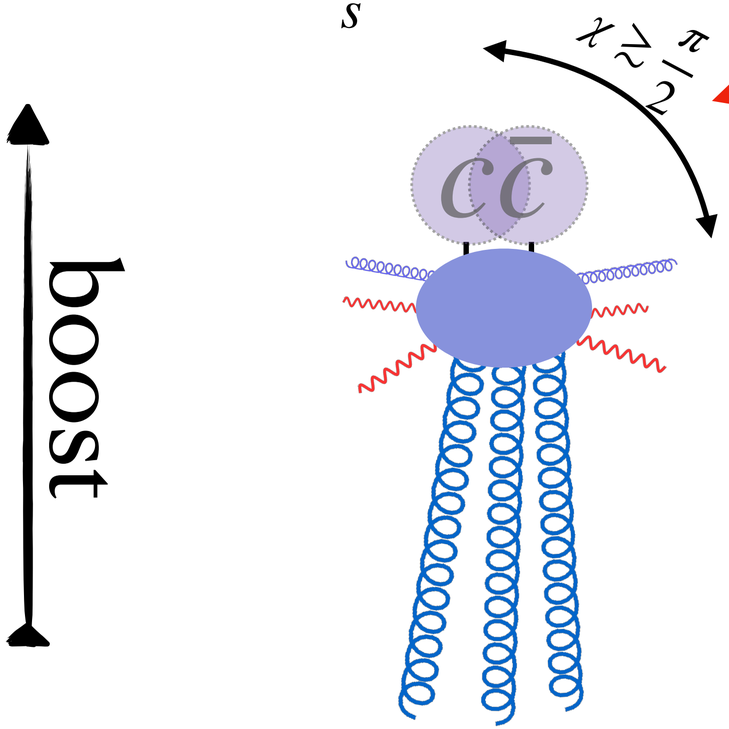
Chen et al., 2405.10056

Quarkonium Energy Correlator and hadronization

Generic configuration of boost J/ψ production in pQCD

J/ψ rest frame $r \equiv \frac{M^2}{\hat{s}} \ll 1$

Near side radiation will be depleted.

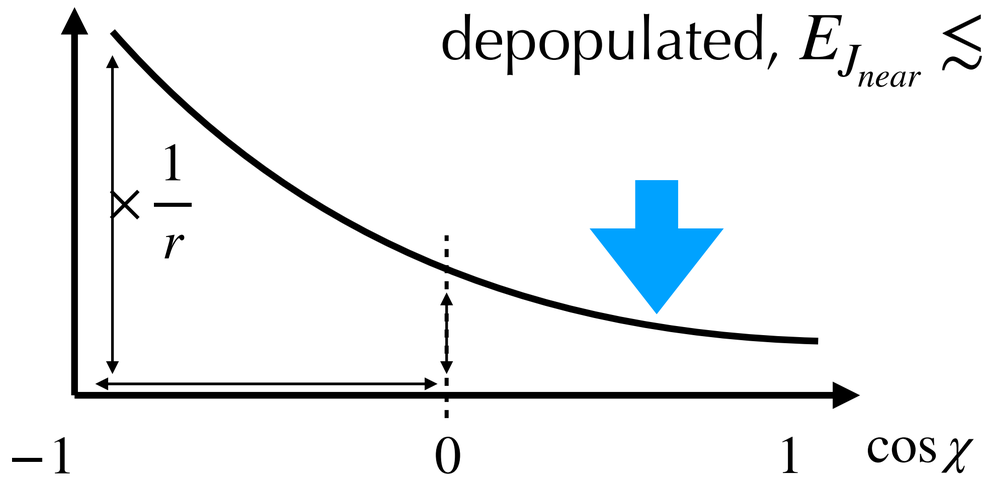


$E_{J_{near}} \sim E_s \sim \mathcal{O}(M), E_{J_{away}} \sim \mathcal{O}\left(\frac{\hat{s}}{M}\right)$

$E_{J_{away}}/E_{J_{near}} \sim \text{boost factor}^2 \sim r^{-1}$

pQCD:

hard radiation depopulated, $E_{J_{near}} \lesssim M$



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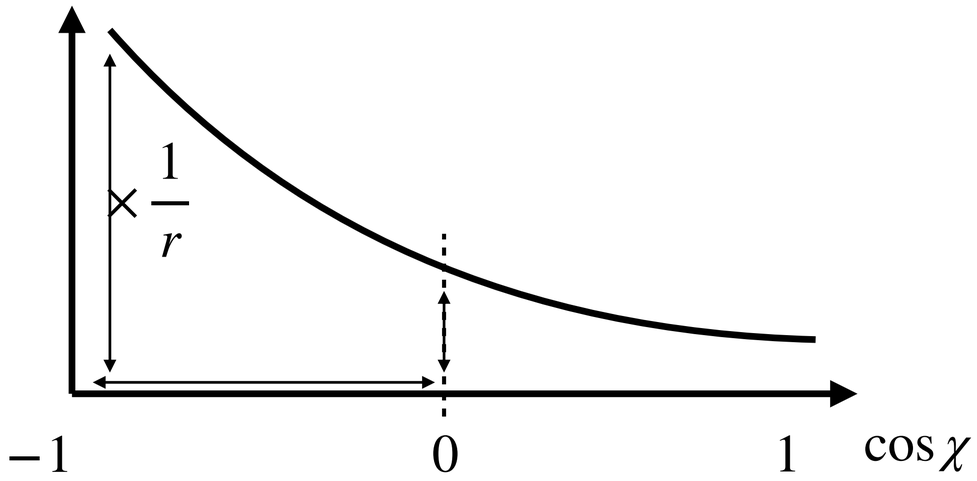
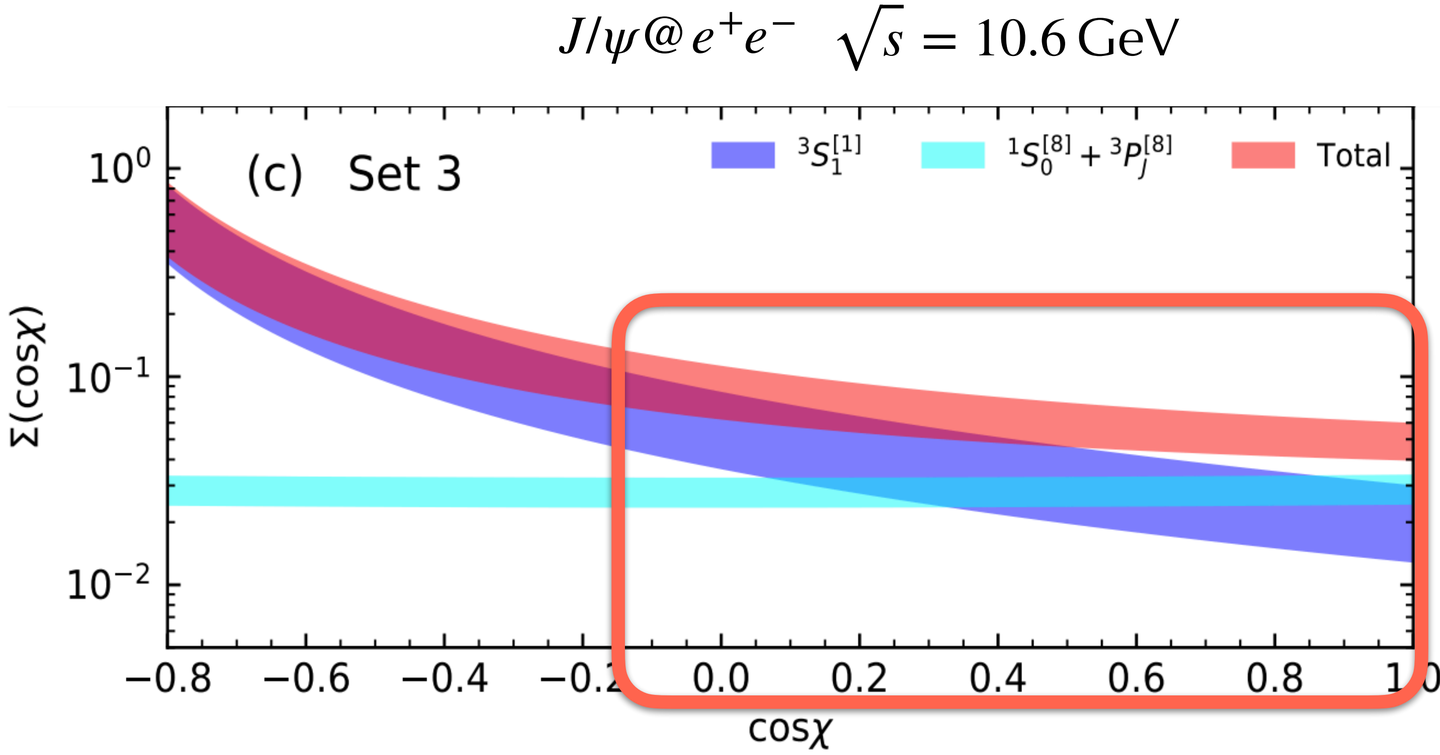
Quarkonium Energy Correlator and hadronization

NRQCD Predictions:



NP model:

- $c\bar{c} \to J/\psi + g_s$
- NRQCD matrix element scaling
- HF spin (rotational co-variance) symmetry

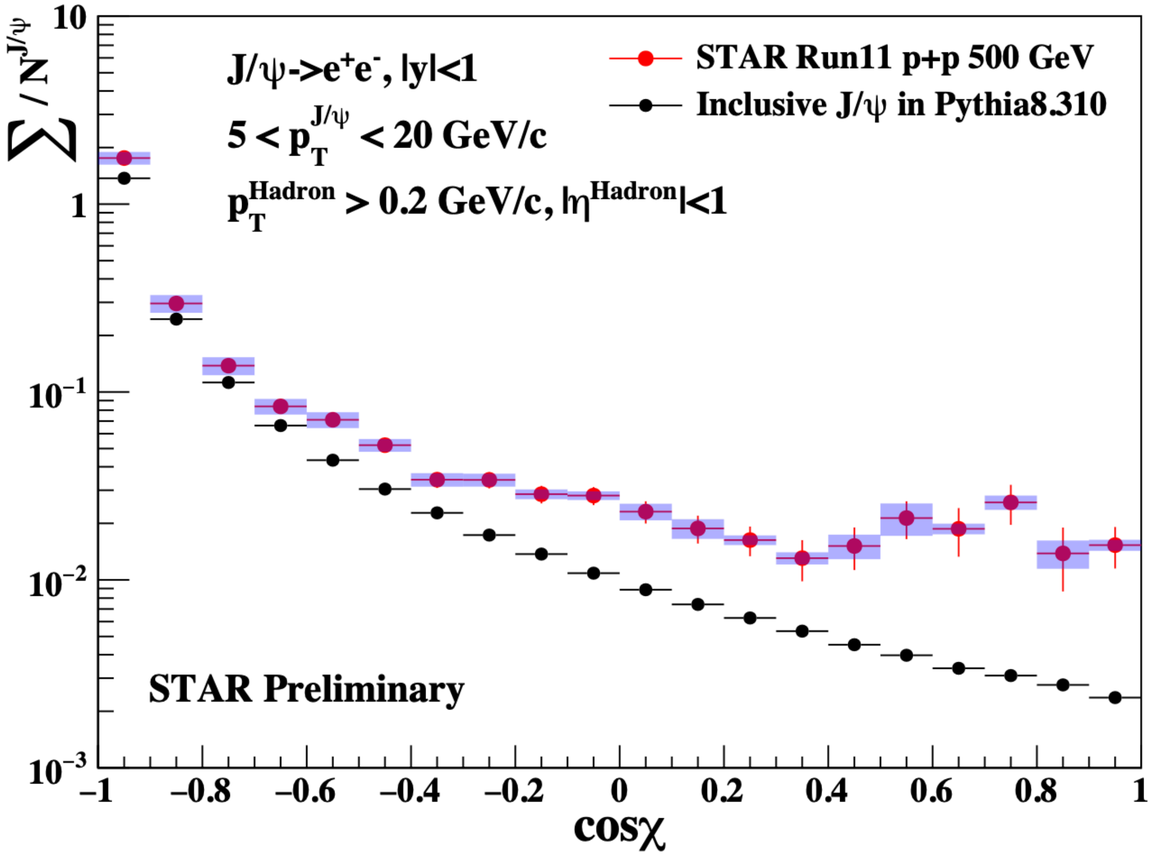


Sizable hadronization effect

"See" the hadronization energy distribution

Chen et al., 2405.10056

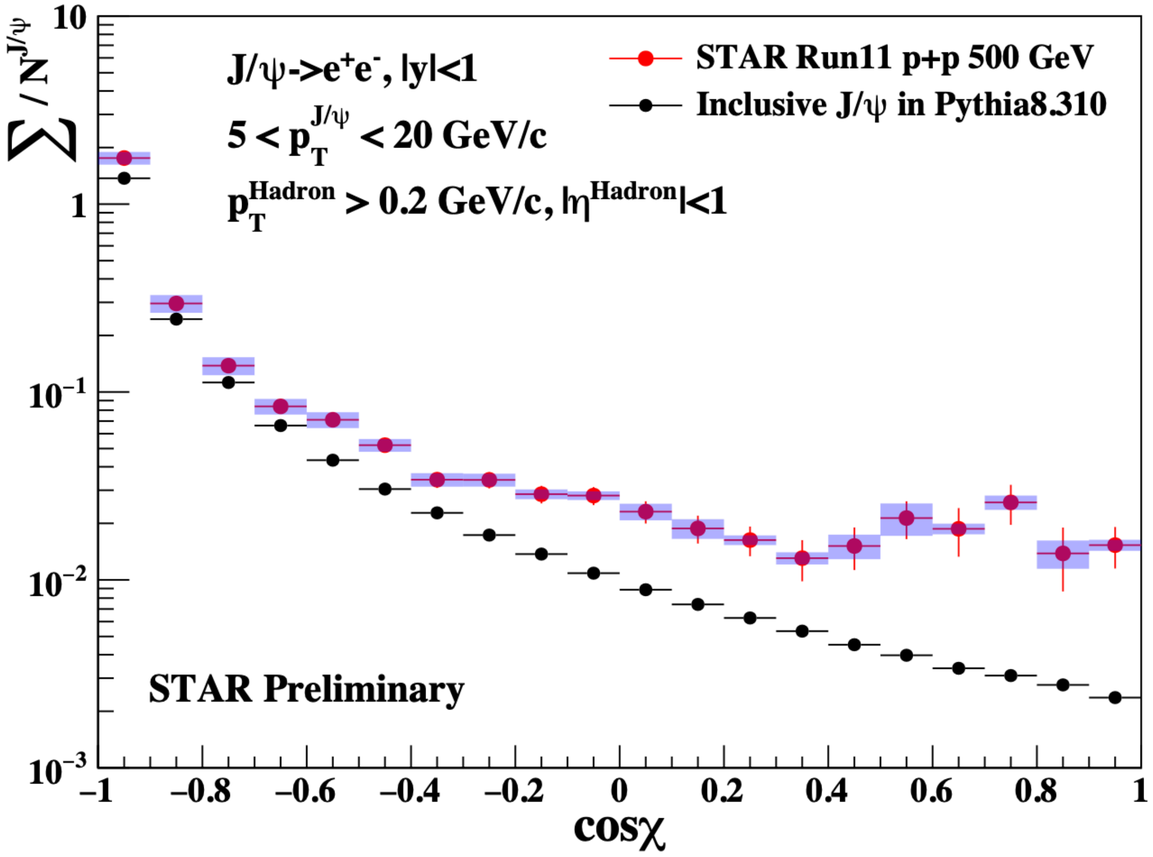
Quarkonium Energy Correlator and hadronization



Dandan Shen's Poster @ QM 2025

- Pythia does not capture correctly the J/ψ EC when $\chi < \pi/2$ (radiations around J/ψ)
- Pythia shape consistent with pQCD expectation
  - Pythia models pQCD radiations reasonably well?

Quarkonium Energy Correlator and hadronization



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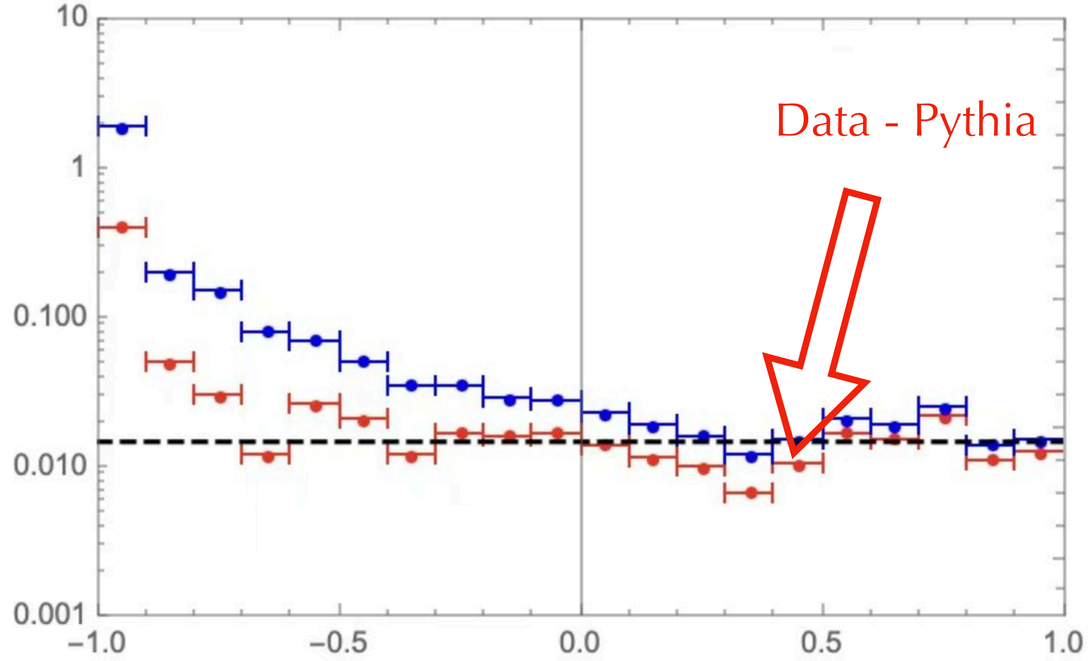

- Data - Pythia consistent with the NRQCD NP model
  - Have we seen the energy from hadronization? NEED pQCD INPUT!

Conclusion

- The Quarkonium Energy Correlator can provide us new insights into heavy quark hadronization
- High chance to identify the energy distribution during hadronization at current available facilities
- Calls for inputs from precision calculation

Thanks