Quarkonium Energy Correlator

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第4届LHCb前沿物理研讨会

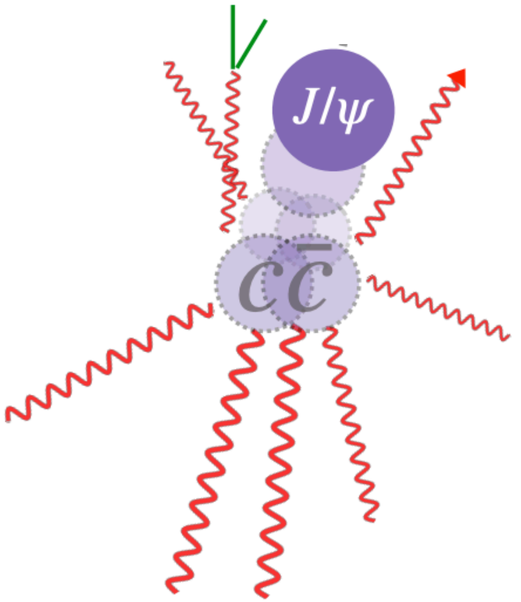
北京師範大學
BEIJING NORMAL UNIVERSITY

Chen, XL, Ma, **2405.10056**

Motivation

Quarkonium Physics

- regarded as an excellent place to study non-pert phenomenon for a long time
- How $c\bar{c} \rightarrow J/\psi$?
  - NRQCD: encoded in $\langle \mathcal{O}_1 \rangle$, $\langle \mathcal{O}_8 \rangle$
  - remains largely unknown: amount of energy released? Energy Distribution?



Motivation

Recent attempts using jet

Probing Quarkonium Production Mechanisms with Jet Substructure

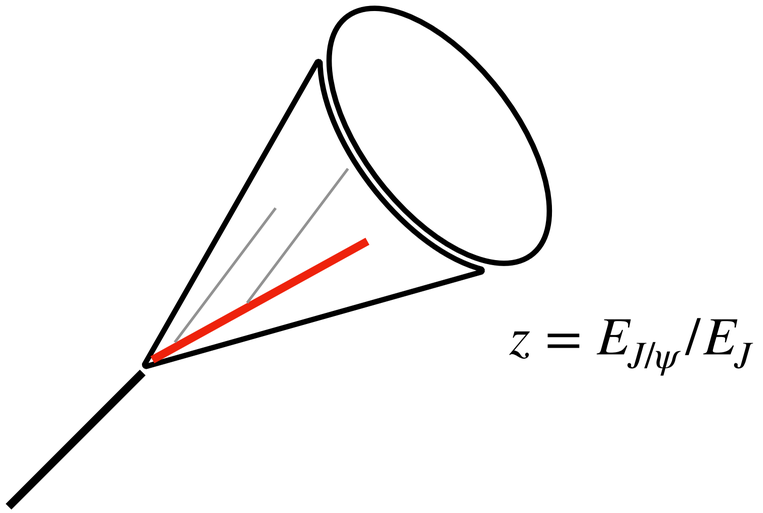
Matthew Baumgart[a],[1] Adam K. Leibovich[b],[2] Thomas Mehen[c],[3] and Ira Z. Rothstein[d1]

[1] *Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213*

[2] *Pittsburgh Particle Physics Astrophysics and Cosmology Center (PITT PACC) Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260*

[3] *Department of Physics, Duke University, Durham, NC 27708*

(Dated: June 27, 2018)



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

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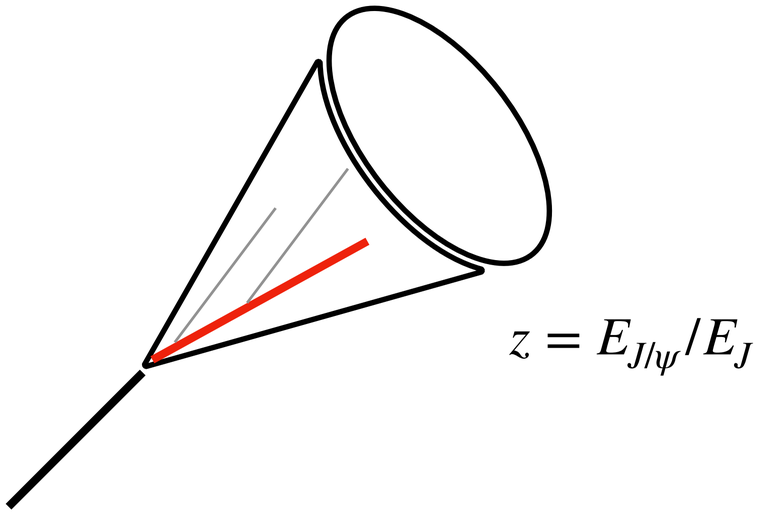


Unlike light hadron fragmentation, $D_{q\to J/\psi}(z)$ dominated by perturbative radiation

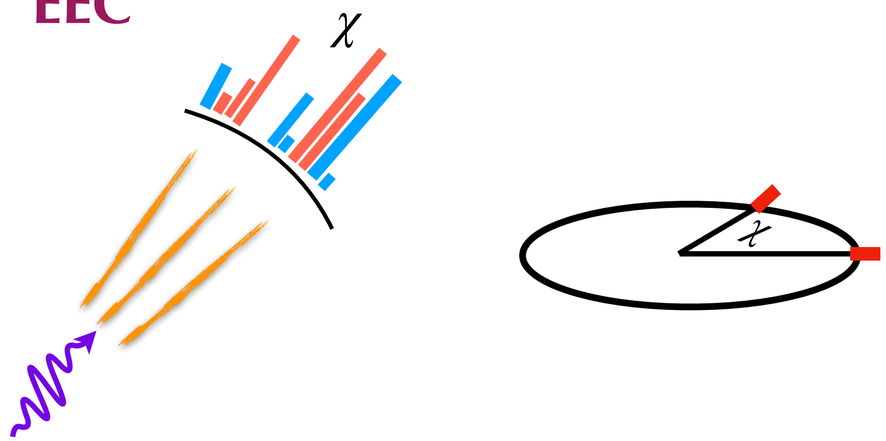
Chance to “see” hadronziation?

Outline

- Motivation
- Energy Correlators
- Adapt to quarkonium studies — the Quankonium energy correlator
- Conclusion

Energy Correlators

EEC



$$\Sigma_{\text{EEC}} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij})$$

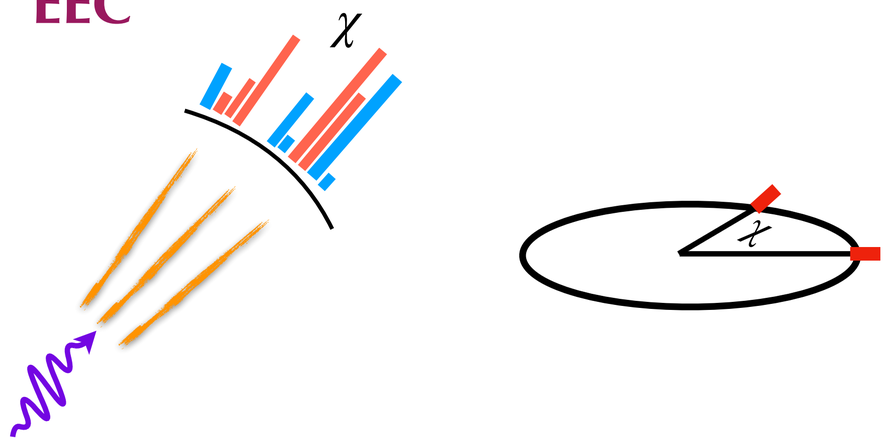
$$= \frac{1}{Q^2}\langle J^\mu(x)\mathcal{E}(n_1)\mathcal{E}(n_2)J^\nu(0)\rangle_\Omega$$

Sterman, 1975

Bashman, et al. 1978

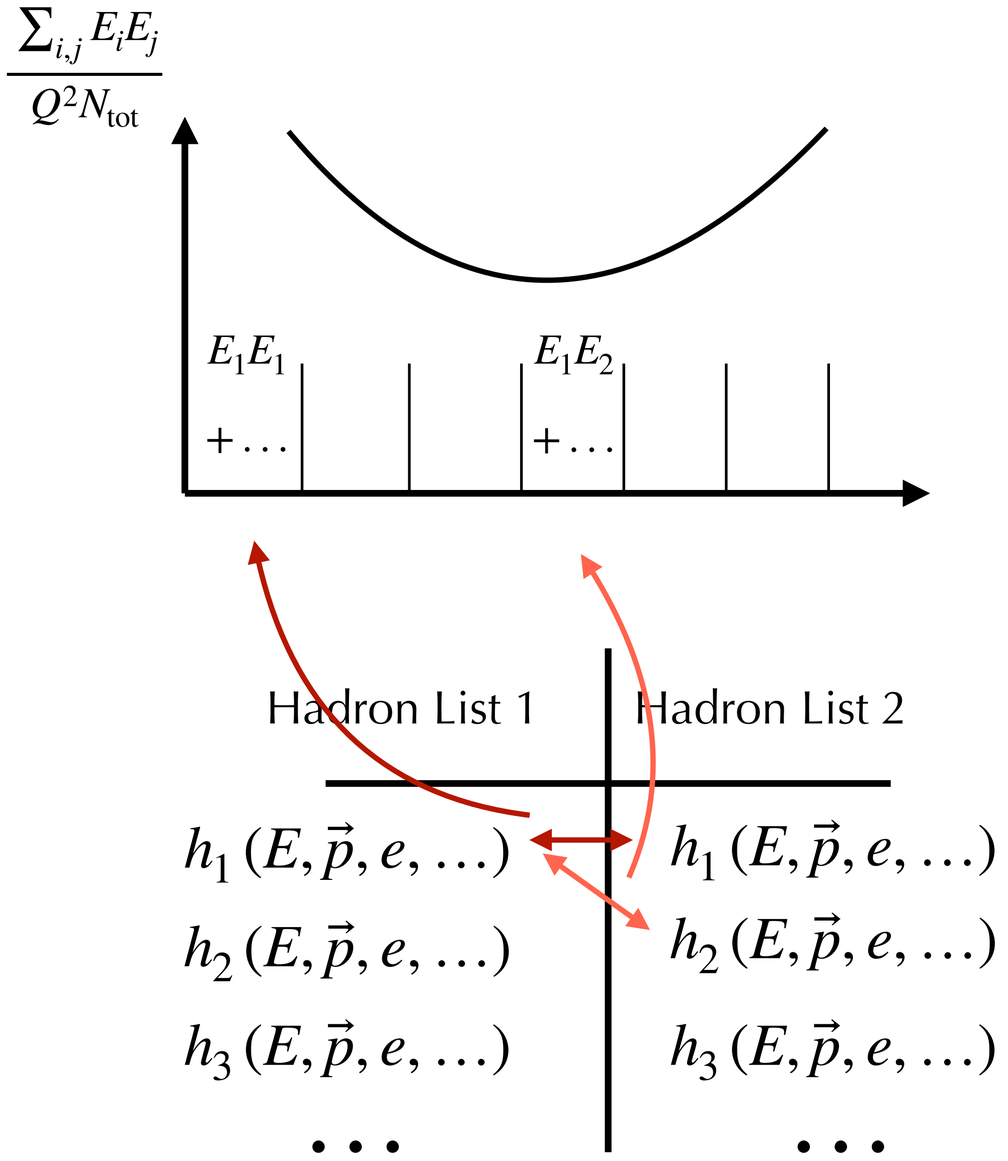
Energy Correlators

EEC



$$\Sigma_{\text{EEC}} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij})$$

- Easy to implement, **"Jet w/o jet"**
- Perturbatively predictable



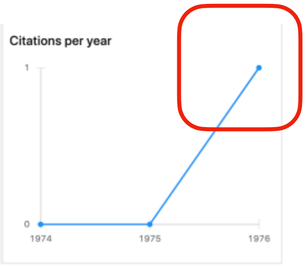
Energy Correlators

Jet Structure in e+ e- Annihilation with Massless Hadrons

George F. Sterman (Illinois U., Urbana)
Dec, 1975

10 pages
Report number: ILL-TH-75-32
View in: KEK scanned document

pdf cite claim reference search 1 citation



Our ensembles will thus be specified in terms of set

states. To make this idea more quantitative we defi n

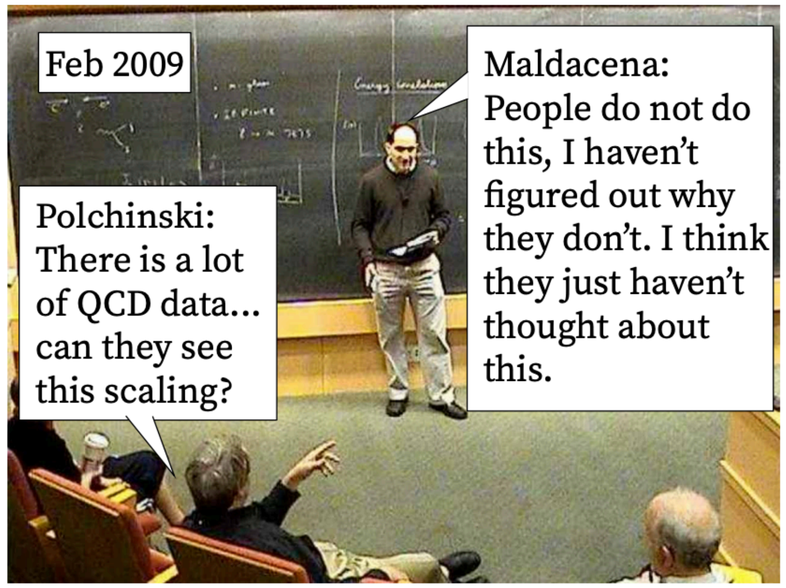
"angular energy current" in the e^+e^- CM frame:

$$j_a(\Omega) = \sum_{i=1}^{n_a} \eta_i \delta(\Omega - \omega_i)$$

Conformal collider physics:
Energy and charge correlations

Diego M. Hofman[a] and Juan Maldacena[b]

[a] *Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, USA*
[b] *School of Natural Sciences, Institute for Advanced Study Princeton, NJ 08540, USA*

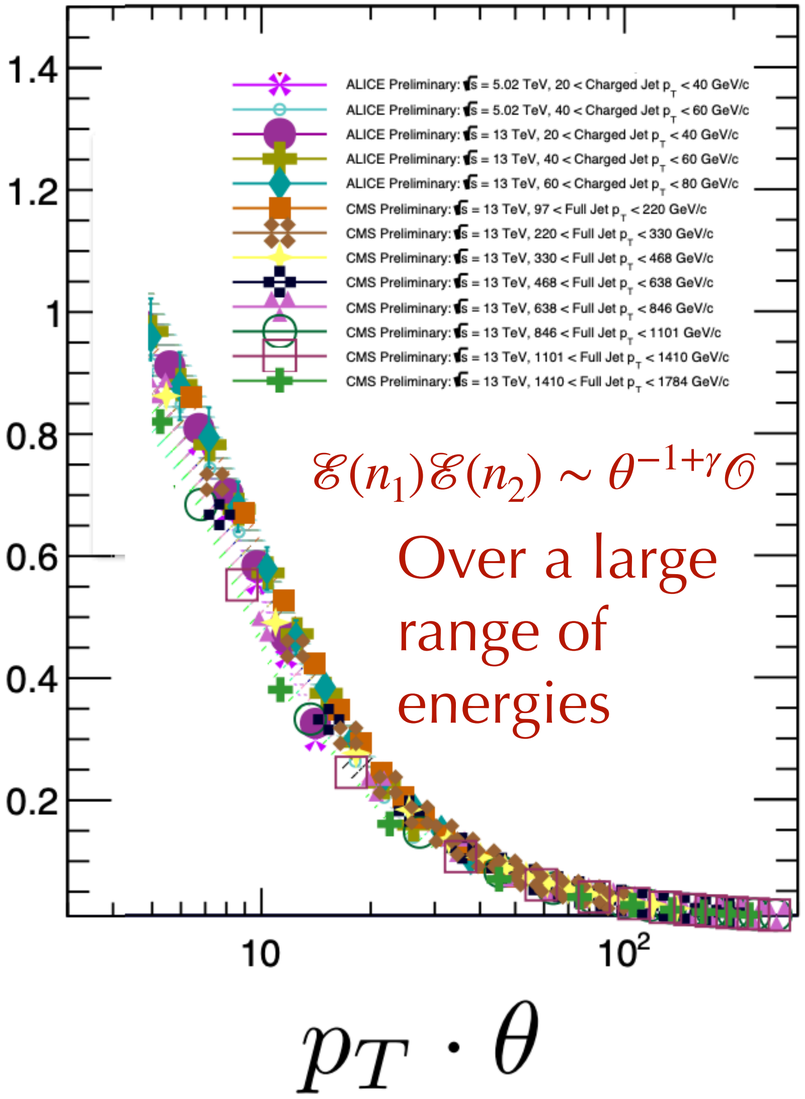


$$\mathcal{E}(n_1)\mathcal{E}(n_2) \sim \theta^{-1+\gamma}\mathcal{O}$$

Scaling rule by conformal theory Hofman, Maldecena, 2008

Energy Correlators

As of 2024

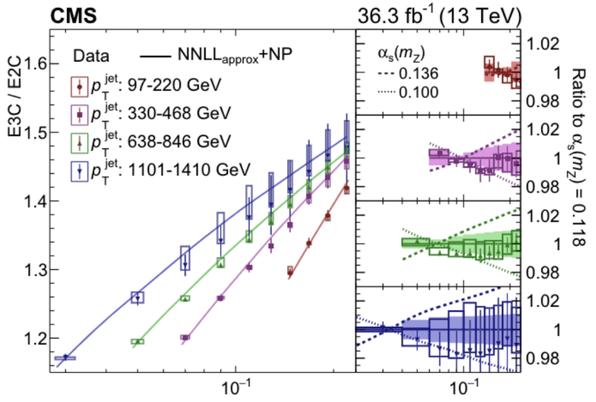


$\langle \mathcal{E}_1 \mathcal{E}_2 \rangle$

$\mathcal{E}(n_1)\mathcal{E}(n_2) \sim \theta^{-1+\gamma}\mathcal{O}$

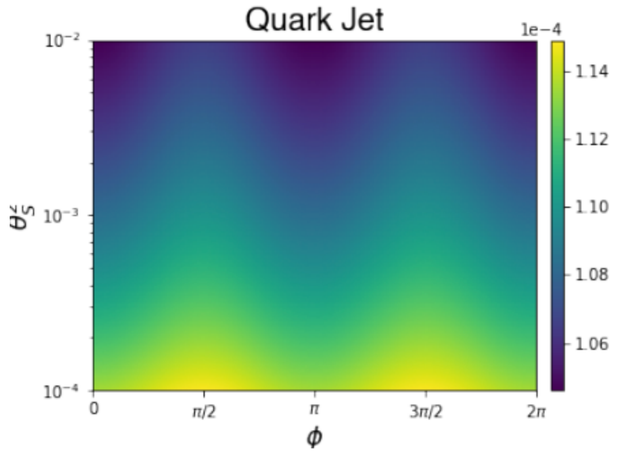
Over a large range of energies

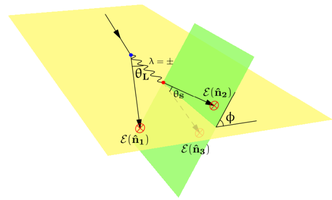
$p_T \cdot \theta$



Most precise α_s extraction using jet substructure

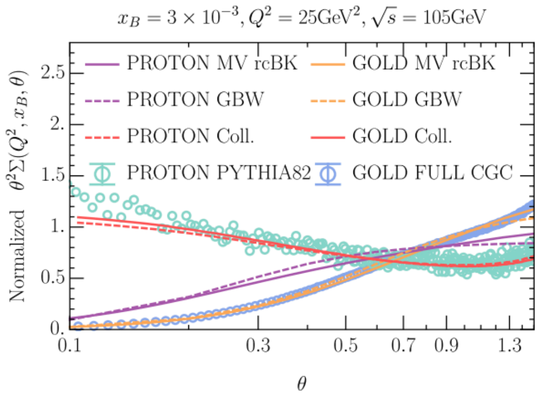
(Meng et al., 2024)

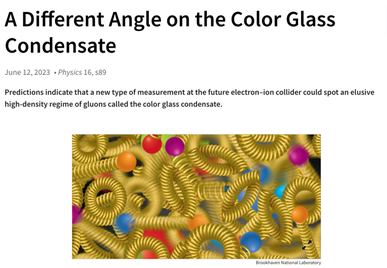




Spinning gluon

Chen, Moult, Zhu, PRL 2021





XL, Zhu, PRL 2023

Physics

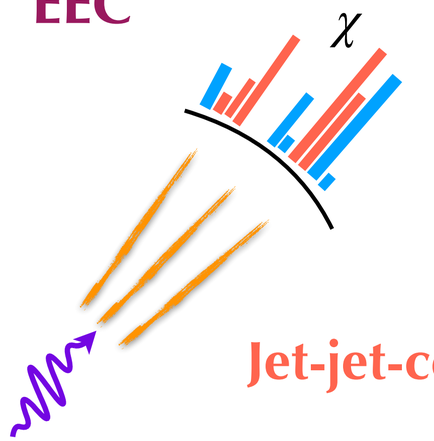
NEEC as a promising probe of the gluon saturation

Liu, XL, Pan, Yuan, Zhu, PRL 2023

Quarkonium Energy Correlator

Chen, XL, Ma, **2405.10056**

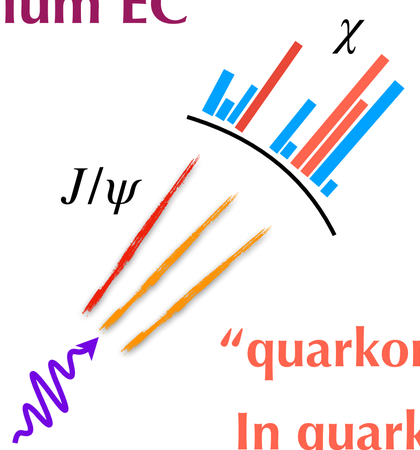
EEC



Jet-jet-correlation

$$\Sigma_{\rm EEC} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij})$$

Quarkonium EC



"quarkonim-Jet correlation"

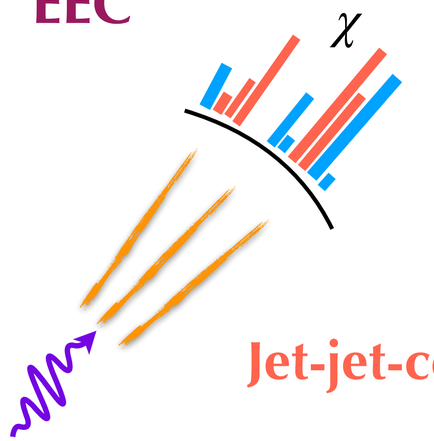
In quarkonium rest frame!!

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

Quarkonium Energy Correlator

Chen, XL, Ma, **2405.10056**

EEC



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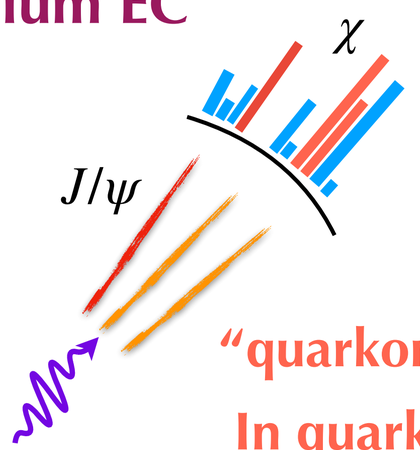
Quarkonium EC



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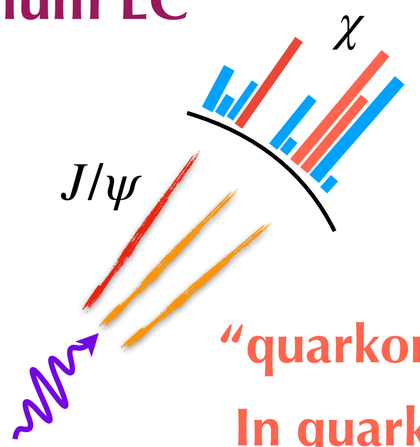
~ average energy at the angle χ

Quarkonium Energy Correlator

Chen, XL, Ma, **2405.10056**

- $\Sigma_{@EC} = \Sigma_{@EC,P.T.} + \Sigma_{@EC,had.}$
  - Hadronization enters as an additive correction, not in the form of convolution
  - Hadronization could be large

Quarkonium EC



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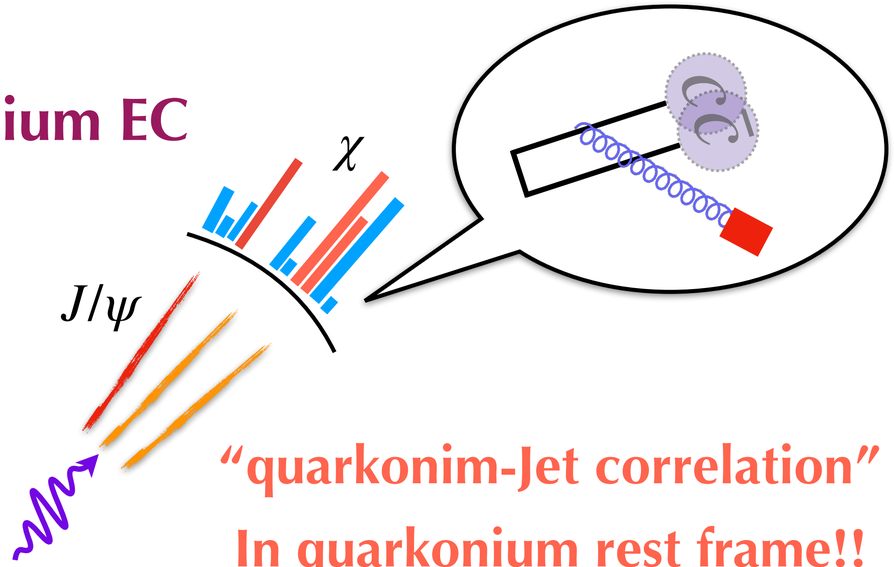
$$\Sigma_{@EC,P.T.} \sim \alpha_s(\mu)\frac{E(\chi)}{M}E^2(\chi)\langle\mathcal{O}_{\mathbf{1},\mathbf{8}}\rangle,$$

$$\Sigma_{@EC,had.} \sim \frac{Mv}{M}M^2v^2\langle\mathcal{O}_{\mathbf{1},\mathbf{8}}\rangle$$

Quarkonium EC



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In quarkonium rest frame!!

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

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

Quarkonium Energy Correlator

Chen, XL, Ma, **2405.10056**

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$$\Sigma_{@EC,had.} \sim \frac{Mv}{M}M^2v^2\langle\mathcal{O}_{\mathbf{1},\mathbf{8}}\rangle$$

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

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

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

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

Excellent place to study the non-perturbative physics!

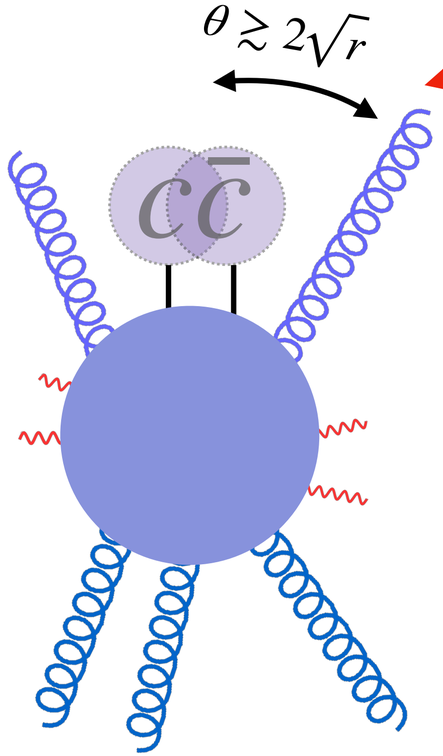
Quarkonium Energy Correlator

Chen, XL, Ma, **2405.10056**

Generic J/ψ production configuration 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**

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

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

Quarkonium Energy Correlator

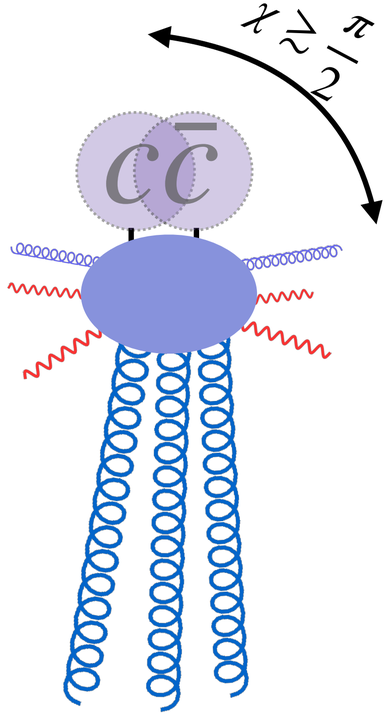
Chen, XL, Ma, **2405.10056**

Generic J/ψ production configuration in pQCD

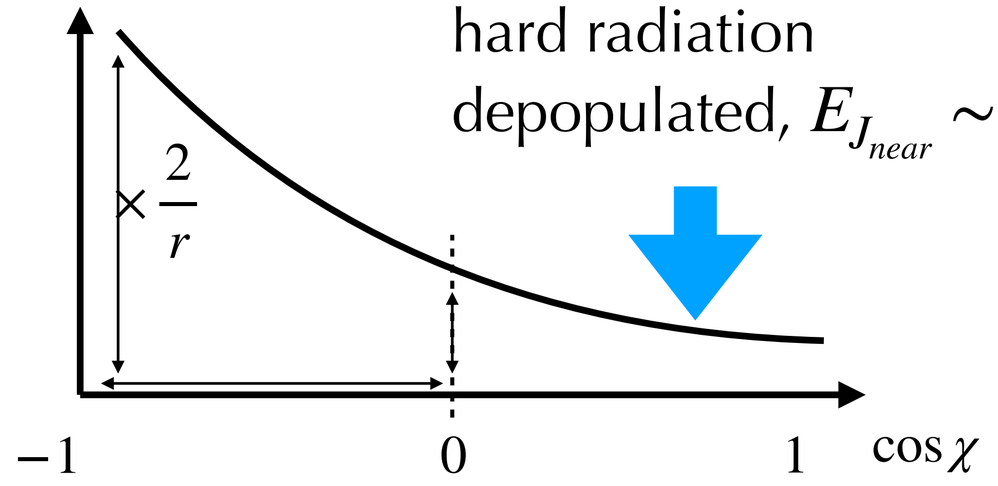
COM frame

boost

J/ψ rest frame



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



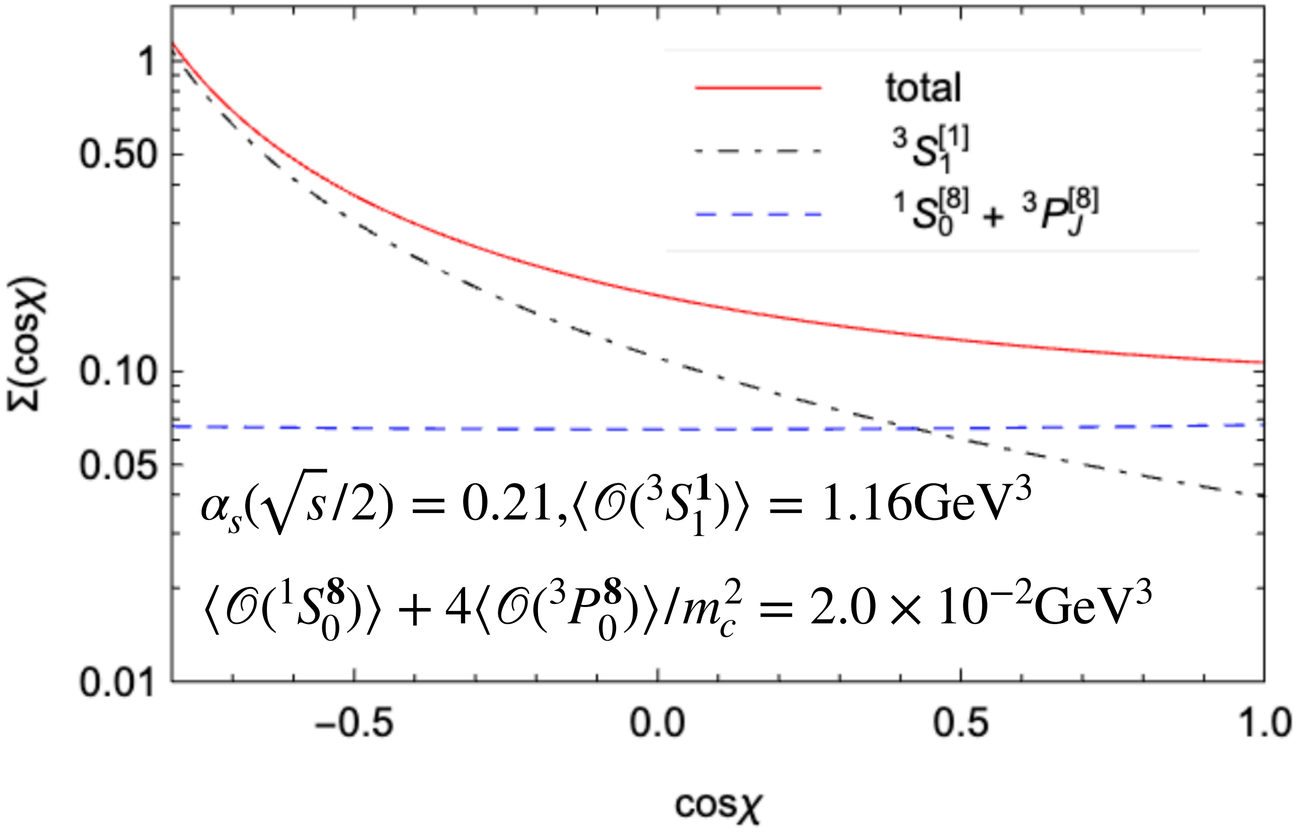
$$E_{J_{near}} \sim E_s \sim \mathcal{O}(M), E_{J_{away}} \sim \mathcal{O}\left(\frac{\hat{s}}{2M}\right)$$

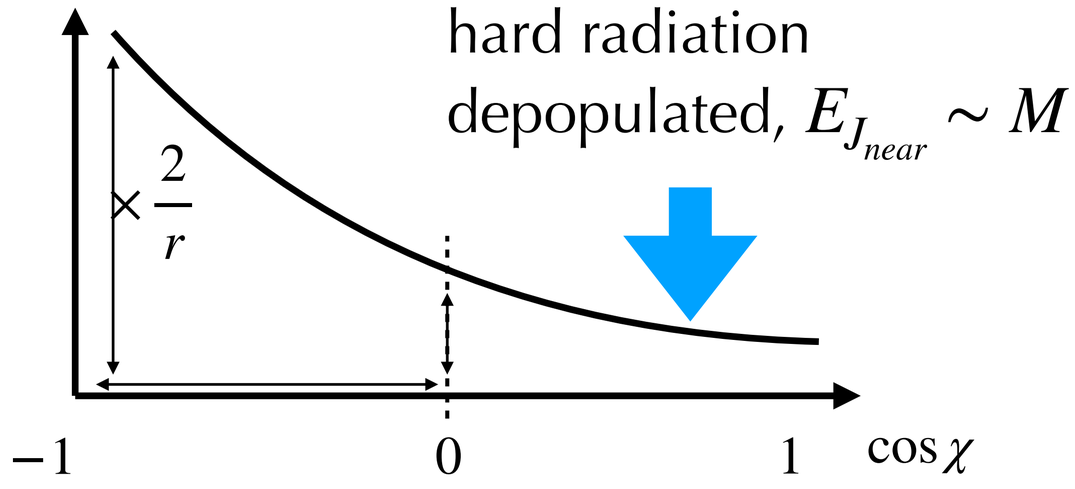
Quarkonium Energy Correlator

Chen, XL, Ma, **2405.10056**

Sizable hadronization effect!!

$$e^+e^- \to J/\psi + X$$





Quarkonium Energy Correlator

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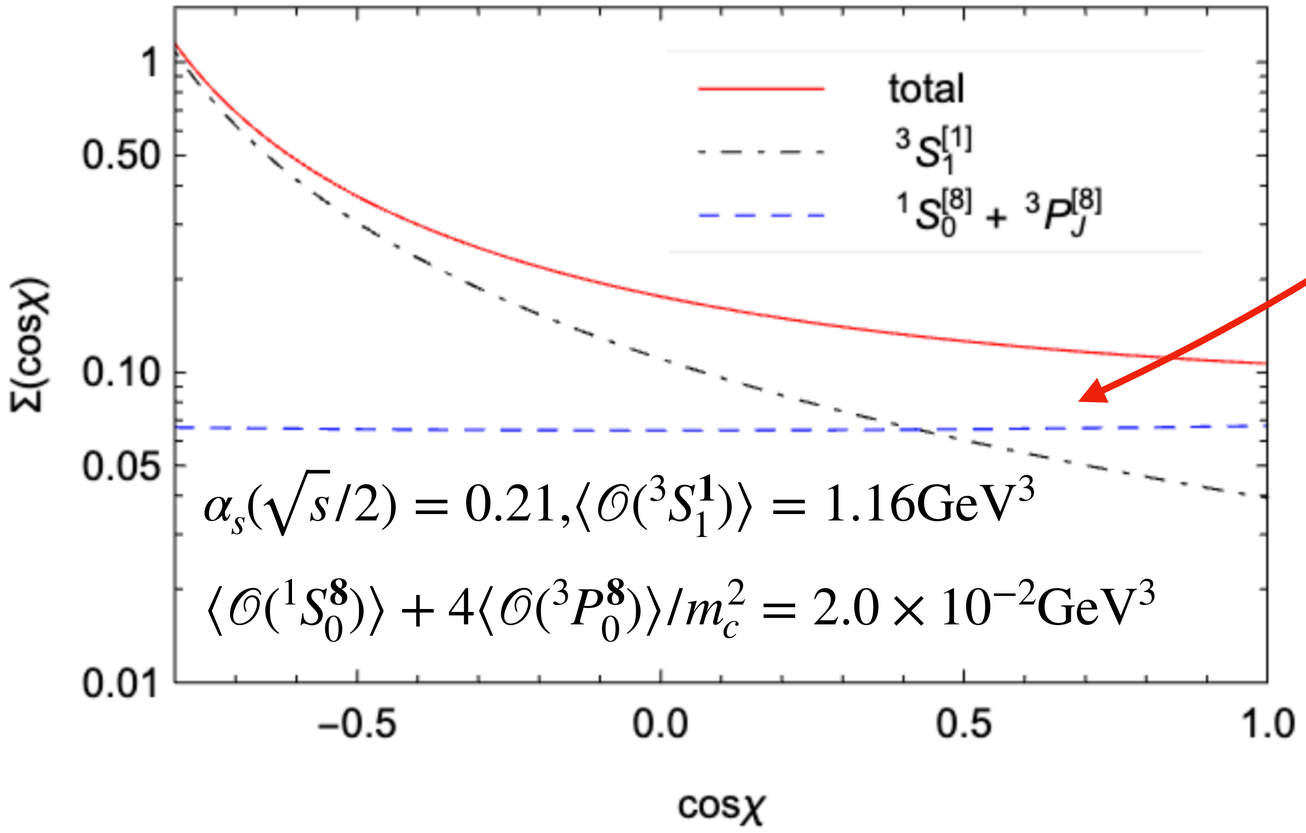
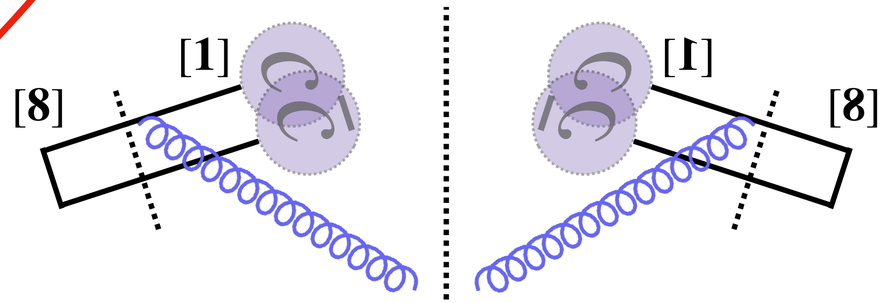
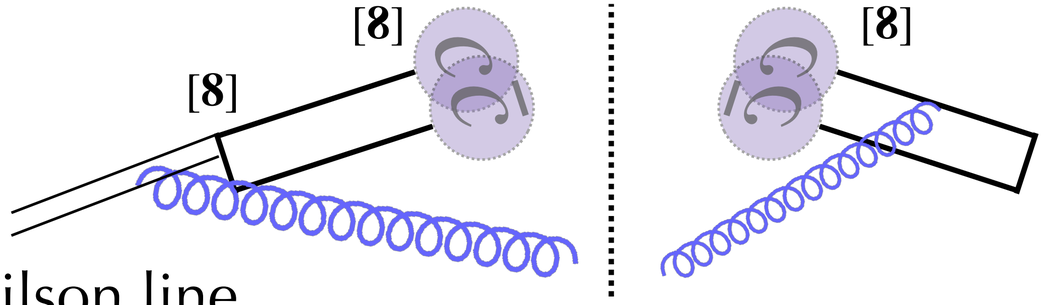


Ignore interference, rotational covariant



interference, boost covariant



Wilson line

Quarkonium Energy Correlator

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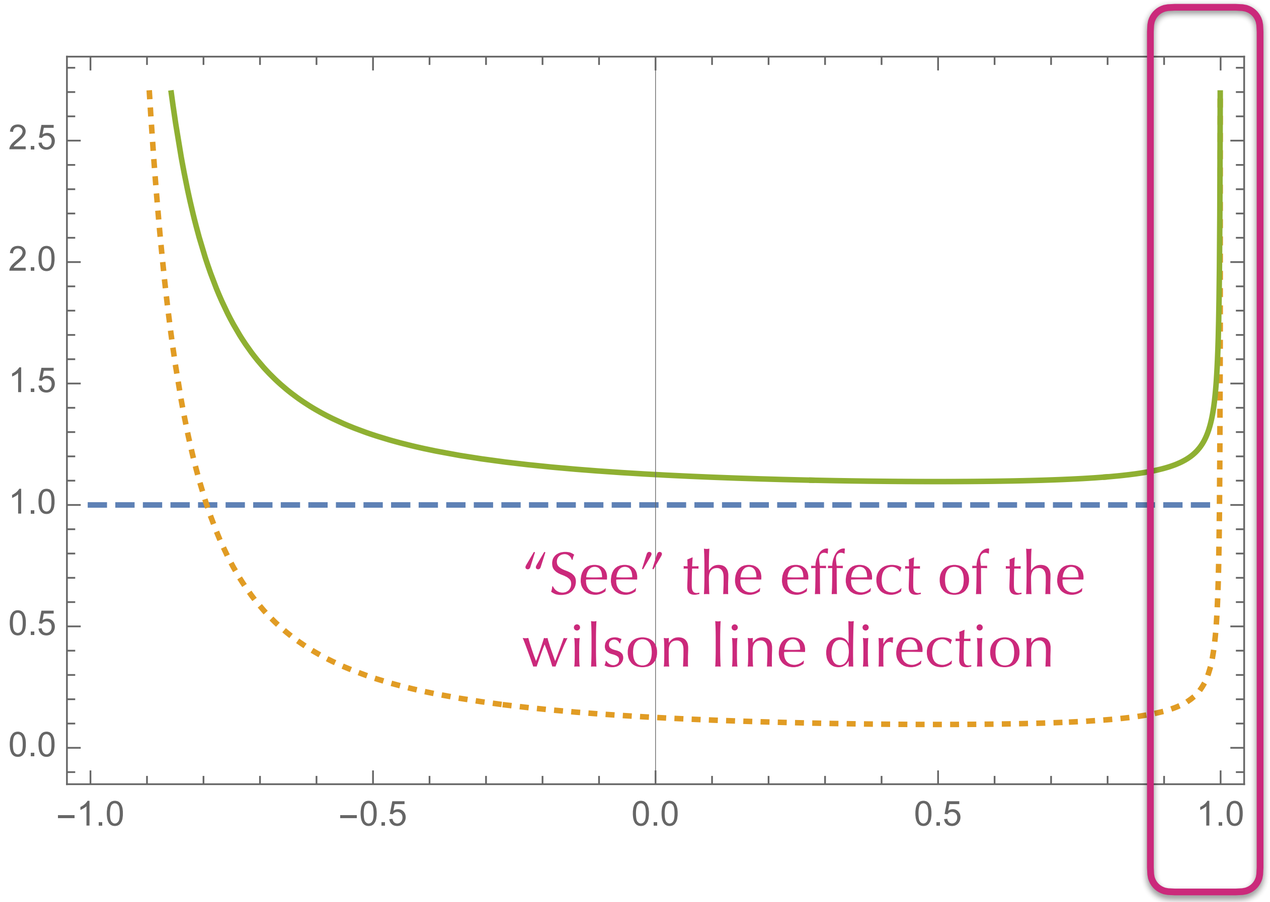
Relative size between non-inter vs interference



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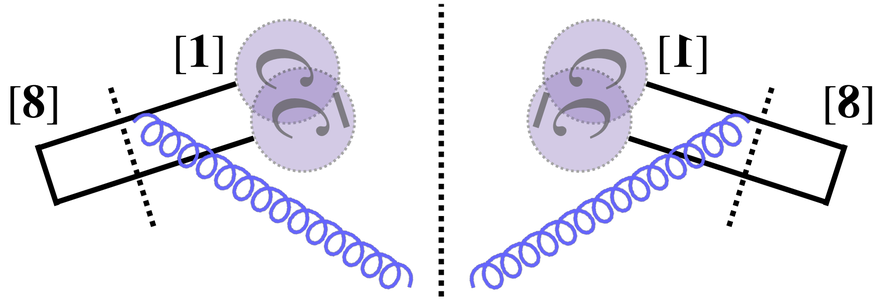

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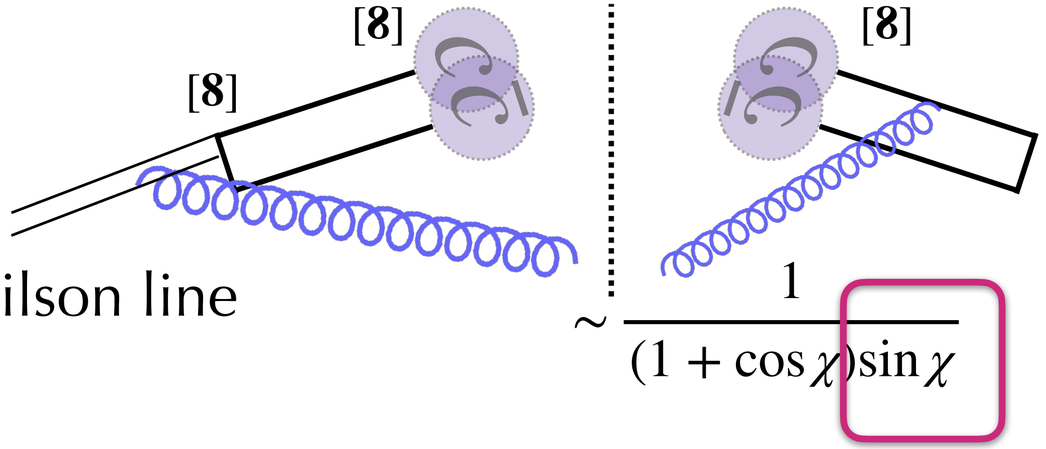

Quarkonium Energy Correlator

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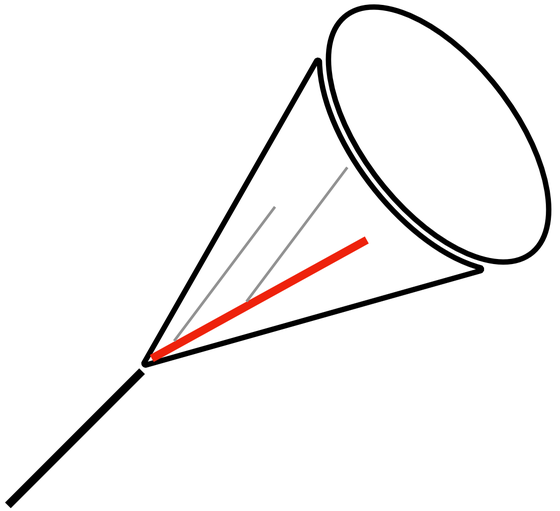
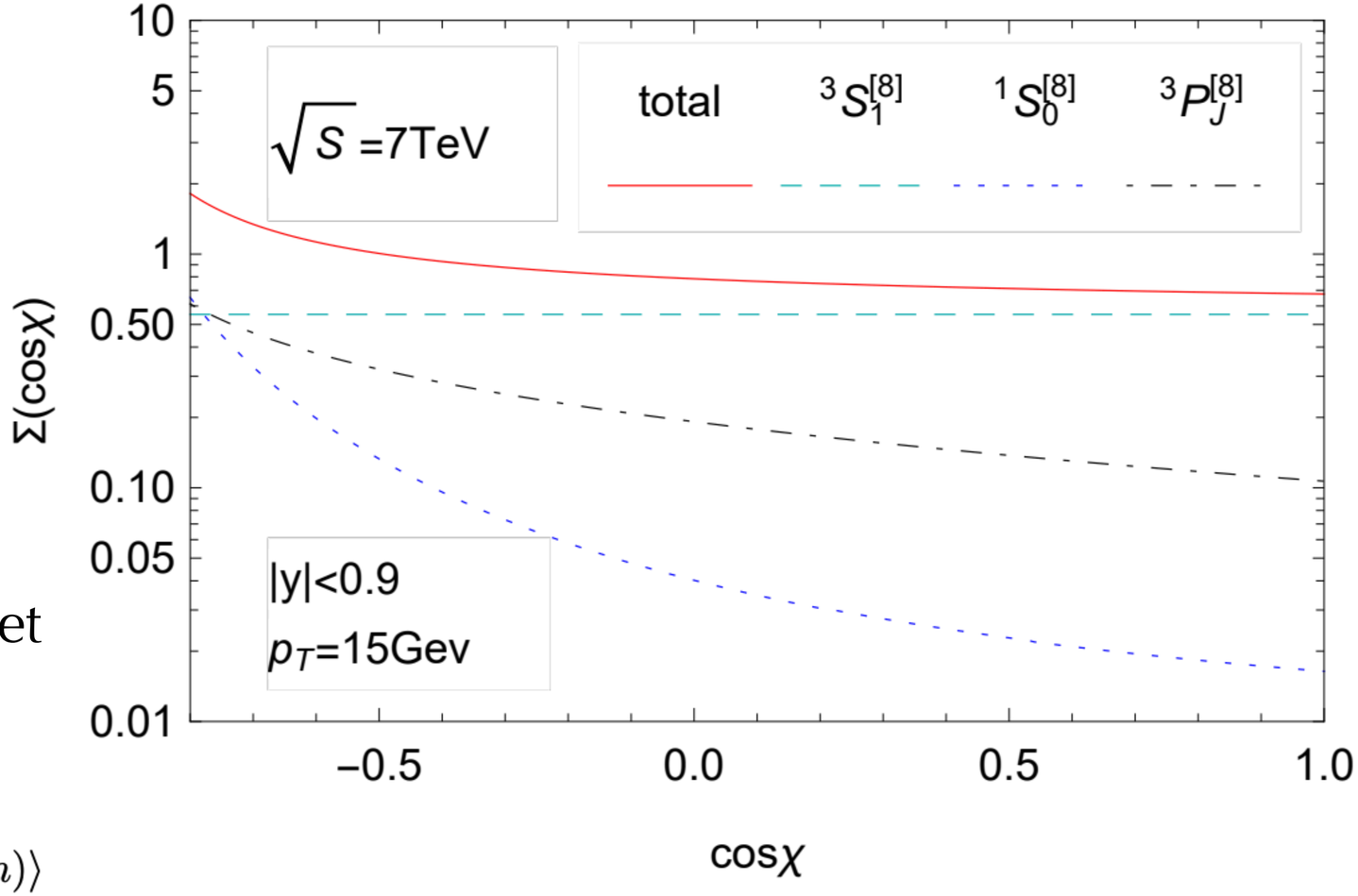
Similar story happens to *pp*



Preselecting particles inside a fat jet

$$\Sigma(\cos\chi) = \sum_n \int_0^1 dz d\hat{\sigma}_{A+B\to g+X}(\hat{p}/z, \mu_F) \times \hat{D}_{g\to c\bar{c}[n]}(z, \cos\chi, \mu_F)\langle \mathcal{O}^{J/\psi}(n)\rangle$$



Conclusion

- Energy correlators provide a new insight to quarkonium hadronization
- The results showed in this talk are quite generic, independent of production channels, ee, pp, ep …
- Suitable for LHCb …

Thanks