Energy Correlators for Light Hadrons and Quarkonium

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Heavy Flavor and QCD workshop @ Qingdao, 2024

北京師範大學
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XL, Zhu, **arxiv: 2403.08874**

XL, Shao, Zhu, **in preparation**

Chen, XL, Ma, **to appear**

Outline

Adapt EEC to QCD non-perturbative Studies

- TMDs out of the Semi-Inclusive Energy Correlators
- Hadronization in Quarkonium
- Conclusion

We are grateful to Miguel Arratia, Hao Chen, Zhong-bo Kang, Ian Moult, Jinlong Zhang, and Jian Zhou for insightful discussions. We are grateful for the hospitality of the committee for the "Heavy flavor and QCD" workshop held in Changsha where this work was initiated. We appreciate stimulating feedback from the EicC bi-week meeting. This work is supported by the Natural Science Foundation of China under Contract No. 12175016 (X. L.), No. 11975200 (H. X. Z.), and No. 12147103 (H. X. Z.).

XL and Zhu, **Phys. Rev. Lett. 130 (2023), 9, 9**

Motivation

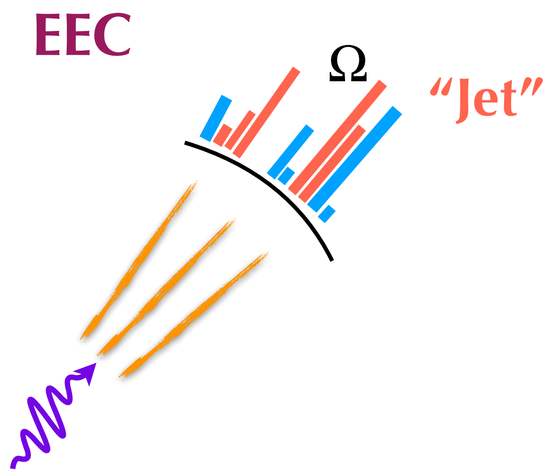
- Non-perturbative QCD/Confinement
  - Hadron structures: TMDs, GPDs, …
  - Hadronization: FF? LFWFs? LDME? …

How many energy emitted?

Distribution of the emissions?

Largely remains a mystery

Adapt EEC to Structure Studies

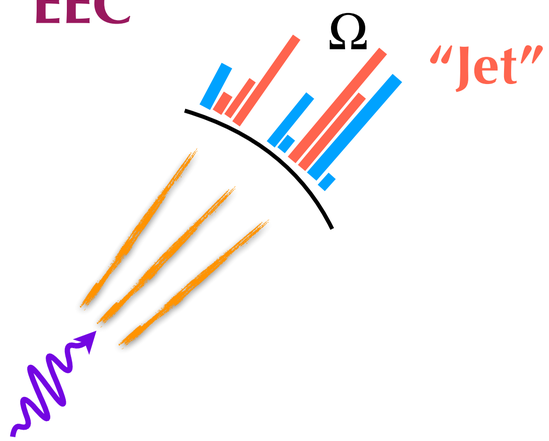


$$\Sigma_{\mathrm{EEC}} \propto \frac{1}{\sigma}\int d\sigma \frac{E_i E_j}{Q^2}\delta(\Omega - \Omega_{ij})$$

- See Hua Xing's talk for theory details

Adapt EEC to Structure Studies

EEC



$$\Sigma_{\mathrm{EEC}} \propto \frac{1}{\sigma}\int d\sigma \frac{E_i E_j}{Q^2}\delta(\Omega - \Omega_{ij})$$

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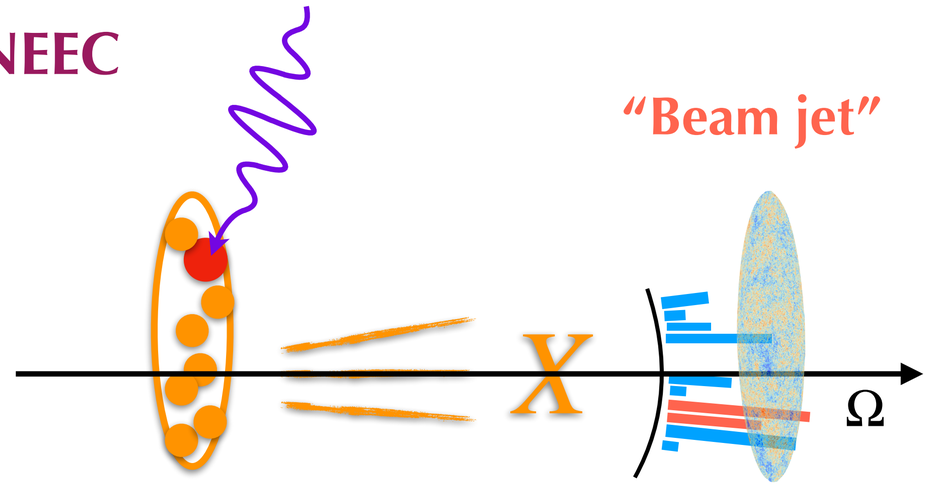
NEEC

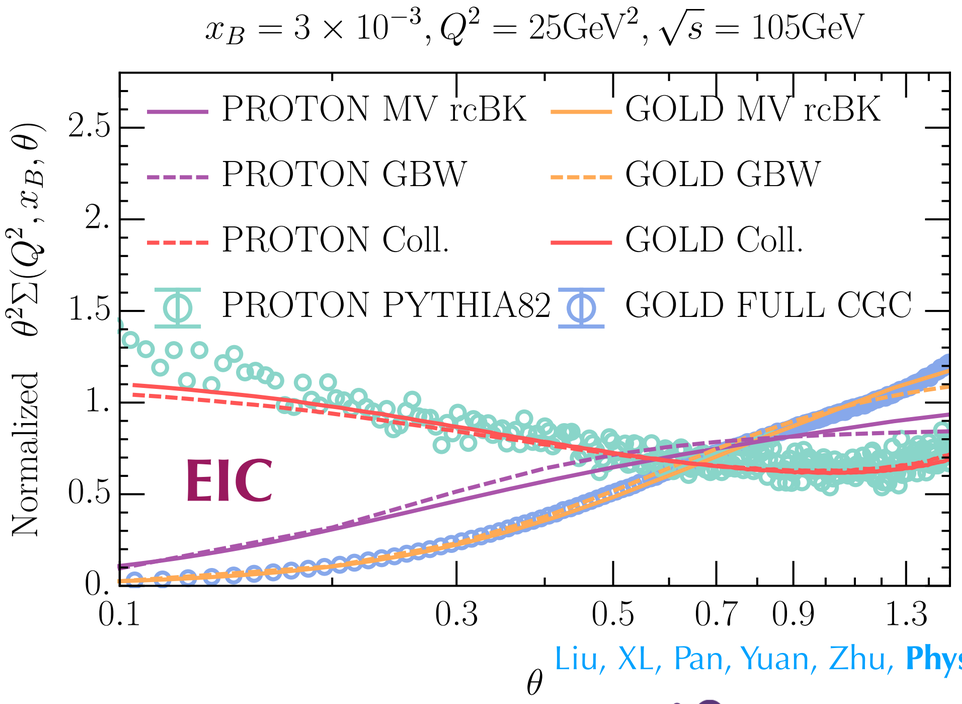


XL and Zhu, **Phys. Rev. Lett. 130 (2023), 9, 9**

$$\Sigma_{\mathrm{NEEC}} \propto \frac{1}{\sigma}\int d\sigma \frac{E_i}{E_P}\delta(\Omega - \Omega_i)$$

- $f_{EEC}(x,\theta) \propto \langle P|\bar{\psi}(y^-)\mathscr{E}(\Omega)\psi(0)|P\rangle$
- A new probe of/sensitive to the internal transverse dynamics

Adapt EEC to Structure Studies



The shape is dramatically modified when gluons saturate, due to dynamically generated $k_t \gg \Lambda_{QCD}$

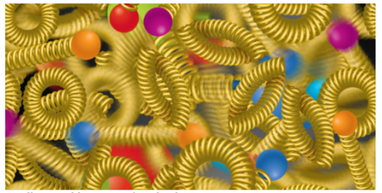
Liu, XL, Pan, Yuan, Zhu, **Phys. Rev. Lett. 130 (2023), 18, 18**

Physics SYNOPSIS

A Different Angle on the Color Glass Condensate

Predictions indicate that a new type of measurement at the future electron–ion collider could spot an elusive high-density regime of gluons called the color glass condensate.

By Nikhil Karthik

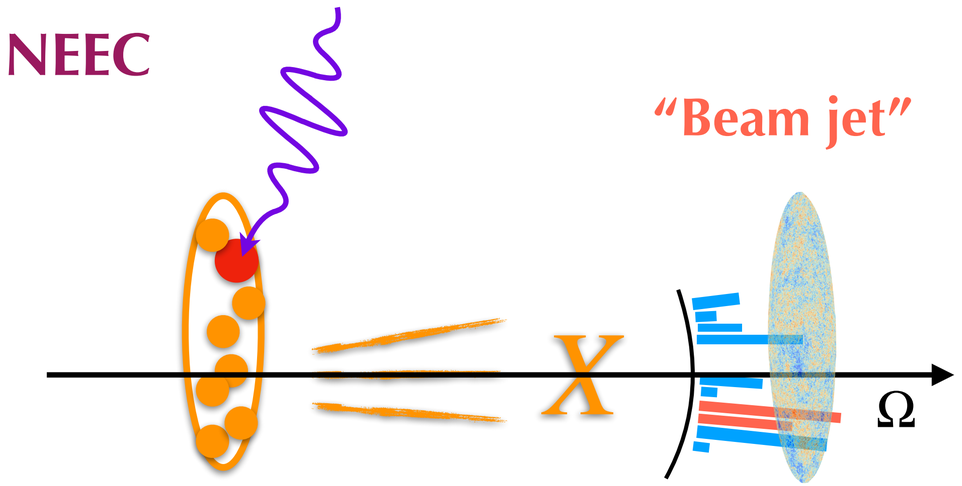


Credit: Brookhaven National Laboratory

New Method Could Explore Gluon Saturation at the Future Electron-Ion Collider

Theorists propose nucleon energy-energy correlator as a probe to the gluon saturation phenomena at the future electron-ion collider.

U.S. DEPARTMENT OF ENERGY | Office of Science



XL and Zhu, **Phys. Rev. Lett. 130 (2023), 9, 9**

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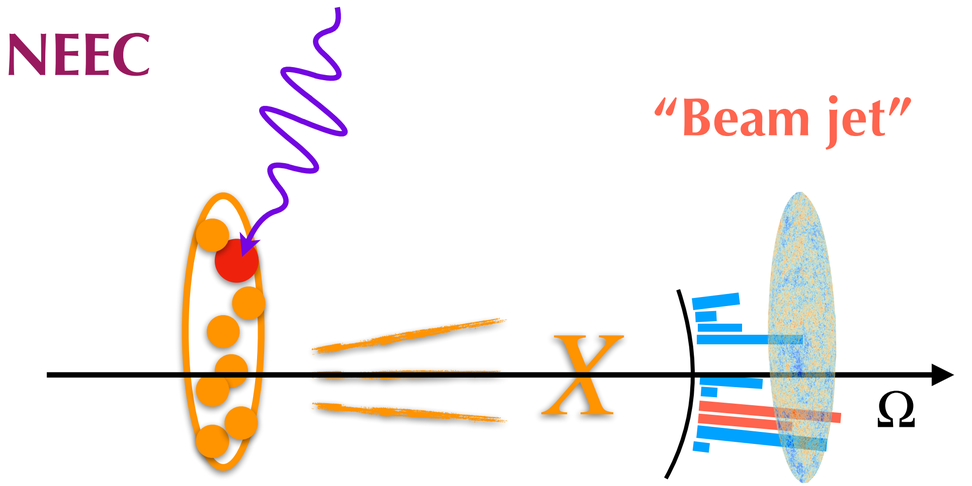
- $f_{EEC}(x,\theta) \propto \langle P|\bar{\psi}(y^-)\mathscr{E}(\Omega)\psi(0)|P\rangle$
- A new probe of/sensitive to the internal transverse dynamics

Adapt EEC to Structure Studies

Connection to TMDs?



XL and Zhu, **Phys. Rev. Lett. 130 (2023), 9, 9**

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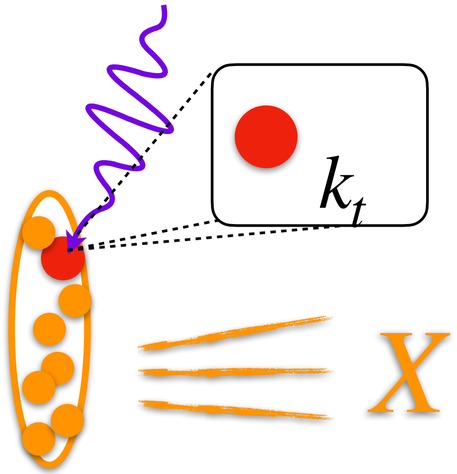
TMDs out of the Semi-inclusive ECs

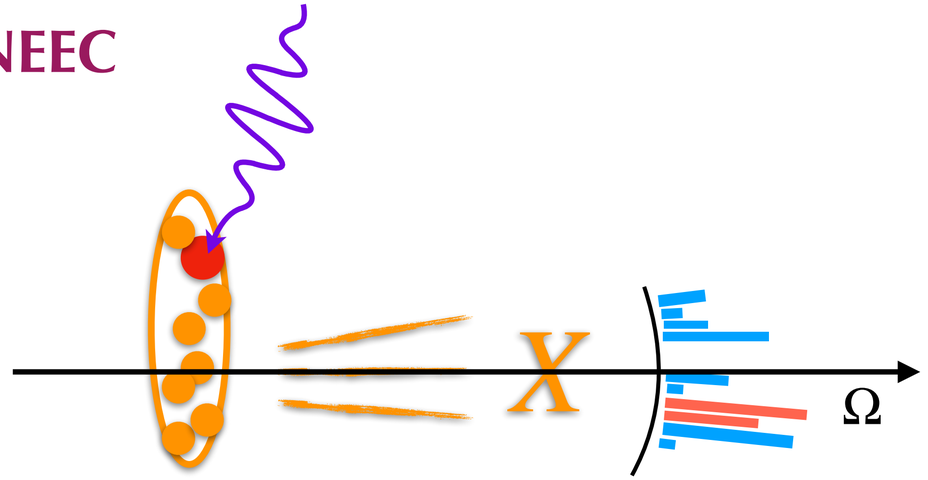
XL, Zhu, **arxiv: 2403.08874**

TMD



$$\vec{k}_t = -\sum_{i\in X} \vec{p}_{i,t} = -\sum_{i\in X} E_i \sin\theta_i(\cos\phi_i, \sin\phi_i)$$

NEEC



$$\mathscr{E}(\Omega) = \sum_{i\in X} E_i \delta(\Omega - \Omega_i)$$

TMDs out of the Semi-inclusive ECs

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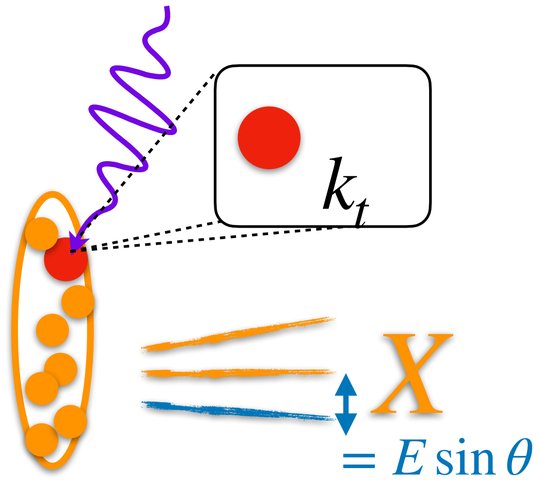
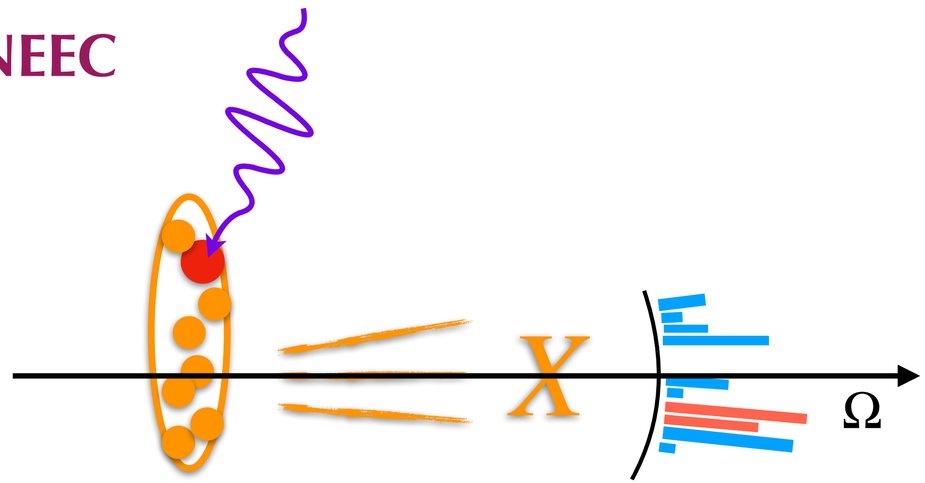
TMD



NEEC



$$\overrightarrow{k}_t = -\int d\theta d\phi \ \sin\theta(\cos\phi, \sin\phi)\, \mathscr{E}(\Omega)$$

$$\mathscr{E}(\Omega) = \sum_{i\in X} E_i \delta(\Omega - \Omega_i)$$

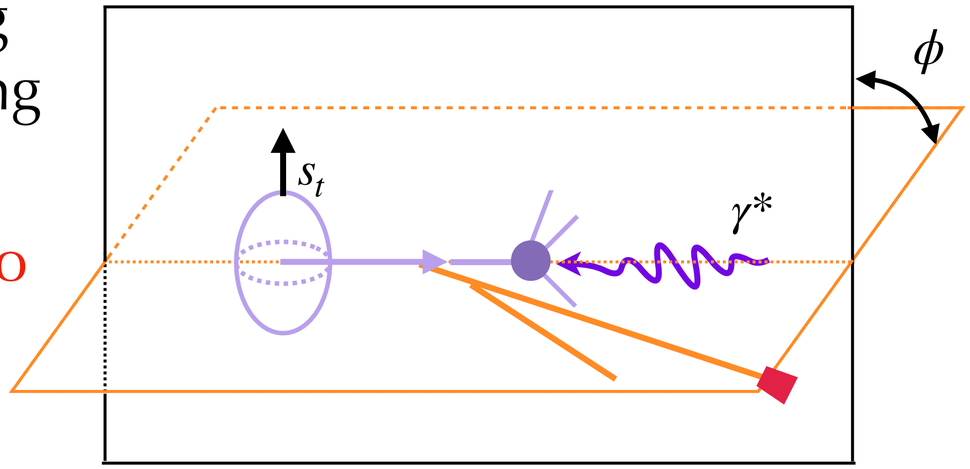
$$\int^{\mu} dk_t k_t^n f(k_t) = (-)^n \int^{R} \prod_n d\Omega\, w(\Omega_1)\ldots w(\Omega_n) \langle P | \ldots \mathscr{E}(\Omega_1)\ldots\mathscr{E}(\Omega_n)\ldots | P\rangle$$

TMDs out of the Semi-inclusive ECs

XL, Zhu, **arxiv: 2403.08874**

$$\int dk_t k_t^n f(k_t) = (-)^n \int \prod_n d\Omega\, w(\Omega_1)\ldots w(\Omega_n)\langle P|\ldots\mathscr{E}(\Omega_1)\ldots\mathscr{E}(\Omega_n)\ldots|P\rangle$$

- TMD PDFs (moment) can be obtained by measuring N-pt Nucleon Energy Correlator, by suitably selecting $w(\Omega)$
- Inclusive measurement! Do not force b-to-b limit, no jets/fragmentation function involved !
- Nucleon Energy Correlator can be regarded as a generating observable, contains more comprehensive information



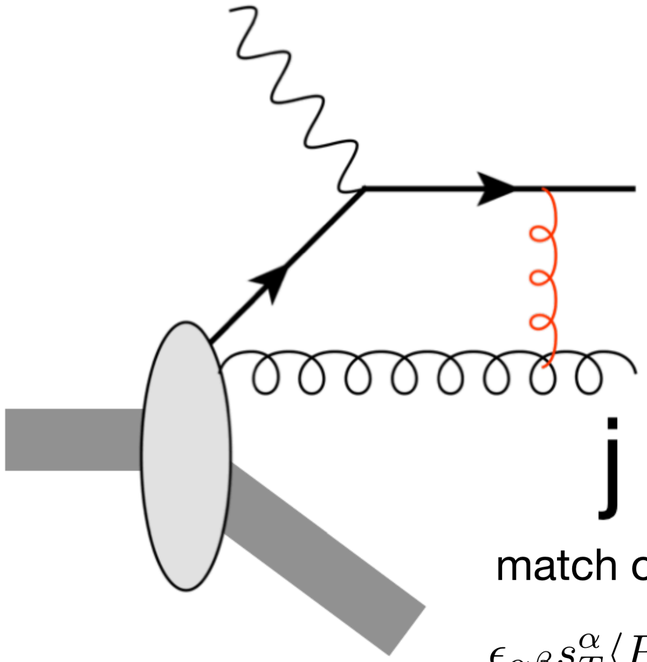
Sivers and only Sivers!

$$w \sim \sin\phi$$

TMDs out of the Semi-inclusive ECs

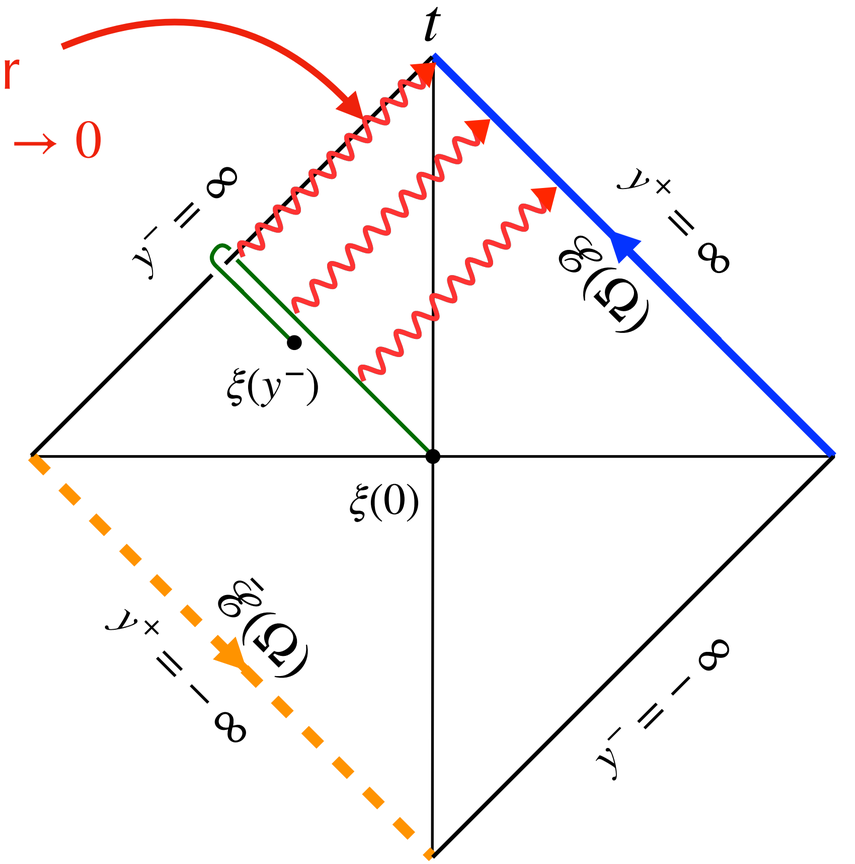
XL, Zhu, **arxiv: 2403.08874**

$$f^{\rm DIS}_{q,n=1}(x,\Omega)=\int\frac{dy^-}{2\pi}e^{-ixy^-P^+}\langle P\boldsymbol{s}_t|\bar\xi(y^-,\mathbf{0})\mathcal{L}(y^-,\infty)\mathcal{E}(\Omega)\frac{\gamma^+}{2}\mathcal{L}(\infty,0)\xi(0)|P\boldsymbol{s}_t\rangle$$



Glauber

$g^+\to 0\,, g^-\to 0$



match onto the Qiu-Sterman function

$$\epsilon_{\alpha\beta}s_T^\alpha\langle P,s|\bar\psi(0)F^{+\beta}(y_2^-)\Gamma\psi(y_1^-)|P,s\rangle$$

Hua Xing SCET talk

XL, Shao, Zhu, **in preparation**

TMDs out of the Semi-inclusive ECs

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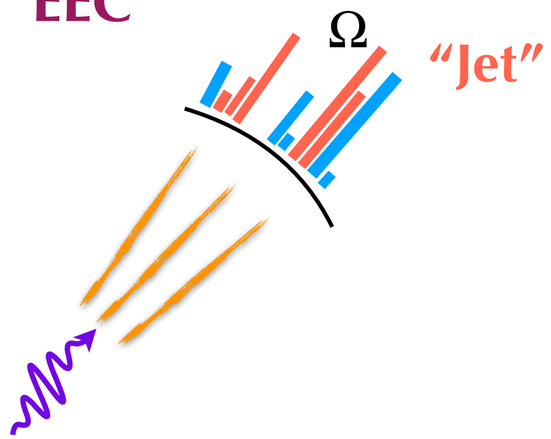
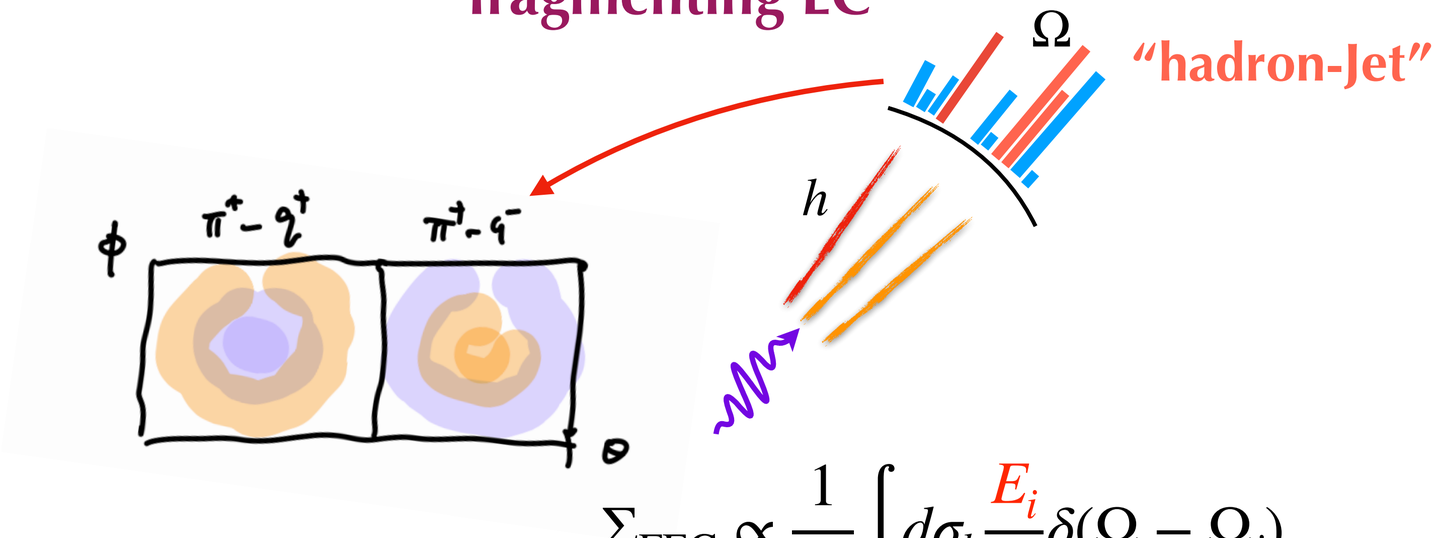
EEC



$$\Sigma_{\mathrm{EEC}} \propto \frac{1}{\sigma}\int d\sigma \frac{E_i E_j}{Q^2}\delta(\Omega-\Omega_{ij})$$

fragmenting EC



$$\Sigma_{\mathrm{FEC}} \propto \frac{1}{\sigma_h}\int d\sigma_h \frac{E_i}{Q}\delta(\Omega-\Omega_i)$$

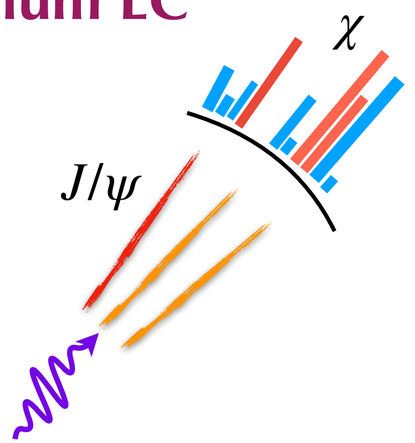
- $D_{EEC}(x,\theta) \propto \langle 0|\bar{\psi}(y^-)\mathscr{E}(\Omega)a_h^\dagger(P)a_h(P)\psi(0)|0\rangle$
- Provides a comprehensive picture for light hadron hadronization, Collins …
- Fit well to light hadron studies at EicC

Quarkonium Energy Correlator

Chen, XL, Ma, **to appear**

- NRQCD factorization for quarkonium production
  - regarded as an excellent place to study non-pert phenomenon for a long time
  - $\langle \mathcal{O}_{\mathbf{1}} \rangle$, $\langle \mathcal{O}_{\mathbf{8}} \rangle$
  - Hadronization $c\bar{c} \to J/\psi$? remains largely unknown: amount of energy released? Energy Distribution?

Quarkonium EC



"quarkonim-Jet"

Rest frame!!

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

$\Sigma(\cos\chi)$ could provide new venue to these problems

Quarkonium Energy Correlator

Chen, XL, Ma, **to appear**

$\Sigma(\cos\chi)$ could provide new venue to these problems

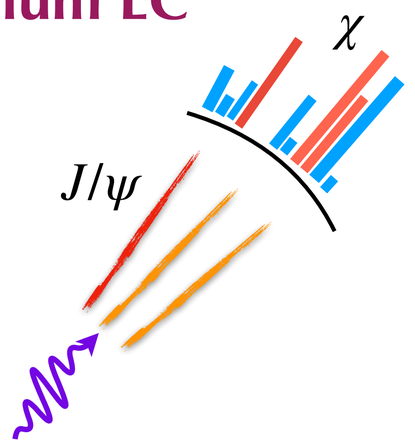
- $\Sigma_{@EC} = \Sigma_{@EC,P.T.} + \Sigma_{@EC,had.}$
- $\Sigma_{@EC,had.}$ relatively large $\sim \frac{Mv}{M} M^2 v^2 \langle \mathcal{O}_{\mathbf{1,8}} \rangle$,

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

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

$\Sigma_{@EC,had.}/\Sigma_{@EC,P.T.} \sim \frac{v^3}{\alpha_s}$, if $\frac{E}{M} \sim 1$

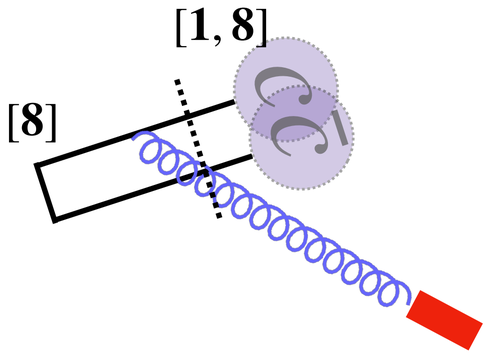
Quarkonium EC



"quarkonim-Jet"

Rest frame!!

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



$$\sim \frac{1}{\sigma} \int^{Mv} \frac{E^2 dE d\Omega}{2E(2\pi)^3} \frac{E}{M} \langle \mathcal{O}_{\mathbf{1,8}} \rangle \sim v\,(mv)^2 \langle \mathcal{O}_{\mathbf{1,8}} \rangle$$

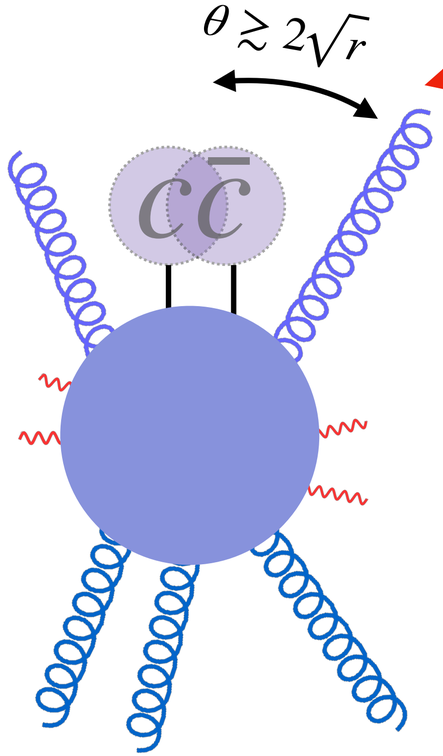
Quarkonium Energy Correlator

Chen, XL, Ma, **to appear**

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

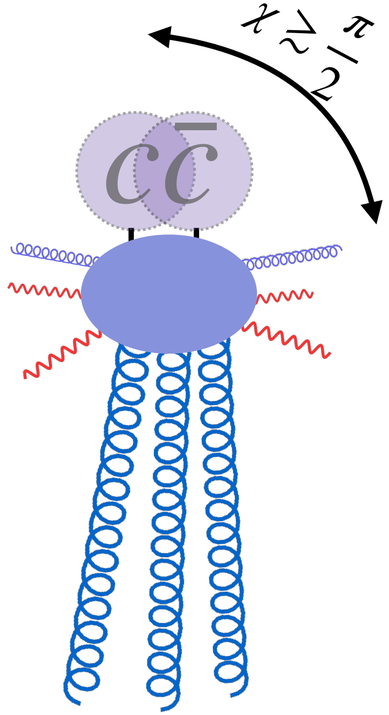
Chen, XL, Ma, **to appear**

Generic J/ψ production configuration in pQCD

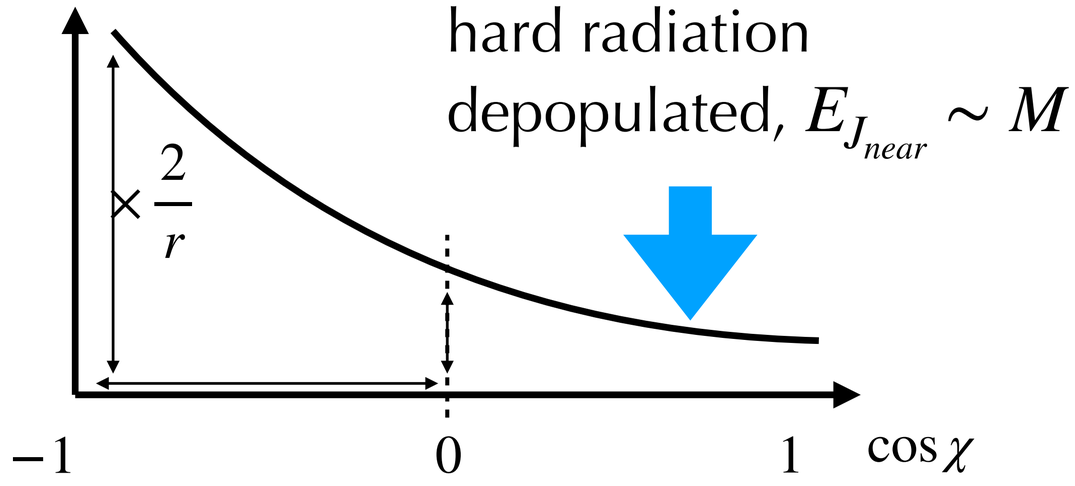
COM frame

boost

J/ψ rest frame



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



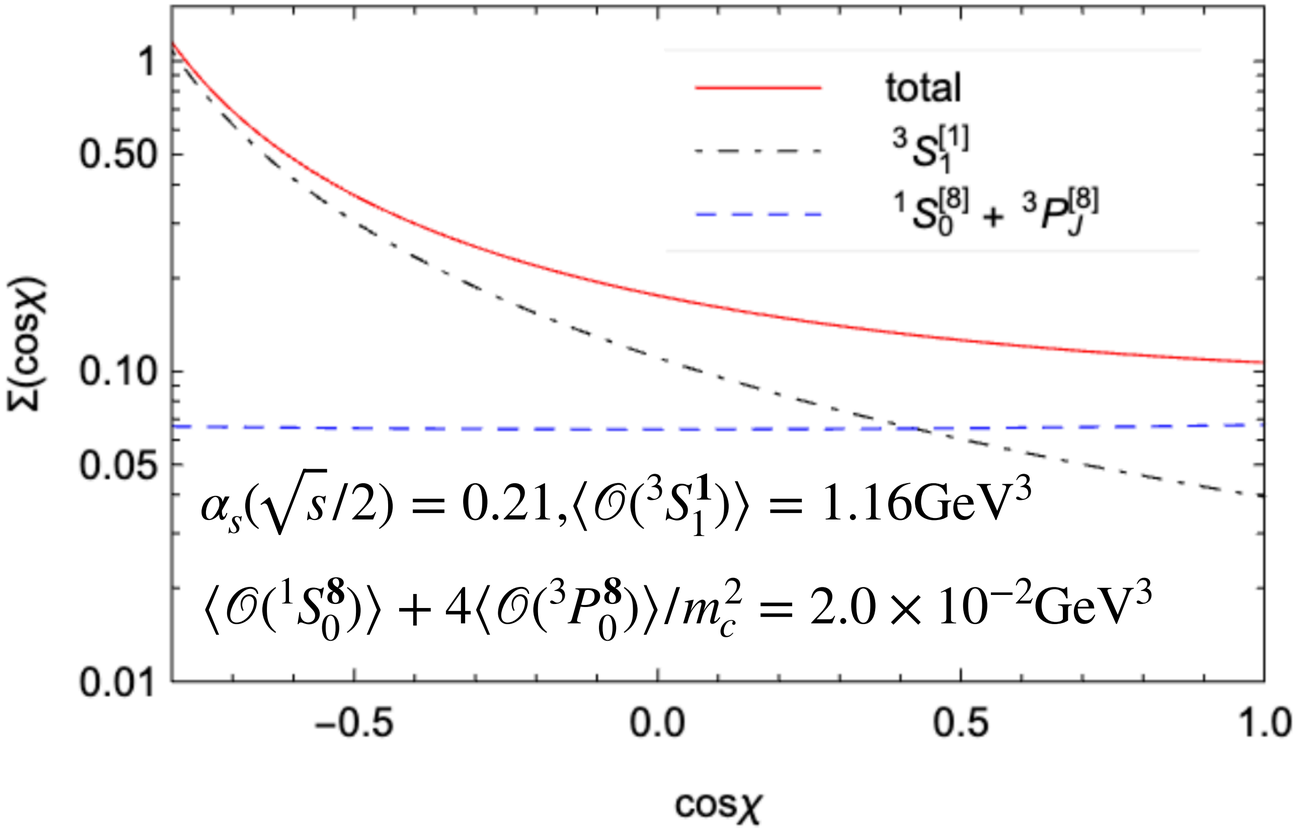
$$E_{J_{near}} \sim E_s \sim \mathcal{O}(M), E_{J_{away}} \sim \mathcal{O}\left(\frac{\hat{s}}{2M}\right)$$

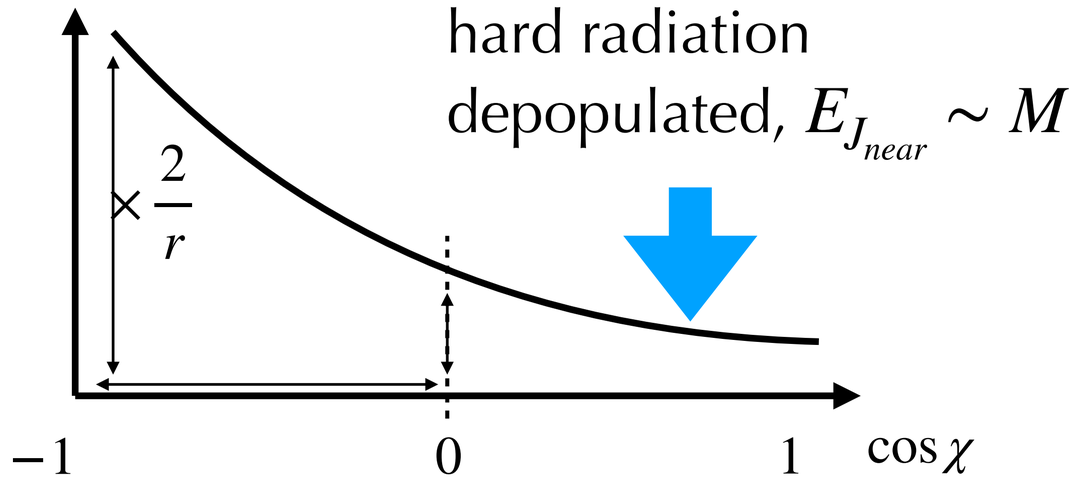
Quarkonium Energy Correlator

Chen, XL, Ma, **to appear**

Sizable hadronization effect!!

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





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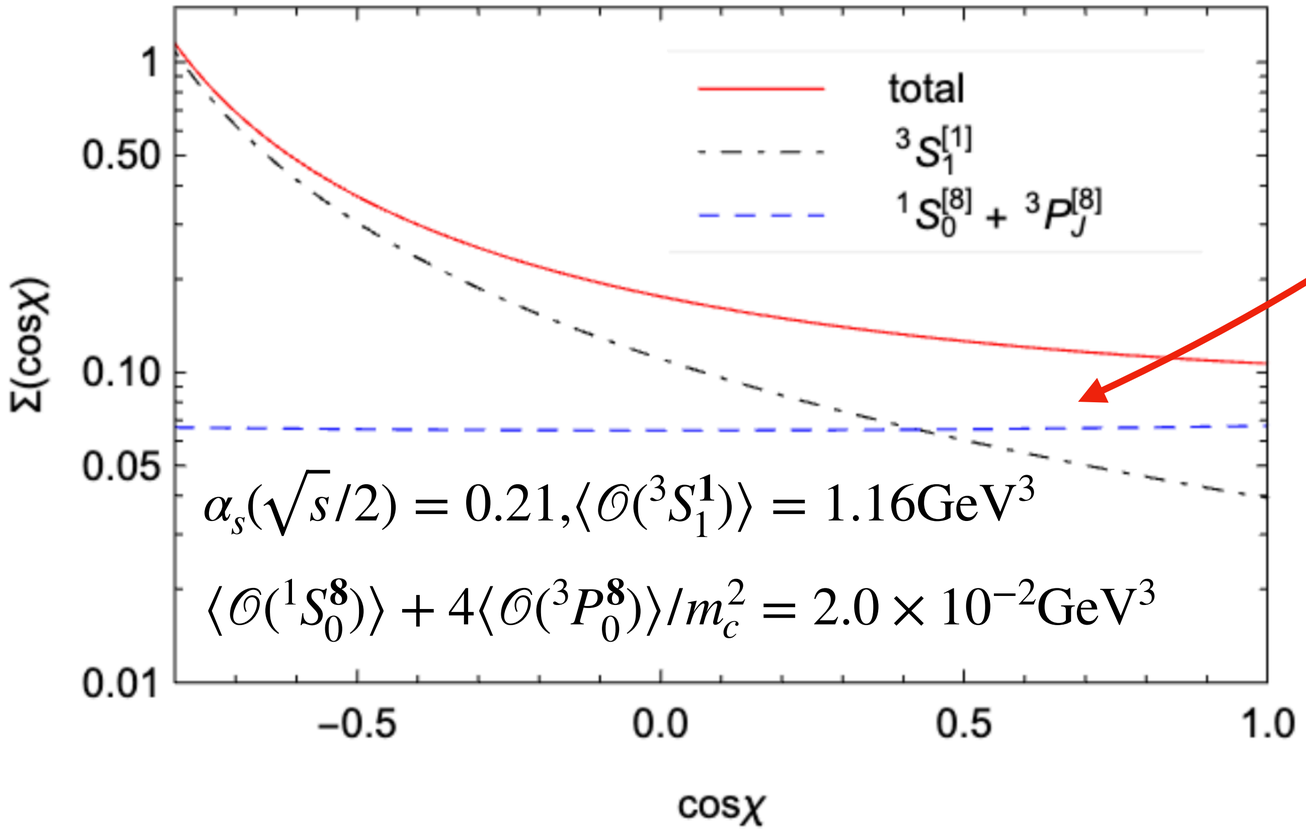
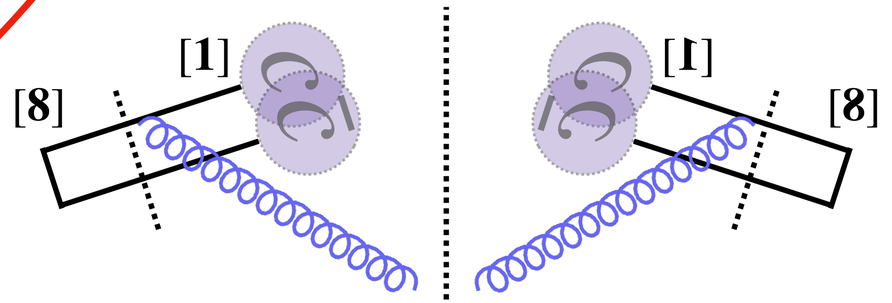
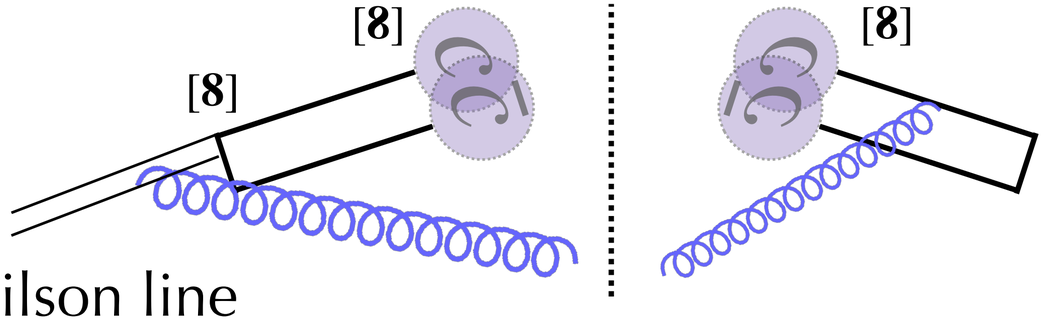


Ignore interference, rotational covariant



interference, boost covariant

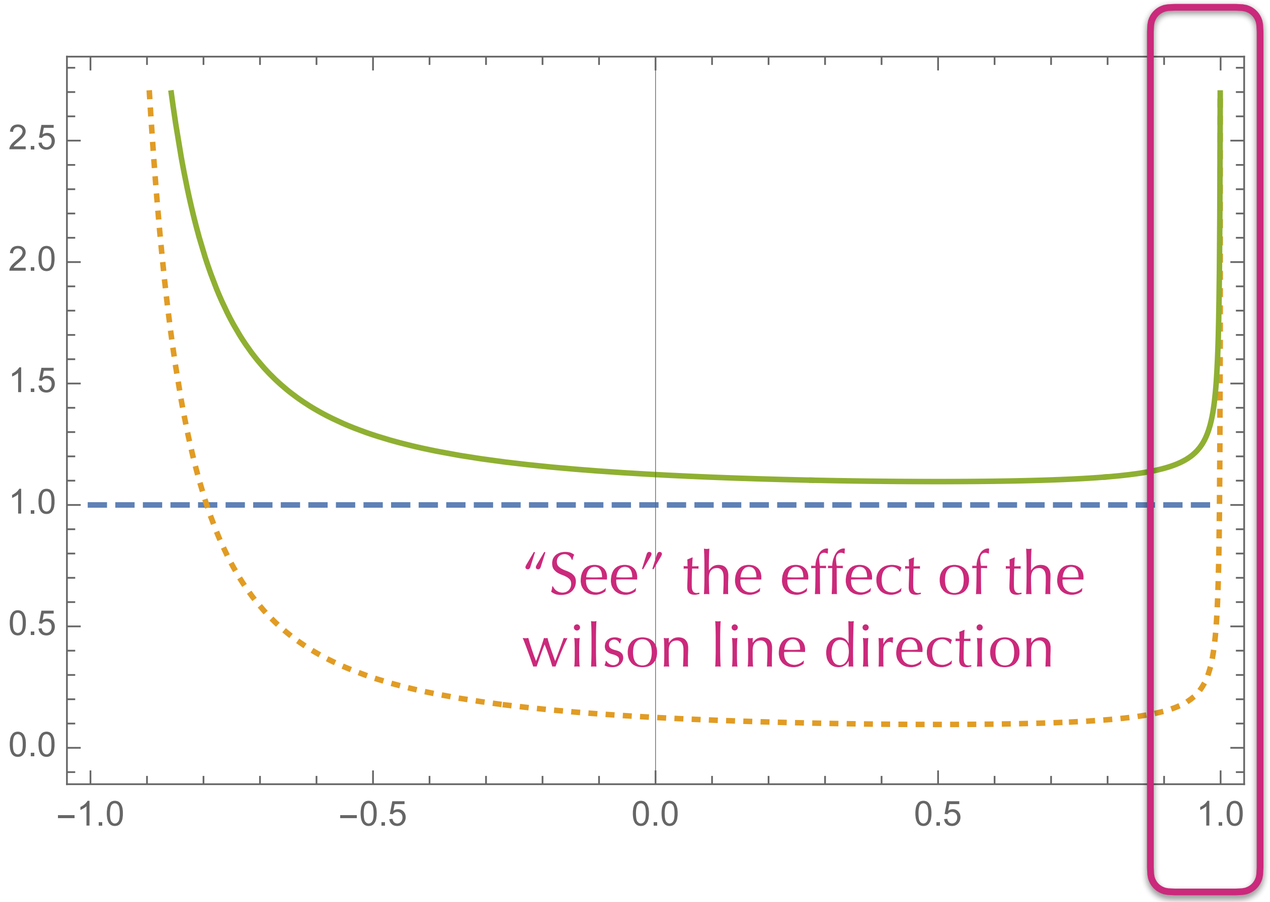


Wilson line

Quarkonium Energy Correlator

Chen, XL, Ma, **to appear**

Relative size between non-inter vs interference



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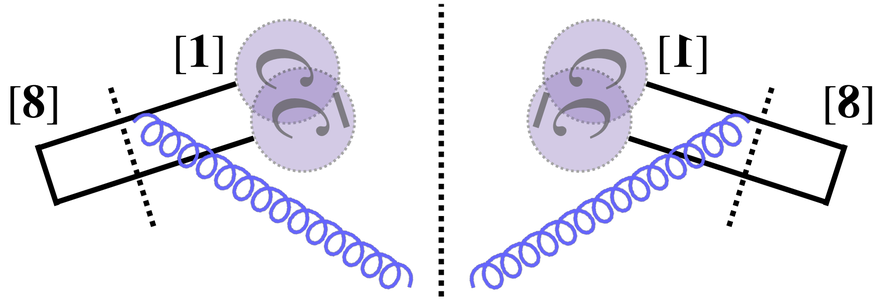
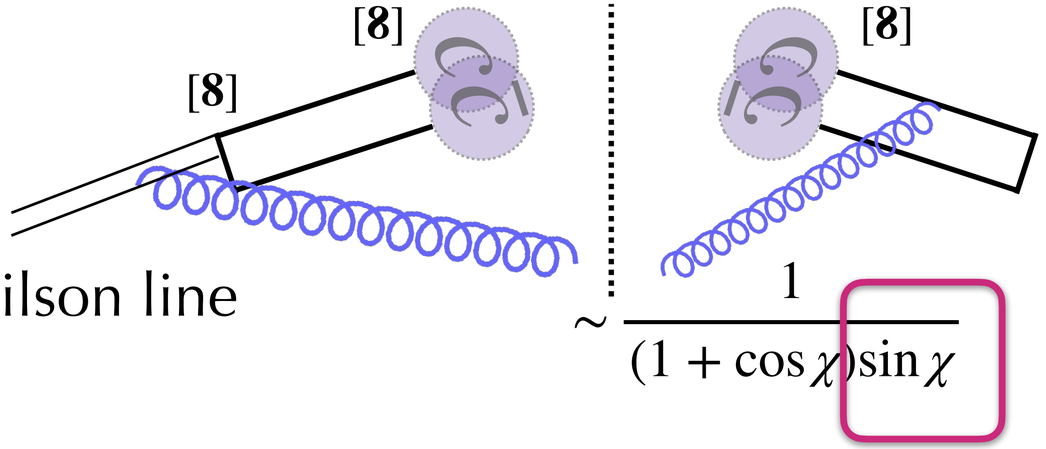


interference, boost covariant



Conclusion

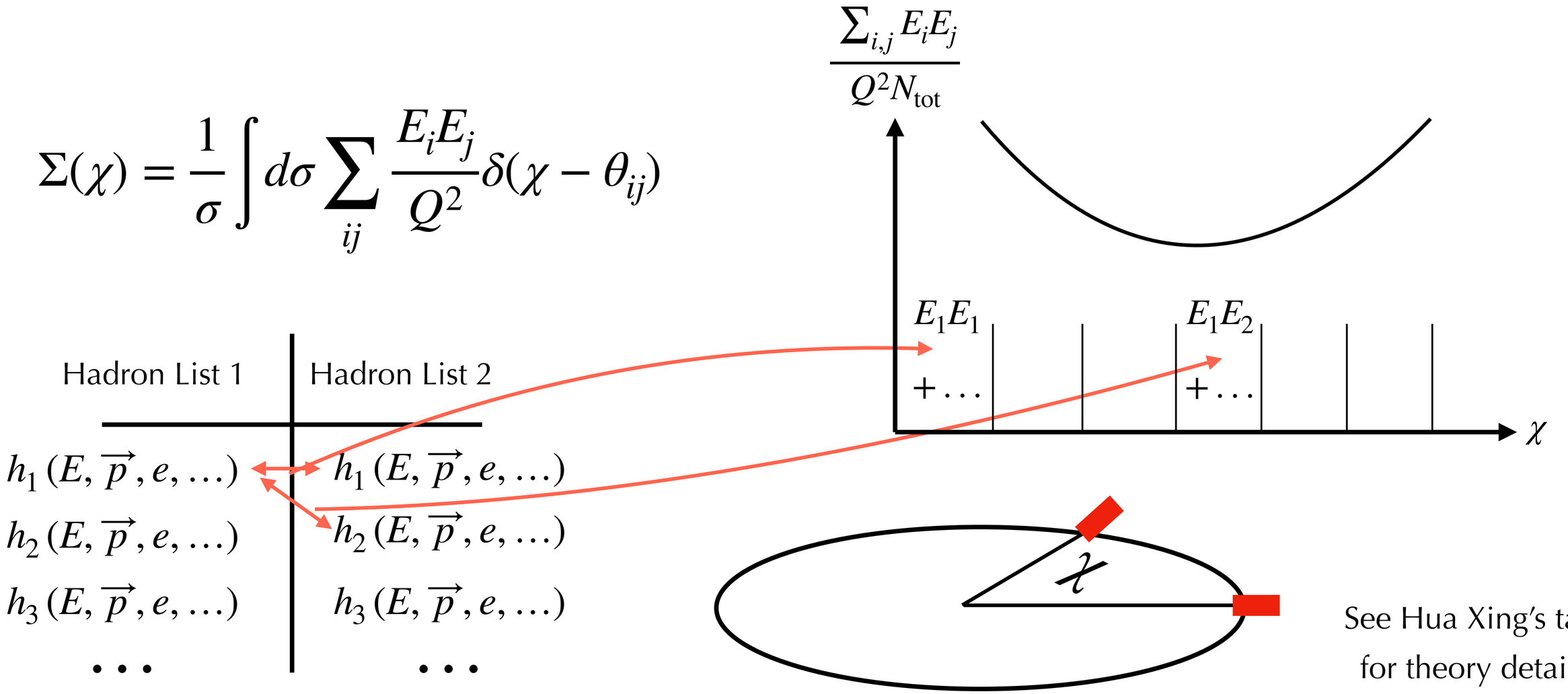
- Energy correlators provide new insight/tool to non-pert. studies
- Suitable for EicC, Belle …
- More (theory/pheno) in the future

Thanks

Backup slides

Exp. Measures

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



See Hua Xing's talk for theory details