DIS2023: XXX International Workshop on Deep-Inelastic Scattering and Related Subjects

Collins-type Energy-Energy Correlators and Nucleon Structures

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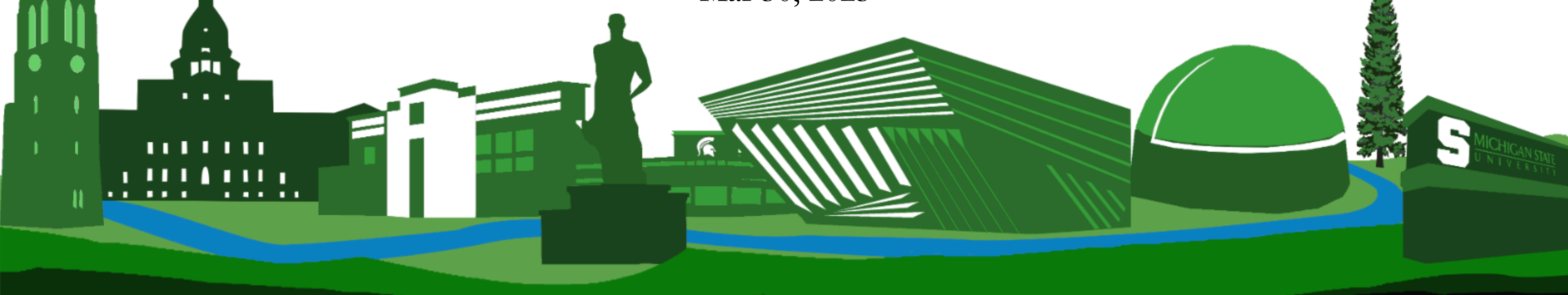
University of California, Los Angeles (UCLA)

In collaboration with: Zhongbo Kang, Kyle Lee, Dingyu Shao

arXiv: 2303.xxxx

Mar 30, 2023

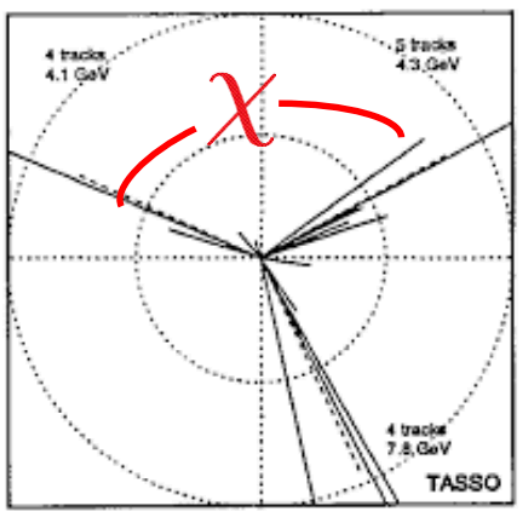


Outline

- **Introduction of Energy-Energy Correlators (EEC)**
- **EEC for e^+e^- collisions w/ polarized partonic processes**
- **EEC for ep collisions w/ polarized proton beam**
- **Summary**

Introduction

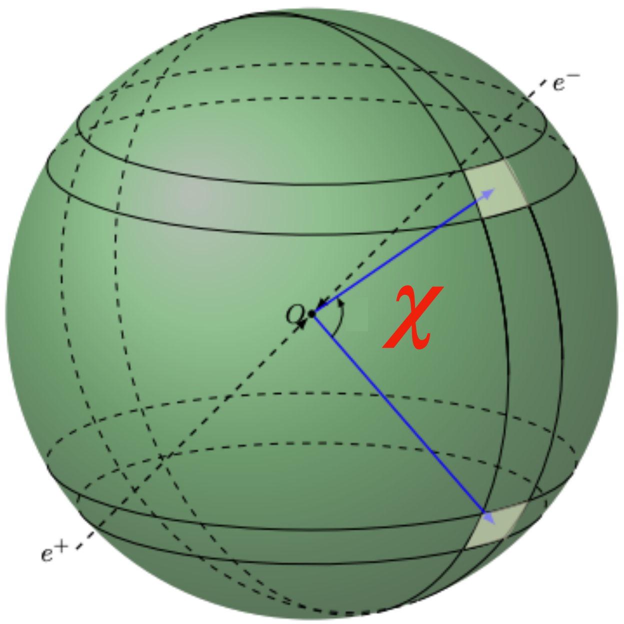
$\chi \in [0, \pi]$



Energy-Energy Correlators (EEC):

- Measures the correlations of energy deposition in two detectors with opening angle χ
- Extensively investigated at various colliders
- One of the first infrared safe event-shapes defined in QCD Basham, Brown, Ellis, Love `78 `79

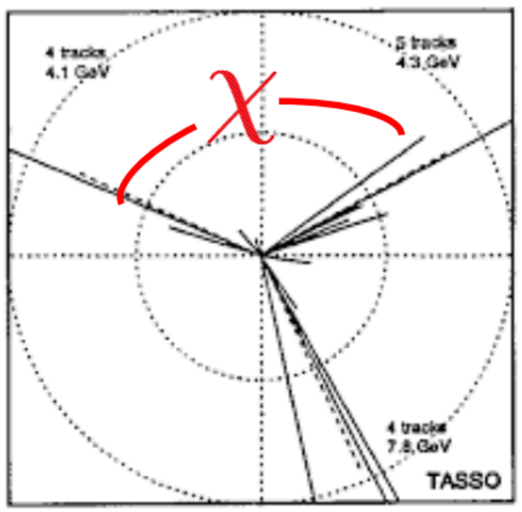
TASSO, JADE, PLUTO, OPAL, L3, ALEPH, …

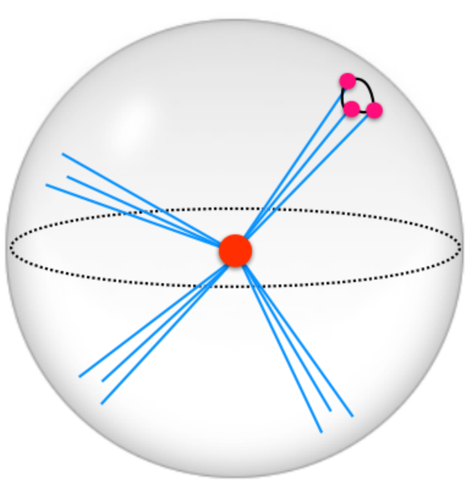


Moult, Zhu `18

Introduction

$\chi \in [0,\pi]$





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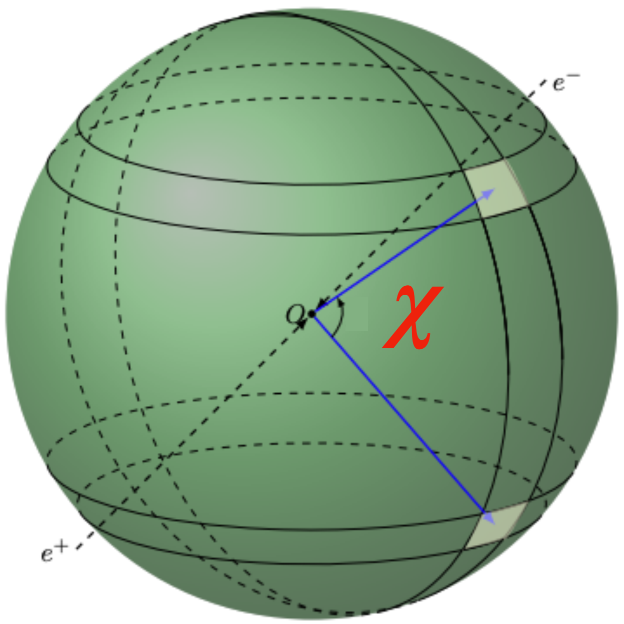
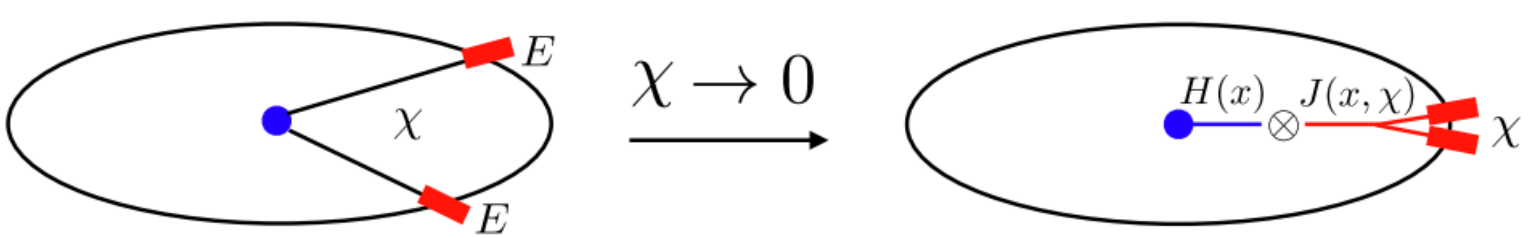


Moult, Zhu `18

1. Collinear limit $\chi \to 0$: probe jet substructure.

Dixon, Moult, Zhu, `19
Chen, Dixon, Luo, Moult, Yang, Zhang, Zhu, `19

Factorization of the two point correlator



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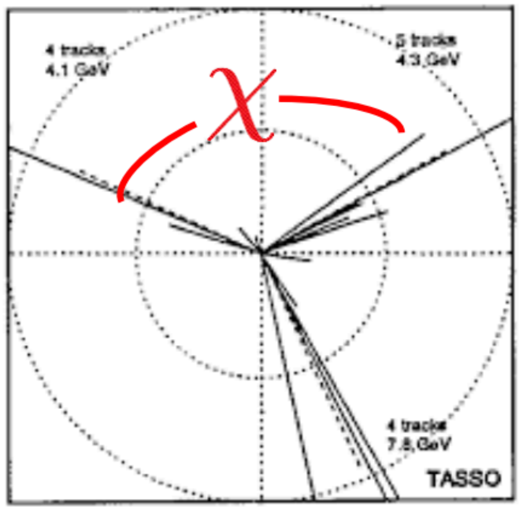
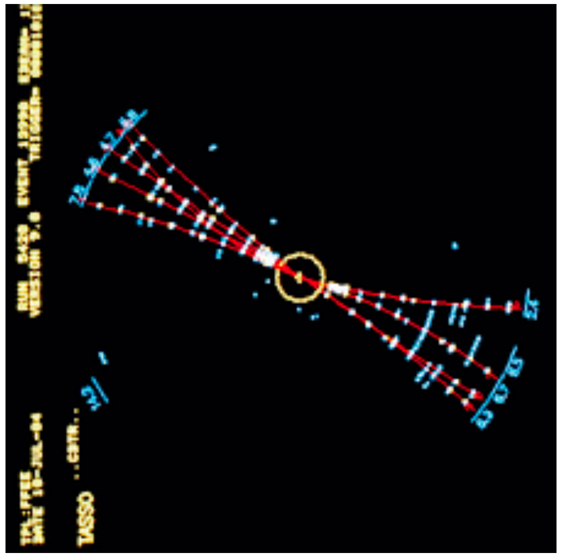
$\chi \in [0,\pi]$



$\chi \to \pi$



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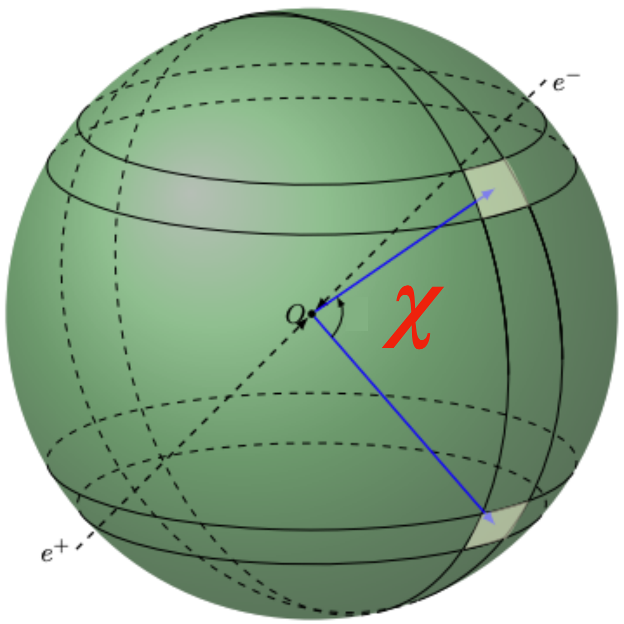
Basham, Brown, Ellis, Love `78 `79



Moult, Zhu `18

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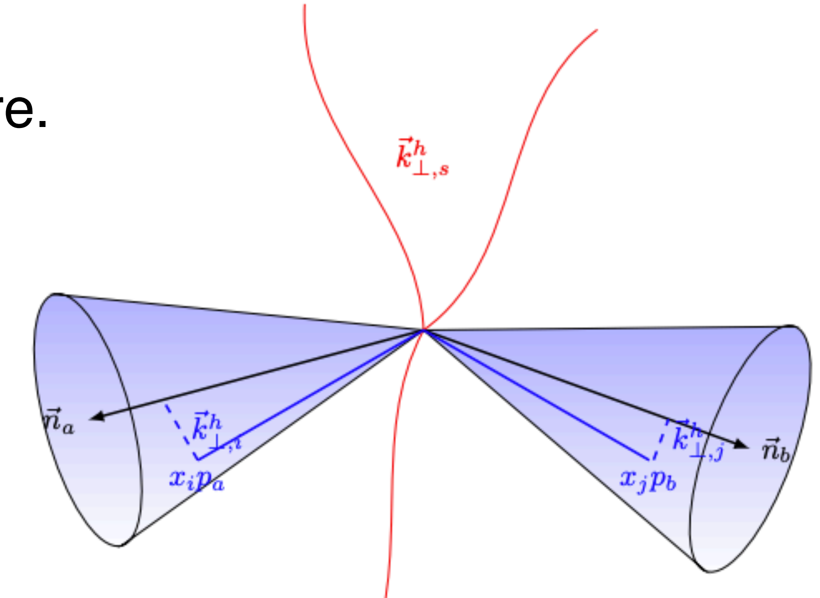
2. Back-to-back limit $\chi \to \pi$: dominated by soft/collinear radiations



Moult, Zhu `18

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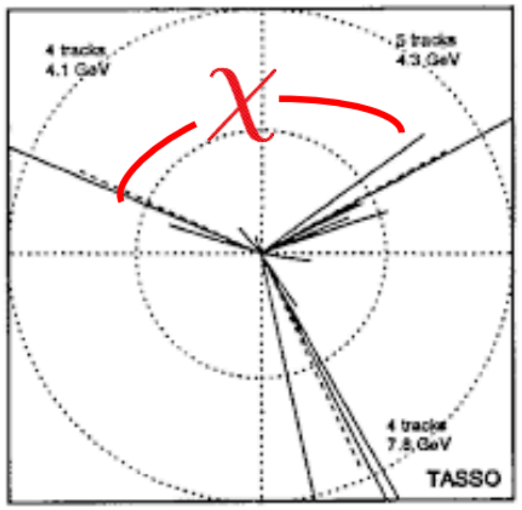

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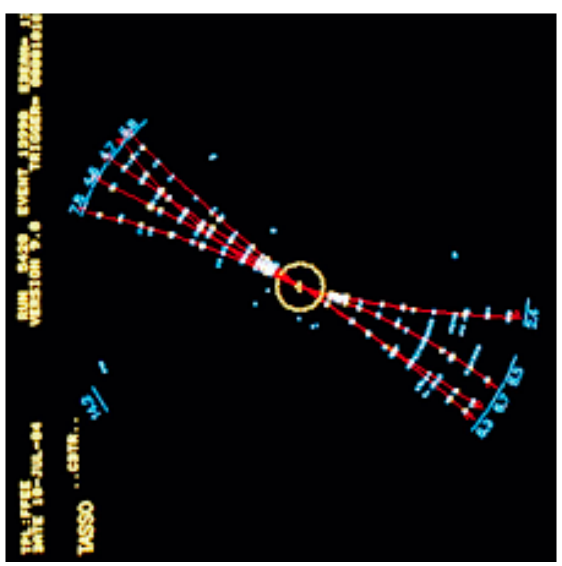

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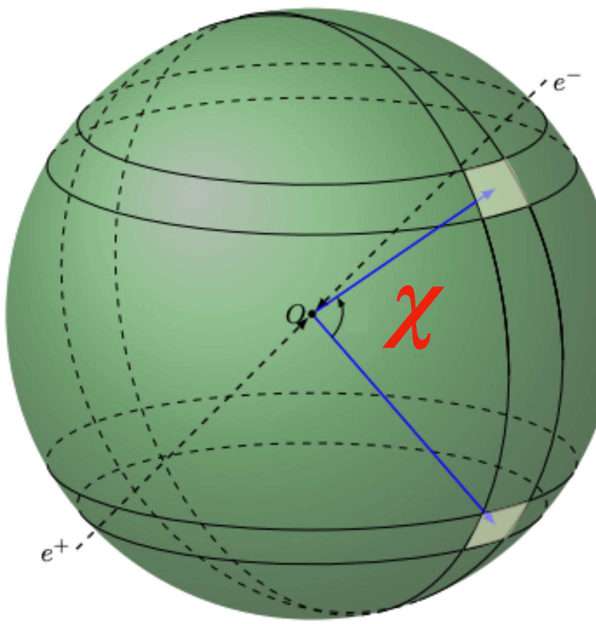
Basham, Brown, Ellis, Love \`78 \`79



Moult, Zhu \`18

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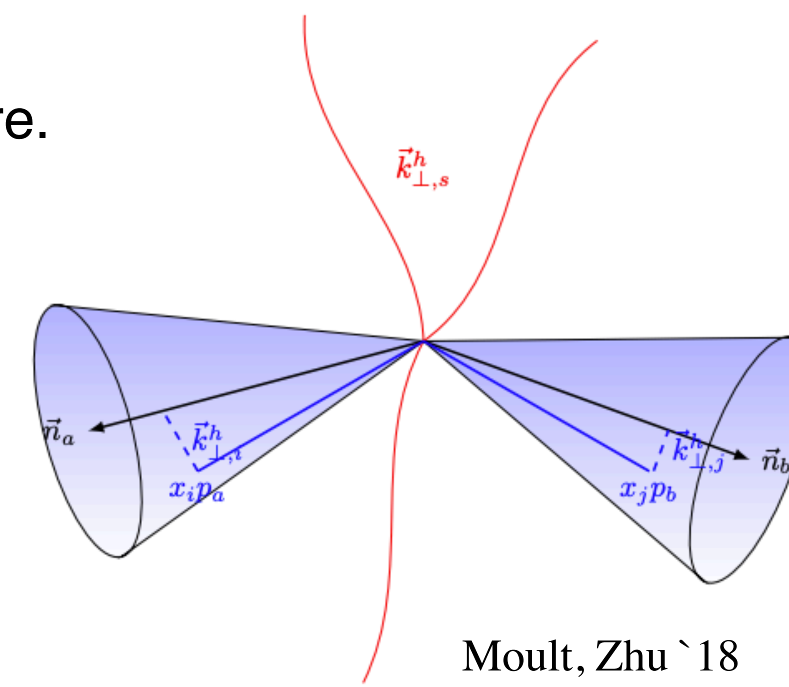
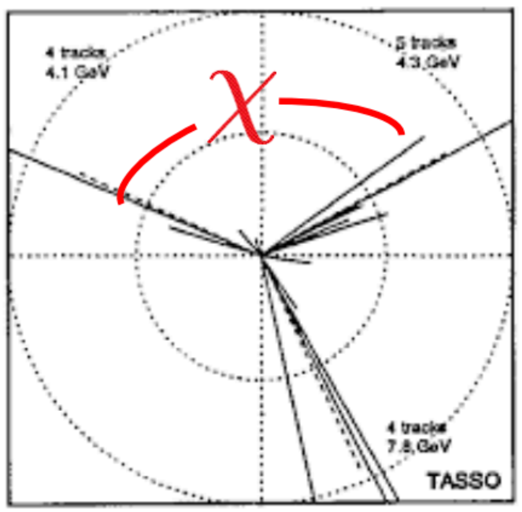


Moult, Zhu \`18

EEC at the back-to-back limit

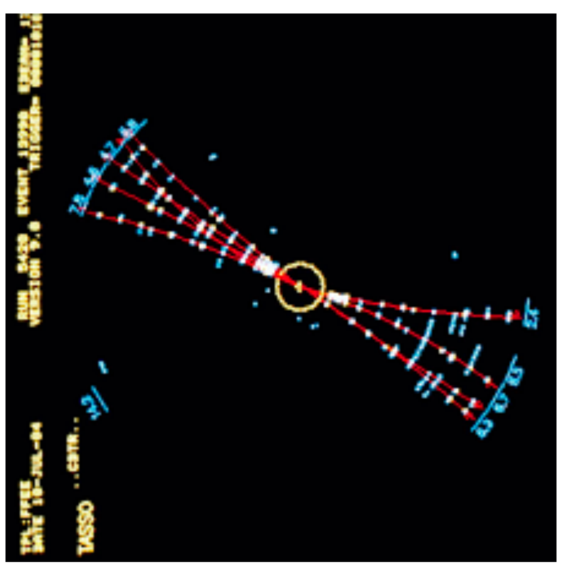
Basham, Brown, Ellis, Love `78 `79
Moult, Zhu `18
Ebert, Mistlberger, Vita `20
…

$\chi \in [0,\pi]$



$\tau \in [0,1]$

$\chi \to \pi$



$\tau \to 0$

$$\frac{d\Sigma_{e^+e^-}}{d\cos\chi} = \sum_{i,j} \int d\sigma \frac{E_i E_j}{Q^2} \delta\left(\cos\theta_{ij} - \cos\chi\right)$$

$$\tau = \frac{1+\cos\chi}{2}, \tau \in [0,1]$$

$$\mathrm{EEC}_{e^+e^-}(\tau) \equiv \frac{1}{\sigma}\frac{d\Sigma_{e^+e^-}}{d\tau} = \frac{1}{2}\sum_{i,j}\int d\boldsymbol{q}_T^2 dz_i dz_j \, z_i z_j \frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2 dz_i dz_j}\delta\left(\tau - \frac{\boldsymbol{q}_T^2}{Q^2}\right)$$

Definition

EEC at the back-to-back limit

Basham, Brown, Ellis, Love `78 `79
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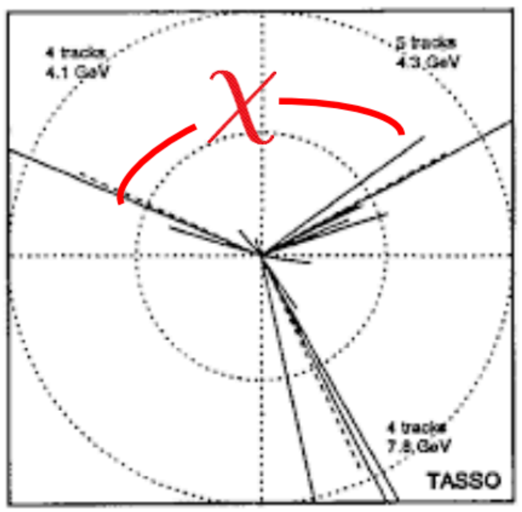

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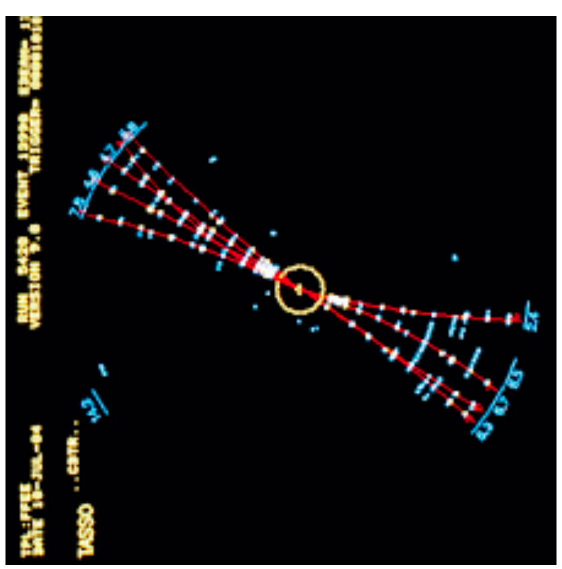
Definition

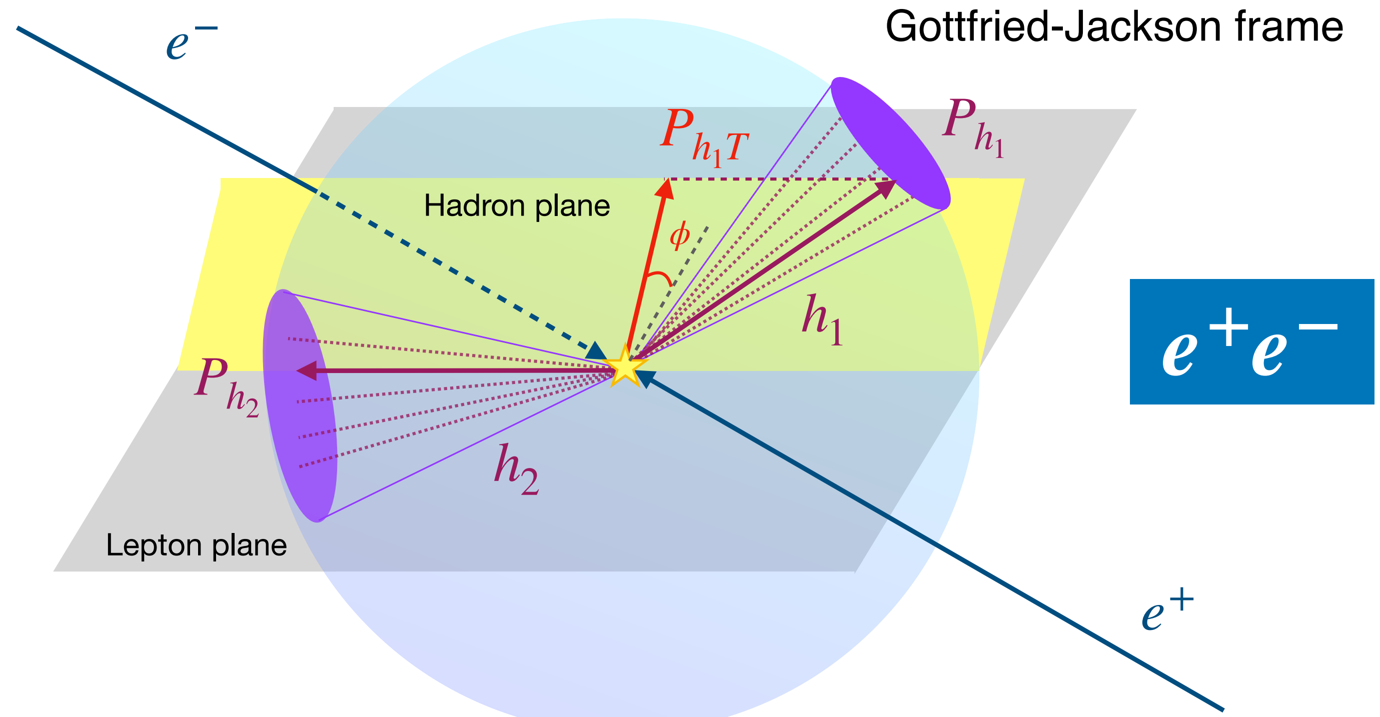
$\chi \to \pi$



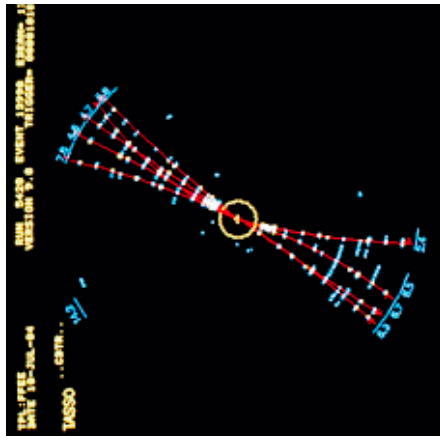
$\tau \to 0$

$$\tau = \frac{\boldsymbol{P}_{h_1T}^2}{z_1^2 Q^2}$$

$$q_T = \frac{|\boldsymbol{P}_{h_1T}|}{z_1}$$



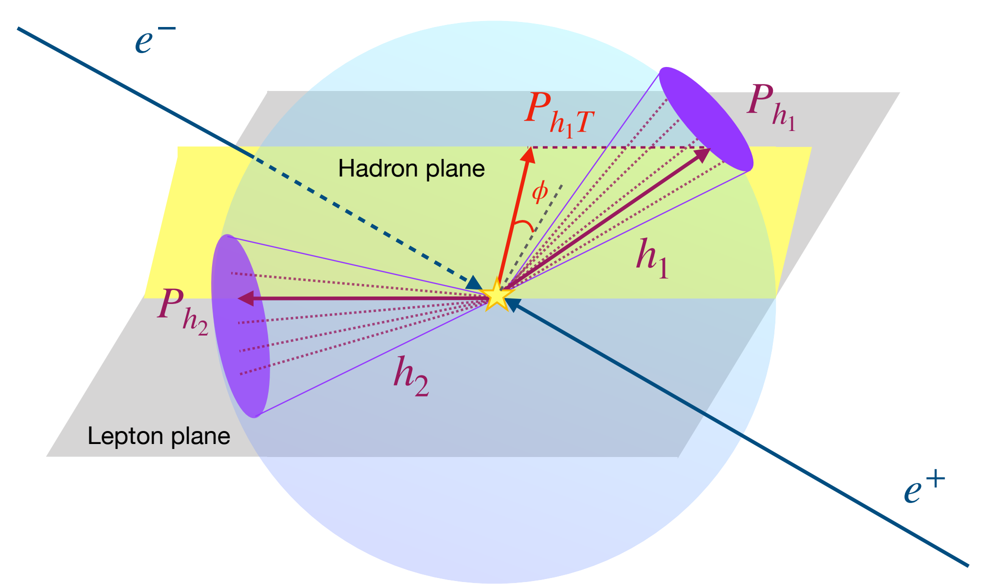
e^+e^-



EEC at the back-to-back limit

e^+e^-

Gottfried-Jackson frame



In the back-to-back limit ($\chi \to \pi,\ \tau \to 0$):

- Unpolarized processes in both e^+e^- collisions have been studied and observed.

Definition:

$$\mathrm{EEC}_{e^+e^-}(\tau) \equiv \frac{1}{\sigma}\frac{d\Sigma_{e^+e^-}}{d\tau} = \frac{1}{2}\sum_{i,j}\int d\boldsymbol{q}_T^2 dz_i dz_j\, z_i z_j \frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2 dz_i dz_j}\delta\left(\tau - \frac{\boldsymbol{q}_T^2}{Q^2}\right)$$

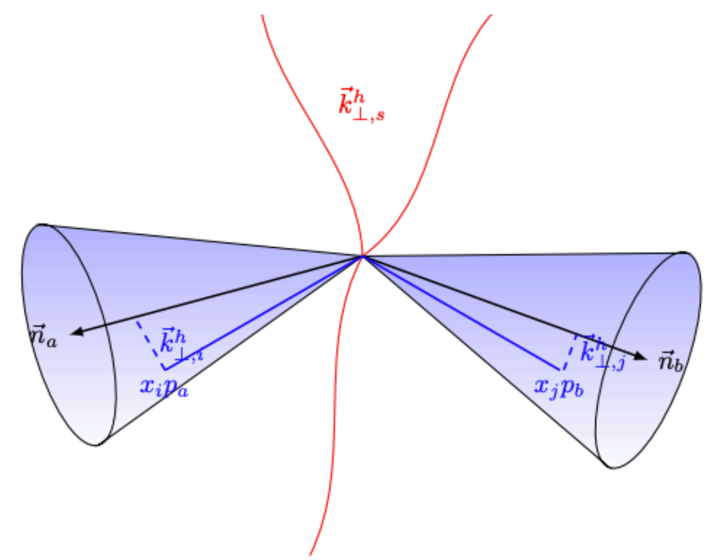
Factorization:

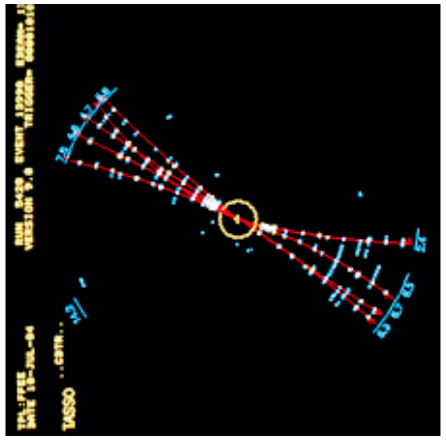
$$\frac{d\Sigma_{e^+e^-}}{d\tau} = \frac{2\pi N_c \alpha_{em}^2}{3Q^2}\sum_q e_q^2 \int d\boldsymbol{q}_T^2 \delta\left(\tau - \frac{\boldsymbol{q}_T^2}{Q^2}\right)\int \frac{bdb}{2\pi} J_0(bq_T)\boxed{J_q(\boldsymbol{b},\mu,\zeta/\nu^2)}\boxed{J_{\bar{q}}(\boldsymbol{b},\mu,\zeta/\nu^2)}\boxed{S(\boldsymbol{b}^2,\mu,\nu)}$$

z-weighted FF sum over hadrons produced in the final states

$$J_q(\boldsymbol{b},\mu,\zeta/\nu^2) \equiv \sum_h \int_0^1 dz\, z\, \tilde{D}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta/\nu^2)\,,$$

Moult, Zhu `18





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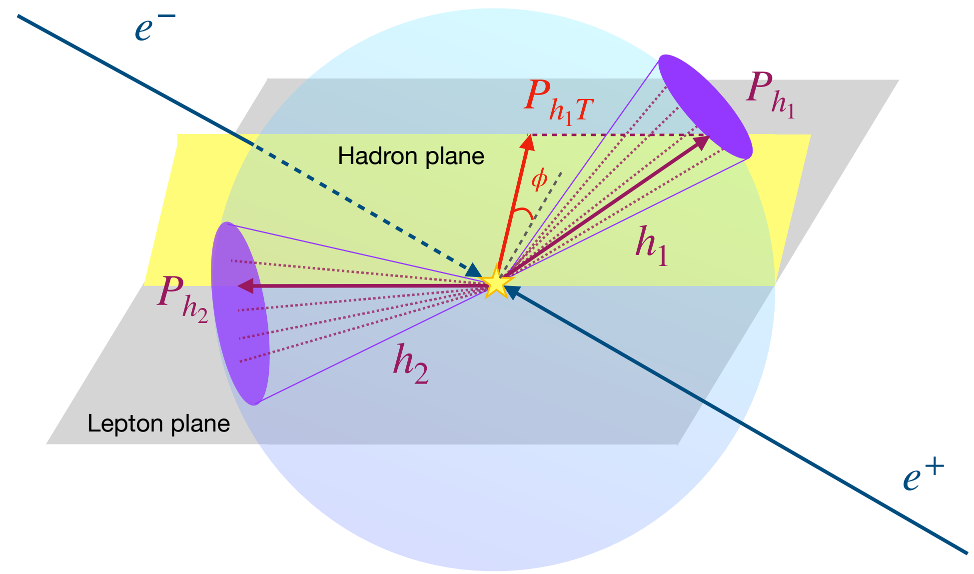

In the back-to-back limit ($\chi \to \pi$, $\tau \to 0$):

- Related to more TMD observables.
- Include transverse partonic process

New Definition:

$$\mathrm{EEC}_{e^+e^-}(\tau,\phi) \equiv \frac{1}{\sigma}\frac{d\Sigma_{e^+e^-}}{d\tau d\phi} = \frac{1}{2}\sum_{i,j}\int d\boldsymbol{q}_T^2 dz_i dz_j \frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2 dz_i dz_j}\delta\left(\tau - \frac{\boldsymbol{q}_T^2}{Q^2}\right)\delta(\phi-\phi_{q_T})$$

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Moult, Zhu `18

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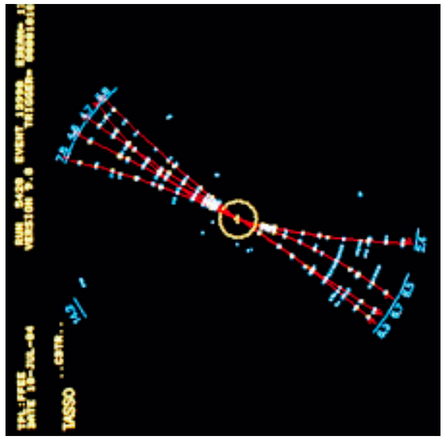

EEC at the back-to-back limit

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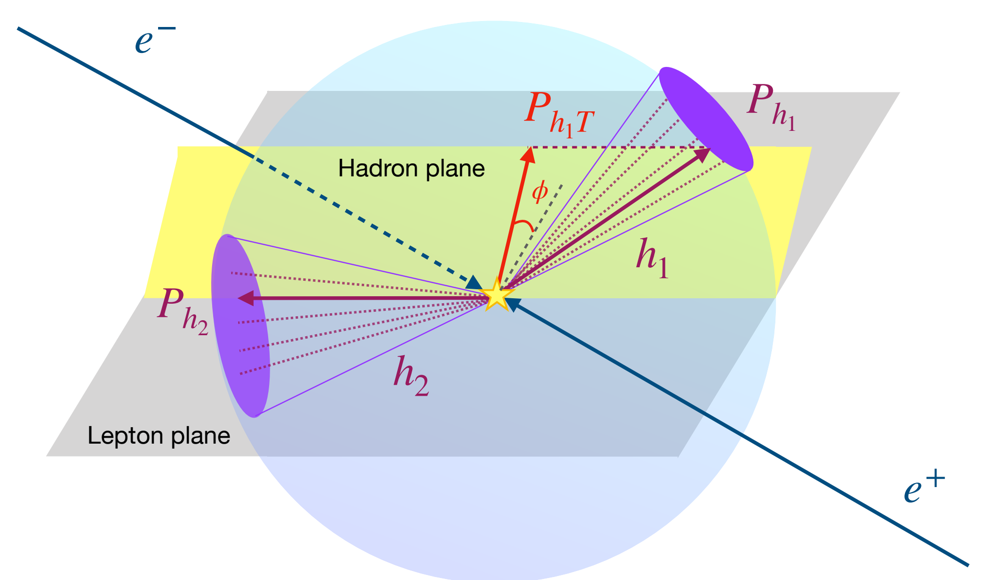

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Moult, Zhu \`18

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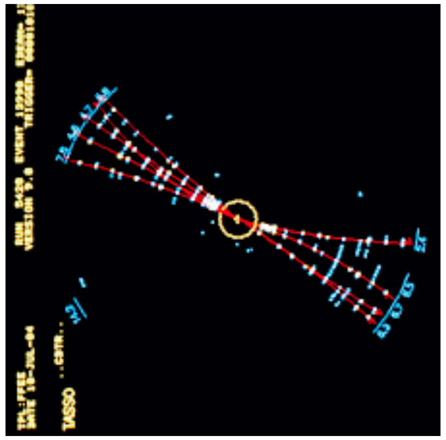
Kang, Lee, Shao, FZ (arXiv: 2303.xxxx)

$$\boxed{\left(-\frac{i b^\alpha}{2}\right) J_q^\perp(\boldsymbol{b},\mu,\zeta/\nu^2) \equiv \sum_h \int_0^1 dz\, z\, \tilde{H}_{1,h/q}^{\perp\,\alpha}(z,\boldsymbol{b}^2,\mu,\zeta/\nu^2).}$$

$\tilde{H}_1^\perp$: Collins function in b-space

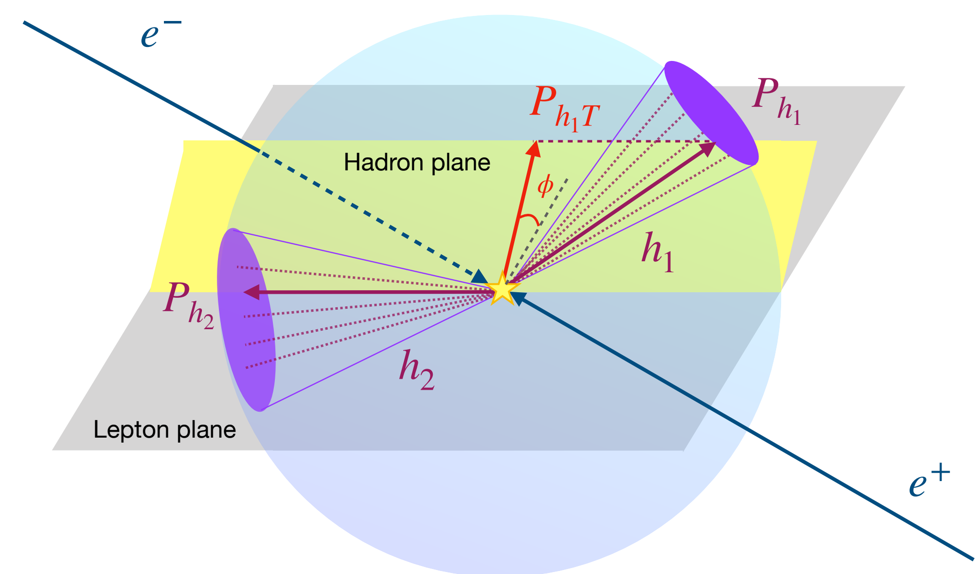
Collins-type



EEC with a subset $\mathbb{S}$

Gottfried-Jackson frame

e^+e^-



Flexible to change the summation over all h to a subset $\mathbb{S}$ of h

$$\sum_h \Rightarrow \sum_{h \in \mathbb{S}}$$

E.g. $\mathbb{S}$ = charged particles

Better energy resolution and smaller experimental uncertainties

$\mathbb{S} = h$

Probe fragmentation function

Moult, Zhu `18

$$J_q(\boldsymbol{b}, \mu, \zeta/\nu^2) \equiv \sum_h \int_0^1 dz\, z\, \tilde{D}_{1,h/q}(z, \boldsymbol{b}^2, \mu, \zeta/\nu^2)\,,$$

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Kang, Lee, Shao, FZ (arXiv: 2303.xxxx)

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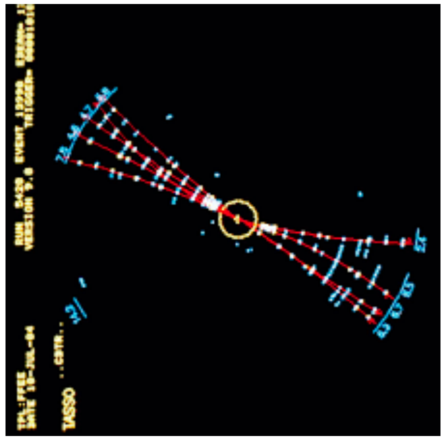

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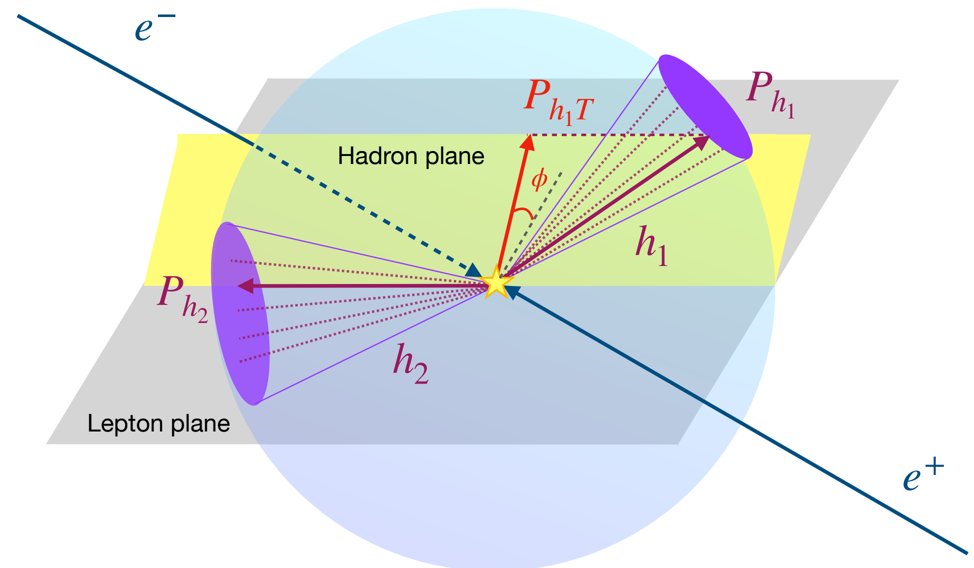

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$$\sum_h \Rightarrow \sum_{h\in\mathbb{S}}$$

E.g. $\mathbb{S}$ = charged particles — Better energy resolution and smaller experimental uncertainties

$\mathbb{S} = h$ — Probe fragmentation functions (FFs)

Phenomenology: $\mathbb{S} = \{\pi^+\}, \{\pi^-\}, \{\pi^+, \pi^-\}$ — Available extraction of pion FFs

Moult, Zhu `18

Kang, Lee, Shao, FZ (arXiv: 2303.xxxx)

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z-weighted sum over hadrons produced in the final states

$\tilde{H}_1^\perp$: Collins function in b-space

Example for EEC in e^+e^-: Collins asymmetry

$$\sum_{h_1,h_2} \Rightarrow \sum_{h_1,h_2 \in \mathbb{S}\times\mathbb{S}}$$

$$\mathcal{A}^{\mathbb{S}\times\mathbb{S}}_{e^+e^-} = \frac{J_q^\perp \otimes J_q^\perp \otimes S}{J_q \otimes J_q \otimes S}$$

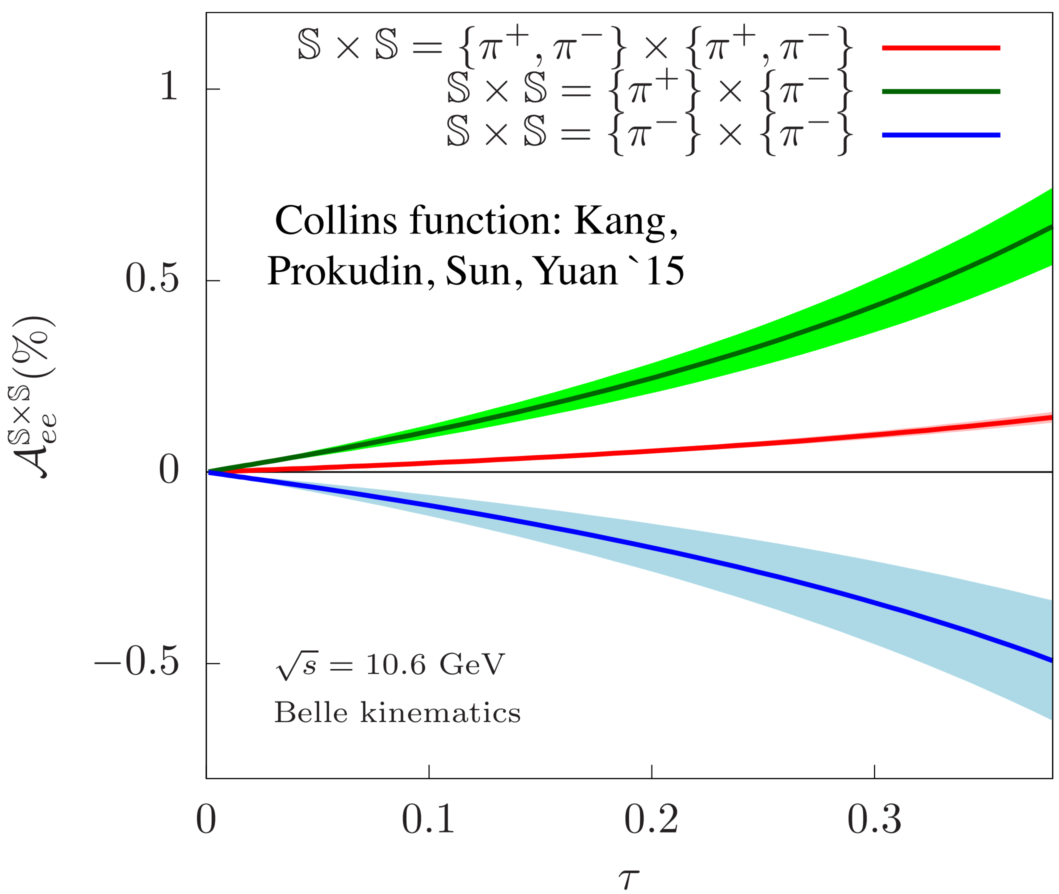
$$\mathrm{EEC}_{e^+e^-}(\tau,\phi) \equiv \frac{1}{\sigma}\frac{d\Sigma_{e^+e^-}}{d\tau d\phi}$$

$$= \frac{1}{2}\sum_{i,j}\int d\theta_{ij} dz_i dz_j z_i z_j \frac{1}{\sigma}\frac{d\sigma}{d\theta_{ij} d\phi_{ij} dz_i dz_j}\delta\left(\tau - \left(\frac{1+\cos\theta_{ij}}{2}\right)\right)\delta(\phi-\phi_{ij}),$$

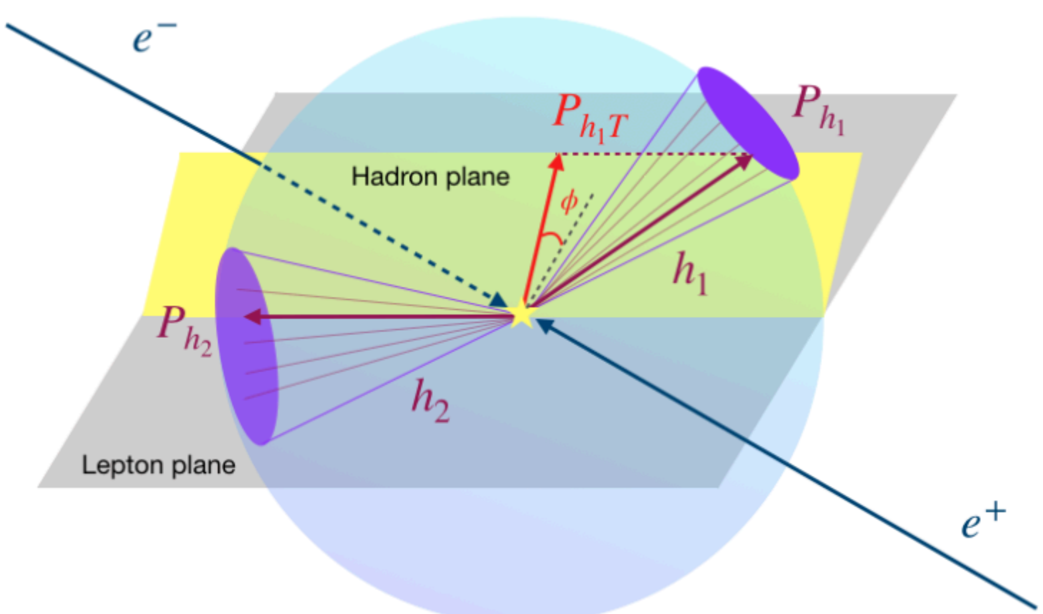
$$\mathrm{EEC}_{e^+e^-} \sim \sum_q \left[J_q \otimes J_{\bar{q}} \otimes S + \cos 2\phi\, J_q^\perp \otimes J_{\bar{q}}^\perp \otimes S\right].$$

$$J_q(\boldsymbol{b},\mu,\zeta/\nu^2) \equiv \sum_h \int_0^1 dz\, z\, \tilde{D}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta/\nu^2),$$

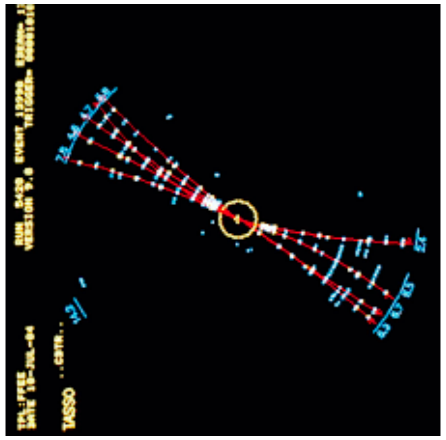
$$\left(-\frac{i\boldsymbol{b}^\alpha}{2}\right) J_q^\perp(\boldsymbol{b},\mu,\zeta/\nu^2) \equiv \sum_h \int_0^1 dz\, z\, \tilde{H}^{\perp\,\alpha}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta/\nu^2).$$



Prediction for Collins asymmetry at Belle kinematics



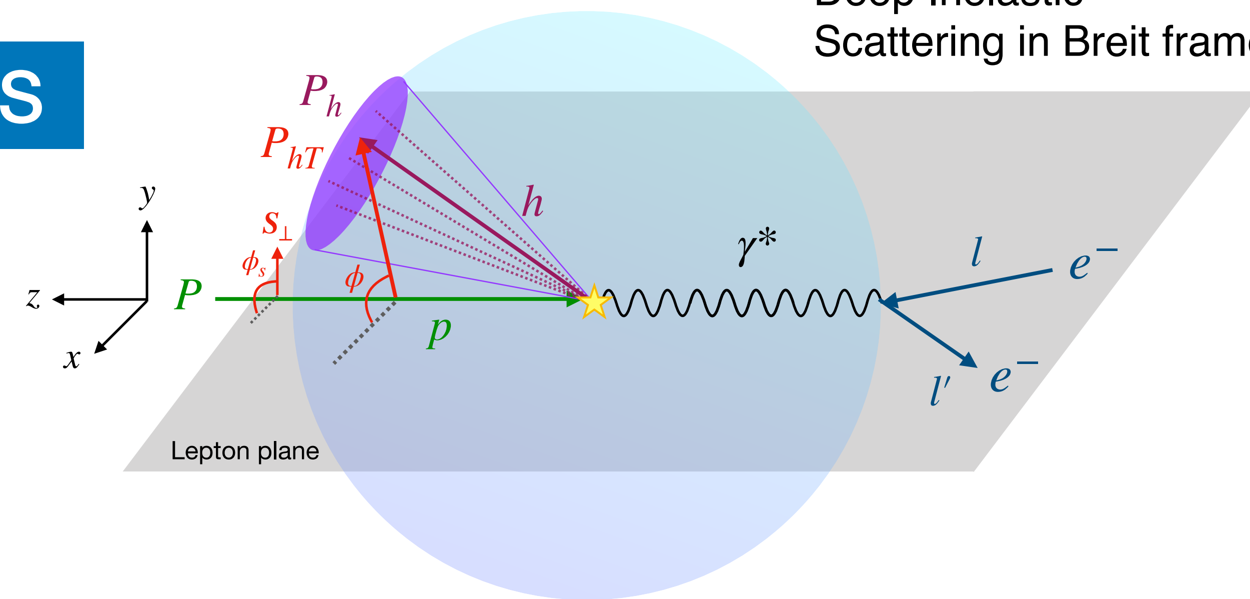
Gottfried-Jackson frame



EEC at the back-to-back limit

SIDIS

Deep Inelastic Scattering in Breit frame



In the back-to-back limit ($\chi \to \pi$, $\tau \to 0$):

- Unpolarized processes in ep collisions have been studied and observed.

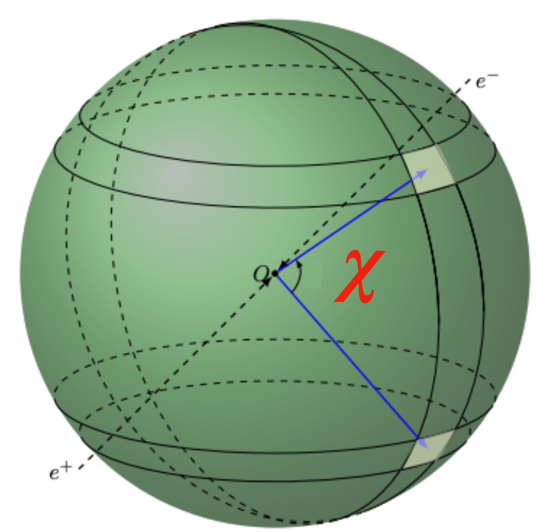
Li, Vitev, Zhu `20
Li, Marks, Vitev `21

Definition:

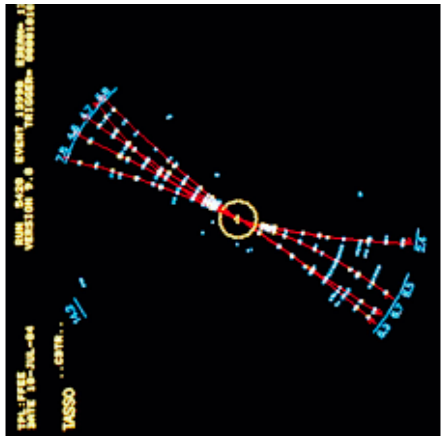
$$\mathrm{EEC}_{\mathrm{DIS}}(\tau) \equiv \frac{1}{\sigma}\frac{d\Sigma_{\mathrm{DIS}}}{d\tau} = \frac{1}{2}\sum_a \int d\theta_a dz_a z_a \frac{1}{\sigma}\frac{d\sigma}{d\theta_{ap} d\phi_{ap} dz_a}\delta\left(\tau - \left(\frac{1+\cos\theta_{ap}}{2}\right)\right)$$

$$\frac{q_T^2}{Q^2}$$

Compare to e^+e^- :

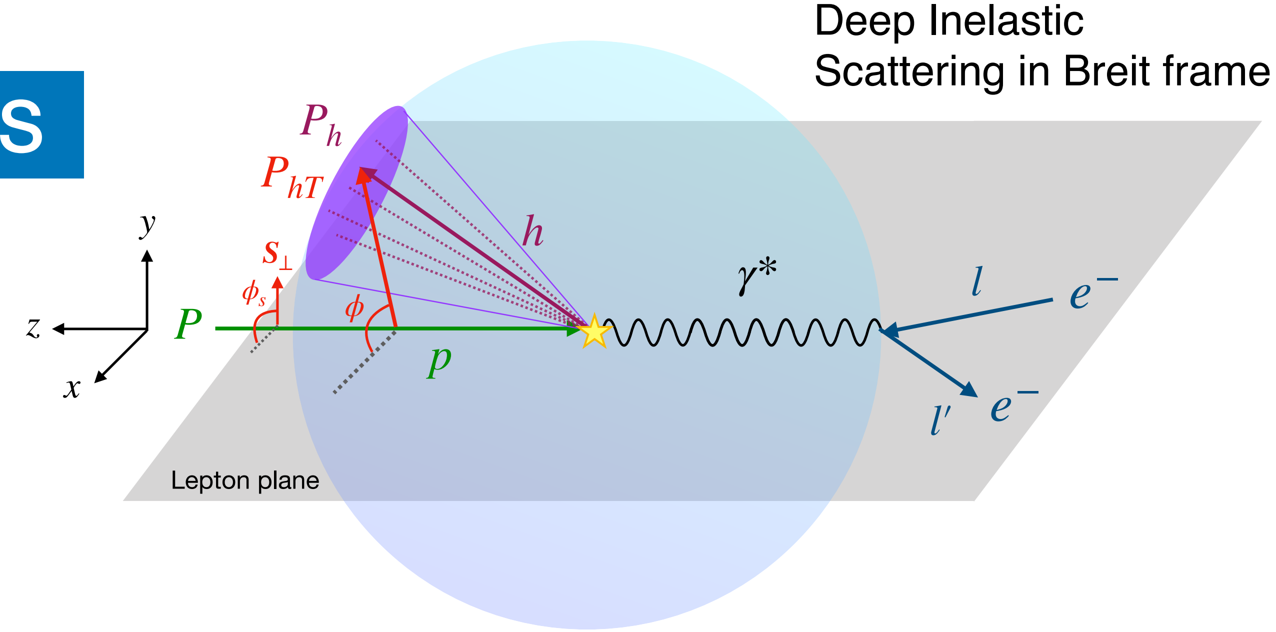


$$\tau = \frac{1+\cos\chi}{2}$$



EEC at the back-to-back limit

SIDIS



In the back-to-back limit ($\chi \to \pi,\ \tau \to 0$):

- Unpolarized processes in ep collisions have been studied and observed.

Li, Vitev, Zhu `20
Li, Marks, Vitev `21

Definition:

$$\mathrm{EEC}_{\mathrm{DIS}}(\tau) \equiv \frac{1}{\sigma}\frac{d\Sigma_{\mathrm{DIS}}}{d\tau} = \frac{1}{2}\sum_a \int d\theta_a dz_a z_a \frac{1}{\sigma}\frac{d\sigma}{d\theta_{ap} d\phi_{ap} dz_a}\delta\left(\tau - \left(\frac{1+\cos\theta_{ap}}{2}\right)\right)$$

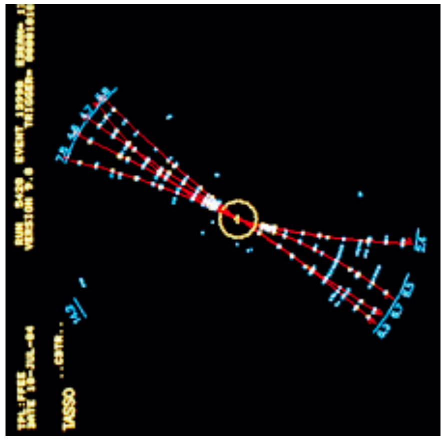
$$\frac{q_T^2}{Q^2}$$

New Definition:

$$\mathrm{EEC}_{\mathrm{DIS}}(\tau,\phi) \equiv \frac{1}{\sigma}\frac{d\Sigma_{\mathrm{DIS}}}{d\tau d\phi} = \frac{1}{2}\sum_a \int d\theta_a dz_a z_a \frac{1}{\sigma}\frac{d\sigma}{d\theta_{ap} d\phi_{ap} dz_a}\delta\left(\tau - \left(\frac{1+\cos\theta_{ap}}{2}\right)\right)\delta(\phi - \phi_{ap}).$$

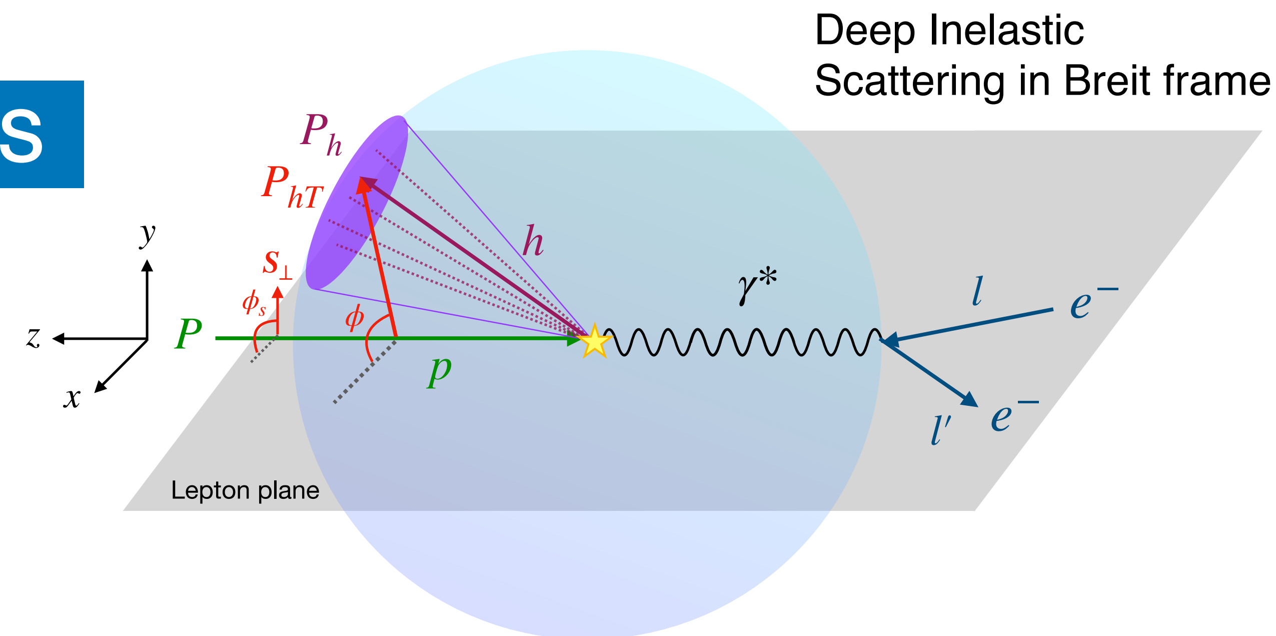
Kang, Lee, Shao, FZ
(arXiv: 2303.xxxx)

Collins-type



EEC at the back-to-back limit

SIDIS



In the back-to-back limit ($\chi \to \pi$, $\tau \to 0$):

- Related to more TMD observables.
- Include transverse partonic process

$$\frac{d\Sigma_{\rm DIS}}{dx dy d\tau d\phi} = \frac{2\pi\alpha_{\rm em}^2}{Q^2}\frac{1+(1-y)^2}{y}\int d^2\boldsymbol{q}_T \delta(\tau - \frac{\boldsymbol{q}_T^2}{Q^2})\delta(\phi-\phi_{q_T})\int \frac{db\, b}{2\pi}\Big\{\mathcal{F}_{UU}$$

$$+\cos(2\phi_{q_T})\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UU}^{\cos(2\phi_{q_T})} + S_\parallel \sin(2\phi_{q_T})\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UL}^{\sin(2\phi_{q_T})}$$

$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_{q_T}-\phi_s)\mathcal{F}_{UT}^{\sin(\phi_{q_T}-\phi_s)} + \sin(\phi_{q_T}+\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(\phi_{q_T}+\phi_s)}$$

$$+\sin(3\phi_{q_T}-\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(3\phi_{q_T}-\phi_s)}\Big]$$

$$+\lambda_e\Big[S_\parallel\frac{y(2-y)}{1+(1-y)^2}\mathcal{F}_{LL} + |\boldsymbol{S}_\perp|\cos(\phi_{q_T}-\phi_s)\mathcal{F}_{LT}^{\cos(\phi_{q_T}-\phi_s)}\Big]\Big\},$$

Li, Vitev, Zhu \`20
Li, Marks, Vitev \`21

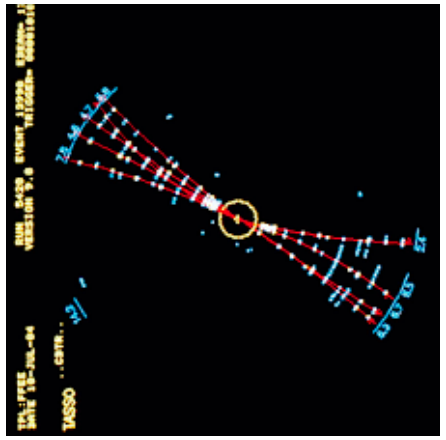
Incoming p pol.

Incoming e^- pol.

Kang, Lee, Shao, FZ
(arXiv: 2303.xxxx)

Collins-type

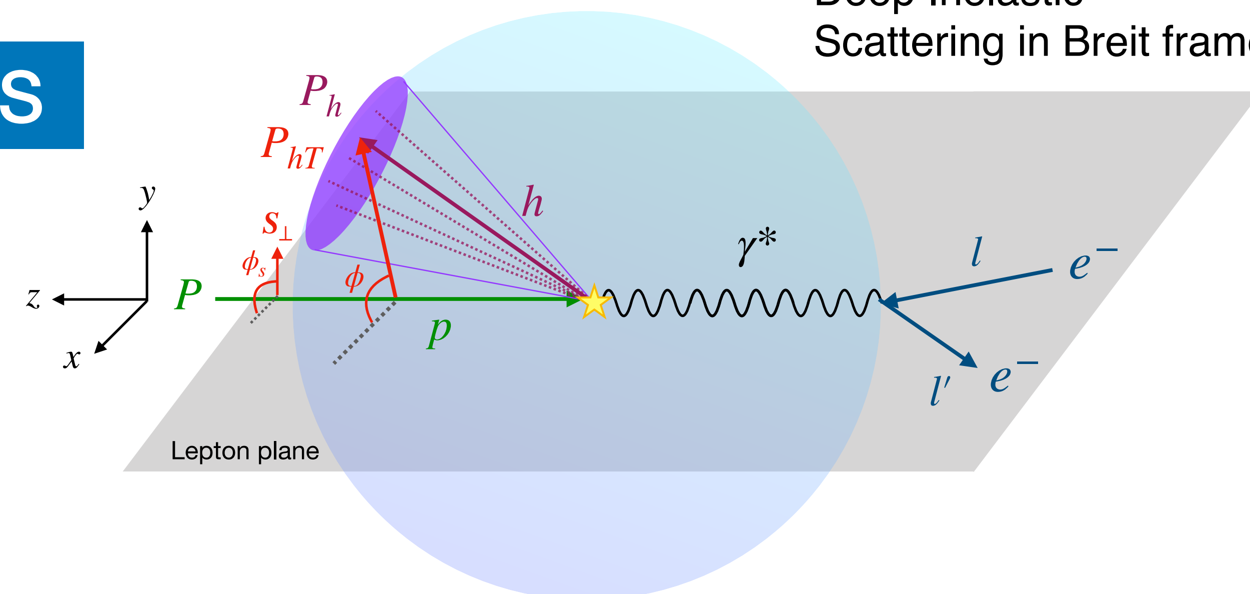
New probe for all TMDPDFs



EEC at the back-to-back limit

SIDIS

Deep Inelastic Scattering in Breit frame



In the back-to-back limit ($\chi \to \pi$, $\tau \to 0$):

- Related to more TMD observables.
- Include transverse partonic process

$$\frac{d\Sigma_{\rm DIS}}{dx dy d\tau d\phi} = \frac{2\pi\alpha_{\rm em}^2}{Q^2}\frac{1+(1-y)^2}{y}\int d^2\boldsymbol{q}_T \delta\left(\tau - \frac{\boldsymbol{q}_T^2}{Q^2}\right)\delta(\phi-\phi_{q_T})\int\frac{db\, b}{2\pi}\Bigg\{\mathcal{F}_{UU}$$

$$+\cos(2\phi_{q_T})\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UU}^{\cos(2\phi_{q_T})} + S_\parallel \sin(2\phi_{q_T})\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UL}^{\sin(2\phi_{q_T})}$$

$$+|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_{q_T}-\phi_s)\mathcal{F}_{UT}^{\sin(\phi_{q_T}-\phi_s)} + \sin(\phi_{q_T}+\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(\phi_{q_T}+\phi_s)}$$

$$+\sin(3\phi_{q_T}-\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(3\phi_{q_T}-\phi_s)}\Bigg]$$

$$+\lambda_e\left[S_\parallel\frac{y(2-y)}{1+(1-y)^2}\mathcal{F}_{LL} + |\boldsymbol{S}_\perp|\cos(\phi_{q_T}-\phi_s)\mathcal{F}_{LT}^{\cos(\phi_{q_T}-\phi_s)}\right]\Bigg\},$$

Li, Vitev, Zhu `20
Li, Marks, Vitev `21

Incoming p pol.

Incoming e^- pol.

New probe for all TMDPDFs

Flexible to change the summation over all h to a subset $\mathbb{S}$ of h

$$\sum_h \Rightarrow \sum_{h\in\mathbb{S}}$$

Kang, Lee, Shao, FZ (arXiv: 2303.xxxx)

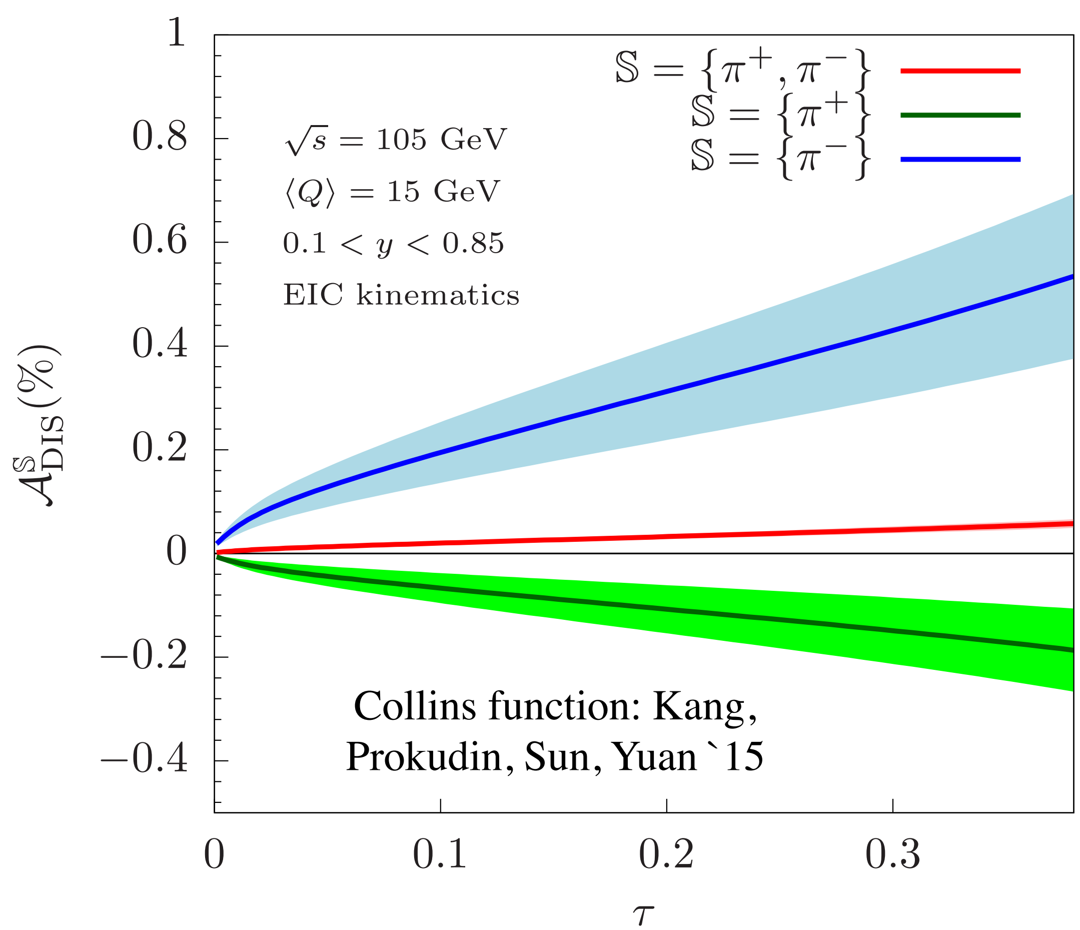
Collins-type

Example for EEC in SIDIS: Collins asymmetry

$$\mathcal{A}_{\rm DIS}^{\mathbb{S}} = \frac{2(1-y)}{1+(1-y)^2}\frac{\mathcal{F}_{UT}^{\sin(\phi_{q_T}+\phi_s)}}{\mathcal{F}_{UU}}$$

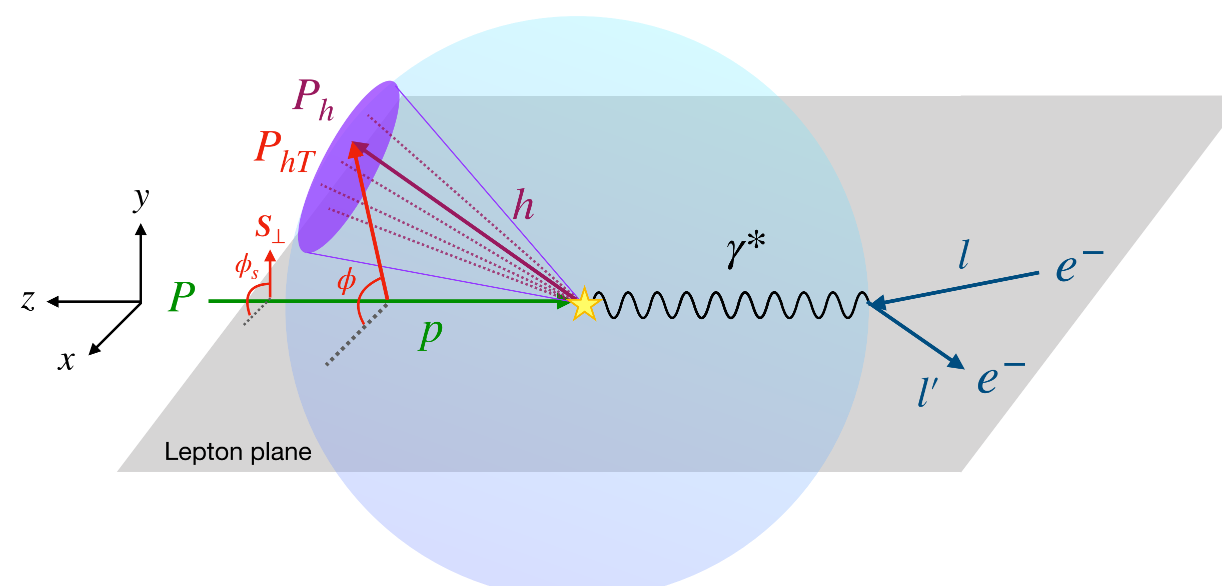
$$\mathcal{F}_{UT}^{\sin(\phi_{q_T}+\phi_s)} \sim h_1 \otimes J_q^{\perp}$$

$$\mathcal{F}_{UU} \sim f_1 \otimes J_q$$



Prediction for Collins asymmetry at EIC kinematics

$$\frac{d\Sigma_{\rm DIS}}{dx\,dy\,d\tau\,d\phi} = \frac{2\pi\alpha_{\rm em}^2}{Q^2}\frac{1+(1-y)^2}{y}\int d^2\boldsymbol{q}_T\,\delta(\tau - \frac{\boldsymbol{q}_T^2}{Q^2})\int\frac{db\,b}{2\pi}\Big\{\boxed{\mathcal{F}_{UU}}$$
$$+\cos(2\phi_{q_T})\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UU}^{\cos(2\phi_{q_T})} + S_{\parallel}\sin(2\phi_{q_T})\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UL}^{\sin(2\phi_{q_T})}$$
$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_{q_T}-\phi_s)\mathcal{F}_{UT}^{\sin(\phi_{q_T}-\phi_s)} + \boxed{\sin(\phi_{q_T}+\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(\phi_{q_T}+\phi_s)}}$$
$$+\sin(3\phi_{q_T}-\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(3\phi_{q_T}-\phi_s)}\Big]$$
$$+\lambda_e\Big[S_{\parallel}\frac{y(2-y)}{1+(1-y)^2}\mathcal{F}_{LL} + |\boldsymbol{S}_\perp|\cos(\phi_{q_T}-\phi_s)\mathcal{F}_{LT}^{\cos(\phi_{q_T}-\phi_s)}\Big]\Big\},$$



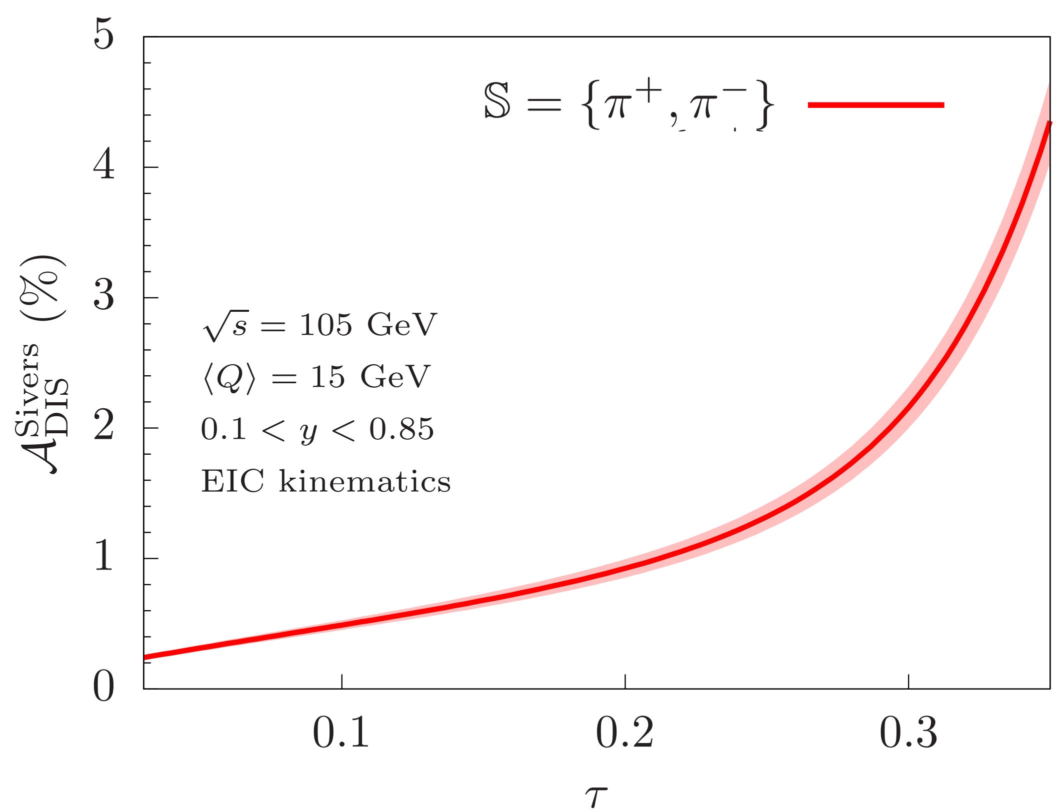
Example for EEC in SIDIS: Sivers asymmetry

$$\mathcal{A}_{\rm DIS}^{Sivers} = \frac{\mathcal{F}_{UT}^{\sin(\phi_{q_T}-\phi_s)}}{\mathcal{F}_{UU}}$$

$$\mathcal{F}_{UT}^{\sin(\phi_{q_T}-\phi_s)} \sim f_{1T}^{\perp} \otimes J_q$$

$$\mathcal{F}_{UU} \sim f_1 \otimes J_q$$

Sivers function: Echevarria, Kang, Terry `20



Prediction for Sivers asymmetry at EIC kinematics

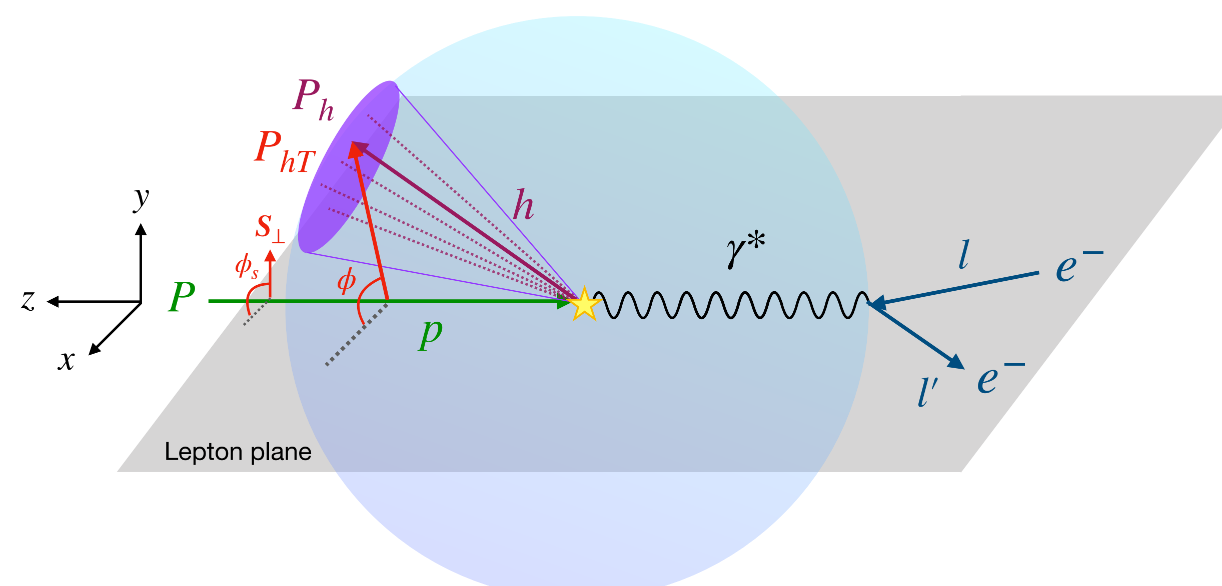
$$\frac{d\Sigma_{\rm DIS}}{dx\,dy\,d\tau\,d\phi} = \frac{2\pi\alpha_{\rm em}^2}{Q^2}\frac{1+(1-y)^2}{y}\int d^2\boldsymbol{q}_T\,\delta\Big(\tau - \frac{\boldsymbol{q}_T^2}{Q^2}\Big)\int\frac{db\,b}{2\pi}\Big\{\boxed{\mathcal{F}_{UU}}$$

$$+\cos(2\phi_{q_T})\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UU}^{\cos(2\phi_{q_T})} + S_\parallel\sin(2\phi_{q_T})\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UL}^{\sin(2\phi_{q_T})}$$

$$+|\boldsymbol{S}_\perp|\Big[\boxed{\sin(\phi_{q_T}-\phi_s)\mathcal{F}_{UT}^{\sin(\phi_{q_T}-\phi_s)}} + \sin(\phi_{q_T}+\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(\phi_{q_T}+\phi_s)}$$

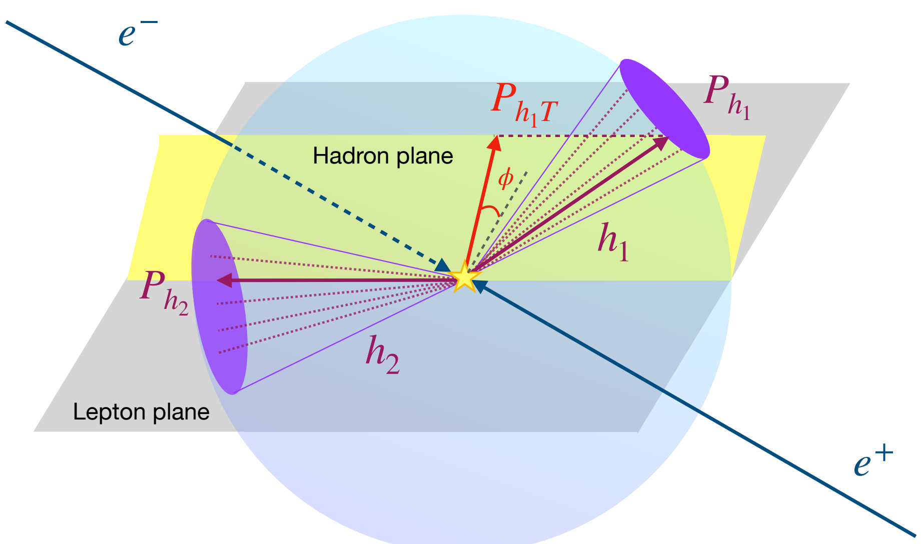
$$+\sin(3\phi_{q_T}-\phi_s)\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UT}^{\sin(3\phi_{q_T}-\phi_s)}\Big]$$

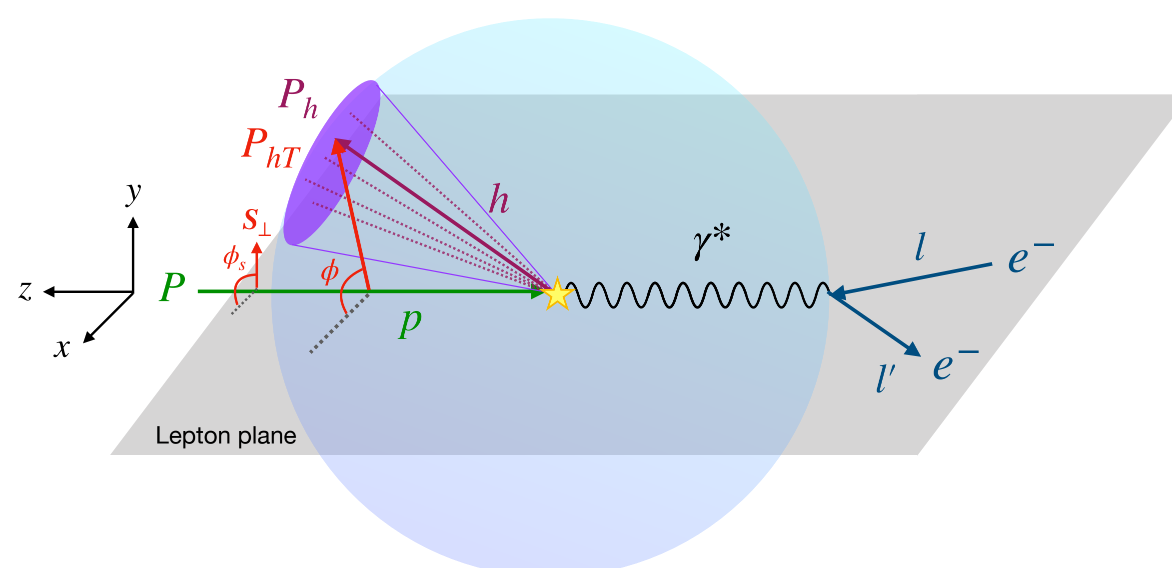
$$+\lambda_e\Big[S_\parallel\frac{y(2-y)}{1+(1-y)^2}\mathcal{F}_{LL} + |\boldsymbol{S}_\perp|\cos(\phi_{q_T}-\phi_s)\mathcal{F}_{LT}^{\cos(\phi_{q_T}-\phi_s)}\Big]\Big\},$$

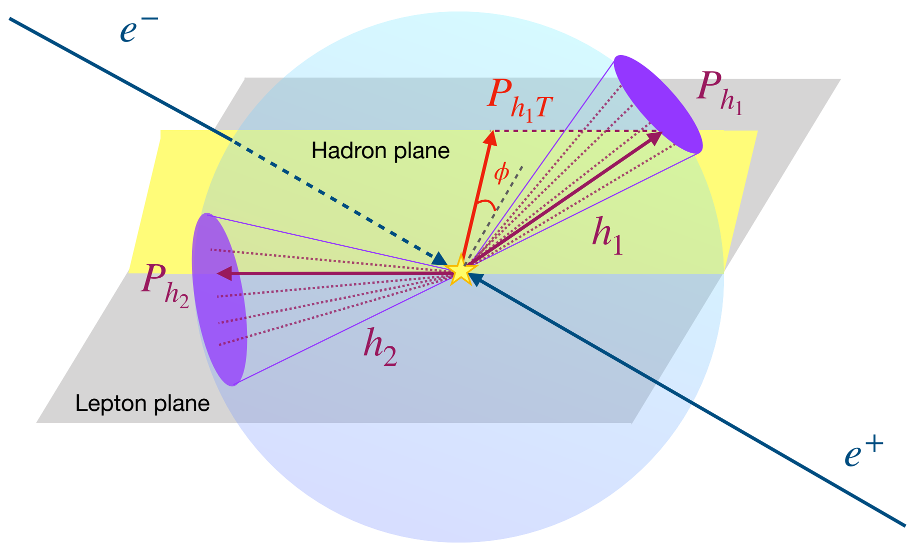


Summary

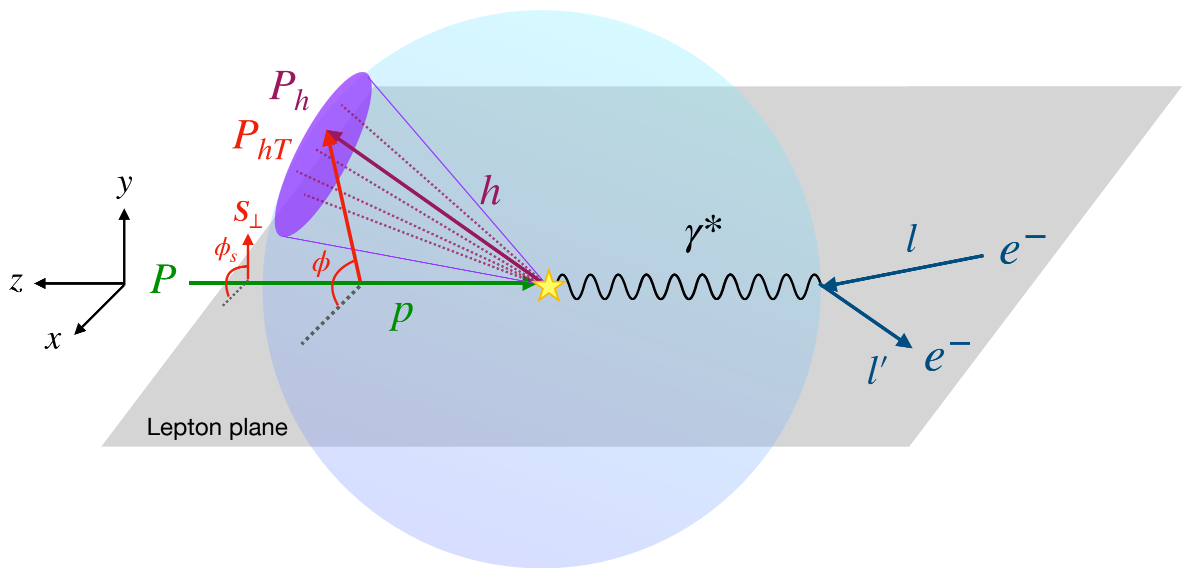
- EEC in the early literatures: handles only the unpolarized scattering (e^+e^- annihilation and ep collisions).
- By generalizing the EEC with azimuthal angle dependence, one gets access to spin-dependent effects (polarized incoming p).
- We introduce a Collins-type EEC jet function $\Rightarrow$ probe all the TMD PDFs, e.g. Sivers function, etc.
- Polarized beam at the future EIC: enable studies along this direction

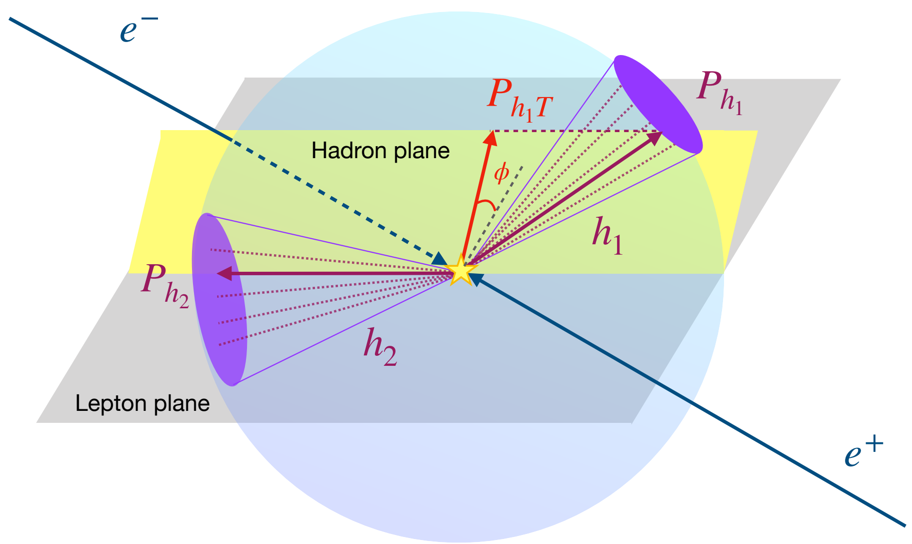




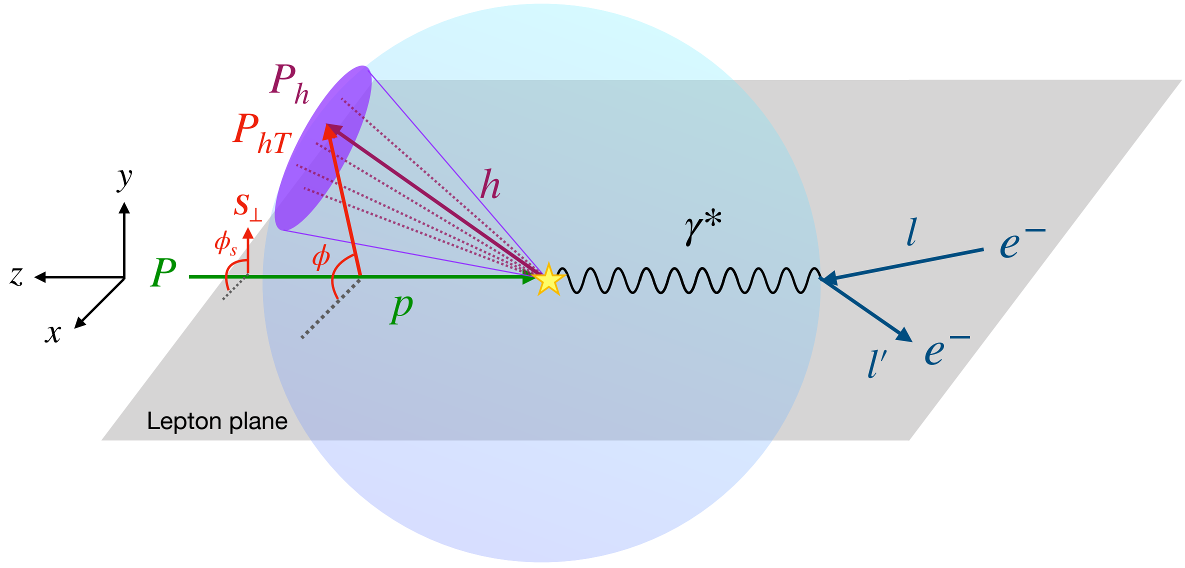


Thanks for your attention!




e^-
P_{h_1T}
P_{h_1}
Hadron plane
ϕ
h_1
P_{h_2}
h_2
Lepton plane
e^+

Backup


P_h
P_{hT}
h
y
$S_\perp$
γ^*
ϕ_s
ϕ
z
P
l
e^-
p
x
l'
e^-
Lepton plane

TMD factorization:

$$\tilde{D}^{\text{sub}}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta_f) = \tilde{D}^{\text{sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i) e^{-S_{\text{pert}}(\mu,\mu_{b_*}) - S^{D_1}_{\text{NP}}(b,Q_0,\zeta_f)} \left(\sqrt{\frac{\zeta_f}{\zeta_i}}\right)^{\kappa(b,\mu_{b_*})}, \tag{3.3}$$

$$\tilde{H}^{\perp\,\alpha,\text{sub}}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta_f) = \left(-\frac{ib^\alpha}{2z}\right) \tilde{H}^{\perp,\,\text{sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i) e^{-S_{\text{pert}}(\mu,\mu_{b_*}) - S^{H_1^\perp}_{\text{NP}}(b,Q_0,\zeta_f)} \left(\sqrt{\frac{\zeta_f}{\zeta_i}}\right)^{\kappa(b,\mu_{b_*})},$$

Collinear matching:

$$\tilde{D}^{\text{sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i) = \left[C_{j\leftarrow q}\otimes D_{1,h/j}\right](z,\mu_{b_*},\zeta_i) + \mathcal{O}(\boldsymbol{b}^2\Lambda^2_{\text{QCD}}),$$

$$\tilde{H}^{\perp,\,\text{sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i) = \left[\delta C^{\text{Collins}}_{j\leftarrow q}\otimes \hat{H}^{\perp(3)}_{1,h/j} + A_{j\leftarrow q}\tilde{\otimes}\hat{H}_{F,h/j}\right](z,\mu_{b_*},\zeta_i) + \mathcal{O}(\boldsymbol{b}^2\Lambda^2_{\text{QCD}}),$$

Sum rule:

$$\sum_h \int_0^1 dz\, z\, D_{1,h/j}(z,\mu) = 1\,,$$

$$\sum_h \int_0^1 dz\, \hat{H}^{\perp(3)}_{1,h/q}(z,\mu) = 0\,.$$

TMD factorization:

$$\tilde{D}^{\mathrm{sub}}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta_f)=\tilde{D}^{\mathrm{sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i)e^{-S_{\mathrm{pert}}(\mu,\mu_{b*})-S^{D_1}_{\mathrm{NP}}(b,Q_0,\zeta_f)}\left(\sqrt{\frac{\zeta_f}{\zeta_i}}\right)^{\kappa(b,\mu_{b*})},$$

$$\tilde{H}^{\perp\,\alpha,\mathrm{sub}}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta_f)=\left(-\frac{ib^\alpha}{2z}\right)\tilde{H}^{\perp,\,\mathrm{sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i)e^{-S_{\mathrm{pert}}(\mu,\mu_{b*})-S^{H_1^\perp}_{\mathrm{NP}}(b,Q_0,\zeta_f)}\left(\sqrt{\frac{\zeta_f}{\zeta_i}}\right)^{\kappa(b,\mu_{b*})},$$

Collinear matching:

$$\tilde{D}^{\mathrm{sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i)=\left[C_{j\leftarrow q}\otimes D_{1,h/j}\right](z,\mu_{b_*},\zeta_i)+\mathcal{O}(\boldsymbol{b}^2\Lambda^2_{\mathrm{QCD}}),$$

$$\tilde{H}^{\perp,\,\mathrm{sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i)=\left[\delta C^{\mathrm{Collins}}_{j\leftarrow q}\otimes\hat{H}^{\perp(3)}_{1,h/j}+A_{j\leftarrow q}\tilde{\otimes}\hat{H}_{F,h/j}\right](z,\mu_{b_*},\zeta_i)+\mathcal{O}(\boldsymbol{b}^2\Lambda^2_{\mathrm{QCD}}),$$

Sum rule:

$$\sum_h\int_0^1 dz\,z\,D_{1,h/j}(z,\mu)=1\,,$$

$$\sum_h\int_0^1 dz\,\hat{H}^{\perp(3)}_{1,h/q}(z,\mu)=0\,.$$

$$\begin{aligned}
J^{\mathrm{sub}}_q(\boldsymbol{b}^2,\mu,\zeta)&=\sum_h\int_0^1 zdz\,\tilde{D}^{\mathrm{sub}}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta)\\
&=\sum_h\int_0^1 zdz\int_z^1\frac{dx}{x}\,C_{j\leftarrow q}\left(\frac{z}{x},\mu_{b_*},\zeta\right)D_{1,h/j}(x,\mu_{b_*})\,e^{-S_{\mathrm{pert}}(\mu,\mu_{b_*})}\\
&=\int_0^1\tau d\tau\,C_{j\leftarrow q}(\tau,\mu_{b_*},\zeta)\left[\sum_h\int_0^1 dx\,x\,D_{1,h/j}(x,\mu_{b_*})\right]e^{-S_{\mathrm{pert}}(\mu,\mu_{b_*})}\\
&=\int_0^1\tau d\tau\,C_{j\leftarrow q}(\tau,\mu_{b_*},\zeta)e^{-S_{\mathrm{pert}}(\mu,\mu_{b_*})},
\end{aligned}$$

TMD factorization:

$$\tilde{D}^{\rm sub}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta_f)=\tilde{D}^{\rm sub}_{1,h/q}(z,\mu_{b_*},\zeta_i)e^{-S_{\rm pert}(\mu,\mu_{b_*})-S_{\rm NP}^{D_1}(b,Q_0,\zeta_f)}\left(\sqrt{\frac{\zeta_f}{\zeta_i}}\right)^{\kappa(b,\mu_{b_*})},$$

$$\tilde{H}^{\perp\,\alpha,{\rm sub}}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta_f)=\left(-\frac{ib^\alpha}{2z}\right)\tilde{H}^{\perp,\,{\rm sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i)e^{-S_{\rm pert}(\mu,\mu_{b_*})-S_{\rm NP}^{H_1^\perp}(b,Q_0,\zeta_f)}\left(\sqrt{\frac{\zeta_f}{\zeta_i}}\right)^{\kappa(b,\mu_{b_*})},$$

Collinear matching:

$$\tilde{D}^{\rm sub}_{1,h/q}(z,\mu_{b_*},\zeta_i)=\left[C_{j\leftarrow q}\otimes D_{1,h/j}\right](z,\mu_{b_*},\zeta_i)+\mathcal{O}(\boldsymbol{b}^2\Lambda^2_{\rm QCD}),$$

$$\tilde{H}^{\perp,\,{\rm sub}}_{1,h/q}(z,\mu_{b_*},\zeta_i)=\left[\delta C^{\rm Collins}_{j\leftarrow q}\otimes\hat{H}^{\perp(3)}_{1,h/j}+A_{j\leftarrow q}\tilde{\otimes}\hat{H}_{F,h/j}\right](z,\mu_{b_*},\zeta_i)+\mathcal{O}(\boldsymbol{b}^2\Lambda^2_{\rm QCD}),$$

Sum rule:

$$\sum_h\int_0^1 dz\,z\,D_{1,h/j}(z,\mu)=1\,,$$

$$\sum_h\int_0^1 dz\,\hat{H}^{\perp(3)}_{1,h/q}(z,\mu)=0\,.$$

$$\left(-\frac{i\boldsymbol{b}^\alpha}{2}\right)J_q^{\perp{\rm sub}}(\boldsymbol{b}^2,\mu,\zeta)=\sum_h\int_0^1 dz z\tilde{H}^{\perp\,\alpha,{\rm sub}}_{1,h/q}(z,\boldsymbol{b}^2,\mu,\zeta)$$

$$=\left(-\frac{i\boldsymbol{b}^\alpha}{2}\right)\sum_h\int_0^1 dz\int_z^1\frac{dx}{x}\,\delta C^{\rm Collins}_{q\leftarrow q}\left(\frac{z}{x},\mu_{b_*},\zeta\right)\hat{H}^{\perp(3)}_{1,h/q}(x,\mu_{b_*})\,e^{-S_{\rm pert}(\mu,\mu_{b_*})}$$

$$=\left(-\frac{i\boldsymbol{b}^\alpha}{2}\right)\int_0^1 d\tau\delta C^{\rm Collins}_{q\leftarrow q}(\tau,\mu_{b_*},\zeta)\left[\sum_h\int_0^1 dx\,\hat{H}^{\perp(3)}_{1,h/q}(x,\mu_{b_*})\right]e^{-S_{\rm pert}(\mu,\mu_{b_*})}$$

$$=0\,,$$