Collins-type Energy-Energy Correlators and Nucleon Structures

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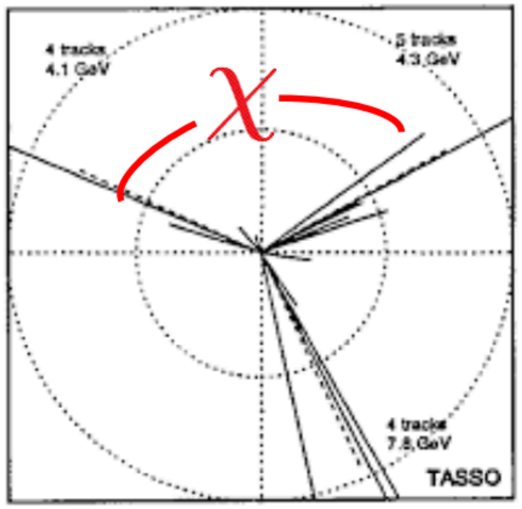
In collaboration with: Kang, Lee, Shao

Thanks to the support from UCOP MRPI grant !

Jan 28, 2023

Introduction

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



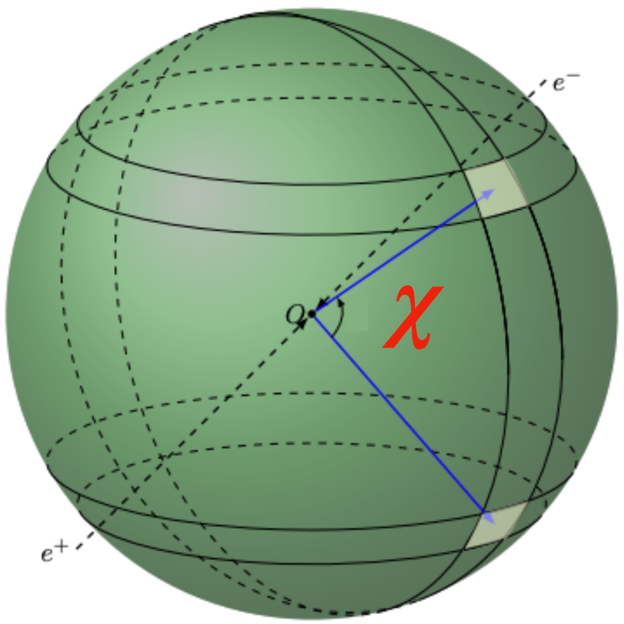
- Energy-Energy Correlators (EEC): measures the correlations of energy deposition in two detectors with opening angle χ

  (one of the first infrared safe event-shapes defined in QCD)

- In e^+e^- annihilation:

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

Basham, Brown, Ellis, Love `78 `79



Moult, Zhu `18

Introduction

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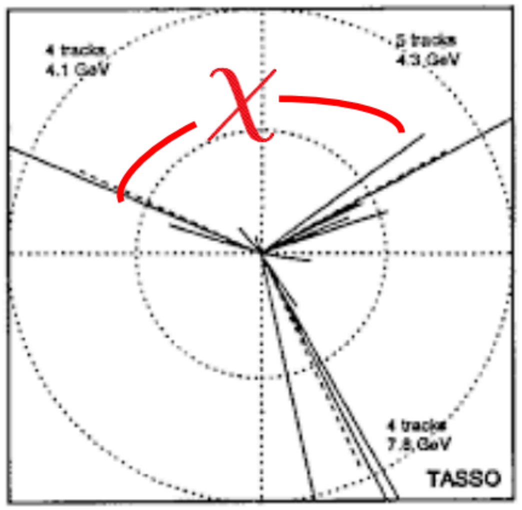

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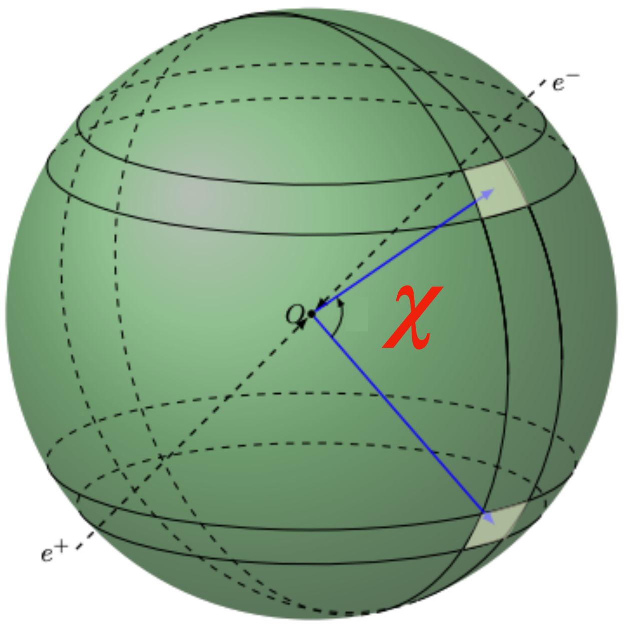
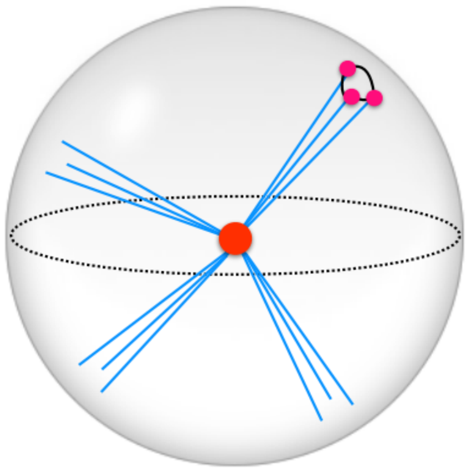


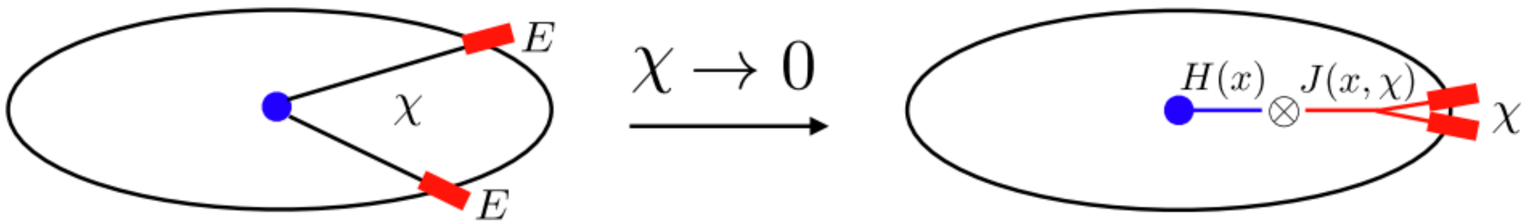
Moult, Zhu `18



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



Introduction

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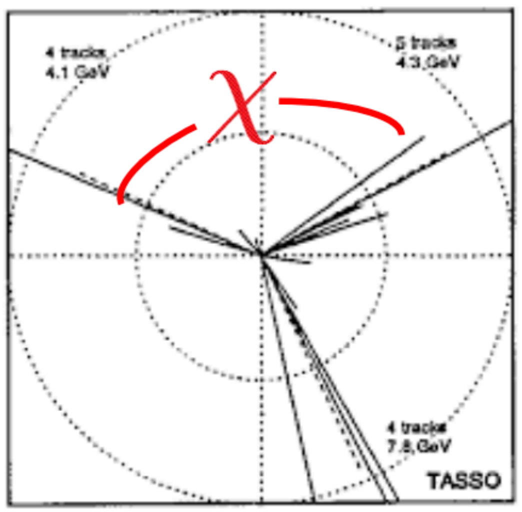

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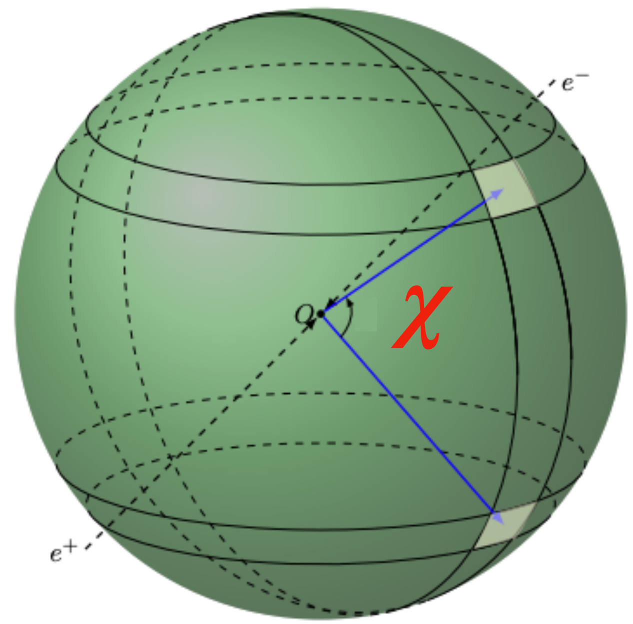
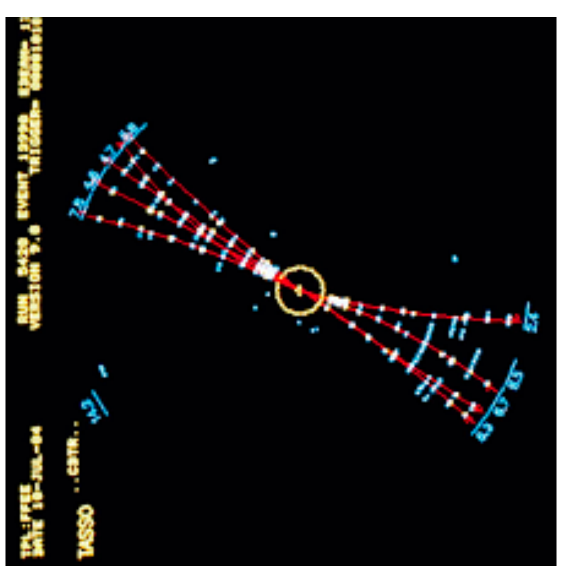


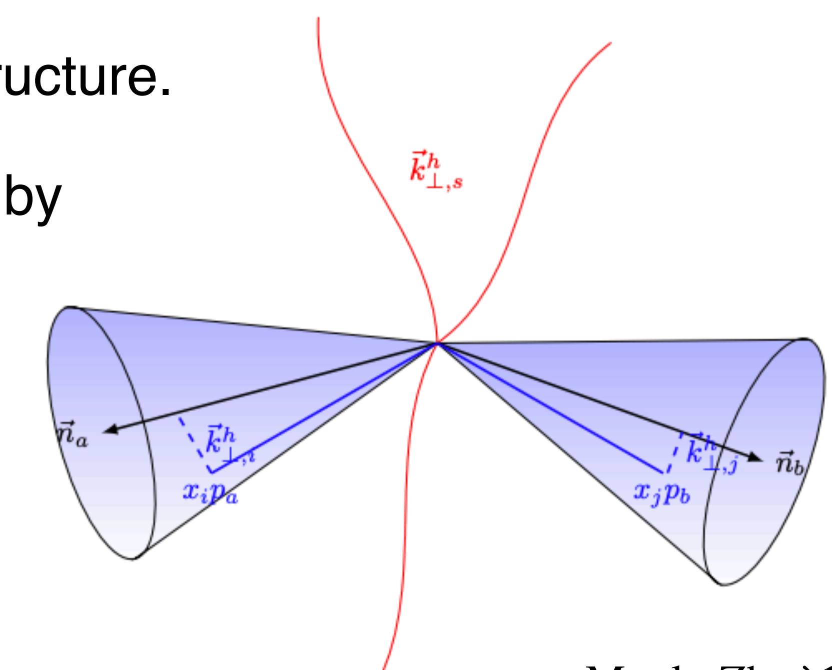
Moult, Zhu `18

$\chi \to \pi$



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

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

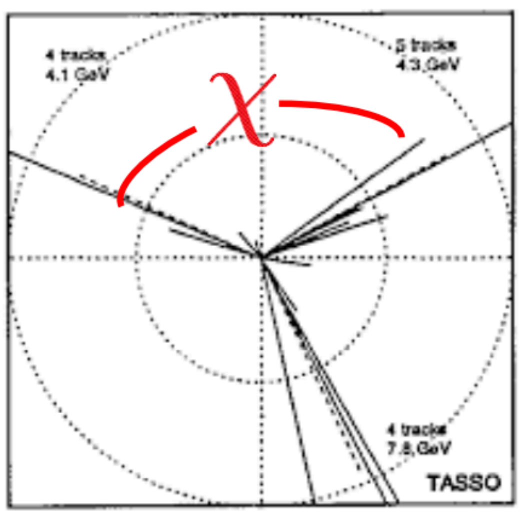


Moult, Zhu `18

EEC at the back-to-back limit

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

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



$$\tau \in [0,1]$$

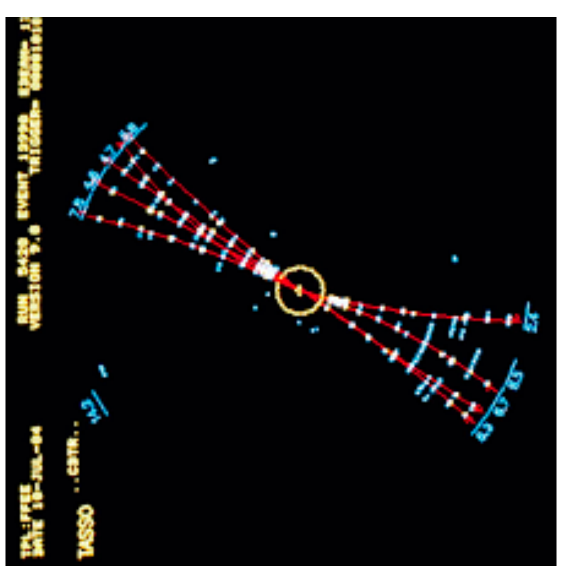
$$\frac{d\Sigma_{e^+e^-}}{d\cos\chi} = \sum_{i,j} \int d\sigma \frac{E_i E_j}{Q^2} \delta\left(\cos\theta_{ij} - \cos\chi\right)$$

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

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

Definition

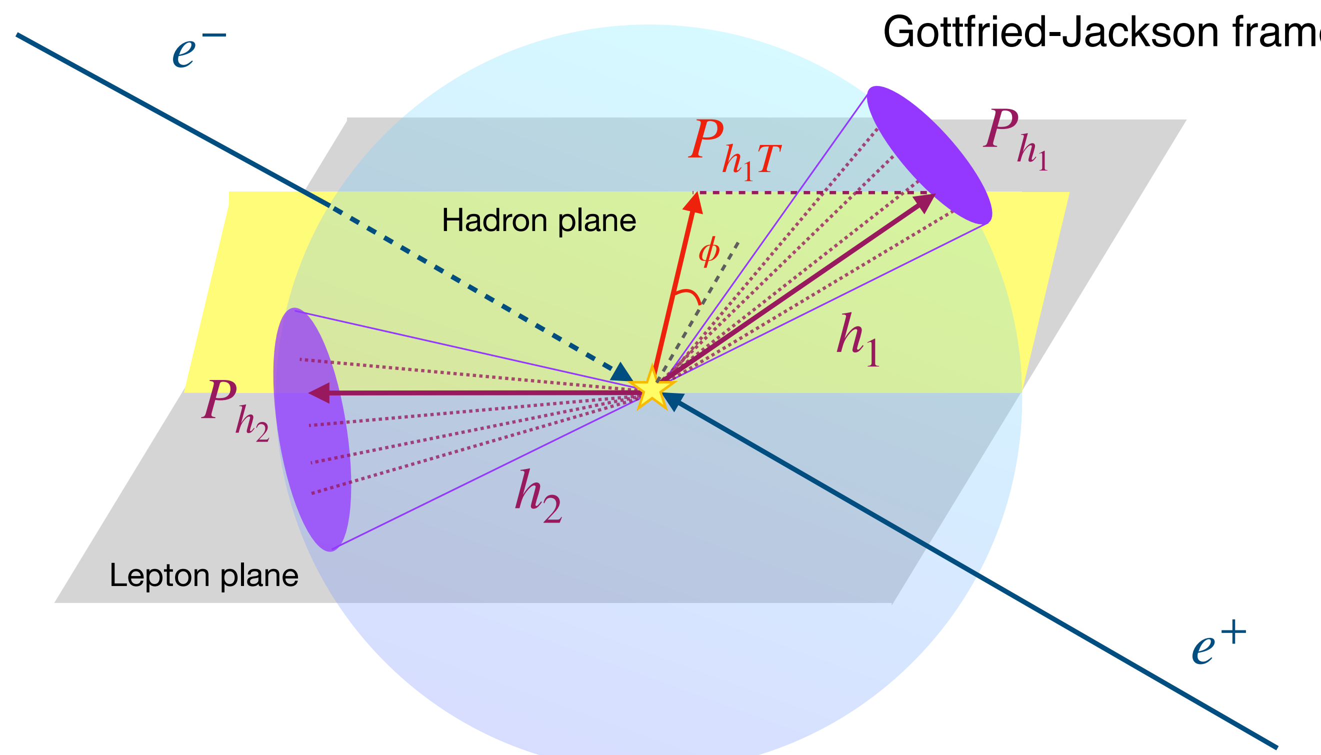
$$\chi \to \pi$$

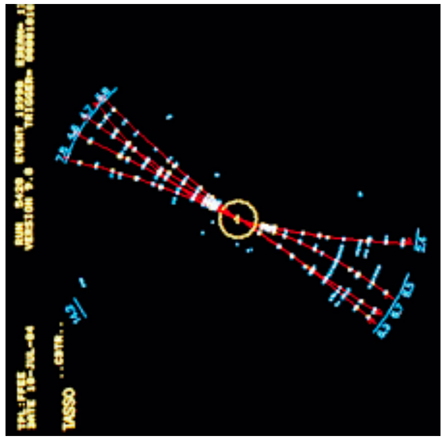


$$\tau \to 0$$

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

$$\boldsymbol{q}_T = -\frac{\boldsymbol{P}_{h_1T}}{z_1}$$

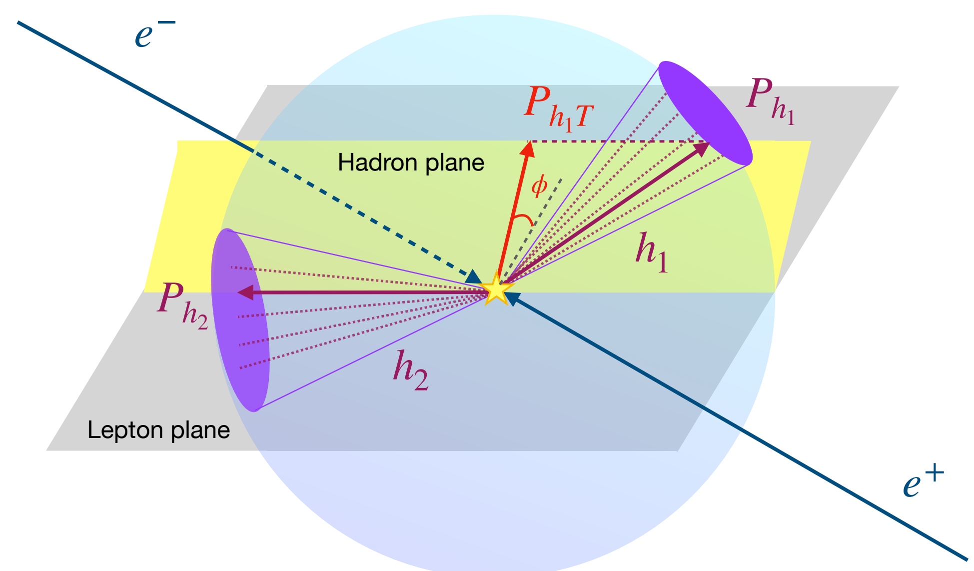




EEC at the back-to-back limit

Gottfried-Jackson frame

e^+e^-



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

- Related to the TMD observables.
- Unpolarized processes in both e^+e^- and ep collisions have been studied and observed.

Definition:

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

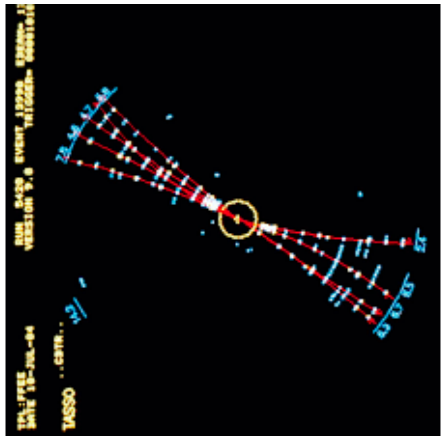
Factorization:

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

Moult, Zhu `18

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

z-weighted sum over hadrons produced in the final states



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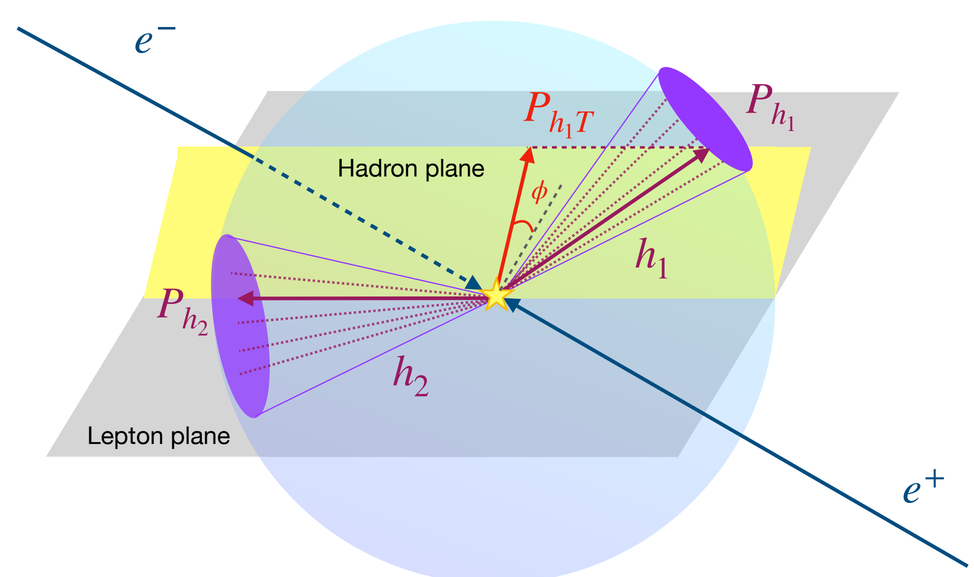


In the back-to-back limit ($\chi \to \pi,\ \tau \to 0$):

- Related to the TMD observables.
- Unpolarized processes in both e^+e^- and ep collisions have been studied and observed.

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

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

$$\boxed{+\frac{b^2}{8}\cos 2\phi J_2(bq_T)\ J_q^\perp(\boldsymbol{b},\mu,\zeta/\nu^2)J_{\bar q}^\perp(\boldsymbol{b},\mu,\zeta/\nu^2)S(\boldsymbol{b}^2,\mu,\nu)\Big]}\ ,$$

Moult, Zhu `18

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

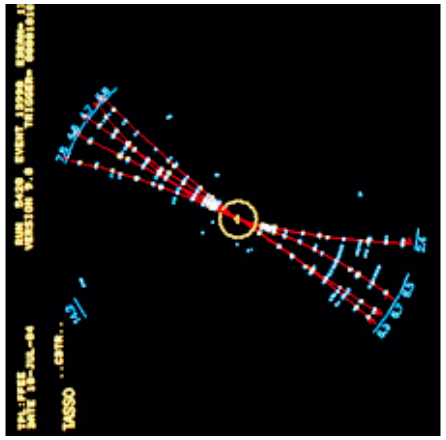
z-weighted sum over hadrons produced in the final states

Kang, Lee, Shao, FZ (arXiv: 2301.xxxx)

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

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

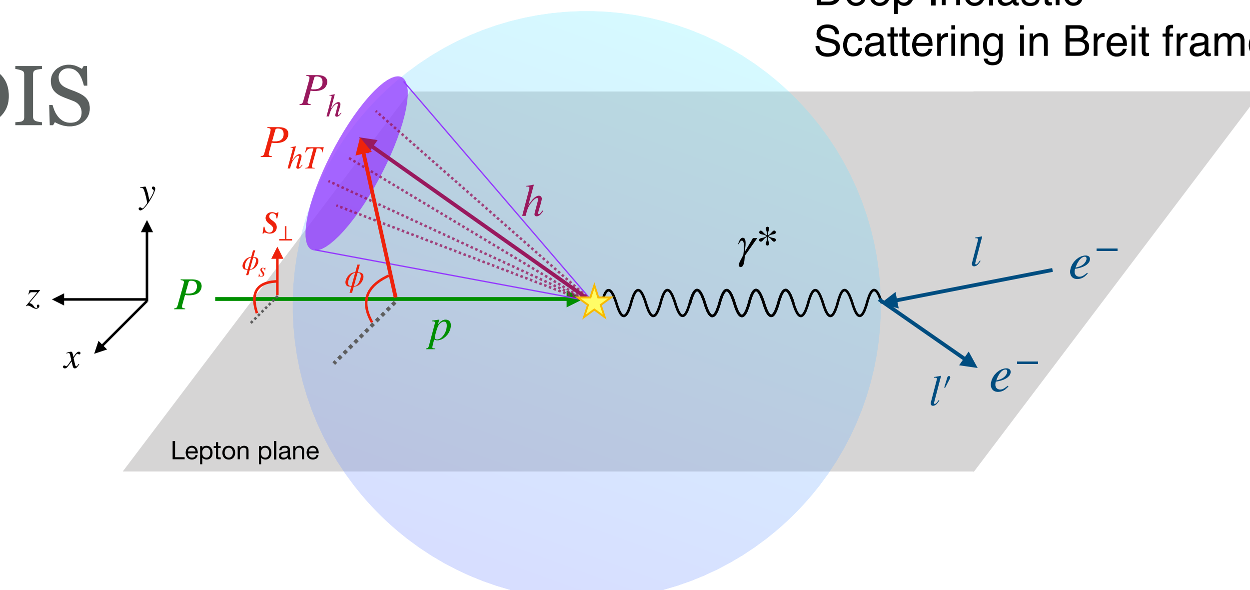
Collins-type



EEC at the back-to-back limit

SIDIS

Deep Inelastic Scattering in Breit frame



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

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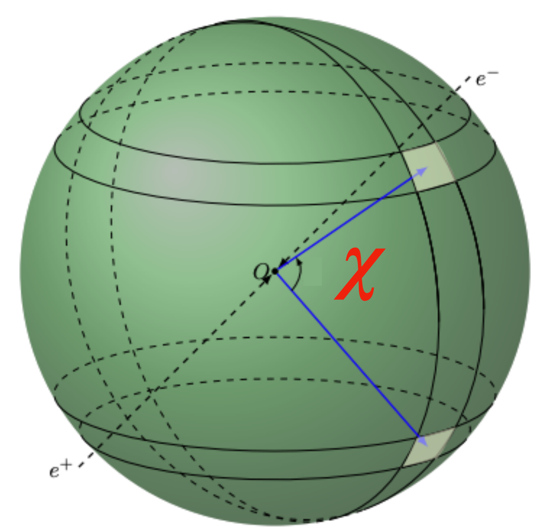
Li, Vitev, Zhu `20
Li, Marks, Vitev `21

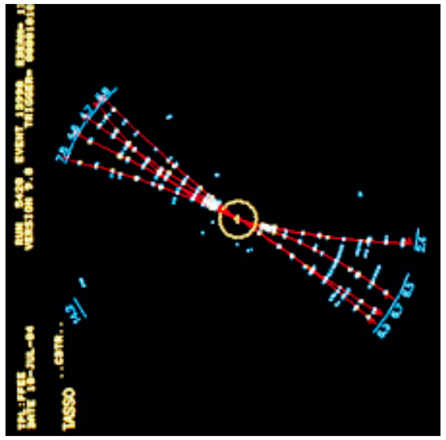
Definition:

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

e^+e^-



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



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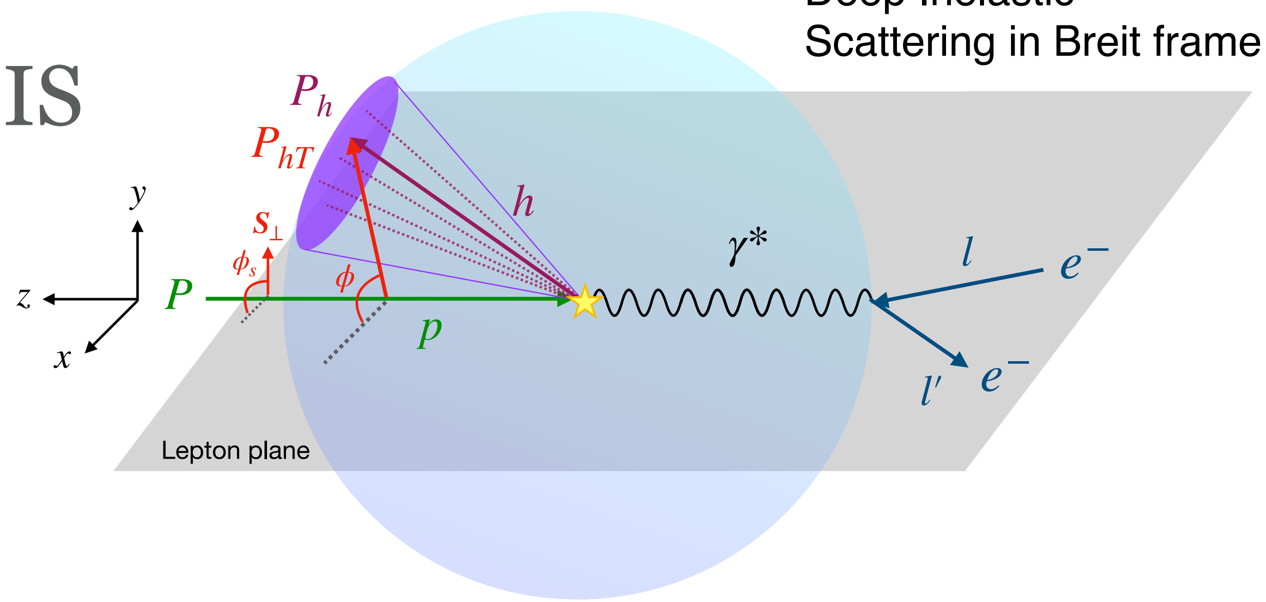

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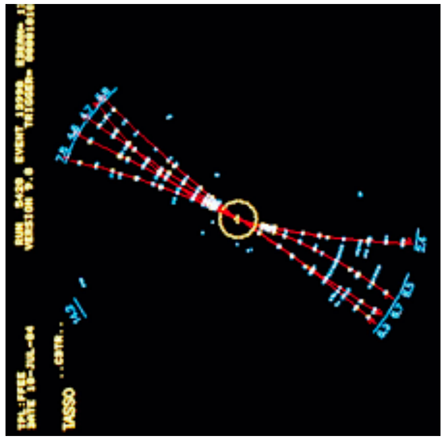
New Definition:

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

Kang, Lee, Shao, FZ
(arXiv: 2301.xxxx)

Collins-type



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Deep Inelastic
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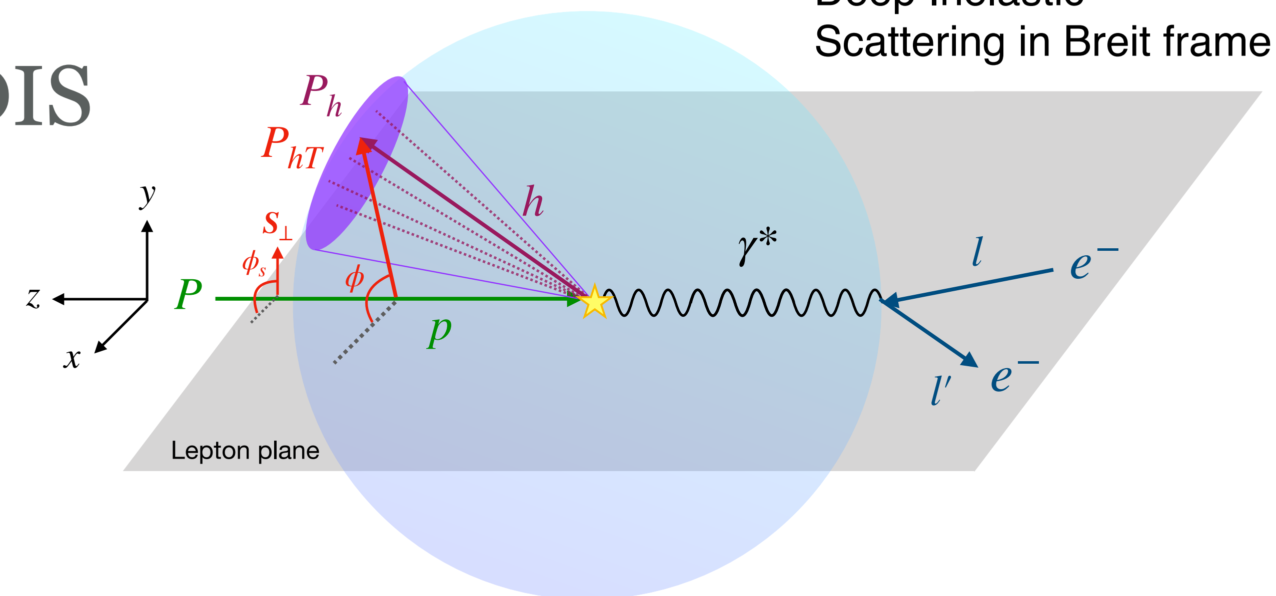

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Li, Marks, Vitev \`21

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

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

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

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

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

Factorization:

Incoming p pol.

Incoming e^- pol.

Kang, Lee, Shao, FZ
(arXiv: 2301.xxxx)

Collins-type

New probe for all TMDPDFs

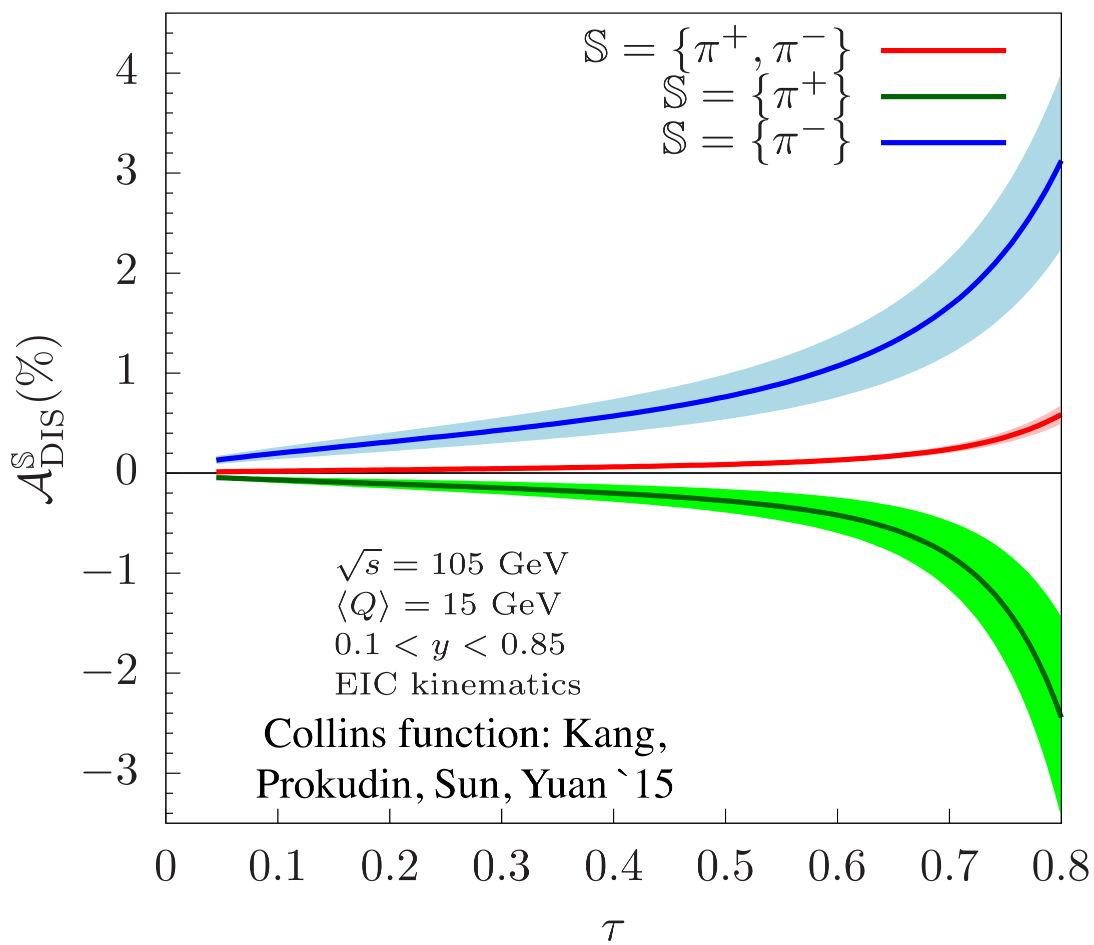
Phenomenology I: Collins asymmetry

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

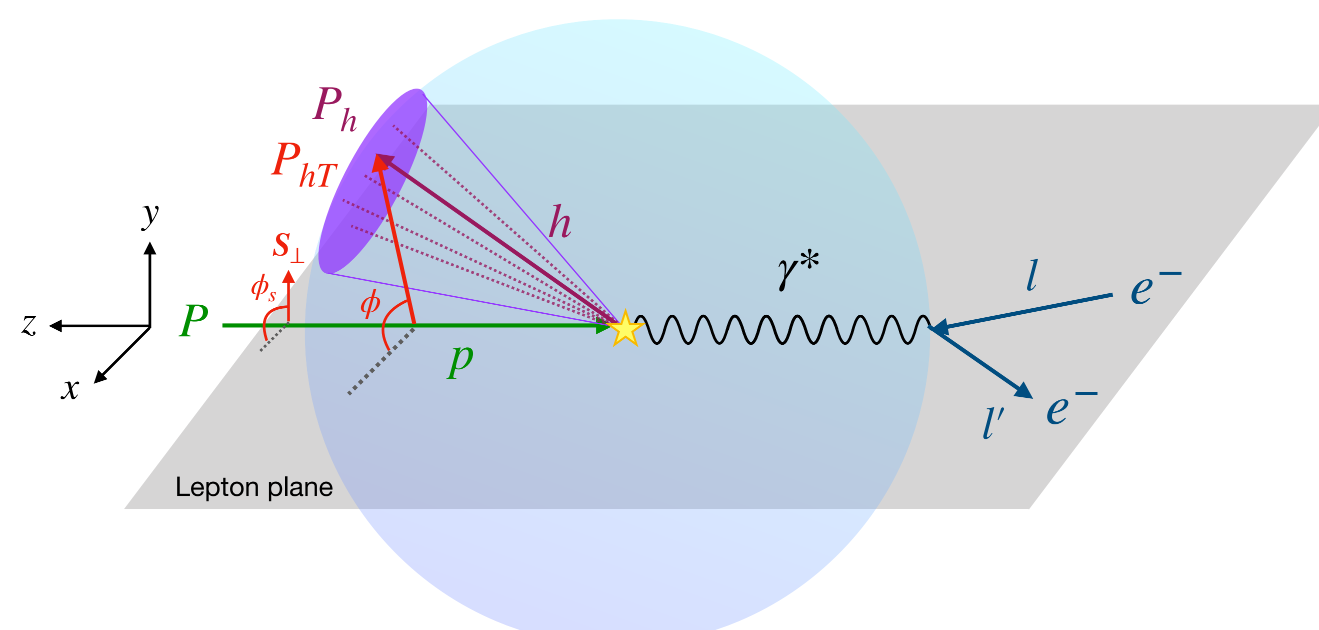
$$\mathcal{F}_{UT}^{\sin(\phi_{q_T}+\phi_s)} \sim h_1 \otimes J_q^{\perp}$$

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

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



Prediction for Collins asymmetry at EIC kinematics



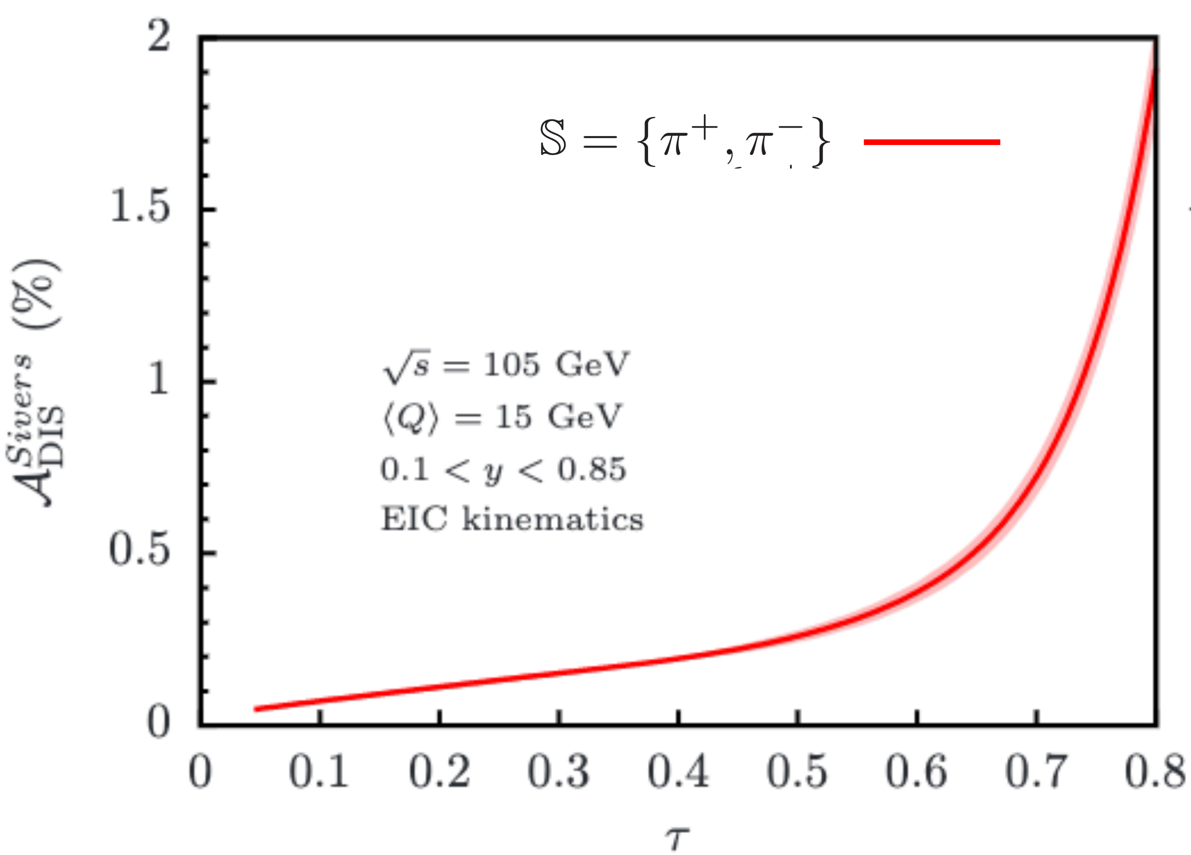
Phenomenology II: Sivers asymmetry

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

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

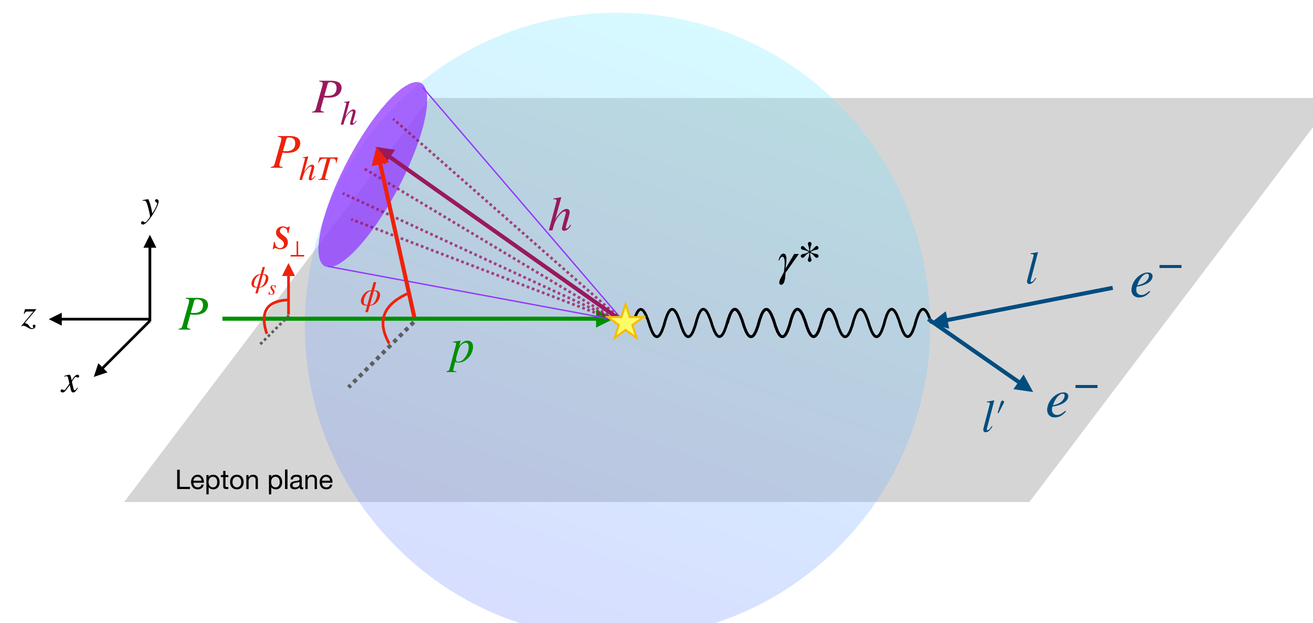
$$\mathcal{F}_{UU} \sim f_1 \otimes J_q$$

Sivers function: Echevarria, Kang, Terry `20



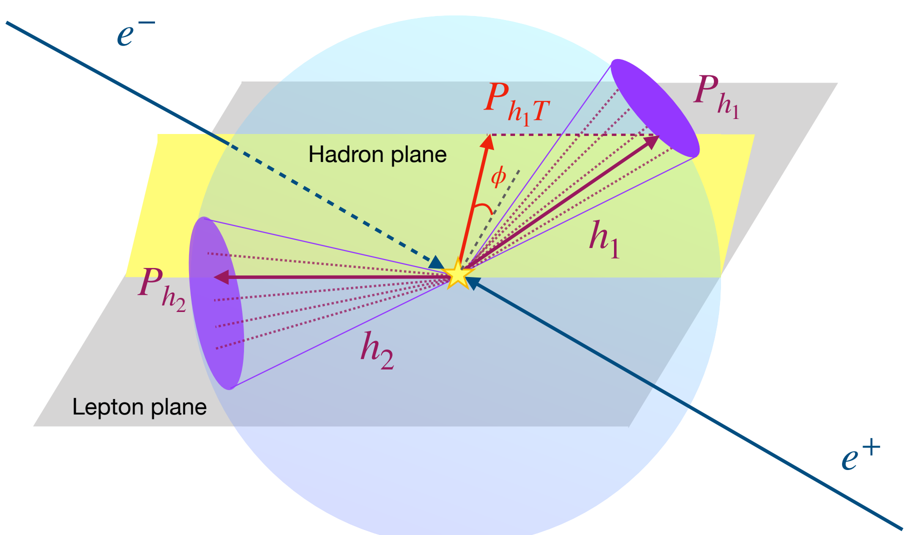
Prediction for Sivers asymmetry at EIC kinematics

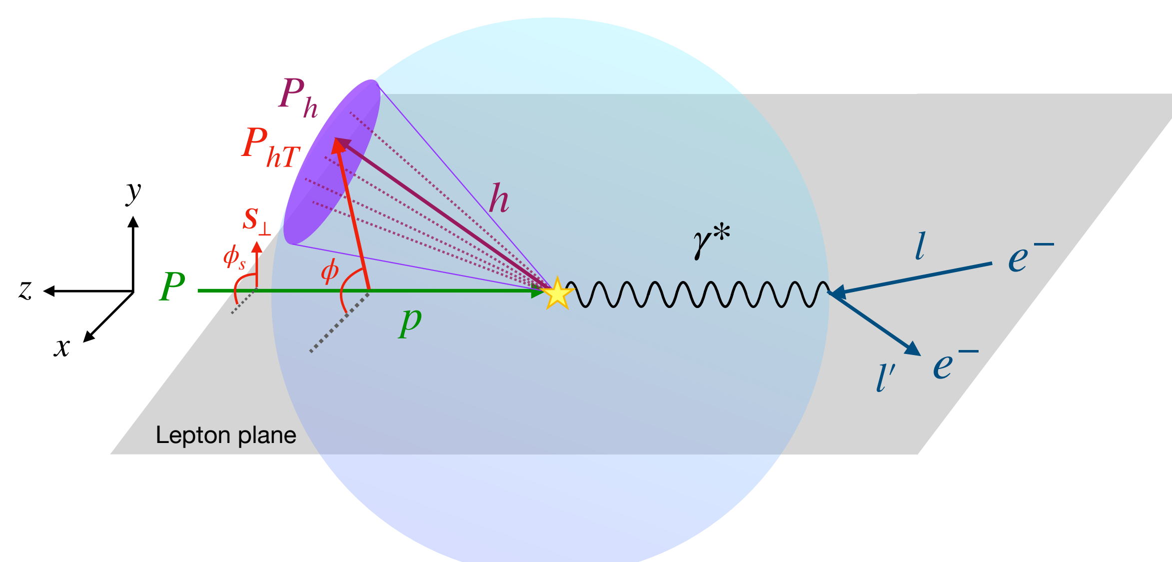
$$\begin{aligned}
\frac{d\Sigma_{\rm DIS}}{dx\,dy\,d\tau\,d\phi} = {} & \frac{2\pi\alpha_{\rm em}^2}{Q^2}\frac{1+(1-y)^2}{y}\int d^2\boldsymbol{q}_T\,\delta\Big(\tau-\frac{\boldsymbol{q}_T^2}{Q^2}\Big)\int\frac{db\,b}{2\pi}\Big\{\boxed{\mathcal{F}_{UU}} \\
& + \cos(2\phi_{q_T})\frac{2(1-y)}{1+(1-y)^2}\mathcal{F}_{UU}^{\cos(2\phi_{q_T})}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

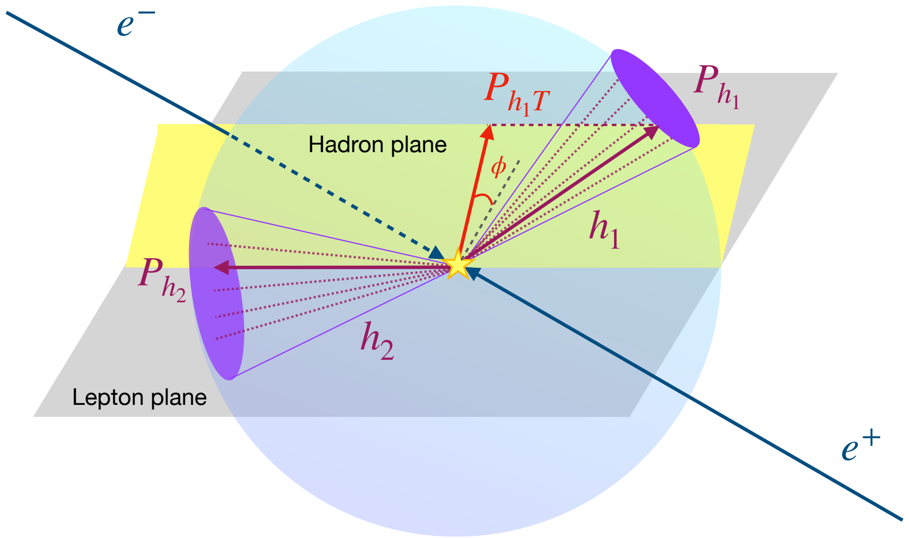


Summary

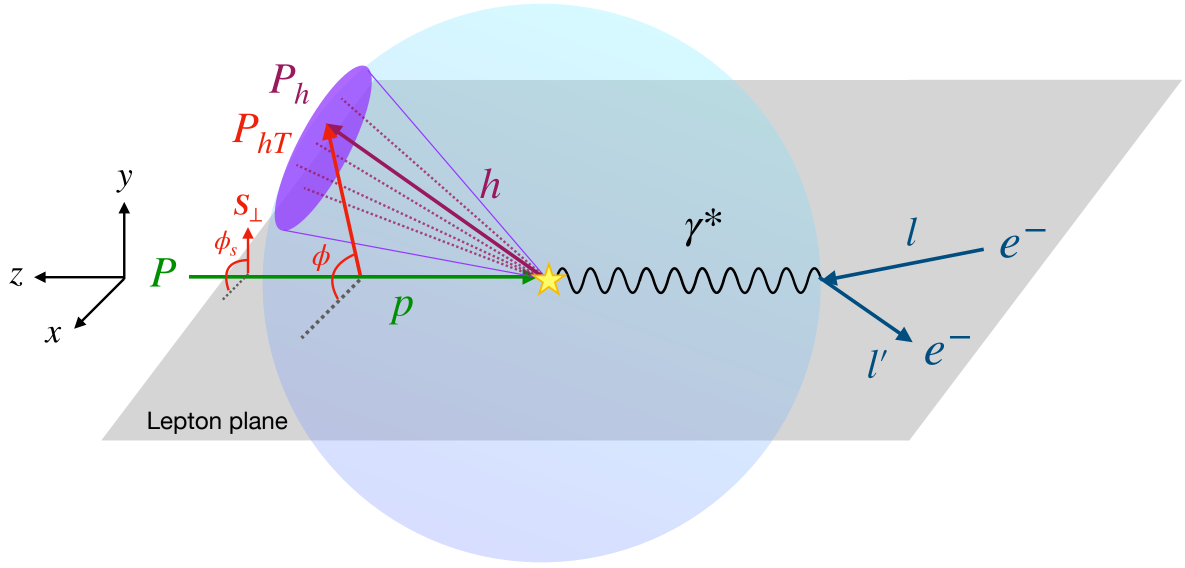
- EEC in the early literatures: handles only the unpolarized scattering (e^+e^- annihilation and ep collisions).
- By generalizing the EEC with azimuthal angle dependence, one gets access to spin-dependent effects (polarized incoming p).
- We introduce a Collins-type EEC jet function $\Rightarrow$ all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






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
$S_\perp$
ϕ_s
ϕ
γ^*
l
e^-
z
P
p
x
l'
e^-
Lepton plane

e^+e^-

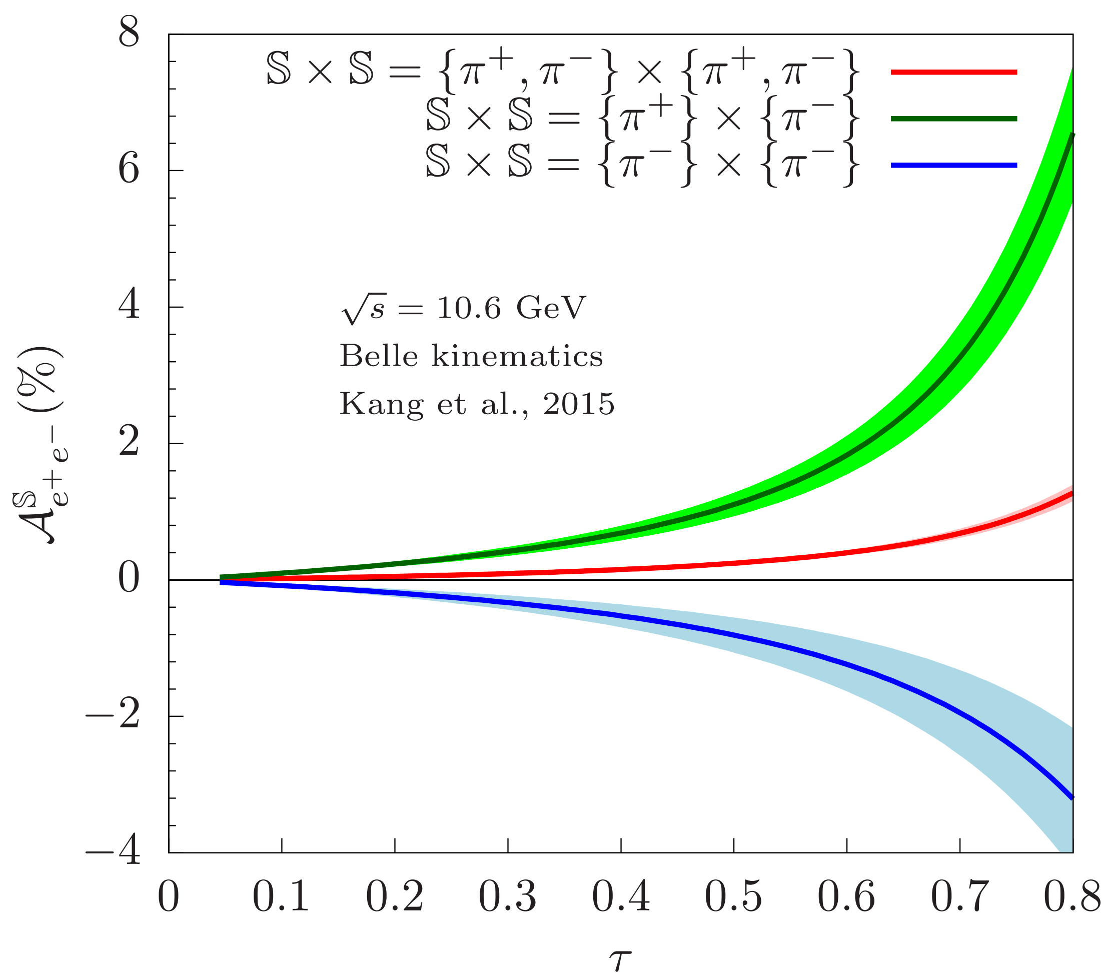
EEC at the back-to-back limit

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

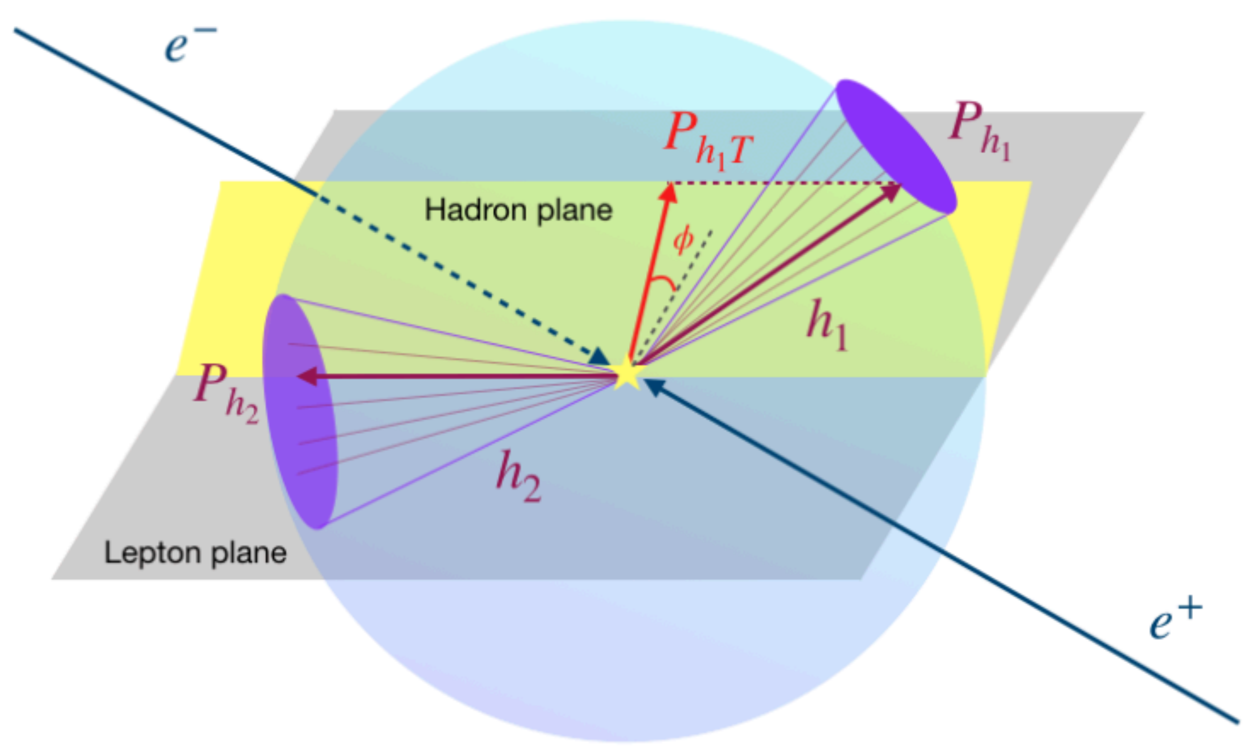
$$= \frac{1}{2}\sum_{i,j}\int d\theta_{ij}dz_i dz_j z_i z_j \frac{1}{\sigma}\frac{d\sigma}{d\theta_{ij}d\phi_{ij}dz_i dz_j}\delta\left(\tau - \left(\frac{1+\cos\theta_{ij}}{2}\right)\right)\delta(\phi-\phi_{ij}),$$

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

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



Prediction for Collins asymmetry at Belle kinematics



Gottfried-Jackson frame