Spin asymmetries in jet production at the EIC

(two examples)

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Outline:

- A_{LL} in $\ell p \to \mathrm{jet}\, X$ at the EIC

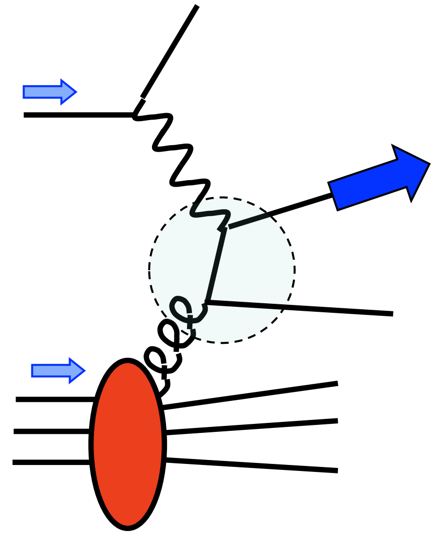
  P. Hinderer, M. Schlegel, WV

- T-odd single-helicity observable at the EIC

  M. Abele, M. Aicher,
  F. Piacenza, A. Schäfer, WV

Introduction

- A_{LL} in high-p_T production at the EIC:



- probe of helicity PDFs:

$$\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx\, \Delta f(x,\mu)\, \Delta\hat{\sigma}^{ef\to \mathrm{jet}+X}(xP, \alpha_s(\mu), \ldots)$$

- NLO known for:

$\vec{e}\,\vec{p} \to e + \mathrm{jet} + X$ — Mirkes et al.

$\vec{\gamma}\,\vec{p} \to \mathrm{jet} + X$ — Jäger; Frixione, de Florian

$\vec{e}\,\vec{p} \to \mathrm{jet} + X$ — Hinderer,Schlegel,WV; Boughezal,Petriello,Xing

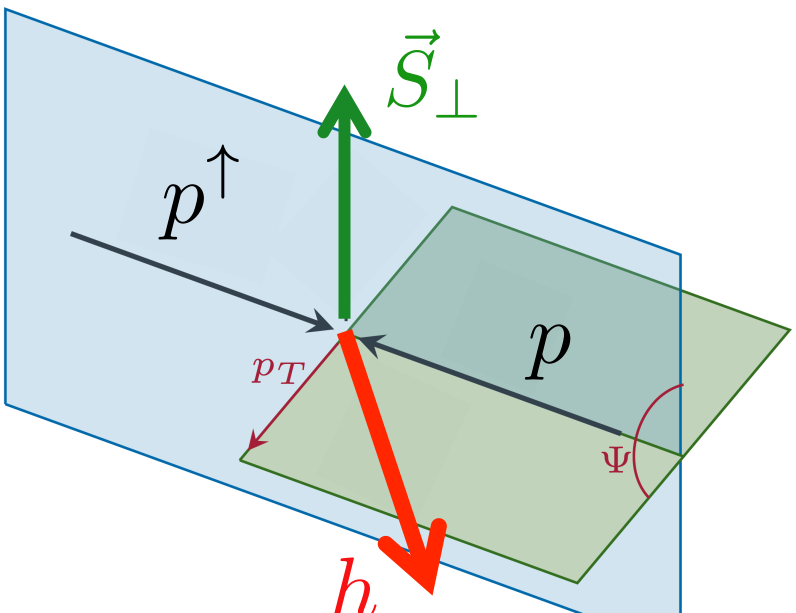
A_{LL} in $\ell p \to \mathrm{jet}\, X$ at the EIC

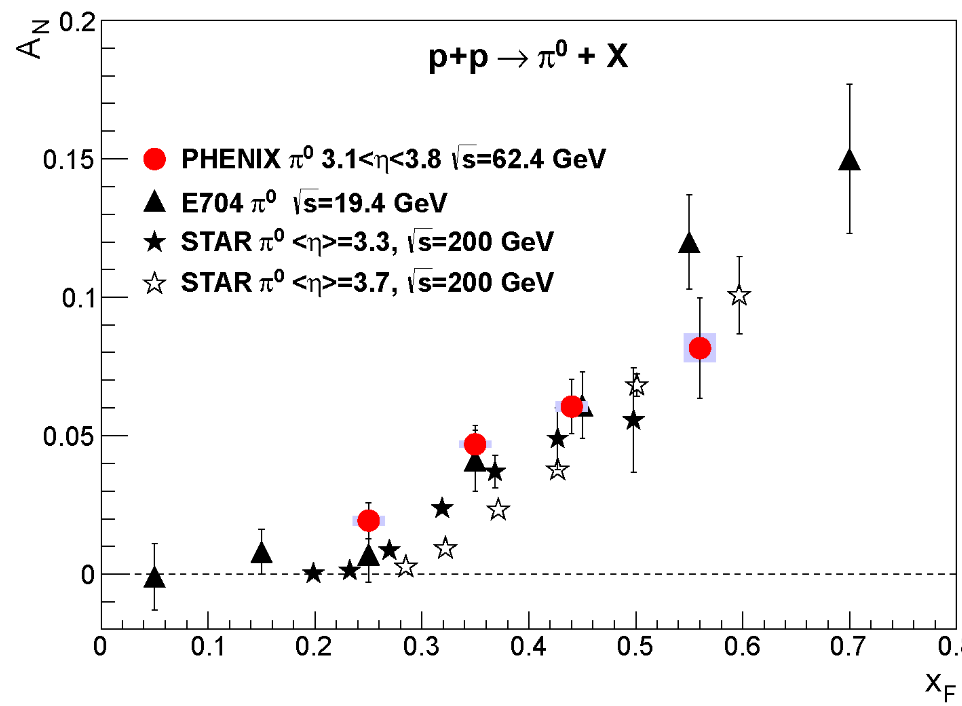
Single-inclusive scattering: $\ell p \rightarrow \text{jet}\, X$

$$\ell p \rightarrow h\, X$$

Why care?

Large single-spin asymmetries in $p^{\uparrow} p \rightarrow h\, X$





$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- A_N in $p^\uparrow p \to h\, X$ power-suppressed in QCD
  - ★ a plethora of contributions, even at LO
  - ★ all studies LO so far, no proper evolution
- process $p^\uparrow \ell \to \text{jet}\, X$:

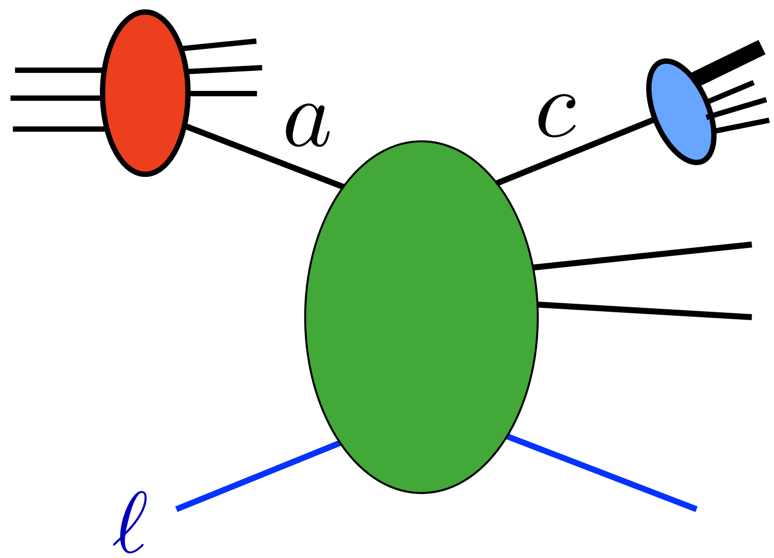
Anselmino, Boglione, Hansson, Murgia '99; … Koike '00, '02

  - ★ can choose same kinematics as for $p^\uparrow p$
  - ★ simpler -- fewer subprocesses, contributions
  - ★ may serve as testbed for theoretical calculations

especially: higher-order QCD corrections,
and process interesting by its own right

NLO for $\ell p \to hX$

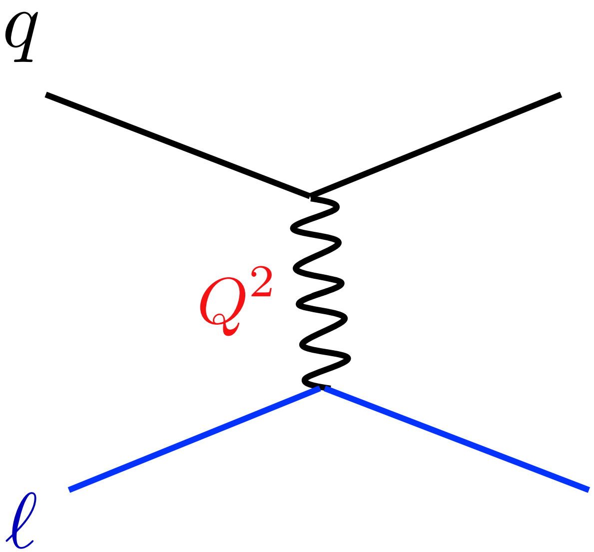
Hinderer, Schlegel, WV



$$\frac{E_h d^3\sigma^{p\ell\to hX}}{d^3P_h} = \frac{1}{\pi S}\sum_{a,c}\int\frac{dx}{x}\int\frac{dz}{z^2}\, f_a(x,\mu)\, D_c^h(z,\mu)\,\frac{d^2\hat{\sigma}^{a\ell\to cX}}{v\,dvdw}$$

$$v = 1+\frac{t}{s} \qquad w = -\frac{u}{t+s}$$

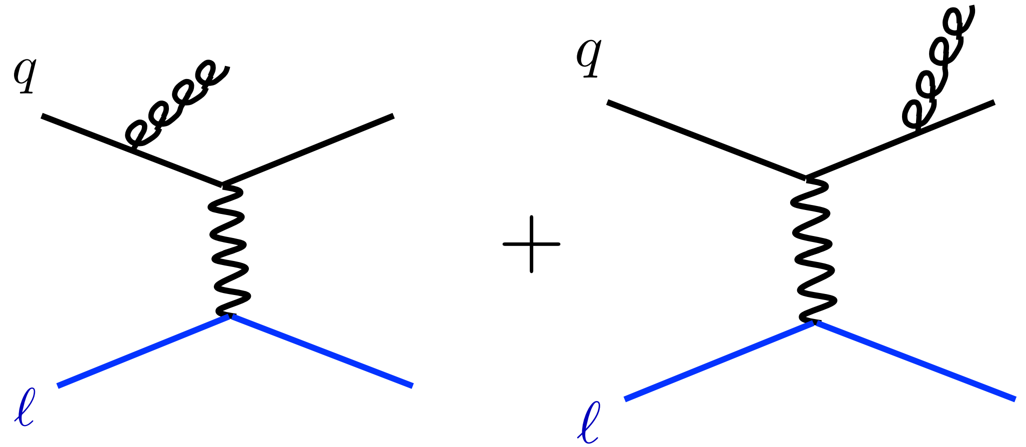
LO:

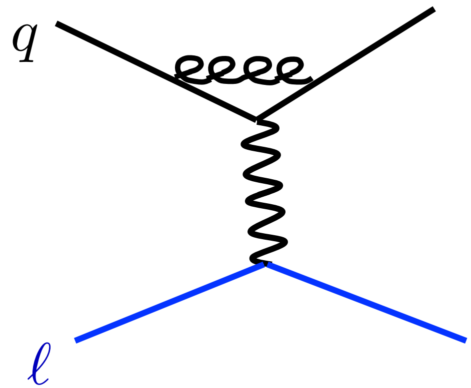


- always at large Q^2

$$\frac{d^2\hat{\sigma}_{\mathrm{LO}}^{q\ell\to q\ell}}{v\,dvdw} \propto \alpha_{\mathrm{em}}^2\,\delta(1-w)\;\frac{1+v^2}{(1-v)^2}$$

NLO:

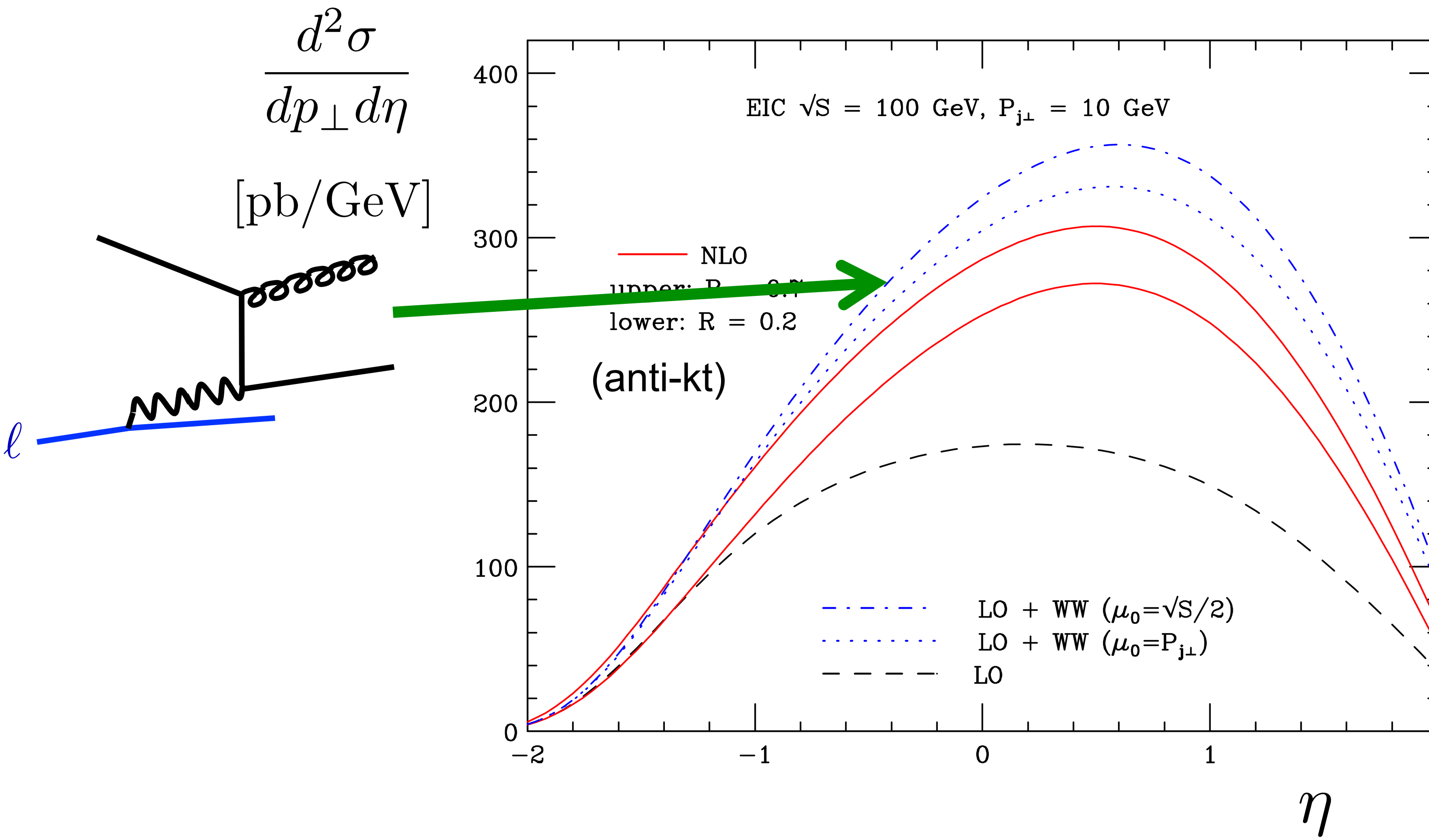




(interfering with Born)

$$\frac{d\hat{\sigma}^{q\to q}_{\rm NLO}}{v\,dvdw} \propto \alpha_{\rm em}^2\,\alpha_s \Bigg[A_0^{q\to q}(v)\,\delta(1-w) + A_1^{q\to q}(v) \left(\frac{\ln(1-w)}{1-w}\right)_+ + \frac{1}{(1-w)_+} A_2^{q\to q}(v) + R(v,w) \Bigg]$$

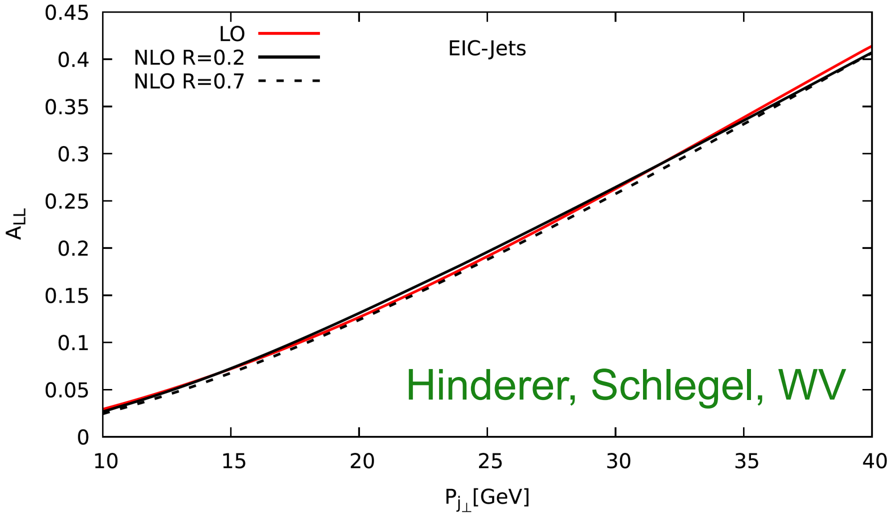
$ep \to \mathrm{jet}\,X$ EIC



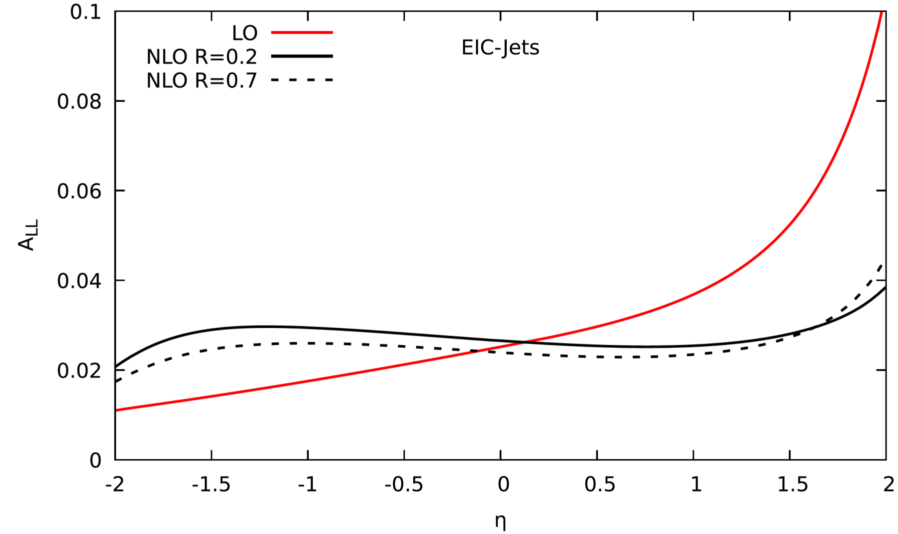
NB: NNLO available now!

Abelof, Boughezal, Liu, Petriello

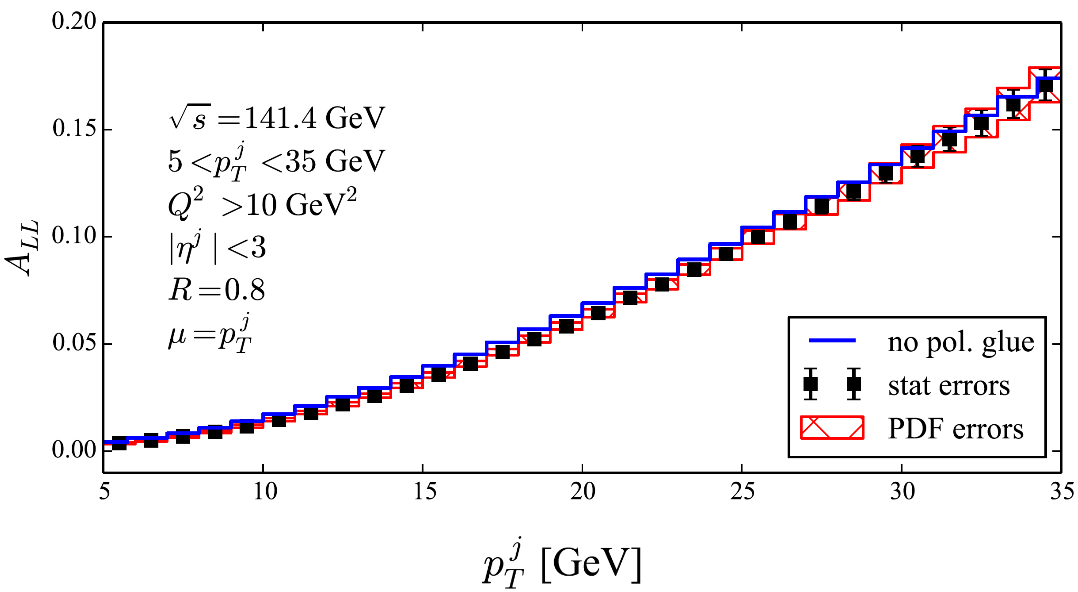
$\sqrt{s} = 100$ GeV $|\eta_J| \leq 2$

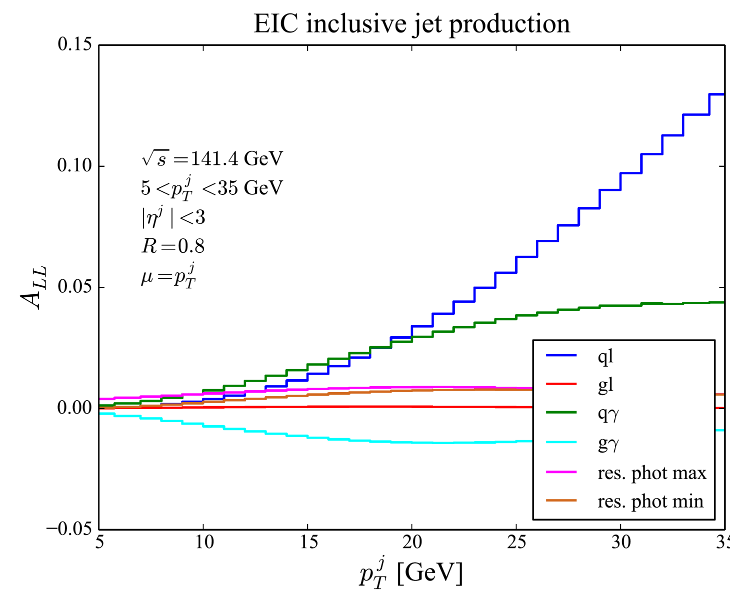


$p_{T,J} = 10\,\mathrm{GeV}$



$\sqrt{s} = 141$ GeV Boughezal,Petriello,Xing

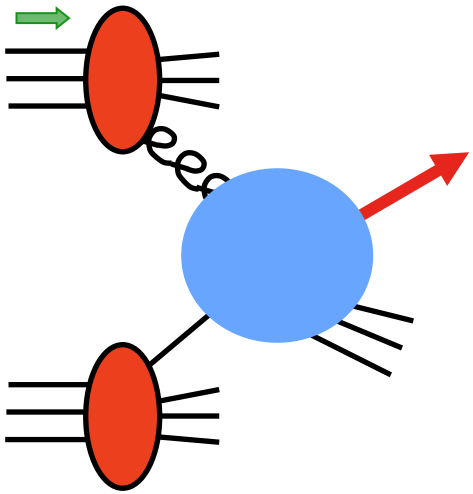




Single-helicity observable at EIC

M. Abele, M. Aicher,
F. Piacenza, A. Schäfer, WV

- A_L for single-inclusive process:



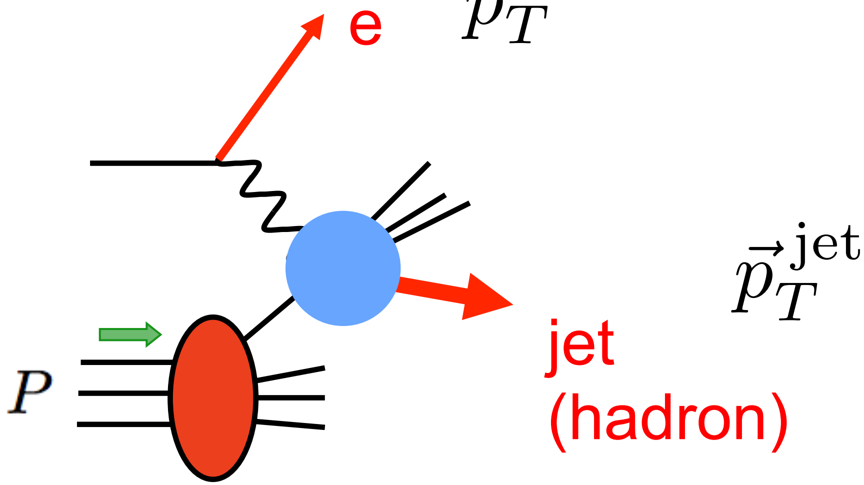
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$A_L \neq 0$ requires parity violation

(only $\vec{p}_T \cdot \vec{S}_L$ available)

- (key to RHIC W boson physics)

- however:



P even

"T-odd"

$$A_L \sim \vec{S}_L \cdot \left(\vec{p}_T^{\,e^-} \times \vec{p}_T^{\,\rm jet}\right) \sim \sin\phi$$

and $$A_L \sim \vec{S}_L \cdot (\vec{p}_T^{\,e^-} \times \vec{p}_T^{\,\rm jet}) \, (\vec{p}_T^{\,e^-} \cdot \vec{p}_T^{\,\rm jet}) \sim \sin\phi \, \cos\phi$$

$$= \frac{1}{2} \sin(2\phi)$$

$$A_L = \mathcal{A} \sin\phi + \mathcal{B} \sin(2\phi)$$

Hagiwara, Hikasa, Kai

cf. Sivers effect

$$\langle\, f \,|\, \hat{T} \,|\, i \,\rangle \;=\; \mathcal{M}_{fi}\,(2\pi)^4\,\delta^4(P_f - P_i)$$

- states $|i\rangle, |f\rangle$ with reversed momenta and spins: $|\tilde{i}\rangle, |\tilde{f}\rangle$

- T invariance: $$|\mathcal{M}_{fi}|^2 \;=\; |\mathcal{M}_{\tilde{i}\tilde{f}}|^2$$

- "T odd": $$|\mathcal{M}_{fi}|^2 \,-\, |\mathcal{M}_{\tilde{f}\tilde{i}}|^2$$

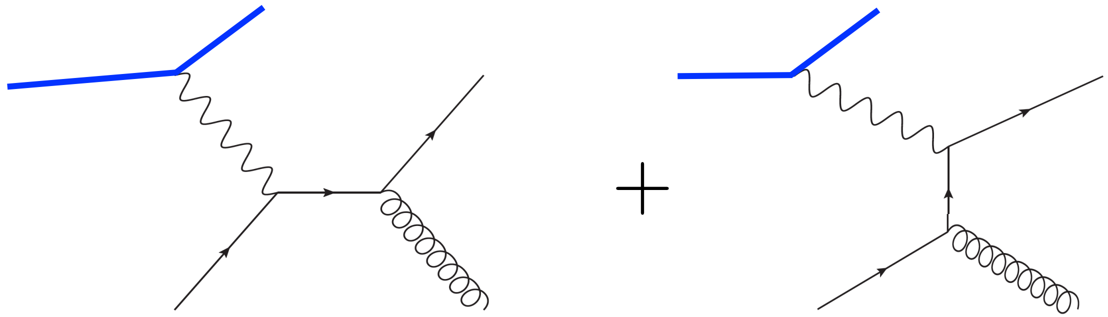
$$=\; -2\,\mathrm{Im}\Big(\mathcal{M}^*_{fi}\,\alpha_{fi}\Big) - |\alpha_{fi}|^2$$

where

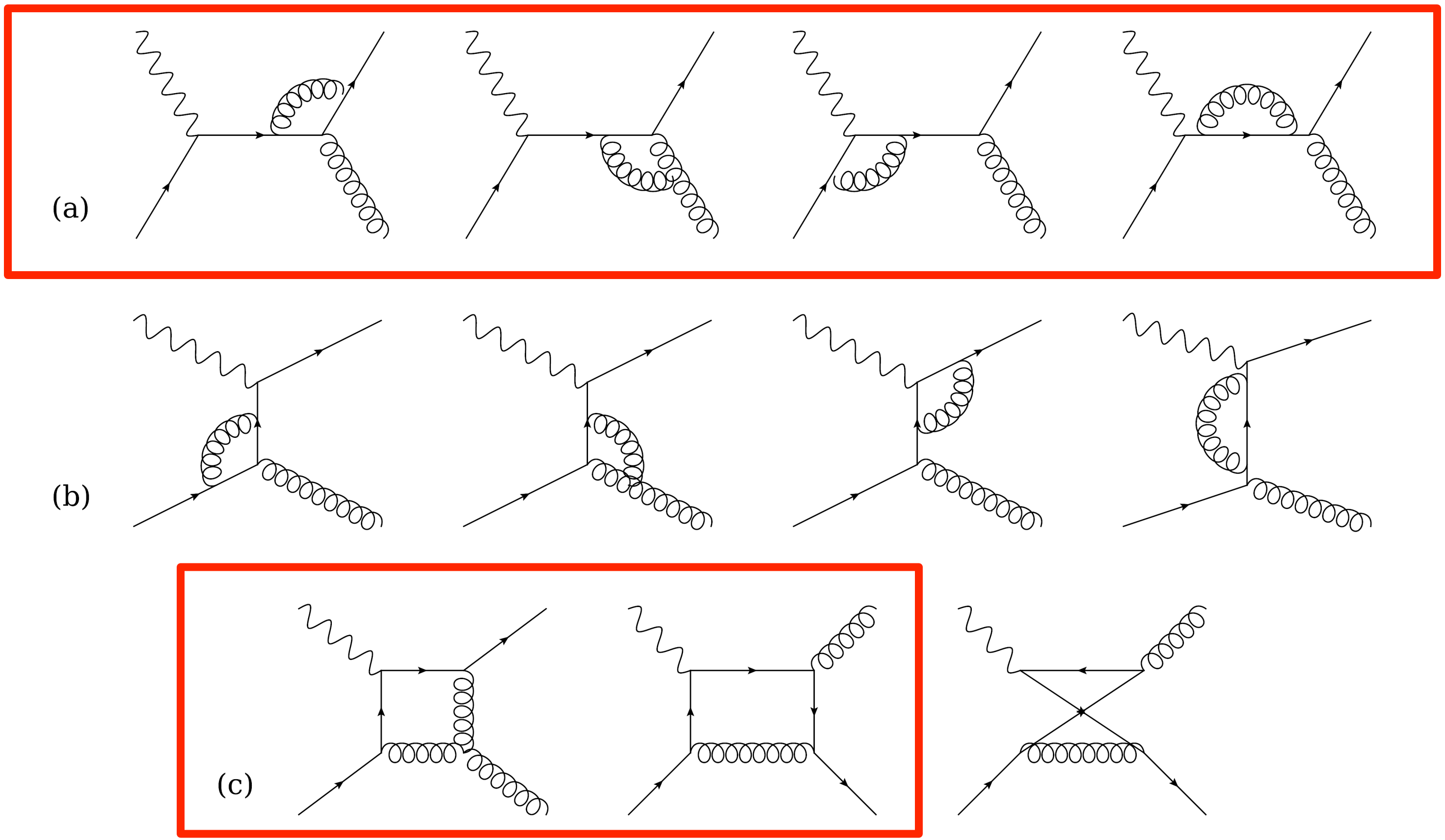
$$i\alpha_{fi} \;\equiv\; \mathcal{M}_{fi} - \mathcal{M}^*_{if} \;=\; i\sum_X \mathcal{M}^*_{Xf}\,\mathcal{M}_{Xi}\,(2\pi)^4\,\delta^4(P_X - P_i)$$

- → interference of Born with 1-loop diagrams. Born real.

- Born diagrams for $ep \to ehX$:



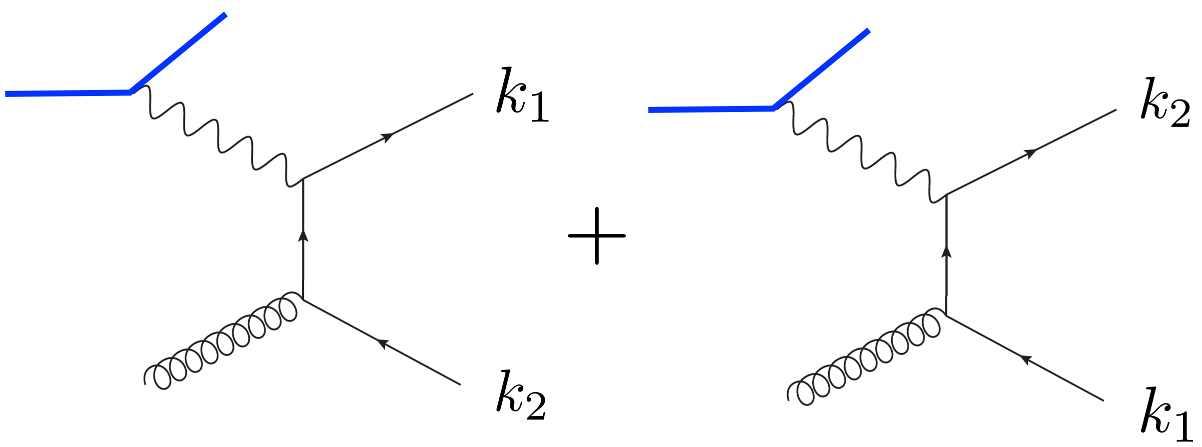
- 1-loop



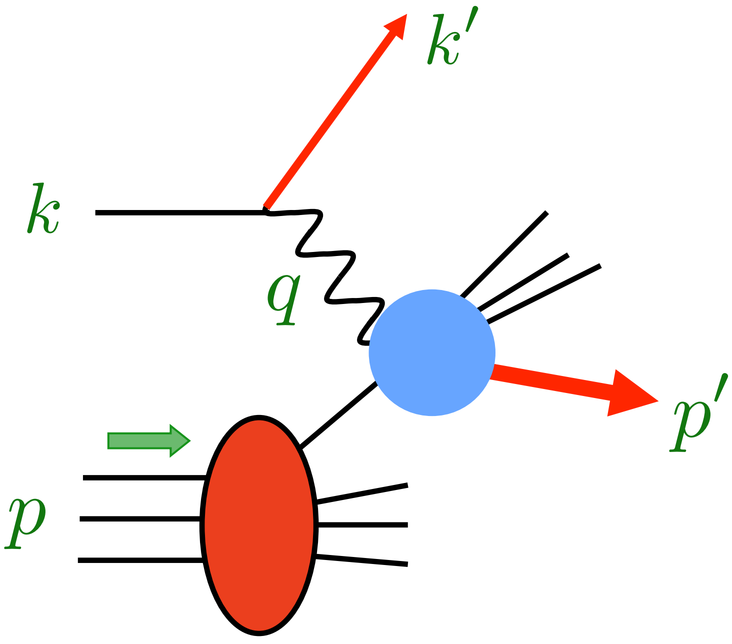
- imaginary part must be finite

- still, individual diagrams have poles
  → dimensional reg. (need γ^5 and $\varepsilon^{\mu\nu\rho\sigma}$)
  ('t Hooft-Veltman-Breitenlohner-Maison)

- also gluon channel:



- DIS kinematics:



$$x = \frac{Q^2}{2p\cdot q}, \quad y = \frac{p\cdot q}{p\cdot k}$$

$$z = \frac{p\cdot p'}{p\cdot q}, \quad \kappa^2 = \frac{{p'_\perp}^2}{Q^2}$$

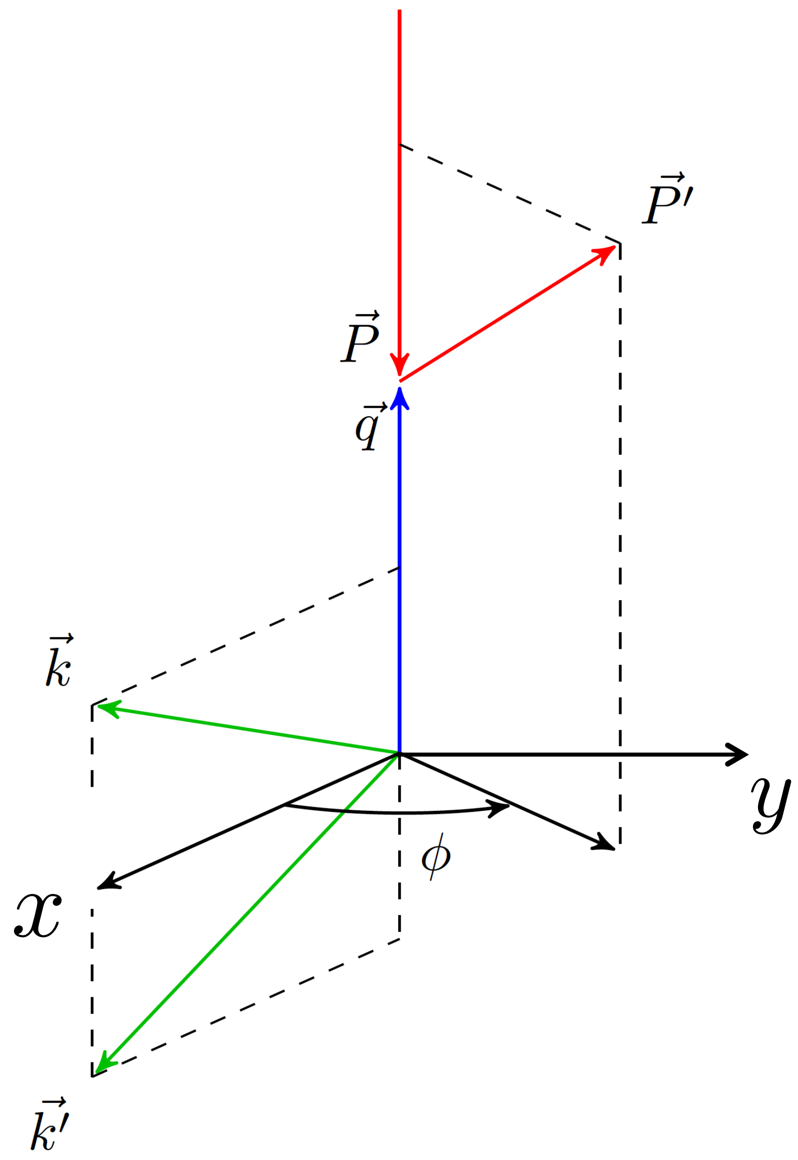
- best evaluated in Breit frame:

$$q = (0, 0, 0, Q)$$

$$p = \left(\frac{Q}{2x}, 0, 0, -\frac{Q}{2x} \right)$$

$$k = (k_0, k_\perp, 0, Q/2)$$

$$p' = (p'_0, p'_\perp \cos\phi, p'_\perp \sin\phi, p'_3)$$



$$\frac{\mathrm{d}\Delta\sigma}{\mathrm{d}x\ \mathrm{d}Q^2\ \mathrm{d}z\ \mathrm{d}\kappa^2\ \mathrm{d}\phi} = \frac{\pi\alpha^2 y^2}{4Q^4 z} L^{\mu\nu}\Delta W_{\mu\nu} \qquad \kappa^2 = \frac{P_T'^2}{Q^2}$$

$$L_{\mu\nu} = 2\left(k_\mu k'_\nu + k_\nu k'_\mu + \frac{q^2}{2} g_{\mu\nu}\right)$$

$$\Delta W_{\mu\nu} = \sum_{a,b}\int_x^1 \frac{\mathrm{d}\xi}{\xi}\int_z^1 \frac{\mathrm{d}\eta}{\eta^2} D_a^H(\eta) e_{ab}\Delta H_{\mu\nu}^{ab}\Delta f_b^p(\xi)$$

- for partonic process $\gamma^*(q) + b(p) \to a(p') + X$:

$$\Delta H_{\mu\nu}^{ab} = \int d\mathcal{PS}\ \left(|\mathcal{M}^+|^2_{\mu\nu}(b \to a) - |\mathcal{M}^-|^2_{\mu\nu}(b \to a) \right)$$

$$L^{\mu\nu}\Delta W_{\mu\nu} = \sum_{a,b}\int_x^1 \frac{\mathrm{d}\xi}{\xi}\int_z^1 \frac{\mathrm{d}\eta}{\eta^2} D_a^H(\eta)\Delta f_b^p(\xi)\frac{2\hat{z}e_{ab}}{(2\pi)^3 y^2}\left(\mathcal{A}^{ab}\sin\phi + \mathcal{B}^{ab}\sin(2\phi)\right)$$
$$\times\,\delta\left(\hat{\kappa}^2 - \frac{1-\hat{x}}{\hat{x}}\hat{z}(1-\hat{z})\right)$$

where

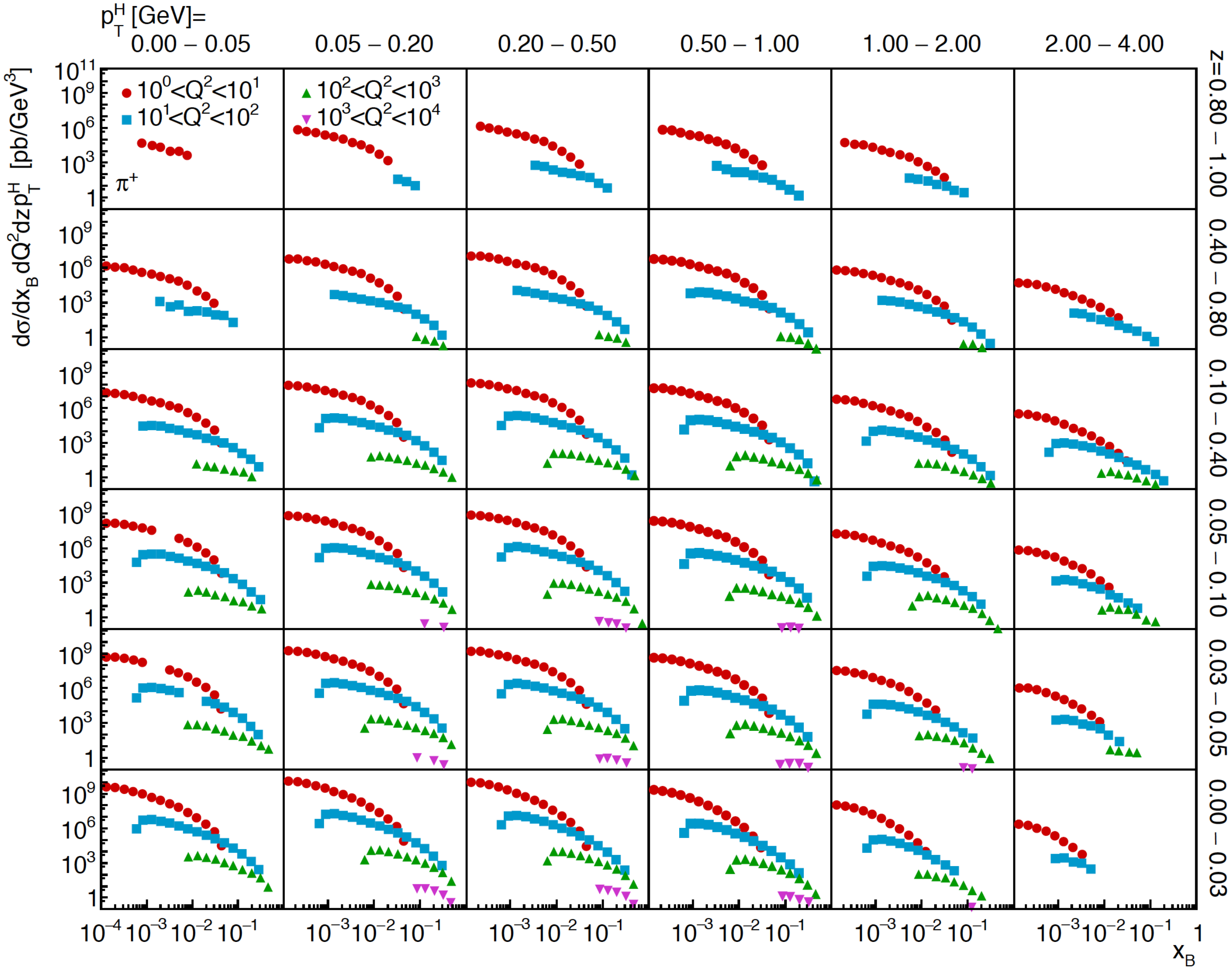
$$\mathcal{A}^{ab} = \sqrt{1-y}(2-y)i\frac{\hat{\kappa}}{2\hat{x}}\left[\frac{1}{\hat{x}}\Delta h_8^{ab} + \left(\hat{z} + \frac{\hat{\kappa}^2}{\hat{z}}\right)\Delta h_9^{ab}\right]$$
$$\mathcal{B}^{ab} = -(1-y)i\frac{\hat{\kappa}^2}{\hat{x}}\Delta h_9^{ab}$$

$$\Delta h_8^{qq} = -\,8i\pi\alpha_s^2(Q)\frac{\hat{x}^3(1-\hat{x}-\hat{z})}{(1-\hat{x})(1-\hat{z})}$$
$$\times\left[\frac{1}{2}C_F C_A + C_F\left(C_F - \frac{C_A}{2}\right)\left(\frac{3-\hat{z}}{1-\hat{z}} + \ln(\hat{z})\frac{2}{(1-\hat{z})^2}\right)\right]$$

$$\Delta h_9^{qq} = 8i\pi\alpha_s^2(Q)\frac{\hat{x}^3}{(1-\hat{x})(1-\hat{z})}$$
$$\times\left[\frac{3}{2}C_F C_A + C_F\left(C_F - \frac{C_A}{2}\right)\left(\frac{1-3\hat{z}}{1-\hat{z}} + \ln(\hat{z})\frac{2(1-2\hat{z})}{(1-\hat{z})^2}\right)\right]$$

Prospects at EIC: spin-averaged

$$\frac{d\sigma}{dx dQ^2 dz dp_T^h} \left[\frac{\text{pb}}{\text{GeV}^2}\right]$$

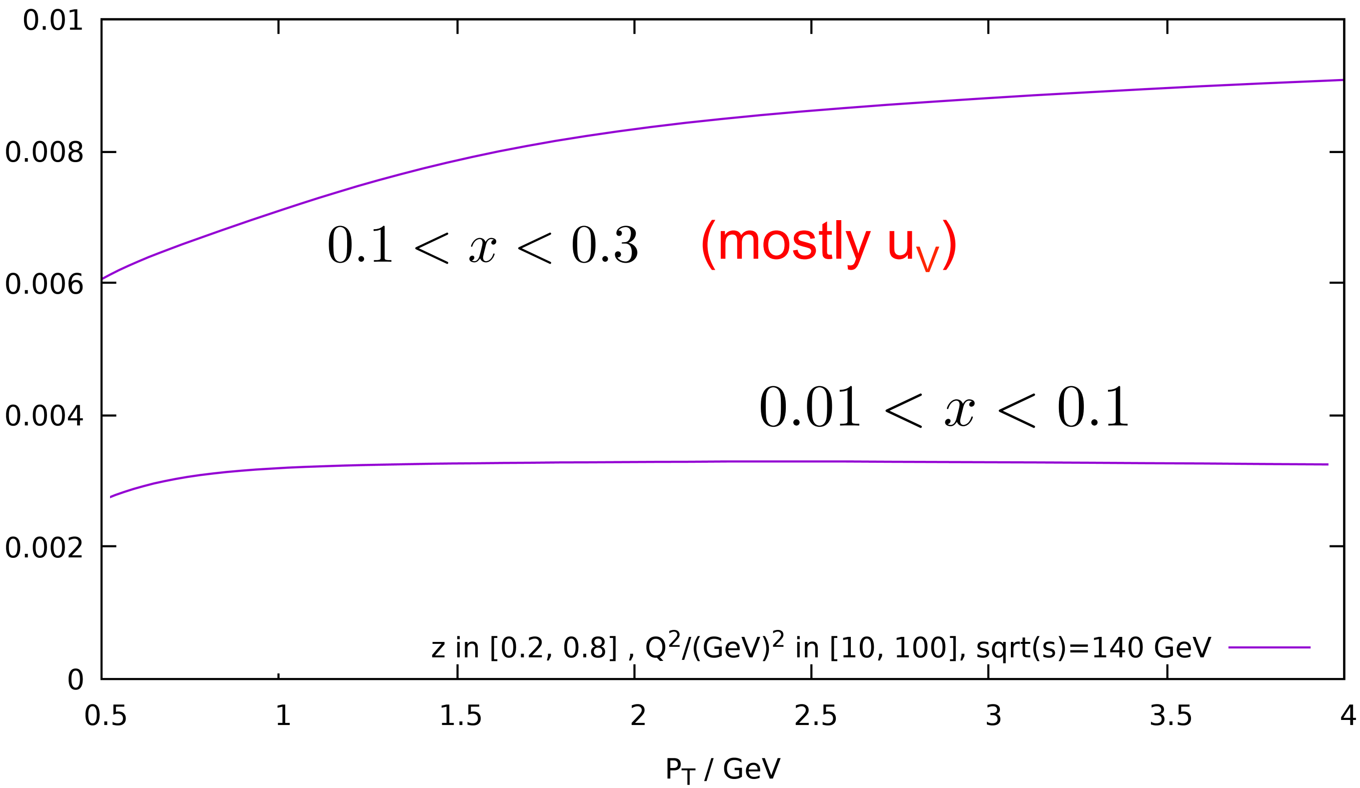


$$ep \to e'\pi^+ X$$

Aschenauer , Borsa, Sassot, van Hulse (2019)

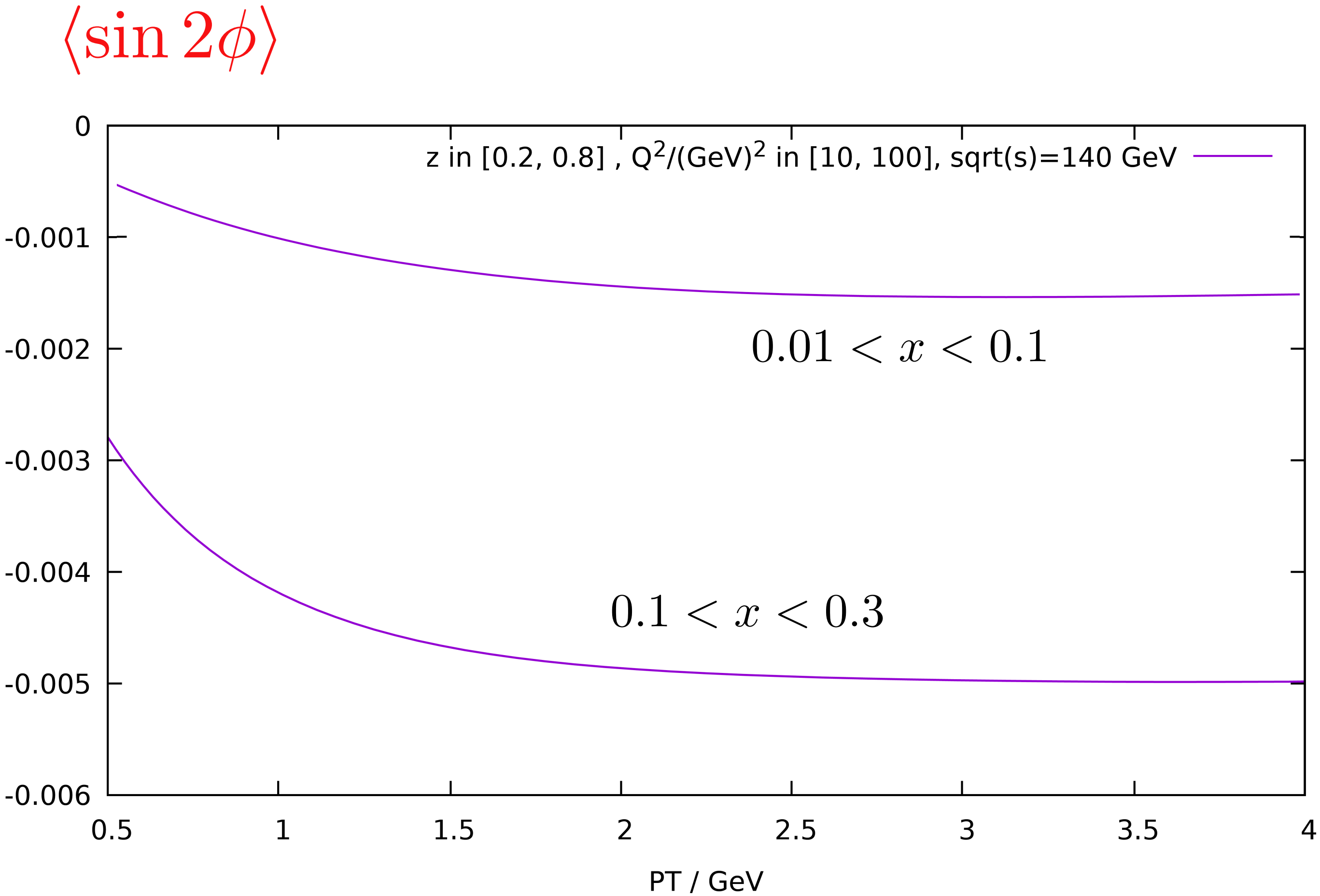
$$\langle \sin(n\phi) \rangle \equiv \frac{\int \mathrm{d}x \mathrm{d}z \mathrm{d}\phi \, \sin(n\phi) \frac{\mathrm{d}\Delta\sigma}{\mathrm{d}x \mathrm{d}Q^2 \mathrm{d}z \mathrm{d}\kappa^2 \mathrm{d}\phi}}{\int \mathrm{d}x \mathrm{d}z \mathrm{d}\phi \frac{\mathrm{d}\sigma}{\mathrm{d}x \mathrm{d}Q^2 \mathrm{d}z \mathrm{d}\kappa^2 \mathrm{d}\phi}}$$

$\langle \sin \phi \rangle$



$ep \to e' \pi^+ X$

DSSV,
DSS fragm.



⟨sin 2φ⟩
z in [0.2, 0.8] , Q2/(GeV)2 in [10, 100], sqrt(s)=140 GeV
0.01 < x < 0.1
0.1 < x < 0.3
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
0.5
1
1.5
2
2.5
3
3.5
4
PT / GeV

Conclusions:

- well-developed framework for studies of spin asymmetries in jet production at the EIC
- T-odd observables new opportunity at EIC