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MARIE CURIE ACTIONS



INFN CAGLIARI

Probing the Collins effect in $\gamma\gamma$ collisions

Carlo Flore

Università di Cagliari & INFN - Sezione di Cagliari

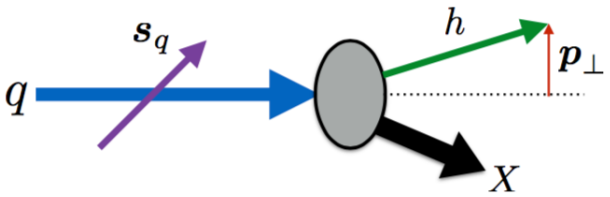
REF 2026

IGFAE Santiago de Compostela

Oct 19th, 2026

S. Anedda, CF, F. Murgia, C. Pisano, arXiv:261x:xxxx

Introduction - the Collins function

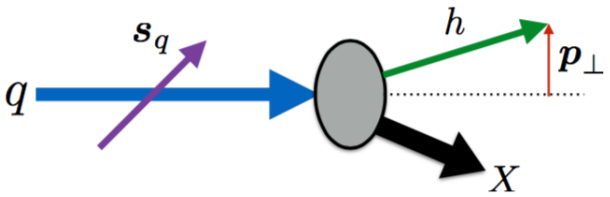


J.C. Collins, NPB 396:161-182 (1993)

$$D_{h/q^\uparrow}(z, \mathbf{p}_\perp) - D_{h/q^\uparrow}(z, -\mathbf{p}_\perp)$$
$$= \Delta^N D_{h/q^\uparrow}(z, p_\perp^2) \frac{(\hat{\mathbf{p}}_q \times \mathbf{p}_\perp) \cdot \mathbf{s}_q}{|\mathbf{p}_\perp|} \quad (TO - CA)$$
$$= -\frac{2|\mathbf{p}_\perp|}{z m_h} H_1^{\perp q}(z, p_\perp^2) \frac{(\hat{\mathbf{p}}_q \times \mathbf{p}_\perp) \cdot \mathbf{s}_q}{|\mathbf{p}_\perp|} \quad (Amsterdam)$$

- genuine TMD fragmentation function

Introduction - the Collins function

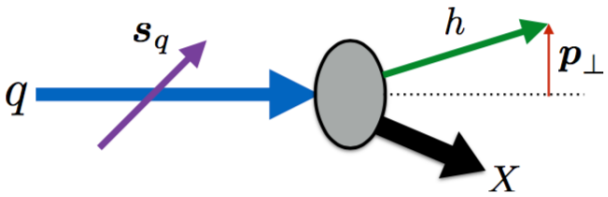


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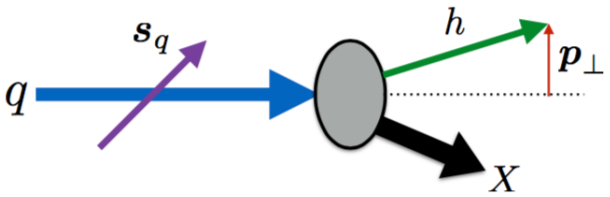
- genuine TMD fragmentation function
- express correlation between quark transverse polarization and produced hadron $\mathbf{p}_\perp$
- extracted, together with TMD transversity h_1^q, in global fits of SIDIS azimuthal asymmetries:

$$N\left[A_{UT}^{\sin(\phi_h+\phi_S)}\right] \sim \mathcal{C}\left[h_1^q H_1^{\perp q}\right]$$

and $e^+e^- \to h_1 h_2 X$ azimuthal asymmetries (double ratio):

$$\frac{R_0^U}{R_0{}^{L(C)}} = \frac{1+P_0^U\cos(2\phi_1)}{1+P_0^{L(C)}\cos(2\phi_1)} \simeq 1+\cos(2\phi_1)A_0^{UL(UC)} \sim \mathcal{C}\left[H_1^{\perp \bar{q}} H_1^{\perp q}\right]$$

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- complementary processes: hadron-in-jet production **[Umberto's talk on Thursday]**

Why photon-photon collisions for TMDs?

Process

$$\gamma_1 \gamma_2 \to q \bar{q} \to h_1 h_2 + X$$

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- Variable hard scale - unlike lepton colliders, $\gamma\gamma$ collisions allow to vary the perturbative energy scale
- Both lepton and heavy-ion UPC colliders currently accessible at colliders

Process

$$\gamma_1\,\gamma_2 \to q\,\bar{q} \to h_1\,h_2 + X$$

Photon sources

1. $\ell^+\ell^-$
2. $\mathcal{N}_1\mathcal{N}_2$

Kinematic in the thrust axis frame

We consider the process

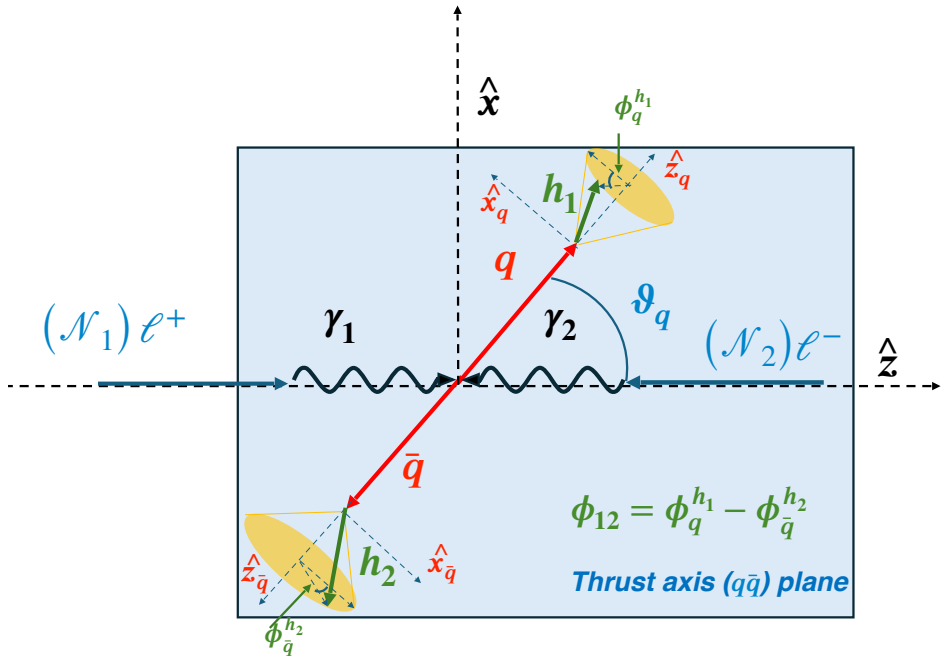
$$\ell^+(l_+)\,\ell^-(l_-) \to h_1(P_1) + h_2(P_2) + X$$

partonic subprocess: $\gamma_1(q_1) + \gamma_2(q_2) \to q(K_q) + \bar{q}(K_{\bar{q}})$

both photons are quasi-real: $q_i^2 \approx 0 \Rightarrow$ Weizsäcker-Williams (WW) approximation

Kinematic variables:

- k_T: hard scale
- $\eta_q, \eta_{\bar{q}}$
- $z_{1,2}$:
  hadron momentum fractions
- $p_{\perp 1}, p_{\perp 2}$:
  hadron $p_\perp$ w.r.t. thrust axis
- $\phi_{12} \equiv \phi_q^{h_1} - \phi_{\bar{q}}^{h_2}$
- $\bar{\xi}_{1,2} = \dfrac{k_T}{\sqrt{s}}\left(e^{\pm\eta_q} + e^{\pm\eta_{\bar{q}}}\right)$:
  photon momentum fraction



Differential cross section

General expression of the cross section within helicity formalism and factorized TMD approach:

$$
\begin{aligned}
d\sigma^{\ell^+\ell^-\to h_1 h_2 X} = & \frac{1}{4\,(l_+\cdot l_-)}\,\frac{d^3\boldsymbol{K}_q}{2(2\pi)^3 K_q^0}\,\frac{d^3\boldsymbol{K}_{\bar{q}}}{2(2\pi)^3 K_{\bar{q}}^0}\,(2\pi)^4\,\delta^{(4)}(q_1+q_2-K_q-K_{\bar{q}}) \\
& \times \sum_q \sum_{\{\lambda_i\}} \rho_{\lambda_1,\lambda_1'}(\gamma_1)\,\rho_{\lambda_2,\lambda_2'}(\gamma_2)\,f_{\gamma_1/\ell^+,\mathcal{P}^{\ell^+}_{\hat{z}_+}}(\xi_1)\,\frac{d\xi_1}{\xi_1}\,f_{\gamma_2/\ell^-,\mathcal{P}^{\ell^-}_{\hat{z}_-}}(\xi_2)\,\frac{d\xi_2}{\xi_2} \\
& \times \hat{H}_{\lambda_q,\lambda_{\bar{q}};\lambda_1,\lambda_2}\,\hat{H}^*_{\lambda_q',\lambda_{\bar{q}}';\lambda_1',\lambda_2'}\,\hat{D}^{h_1}_{\lambda_q,\lambda_q'}(z_1,\boldsymbol{p}_{\perp 1})\,dz_1 d^2\boldsymbol{p}_{\perp 1}\,\hat{D}^{h_2}_{\lambda_{\bar{q}},\lambda_{\bar{q}}'}(z_2,\boldsymbol{p}_{\perp 2})\,dz_2 d^2\boldsymbol{p}_{\perp 2}
\end{aligned}
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& \times \sum_q \sum_{\{\lambda_i\}} \rho_{\lambda_1,\lambda_1'}(\gamma_1)\,\rho_{\lambda_2,\lambda_2'}(\gamma_2)\,f_{\gamma_1/\ell^+,\mathcal{P}^{\ell^+}_{\hat z_+}}(\xi_1)\,\frac{d\xi_1}{\xi_1}\,f_{\gamma_2/\ell^-,\mathcal{P}^{\ell^-}_{\hat z_-}}(\xi_2)\,\frac{d\xi_2}{\xi_2} \\
& \times \hat H_{\lambda_q,\lambda_{\bar q};\lambda_1,\lambda_2}\,\hat H^*_{\lambda_q',\lambda_{\bar q}';\lambda_1',\lambda_2'}\,\hat D^{h_1}_{\lambda_q,\lambda_q'}(z_1,\boldsymbol{p}_{\perp 1})\,dz_1 d^2\boldsymbol{p}_{\perp 1}\,\hat D^{h_2}_{\lambda_{\bar q},\lambda_{\bar q}'}(z_2,\boldsymbol{p}_{\perp 2})\,dz_2 d^2\boldsymbol{p}_{\perp 2}
\end{aligned}
$$

Cross section can be written as:

$$
\begin{aligned}
\frac{d\sigma^{\ell^+\ell^-\to h_1 h_2 X}(\mathcal{P}_+,\mathcal{P}_-)}{d^2\boldsymbol{k}_T\,d\eta_q\,d\eta_{\bar q}\,dz_1\,d^2\boldsymbol{p}_{\perp 1}\,dz_2\,d^2\boldsymbol{p}_{\perp 2}} = {} & \frac{6\,\alpha^2}{s\,k_T^2}\,\frac{1}{1+\cosh(\eta_q-\eta_{\bar q})}\sum_q e_q^4 \\
& \times \left\{ f_{\gamma/\ell^+}(\bar\xi_1)\,f_{\gamma/\ell^-}(\bar\xi_2) - \mathcal{P}_+\,\mathcal{P}_-\,\Delta_L f_{\gamma/\ell^+}(\bar\xi_1)\,\Delta_L f_{\gamma/\ell^-}(\bar\xi_2)\right\} \\
& \times \Big\{ \cosh(\eta_q-\eta_{\bar q})\,D_{h_1/q}(z_1,p_{\perp 1})\,D_{h_2/\bar q}(z_2,p_{\perp 2}) \\
& + \frac{1}{4}\cos(\phi_q^{h_1}-\phi_{\bar q}^{h_2})\,\Delta^N D_{h_1/q^\uparrow}(z_1,p_{\perp 1})\,\Delta^N D_{h_2/\bar q^\uparrow}(z_2,p_{\perp 2})\Big\}
\end{aligned}
$$

Differential cross section

After integrating over hadrons $p_\perp$'s w.r.t. the thrust axis:

$\ell^+\ell^-$ collisions

$$\frac{d\sigma^{\ell^+\ell^-\to h_1 h_2 X}(\mathcal{P}_+,\mathcal{P}_-)}{d^2k_T\, d\eta_q\, d\eta_{\bar q}\, dz_1\, dz_2\, d\phi_{12}} = \frac{6\alpha^2}{s\,k_T^2}\,\frac{1}{1+\cosh(\eta_q-\eta_{\bar q})}$$
$$\times \sum_q e_q^4 \Big[f_{\gamma/\ell^+}(\bar\xi_1)\, f_{\gamma/\ell^-}(\bar\xi_2) - \mathcal{P}_+\mathcal{P}_-\, \Delta_L f_{\gamma/\ell^+}(\bar\xi_1)\, \Delta_L f_{\gamma/\ell^-}(\bar\xi_2) \Big]$$
$$\times \left\{ \cosh(\eta_q-\eta_{\bar q})\, D_{q/h_1}(z_1)\, D_{\bar q/h_2}(z_2) + \frac{1}{4}\cos\phi_{12}\, \Delta^N D_{h_1/q^\uparrow}(z_1)\, \Delta^N D_{h_2/\bar q^\uparrow}(z_2) \right\}$$

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$$\times \left\{ \cosh(\eta_q-\eta_{\bar q})\, D_{q/h_1}(z_1)\, D_{\bar q/h_2}(z_2) + \frac{1}{4}\cos\phi_{12}\,\Delta^N D_{h_1/q^\uparrow}(z_1)\,\Delta^N D_{h_2/\bar q^\uparrow}(z_2)\right\}$$

UPC

$$\frac{d\sigma^{\mathcal{N}_1\mathcal{N}_2\to h_1 h_2 X}}{d^2k_T\,d\eta_q\,d\eta_{\bar q}\,dz_1\,dz_2\,d\phi_{12}} = \frac{6\alpha^2}{s_{NN}\,k_T^2}\,\frac{1}{1+\cosh(\eta_q-\eta_{\bar q})}\sum_q e_q^4\, f_{\gamma/\mathcal{N}_1}(\bar\xi_1)\, f_{\gamma/\mathcal{N}_2}(\bar\xi_2)$$
$$\times \left\{ \cosh(\eta_q-\eta_{\bar q})\, D_{h_1/q}(z_1)\, D_{h_2/\bar q}(z_2) + \frac{1}{4}\cos\phi_{12}\,\Delta^N D_{h_1/q^\uparrow}(z_1)\,\Delta^N D_{h_2/\bar q^\uparrow}(z_2)\right\}$$

Observables - azimuthal moments

Unpolarised cross section and double longitudinal spin asymmetry

$$d\sigma^{\text{unp}} = \tfrac{1}{2}\big[d\sigma(+,+) + d\sigma(+,-)\big], \qquad A_{LL} = \frac{d\sigma(+,+) - d\sigma(+,-)}{d\sigma(+,+) + d\sigma(+,-)}$$

Following [S. Anedda, F. Murgia, C. Pisano, PRD 112 (2025) 014013], one can introduce azimuthal moments:

$$\langle\, d\sigma^{\text{unp}} \,|\, n_q; m_{12} \,\rangle = 2\, \frac{\int d\phi_q\, d\phi_{12}\; d\sigma^{\text{unp}}(\phi_q, \phi_{12})\, \cos[n_q\phi_q + m_{12}\phi_{12}]}{\int d\phi_q\, d\phi_{12}\; d\sigma^{\text{unp}}(\phi_q, \phi_{12})}$$

$$\langle\, A_{LL} \,|\, n_q; m_{12} \,\rangle = 2\, \frac{\int d\phi_q\, d\phi_{12}\; A_{LL}\, d\sigma^{\text{unp}}(\phi_q, \phi_{12})\, \cos[n_q\phi_q + m_{12}\phi_{12}]}{\int d\phi_q\, d\phi_{12}\; d\sigma^{\text{unp}}(\phi_q, \phi_{12})}$$

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The $\cos\phi_{12}$ azimuthal moments ($n_q = 0$, $m_{12} = 1$):

$$\langle\, d\sigma^{\text{unp}} \mid \cos\phi_{12} \,\rangle = \frac{1}{4\cosh(\eta_q - \eta_{\bar{q}})} \frac{\sum_q e_q^4\, \Delta^N D_{h_1/q^\uparrow}(z_1)\, \Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^4\, D_{h_1/q}(z_1)\, D_{h_2/\bar{q}}(z_2)}$$

$$\langle\, A_{LL} \mid \cos\phi_{12} \,\rangle = -\frac{1}{4\cosh(\eta_q - \eta_{\bar{q}})} \frac{\Delta_L f_{\gamma/\ell+}(\bar{\xi}_1)\, \Delta_L f_{\gamma/\ell-}(\bar{\xi}_2)}{f_{\gamma/\ell+}(\bar{\xi}_1)\, f_{\gamma/\ell-}(\bar{\xi}_2)} \frac{\sum_q e_q^4\, \Delta^N D_{h_1/q^\uparrow}(z_1)\, \Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^4\, D_{h_1/q}(z_1)\, D_{h_2/\bar{q}}(z_2)}$$

- $\langle d\sigma^{\text{unp}} | \cos\phi_{12} \rangle$ directly probes the Collins TMD FFs
- $\langle A_{LL} | \cos\phi_{12} \rangle$ more sensitive to kinematical region probed in the WW distributions
- both suppressed by $1/\cosh(\eta_q - \eta_{\bar{q}}) \Rightarrow$ favors central rapidity
- predictions for like-sign (L, $\pi^+\pi^+ + \pi^-\pi^-$) and unlike-sign (U, $\pi^+\pi^- + \pi^-\pi^+$) pairs

TMD parametrization

- two different parametrizations
  - (i) TO-CA24 [M. Boglione et al., PLB 854 (2024) 138712]
  - (ii) JAM3D-2022-nolat [L. Gamberg et al., PRD 106, 034014 (2022)]
- Gaussian ansatz for unpolarized TMD-FF

$$D_{h/q}(z,p_\perp) = D_{h/q}(z)\,\mathcal{G}(p_\perp^2)\,, \quad \text{with } \mathcal{G}(p_\perp^2) = \frac{1}{\pi\langle p_\perp^2\rangle}\exp\left[-p_\perp^2/\langle p_\perp^2\rangle\right]$$

TO-CA24

$$\Delta^N D_{h/q^\uparrow}(z,p_\perp) \equiv \frac{2p_\perp}{zm_h} H_{1\,h/q}^\perp(z,p_\perp)$$
$$= \mathcal{N}_q^C(z)\,\frac{p_\perp}{M_C}\,2\sqrt{2e}\,e^{-p_\perp^2/M_C^2}\,D_{h/q}(z,p_\perp)$$

with q = fav, unf, M_C free param. with mass dimension, and
$\mathcal{N}_{\rm fav}^C(z) = N_{\rm fav}\,z^\gamma$, $\mathcal{N}_{\rm unf}^C(z) = N_{\rm unf}$

JAM3D-2022-nolat

$$H_{1\,h/q}^\perp(z,p_\perp^2) = \frac{2z^2m_h^2}{\langle p_\perp^2\rangle_{H_1^\perp}^{h/q}} H_{1\,h/q}^{\perp(1)}(z)\,\mathcal{G}_{H_1^\perp}^{h/q}(p_\perp^2)$$

$(q = \text{fav, unf})$

- relation between two notations:

$$H_{1\,h/q}^{\perp(1)}(z) = \frac{\sqrt{\langle p_\perp^2\rangle_C}}{2\sqrt{\pi}zm_h}\Delta^N D_{h/q^\uparrow}(z)\,, \quad \text{with } \langle p_\perp^2\rangle_C = M_C^2\,\langle p_\perp^2\rangle/(M_C^2+\langle p_\perp^2\rangle)$$

Setup

e^+e^- collider FCC-ee

$\sqrt{s}$	92 GeV
k_T range	$[3, 20]$, $([20, 40])$ GeV
θ_c	0.03 rad
$\lvert\eta_{q,\bar{q}}\rvert$	$\leq 2.5\,(0.5)$

Photon WW distributions

$$f_{\gamma/\ell}(\xi) = \frac{\alpha}{2\pi}\left[\frac{1+(1-\xi)^2}{\xi}\ln\frac{Q^2_{\max}}{Q^2_{\min}} + 2m_\ell^2\xi\left(\frac{1}{Q^2_{\max}} - \frac{1}{Q^2_{\min}}\right)\right]$$

$$\Delta_L f_{\gamma/\ell}(\xi) = \frac{\alpha}{2\pi}\left[\frac{1-(1-\xi)^2}{\xi}\ln\frac{Q^2_{\max}}{Q^2_{\min}} + 2m_\ell^2\xi^2\left(\frac{1}{Q^2_{\max}} - \frac{1}{Q^2_{\min}}\right)\right]$$

$$Q^2_{\min} = \frac{m_\ell^2\,\xi^2}{1-\xi}, \qquad Q^2_{\max} = \frac{s\,(1-\xi)}{4\,\theta_c^2} + Q^2_{\min}$$

Pb-Pb UPC ATLAS & CMS, ALICE and LHCb

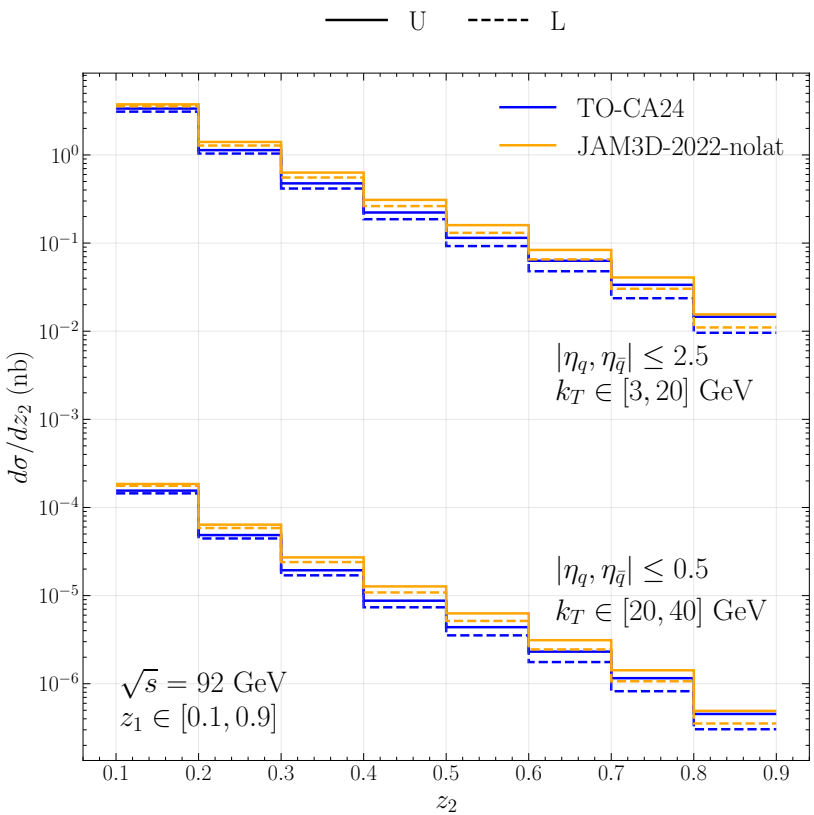
$\sqrt{s_{NN}}$	5360 GeV
k_T range	$[10, 30]$ GeV
$\lvert\eta_{q,\bar{q}}\rvert$	≤ 2.4 (ATLAS/CMS)
	≤ 0.9 (ALICE)
$\eta_{q,\bar{q}}$	$\in [2, 4.5]$ (LHCb)

Nuclear photon flux In the Equivalent Photon Approximation:

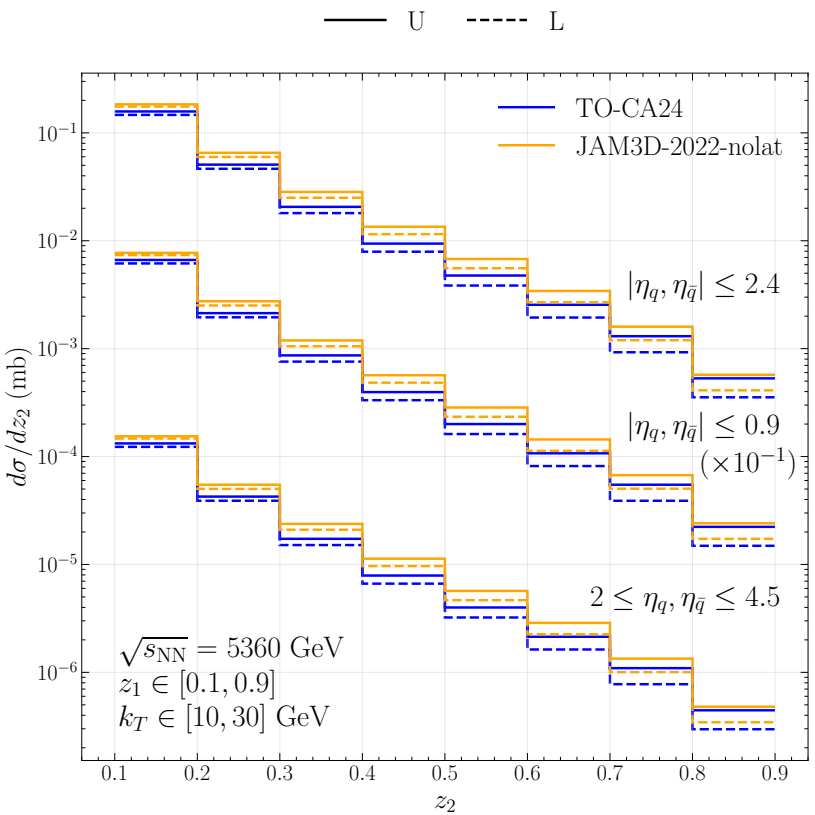
$$f_{\gamma/\mathcal{N}}(\xi) = \frac{Z^2\alpha}{\pi\xi}\left[2x_i K_0(x_i)K_1(x_i) - x_i^2\left(K_1^2(x_i) - K_0^2(x_i)\right)\right]$$

- $K_{0,1}$: modified Bessel functions
- $x_i = \xi M_N b_{\min}$
- $b_{\min} = 2R_{\mathcal{N}}$ (symmetric ion beams)
- $R_{\mathcal{N}} = R_0 A^{1/3}$, with $R_0 = 1.2$ fm

Results - unpolarized cross sections

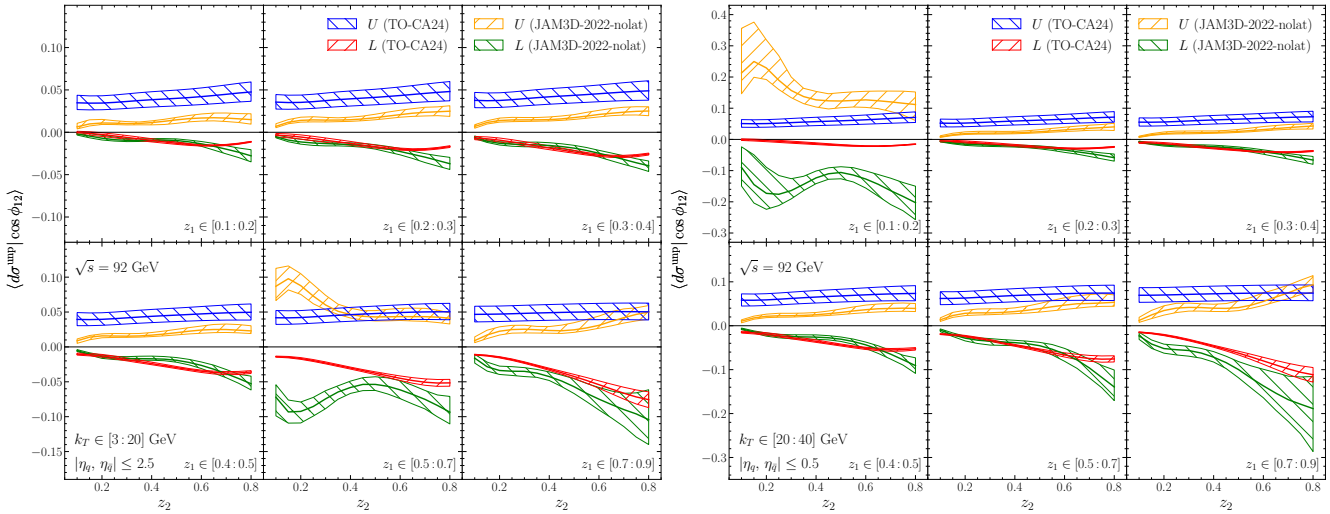


(a) FCC-ee



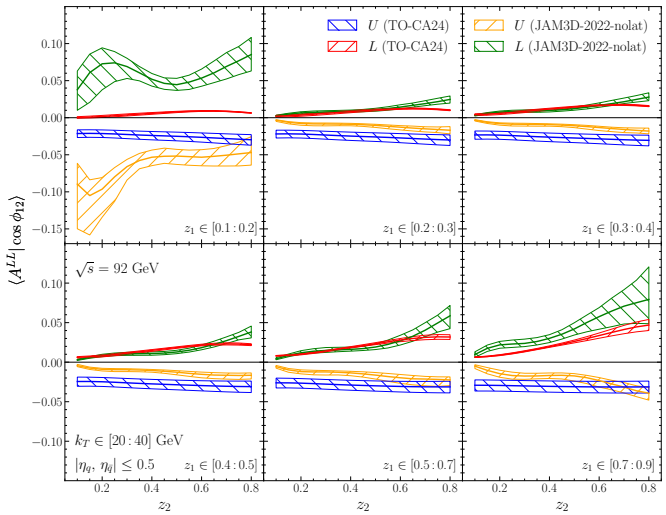
(b) UPC @ LHC

Results - $\langle d\sigma^{\text{unp}} \mid \cos\phi_{12} \rangle$ - FCC-ee



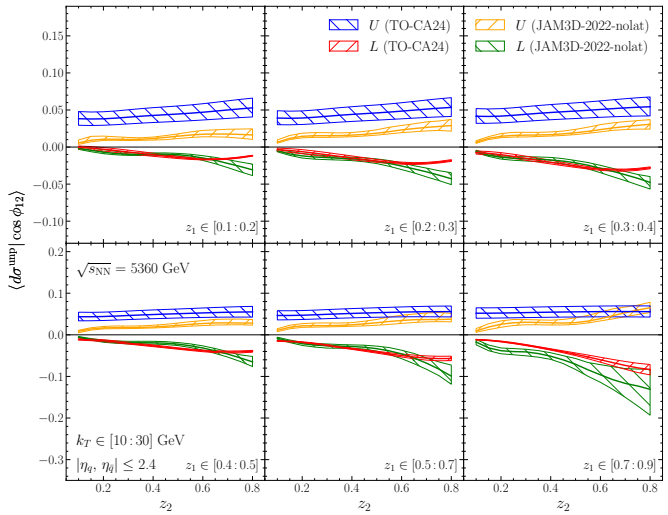
(a) $k_T \in [3, 20]$ GeV

(b) $k_T \in [20, 40]$ GeV

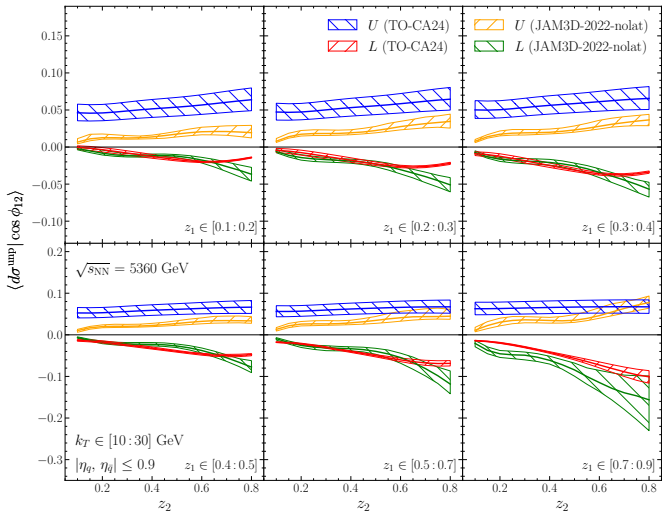


(c) A_{LL}, $k_T \in [20, 40]$ GeV

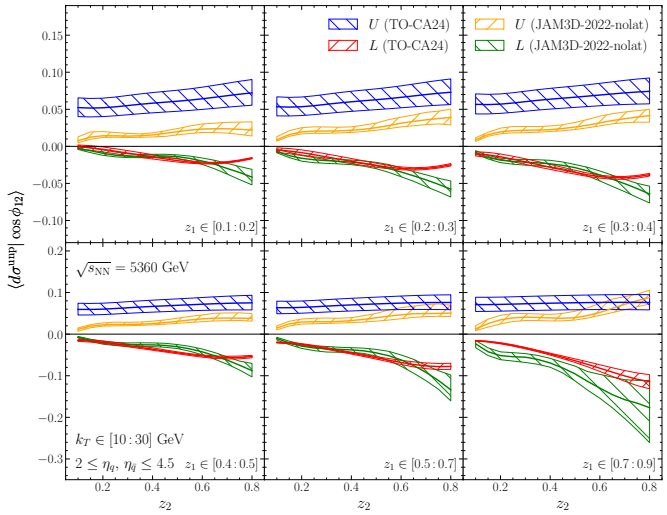
Results - $\langle d\sigma^{\text{unp}} \mid \cos\phi_{12} \rangle$ - HL-LHC



(a) ATLAS/CMS



(b) ALICE



(c) LHCb

Conclusions and outlook

Summary:

- $\gamma\gamma$ collisions: a proxy to access the Collins effect
- computed TMD cross section and azimuthal moments
- predictions for FCC-ee and Pb-Pb UPC at HL-LHC

$\Rightarrow$ sizeable $\cos\phi_{12}$ asymmetry

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- updated Collins extractions with different parametrizations

$\Rightarrow$ implementing CSS evolution

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- include other mesons (e.g. kaons) or spin 1/2 baryons (e.g. Λ)

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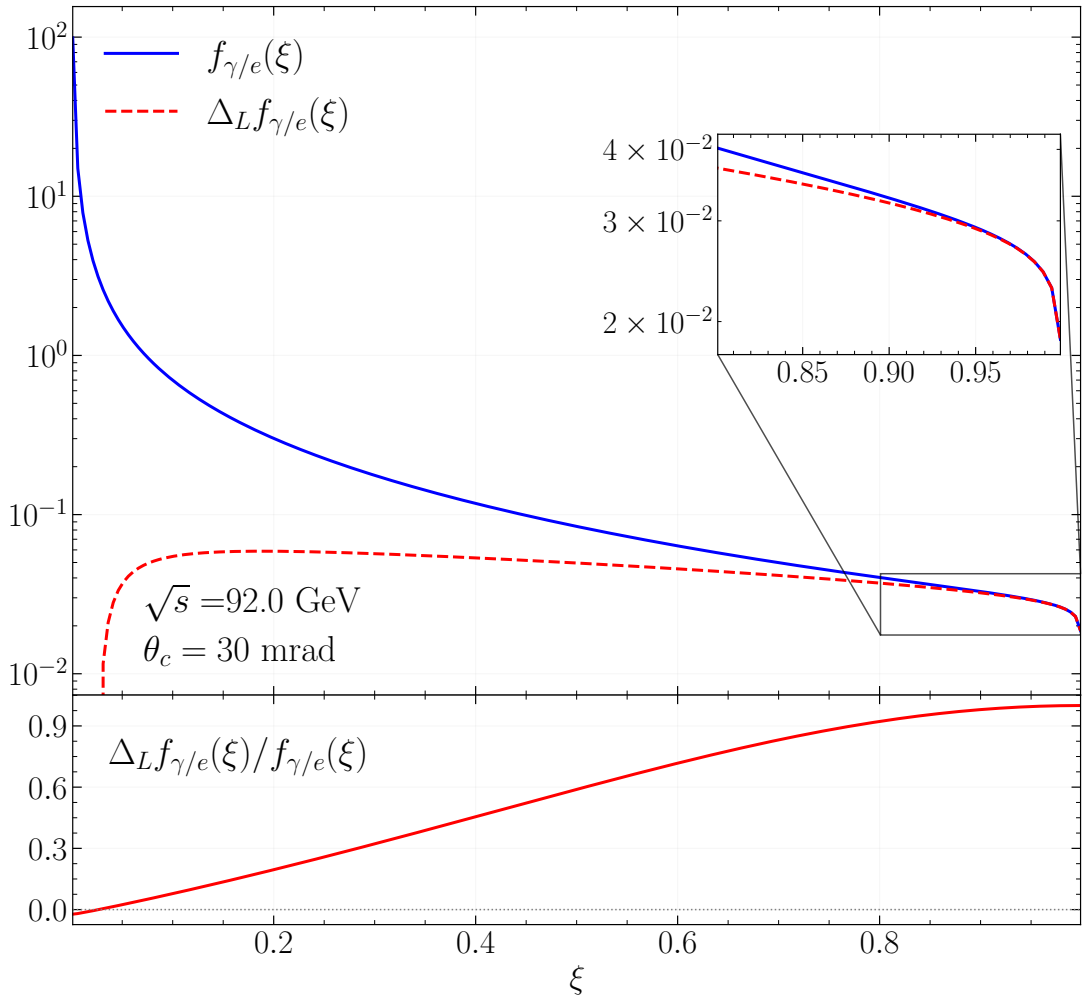
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Thank you

Backup

Weizsäcker-Williams distributions



Collins TMD FFs - TO-CA24 vs JAM3D-2022

