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Physics & Astronomy

Determination of the αs(mZ) and Collins-Soper Kernel from EEC in electron-positron collision

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arXiv: 2410.21435 **v2** (Nov 26)

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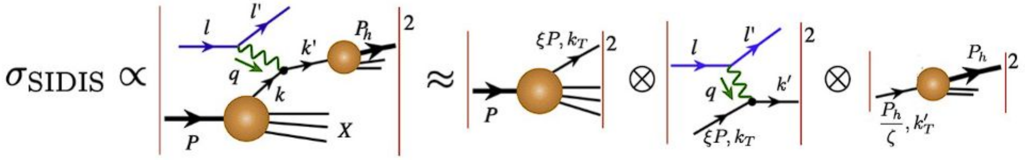
Jan 09, 2024

Collins-Soper Kernel and TMD factorization

- CS-kernel → crucial for Transverse-Momentum-Dependent (TMD) factorization
- The TMD factorization is a formalism to calculate observables in QCD scattering



Processes	Observables
$e^+ + e^- \to h_1 + h_2 + X$	EEC, TEEC
$e^- + p(A) \to e^- + h + X$	X-section, Sivers asymmetry, single spin asymmetry
$p + p(A) \to e^+ + e^- + X$	

- Momentum and spin structure of hadrons/nucleus
- Quark Gluon Plasma
- Precision physics (W boson mass)

Collins Soper Kernel

- TMD factorization rely on TMD functions (PDF, FF, jet…)
  → non-perturbative information of momentum/spin structures
- All TMD functions depends on Collins-Soper scale (ζ).
  → CS kernel K controls TMDs' **scaling** in ζ

$$\frac{d\ln F(b,\mu,\zeta)}{d\ln\zeta} = \frac{K(b,\mu)}{2}$$

- The CS kernel K has perturbative & non-perturbative (large b)

$$K(b,\mu) = K_{\text{pert}}(b,\mu) - 2D_{\text{NP}}(b)$$

- CS kernel is conjectured to be **universal** (**independent** of process and observable)
  → it could be extracted from DY, SIDIS, e+ e- annihilation
- However, past phenomenological extractions limited to **DY, SIDIS**

Global Energy-Energy Correlator

$$e^+ + e^- \to h_1 + h_2 + X$$

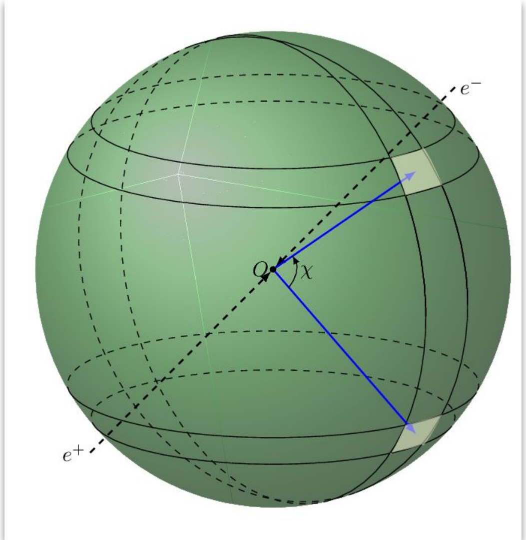
- No effort in extracting K from Energy-Energy Correlator (EEC)
- EEC measures angular distribution of energy weight differential cross-section:

$$\sum_{i,j} \int \mathrm{d}\sigma_{e^+e^- \to ij+X} \frac{E_i E_j}{Q^2} \delta(\cos\theta_{ij} - \cos\chi)$$

- χ: angle between pairs of final state particles
- Q: C.O.M energy

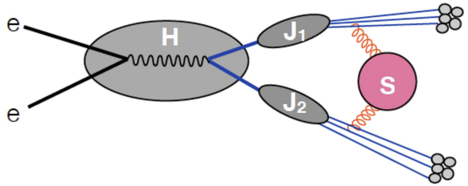
EEC is advantageous for extraction of K:

- less susceptible to hadronization effects
  → no reliance on TMDFF/TMDPDF
- TMDFF/TMDPDF have **dozens** of parameters
  -> **mixing** with CS Kernel
- EEC **only 2** parameters for NP TMD jet function
  -> less **mixing**



Factorization for EEC in the back-to-back limit

$$\frac{d\Sigma}{d\chi} \propto Q^2 \sin(\chi) H(Q,\mu) \int_0^\infty db^2 J_0(bQ\sin(\frac{\pi}{2}-\frac{\chi}{2})) \boldsymbol{J_q}(b,\mu,\zeta) \boldsymbol{J_{\bar{q}}}(b,\mu,\zeta) e^{-2S_{\rm NP}(b)}$$



We use the following parameterization for NP Sudakov (hadronization effects)

$$S_{\rm NP}(b) = a_1 b^{a_2}$$

And for NP Collins Soper Kernel K we consider 2 parameterizations:

$$D_{\rm NP}^{\rm Fit\,1} = g_2\, b\, b_*,\; D_{\rm NP}^{\rm Fit\,2} = g_2'\, \ln\left(\frac{b}{b_*}\right)$$

, where $b_* = b/\sqrt{1+b^2/b_{\rm max}^2}$

Data selection

v1 → v2:
Added 30 very **low uncertainty** **OPAL** data points

Criterias	
Provided both statistical and systematic uncertainties	
Measured both charged and neutral final state particles	
Q >= 29 GeV	(Avoiding quark mass effects)
145° < χ < 175°	(Focusing back to back region)

Collaboration	Q (GeV)	N_{data}
OPAL [16]	91.2	30
SLD [14]	91.2	9
TOPAZ [17]	59.5	9
TOPAZ [17]	53.3	9
TASSO [18]	43.5	9
TASSO [18]	34.8	9
MARKII [21]	29.0	9
MAC [20]	29.0	9
Total		93

Fit Result

Collaboration	Q (GeV)	$\mathrm{N_{data}}$	χ^2 (Fit 1)	χ^2 (Fit 2)
OPAL [16]	91.2	30	12.4	12.4
SLD [14]	91.2	9	2.5	2.4
TOPAZ [17]	59.5	9	11.3	11.3
TOPAZ [17]	53.3	9	12.7	12.7
TASSO [18]	43.5	9	8.6	8.7
TASSO [18]	34.8	9	10.3	10.4
MARKII [21]	29.0	9	12.8	12.8
MAC [20]	29.0	9	14.2	14.3
Total		93	84.8	84.9

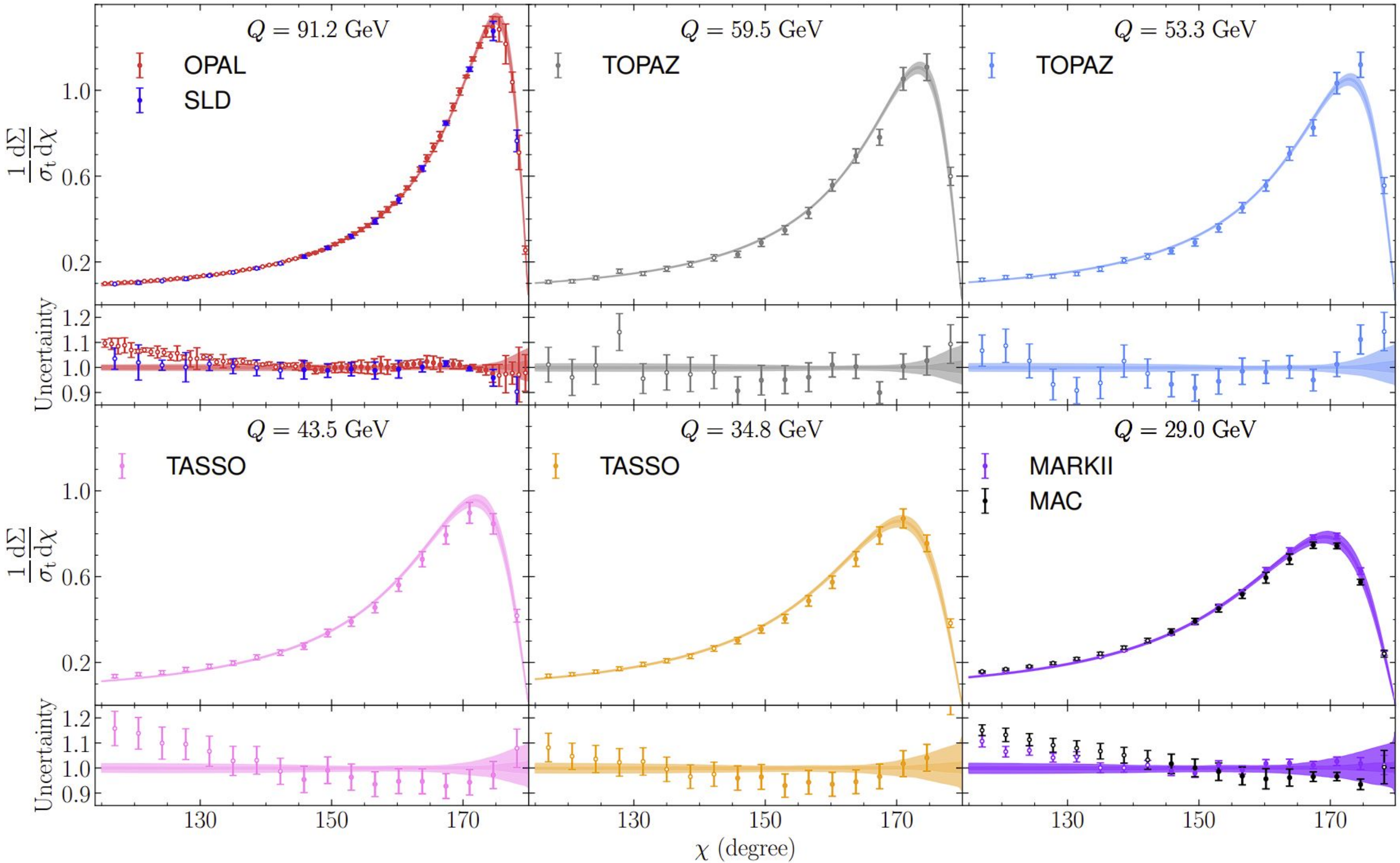
χ^2/d.o.f = 0.95

$$S_{\mathrm{NP}}(b) = a_1 b^{a_2}$$

$$D_{\mathrm{NP}}^{\mathrm{Fit\,1}} = g_2\, b\, b_*,\; D_{\mathrm{NP}}^{\mathrm{Fit\,2}} = g_2' \ln\left(\frac{b}{b_*}\right)$$

	$\alpha_s(m_Z)$	a_1 (GeV^{a_2})	a_2	g_2 (GeV^2)	g_2'
Fit 1	$0.1193^{+0.0009+0.0008}_{-0.0009-0.0013}$	$0.530^{+0.060+0.051}_{-0.067-0.052}$	$1.152^{+0.045+0.064}_{-0.049-0.077}$	$0.076^{+0.014+0.015}_{-0.013-0.012}$	N/A
Fit 2	$0.1193^{+0.0010+0.0009}_{-0.0008-0.0013}$	$0.527^{+0.030+0.051}_{-0.036-0.058}$	$1.152^{+0.040+0.065}_{-0.038-0.079}$	N/A	$0.194^{+0.019+0.037}_{-0.020-0.028}$

Comparison with data



Comparison of strong coupling constant

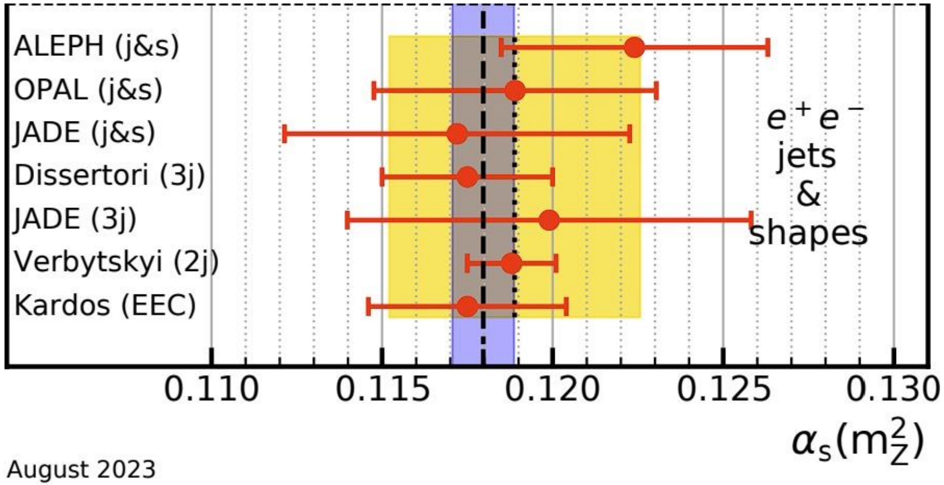
Our result from EEC (**N3LL**)

	$\alpha_s(m_Z)$
Fit 1	$0.1193^{+0.0009+0.0008}_{-0.0009-0.0013}$
Fit 2	$0.1193^{+0.0010+0.0009}_{-0.0008-0.0013}$

v1: 0.1173 → v2: 0.1193

Other groups' αs(mZ) (PDG 2024)	
World Average	0.1180 ± 0.0009
e+ e- shapes (**NLL**)	0.1189 ± 0.0043
OPAL (**NLL**)	0.1189 ± 0.0037

averages per sub-field	unweighted
τ decays & low Q^2	0.1173 ± 0.0017
$Q\bar{Q}$ bound states	0.1181 ± 0.0037
PDF fits	0.1161 ± 0.0022
e^+e^- jets & shapes	0.1189 ± 0.0037
hadron colliders	0.1168 ± 0.0027
electroweak	0.1203 ± 0.0028
PDG 2023 (without lattice)	0.1175 ± 0.0010



Comparison of CS kernel

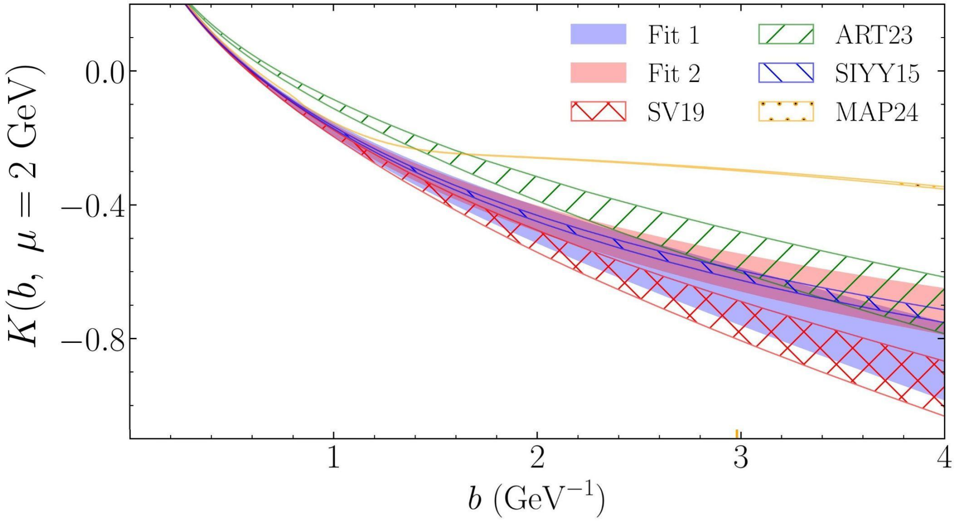
SV19 (Scimemi, Vladimirov)
- Same parameterization as **Fit 1**
- SIDIS + DY

SIYY15 (Sun, Isaacson, C.Yuan, F.Yuan)
- Same parameterization as **Fit 2**
- SIDIS + DY

ART23 (Scimemi, Vladimirov)
- $bb_*(g_2 + g_3 \ln(b_*/b_{\max}))$
- DY

MAP24 (Bacchetta, Bertone, Bissolotti…)
- $\tilde{g}_2\, b^2$
- SIDIS + DY

$$D_{\rm NP}^{\rm Fit\,1} = g_2\, b\, b_*,\ D_{\rm NP}^{\rm Fit\,2} = g_2'\, \ln\left(\frac{b}{b_*}\right)$$



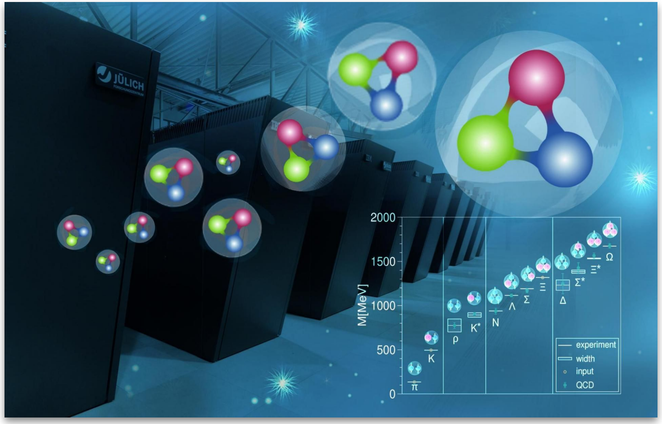
CS kernel from Lattice QCD

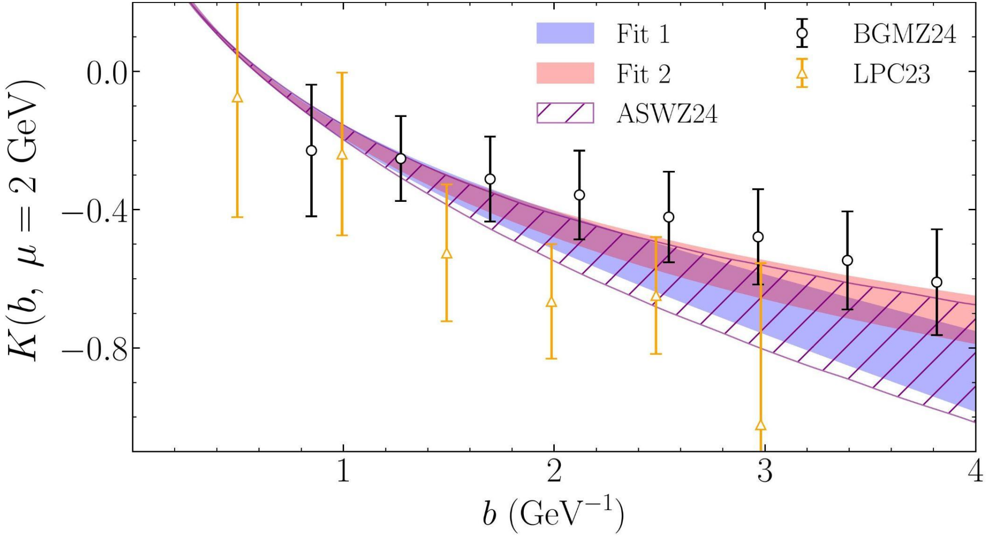
Lattice QCD results (pion TMD wave functions):

ASWZ24 (Avkhadiev, Shanahan, Wagman, Zhao)

LPC23 (Chu, He, Hua, Liang, Ji, Schäfer…)

BGMZ24 (Bollwega, Gao, Mukherjee, Zhao)





Conclusion

- **First** simultaneous extraction of αs and Collins-Soper kernel from EEC
- **First** theoretical description of the EEC peak in the back-to-back region.
- Extracted αs consistent with the e+ e- average: $\alpha_s(M_Z) = 0.1189 \pm 0.0037$
- Extracted Collins-Soper kernel consistent with

→ phenomenological extraction from SIDIS and DY

→ Lattice QCD

→ more evidence for universality of NP CS Kernel

Thank you!