TMD extractions with `artemide`

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Bridging TMD Frameworks: Intersections, Tensions, and Applications

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Outline

1. Overview
2. DY+SIDIS (ART25)
   - Description
   - Non-perturbative models
   - Results
3. EEC
   - Introduction
   - `artemide` implementation
   - Data
   - Results
4. Ongoing work
   - KPCs
   - Fits reanalysis

Overview

→ Code: *Fortran* (+*Python*)

[https://github.com/VladimirovAlexey/artemide-development/]

→ Evaluate observables within the TMD factorization setup:

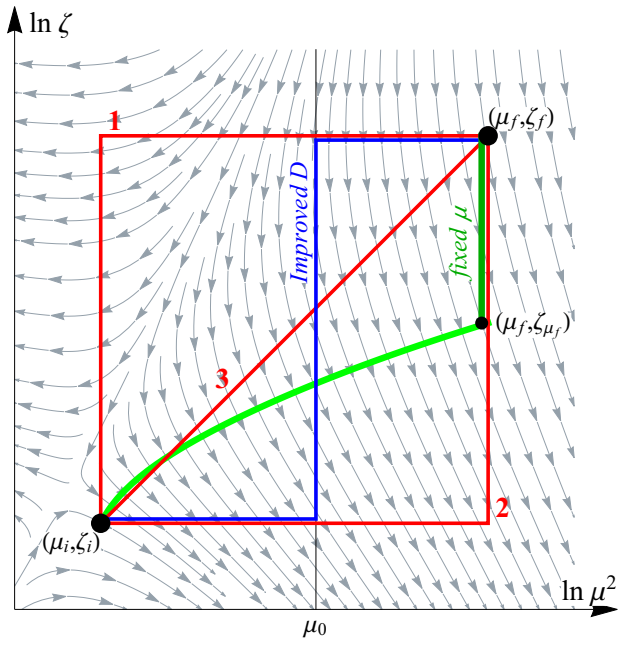
$$\frac{d\sigma}{dX} = d\sigma(q_T) = prefactor \ \times F$$

$$F = \int \frac{bdb}{2} b^n \underbrace{J_n(bq_T)}_{\substack{\text{Bessel J} \\ n^{\text{th}} \text{ order}}} \sum_{ff'} z_{ff'} \underbrace{F_1^f(x_1, b; \mu, \zeta_1)}_{\text{TMD}} \underbrace{F_2^{f'}(x_2, b; \mu, \zeta_2)}_{\text{TMD}}$$

Overview

TMD evolution

→ ζ-prescription: [I.Scimemi, A. Vladimirov]



$$\mu^2 \frac{\mathrm{d}}{\mathrm{d}\mu^2} F_{f\leftarrow h}(x, b; \mu, \zeta) = \frac{\gamma_F^f(\mu, \zeta)}{2} F_{f\leftarrow h}(x, b; \mu, \zeta)$$

$$\zeta \frac{\mathrm{d}}{\mathrm{d}\zeta} F_{f\leftarrow h}(x, b; \mu, \zeta) = -\mathcal{D}^f(\mu, b) F_{f\leftarrow h}(x, b; \mu, \zeta)$$

* γ_F^f , $\mathcal{D}^f$ $\leftrightarrow$ TMD, rapidity anomalous dimensions

Null-evolution lines: $\zeta_\mu(b)$

$$\Rightarrow F_{f\leftarrow h}(x, b; \mu, \zeta) = \left(\frac{\zeta}{\zeta_\mu(b)}\right)^{-\mathcal{D}^f(\mu,b)} \underbrace{F_{f\leftarrow h}(x, b; \mu, \zeta_\mu(b))}_{F_{f\leftarrow h}(x,b) \text{ Optimal TMD}}$$

Overview

Collins-Soper (CS) kernel and Optimal TMD

→ CS kernel:

$$\mathcal{D}(\mu, b) = \mathcal{D}_{\text{pert}}(b^*, \mu^*) + \int_{\mu^*}^{\mu} \frac{d\mu'}{\mu'} \Gamma_{\text{cusp}}(\mu') + \mathcal{D}_{\text{NP}}(b)$$

- b^*-prescription: Avoids evaluation below Λ_{QCD}
  - $b^*(b \to \infty) \equiv B_{\text{NP}}$

→ Optimal TMD: LO OPE (collinear matching) & model

$$F_f(x, b) = \int_x^1 \frac{dz}{z} \underbrace{C_{f \leftarrow f'}(z, b, \mu_{\text{OPE}})}_{\text{perturbative coefficient}} \overbrace{f_{f'}(\frac{z}{x}, \mu_{\text{OPE}})}^{\text{collinear distribution}} \underbrace{f^f_{NP}(x, z, b, \{\lambda\})}_{\text{Non-Pertubative Model}}$$

- Collinear distribution: Input

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ART25

→ [V. Moos, I. Scimemi, A. Vladimirov & P. Zurita]

→ Implementation of the highest known perturbative results: N^{4}LL resummation.

→ Fit of Drell-Yan and semi-inclusive deep inelastic scattering data:

- DY: $P_1 + P_2 \longrightarrow \gamma^*/Z/W + X \longrightarrow \ell + \ell' + X$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T^2} \sim \int db\, b\, J_0 \underbrace{f_{1,f\leftarrow P_1}}_{\text{uPDF}} \underbrace{f_{1,f'\leftarrow P_2}}_{\text{uPDF}}$$

- SIDIS: $P + \ell \longrightarrow \ell + h + X$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{h,T}^2} \sim \int db\, b\, J_0 \underbrace{f_{1,f\leftarrow H}}_{\text{uPDF}} \underbrace{D_{1,h\to f'}}_{\text{uFF}}$$

→ Extraction of:

- CS kernel
- unpolarized proton TMDPDF
- unpolarized pion and kaon TMDFF

→ Extension of previous DY fit: (ART23)

Non-perturbative models

CS kernel

- b^*-prescription:

$$b^*(b) = \frac{b}{\sqrt{1 + \frac{b^2}{B_{\mathrm{NP}}^2}}}, \qquad \mu^*(b) = \frac{2e^{-\gamma_E}}{b^*(b)}$$

  - $b^*(b \to 0) \sim b$
  - $B_{\mathrm{NP}} \overset{\text{fixed}}{\equiv} 1.5\mathrm{GeV}^{-1}$ ($B_{\mathrm{NP}}^{\mathrm{ART23}} \overset{\text{fitted}}{=} 1.56\mathrm{GeV}^{-1}$ high correlation)

- Non-perturbative correction: (same as ART23)

$$\mathcal{D}_{\mathrm{NP}}(b) = b\, b^* \left[c_0 + c_1 \ln\left(\frac{b^*}{B_{\mathrm{NP}}} \right) \right]$$

  - c_0 and c_1 free parameters

Non-perturbative models

proton unpolarized TMDPDF

- Model:

$$f_{\mathrm{NP}}^{f}(x,b) = \frac{1}{\cosh\left[\left(\lambda_1^f(1-x)^{\lambda_3^f} + \lambda_2^f x\right) b\right]}$$

  - $f = u, \bar{u}, d, \bar{d}, \mathrm{sea}$
  - $\lambda_1^u = \lambda_1^{\bar{u}}$ and $\lambda_1^d = \lambda_1^{\bar{d}}$ (ART23: $\lambda_1^u \neq \lambda_1^{\bar{u}}$ and $\lambda_1^d \neq \lambda_1^{\bar{d}}$)
  - $\lambda_3^{\bar{u}} = \lambda_3^{\bar{d}} = \lambda_3^{\mathrm{sea}} = 1$ (ART23: $\lambda_3^f = 1$)

- OPE scale:

$$\mu_{\mathrm{OPE}}(b) = \frac{2e^{-\gamma_E}}{b} + 5 \text{ GeV}$$

  - (ART23 offset $\rightarrow$ 2 GeV)

Non-perturbative models

pion and kaon TMDFF

- Model:

$$d_{\mathrm{NP}}^{f/h}(z,b) = \frac{1+\eta_1^{h,f}\,\frac{b^2}{z^2}}{\cosh\left(\eta_0^h\,\frac{b}{z}\right)}$$

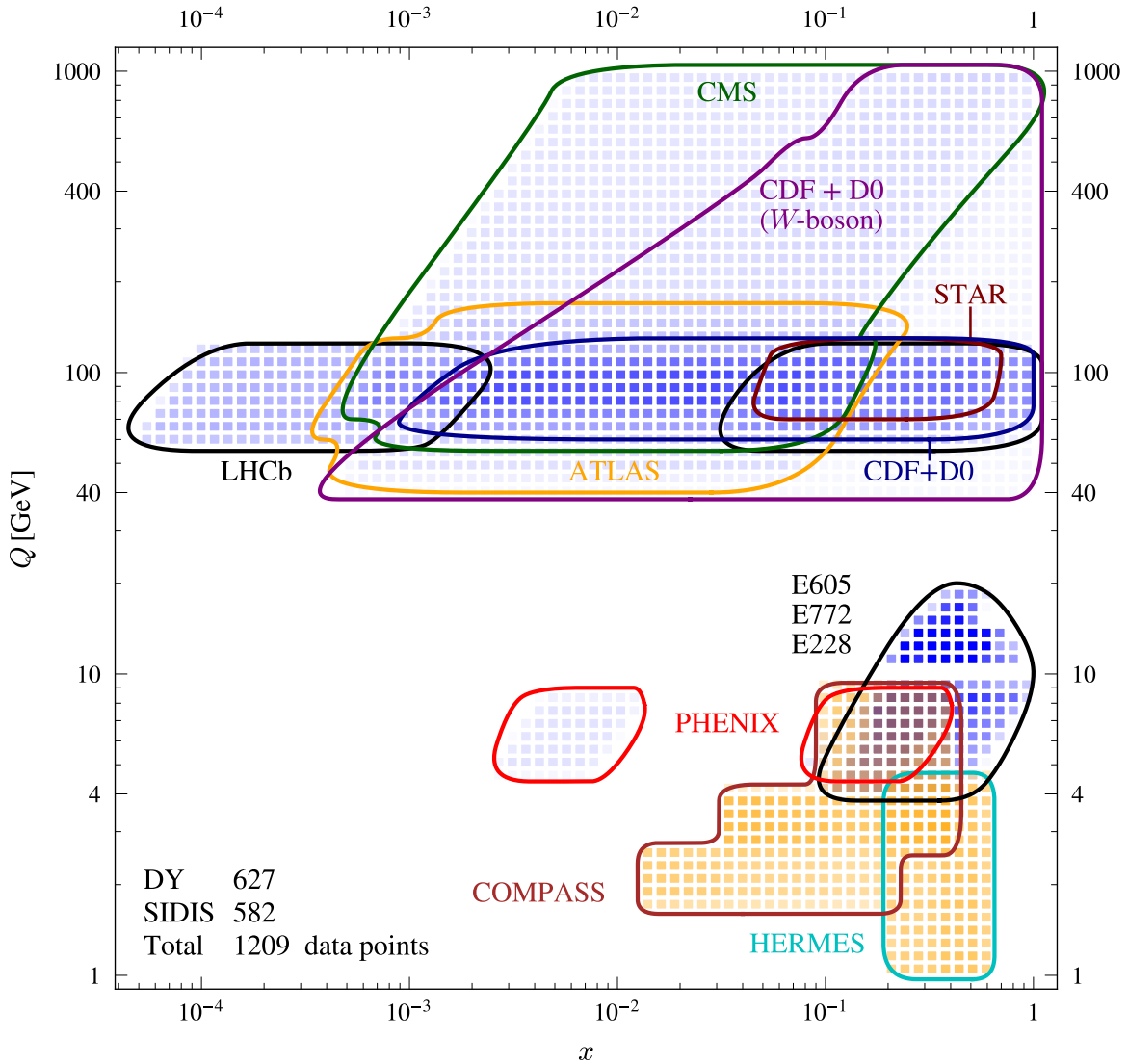
  - $\eta_0^{h,f} = \eta_0^h$ (flavor independent)
  - $\eta_1^{\pi^+,f}$; $f = u, \bar{d}, \bar{u}, r$
  - $\eta_1^{K^+,f}$; $f = u, \bar{s}, \bar{u}, r$

- OPE scale:

$$\mu_{\mathrm{OPE}}^{\mathrm{FF}}(b) = \mu_{\mathrm{OPE}}\left(\frac{b}{z}\right) = \frac{2e^{-\gamma_E}\,z}{b} + 5\ \mathrm{GeV}$$

Data

TMD cut: $\frac{\langle q_T \rangle}{\langle Q \rangle} < 0.25$



Fitting procedure

→ Minimization of χ^2_{test}:

$$\chi^2_{test} = \sum_{i,j \in \text{data}} (m_i - t_i) V_{ij}^{-1} (m_j - t_j)$$

* m_i experimental value
* t_i theoretical prediction
* V_{ij} covariance matrix:

$$V_{ij} = \delta_{ij} \Delta^2_{i,\text{uncorr.}} + \sum_l \Delta^{(l)}_{i,\text{corr.}} \Delta^{(l)}_{j,\text{corr.}}$$

  * $\Delta_{i,\text{uncorr.}}$ uncorrelated uncertainty of measurement i
  * $\Delta^{(l)}_{i,\text{corr.}}$ l-th correlated uncertainty (normalization)

→ Uncertainties: Multiple fits, each varying:

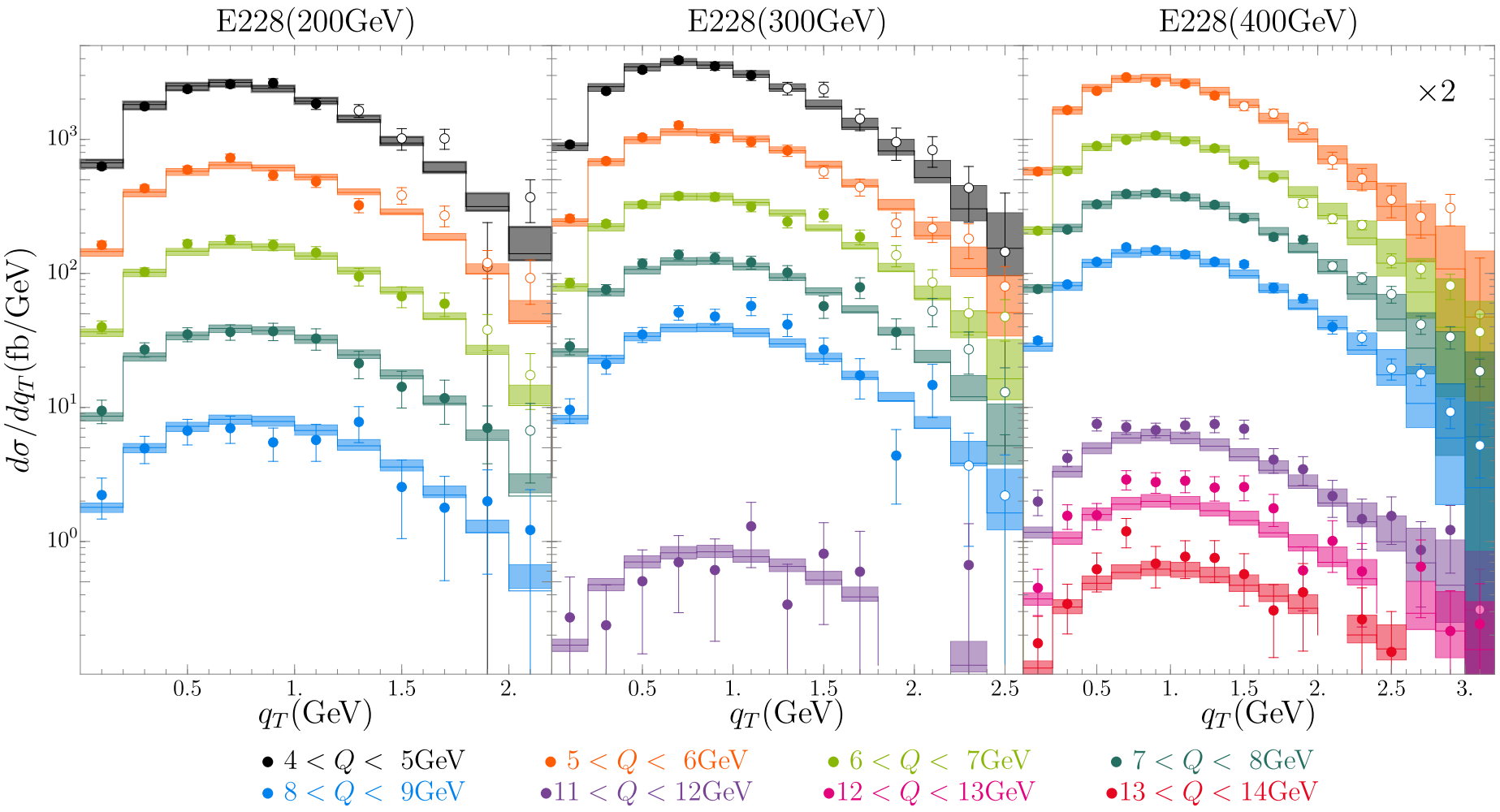
I) Experimental: pseudo-data (gaussian noise to measured values)

II) Collinear: replica of input distributions (randomly)

Parameters Fit

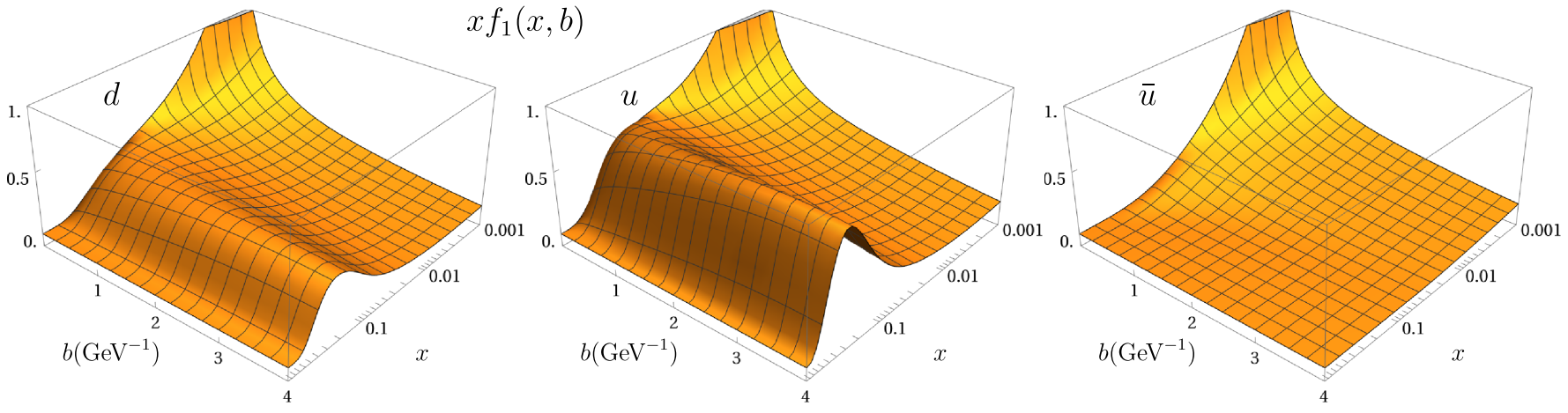
Collins-Soper kernel					
c_0			c_1		
$0.0859^{+0.0023}_{-0.0017}$			$0.0303^{+0.0038}_{-0.0041}$		
Unpolarized TMDPDF					
λ_1^u	λ_2^u	λ_3^u	$\lambda_2^{\bar{u}}$		
$0.486^{+0.048}_{-0.049}$	$0.041^{+0.007}_{-0.036}$	$5.26^{+0.54}_{-0.77}$	$21.1^{+1.5}_{-4.2}$		
λ_1^d	λ_2^d	λ_3^d	$\lambda_2^{\bar{d}}$	λ_1^{sea}	λ_2^{sea}
$0.569^{+0.035}_{-0.045}$	$0.15^{+0.01}_{-0.11}$	$7.7^{+2.0}_{-4.5}$	$0.16^{+0.01}_{-0.15}$	$0.240^{+0.035}_{-0.083}$	$0.07^{+0.00}_{-0.07}$
Unpolarized TMDFF for π					
η_0^π		$\eta_1^{\pi,u}$	$\eta_1^{\pi,\bar{d}}$	$\eta_1^{\pi,\bar{u}}$	$\eta_1^{\pi,r}$
$0.696^{+0.011}_{-0.006}$		$0.626^{+0.047}_{-0.027}$	$0.003^{+0.081}_{-0.080}$	$0.610^{+0.028}_{-0.028}$	$-0.47^{+0.14}_{-0.18}$
Unpolarized TMDFF for K					
η_0^K		$\eta_1^{K,u}$	$\eta_1^{K,\bar{s}}$	$\eta_1^{K,\bar{u}}$	$\eta_1^{K,r}$
$0.884^{+0.020}_{-0.032}$		$0.882^{+0.055}_{-0.147}$	$1.74^{+0.16}_{-0.28}$	$1.15^{+0.11}_{-0.28}$	$-0.10^{+0.36}_{-0.30}$

Cross Section



proton unpolarized TMDPDF

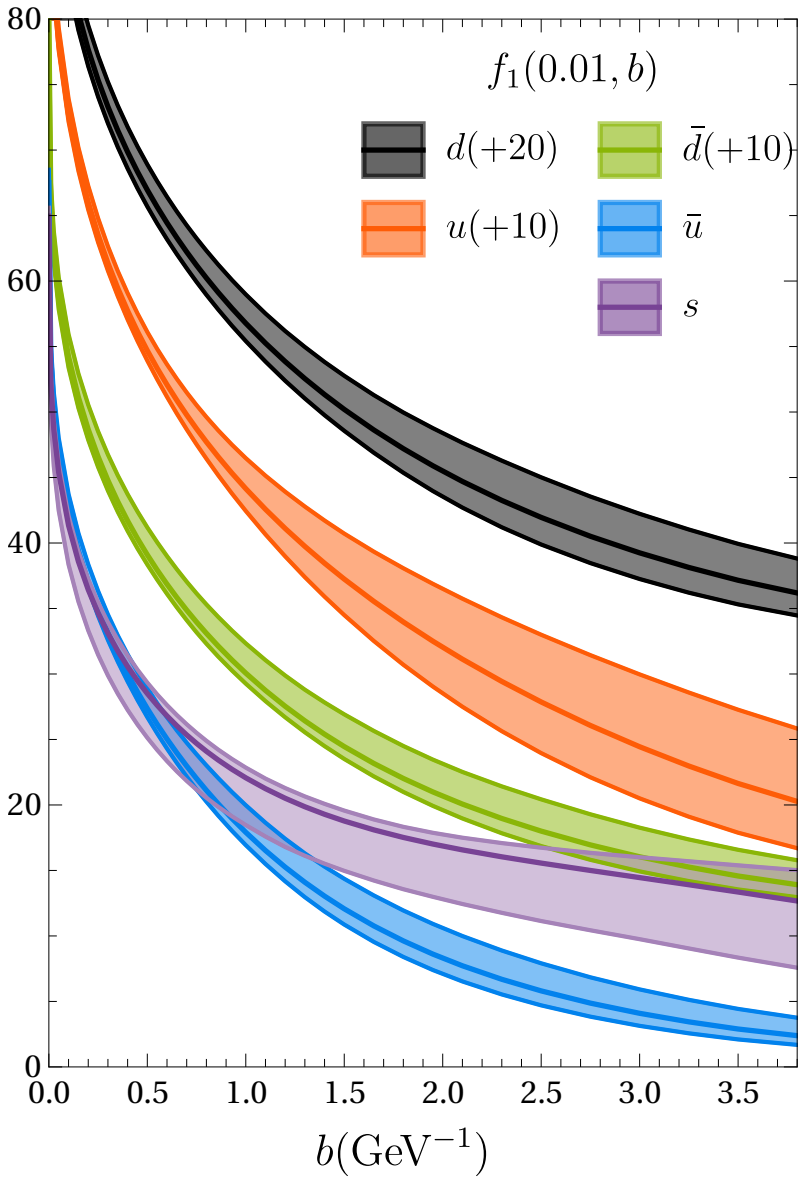
3d plots

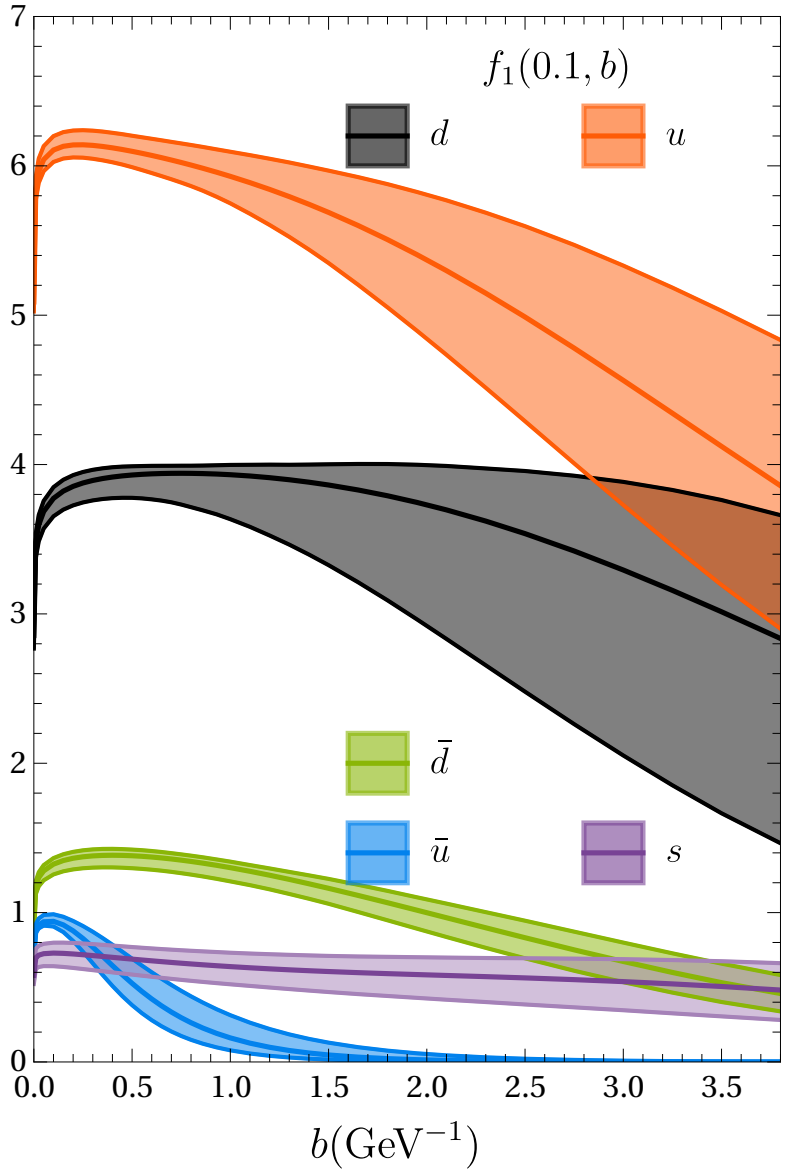


$\rightarrow$ Transverse Momentum Moments (see Alexey's talk later) of obtained distributions were also analyzed.

proton unpolarized TMDPDF

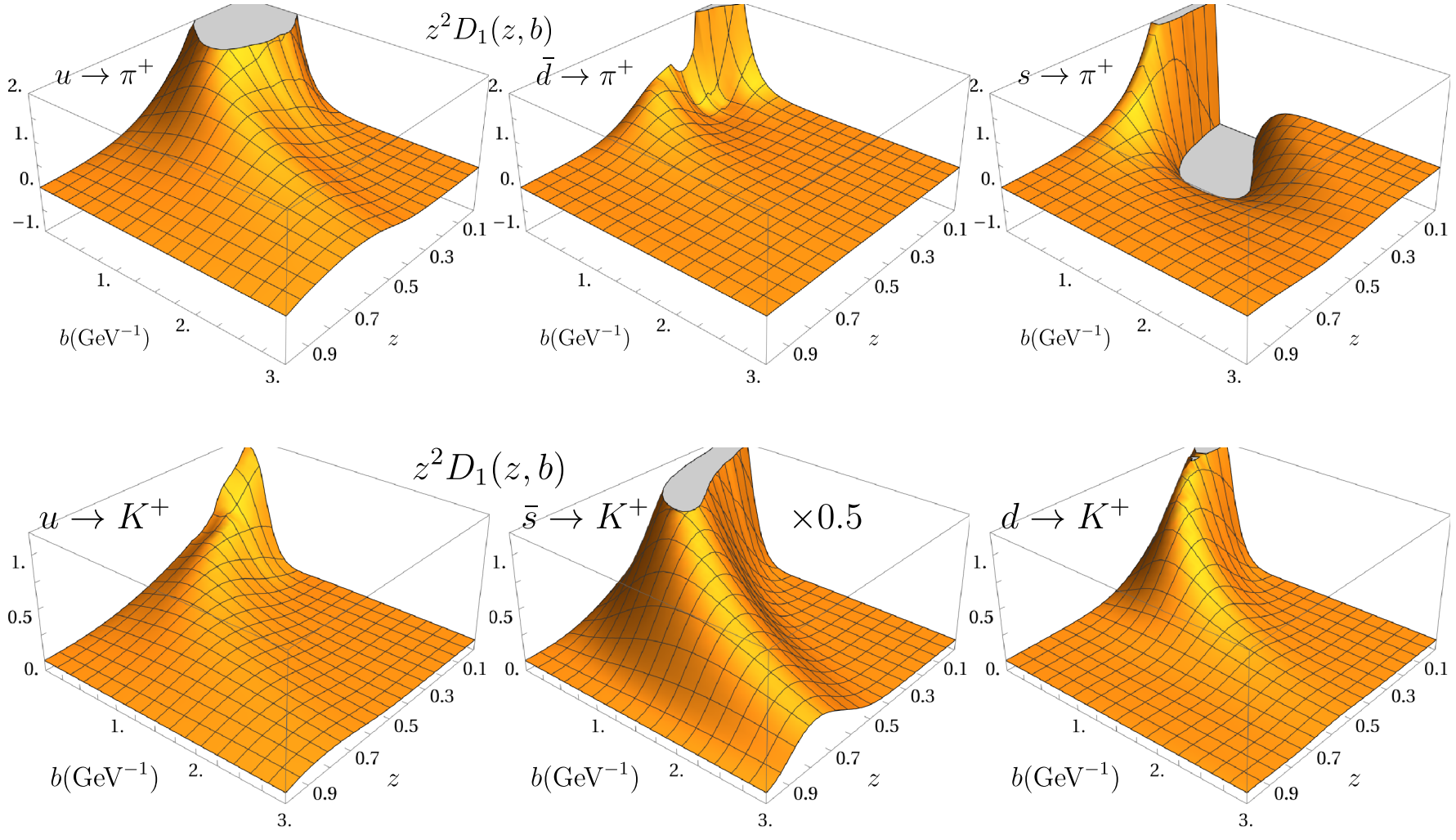
Sections





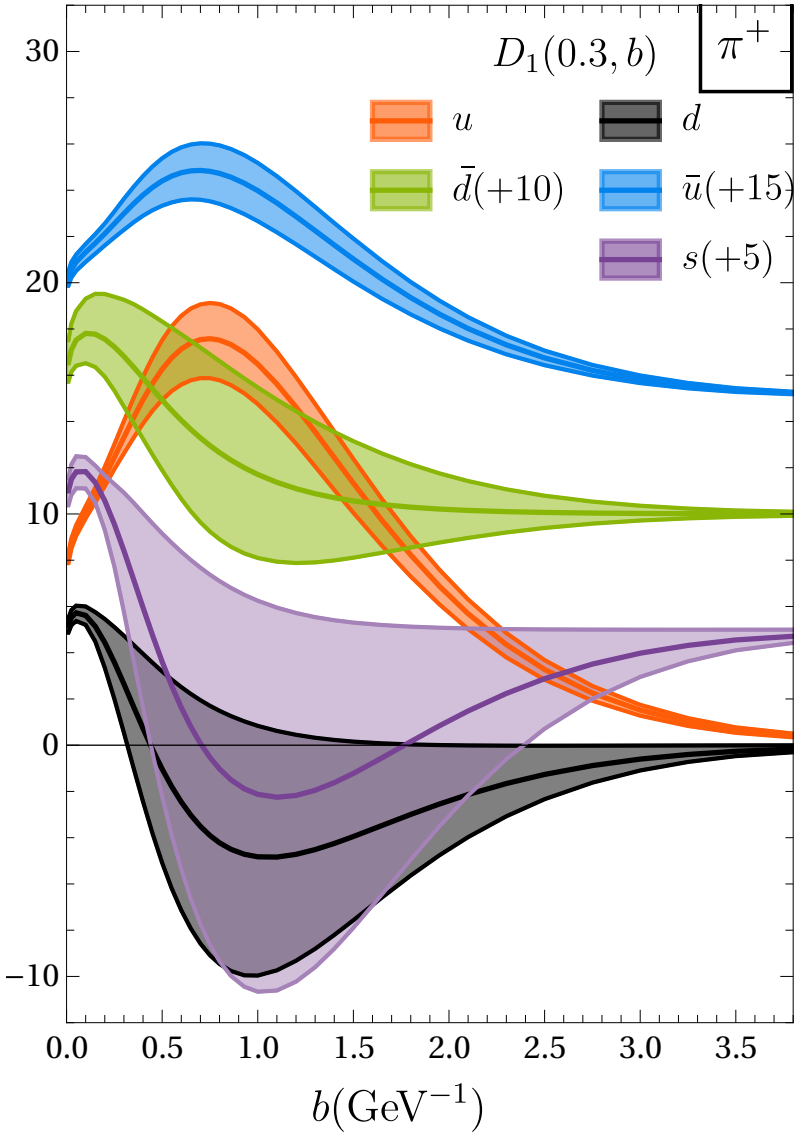
pion and kaon unpolarized TMDFF

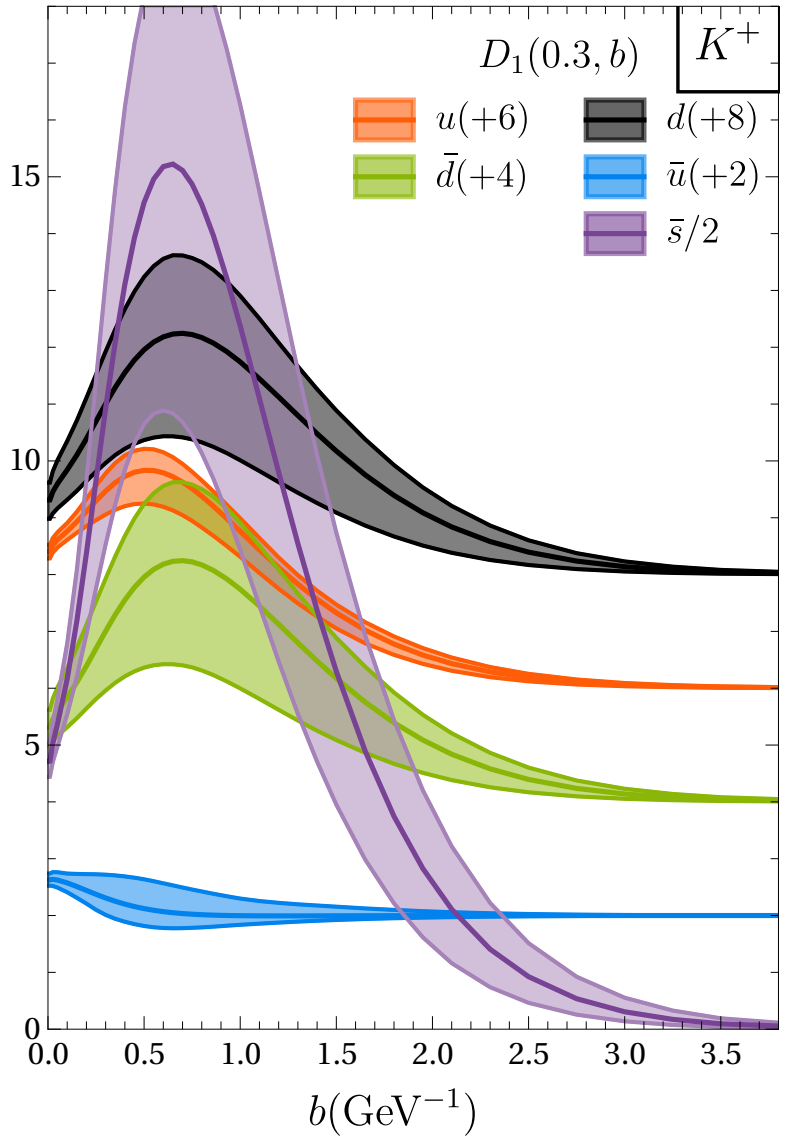
3d plots



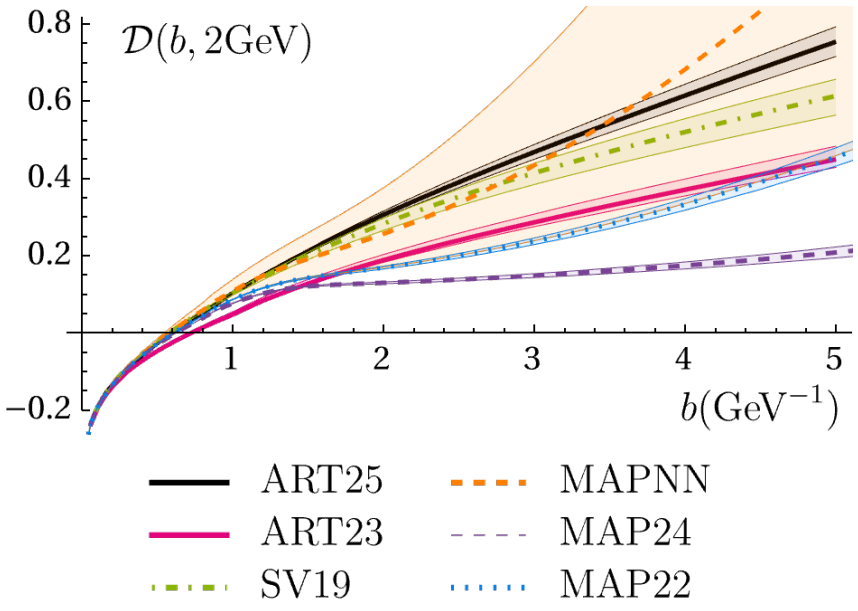
pion and kaon unpolarized TMDFF

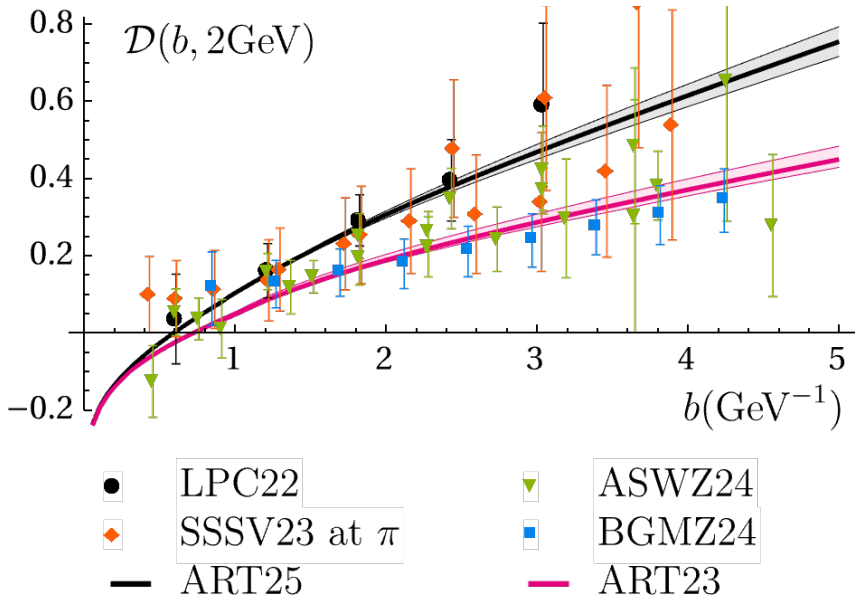
Sections





CS kernel


$\mathcal{D}(b, 2\text{GeV})$
0.8
0.6
0.4
0.2
−0.2
1
2
3
4
5
$b(\text{GeV}^{-1})$
ART25
ART23
SV19
MAPNN
MAP24
MAP22


$\mathcal{D}(b, 2\text{GeV})$
0.8
0.6
0.4
0.2
−0.2
1
2
3
4
5
$b(\text{GeV}^{-1})$
LPC22
SSSV23 at π
ART25
ASWZ24
BGMZ24
ART23

Remarks

→ Fit anomalies: attributed to potential issues in collinear input [M. Bury, F. Hautmann, S. Leal-Gomez, I. Scimemi & A. Vladimirov]

- Unusual behavior of the proton TMDPDF for the $\bar{u}$ flavor: $\lambda_2^{\bar{u}}$ value diverges from the rest $\Rightarrow$ TMDPDF at $x \sim 0.1$ abnormally small with wide relative uncertainty.
- Large size of the K^+ TMDFF for $\bar{s}$

→ CS kernel not compatible (at large b) with ART23 despite the analogous framework.

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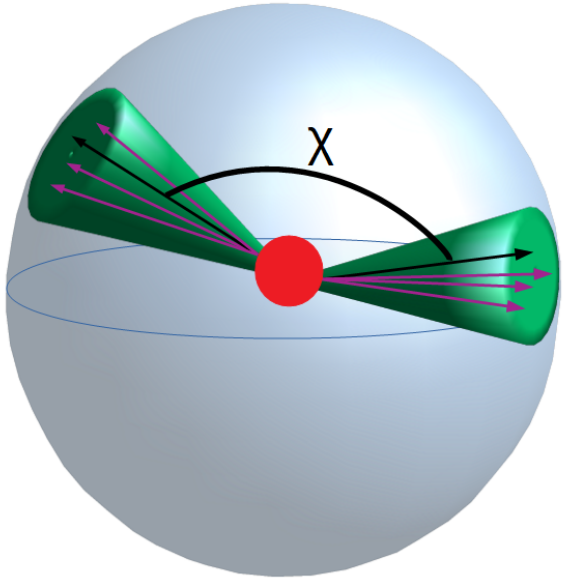
Energy-Energy Correlators

$$e^+ + e^- \longrightarrow \gamma^*/Z \longrightarrow h_1 + h_2 + X$$



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

$$\chi \longleftrightarrow z = \frac{1 - \cos(\chi)}{2}$$

Back-to-back limit

$z \to 1$ ($\chi \to 180^\circ$)

- Fixed order perturbative result: EEC $\sim \log(1-z)$ LARGE LOGARITHMS !!
- All orders resummation:

$$\underbrace{\lim_{z\to 1}\frac{\mathrm{d}\sigma}{\mathrm{d}z} \leftrightarrow \lim_{q_\perp \to 0}\frac{\mathrm{d}\sigma}{\mathrm{d}x_i \mathrm{d}x_j \mathrm{d}^2\vec{q}_\perp} \quad \& \quad \text{TMD factorization}}$$

$$\Downarrow$$

Factorization theorem

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z} = \frac{\hat{\sigma}_0}{8}\sum_{f,\bar{f}} H_{f\bar{f}}(Q,\mu)\int_0^\infty \mathrm{d}(b_T Q)^2 J_0(b_T Q\sqrt{1-z}) J_f(b_T,\mu,\zeta) J_{\bar{f}}(b_T,\mu,\bar{\zeta})$$

- $\hat{\sigma}_0$ Born cross section
- $H_{f\bar{f}}(Q,\mu)$ hard function $\leftrightarrow$ [$\mathcal{O}(\alpha_s^4)$]
- Jet function $J_f(b_T,\mu,\zeta) \equiv \sum_h \int_0^1 \mathrm{d}z\, z^3 \overbrace{D_{f\to h}(z,b_T,\mu,\zeta)}^{\text{TMDFF}} \leftrightarrow \mathrm{N^4LL}+\mathcal{O}(\alpha_s^3)$

$$\mathrm{d}\sigma \sim \int \mathrm{Bessel}_J \times \mathrm{TMD} \times \mathrm{TMD} \Longrightarrow \boxed{\texttt{artemide}}$$

Evolution does not depend on z $\Rightarrow$ same as TMDFF:

$$\frac{d}{d\ln\mu^2}\ln J_f(b_T;\mu,\zeta) = \frac{\Gamma_{\text{cusp}}(\mu)}{2}\ln\left(\frac{\mu^2}{\zeta}\right) - \frac{\gamma_V(\mu)}{2}$$

$$\frac{d}{d\ln\zeta}\ln J_f(b_T;\mu,\zeta) = -\mathcal{D}(b_T,\mu)$$

$\rightarrow$ ζ-prescription:

$$J_f(b_T;\mu,\zeta) = \left(\frac{Q^2}{\zeta_Q(b_T^2)}\right)^{-\mathcal{D}(b_T,\mu)} \underbrace{J_f(b_T)}_{\text{Optimal}}$$

CS kernel model:

$$\mathcal{D}_{\text{NP}}(b) = b\,b^*\left[c_0 + c_1\ln\left(\frac{b^*}{B_{\text{NP}}}\right)\right]$$

artemide implementation

(Optimal) Jet function

→ Optimal Jet function:

$$J_f\left(b_T\right) \equiv \overbrace{\sum_h}^{\text{sum over all hadrons}} \int_0^1 \mathrm{d}z\, z^3\, \overbrace{D_{f\to h}\left(z, b_T\right)}^{\text{Optimal TMDFF}}$$

→ Optimal TMD fragmentation function: LO OPE ⊗ model

$$D_{f\to h}\left(z,b\right) \equiv \frac{1}{z^2}\int_z^1 \frac{\mathrm{d}y}{y} \sum_{f'} y^2\, \overbrace{\mathbb{C}_{f\to f'}\left(y,b,\mu_{\text{OPE}}\right)}^{\text{perturbative coeff.}}\, \overbrace{d_{1,f'\to h}\left(\frac{z}{y},\mu_{\text{OPE}}\right)}^{\text{Collinear FF (DATA)}}\, \overbrace{D^h_{\text{NP}}(z,b)}^{\text{NP model}}$$

✗ $J = \sum_h \int$ LO OPE ⊗ model

Collinear FF data sets do not satisfy the sum rule:

$$\sum_{h\in\text{Data}} \int_0^1 \mathrm{d}z\, z\, d_{f\to h}(z,\mu) \sim 0.5 \neq 1$$

artemide implementation

(Optimal) Jet function

I) $J^{\text{pert.}}(b_T) \equiv \lim_{b_T\to 0} J_f(b_T)\,|_{f=q,\,\bar{q}}$

$$\left.\begin{array}{r}\lim_{b\to 0} D^h_{\rm NP}(z,b)=1\\ \sum_h \int_0^1 \mathrm{d}z\, z\, d_{f\to h}(z,\mu)=1\end{array}\right\} \Rightarrow J^{\text{pert.}}(b_T) = \sum_{f'}\int_0^1 \mathrm{d}y\, y^3 \mathbb{C}_{f\to f'}(y, b_T, \mu_{\rm OPE})\,|_{f=q,\,\bar{q}}$$

$$\begin{aligned} J^{\text{pert.}}(b_T) = 1 &+ \left(\frac{16}{3} - 2\pi^2\right)\alpha_s + \frac{\alpha_s^2}{486}\left[2n_f\left(936\zeta_3 + 594\pi^2 - 989\right) + 3\left(2736\zeta_3 + 516\pi^4 - 9150\pi^2 + 10777\right)\right] \\ &+ \frac{\alpha_s^3}{1377810}\Big\{-28n_f^2\left(1332720\zeta_3 + 3618\pi^4 + 157140\pi^2 - 114055\right) \\ &- 420n_f\left(-1846062\zeta_3 + 30\pi^2(2313\zeta_3 - 23912) - 372600\zeta_5 + 24222\pi^4 + 730687\right) \\ &- 15\Big[126\pi^2(1664467 - 383310\zeta_3) - 21(216\zeta_3(1577\zeta_3 - 20116) - 20741616\zeta_5 + 5925635) \\ &+ 438352\pi^6 - 15926337\pi^4\Big]\Big\} + \mathcal{O}(\alpha_s^4) = J^{\text{pert.}}(b_T, \mu, \zeta_\mu) \quad ([M.A.Ebert, B.Mistlberger, G.Vita]) \end{aligned}$$

* with $\alpha_s \equiv \alpha_s\left(\frac{2e^{-\gamma_E}}{b_T}\right)$

artemide implementation

(Optimal) Jet function

II) $J_f(b_T) \equiv J^{\text{pert.}}(b_J^*)\, J_f^{\text{NP}}(b_T)$

- b_J^*-prescription:

$$b_J^*(b_T) = \frac{b_T}{\sqrt{1+\frac{b_T^2}{B_J^{*2}}}}$$

  - $B_J^* \equiv 0.22\text{GeV}^{-1} \Rightarrow \frac{2e^{-\gamma_E}}{b_J^*} > 5\text{GeV}$ (Avoid numerical fluctuations below bottom threshold m_b)

- Non-perturbative correction:
  - $\rightarrow$ $\lim_{b_T\to 0} J^{\text{NP}}(b_T) = 1$
  - $\rightarrow$ Numerical justification: [H.T. Li, Y. Makris , I. Vitev]

$$\left.\begin{array}{r} J_f^{\text{NP}}(b) \sim \sum_h \int_0^1 \mathrm{d}z\, z\, d_{f\to h}(z,\mu) D_{\text{NP}}^h(z,b)|_{\mu=\mu_0} \\ D_{\text{NP}}^h(z,b) \sim \text{Gaussian} \end{array}\right\} \Rightarrow J_f^{\text{NP}}(b_T) \sim e^{-a\, b_T} \quad (\sim f-\text{independent})$$

  - $\rightarrow$ Similar model used in [Z.-B. Kang, J. Penttala and C. Zhang]

artemide implementation

(Optimal) Jet function

MODEL 1: Exponential model:

$$J^{\rm NP}(b_T) = e^{-a_1 b_T}$$

* One free parameter a_1
* Enough to describe shape of the data

MODEL 2:

$$J^{\rm NP}(b_T) = e^{-a_1 b_T}\,\frac{1+a_2 b_T^2}{1+a_3 b_T^2}$$

* Quadratic corrections a_2, a_3
* $a_3 > 0$

Data

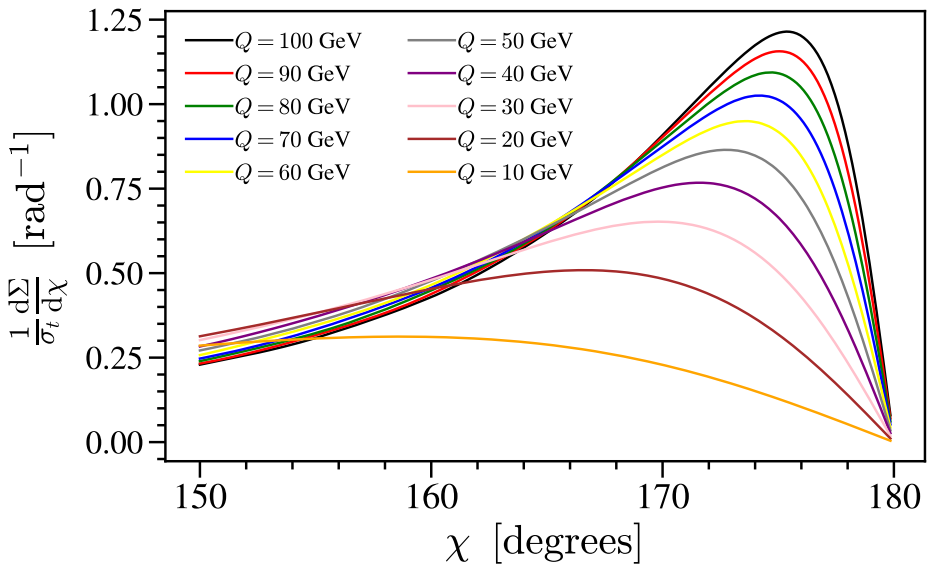
Summary

Experiment	Q (GeV)	References
OPAL	91.0, 91.2, 90.7-91.7	PLB [1990, 1992], [ZPC 1993]
SLD	91.2	[PRD 1995]
TOPAZ	53.3, 59.5	[PLB 1989]
MARKII	29	[PRD 1988]
TASSO	14, 22, 34.8, 43.5	[ZPC 1987]
MAC	29	[PRD 1985]
PLUTO	7.7, 9.4, 12, 13, 17, 22, 27.6, 27.6-31.6	[PLB 1981]
CELLO	22, 34	[ZPC 1982]
JADE	14, 22, 34	[ZPC 1984]
DELPHI	91.2	ZPC [1992, 1993]

Data

Comments

- Publication dates: 1981-1995 $\Rightarrow$ Data from >30 years ago
- Intended for α_s extractions from central region
  (EEC used in conjunction with results for event shapes)
- Few details on error estimation $\Rightarrow$ Uncorrelated uncertainties
- Focus on shape $\Rightarrow$ include set-by-set normalization (best χ^2)



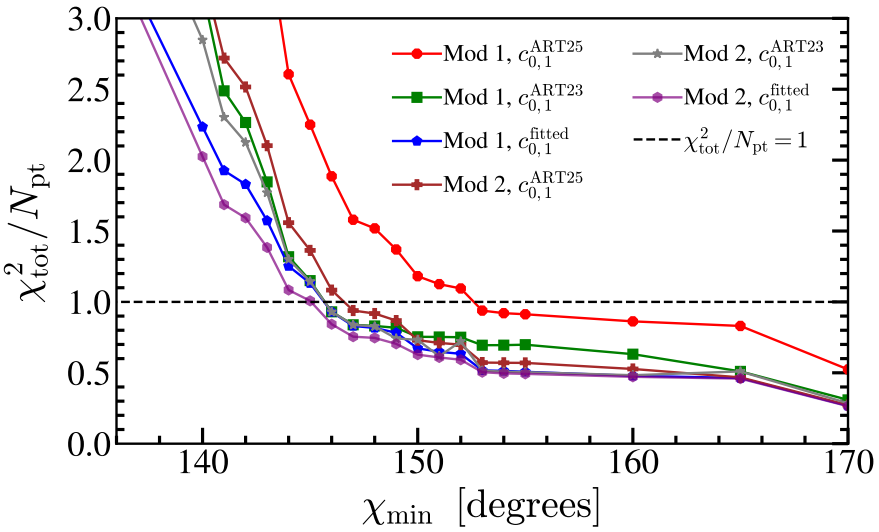
Data

Comments

- Fit range: (validity of back-to-back factorization theorem)

$$\chi_{\min} \equiv 150^\circ$$

$$\left(\sqrt{1-z} \sim \frac{q_T}{Q} \sim 0.25 \implies \chi \sim 150^\circ\right)$$



- Total number of points 243

Fits

→ 3 different fits for each J^{NP}:

I CS kernel fixed to ART25 values (obtained from DY+SIDIS data)
II CS kernel fixed to ART23 values (obtained from DY data)
III CS kernel fitted

→ χ^2_{test} minimization

→ Replicas method. 500 fits, each varying:

- EEC pseudo-data (I, II, III)
- c_0, c_1 results from ART replicas (I, II)

Parameters Fit

Model 1

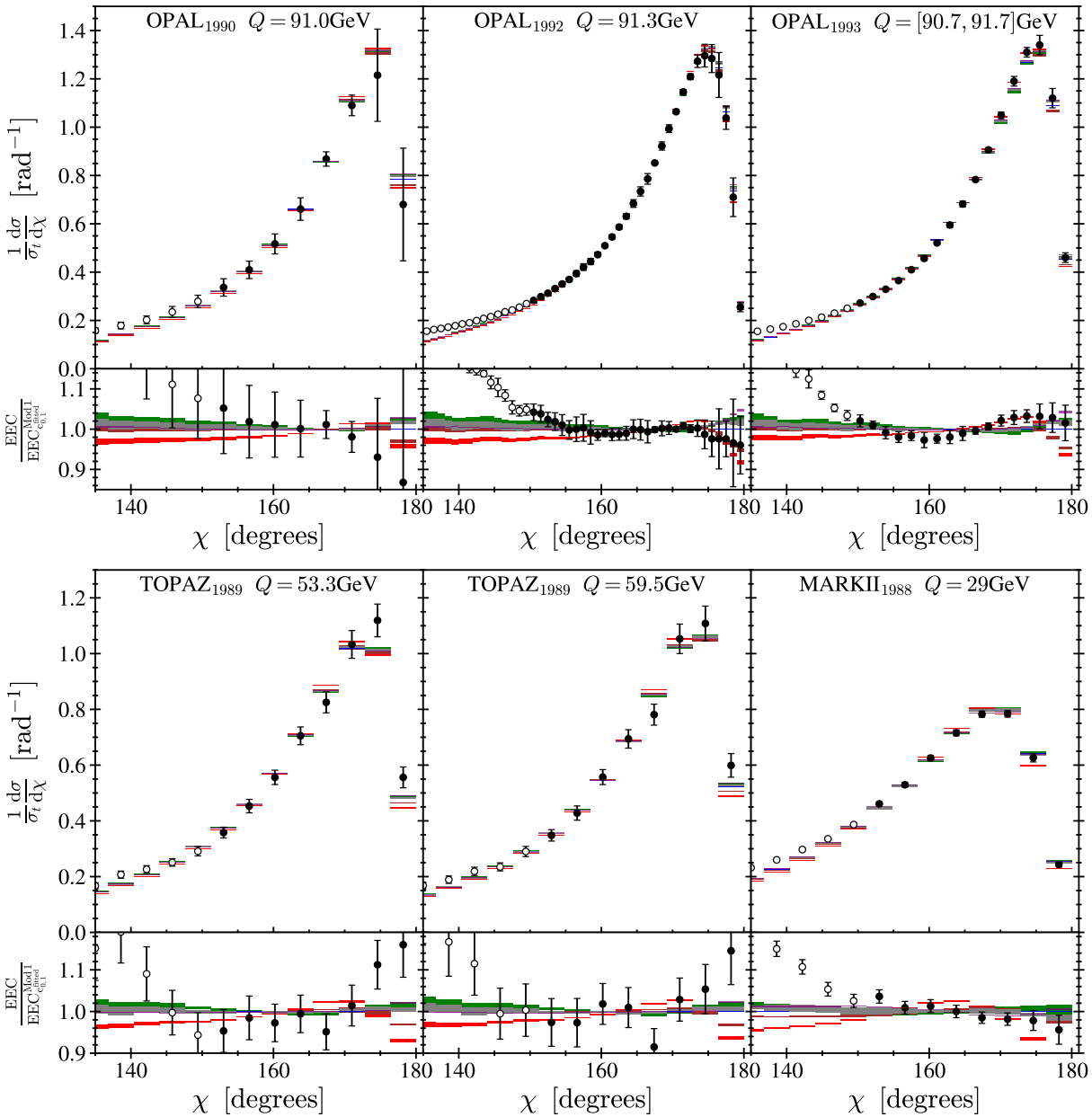
	$c_{0,1}^{\mathrm{ART25}}$	$c_{0,1}^{\mathrm{ART23}}$	$c_{0,1}^{\mathrm{fitted}}$
$c_0[\mathrm{GeV}^{-2}]$	$8.59^{+0.23}_{-0.17} \cdot 10^{-2}$	$3.69^{+0.65}_{-0.61} \cdot 10^{-2}$	$3.17^{+0.04}_{-0.03} \cdot 10^{-2}$
$c_1[\mathrm{GeV}^{-2}]$	$3.03^{+0.38}_{-0.41} \cdot 10^{-2}$	$5.82^{+0.64}_{-0.88} \cdot 10^{-2}$	$2.37^{+0.07}_{-0.1} \cdot 10^{-2}$
$a_1[\mathrm{GeV}]$	$0.879^{+0.014}_{-0.015}$	$1.002^{+0.009}_{-0.016}$	$0.941^{+0.002}_{-0.003}$
$\chi^2_{\mathrm{tot}}/N_{\mathrm{pt}}$	1.18	0.75	0.67

Model 2

	$c_{0,1}^{\mathrm{ART25}}$	$c_{0,1}^{\mathrm{ART23}}$	$c_{0,1}^{\mathrm{fitted}}$
$c_0[\mathrm{GeV}^{-2}]$	$8.59^{+0.23}_{-0.17} \cdot 10^{-2}$	$3.69^{+0.65}_{-0.61} \cdot 10^{-2}$	$1.41^{+0.22}_{-0.19} \cdot 10^{-2}$
$c_1[\mathrm{GeV}^{-2}]$	$3.03^{+0.38}_{-0.41} \cdot 10^{-2}$	$5.82^{+0.64}_{-0.88} \cdot 10^{-2}$	$5.31^{+0.34}_{-0.23} \cdot 10^{-2}$
$a_1[\mathrm{GeV}]$	$0.976^{+0.013}_{-0.013}$	$0.949^{+0.033}_{-0.030}$	$0.917^{+0.003}_{-0.003}$
$a_2[\mathrm{GeV}^2]$	$0.246^{+0.017}_{-0.018}$	$0.83^{+0.95}_{-0.85}$	$0.88^{+0.04}_{-0.04}$
$a_3[\mathrm{GeV}^2]$	$(5.^{+10.}_{-4.7}) \times 10^{-7}$	$1.0^{+1.1}_{-1.0}$	$1.2^{+0.1}_{-0.1}$
$\chi^2_{\mathrm{tot}}/N_{\mathrm{pt}}$	0.73	0.73	0.63

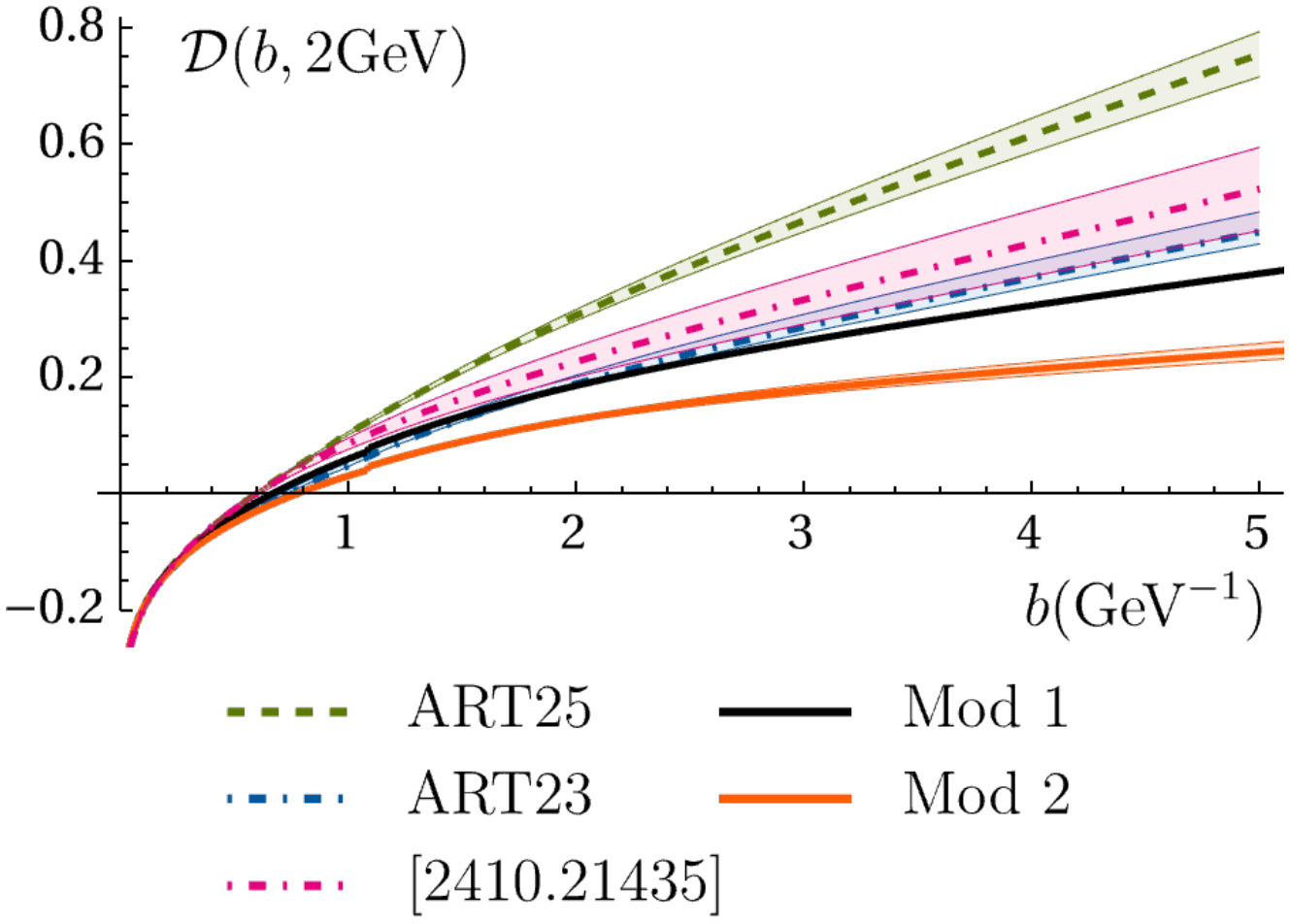
Cross Section

Replica method

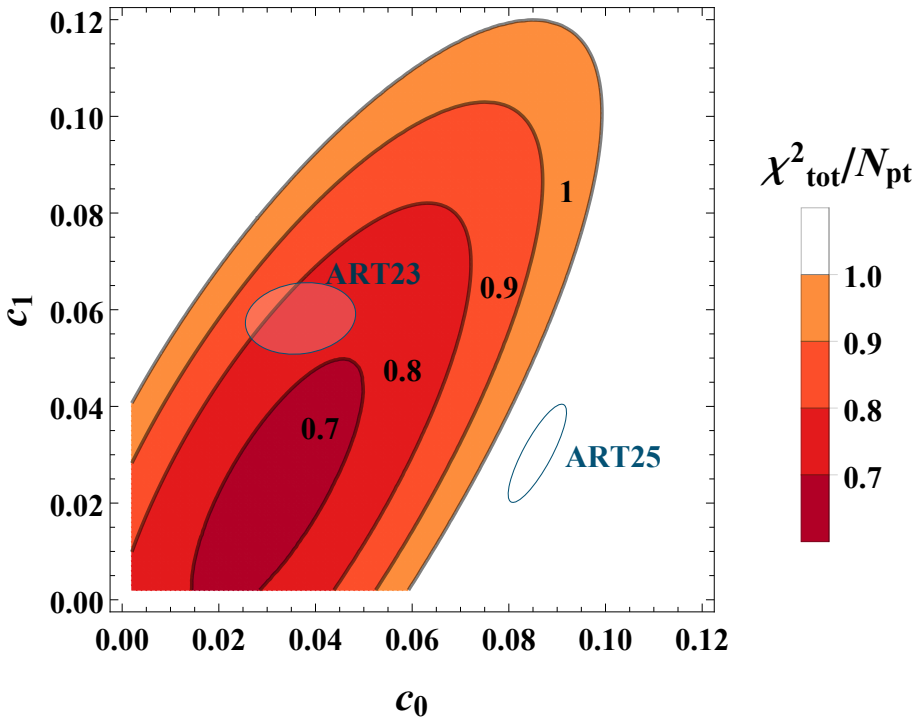


Collins-Soper kernel

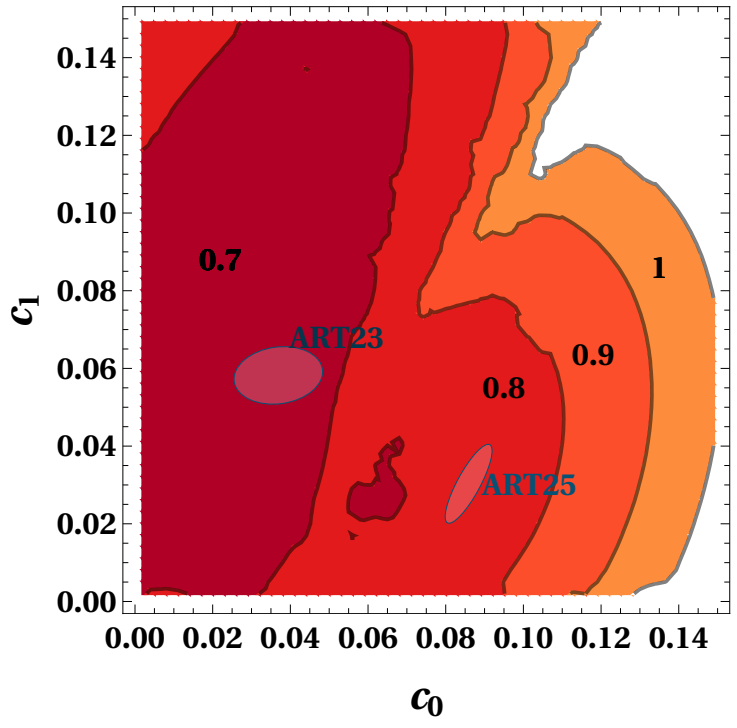
Replica method



scans



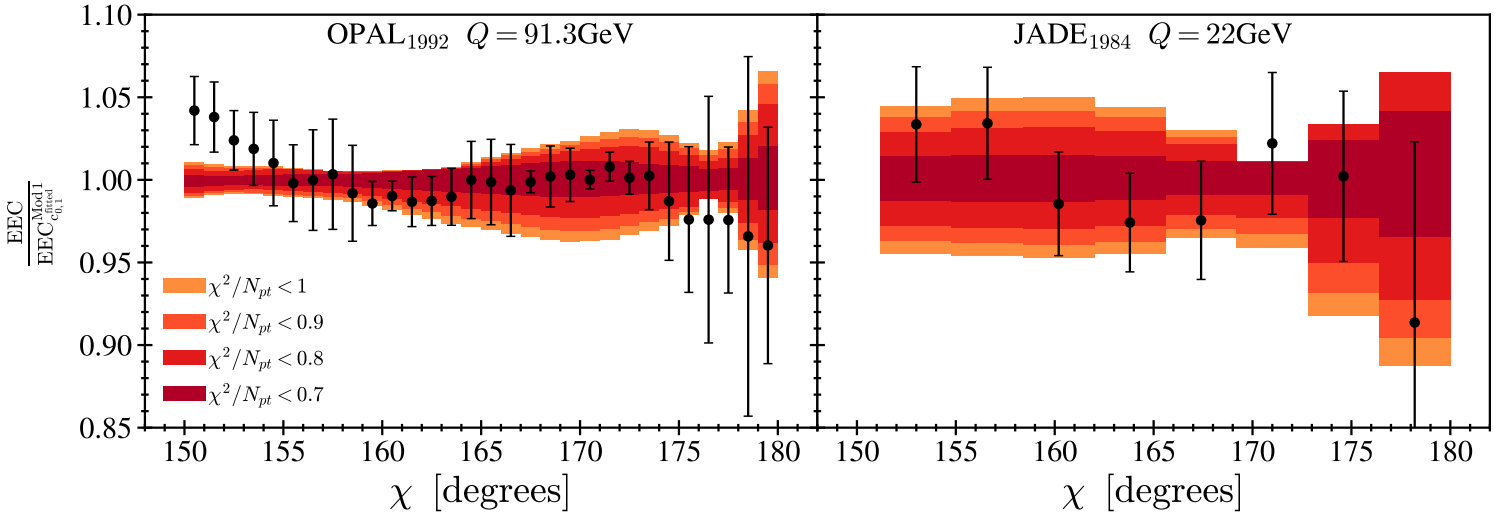
Model 1 (a_1 fitted)

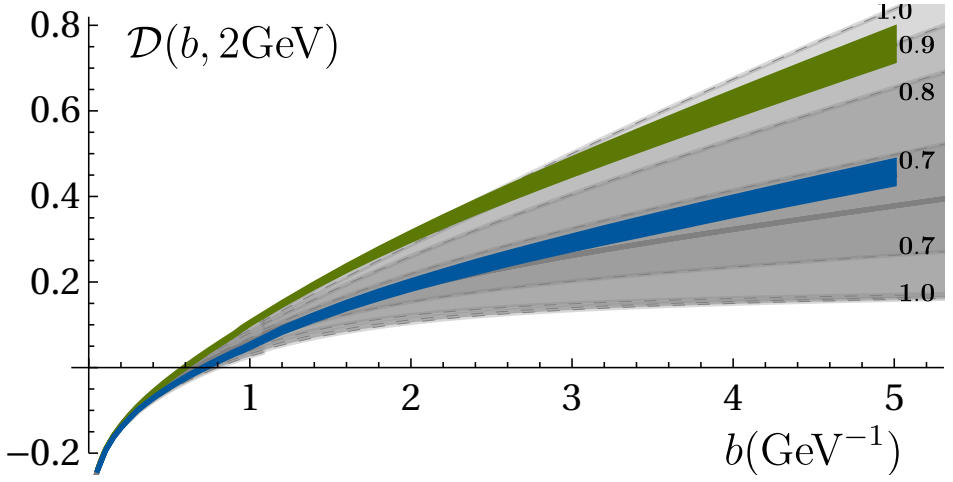


Model 2 ($a_{1,2,3}$ fitted)

scans

Uncertainty bands

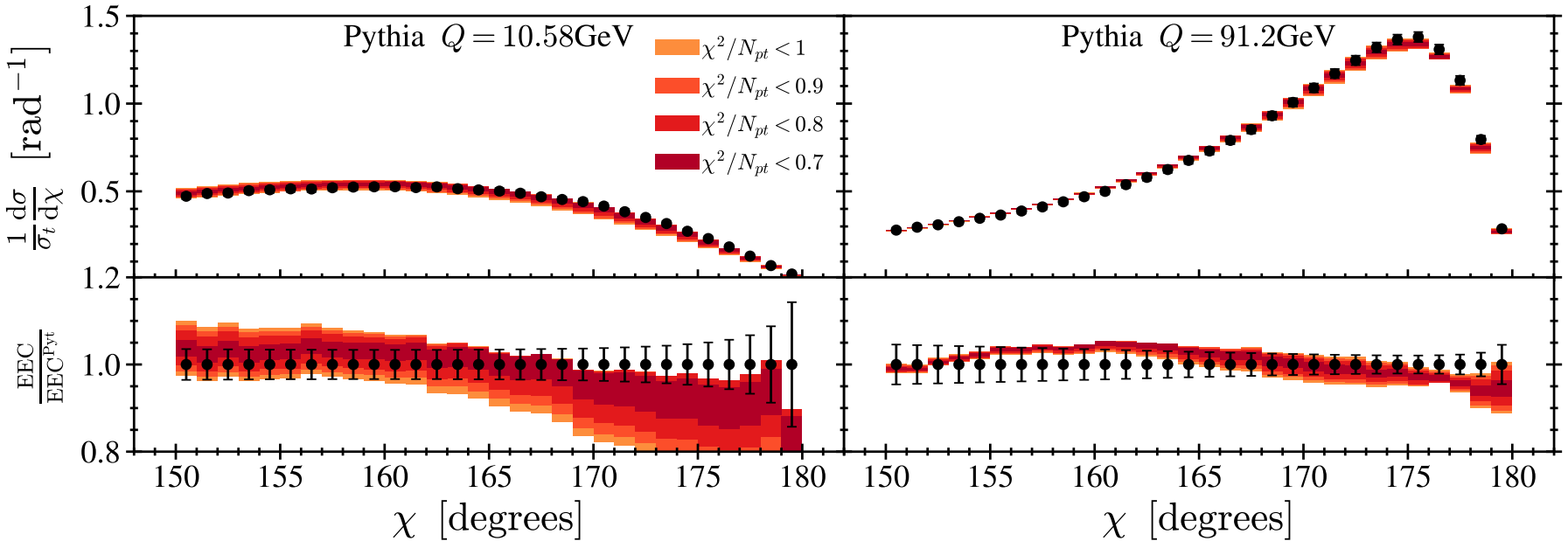




ART25 ART23

Predictions

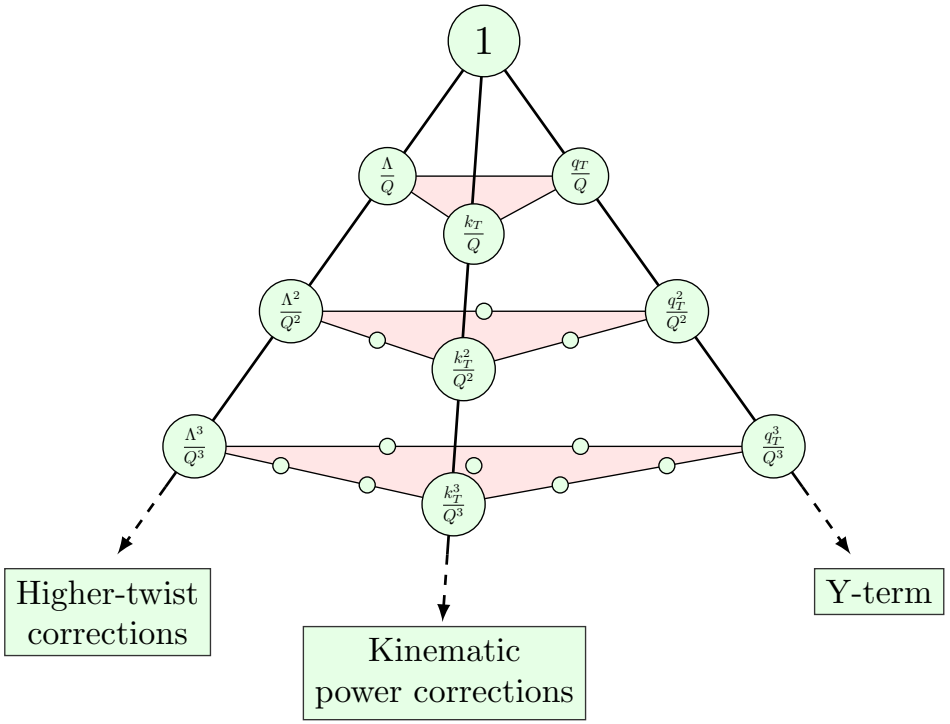
Comparison with [Pythia 8.3 (ffbar2gmZ)]



Outline

1. Overview
2. DY+SIDIS (ART25)
   - Description
   - Non-perturbative models
   - Results
3. EEC
   - Introduction
   - `artemide` implementation
   - Data
   - Results
4. Ongoing work
   - KPCs
   - Fits reanalysis

Power corrections



[S. Piloñeta & A. Vladimirov]

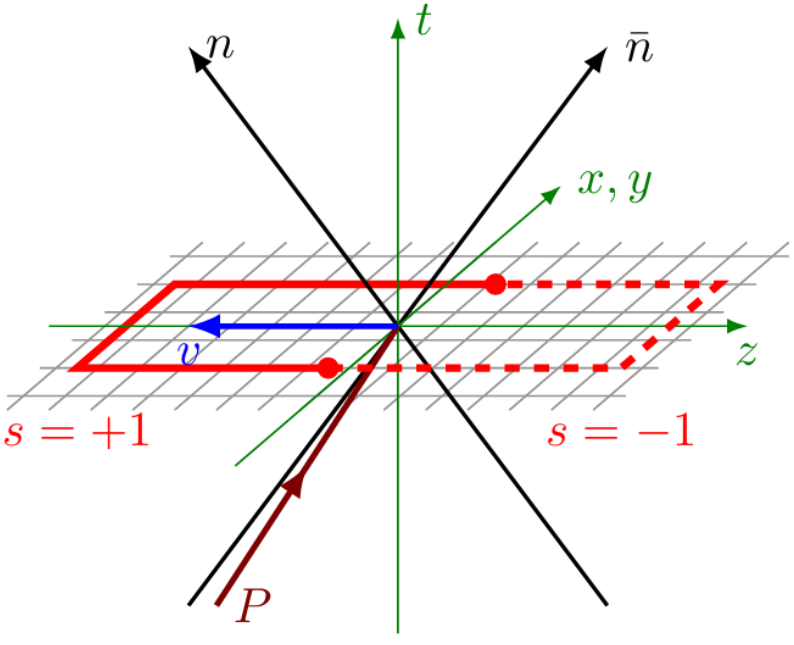
- *Genuine higher-twist corrections:* These corrections describe new multi-parton dynamics that appear at higher power, and is represented via genuine higher-twists distributions.
- *q_T-corrections:* These corrections arise in the limit of small transverse separation between factorized currents.

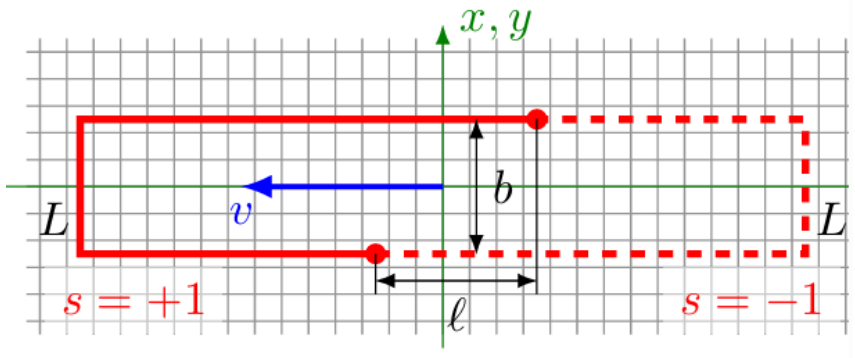
- *Target mass corrections:* These corrections appear due to the finite mass of hadron.
- *Kinematic power corrections (KPCs):* These corrections appear due to non-zero own transverse momentum of partons, and arise as derivatives of TMD matrix elements.

qTMD

qTMD correlator: (see Simone's talk on Monday)

$$\widetilde{\Omega}^{[\Gamma]}_{q/h}(y;\mu) = Z^{-1} \times \langle P,s|\bar{q}(y)[y, y_T + Lv][y_T + Lv, Lv][Lv, 0]\frac{\Gamma}{2}q(0)|P,s\rangle$$





[S. Rodini & A. Vladimirov]

qTMD factorization theorem

→ At large hadron momentum: Matching qTMD↔TMD

→ Matching at leading power: $(\zeta\bar{\zeta} = (2x\mu P_v)^2\ )$

$$\widetilde{\Omega}^{[\Gamma]}_{q/h}(x,b;\mu) \overset{\text{LP}}{=} \underbrace{\Psi(b;\mu,\bar{\zeta})}_{\text{reduced soft factor}} C\left(\frac{(2xP_v)^2}{\mu^2}\right) \frac{K^{[\Gamma]}_{\text{LP}}}{xP_v} \widetilde{\Phi}^{[\Gamma_+]}_{11}(x,b;\mu,\zeta)$$

$$\{\frac{K^{[\Gamma]}_{\text{LP}}}{\sqrt{2}xP_v},\ \Gamma_+\} = \begin{cases} \{0, & -\} & \text{for } \Gamma = 1 \text{ or } \gamma^5, \\ \{\bar{n}^\mu, & \gamma^+\} & \text{for } \Gamma = \gamma^\mu, \\ \{\bar{n}^\mu, & \gamma^+\gamma^5\} & \text{for } \Gamma = \gamma^\mu\gamma^5, \\ \{g_T^{\mu\alpha}\bar{n}^\nu - g_T^{\nu\alpha}\bar{n}^\mu, & i\sigma^{\alpha+}\gamma^5\} & \text{for } \Gamma = i\sigma^{\mu\nu}\gamma^5 \end{cases}$$

→ Current lattice TMD extractions use LP relation:

$$F^{[\Gamma=\gamma_0,\gamma_v]}_{q/h}(x,b;\mu) \equiv \frac{\widetilde{\Omega}^{[\Gamma=\gamma_0,\gamma_v]}_{q/h}(x,b;\mu)}{\Psi(b;\mu,\mu^2)} \overset{\text{LP}}{=} C\left(\frac{(2xP_v)^2}{\mu^2}\right)\left(\frac{(2xP_v)^2}{\zeta}\right)^{-\mathcal{D}(b,\mu)} f_1(x,b;\mu,\zeta)$$

$$\Rightarrow \mathcal{D}(b,\mu) \overset{\text{LP}}{=} \frac{1}{2\log(P_{v,2}/P_{v,1})} \log\left(\frac{C\left(\frac{(2xP_{v,2})^2}{\mu^2}\right)\widetilde{\Omega}^{[\Gamma=\gamma_0,\gamma_v]}_{q/h}(x,b;\mu)|_{P_{v,1}}}{C\left(\frac{(2xP_{v,1})^2}{\mu^2}\right)\widetilde{\Omega}^{[\Gamma=\gamma_0,\gamma_v]}_{q/h}(x,b;\mu)|_{P_{v,2}}}\right)$$

qTMD NLP

[S. Rodini & A. Vladimirov]

→ Computation sketch:

- qTMD expressed through currents:

$$\widetilde{\Omega}^{[\Gamma]} = \langle P,S|\bar{J}_v(y)\,\frac{\Gamma}{2}\,J_v(0)|P,S\rangle,$$

- Background field method: $q = \psi + q_{\bar{n}} + q_v, \qquad A^\mu = B^\mu + A^\mu_{\bar{n}} + A^\mu_v,$

$$\begin{aligned}\{\partial_+,\partial_-,\partial_T\}q_v &\lesssim P_+\{\lambda^2,\lambda^2,\lambda\}q_v,\\ \{\partial_+,\partial_-,\partial_T\}A^\mu_v &\lesssim P_+\{\lambda^2,\lambda^2,\lambda\}A^\mu_v.\end{aligned}$$

→ Result:

$$\begin{aligned}\Omega^{[\Gamma]}(x,b,\mu) = {}& \Psi(b;\mu,\bar{\zeta})\mathbb{C}_{11}\Phi^{[[\Gamma]]}_{11}(x,b;\mu,\zeta)\\ &+ \underbrace{\frac{i}{2xP_+}\mathbb{C}_{11}\Psi(b)\left(\partial_\mu - \frac{1}{2}[\partial_\mu\mathcal{D}(b,\mu)]\ln\left(\frac{\bar{\zeta}}{\zeta}\right)\right)\Phi^{[[\gamma^\mu\gamma^+\Gamma+\Gamma\gamma^+\gamma^\mu]]}_{11}(x,b;\mu,\zeta)}_{\text{NLP KPC}}\\ &+ \ldots\end{aligned}$$

KPCs for qTMD

→ Computation sketch:

- Background Fields to zero
- Multipole expansion
- Equations of motion
- Sum of KPCs:
  - k_T-space
  - $\zeta = \bar{\zeta} = 2x\mu P_v$

→ Result:

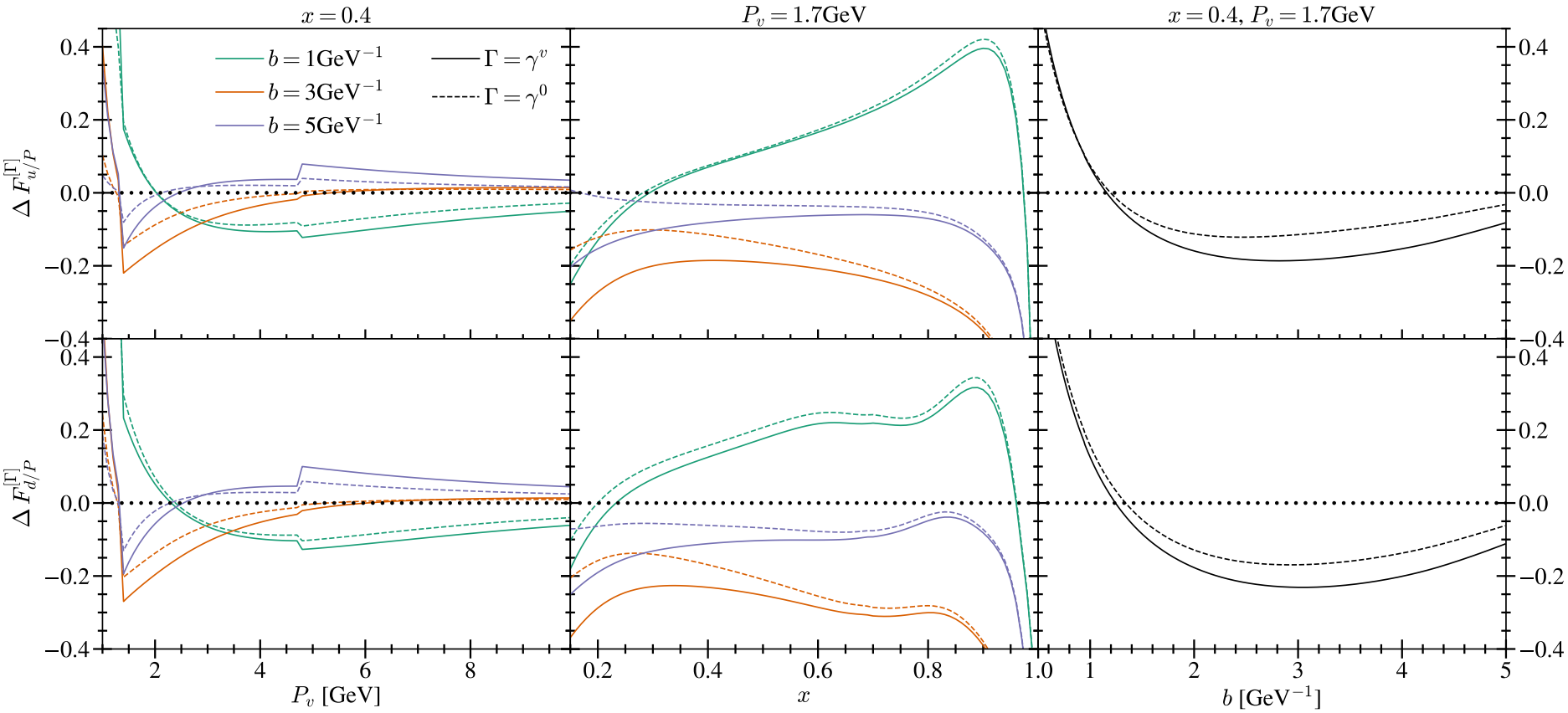
$$F_{q/h}^{[\gamma^0],\,\mathrm{KPCs}}(x,b;\mu) = 2\pi \left(\frac{2xP_v}{\mu}\right)^{-\mathcal{D}(b,\mu)} C\left(\frac{(2xP_v)^2}{\mu^2}\right) \times \int_0^{2P_v\sqrt{1-x}} d|k||k| J_0(|k|b) f_1(\xi, k_T; \mu, \zeta = 2x\mu P_v)$$

$$F_{q/h}^{[\gamma^v],\,\mathrm{KPCs}}(x,b;\mu) = 2\pi \left(\frac{2xP_v}{\mu}\right)^{-\mathcal{D}(b,\mu)} C\left(\frac{(2xP_v)^2}{\mu^2}\right) \times \int_0^{2P_v\sqrt{1-x}} d|k||k| J_0(|k|b) \frac{2\xi - x}{x} f_1(\xi, k_T; \mu, \zeta = 2x\mu P_v)$$

$* \; \xi = \frac{x}{2}\left(1 + \sqrt{1 + \frac{\vec{k}_T^2}{x^2 P_v^2}}\right)$

KPCs for qTMD

$$\Delta F^{[\Gamma]}_{q/P} = (F^{[\Gamma],\mathrm{KPC}}_{q/P} - F^{[\Gamma],\mathrm{LP}}_{q/P})/F^{[\Gamma],\mathrm{LP}}_{q/P}$$



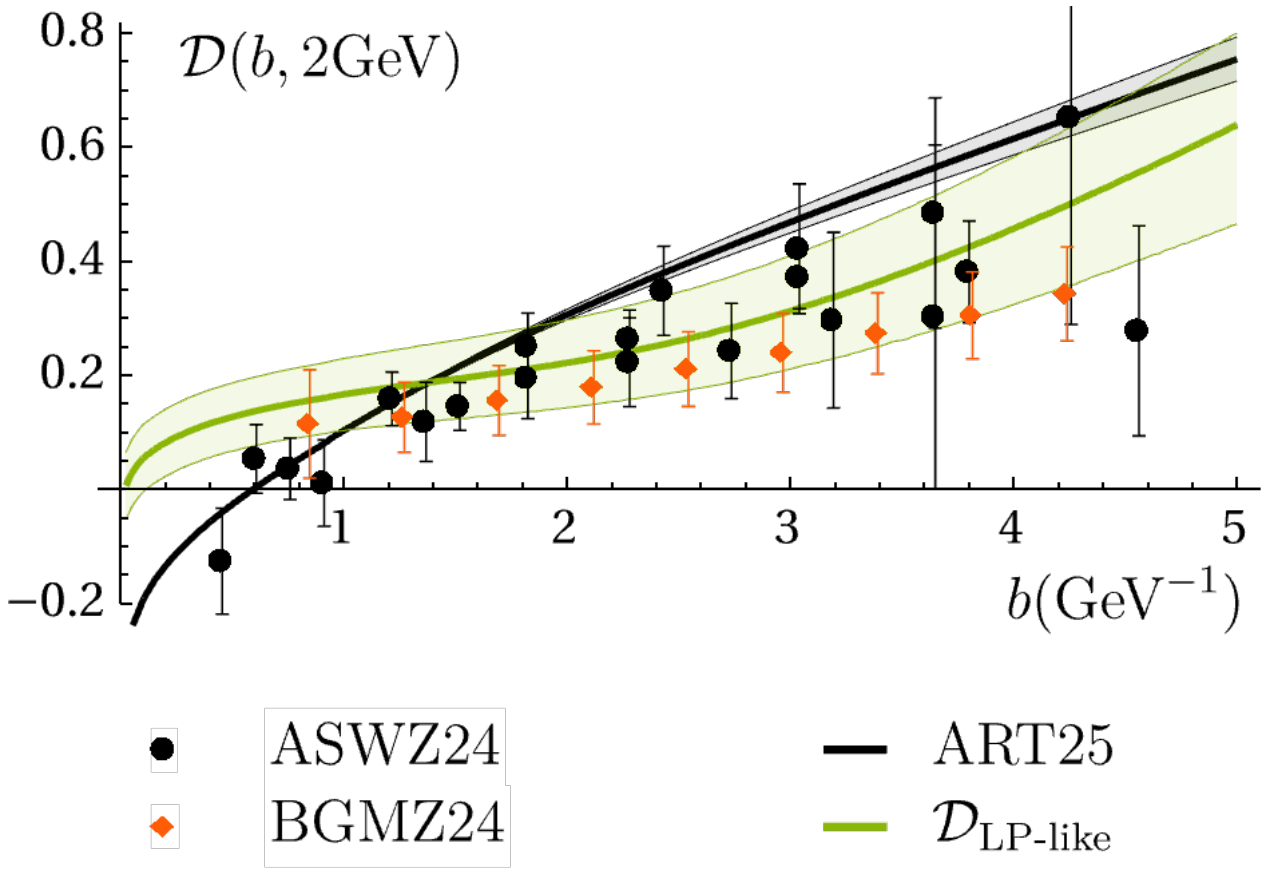
KPCs in lattice extractions

→ Numerical impact on lattice extractions:

1) From input TMDs (taken from ART25) compute pseudo-lattice data for qTMD ($F_{q/h}^{[\Gamma],\mathrm{KPCs}}$) using the factorization theorem with KPCs
2) Apply usual lattice procedure (LP) to extract the TMD distribution from the pseudo-data.
3) Compare input and extracted distributions.

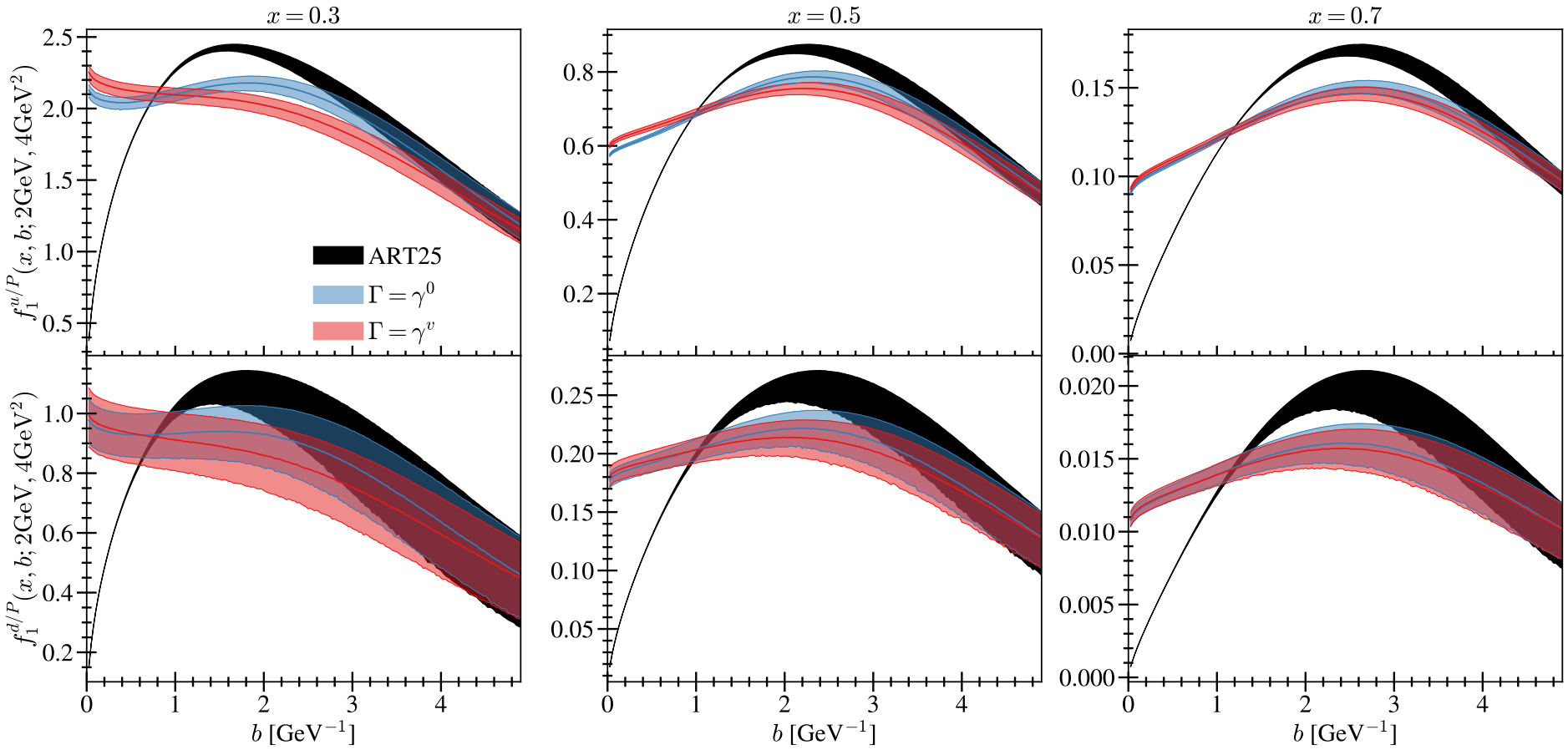
lattice CS extraction

$$\mathcal{D}_{\text{LP-like}}(b,\mu) = \frac{1}{2\log(P_{v,2}/P_{v,1})}\log\left(\frac{C\left(\frac{(2xP_{v,2})^2}{\mu^2}\right)F_{q/h}^{[\Gamma],\text{KPCs}}(x,b;\mu;P_1)}{C\left(\frac{(2xP_{v,1})^2}{\mu^2}\right)F_{q/h}^{[\Gamma],\text{KPCs}}(x,b;\mu,P_2)}\right)$$



lattice TMDPDF extraction

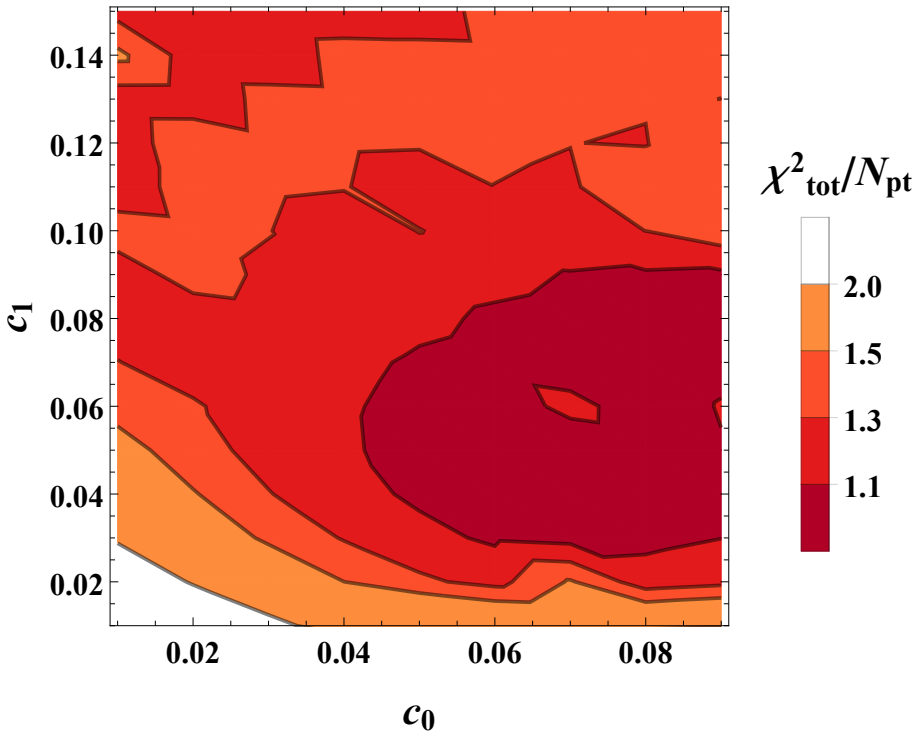
$$f^{q/h}_{\text{LP-like}}(x, b; \mu) = \frac{F^{[\Gamma],\,\text{KPCs}}_{q/h}(x, b; \mu)}{C\left(\frac{(2xP_v)^2}{\mu^2}\right)}$$



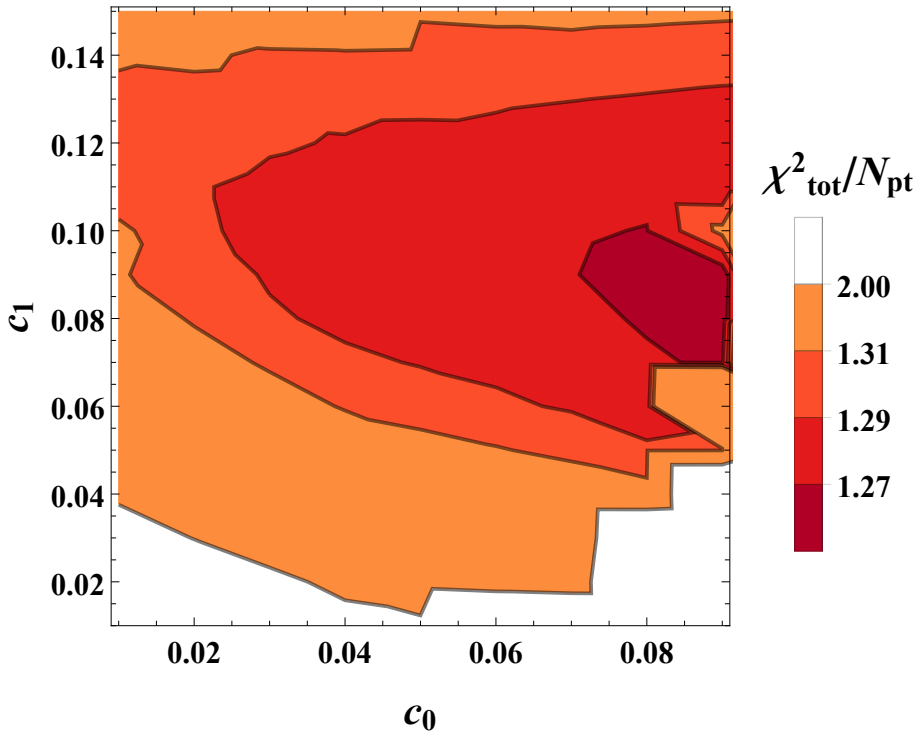
Fits reanalysis

- Recent developments in `artemide` code $\Rightarrow$ huge reduction in fits duration.
- Access to more information about the fitting procedure $\Rightarrow$ reanalysis of ART25 results.
- Parameter space scans: χ^2 computation fixing the values of given parameters and carrying out the fit of the rest.

ART25 CS kernel scans (preliminary)

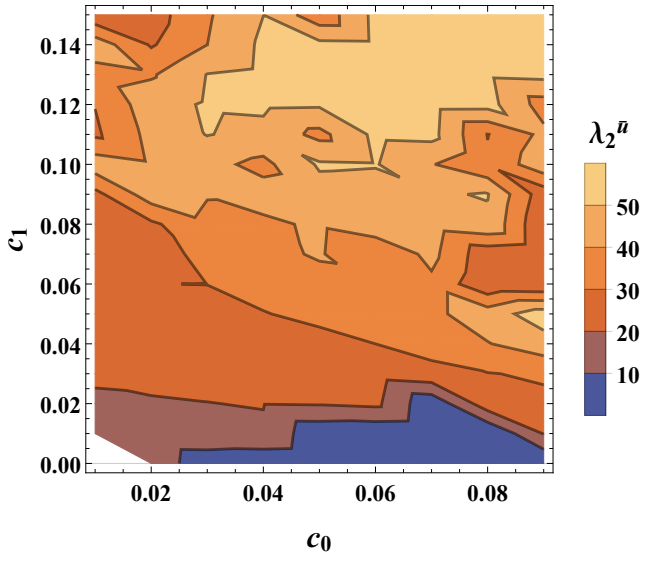


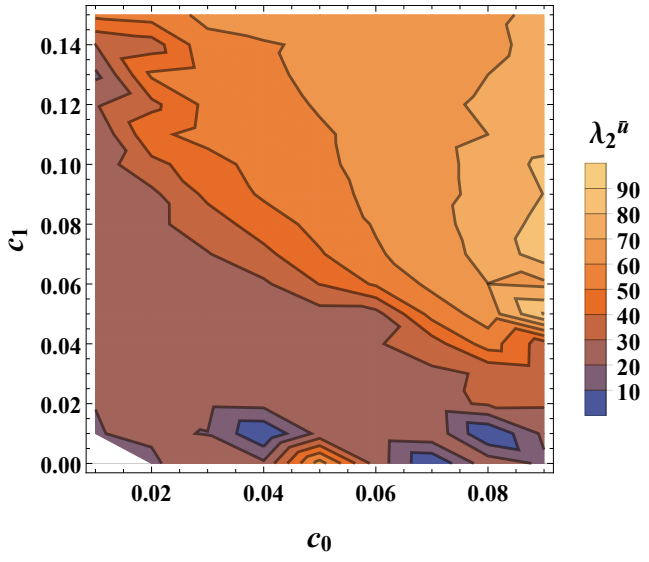
MSHT20 (ART25)

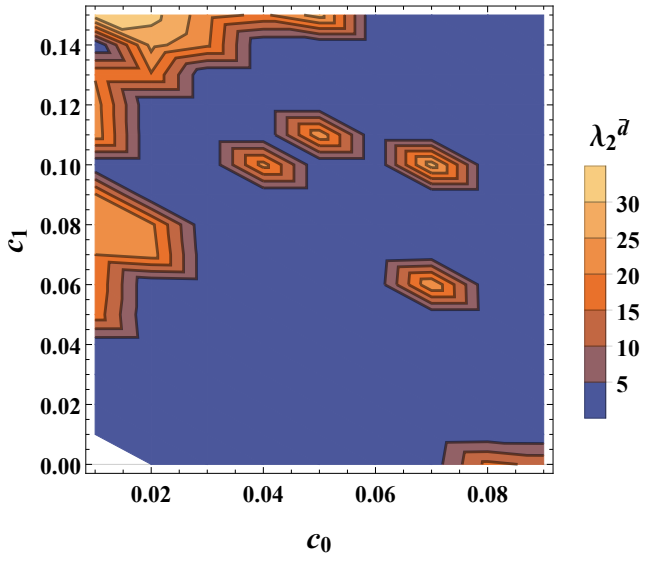


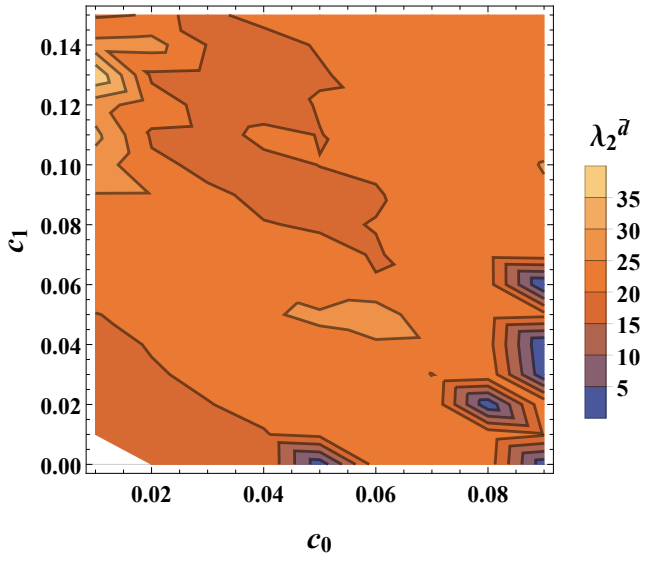
NNPDF

ART25 CS kernel scans (preliminary)









MSHT20 (ART25)

NNPDF

Summary

→ We focused on two of the latest projects carried out within `artemide` framework: global fits to DY+SIDIS and EEC data.

→ In DY+SIDIS fit (ART25), the extraction of the CS kernel together with the unpolarized proton TMDPDF and pion and kaon TMDFFs was carried out.

→ Despite the completeness of ART25, some issues remained to be addressed as the CS kernel incompatibility with ART23 previous result.

→ EEC back-to-back factorization theorem was implemented within `artemide` framework to provide a way to disentangle these discrepancies through a different fit.

→ Current available data for this observable cannot resolve the differences. Predictions were given for future experiments.

→ Finally some of the current efforts to improve the fits and extend `artemide` framework were briefly discussed

Thank you