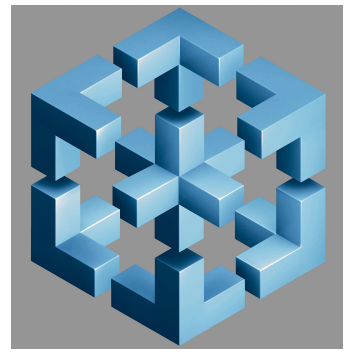
Higher order and higher-twist aspects of exclusive meson production

Kornelija Passek-K.

Rudjer Bošković Institute, Croatia



(Escher 3D, Al Borge)

ACHT2023, Sep 27-29, 2023

HrZZ Croatian Science Foundation

STRONG 2020

Outline

1. Introduction: hard exclusive reactions and GPDs
2. Deeply virtual and wide angle meson production (DVMP, WAMP)
3. DVMP at NLO
4. Higher twist effects for WAMP and DVMP
5. Conclusions

Introduction

Prerequisites

$\exists$ large scale(s)

$\Rightarrow \alpha_S$ expansion (and 1/scale expansion)

$\rightarrow$ factorization:

hard scattering amplitude	$=$	elementary hard-scattering amplitude	$\otimes$	hadron wave functions (DAs, GPDs)
		(via partons)		evolution $\quad$ form
		$\Uparrow$		$\Uparrow \quad \uparrow$
		pQCD		pQCD $\quad$ input

$+$ power corrections/higher-twists

(factorization?)

DA . . . distribution amplitude (meson, baryon)
GPD . . . generalized parton distributions

Hard-scattering amplitude in pure quark picture

$$\mathcal{M} = T_H(x_1, \cdots ; \cdots ; \mu_{F1}, \cdots) \otimes \prod_i \Phi_i(\{x_i\}; \mu_{Fi})$$

x_i . . . longitudinal momentum fractions

DA

$$\Phi(\ldots;\mu_{Fi},\mu_0^2) \quad = \quad \Phi^{(0)}(\ldots;\mu_{Fi},\mu_0^2) + \frac{\alpha_s(\mu_{Fi})}{4\pi}\Phi^{(1)}(\ldots;\mu_{Fi},\mu_0^2) + \cdots$$

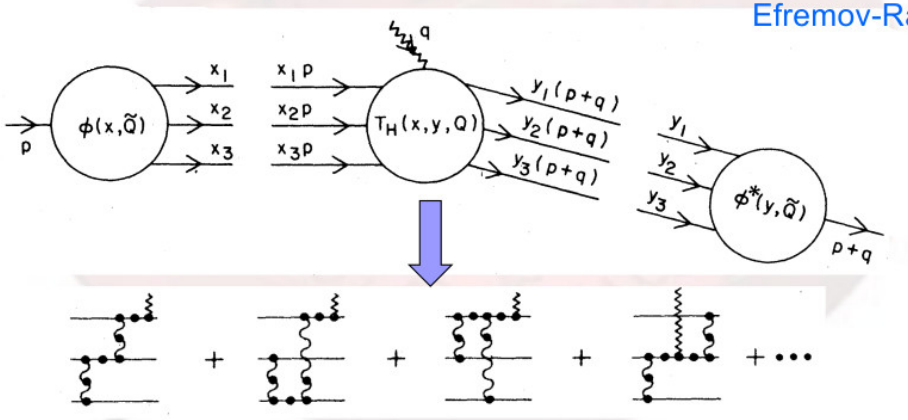
μ_{F_i} . . . factorization scale, μ_0^2 input scale

Example: proton form factor

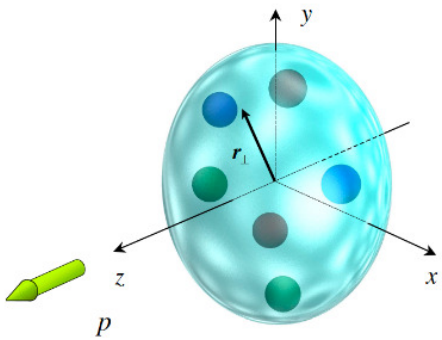
$$T_H(\ldots;Q^2,\{\mu_{Fi}\}) \quad = \quad \frac{\alpha_s^2(\mu_R)}{(4\pi)^2}T_H^{(0)}(\ldots;Q^2) + \frac{\alpha_s^3(\mu_R)}{(4\pi)^2}T_H^{(1)}(\ldots;Q^2,\mu_R,\{\mu_{Fi}\}) +$$

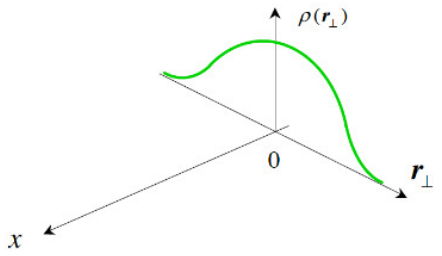
μ_R . . . renormalization scale

Lepage-Brodsky 1980
Efremov-Radyushkin 1980



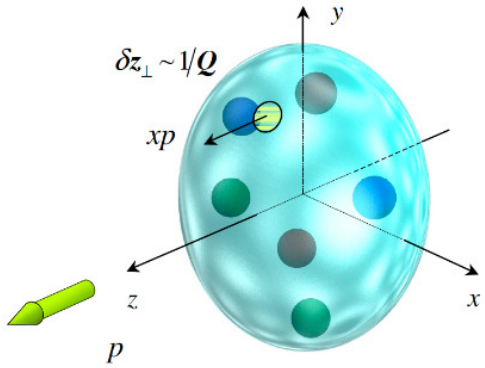
Elastic scattering

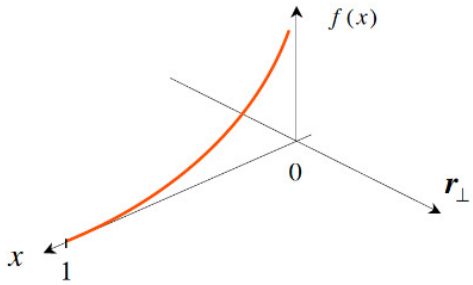




Form factors

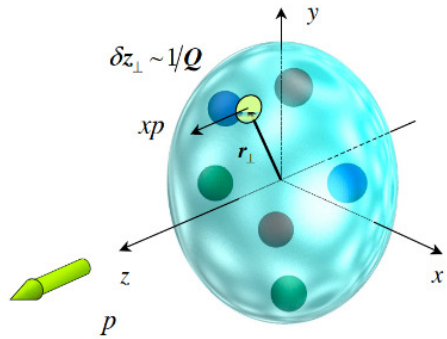
Deep inelastic scattering

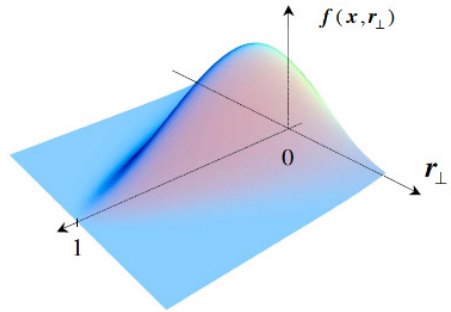




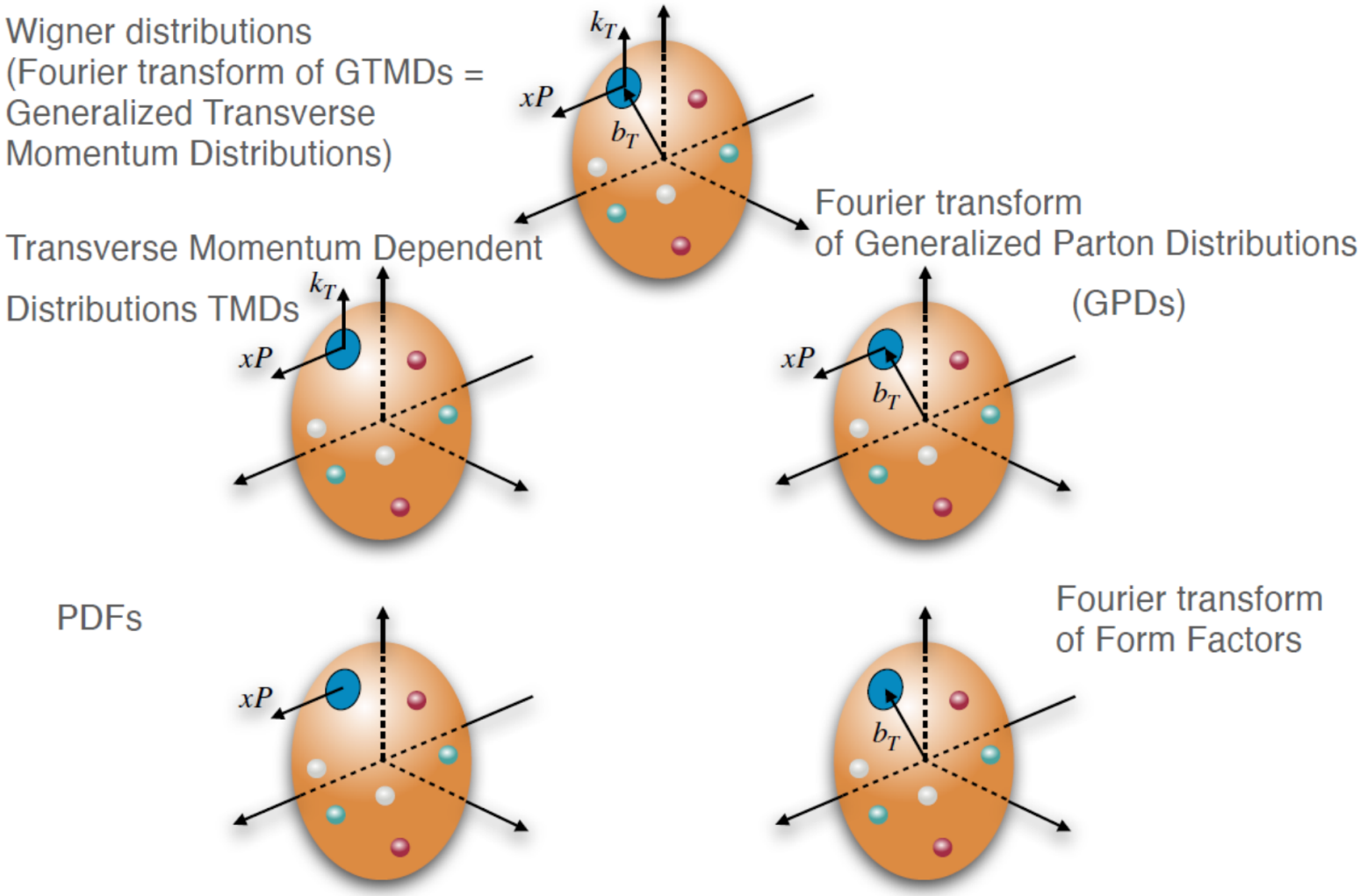
Parton distributions

Hard exclusive processes





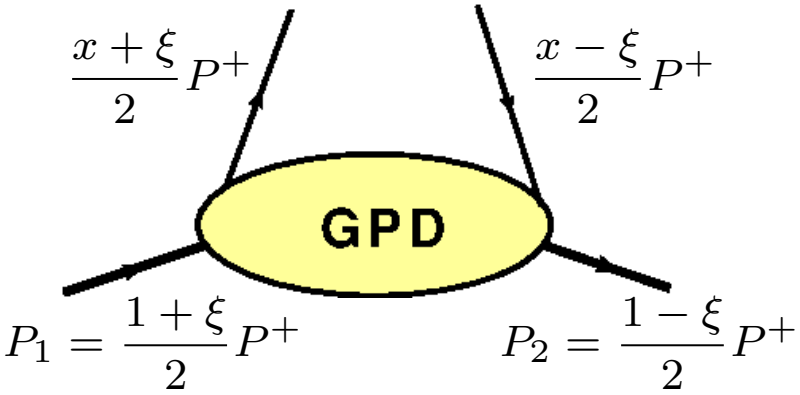
Generalized Parton Distributions (GPDs)



see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Taken from A. Prokudin, STAR Collaboration Meeting 2021.9

Generalized Parton Distributions



$$P = P_1 + P_2$$

$$\Delta = P_2 - P_1$$

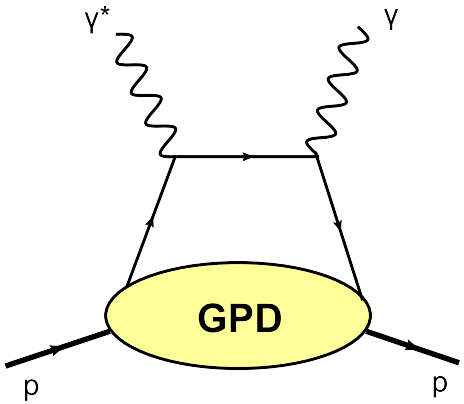
x	parton's "average" longitudinal momentum fraction
$\xi = -\frac{\Delta^+}{P^+}$	longitudinal momentum transfer (skewness)
$\Delta^2 = t$	momentum transfer

GPDs: $\boxed{F^a(x,\xi,t;\mu),\ a \in \{q, G\}}$ μ. . . factorization scale

- vector (H^a, E^a) and axial-vector GPDs ($\widetilde{H}^a$, $\widetilde{E}^a$)
- transversity GPDs (H_T^a, E_T^a, $\widetilde{H}_T^a$, $\widetilde{E}_T^a$)

Selected exclusive processes

DVCS



$$\gamma^* N \to \gamma N$$

factorization:

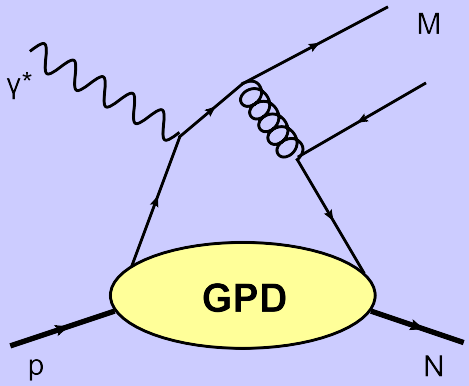
[Collins, Freund '99]

$H^q,\ E^q,\ \widetilde{H}^q,\ \widetilde{E}^q$

$H^G,\ E^G\ \widetilde{H}^G,\ \widetilde{E}^G$

(NLO)

DVMP



$$\gamma^* N \to M N'$$

factorization:

[Collins, Frankfurt, Strikman '97]

$H^{q_i},\ E^{q_i};\ H^G,\ E^G$

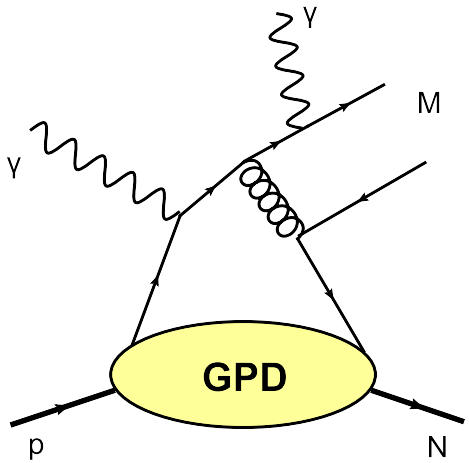
$\widetilde{H}^{q_i},\ \widetilde{E}^{q_i}$

[Collins, Diehl '99]

$(\cancel{\gamma^* N \to V_T N'}) \Rightarrow (\cancel{F_T^q})$

$M_{\text{twist-3}} \Rightarrow F_T^q$

$(\gamma M)P$



$$\gamma N \to \gamma M N'$$

factorization:

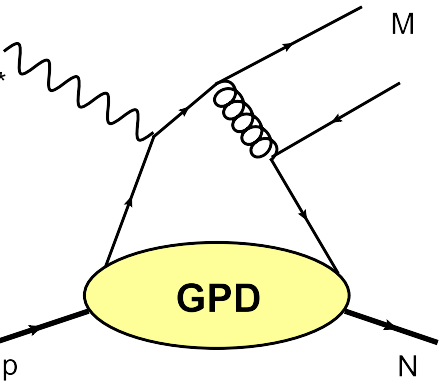
[Qiu, Yu '22]

$H^a,\ E^a,\ \widetilde{H}^a,\ \widetilde{E}^a$

$H_T^a,\ E_T^a\ \widetilde{H}_T^a,\ \widetilde{E}_T^a$

DVMP and WAMP

Meson Production: handbag factorization



$\gamma^{(*)} N \to M N'$

DEEPLY VIRTUAL

$Q^2 >>$, $-t <<$

DVMP

[Collins, Frankfurt, Strikman '97]

- factorization $\boxed{\mathcal{H}^a \otimes GPD}$
- GPDs at small $(-t)$

WIDE ANGLE

$-t$, $-u$, $s >>$

WAMP

[Huang, Kroll '00]

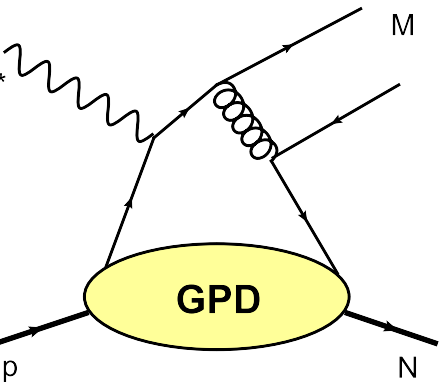
- arguments for factorization $\boxed{\mathcal{H}^a(1/x \otimes GPD(\xi = 0))}$
- GPDs at large $(-t)$

$\mathcal{H}^a$ ... parton subprocess helicity amplitudes

$\Rightarrow \mathcal{M}$ ... hadron helicity amplitudes

$\Rightarrow$ observables (cross sections, asymmetries)

Meson Production: handbag factorization



$\gamma^{(*)} N \to M N'$

DEEPLY VIRTUAL

$Q^2 >>,\ -t <<$

DVMP

[Collins, Frankfurt, Strikman '97]

- factorization $\boxed{\mathcal{H}^a \otimes GPD}$
- GPDs at small $(-t)$
- tw2: γ_L^*, tw3: γ_T^*

WIDE ANGLE

$-t,\ -u,\ s >>$

WAMP

[Huang, Kroll '00]

- arguments for factorization $\boxed{\mathcal{H}^a(1/x \otimes GPD(\xi = 0))}$
- GPDs at large $(-t)$

large scale $\mathcal{Q}^2$ ($\mathcal{Q}^2$, s or ...)

- twist expansion: $\langle\mathcal{H}\rangle^{tw2} + \dfrac{\langle\mathcal{H}\rangle^{tw2}}{\mathcal{Q}} + \ldots$
- α_S expansion for each twist: $\alpha_S(\mathcal{Q}) \langle\mathcal{H}\rangle^{LO} + \alpha_S^2(\mathcal{Q}) \langle\mathcal{H}\rangle^{NLO}$

Meson Production status

- DV (V_L) P:
  - tw-2 predictions can describe the data
- DVπP:
  - tw-2 predictions bellow the data
- WAπP:
  - tw-2 results bellow the data

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  $\Rightarrow$ tw-3 calculations with transversity GPDs (H_T^q...) [Goloskokov, Kroll '10] (2-body approximation)
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- WAπP:
  - tw-2 results bellow the data

  $\Rightarrow$ tw-3 (2- and 3-body) prediction for photoproduction [Kroll, P-K. 18','22]

  $\Rightarrow$ tw-3 prediction for electroproduction ($Q^2 < -t$) [Kroll, P-K. '21]

  $\Rightarrow$ extension to DVπP

pQCD prediction

$$\mathcal{M}(Q^2) = \mathcal{M}^{(0)}(Q^2) + \frac{\alpha_s(\mu_R)}{4\pi}\mathcal{M}^{(1)}(Q^2) + \frac{\alpha_s^2(\mu_R)}{(4\pi)^2}\mathcal{M}^{(2)}(Q^2, \mu_R) + \cdots$$

Q^2 . . . characteristic large scale of the process

μ_R . . . renormalization scale

- finite order prediction!, renormalization scale and scheme dependence $\Rightarrow$ theoretical uncertainty
- higher-order corrections ($\mathcal{M}^{(2)}(Q^2, \mu_R)$, . . .) are important: stabilizing effect reducing the dependence of the predictions on the scales and schemes

DVMP at NLO

DVMP

Transition form factors

$$ {}^a\mathcal{T}(\xi,t,Q^2) = \int \mathrm{d}x \int \mathrm{d}u\, T^a(x,\xi,u,\mu_\varphi,\mu_F)\, F^a(x,\xi,t,\mu_\varphi)\, \phi(u,\mu_F) $$

$a = q, g$ or NS,S(Σ, g)

hard-scattering amplitude (known up to NLO)

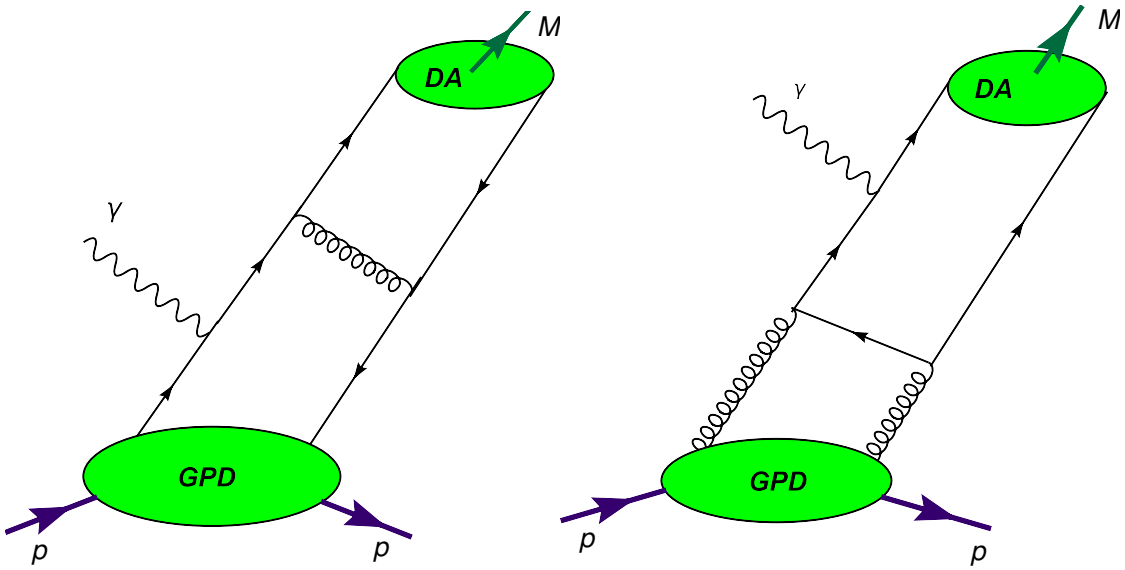
$$ \begin{aligned} T^a(x,\xi,u,\mu_\varphi,\mu_F) &= \frac{\alpha_s(\mu_R)}{4\pi} T^{a(1)}(x,\xi,u) \\ &\quad + \frac{\alpha_s^2(\mu_R)}{(4\pi)^2} T^{a(2)}(x,\xi,u,\mu_R,\mu_\varphi,\mu_F) + \cdots \end{aligned} $$

distribution amplitude (DA) evolution, similarly GPD (F^a) evolution (known up to NNLO)

$$ \begin{aligned} \phi(x;\mu_F,\mu_0) &= \phi^{(0)}(u,\mu_F,\mu_0) + \frac{\alpha_s(\mu_F)}{4\pi} \phi^{(1)}(u,\mu_F,\mu_0) \\ &\quad + \frac{\alpha_s^2(\mu_F)}{(4\pi)^2} \phi^{(2)}(u,\mu_F,\mu_0) + \cdots \end{aligned} $$

DVMP to NLO

$$\gamma^* q \to (q\bar{q})q,\ \gamma^* g \to (q\bar{q})g$$

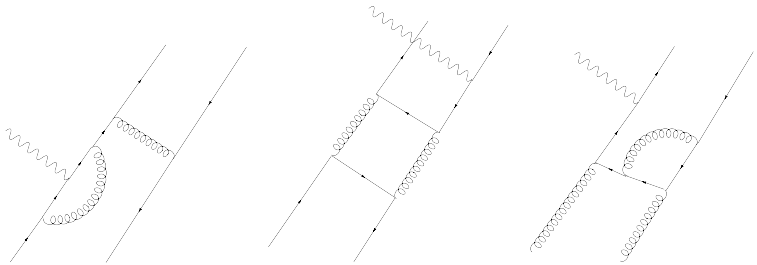


NLO DV PS^+ prod.: [Belitsky and Müller '01]

NLO DV V_L prod.: [Ivanov et al '04,]

NLO DV V_L (corr.), PS, (S, PV_L) prod.:

[Duplančić, Müller, Passek-K. '17]



GPDs from DVMP

DVMP: transition form factors (known up to NLO)

$$ {}^{a}\mathcal{T}(\xi, t, \mathcal{Q}^2) = \int \mathrm{d}x \int \mathrm{d}y \, T^a(x, \xi, y, \mathcal{Q}^2/\mu^2) \, F^a(x, \xi, t, \mu^2) \, \phi(y, \mu^2) $$

- *"Curse of the dimensionality"*
  When the dimensionality increases, the volume of the space increases so fast that the available data become sparse.
- complete deconvolution is impossible
- different modelling venues (momentum fractions space, conformal momentum space)

From x space to conformal momentum space

$$ {}^a\mathcal{T}(\xi,t,Q^2) = \int \mathrm{d}x \int \mathrm{d}u\, T^a(x,\xi,y,\mu^2))\, F^a(x,\xi,t,\mu^2)\, \phi(u,\mu^2) $$

F...GPDs, a=q,G

conformal moments (analogous to Mellin moments in DIS $x^n \to C_n^{3/2}(x), C_n^{5/2}(x)$)

[Müller, Lautenschläger, P-K., Schäfer 2014] [Duplančić, Müller, P-K. 2017]

$$ {}^a\mathcal{T}(\xi,t,\mathcal{Q}^2) = \frac{1}{2i}\int_{c-i\infty}^{c+i\infty} dj \left[i \pm \left\{ \begin{matrix} \tan \\ \cot \end{matrix} \right\} \left(\frac{\pi j}{2} \right) \right] \xi^{-j-1} $$

$$ \times \left[\mathrm{T}_{jk}(\mathcal{Q}^2/\mu^2) \overset{k}{\otimes} \phi_{\mathrm{M},k}(\mu^2) \right] F_j^{\mathsf{a}}(\xi,t,\mu^2) $$

NLO predictions

[Müller, Lautenschlager, P-K., Schäfer '14], [Duplančić, Müller, P-K., '17]

- large NLO corrections and model dependence
- LO evolution important
- NLO calculations should include NLO evolution (conformal momentum representation favorable)
- results sensitive to the choice of DA
- NLO global DIS+DVCS+DVMP fits needed

NLO for DV V_L production

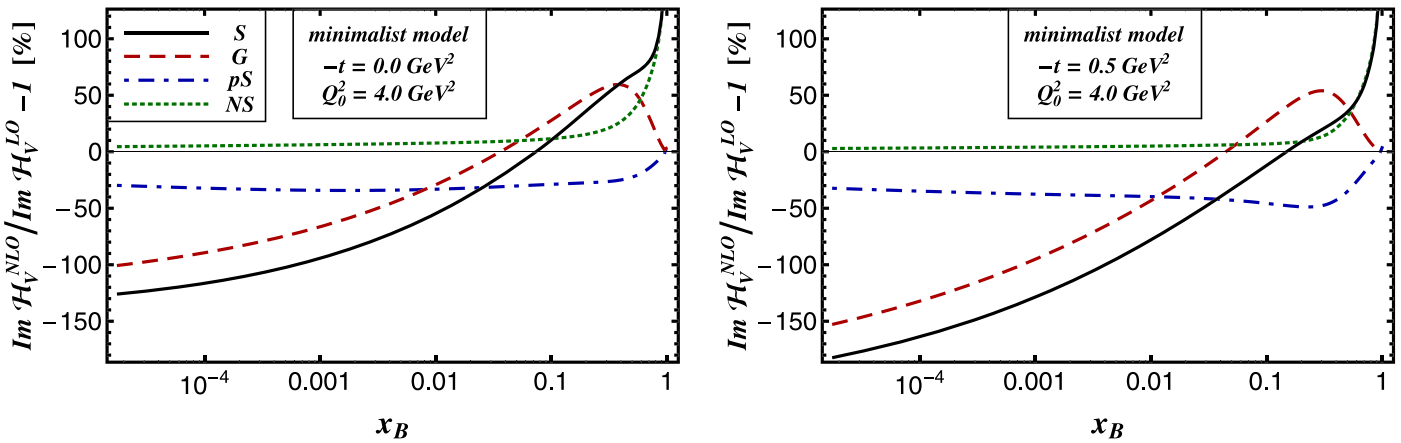


Fig. 6. Relative NLO corrections to the imaginary part of the flavor singlet TFF $\mathcal{F}_{\mathrm{V}}^{\mathrm{S}}$ (solid) broken down to the gluon (dashed), pure singlet quark (dash-dotted) and 'non-singlet' quark (dotted) at $t = 0$ GeV^2 (left panel) and $t = -0.5$ GeV^2 (right panel) at the initial scale $\mathcal{Q}_0^2 = 4$ GeV^2.

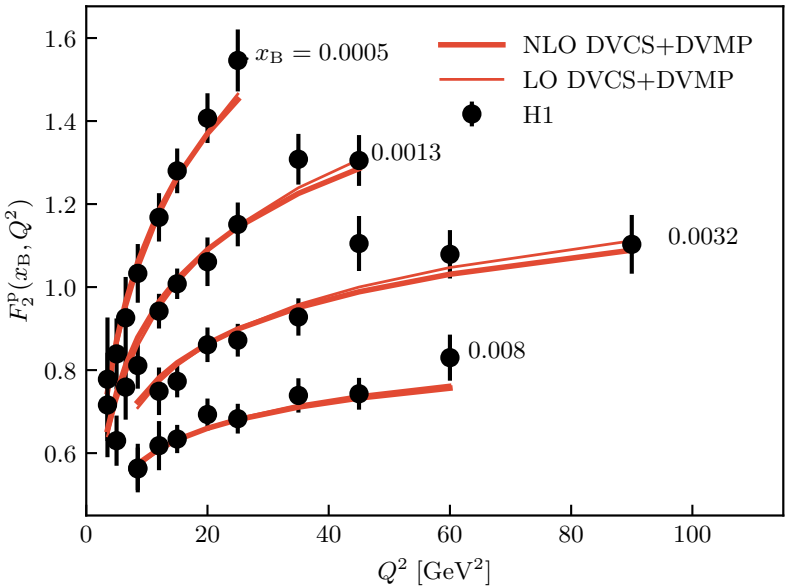
[Müller, Lautenschlager, P-K., Schäfer '14]

- large NLO corrections for small x_B, i.e., ξ

Global NLO fits (DIS+DVCS+DVV$_L$P)

small-x global fits to HERA collider data (ρ_0)

- NLO: [Lautenschlager, Müller, Schäfer '13]
- hard scattering amplitude corrected [Duplančić, Müller, P-K. '17]
- new NLO fit:



[Čuić, Duplančić, Kumerički, P-K. in preparation]

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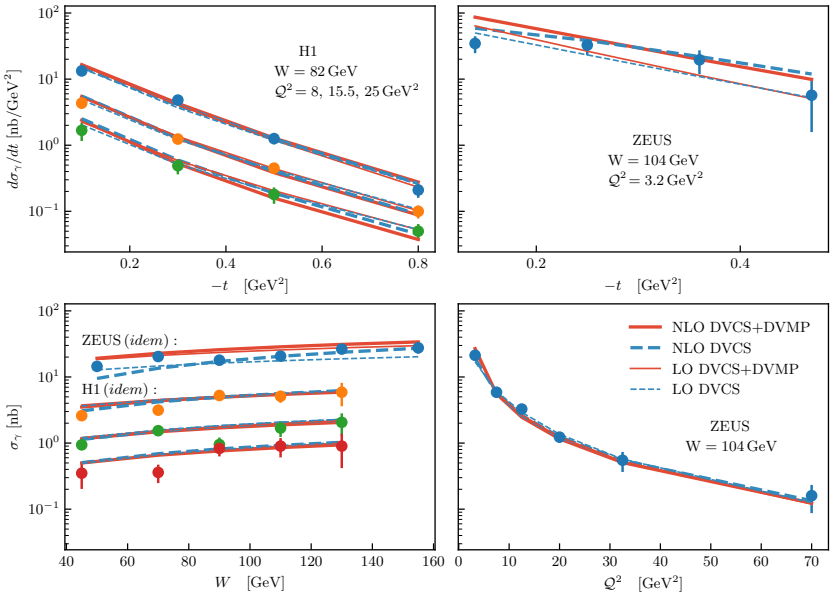

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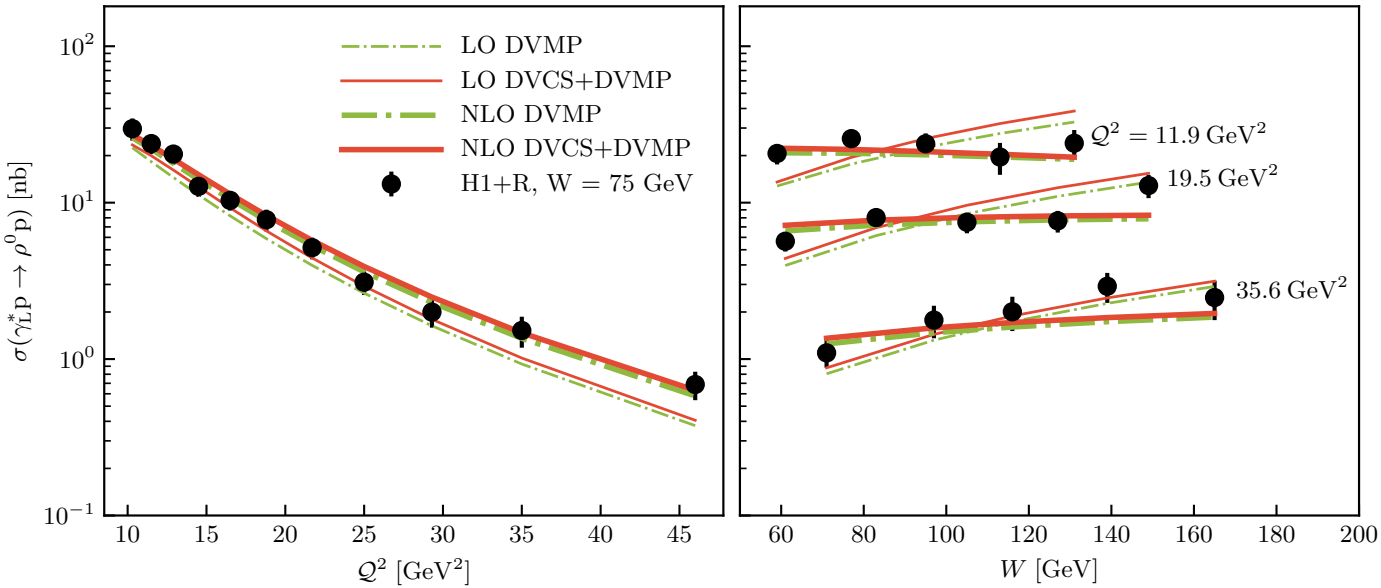

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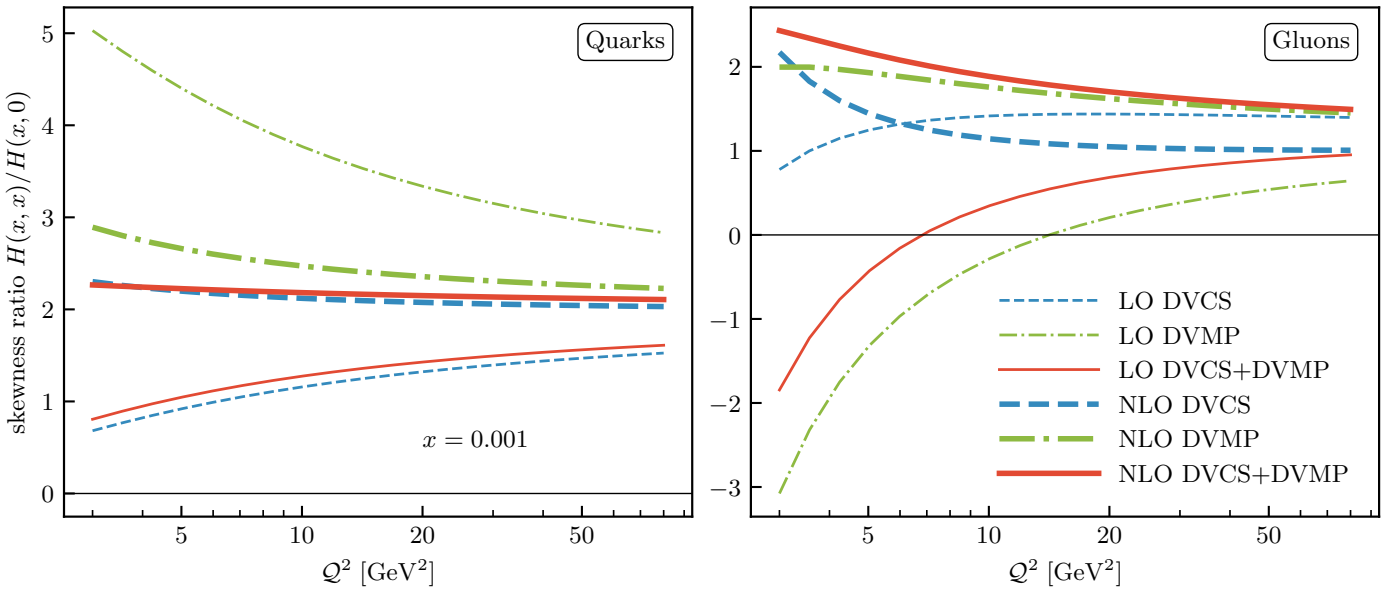


skewness ratio $r = \dfrac{H(x,x)}{H(x,0)}$ measures goodness of GPD extraction

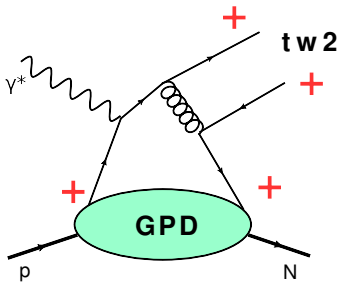
$\Rightarrow$ NLO fit successful

[Čuić, Duplančić, Kumerički, P-K. in preparation]

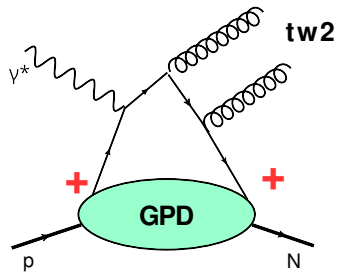
WAMP and DVMP at higher-twist

PS meson production to twist-3

$\mathcal{H}^P_{0\lambda,\mu\lambda}$ ... non-flip subprocess amplitudes (twist-2)

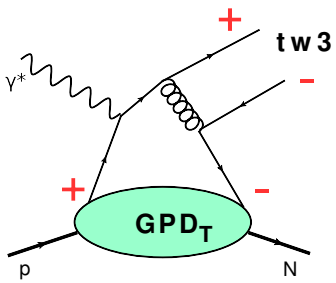


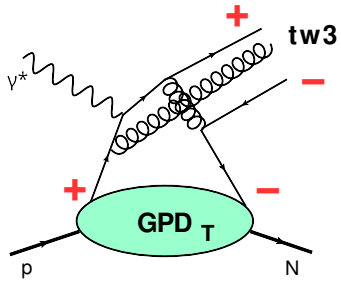
and



for η_1

$\mathcal{H}^P_{0-\lambda,\mu\lambda}$ ... flip subprocess amplitudes (twist-3)





Note: just meson DA tw-3 contributions ($\mu_\pi = 2$ GeV)

distribution amplitudes (DAs):

twist-2 $(q\bar{q})$: ϕ_P

2-body $(q\bar{q})$ twist-3 ϕ_{Pp}, $\phi_{P\sigma}$ 3-body $(q\bar{q}g)$ twist-3 ϕ_{3P}

$\rightarrow$ connected by equations of motion (EOMs)

Subprocess amplitudes: twist-3

General structure:

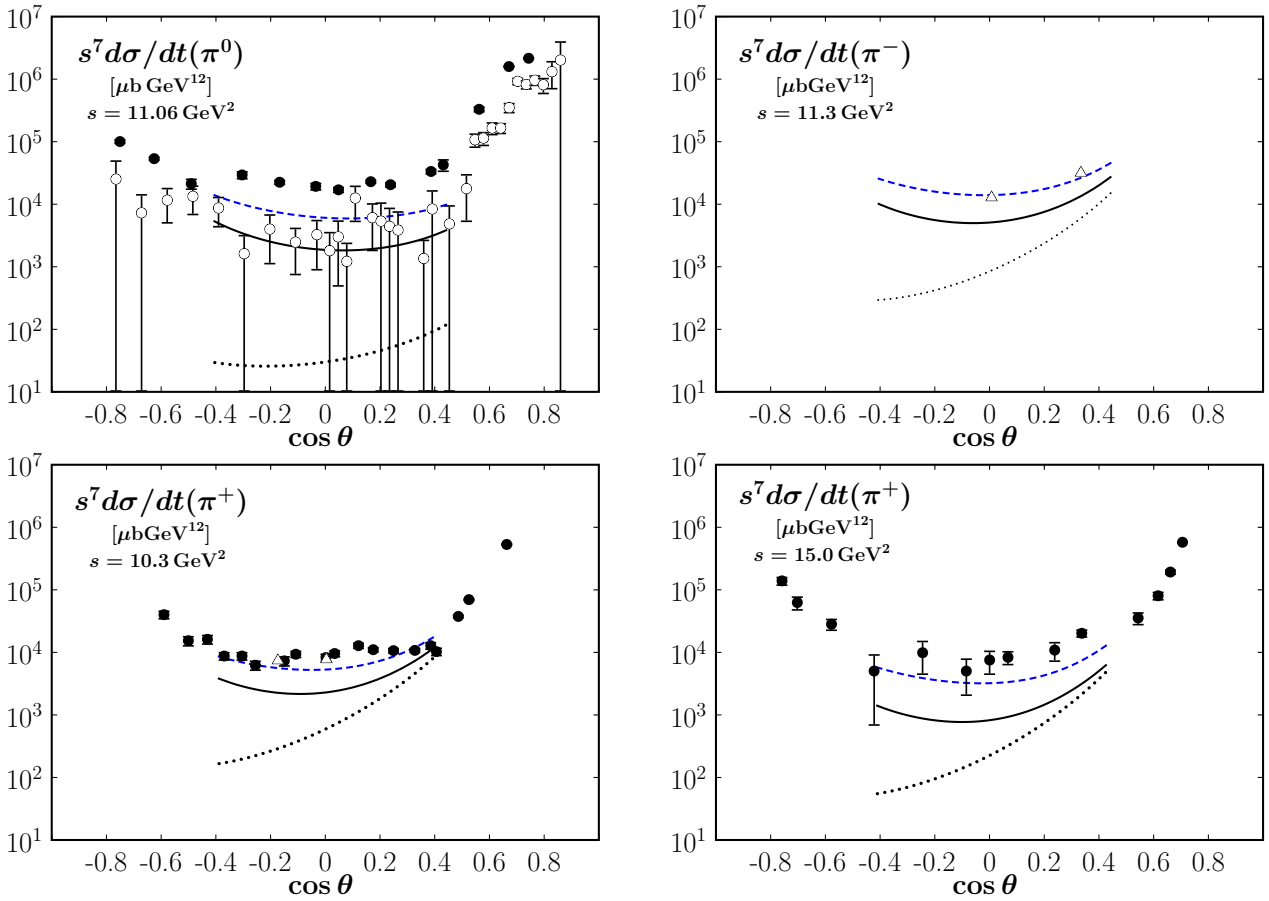
$$\begin{aligned}
\mathcal{H}^{P,tw3} &= \mathcal{H}^{P,tw3,q\bar{q}} + \mathcal{H}^{P,tw3,q\bar{q}g} \\
&= \left(\mathcal{H}^{P,\phi_{Pp}} + \underbrace{\mathcal{H}^{P,\phi^{EOM}_{P2}}\right) + \left(\mathcal{H}^{P,q\bar{q}g,C_F}}} + \mathcal{H}^{P,q\bar{q}g,C_G}\right) \\
&= \mathcal{H}^{P,\phi_{Pp}} + \mathcal{H}^{P,\phi_{3P},C_F} + \mathcal{H}^{P,\phi_{3P},C_G}
\end{aligned}$$

- 2- and 3-body contributions necessary for gauge invariance
- WAMP
  - photoproduction ($Q \to 0$): $\mathcal{H}^{P,\phi_{Pp}} = 0$ [Kroll, P-K '18]
  - no end-point singularities for $\hat{t} \neq 0$!

Photoproduction (π)

- complete tw-3 prediction for π_0 photoproduction fitted to CLAS data and obtained predictions for $\pi^{\pm}$

[Kroll, P-K '21]



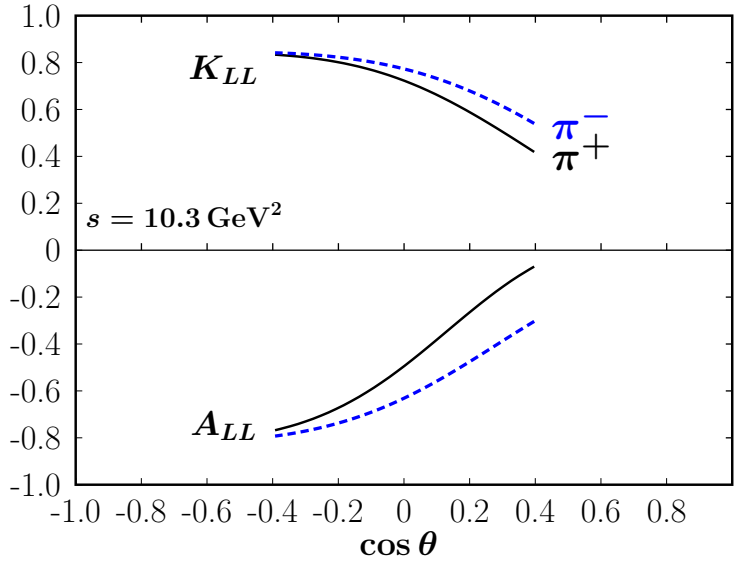
solid curves:
complete twist-3
dotted curves: twist-2

exp data:
full circles [SLAC '76]
open circles [CLAS '17]
triangles [JLab, Hall A '05]

- twist-2 prediction well below the data

Spin effects - photoproduction

[Kroll, P-K '21]: $\pi^{\pm}$



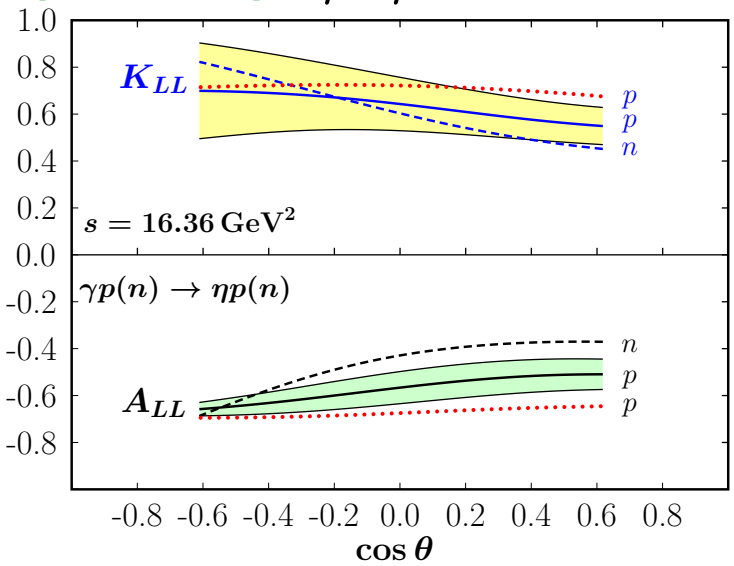
$A_{LL}(K_{LL})$ ... correlation of the helicities of the photon and incoming (outgoing) nucleon

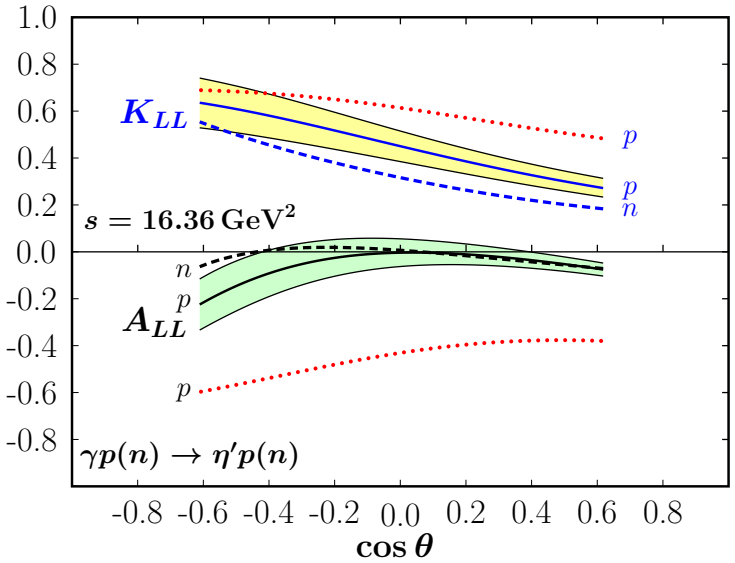
$$A_{LL}^{P,tw2} = K_{LL}^{P,tw2}$$

$$A_{LL}^{P,tw3} = -K_{LL}^{P,tw3}$$

$\rightarrow$ characteristic signature for dominance of twist-3 (like $\sigma_T \gg \sigma_L$ in DVMP)

[Kroll, P-K '22]: η, η'





$\rightarrow$ in contrast to π and η, for η' dominance of twist-2 and sensitivity to gluons

Subprocess amplitudes: twist-3

General structure:

$$\begin{aligned}
\mathcal{H}^{P,tw3} &= \mathcal{H}^{P,tw3,q\bar{q}} + \mathcal{H}^{P,tw3,q\bar{q}g} \\
&= \left(\mathcal{H}^{P,\phi_{Pp}} + \underbrace{\mathcal{H}^{P,\phi^{EOM}_{P2}}\right) + \left(\mathcal{H}^{P,q\bar{q}g,C_F}}} + \mathcal{H}^{P,q\bar{q}g,C_G}\right) \\
&= \mathcal{H}^{P,\phi_{Pp}} + \mathcal{H}^{P,\phi_{3P},C_F} + \mathcal{H}^{P,\phi_{3P},C_G}
\end{aligned}$$

- DVMP ($\hat{t} \to 0$):
  - end-point singularities in $\mathcal{H}^{P,\phi_{Pp}}$ $\int_0^1 \frac{d\tau}{\bar{\tau}} \phi_{Pp}(\tau)$

$$\phi_{Pp}(\tau) = 1 + a_{Pp}\, C_2^{1/2}(2\tau - 1) + \ldots$$

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    $\Rightarrow$ modified hard-scattering picture

    (with $k_\perp$ quark transverse momenta)

    $\Rightarrow$ pure collinear picture with effective m_g^2
  - DVπ_0P numerical analysis underway [Duplančić, Kroll, P-K., Szymanowski work in progress]

Summary and conclusions

- DV (V_L) P
  - twist-2 NLO contributions can describe the data
  - global DIS+DVCS+DVMP fits promising
- DV (PS) P
  - twist-3 dominates
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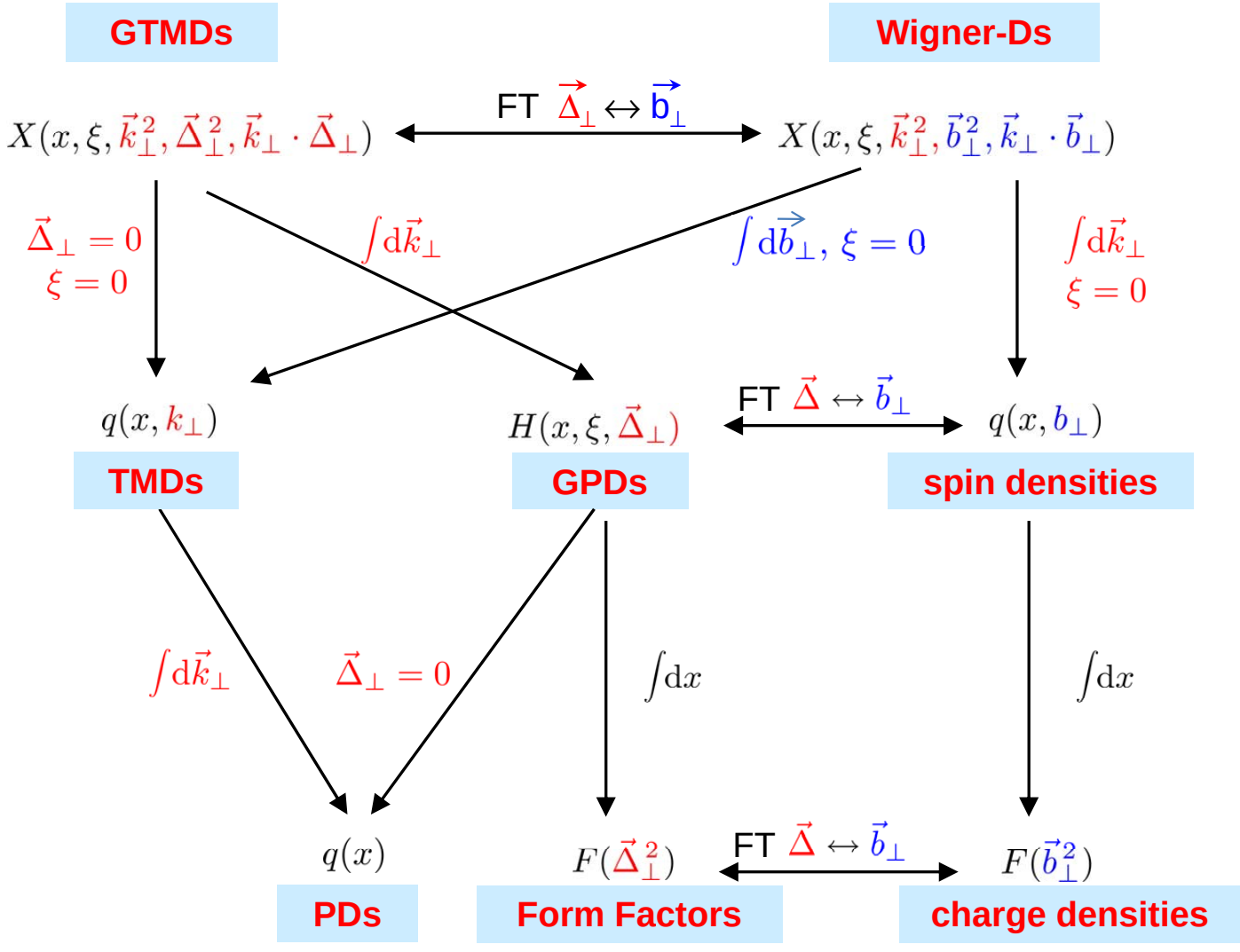
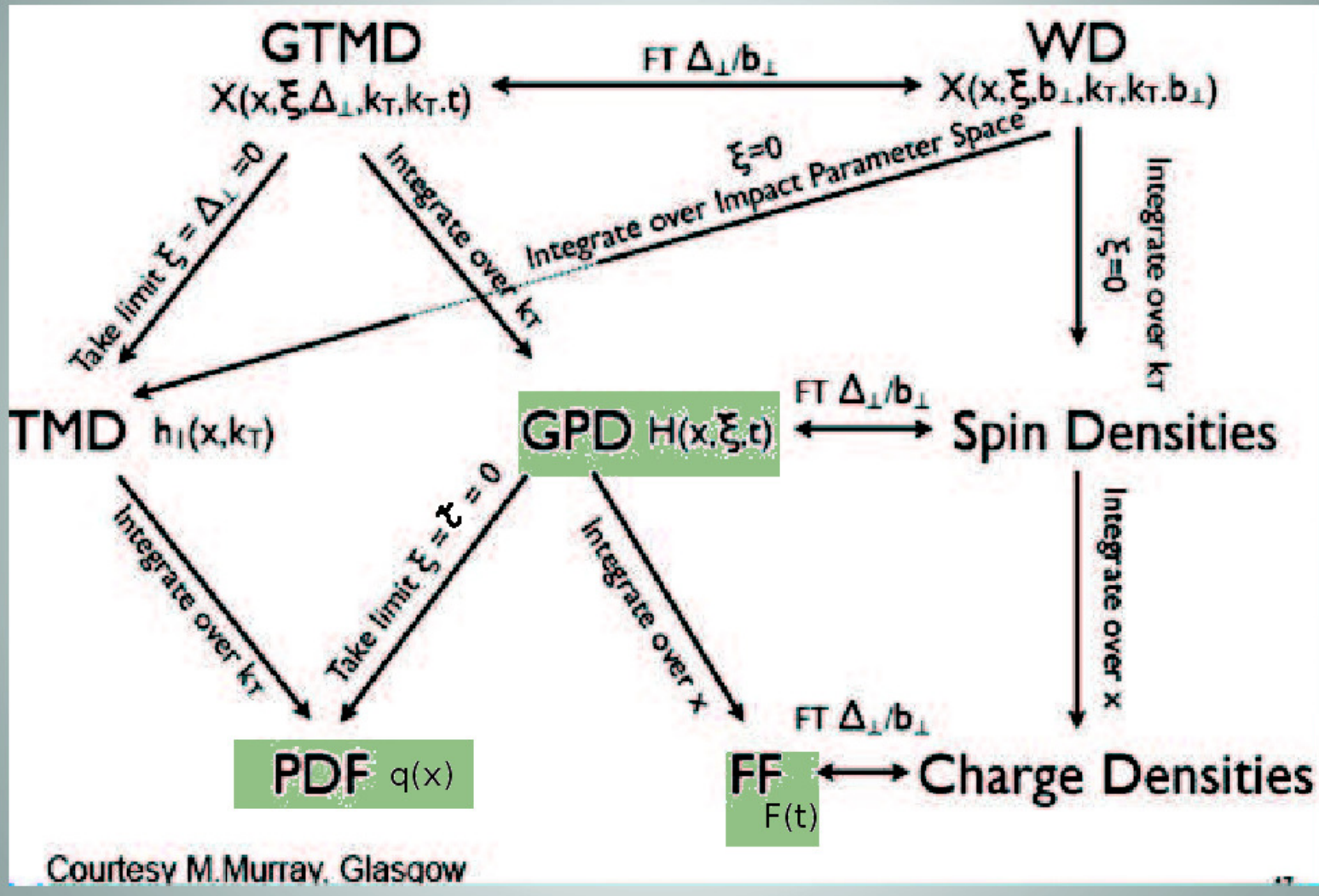
Thank you.



[B. Pasquini, 2010]

Contempory hierarchy of parton distributions



Generic questions

- are accessible energies high enough for perturbative treatment? and/or pure-quark picture?

- are power corrections/higher-twist effects important/to be included at experimentally accessible energies?

Generic questions

- is factorization proven/assumed? broken?
- pQCD calculation:
  - are higher-orders included?
  - which are technical difficulties in calculating higher-orders?
  - which are theoretical uncertainties of finite order predictions?
- nonperturbative input:
  - form/modeling of GPDs (DAs)