Structure of Mesons and its impact on Baryons one

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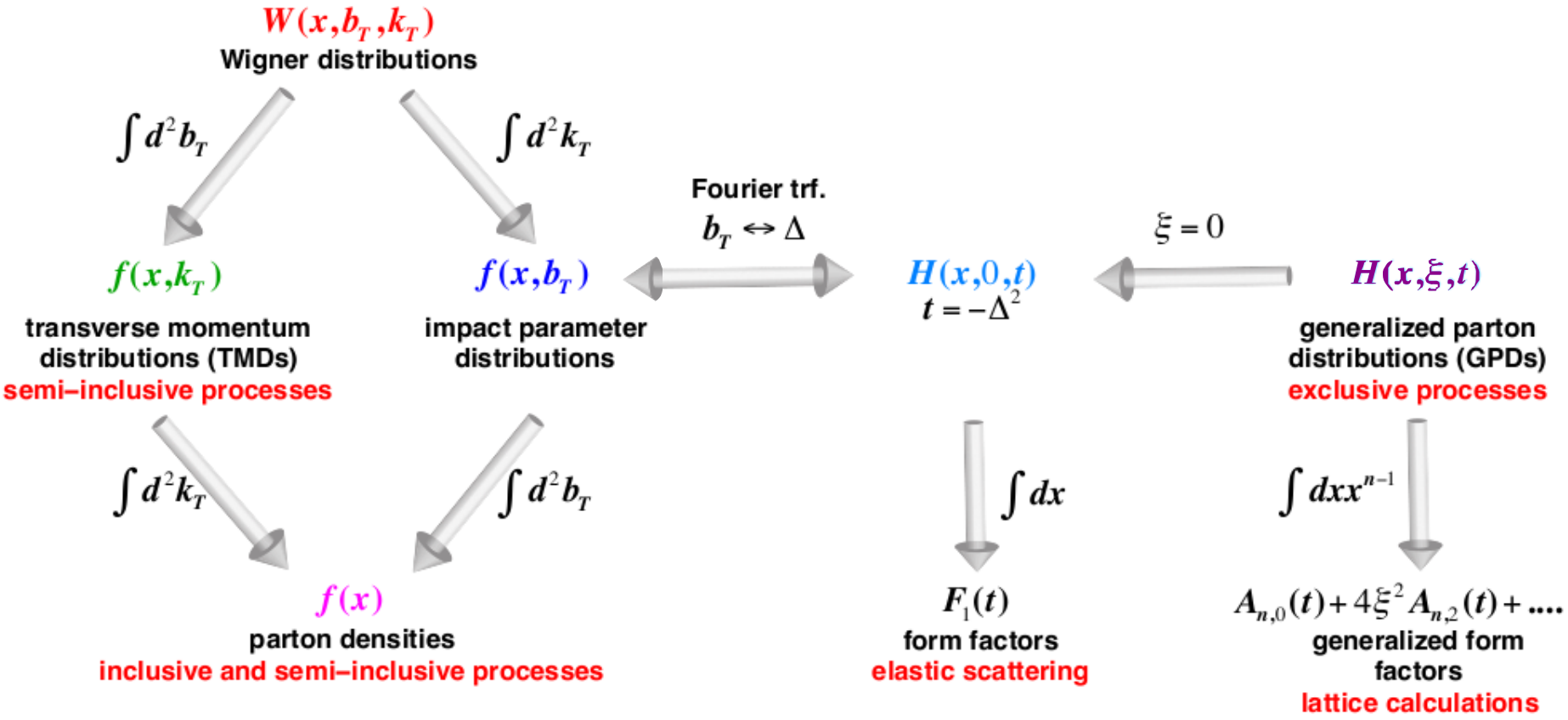
In collaboration with:
J.M. Morgado Chavez, H. Moutarde, J.Rodriguez-Quintero

Zoo of hadron structure

Various matrix elements are used today
to describe hadron structure from 1D to 5D



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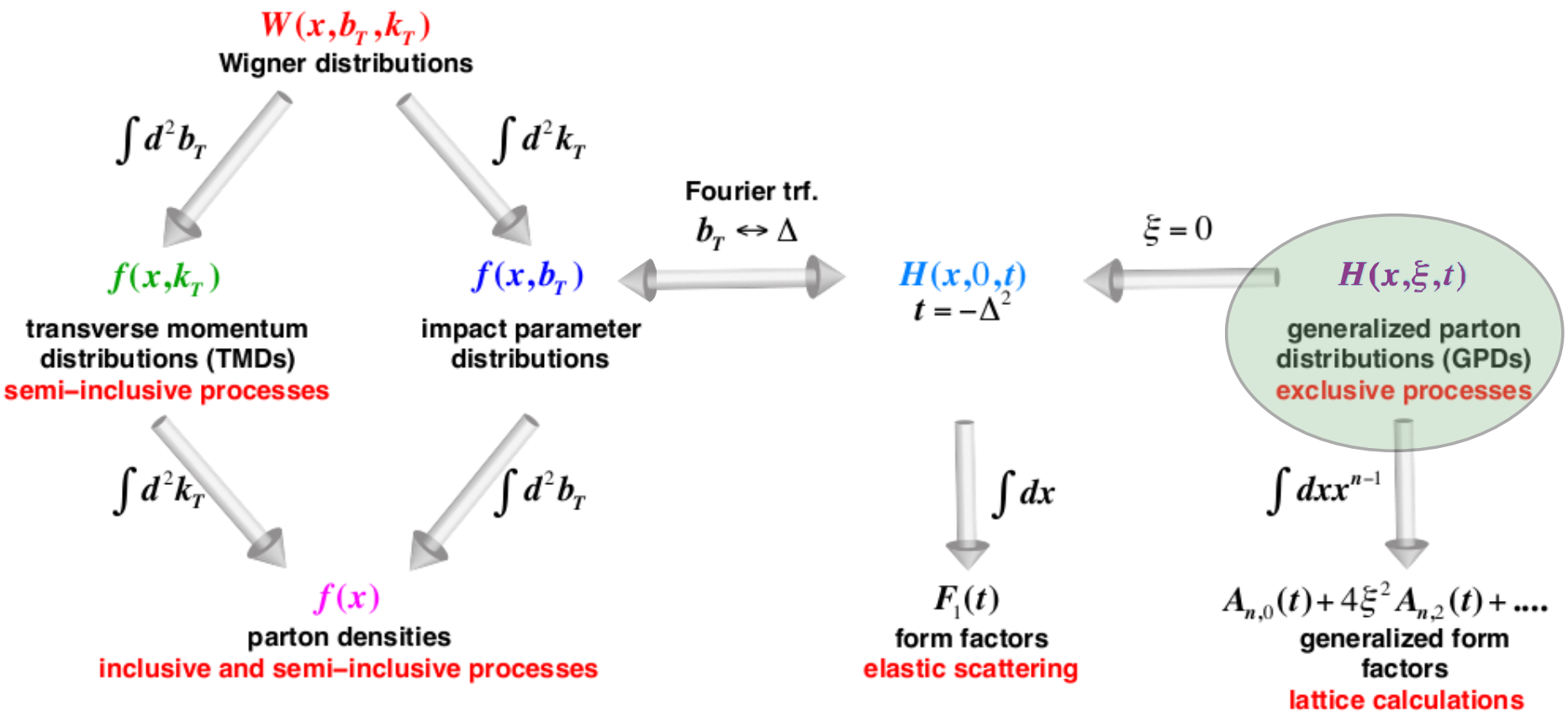

Generalised Parton Distributions

Fourier transform of non-local matrix elements:

$$H(x,\xi,t) = \frac{1}{2}\int \frac{e^{ixP^+z^-}}{2\pi}\langle P+\frac{\Delta}{2}|\bar{\psi}^q(-\frac{z}{2})\gamma^+\psi^q(\frac{z}{2})|P-\frac{\Delta}{2}\rangle \mathrm{d}z^-|_{z^+=0,\mathbf{z}=0}$$

D. Müller *et al.*, Fortsch. Phy. 42 101 (1994)
X. Ji, Phys. Rev. Lett. **78**, 610 (1997)
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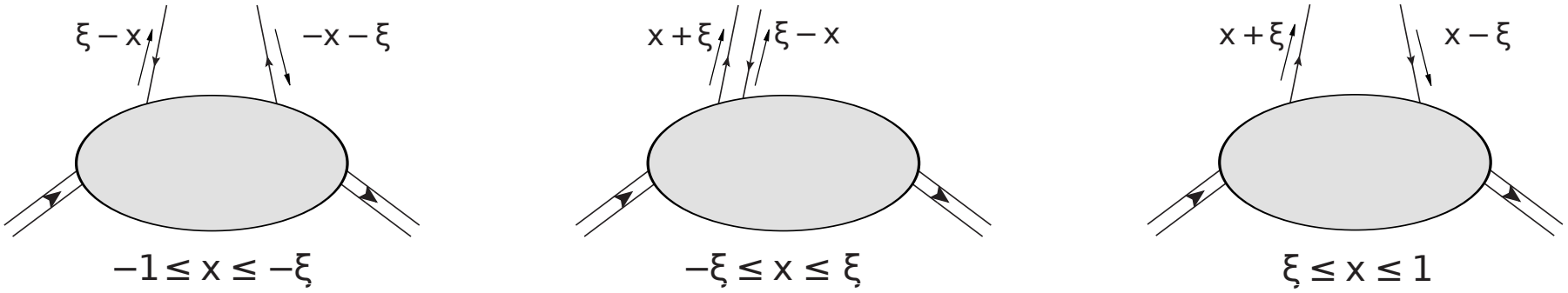

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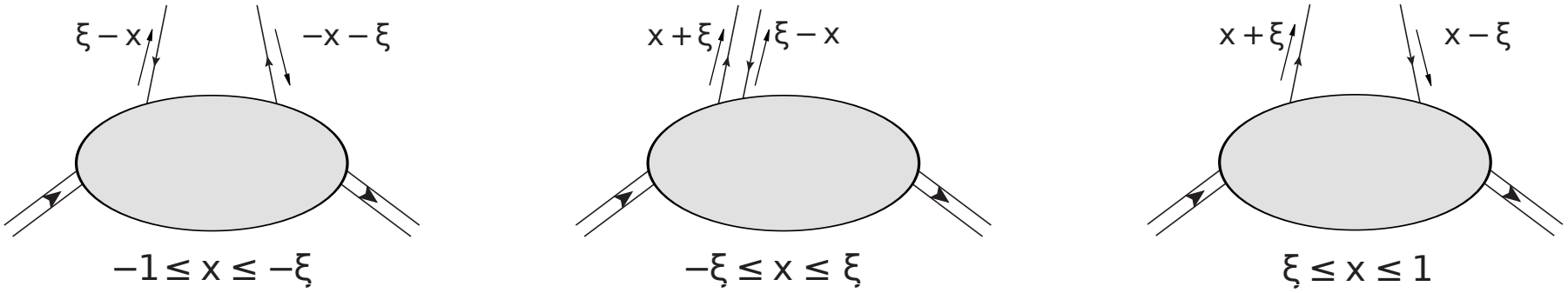

Experimental access

GPDs can be extracted from deeply virtual exclusive processes

Properties

- Polynomiality Property:

$$\int_{-1}^{1} \mathrm{d}x\ x^m H^q(x,\xi,t) = \sum_{j=0}^{\left[\frac{m}{2}\right]} \xi^{2j} C^q_{2j}(t) + mod(m,2)\xi^{m+1} C^q_{m+1}(t)$$

Lorentz Covariance

Properties

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

$$|H^q(x,\xi,t)| \leq \sqrt{q\left(\frac{x+\xi}{1+\xi}\right) q\left(\frac{x-\xi}{1-\xi}\right)}$$

A. Radysuhkin, Phys. Rev. **D59**, 014030 (1999)
B. Pire *et al.*, Eur. Phys. J. **C8**, 103 (1999)
M. Diehl *et al.*, Nucl. Phys. **B596**, 33 (2001)
P.V. Pobilitsa, Phys. Rev. **D65**, 114015 (2002)

Positivity of Hilbert space norm

Properties

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

Positivity of Hilbert space norm

- Support property:

$$x \in [-1; 1]$$

M. Diehl and T. Gousset, Phys. Lett. **B428**, 359 (1998)

Relativistic quantum mechanics

Properties

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- Soft pion theorem (pion GPDs only)

  M.V. Polyakov, Nucl. Phys. **B555**, 231 (1999)
  CM *et al.*, Phys. Lett. **B741**, 190 (2015)

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Problem

There is no model (until now) fulfilling a priori all these constraints.

3D structure of the pion: motivations

- The pion is the Goldstone boson of Chiral symmetry breaking
  - unique opportunity to study the 3D structure of a Goldstone boson
  - impact of the DCSB on the internal 3D structure of the pion

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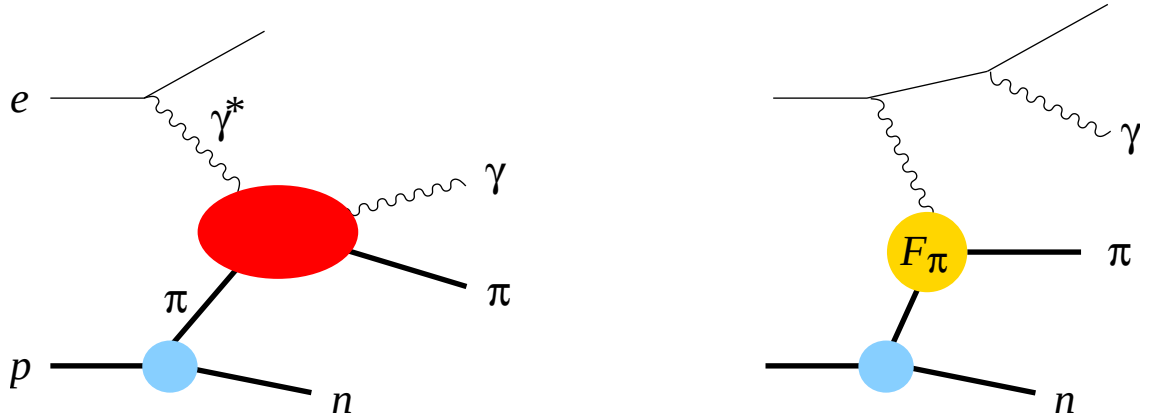

figure from D. Amrath *et al.*,Eur.Phys.J. C58 (2008) 179-192

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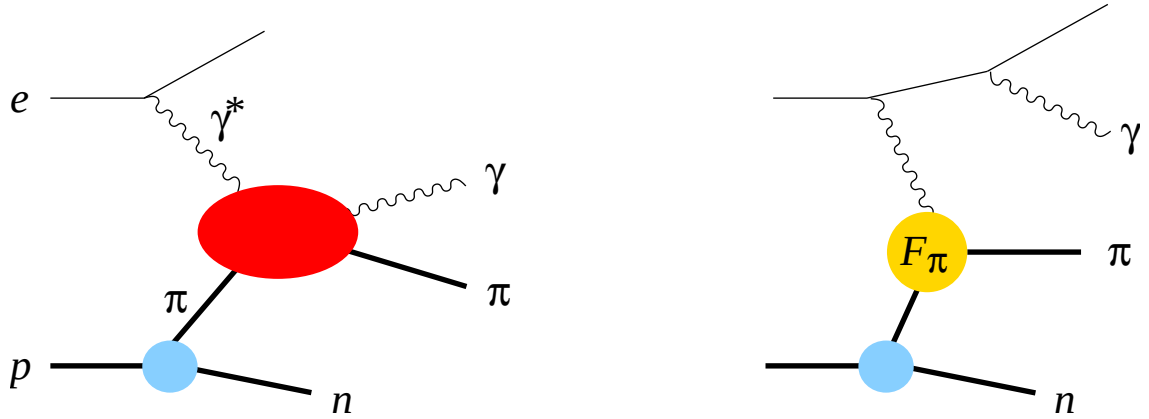

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JLab 12 and EIC might be able to look at such processes

The feasibility studies require models of pion GPDs

Models of Pion GPDs

Polynomiality oriented models

- Double Distribution models based mostly on RDDA

D. Amrath *et al.*, Eur.Phys.J.C 58 (2008) 179-192
I. Musatov and A Radyushkin, Phys.Rev., 2000, D61, 074027

- Pion PDFs are inputs, Pion FFs used to fit t dependence.

Positivity oriented models

- It usually relies on Lightfront Wave Functions
- Standard computations violates polynomiality due to Fock space truncation
- We have developed a technique to bypass this issue

N. Chouika *et al.* Eur.Phys.J. C77 (2017) no.12, 906
N. Chouika *et al.* Phys.Lett. B780 (2018) 287-293

Hadrons on the lightfront

- Lightfront quantization allows to expand hadrons on a Fock basis:

$$|P,\pi\rangle \propto \sum_\beta \Psi_\beta^{q\bar{q}}|q\bar{q}\rangle + \sum_\beta \Psi_\beta^{q\bar{q},q\bar{q}}|q\bar{q},q\bar{q}\rangle + \dots$$

$$|P,N\rangle \propto \sum_\beta \Psi_\beta^{qqq}|qqq\rangle + \sum_\beta \Psi_\beta^{qqq,q\bar{q}}|qqq,q\bar{q}\rangle + \dots$$

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- Non-perturbative physics is contained in the N-particles Lightfront-Wave Functions (LFWF) Ψ^N
- NB for the next section: schematically a distribution amplitude φ is related to the LFWF through:

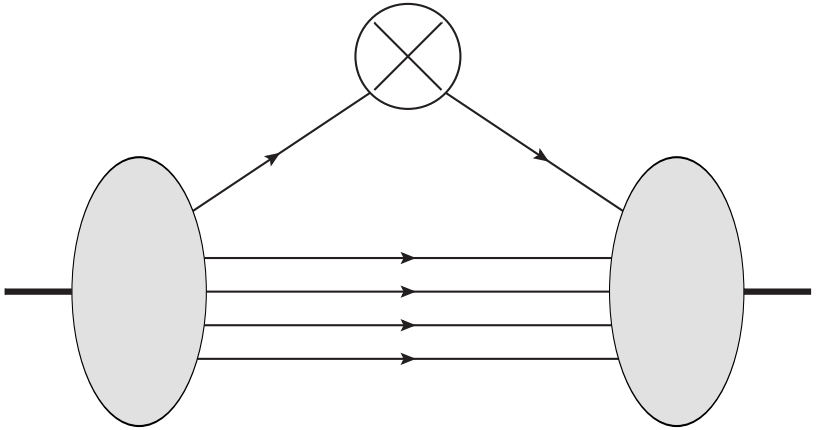
$$\varphi(x) \propto \int \frac{\mathrm{d}^2 k_\perp}{(2\pi)^2}\Psi(x,k_\perp)$$

S. Brodsky and G. Lepage, PRD 22, (1980)

LFWFs picture polynomiality

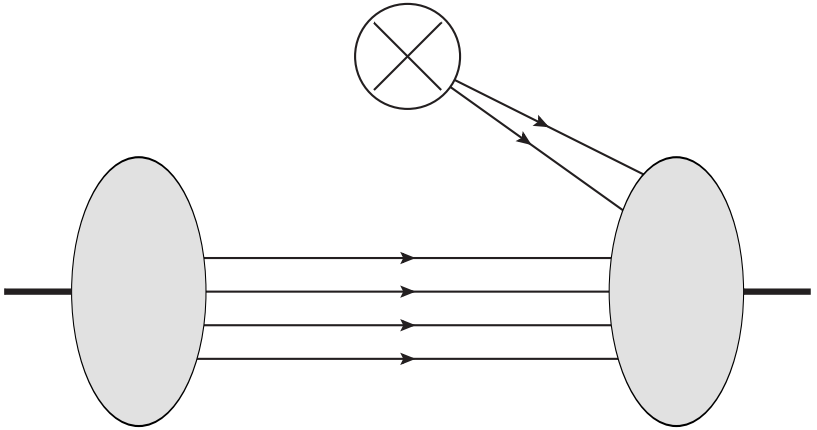
- On the light front, hadronic states can be expanded on a Fock basis

DGLAP: $|x| > |\xi|$



- Same N LFWFs
- No ambiguity

ERBL: $|x| < |\xi|$



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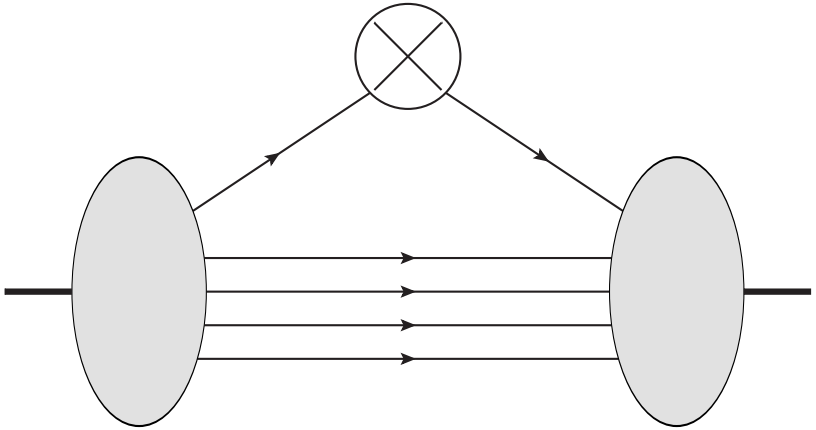

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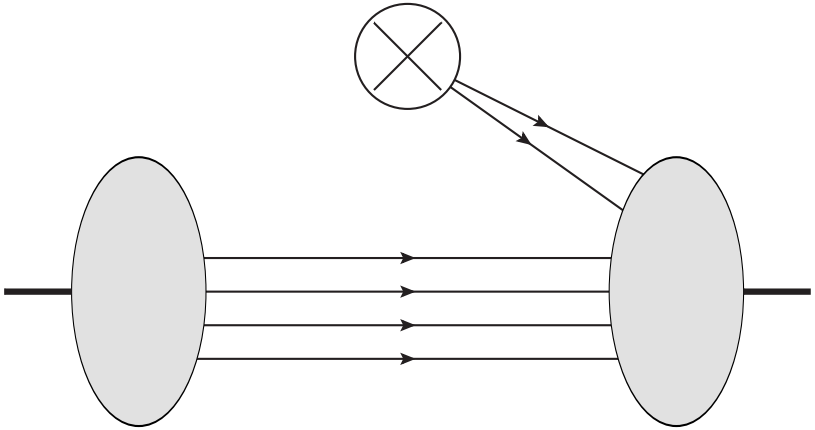

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LFWFs formalism has the positivity property inbuilt but polynomiality is lost by truncating both in DGLAP and ERBL sectors.

Inverse Radon Transform

$$H(x,\xi,t) = \int_{\Omega} \mathrm{d}\beta \mathrm{d}\alpha \delta\left(x-\beta-\alpha\xi\right)\left[F(\beta,\alpha,t)+\xi\delta(\beta)D(\alpha)\right]$$

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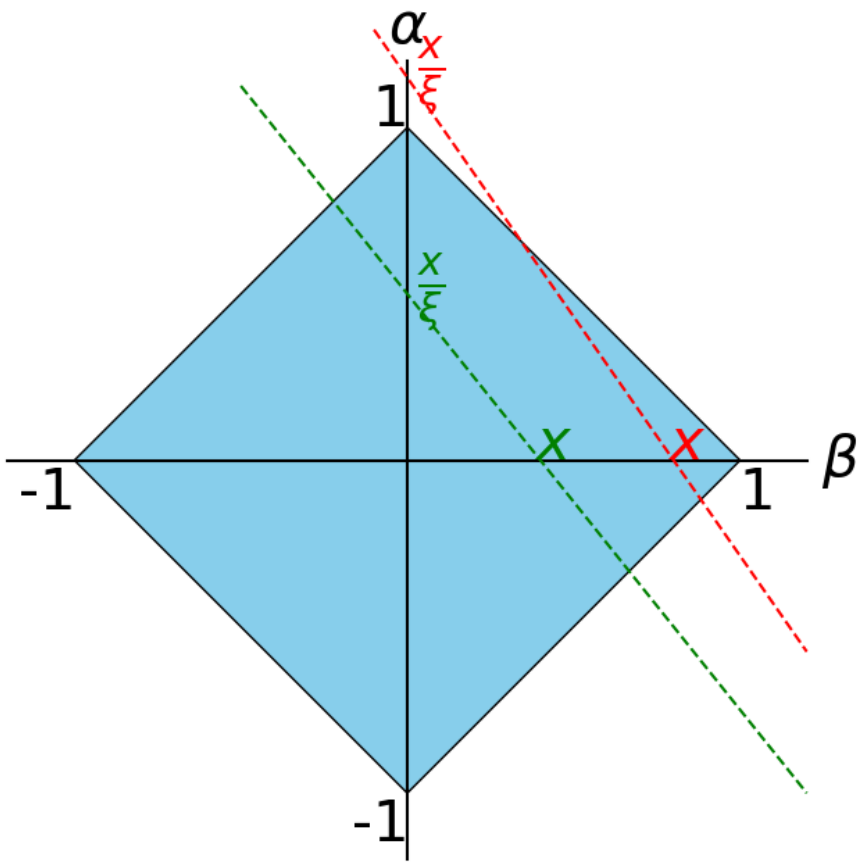

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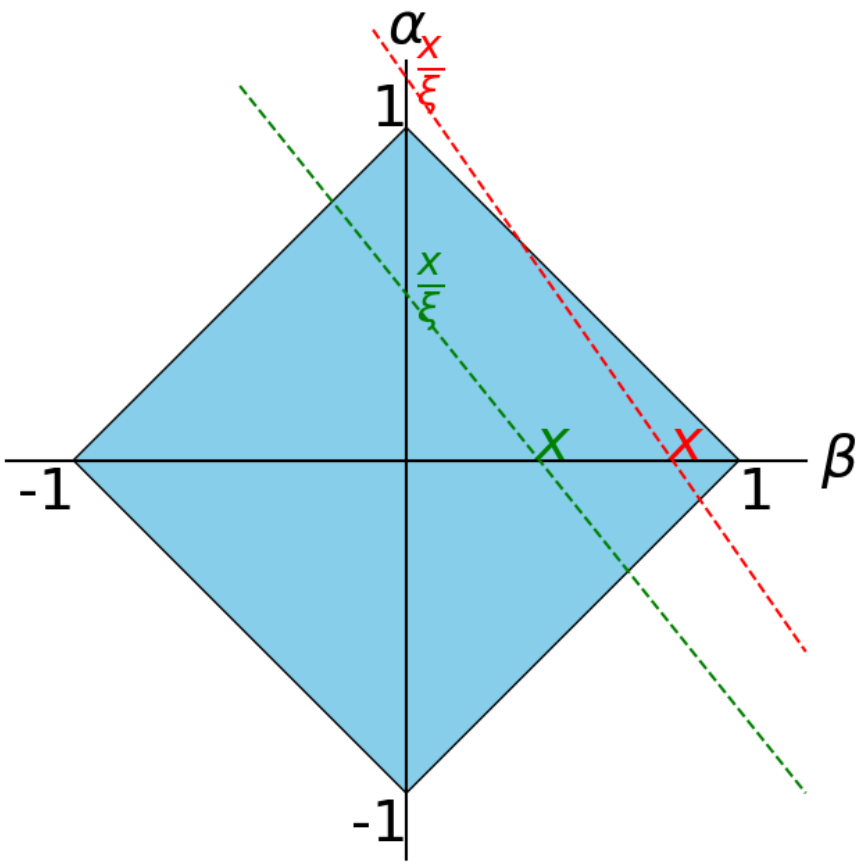
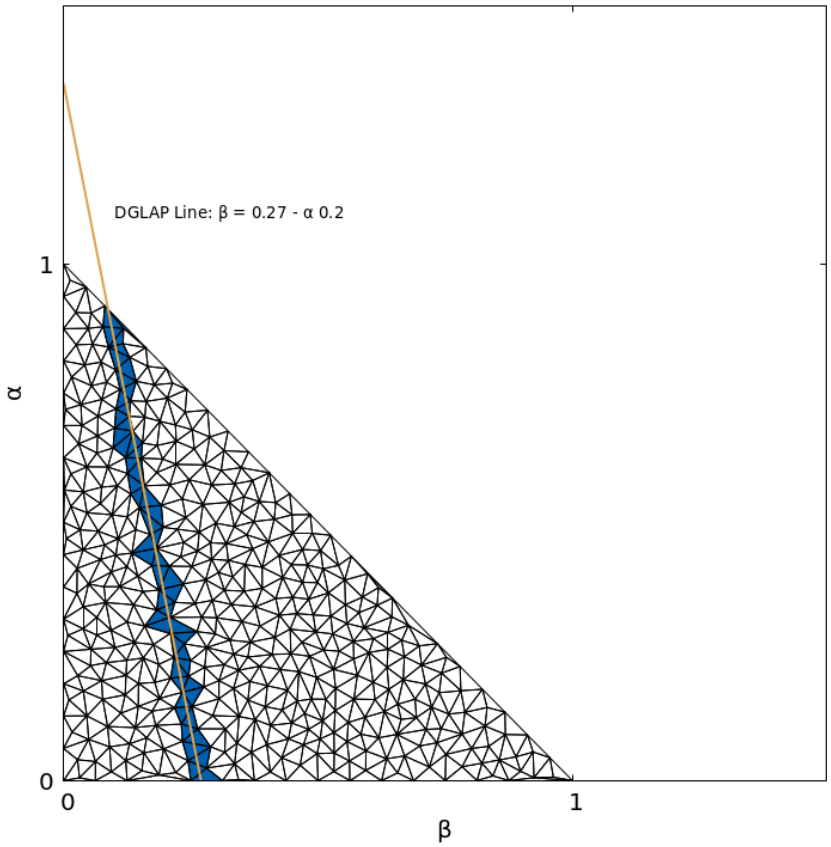
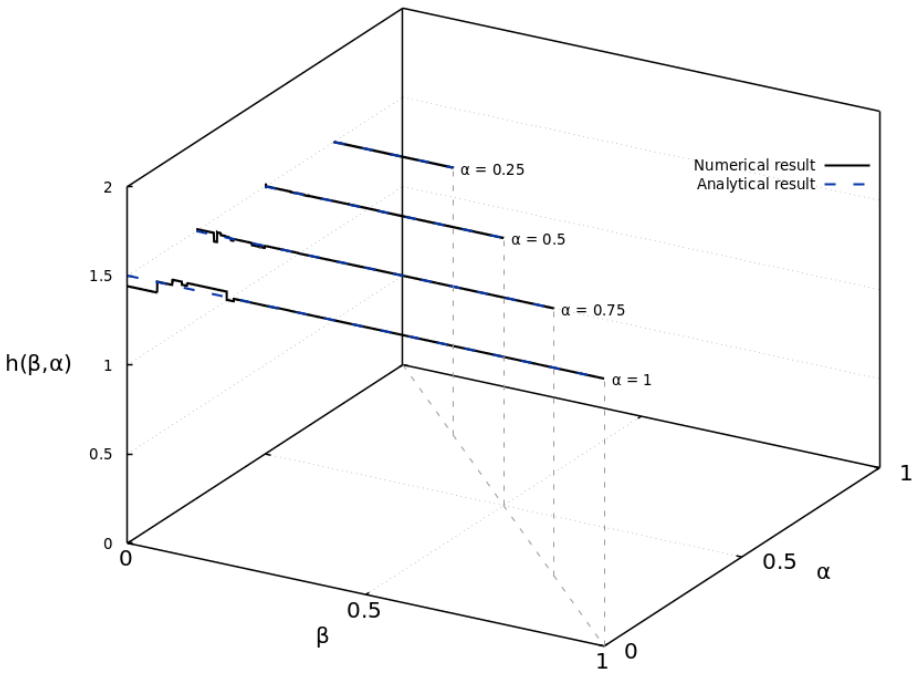




Examples



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- A bit of noise where it is expected

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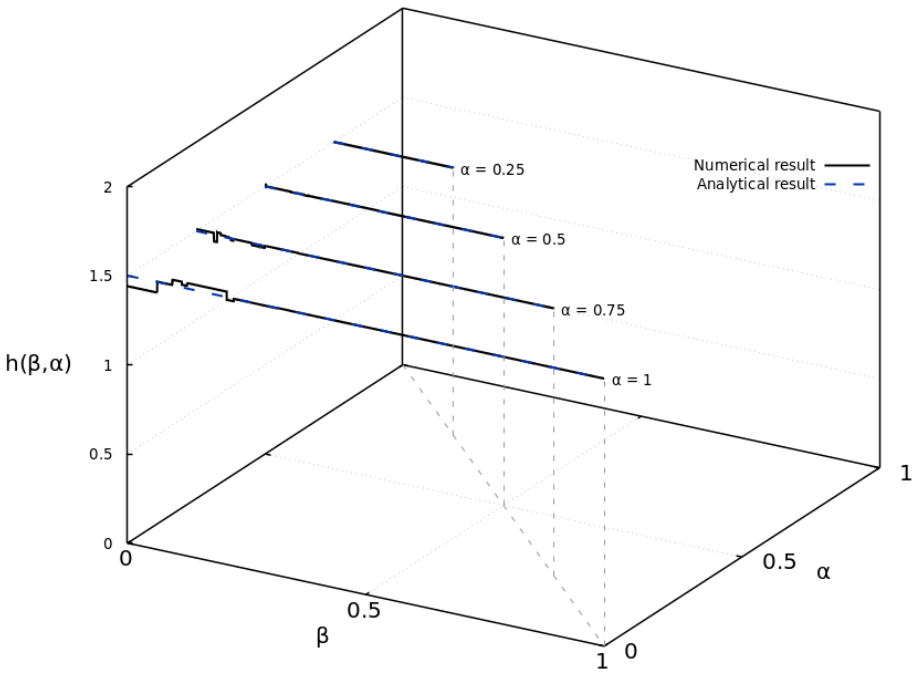

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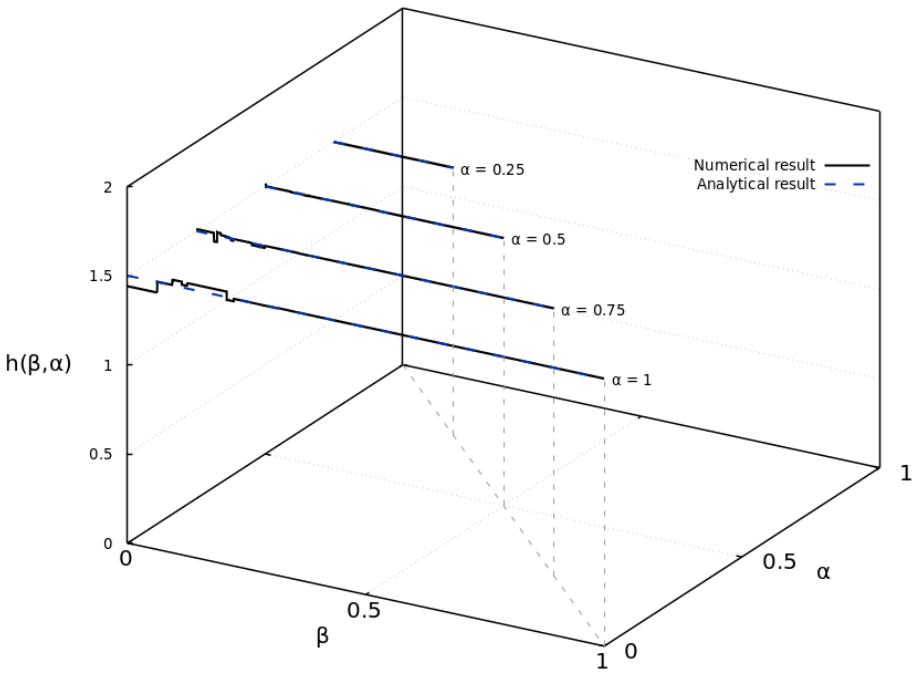

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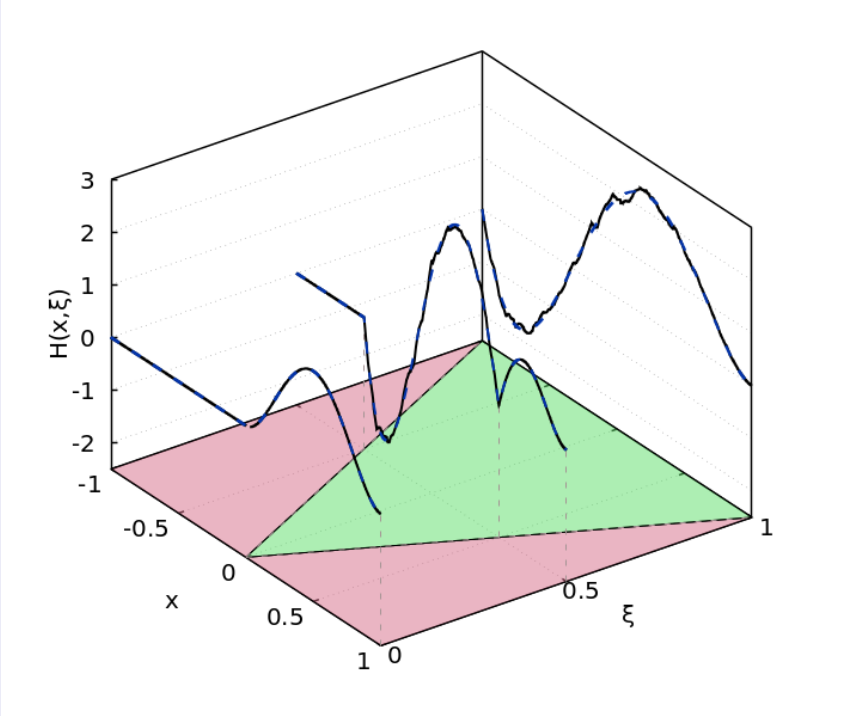
Uniqueness is guaranteed by Boman and Todd-Quinto theorem

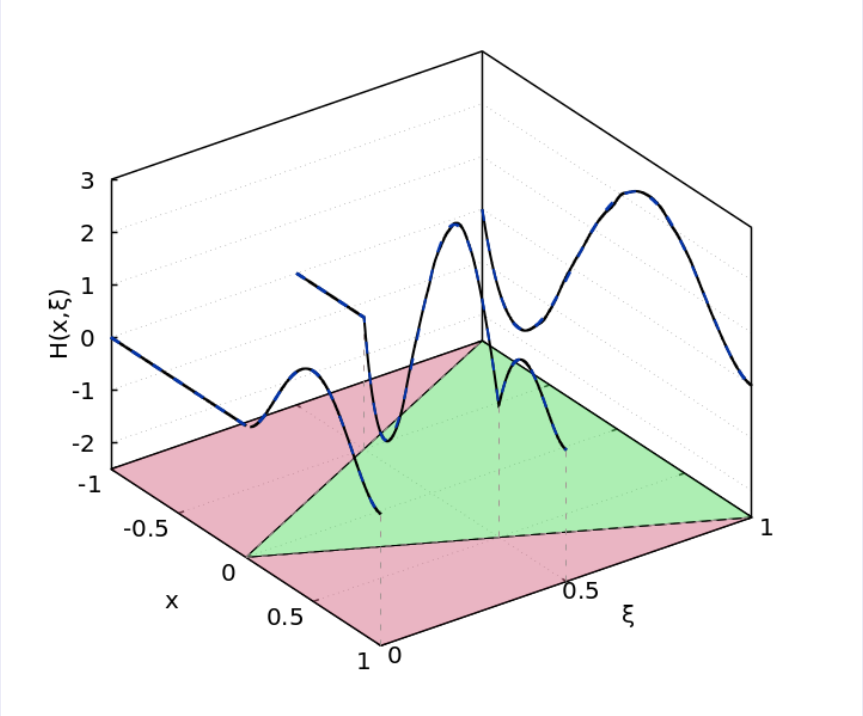
New techniques to compute GPDs

- The inverse Radon transform is an ill-posed problem
- Numerical implementation can be challenging due to noise

P_0



P_1



LFWF model from N. Chouika *et al.*, PLB 780 (2018) 287-293

Pion 3D structure

What we have

- A new technique to compute GPDs which fulfil all theoretical constraints
- Tested on simple examples $\rightarrow$ proof of principle

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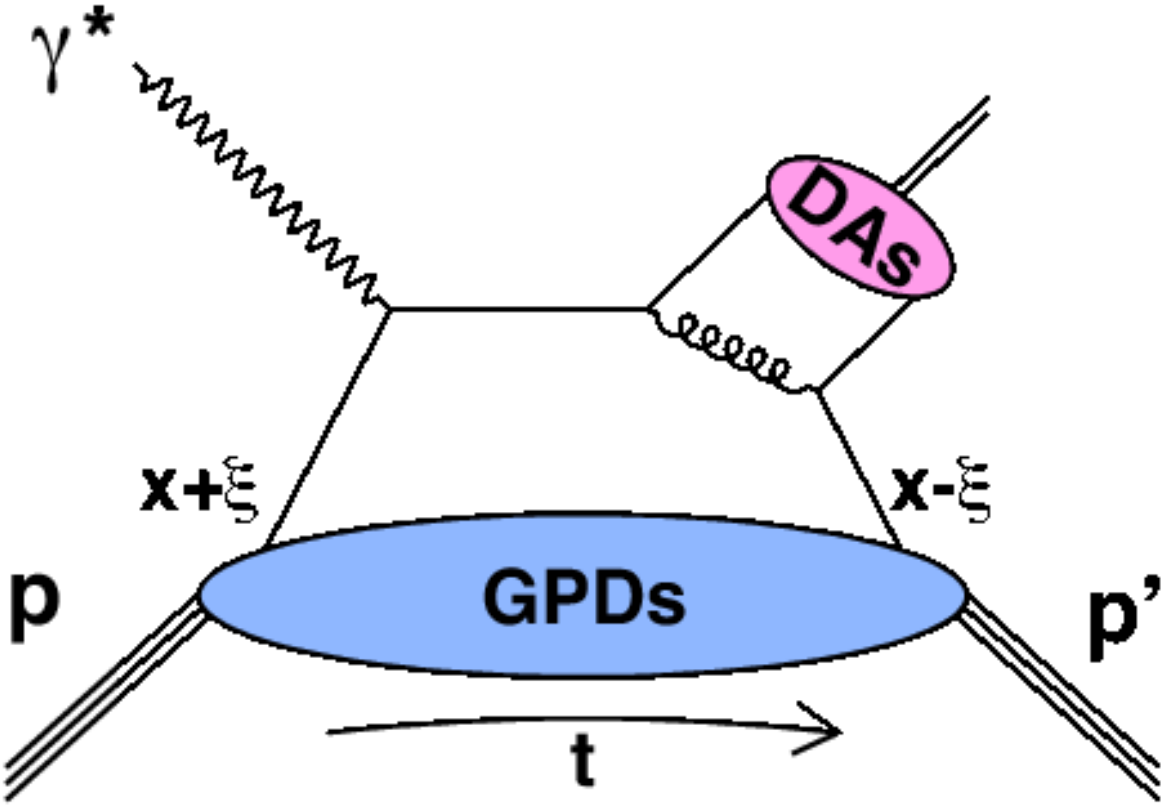
What remains to be done

- Apply realistic LFWFs coming from non-perturbative framework (DSE,...) to connect our pion GPDs models with dynamical properties of QCD.
- Assessment of cross sections for Tagged deep exclusive processes $\rightarrow$ can we extract pieces of information on pion GPDs from current and future facilities?

Mesons structure: a key ingredient to understand baryon structure



Distribution amplitudes: definitions

$$\langle 0|O^{\alpha,\cdots}(z_1^-,\ldots,z_n^-)|P,\lambda\rangle$$

- Lightcone operator O of given number of quark and gluon fields

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Both mesons and baryons can (in principle) have multiple independent leading twist DA, and higher-twist DA.

DVMP factorisation at LO

$$\mathcal{F}^q(\xi, t, Q^2) \propto \frac{\alpha_s(\mu_R)}{Q} \int_{-1}^{1} \mathrm{d}x \frac{F^q(x, \xi, t, \mu_F^2)}{\xi - x - i\epsilon} \int_0^1 \mathrm{d}z \frac{\varphi(z, \mu_\varphi)}{(1-z)}$$

see e.g. D. Mueller *et al.* Nucl.Phys. B884 (2014) 438-546

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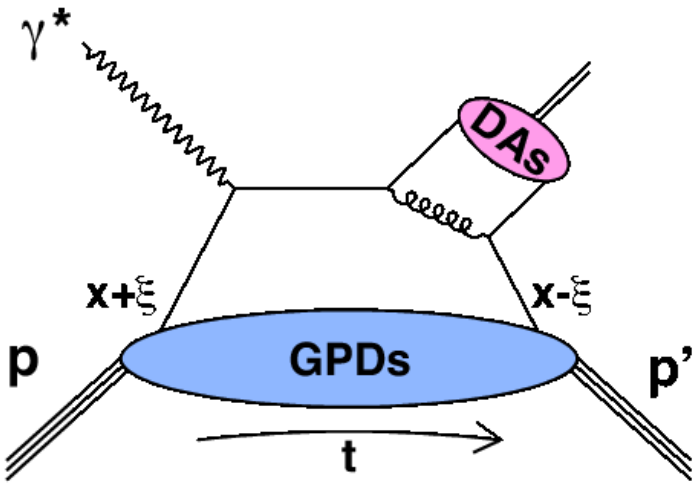

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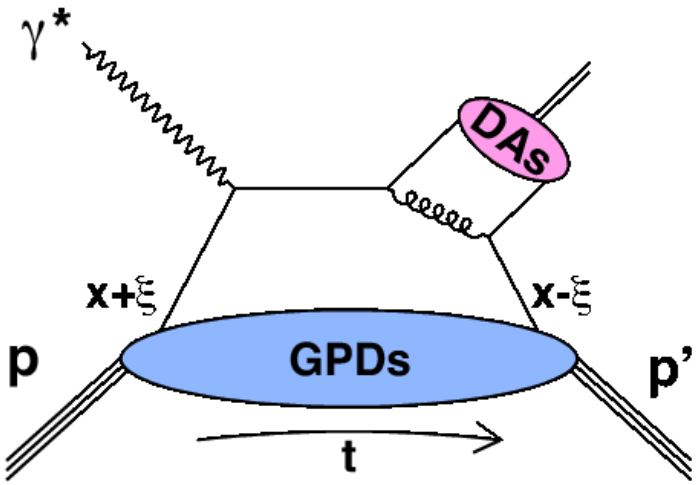

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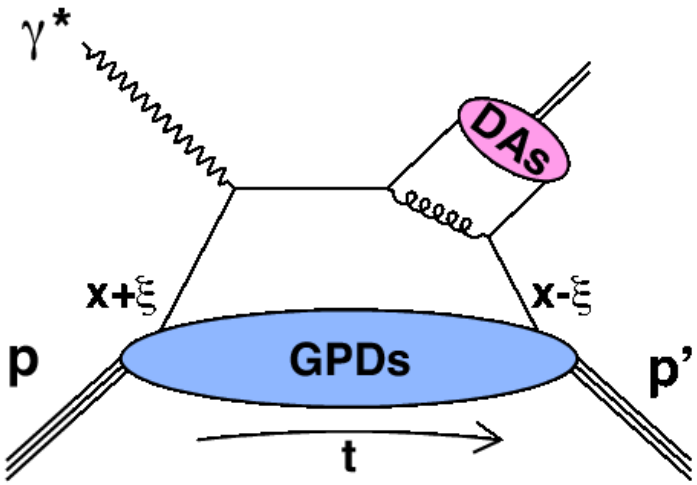

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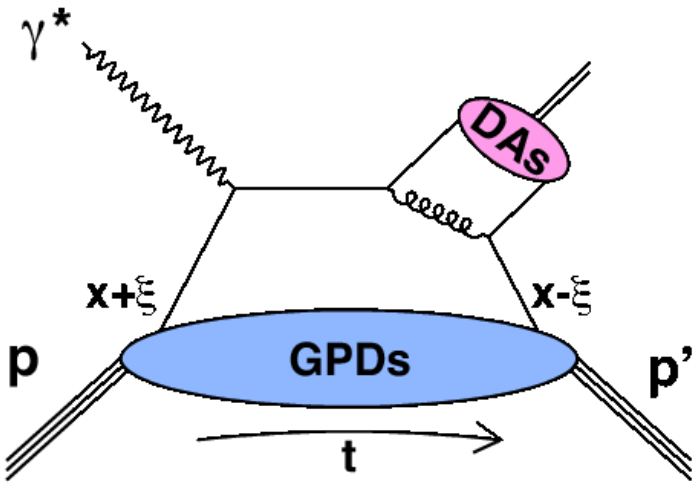

What is the impact of various models on DVMP?

Models of Pion DA

- Asymptotic DA : $\varphi_{AS} = 6x(1-x)$
- Square-root DA : $\varphi_{SR} = \frac{8}{\pi}\sqrt{x(1-x)}$

A. Radyushkin, Nucl.Phys. A532 (1991) 141-154
S. Brodsky *et al.* Int.J.Mod.Phys.Conf.Ser. 39 (2015) 1560081

- Fits on Lattice second moment of DA

V. Braun *et al.* Phys.Rev. D92 (2015) no.1, 014504

  - Power model : $\varphi_p(x) \propto (x(1-x))^{\nu}$

J. Segovia *et al.*, Phys.Lett. B731 (2014) 13-18

  - Log model : $\varphi_{\ln}(x) \propto 1 - \frac{\ln[1+\kappa x(1-x)]}{\kappa x(1-x)}$

C. Mezrag *et al.*, Phys.Lett. B783 (2018) 263-267

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Bottom line

- 4 different *concave* pion DA models
- 2 tuned to Lattice QCD results of the second moment

$n = -1$ Mellin Moment

	$x(1-x)$	$\varphi_{\ln}(x)$	$(x(1-x))^{\nu}$	$\sqrt{x(1-x)}$
$\langle x^{-1} \rangle$	3	3.38	3.61	4
$\frac{\langle x^{-1} \rangle}{\langle x^{-1} \rangle_{As}}$	1	1.13	1.20	1.33

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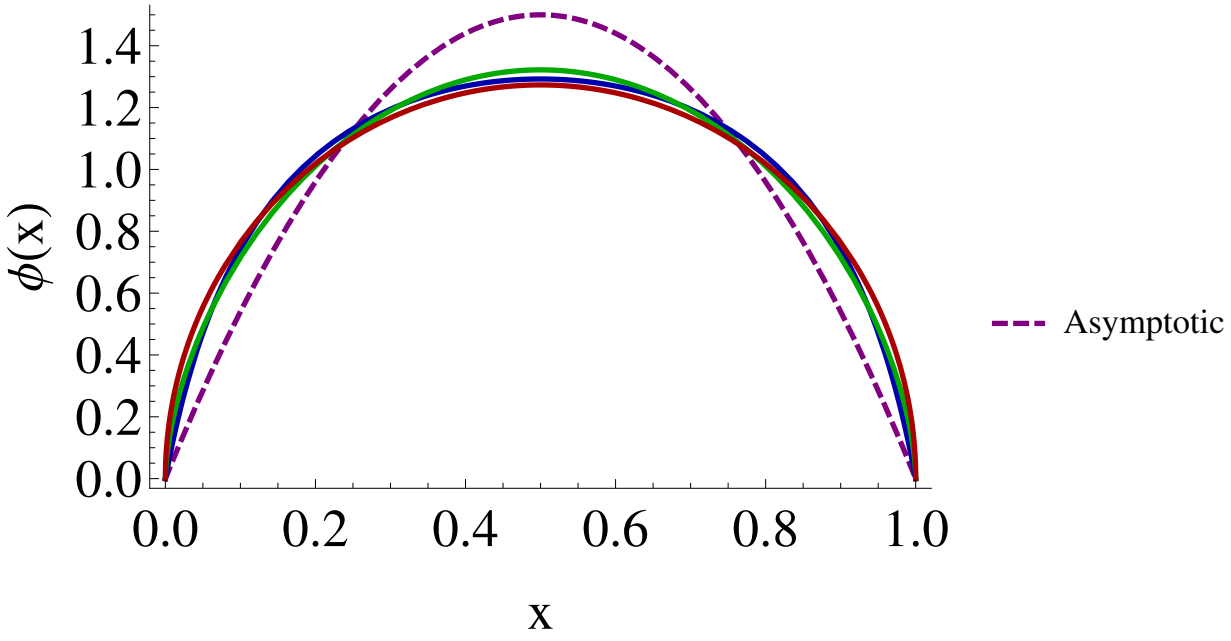

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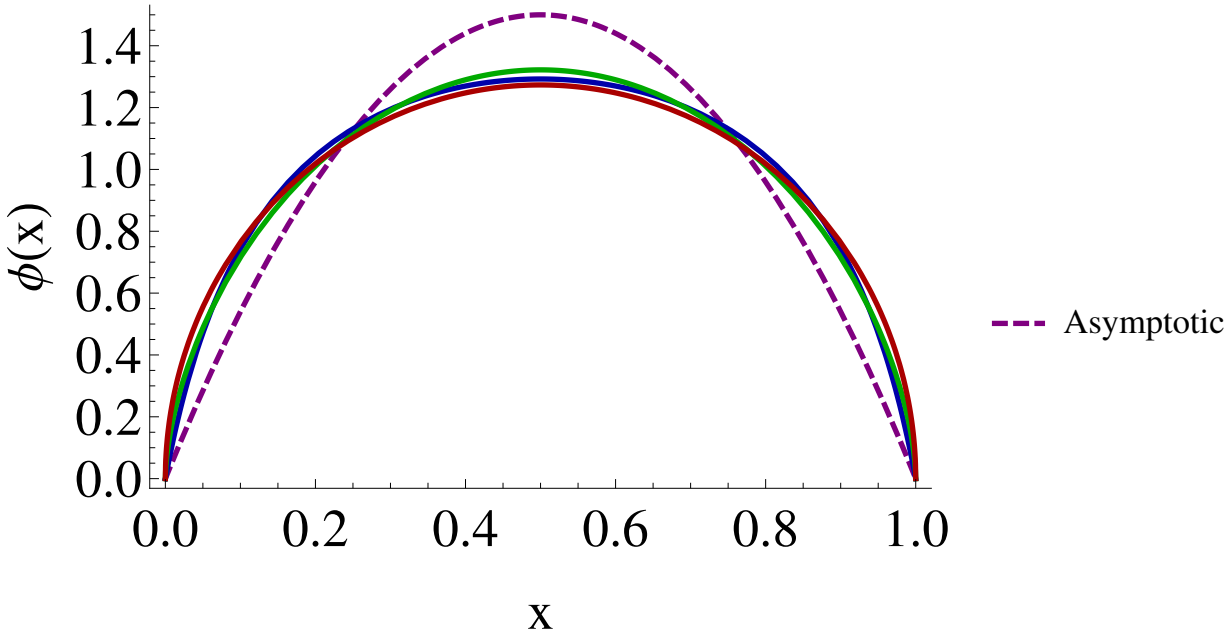

Additionnal complication : evolution and scale setting

Pion specificity

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\mathrm{d}x_b\mathrm{d}t\mathrm{d}\phi} = \frac{1}{2\pi}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}x_b\mathrm{d}Q^2}\left[\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \epsilon\frac{\mathrm{d}\sigma_L}{\mathrm{d}t} + \sqrt{1\epsilon(1+\epsilon)}\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t} + \epsilon\cos(2\phi)\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t}\right]$$

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M. Defurne *et al.* Phys.Rev.Lett. 117 (2016) no.26, 262001

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Consequences

- If true, it sheds experimental light on new nucleon matrix elements
- Difficulty: higher-twist structures hardly known

C. Shi *et al.*, Phys.Rev. D92 (2015) 014035

DVMP and PARTONS

http://partons.cea.fr

- PARTONS $\rightarrow$ open-source software for GPDs phenomenology
- Flexible code architecture allowing GPDs studies in a broad range of assumptions.
- The development on the DVMP branch is now well engaged (Kemal Tezgin and Pawel Sznajder).
  We would like :
  - Standard colinear factorisation : LO and NLO perturbative kernel
  - Suggested chiral-odd mechanisms (Goloskokov-Kroll)
  - Various models of DA
  - Evolution code for the leading twist DA

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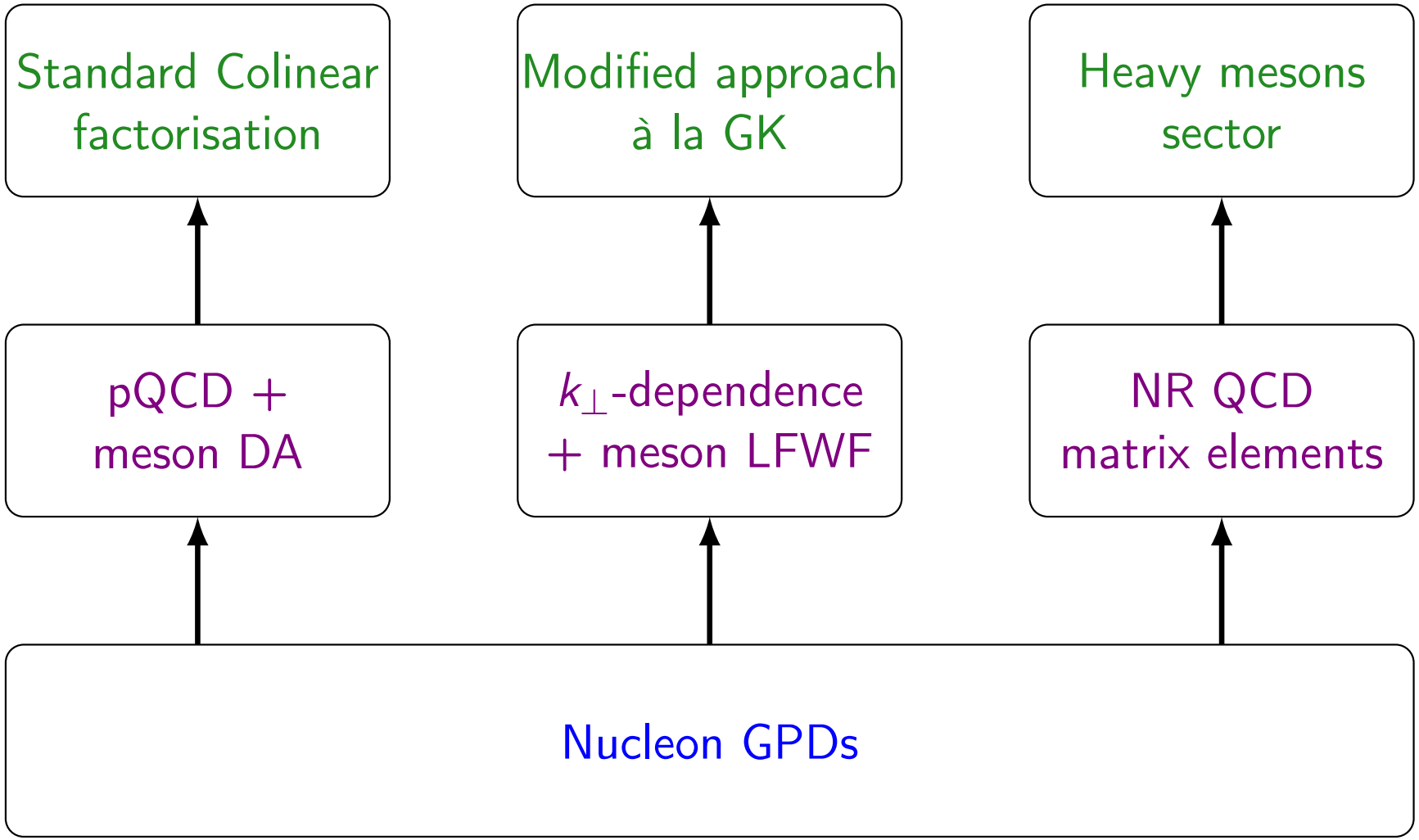
- PARTONS → first quantitative studies of the impact of the meson DA at LO and NLO on GPD extraction
- PARTONS → comparison with different non-perturbative predictions of the meson DA and the GPDs

DVMP in PARTONS



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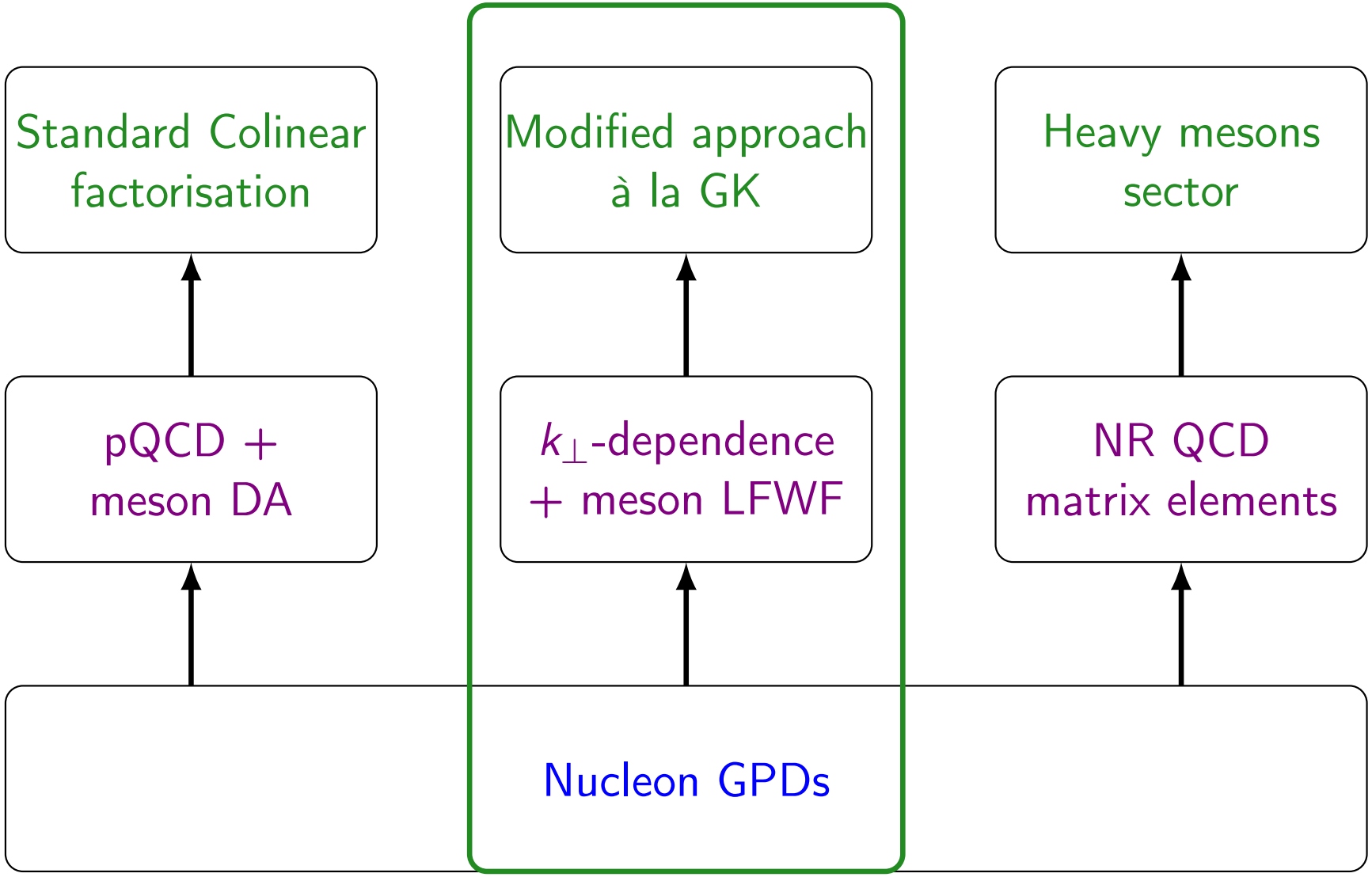

Summary and Conclusion

Meson Structure

- Study of meson structure is interesting by itself
- Goal: A formalism able to handle all type of matrix elements
- We have highlighted limitations of the impulse approximation and propose new method based on LFWF to study meson 3D structure
- Shed light on diquark correlations

DVMP and DA

- DVMP is very sensitive to the shape of DA
- Non-perturbative approaches help but still no definitive solution
- DVMP studies may need to be coupled to other processes sensitive to GPDs (DVCS) and DA (Meson Form Factors?)
- PARTONS will be a good tool to exploit DVMP data

Thank you for your attention