Nucleon Distribution Amplitudes

C. Mezrag

Argonne National Laboratory

April 21^{th}, 2016

In collaboration with: C.D. Roberts

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And some slides on GPDs also!

Warning

Lightcone Wave functions

- Lightcone quantization : $z^0 \to z^+ = z^0 + z^3$
- Lightcone-QCD allows decomposition of hadrons in Fock states:

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

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

- Often restricted to the first term, *i.e.* $\Psi_\beta^{q\bar{q}}$ and Ψ_β^{qqq}.
- Schematically (disregarding twist decomposition), the DA φ:

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

Evolution

- DA are scale dependent objects
- They obey evolution equation and can be written as:

$$\varphi_\pi(x,\mu^2) = \varphi_\pi^{As}(x)\left(1 + \sum_{j=2,4\ldots}^{\infty} a_j^{(\frac{3}{2})}(\mu^2) C_j^{(\frac{3}{2})}(x)\right)$$

Efremov and Radyushkin (1980)
Lepage and Brodsky (1980)

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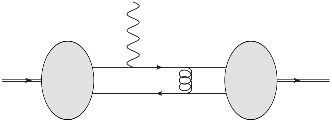
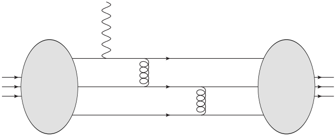
Caveat

What does *large enough* mean?

Fock space at high Q^2





- At large Q^2,

$$F(Q^2) \simeq \int [\mathrm{d}x][\mathrm{d}y]\varphi^*(y)T(x,y)\varphi(x)$$

- Higher Fock states suppressed by $\left(\frac{\alpha_S(Q^2)}{Q^2}\right)$ per additional constituent.
- T can be computed through perturbation theory.

From DA to Form factors

- Pion case:

$$Q^2 F_\pi(Q^2) = 16\pi\alpha_S(Q^2) f_\pi \omega_\varphi^2 \quad \text{for large enough } Q^2$$

with

$$\omega_\varphi = \frac{1}{3}\int \mathrm{d}x \frac{\varphi(x,Q^2)}{x}, \quad \omega_{As} = 1$$

Farrar and Jackson (1979),
Efremov and Radyushkin (1980),
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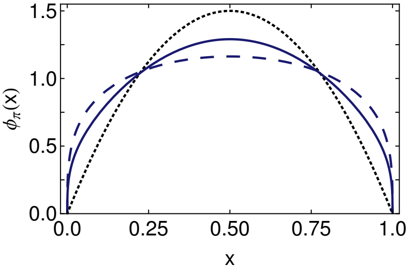
- Proton case:
  - same reasoning but absolute normalisation unknown,
  - when assuming isospin symmetry, the ratio between the magnetic form factors of the proton and neutron can be predicted.

Pion distribution amplitude

$$\phi_{As}(x) = 6x(1-x)$$



Chang *et al.* (2013)

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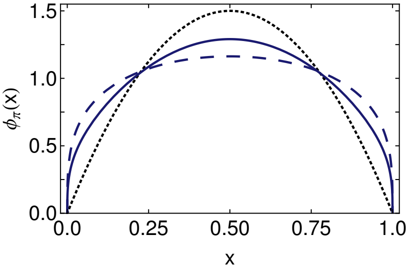

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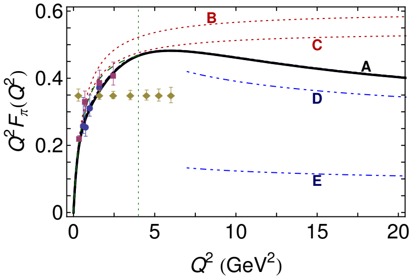

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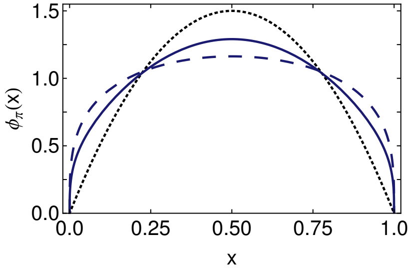

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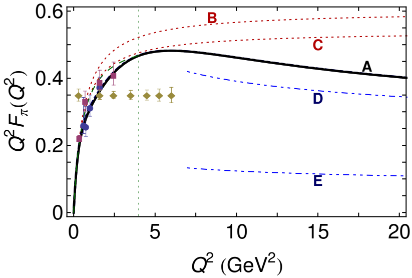
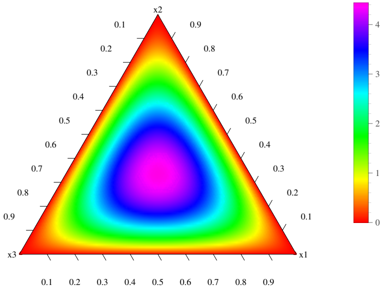


Chang *et al.* (2013)

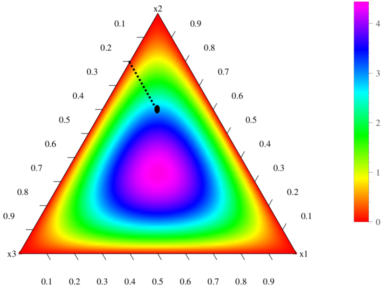
- Broad DSE pion DA is much more consistent with the form factor than the asymptotic one.
- The scale when the asymptotic DA become relevant is huge.

Proton distribution amplitude



$$\varphi_{As}(x_1, x_2, x_3) = 120 x_1 x_2 x_3$$

Proton distribution amplitude



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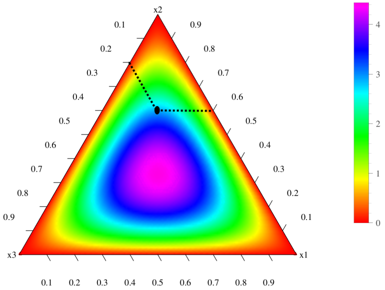

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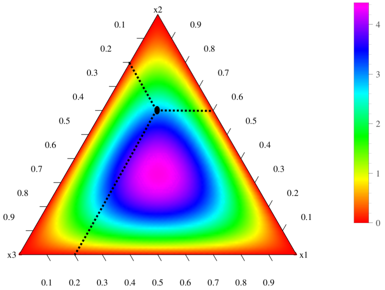

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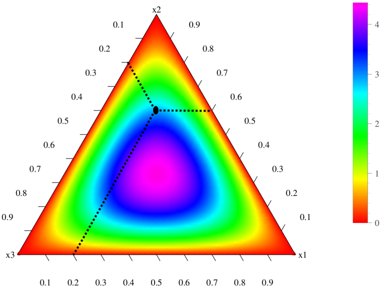

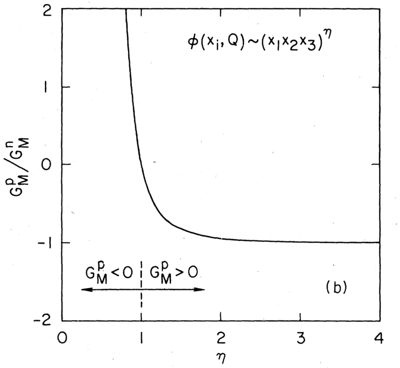

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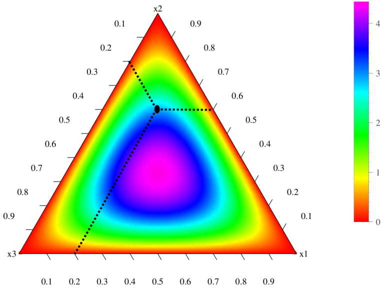

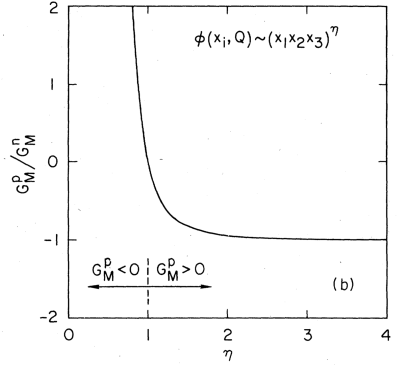

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What happen when computing the Proton DA within DSEs framework?

Quark-diquark degrees of freedom

- Interactions generating meson also generate diquarks in a $\bar{3}$-colour state.
- Two types of diquark correlations inside the nucleon:
  - Scalar diquarks.
  - Axial-Vector diquarks.

Cahill *et al.*, (1987)

- This allow to solve a simplified Faddeev equation...
- .. and to compute in the DSE framework of different baryon observables, including the nucleon form factors.

We would like to apply this approximation to compute nucleon DA.

Leading Twist Nucleon DA

- Parameterisation of non-local matrix element in 24 invariant functions:

$$\langle 0|\epsilon^{ijk} u_\alpha^i(z_1) u_\beta^j(z_2) d_\gamma^k(z_3)|P\rangle$$
$$= \frac{1}{4}\Big[\left(\not{p}C\right)_{\alpha\beta}\left(\gamma_5 N^+\right)_\gamma V(z_i^-) + \left(\not{p}\gamma_5 C\right)_{\alpha\beta}\left(N^+\right)_\gamma A(z_i^-)$$
$$- \left(ip^\mu \sigma_{\mu\nu} C\right)_{\alpha\beta}\left(\gamma^\nu \gamma_5 N^+\right)_\gamma T(z_i^-)\Big] + \text{higher twist.}$$

Braun *et al.* 2000

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Braun *et al.* 2000

- Nucleon leading twist DA defined as:

$$\varphi(x_i) = V(x_i) - A(x_i)$$

Matrix element of the leading twist DA

- Definition of the leading twist DA in terms of matrix element:

$$\langle 0|\epsilon^{ijk}\left(u^i_\uparrow(z_1)C\not{z}u^j_\downarrow(z_2)\right)\not{z}d^k_\uparrow(z_3)|P\rangle$$
$$= -\frac{1}{2}(p\cdot z)\not{z}N^\uparrow\int\mathcal{D}x_i\varphi(x_1,x_2,x_3)e^{-i\sum_i x_i P\cdot z_i}.$$

  - quark of given chirality: $q^{\uparrow(\downarrow)}=\frac{1\pm\gamma_5}{2}q$
  - momentum conservation: $\mathcal{D}x_i=\mathrm{d}x_i\delta(1-x_1-x_2-x_3)$

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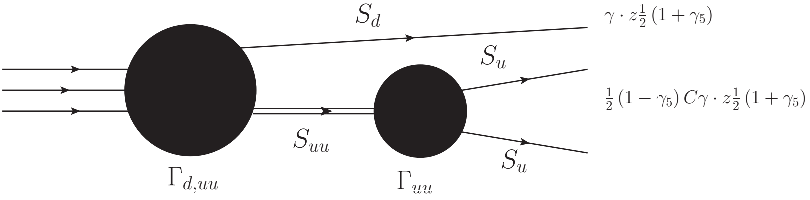
  - Interaction with the remaining quark d.

Quark-Diquark DA



- Need of specific ingredients:
  - quark propagator S_u (S_d),
  - AV diquark propagator S_{uu},
  - diquark Bethe-Salpeter amplitude Γ_{uu},
  - nucleon Bethe-Salpeter amplitude $\Gamma_{d;uu}$.

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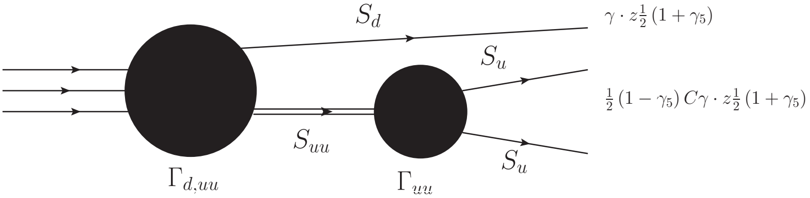

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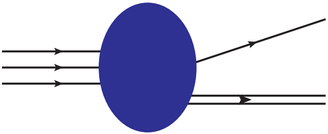
All these objects can be computed non-pertubatively using DSEs-BSEs.



- quark propagator:

$$S_q(q) = \frac{-i\gamma \cdot q + M}{q^2 + M^2}$$

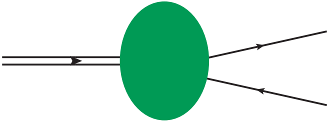
- diquark propagator:

$$S_{qq}(K) = \frac{1}{K^2 + \widetilde{M}^2}\left(\delta_{\mu\nu} + \frac{K^\mu K^\nu}{K^2}\right)$$

- Nakanishi representation for the quark-diquark Bethe-Salpeter Amplitude:

$$\mathcal{A}_\mu(K,P) = i\gamma_5 P_\mu \frac{\bar{M}}{f_N}\bar{M}^{2\sigma}\int_{-1}^{+1} \mathrm{d}z\,\rho_\sigma(z)\left[\frac{1}{\left(\left(K - \frac{1-z}{2}P\right)^2 + \Lambda_N^2\right)}\right]^\sigma$$

Nakanishi representation: Diquark Amplitude



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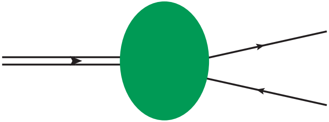

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$$\Gamma_\mu = i\widetilde{\gamma}_\mu C \frac{M}{f} M^{2\nu}, \qquad \widetilde{\gamma}_\mu = \gamma_\mu - \frac{K_\mu}{K^2}\gamma \cdot K$$

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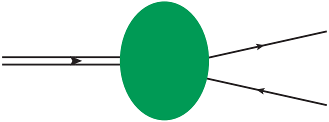

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- Extended Bethe-Salpeter Amplitude:

$$\Gamma_\mu(q,K) = i\tilde{\gamma}_\mu C \frac{M}{f} M^{2\nu} \int_{-1}^{+1} \mathrm{d}z\, \rho_\nu(z) \left[\frac{1}{\left(\left(q - \frac{1-z}{2}K\right)^2 + \Lambda_q^2\right)} \right]^\nu$$

A point-like diquark?

- The DA resulting from a point-like BS ampltitude presents two main features:
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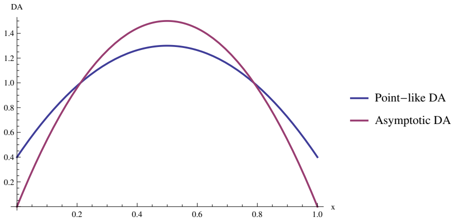

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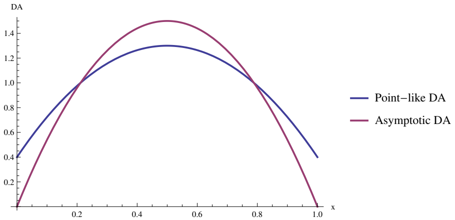

- We expect this to affect the Nucleon DA in our quark-diquark approach.

Mellin moments approach

- Computation of the Mellin moment of the nucleon DA:

$$\widetilde{\varphi}(n_1, n_2, n_3) = \int \mathcal{D}x_i \; x_1^{n_1} x_2^{n_2} x_3^{n_3} \varphi(x_1, x_2, x_3)$$

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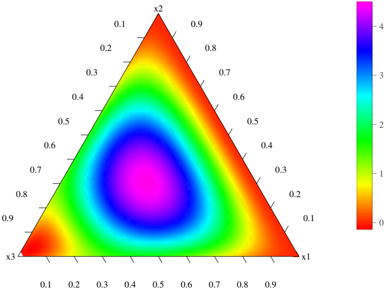
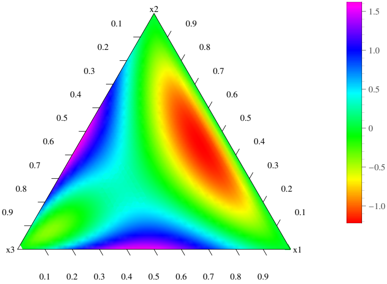
Analytical results for very simple Ansätze.

Result 1: Point-like diquark

$\varphi_{PL}(x_1, x_2, x_3)$



$\varphi_{PL}(x_1, x_2, x_3) - \varphi_{AS}(x_1, x_2, x_3)$



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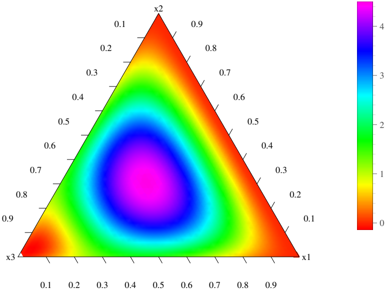

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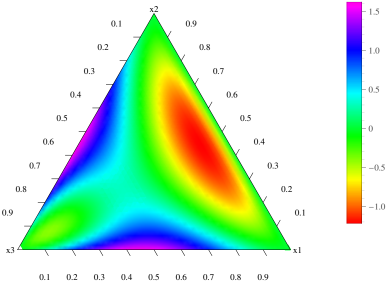

- It looks almost symmetric and therefore close to the asymptotic distribution. **Very encouraging result.**

Result 1: Point-like diquark

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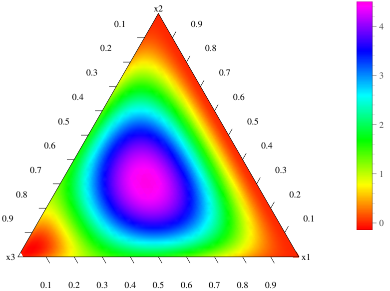

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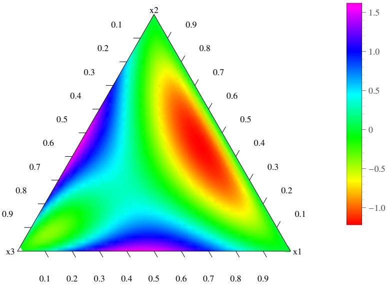

- It looks almost symmetric and therefore close to the asymptotic distribution. **Very encouraging result.**
- Please notice:
  - A feature of the point-like diquark: non-zero values for $x_1 = 0$ or $x_2 = 0$.

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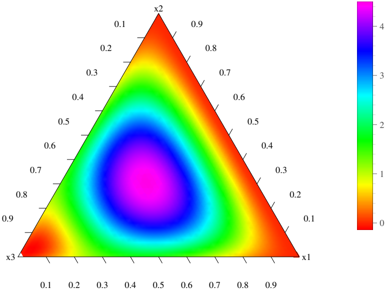

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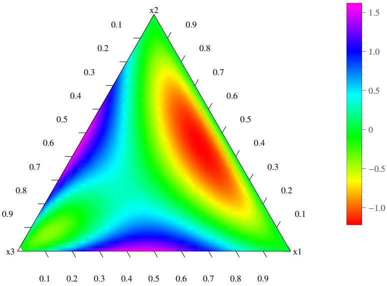

- It looks almost symmetric and therefore close to the asymptotic distribution. **Very encouraging result.**
- Please notice:
  - A feature of the point-like diquark: non-zero values for $x_1 = 0$ or $x_2 = 0$.
  - Slight unexpected sign change near $x_3 \simeq 1$.

From point-like to asymptotic diquark

- Change of the Bethe-Salpeter Amplitude:

$$\Gamma_\mu(q,K) = i\tilde{\gamma}_\mu C \frac{M}{f} M^{2\nu} \int_{-1}^{+1} \mathrm{d}z\, \rho_\nu(z) \left[\frac{1}{\left(\left(q - \frac{1-z}{2} K \right)^2 + \Lambda_q^2 \right)} \right]^\nu$$

- For $\rho \propto (1-z^2)$ and $\nu = 1$, one recovers the asymptotic DA:

$$\phi(x) = 6x(1-x)$$

Gao *et al.* (2014)

- Doing so we lose sensitivity in Λ_q^2.

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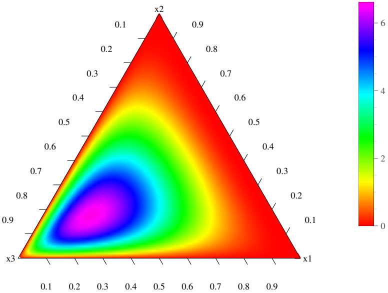
- Doing so we lose sensitivity in Λ_q^2.

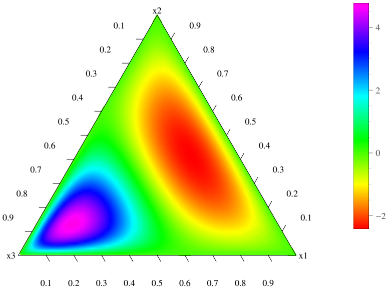
Good second step!

Result 2: Extended Asymptotic-like Diquark

$\varphi_{Ex}(x_1, x_2, x_3)$



$\varphi_{Ex}(x_1, x_2, x_3) - \varphi_{AS}(x_1, x_2, x_3)$



- No more sign change and the DA vanishes on the edges.
- Deform toward the large x_3.

Modification of the ρ function

$$\mathcal{A}_\mu(K,P) = i\gamma_5 P_\mu \frac{\bar{M}}{f_N}\bar{M}^{2\sigma}\int_{-1}^{+1} \mathrm{d}z\, \rho_\sigma(z)\left[\frac{1}{\left(\left(K-\frac{1-z}{2}P\right)^2+\Lambda_N^2\right)}\right]^\sigma$$

- All the previous plots, $\rho_\sigma(z) \propto (1-z^2)$

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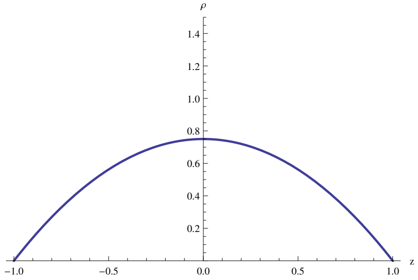

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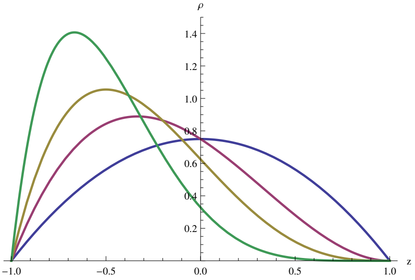
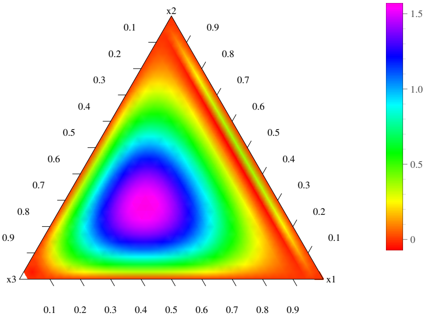


Modification of ρ to generate an asymmetric distribution of momentum

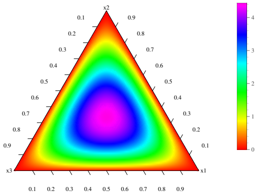
Preliminary result



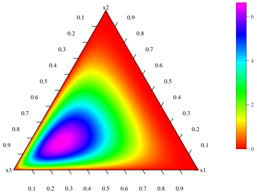
- More central than previously
- Still preliminary
- It starts becoming numerically challenging

Results summary

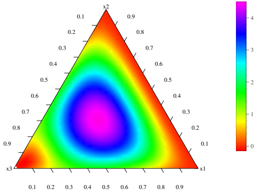
Asymptotic



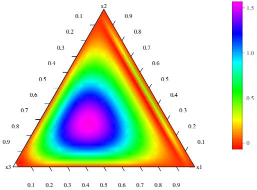
Extended diquark



Point-like



Asymmetric extended diquark



Summary and conclusion

- At high enough Q^2, it is possible to compute the form factor through the DA.
- Results on the pion show that at available energy, the asymptotic DA is not relevant for such a computation.
- To compute the nucleon DA and see how it differs from the asymptotic one.
- We developed algebraic models as a first step.
- Results are encouraging.

Outlook

- Short term outlooks:
  - Finish the algebraic computations.
  - Numerical computation using solution of the DSEs.
  - Comparison with lattice data
  - Computation of the ratio of the proton and neutron magnetic form factors.
- Longer term outlooks → computations of other structure functions:
  - Valence nucleon PDF.
  - Valence nucleon GPD,
    → following the methods highlighted in arXiv:1602.07722 for the pion.
    → using the PARTON Software developed at Saclay (1512.06174).

PARTONS Project

PARtonic
Tomography
Of
Nucleon
Software

Members and areas of expertise

Network of developers, upstream contributors and users

PARTONS team


Berthou (Irfu)


Binosi (ECT*)


Chouika (Irfu)


Guidal (IPNO)


Mezrag (ANL)


Moutarde (Irfu)


Sabatié (Irfu)


Sznajder (IPNO)


Wagner (NCBJ)

IPN et LPT (Orsay), Irfu (Saclay) and CPhT (Polytechnique)

- Experimental data analysis
- Perturbative QCD
- World data fits
- GPD modeling

Experimental data and phenomenology	Full processes
Computation of amplitudes	Small distance contributions
First principles and fundamental parameters	Large distance contributions

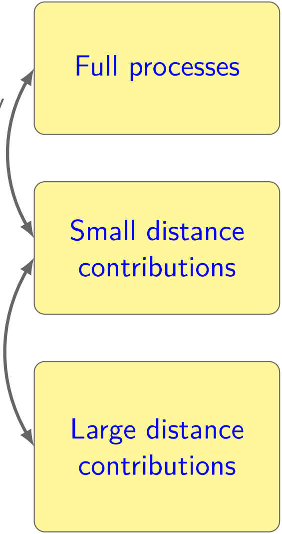
Computing chain design.

Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



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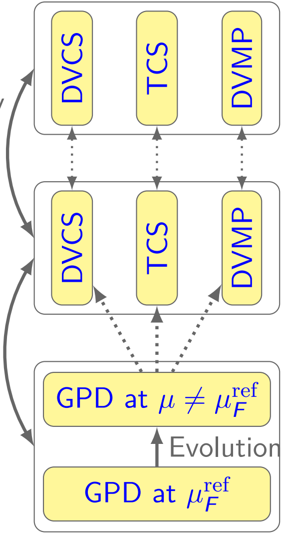

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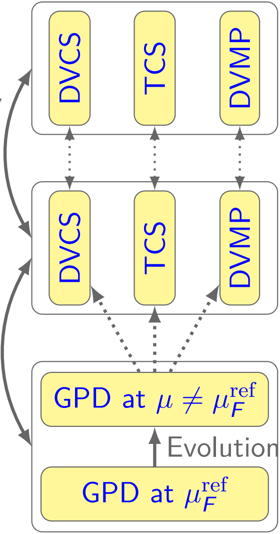


- Many observables.
- Kinematic reach.

Computing chain design.

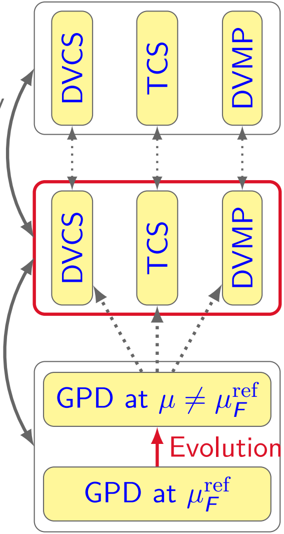
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



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- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

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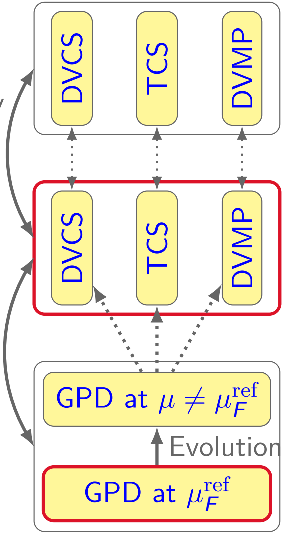

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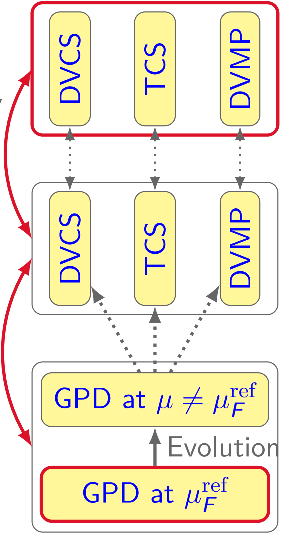

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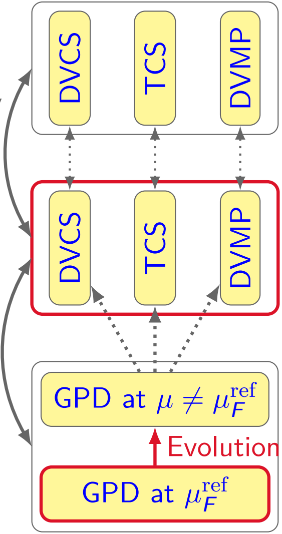

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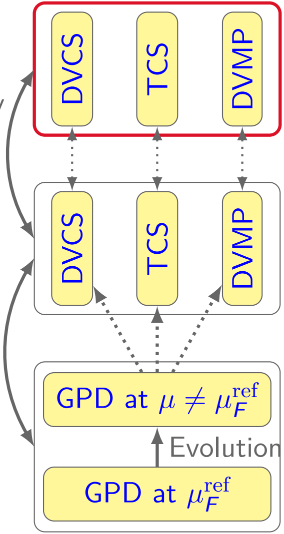

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Thank you for your attention!