Structure of the nucleon and its resonances

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Chapter 1:

Dyson-Schwinger equations

Dyson-Schwinger Equations in a nutshell

- Dyson-Schwinger equations relate Green (Schwinger) functions among each other.
- One get in the case of QCD, an infinite system $\rightarrow$ truncations are required.
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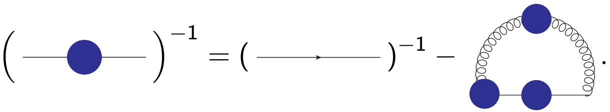
Truncating the DSEs yields an non-perturbative approximation of QCD Schwinger functions.

- The gap equation for the quark propagator $S(q)$:



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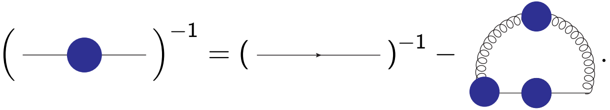
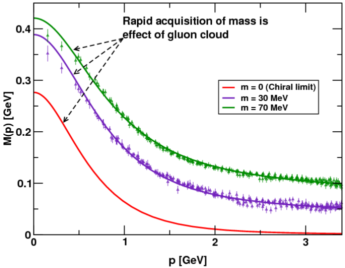


- It has successfully described the quark mass behaviour:



- $S(q)^{-1} = i\not{q}A(q^2) + B(q^2)$
- Non-perturbative description of the quark mass
- Dynamical mass generation
- Figure from Bashir *et al.* (2012)

Baryon and Diquarks

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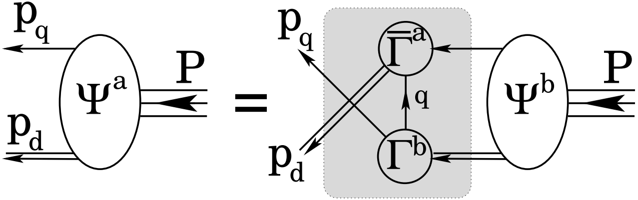

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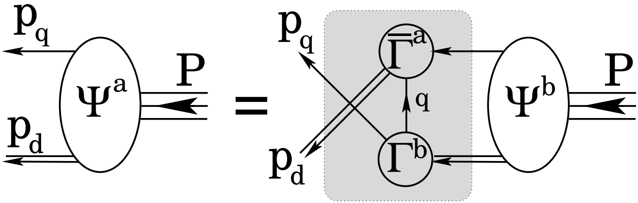

- Mostly two types of diquark are dynamically generated by the Faddeev equation:
  - Scalar diquarks, whose mass is roughly 2/3 of the nucleon mass,
  - Axial-Vector (AV) diquarks, whose mass is around 3/4 of the nucleon one.

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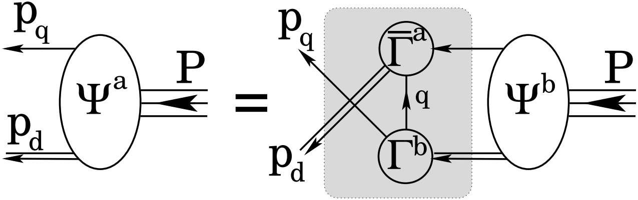

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- Can we understand the nucleon structure in terms of quark-diquarks correlations?

Chapter 2:
Baryon Distribution Amplitudes

CM, J. Segovia, L. Chang, C.D. Roberts,
arXiv:1711.09101

Hadrons seen as Fock States

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

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

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- Non-perturbative physics is contained in the N-particles Lightfront-Wave Functions (LFWF) Ψ^N
- 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)

Nucleon Distribution Amplitudes

- 3 bodies matrix element:

$$\langle 0|\epsilon^{ijk} u^i_\alpha(z_1) u^j_\beta(z_2) d^k_\gamma(z_3)|P\rangle$$

- 3 bodies matrix element expanded at leading twist:

$$\langle 0|\epsilon^{ijk} u^i_\alpha(z_1) u^j_\beta(z_2) d^k_\gamma(z_3)|P\rangle = \frac{1}{4}\Big[\left(\not{p}C\right)_{\alpha\beta}\left(\gamma_5 N^+\right)_\gamma V(z_i^-)$$
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V. Chernyak and I. Zhitnitsky, Nucl. Phys. B 246, (1984)

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- Isospin symmetry:

$$2T(x_1,x_2,x_3) = \varphi(x_1,x_3,x_2) + \varphi(x_2,x_3,x_1)$$

Evolution and Asymptotic results

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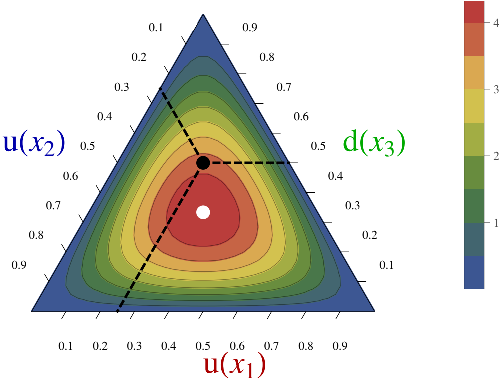
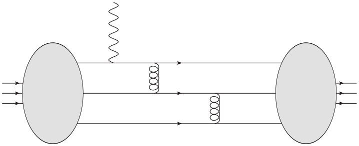
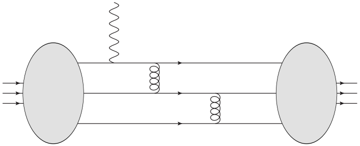
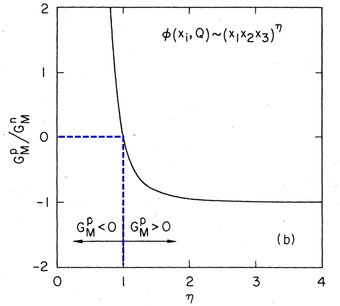
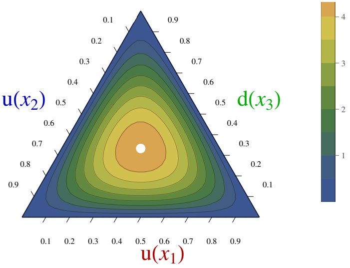


Form Factors: Nucleon case









$\eta = 1$

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

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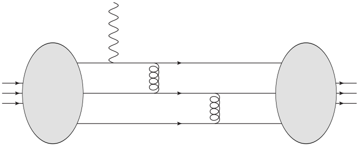
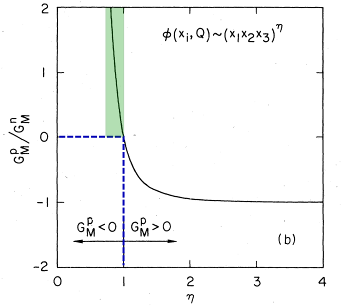
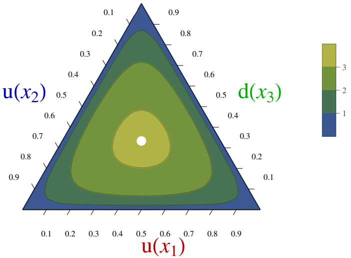
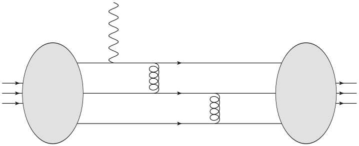


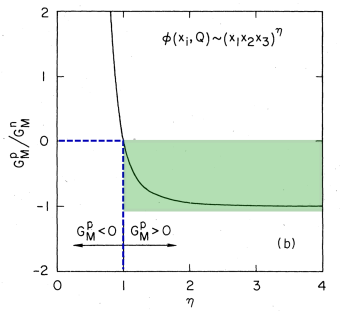


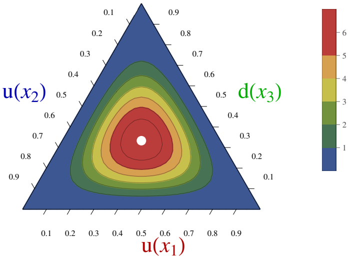


$\eta = 0.5$

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







$\eta = 2$

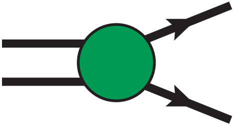
S. Brodsky and G. Lepage, PRD 22, (1980)

Some previous studies of DA

- QCD Sum Rules
  - V. Chernyak and I. Zhitnitsky, Nucl. Phys. B 246 (1984)
- Relativistic quark model
  - Z. Dziembowski, PRD 37 (1988)
- Scalar diquark clustering
  - Z. Dziembowski and J. Franklin, PRD 42 (1990)
- Phenomenological fit
  - J. Bolz and P. Kroll, Z. Phys. A 356 (1996)
- Lightcone quark model
  - B. Pasquini *et al.*, PRD 80 (2009)
- Lightcone sum rules
  - I. Anikin *et al.*, PRD 88 (2013)
- Lattice Mellin moment computation
  - G. Bali *et al.*, JHEP 2016 02

Faddeev WF Model

- Algebraic parametrisation inspired by the results obtained from DSEs and Faddeev equations.
- It is based on Nakanishi representation, which is completely general.
- This is an exploratory work: we want to know what we can or cannot do.
- We also assume the dynamical diquark correlations, both scalar and AV, and compare in the end with Lattice QCD one.



At all order of perturbation theory, one can write (Euclidean space):

$$\Gamma(k,P) = \mathcal{N}\int_0^\infty \mathrm{d}\gamma \int_{-1}^{1} \mathrm{d}z \frac{\rho_n(\gamma,z)}{(\gamma + (k+\frac{z}{2}P)^2)^n}$$

We use a "simpler" version of the latter as follow:

$$\tilde{\Gamma}(q,P) = \mathcal{N}\int_{-1}^{1} \mathrm{d}z \frac{\rho_n(z)}{(\Lambda^2 + (q-\frac{1-z}{2}P)^2)^n}$$

- Operator point of view for every DA (and at every twist):

$$\langle 0|\epsilon^{ijk}\left(u_\uparrow^i(z_1)C\not{n}u_\downarrow^j(z_2)\right)\not{n}d_\uparrow^k(z_3)|P,\lambda\rangle \rightarrow \varphi(x_1,x_2,x_3),$$

Braun *et al.*, Nucl.Phys. B589 (2000)

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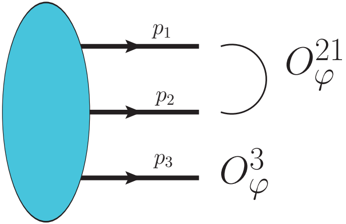

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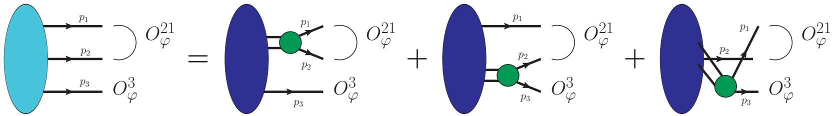

Nucleon Distribution Amplitude

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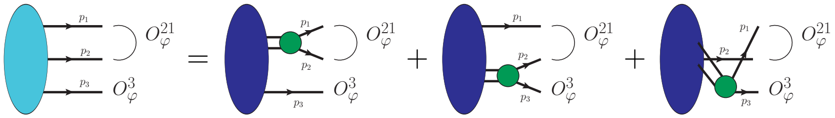

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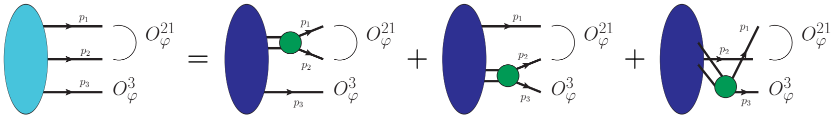
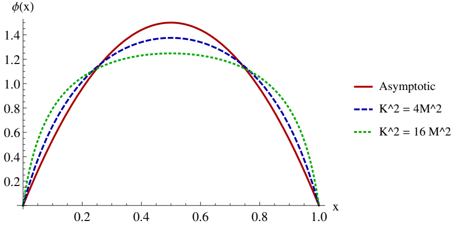


- The operator then selects the relevant component of the wave function.
- Our ingredients are:
  - Perturbative-like quark and diquark propagator
  - Nakanishi based diquark Bethe-Salpeter-like amplitude (green disks)
  - Nakanishi based quark-diquark amplitude (dark blue ellipses)

Diquark DA

$$\phi(x) \propto 1 - \frac{M^2}{K^2} \frac{\ln\left[1 + \frac{K^2}{M^2} x(1-x)\right]}{x(1-x)}$$

Scalar diquark



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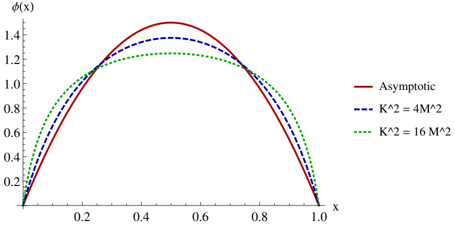
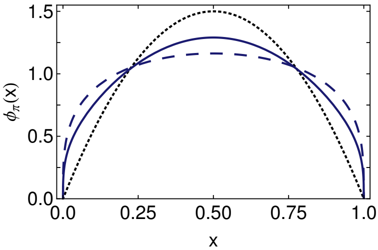


Pion



Pion figure from L. Chang *et al.*, PRL 110 (2013)

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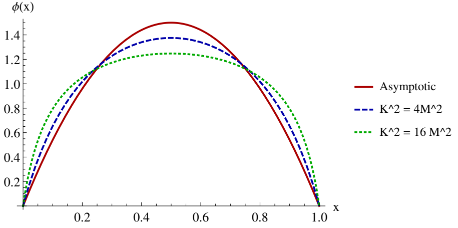

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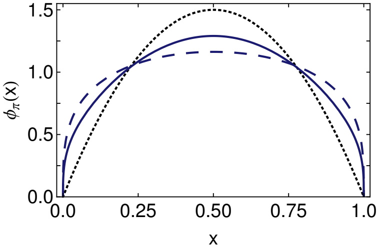
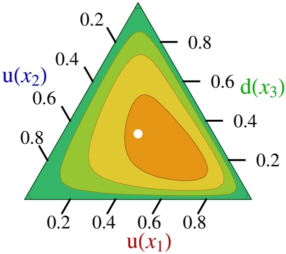


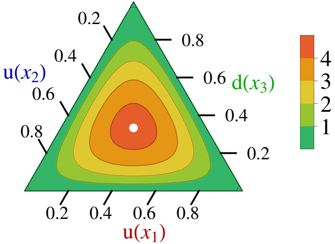
Pion figure from L. Chang *et al.*, PRL 110 (2013)

- This results provide a broad and concave meson DA parametrisation
- The endpoint behaviour remains linear

Results at 2GeV



Nucleon DA

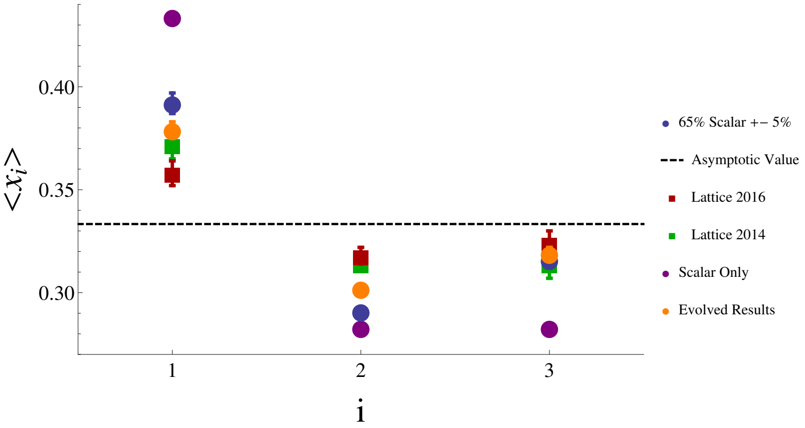


Asymptotic DA

- Results evolved from 0.51 to 2 GeV with both scalar and AV diquark
- Nucleon DA is skewed compared to the asymptotic one
- It is also broader than the asymptotic results
- These properties are consequences of our quark-diquark picture

Comparison with lattice

$$< x_i >_\varphi = \int \mathcal{D}x \; x_i \varphi(x_1, x_2, x_3)$$



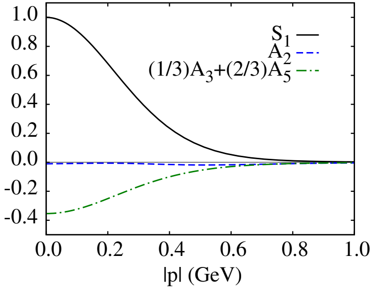
Lattice data from V.Braun *et al*, PRD 89 (2014)

G. Bali *et al.*, JHEP 2016 02

Chapter 3:
Diquarks and the Roper resonance

The Roper as a quark-diquark bound state

- The Roper can be described almost exactly in the same way than the nucleon...
- ... but modifying slightly the Quark-Diquark amplitude



Figures from J.Segovia *et al.*, PRL 115 171801 (2015)

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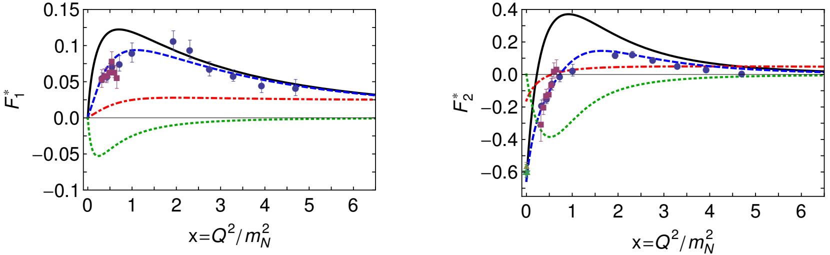
- ... but modifying slightly the Quark-Diquark amplitude
- The quark-diquark picture has been succefully applied to the transition FF



Figures from J.Segovia *et al.*, PRL 115 171801 (2015)

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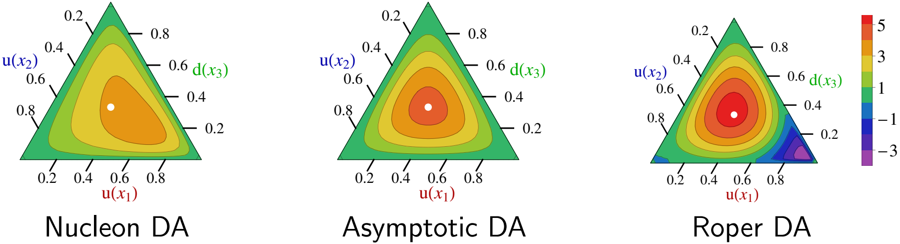
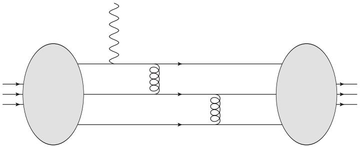


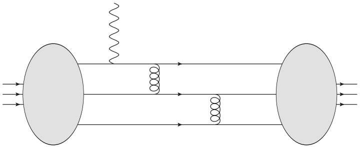
- Results evolved from 0.51 to 2 GeV with both scalar and AV diquark
- Contrary to the nucleon PDA, the Roper PDA **is not** positive definite
- The picture is consistent with our idea of QM radially excited states
- There is a curve of zero, *i.e.* of "forbidden momenta".

Chapter 4:
Form Factors

Form Factors



$$F_1(Q^2) = \mathcal{N} \int [\mathrm{d}x_i][\mathrm{d}y_i] \left[\varphi(x_i,\zeta_x^2) H_\varphi(x_i,y_i,Q^2,\zeta_x^2,\zeta_y^2)\varphi(y_i,\zeta_y^2) \right.$$
$$\left. + T(x_i,\zeta_x^2) H_T(x_i,y_i,Q^2,\zeta_x^2,\zeta_y^2) T(y_i,\zeta_y^2)\right]$$



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$$\left.+T(x_i,\zeta_x^2)H_T(x_i,y_i,Q^2,\zeta_x^2,\zeta_y^2)T(y_i,\zeta_y^2)\right]$$

- LO Kernel well known since more than 30 years...
- ...but different groups have argued different choices for the treatment of scales:
  - for the DA : $\varphi(Q^2), \varphi((min(x_i)\times Q)^2)...,$
  - for the strong coupling constant : $\alpha_S(Q^2), \alpha_s(< x_i >^2 Q^2), \alpha_s^{\mathrm{reg}}(g(x_i,y_j)Q^2)$
- Use of perturbative coupling vs. effective coupling?

Digression: Pion FF

- In the pion case, the hard kernel is known at NLO allowing us to discuss more extensively the scale effects.

R Field *et al.*, NPB 186 429 (1981)
F. Dittes and A. Radyushkin, YF 34 529 (1981)
B. Melic *et al.*, PRD 60 074004 (1999)

- The UV scale dependent term behaves like:

$$f_{UV}(\mu) \propto \beta_0 \left(5/3 - \ln((1-x)(1-y)) + \ln\left(\frac{\mu^2}{Q^2}\right)\right)$$

- Here I take two examples:
  - the standard choice of $\zeta_x^2 = \zeta_y^2 = \mu^2 = Q^2/4$
  - the regularised BLM-PMC scale $\zeta_x^2 = \zeta_y^2 = \mu^2 = e^{-5/3}Q^2/4$

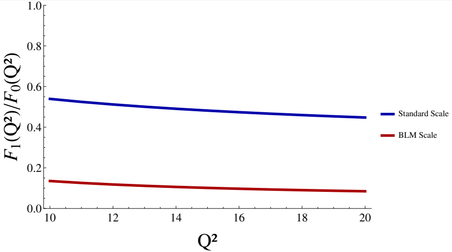
S. Brodsky *et al.*, PRD 28 228 (1983)
S. Brodsky and L. Di Giustino, PRD 86 085026 (2011)

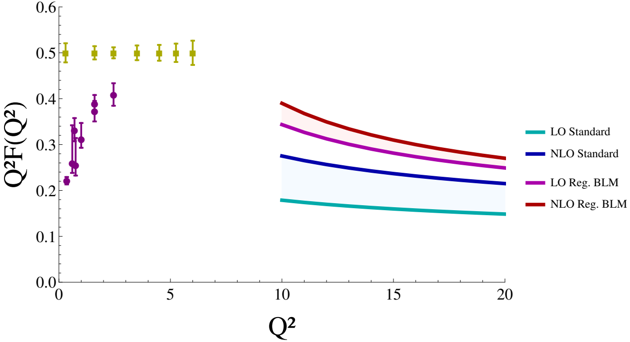
- What is the effect on our meson like DA?

$$\varphi_\pi(x, \zeta^2 = 4GeV^2) = \mathcal{N}\left(1 - \frac{\ln\left[1 + \alpha x(1-x)\right]}{\alpha x(1-x)}\right)$$

α is tuned on LQCD Mellin Moments

Digression: Pion FF





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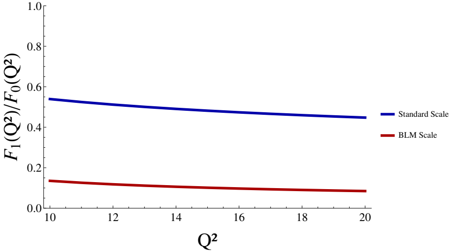

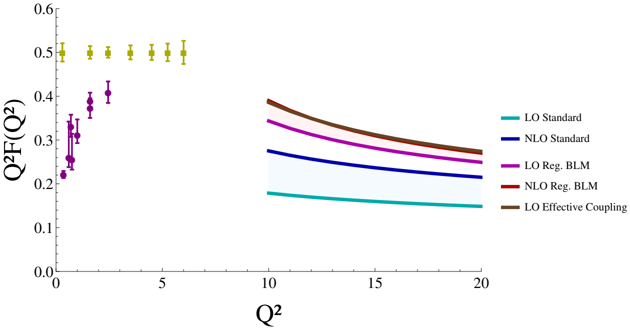

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- BLM scale reduces significantly the impact of the NLO corrections and increase dramatically the LO one.

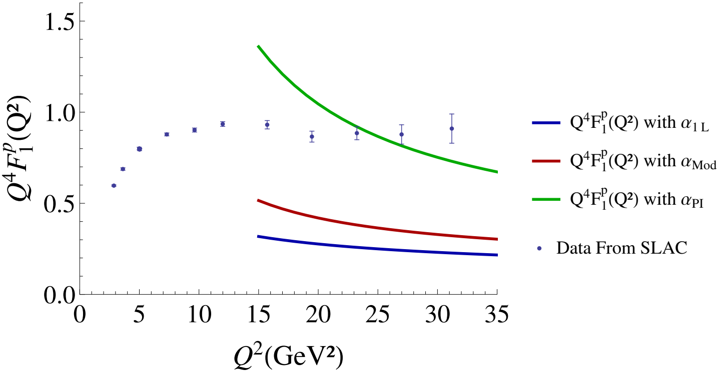
Proton case

- Unfortunately, only the LO treatment has been performed
  $\Rightarrow$ BLM scale is therefore unknown
- We use the Chernyak-Zhitnitsky formalism to compute the nucleon for factor with:
  - the CZ scale setting $\rightarrow \alpha_s(Q^2/9)\alpha_s(4Q^2/9)$
  - the pion BLM factor $\rightarrow \alpha_s(Q^2/9\, e^{-5/3})\alpha_s(4Q^2/9\, e^{-5/3})$

  and using both perturbative and effective couplings.

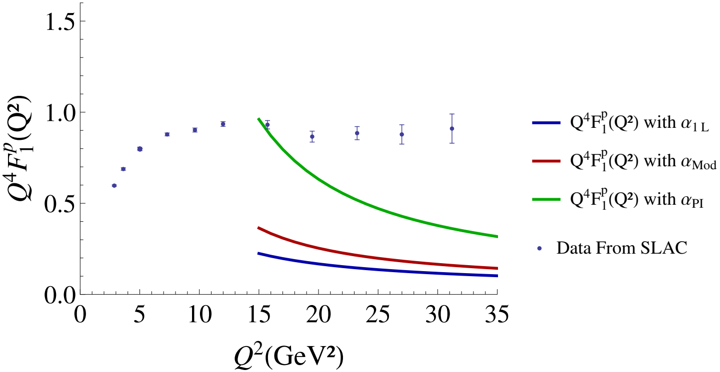
Proton case

CZ scale setting with frozen PDA at 1GeV^2



Data from Arnold et al. PRL 57

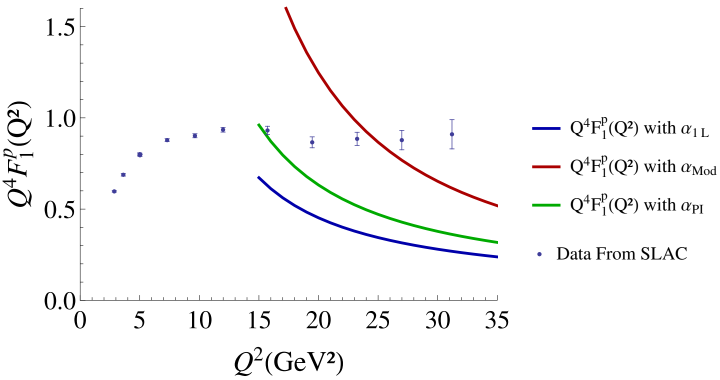
CZ scale setting + evolution



Data from Arnold et al. PRL 57

Proton case

Pion BLM Factor + evolution



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  and using both perturbative and effective couplings.
- The data remain flat while the perturbative running show a logarithmic decreasing.
- More work are required to conclude on the validity of the perturbative approach:
  - Theory side : we need NLO corrections
  - Experimental side : more precise data to spot a logarithmic decreasing

Conclusion

Conclusion

Baryon PDA

- **DSE compatible** framework for Baryon PDAs.
- Simple Nakanishi representation works **well** for the nucleon PDA.
- **First** calculation of the Roper PDA has been performed
- **Extend** the results to more realistic models (running quark masses...).

Form Factors

- Calculation of **Leading Order** Form Factors is done
- There is a systematic discrepency with available data.
  - NLO Corrections?
  - Scale Setting?
- **More work** is required

Thank you for your attention

Back up slides

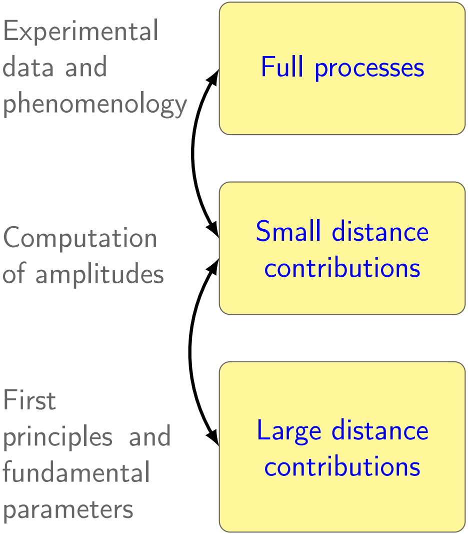
Chapter 6:

PARTONS

B. Berthou *et al.*, accepted in EPJC

A GPDs dedicated Software

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



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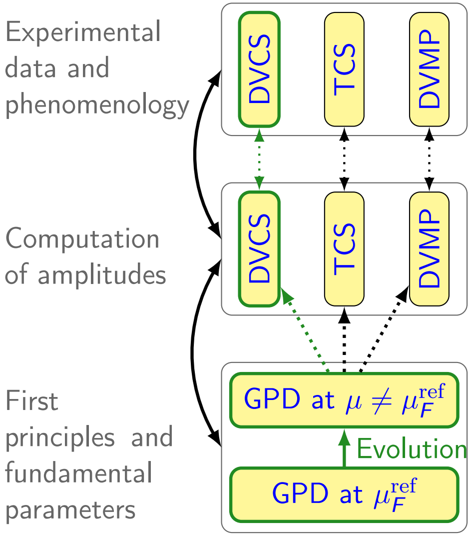
A GPDs dedicated Software



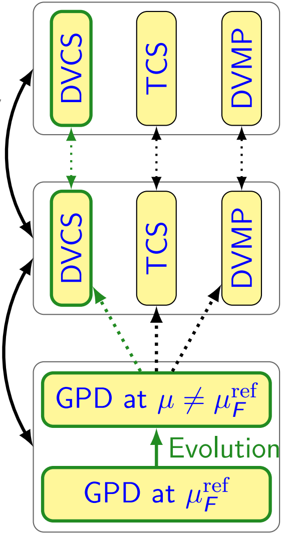
- DVCS chain is done and working
- Including LO evolution and NLO CFF

A GPDs dedicated Software

Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



- DVCS chain is done and working
- Including LO evolution and NLO CFF

- TCS code exists at NLO but needs to be implemented in PARTONS
- DVMP requires more work due to meson PDAs

http://partons.cea.fr

PARTONS

PARtonic Tomography Of Nucleon Software

Main Page   Reference documentation +   Search

Main Page

What is PARTONS?

PARTONS is a C++ software framework dedicated to the phenomenology of Generalized Parton Distributions (GPDs). GPDs provide a comprehensive description of the partonic structure of the nucleon and contain a wealth of new information. In particular, GPDs provide a description of the nucleon as an extended object, referred to as 3-dimensional nucleon tomography, and give an access to the orbital angular momentum of quarks.

PARTONS provides a necessary bridge between models of GPDs and experimental data measured in various exclusive channels, like Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP). The experimental programme devoted to study GPDs has been carrying out by several experiments, like HERMES at DESY (closed), COMPASS at CERN, Hall-A and CLAS at JLab. GPD subject will be also a key component of the physics case for the expected Electron Ion Collider (EIC).

PARTONS is useful to theorists to develop new models, phenomenologists to interpret existing measurements and to experimentalists to design new experiments. A detailed description of the project can be found here.

Table of Contents

Get PARTONS

Here you can learn how to get your own version of PARTONS. We offer two ways.

You can use our provided virtual machine with an out-of-the-box PARTONS runtime and development environment. This is the easiest way to start your experience with PARTONS.

Using PARTONS with our provided Virtual Machine

You can also build PARTONS by your own on either GNU/Linux or Mac OS X. This is useful if you want to have PARTONS on your computer without using the virtualization technology or if you want to use PARTONS on computing farms.

Using PARTONS on GNU/Linux

Using PARTONS on Mac OS X

Configure PARTONS

If you are using **our virtual machine**, you will find all configuration files set up and ready to be used. However, if you want to tune the configuration or if you have installed PARTONS by your own, this tutorial will be helpful for