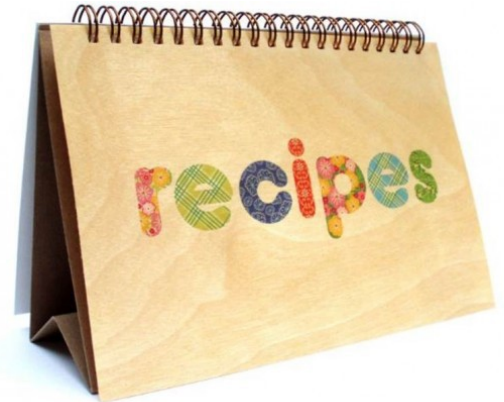

Internal structure of the pion inspired by AdS/QCD correspondence

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Part I – Ingredients

- Parton Distributions
- Light-Front Wave Functions (LFWFs)
- Tomography of the hadron

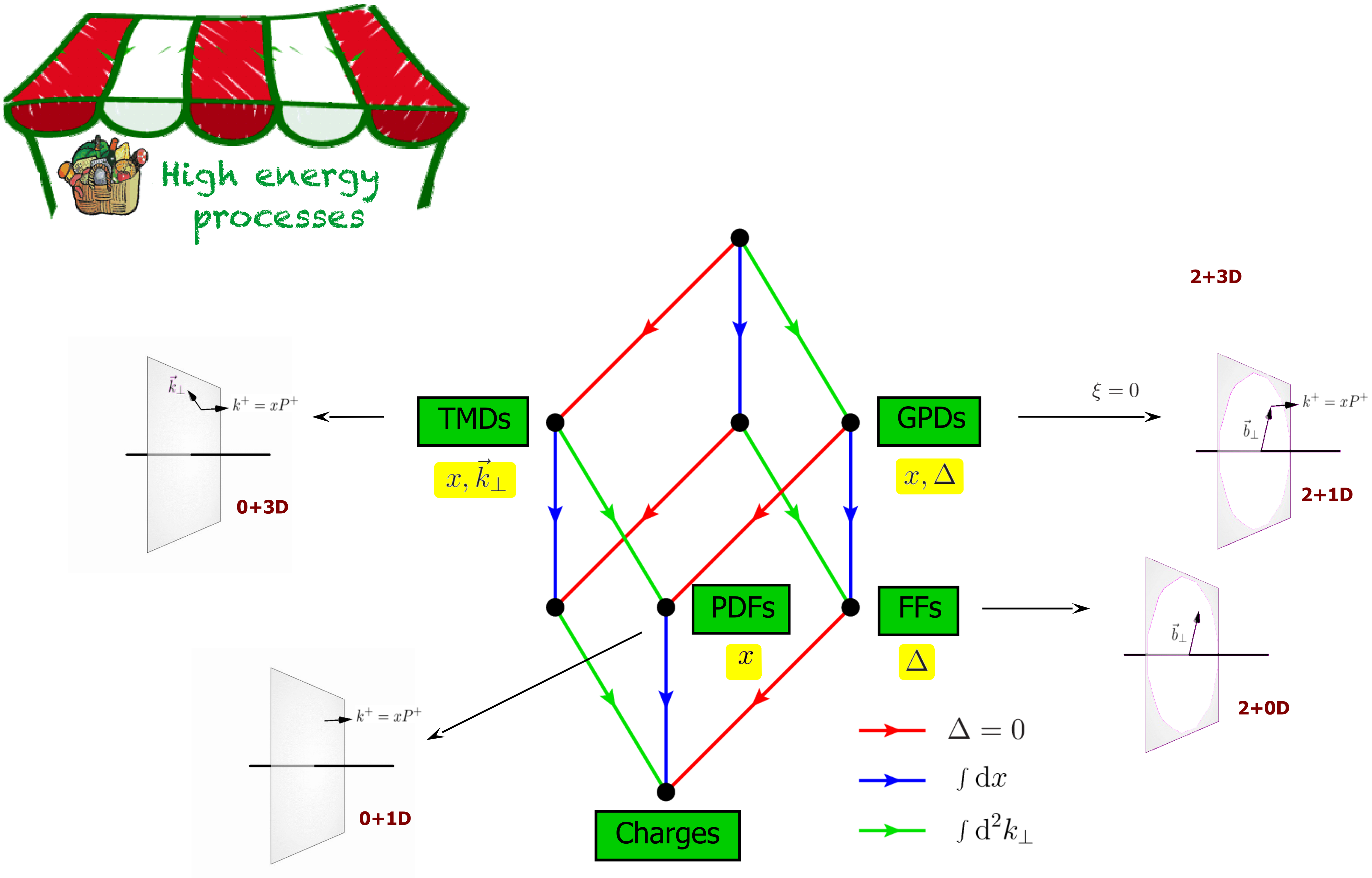
Part II – Recipe

- AdS/QCD correspondence
- Pion LFWFs inspired by AdS/QCD

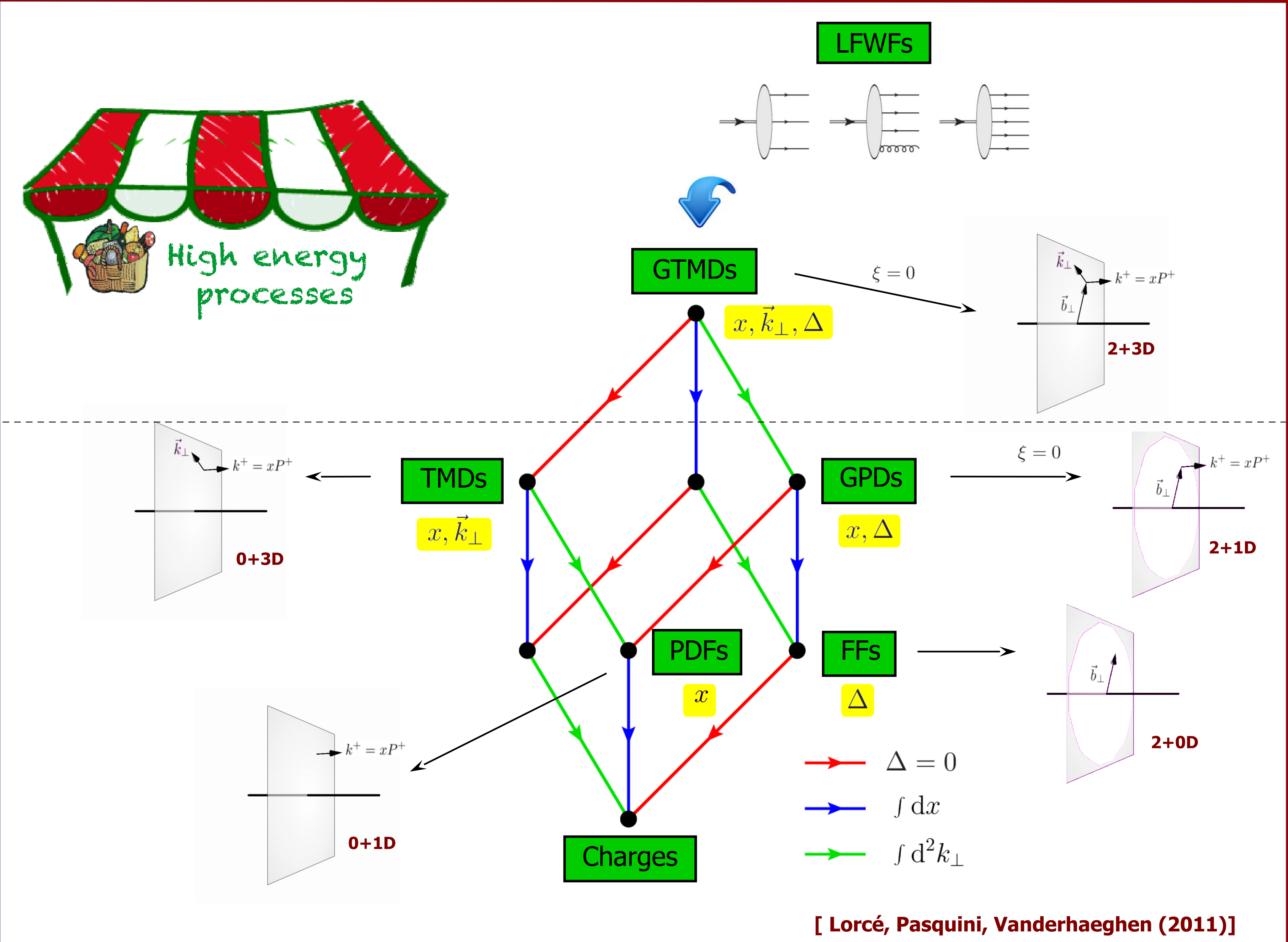
Part III – Phenomenology

- Pion PDF and FF
- Results for the TMD and the strong coupling

Conclusions



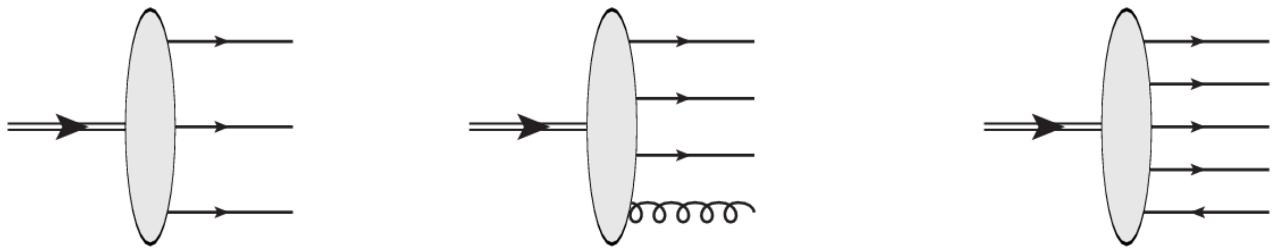
[Lorcé, Pasquini, Vanderhaeghen (2011)]



High energy processes
LFWFs
GTMDs
$x, \vec{k}_\perp, \Delta$
$\xi = 0$
$\vec{k}_\perp$
$k^+ = xP^+$
$\vec{b}_\perp$
2+3D
TMDs
$x, \vec{k}_\perp$
0+3D
GPDs
x, Δ
2+1D
PDFs
x
FFs
Δ
2+0D
0+1D
Charges
$\Delta = 0$
$\int dx$
$\int d^2 k_\perp$
[Lorcé, Pasquini, Vanderhaeghen (2011)]

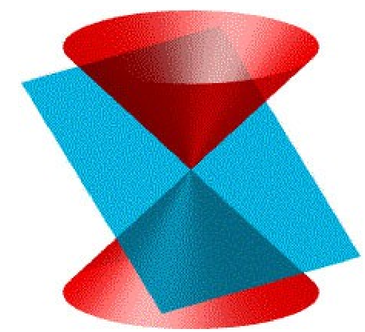
Fock expansion of the hadronic state (e.g. nucleon)

$$|p\rangle = \Psi_{qqq} \; |qqq\rangle + \Psi_{qqqg} \; |qqqg\rangle + \Psi_{qqqq\bar{q}} \; |qqqq\bar{q}\rangle + \cdots$$



Convenient formalism→ Light-Front quantization

$$\mathrm{x}^{+} = \frac{1}{\sqrt{2}}\left(x^{0}+x^{3}\right); \quad x^{-} = \frac{1}{\sqrt{2}}\left(x^{0}-x^{3}\right)$$



$$|P,\Lambda\rangle = \sum_{N,\beta} \int \left[\frac{dx}{\sqrt{x}}\right]_{N} \left[d^{2}k_{\perp}\right]_{N} \Psi^{\Lambda}_{N,\beta}\left(r_{1},\cdots,r_{N}\right) \left| N,\beta;\, \tilde{k}_{1},\ldots,\tilde{k}_{N}\right\rangle$$

Light-front Wave Functions

ψ_N → Probability amplitude to find the N-th state inside the proton

Advantages:

- Positive longitudinal momenta
- Galilean subgroup of Poincaré group:
  non relativistic system in the transverse plane.
- LFWFs depend only on the intrinsic coordinates.
- All the hadronic observables are expressed in terms of overlap of LFWFs.
- When possible, the probabilistic interpretation of the parton distributions is evident.

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PDF

$$f_{1q}^{\Lambda}(x) = \frac{1}{2}\sum_{\beta}\int \frac{d^2\boldsymbol{k}_\perp}{16\pi^3}\left|\psi_\beta^{\Lambda}(x,\boldsymbol{k}_\perp)\right|^2$$

EFF

$$\mathcal{F}^q_{\Lambda\Lambda'}\left(Q^2\right) = 2P^+\sum_{\beta=\beta'} e_q \int dx \int \frac{d^2\boldsymbol{k}_\perp}{16\pi^3}\psi^{*\Lambda'}_{\beta'}\left(r'\right)\psi^{\Lambda}_{\beta}\left(r\right)$$

TMD

$$f_{1q}^{\Lambda}(x,\boldsymbol{k}_\perp) = \frac{1}{2}\mathrm{Tr}[\Phi_q] = \frac{1}{2}\frac{1}{16\pi^3}\sum_{\beta}\left|\psi_\beta^{\Lambda}(x,\boldsymbol{k}_\perp)\right|^2$$

Are we ready to serve
the hadron tomography?

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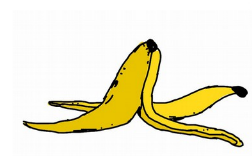
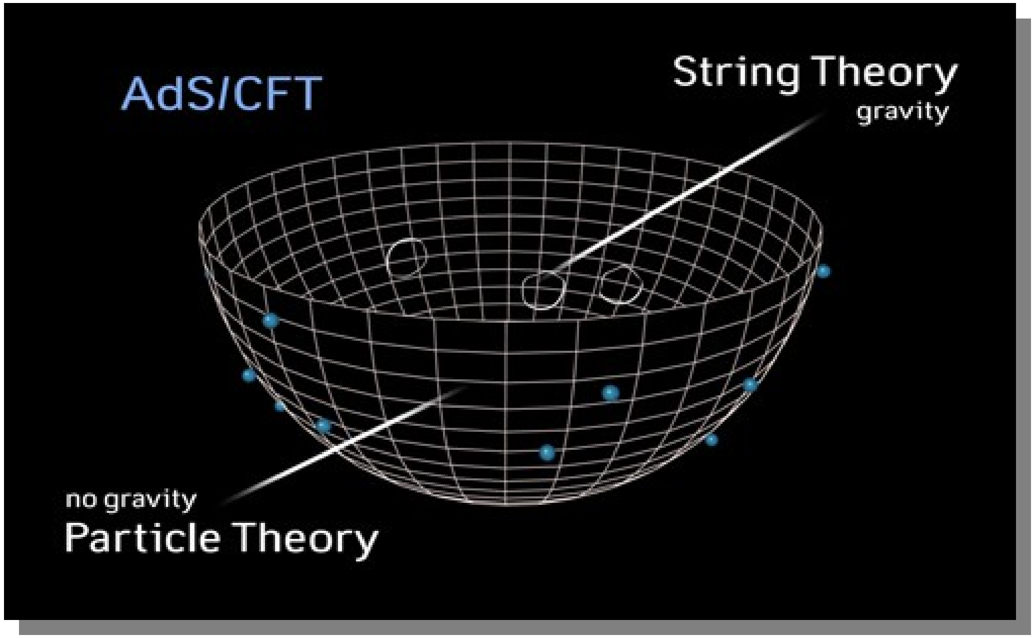


Problem: LFWFs are non perturbative objects.
How can we access them?

Possible approaches → Lattice QCD, Dyson-Schwinger Equation, **gauge/gravity duality**,...



$$ds^2 = \frac{R^2}{z^2}\left(\sum_{i=1}^{3} dx_i dx^i - dz^2\right)$$

Non gravitational dual field theory → Supersymmetric conformal Theory

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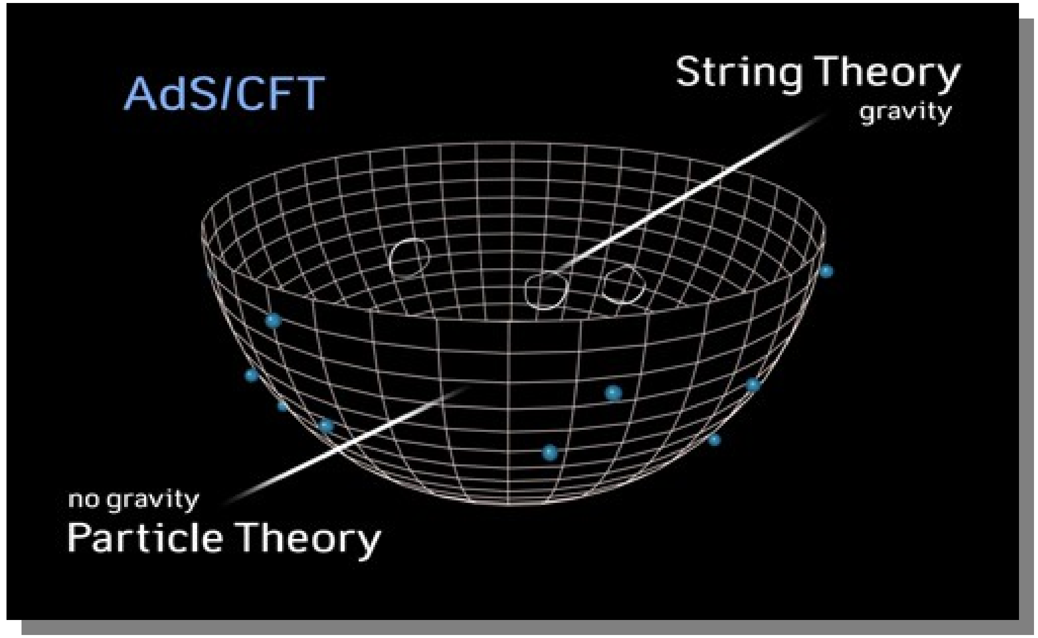

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Non gravitational dual field theory → Supersymmetric conformal Theory

Applicability to QCD? → Massless quarks and non running coupling

$$\mathcal{L}_{QCD} = \bar{\psi}_i \left(i\gamma^\mu D_\mu\right)_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

[Brodsky, de Téramond et al., 2004-2015]

Bottom-up approach:

Modification of the AdS metric in order to obtain (a first approximation of) QCD

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Modification of the AdS metric in order to obtain (a first approximation of) QCD

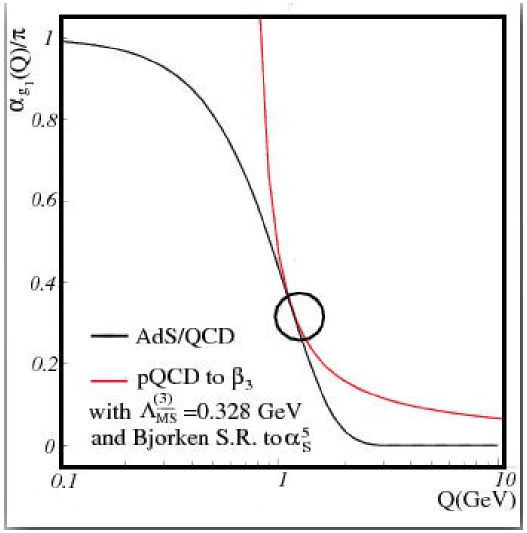
- Insertion of a dilaton field in order to have confinement:

$$S = \int d^4x dz \sqrt{|g|} e^{\varphi(z)} \left(g^{MN} \partial_M \Phi(x,z) \partial_N \Phi(x,z) - \mu^2 \Phi^2(x,z) \right)$$

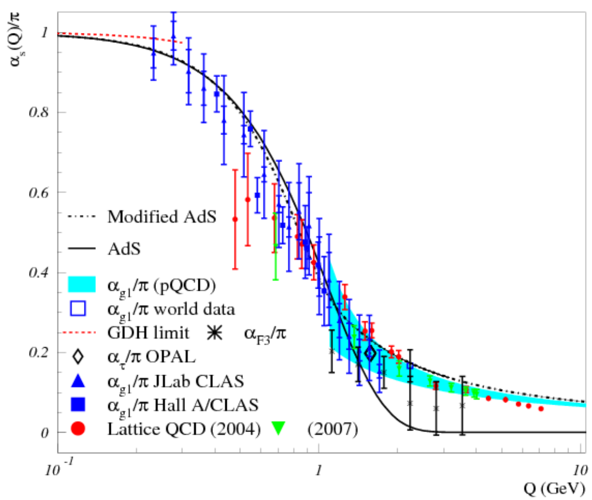
$$\varphi(z) = \kappa^2 z^2$$ Soft-wall model

$$e^{\varphi(z)} \to 1 \quad z \to 0$$ AdS_5

- Freezing of the coupling constant at low energy (large distance):



[Deur, Brodsky, de Téramond, arXiv:1409.5488 [hep-ph], 2014]



[Deur, Burkert, Chen, Korsch, Phys. Lett. B 650 (4) (2007)]
[Brodsky, de Téramond, Deur, Phys. Rev. D 81, 096010 (2010)]

Matching the expression of the meson form factor:

$$\int d^4x \int dz \sqrt{g}\; A^M(x,z)\, \Phi^*_{P'}(x,z) \overleftrightarrow{\partial}_M \Phi(x,z)$$

$$\Updownarrow$$

$$(2\pi)\, \delta^{(4)}(P' - P - q)\, \epsilon_\mu (P' + P)^\mu F\left(q^2\right)$$

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Analytical expression for the valence state LFWF of the pion:

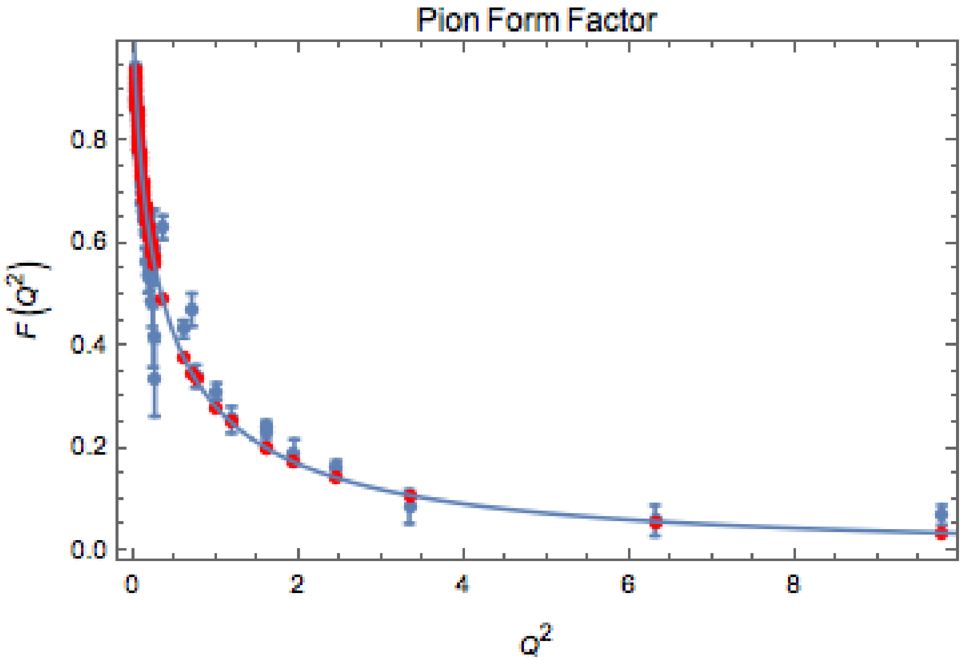
$$\psi_{q\bar{q}/\pi}(x,\ \mathbf{k}_\perp) = \frac{4\pi}{\kappa\sqrt{(1-x)\,x}}\sqrt{P_{q\bar{q}}}\,e^{-\frac{1}{2}\frac{\mathbf{k}_\perp^2}{\kappa^2 x(1-x)}}$$

Need for a phenomenological improvement!

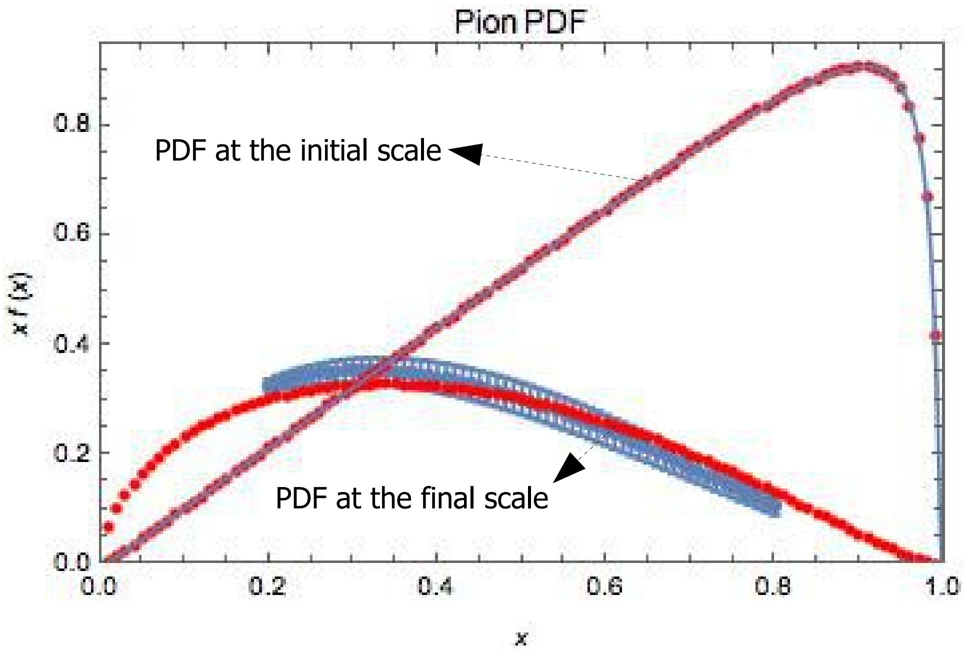
- We introduce the normalization constant and the quark mass parameters in a Lorentz invariant way (Brodsky's ansatz)
- We fit the free parameters using PDF parametrizations and FF experimental data
- We **obtain a set of parameters** which can be used for other **predictions** (e.g. TMD and running of the QCD coupling)

Preliminary results

- Our fit
- Parametrization/experimental data



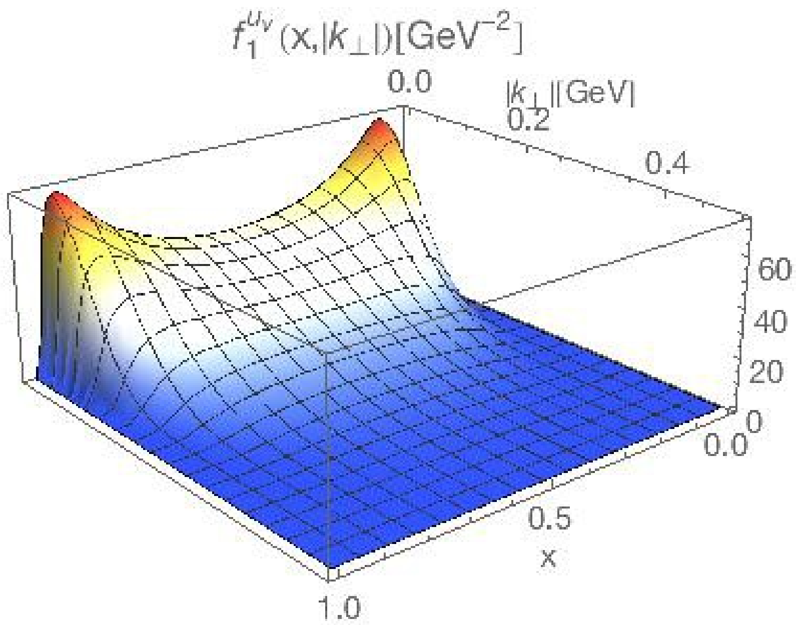
[J. Volmer et al. Phys Rev.Lett. 86 (2001) 1713-1716]



The PDF evolution is included in the fit procedure. The initial scale is a free parameter at this stage of the work.

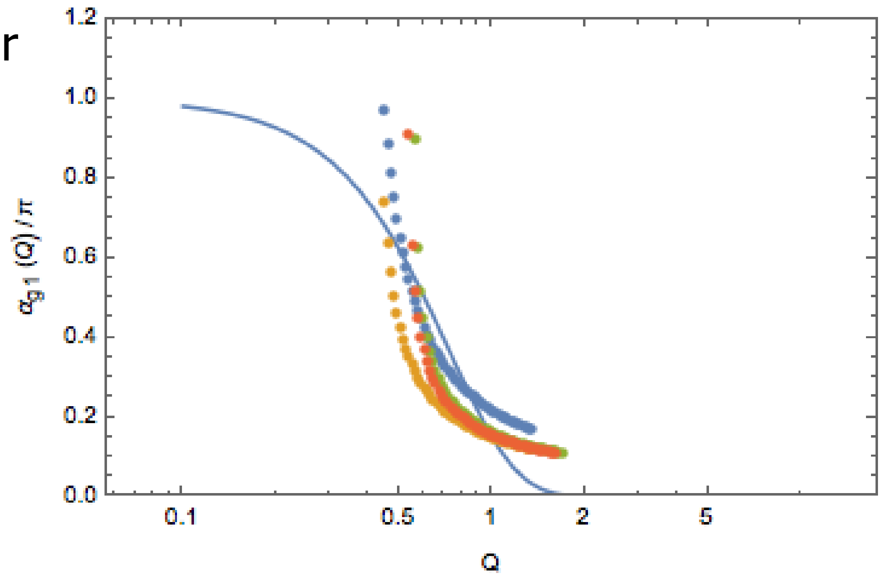
[K. Wijesooriya, et al., Phys Rev C 72,065203 (2005)]

Preliminary results



3D picture of the pion in momentum space: plot of the **unpolarized TMD** at the initial scale. QCD evolution is needed in order to compare this prediction with available (and future) experimental data.

QCD running coupling



- Our prediction for the low energy behavior based on the AdS/QCD approach
- LO for $\alpha_s(Q_0) = 0.139$
- NLO for $\alpha_s(Q_0) = 0.119$
- NNLO for $\alpha_s(Q_0) = 0.119$
- NNLO for $\alpha_s(Q_0) = 0.120$

Conclusions:

•Importance of the LFWFs to model parton distributions and get information on the internal stucture of hadrons.
•Need for a model which provides the hadronic LFWFs.
•Meson LFWFs inspired by AdS/QCD correspondence.

•Pure AdS/QCD correspondence provides LFWFs which have a rigid form.
•No reasonable description of the pion.
•Phenomenological changes are needed in order to describe the pion.

(in progress)
•Improvement of TMDs analysis, including QCD evolution.
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Thank you!