UNIVERSIDAD PABLO DE OLAVIDE SEVILLA

Ciencia y Tecnología

Secretaría de Ciencia, Humanidades, Tecnología e Innovación

Heavy-Light Pseudoscalar Mesons:

Structure and Parton Distributions

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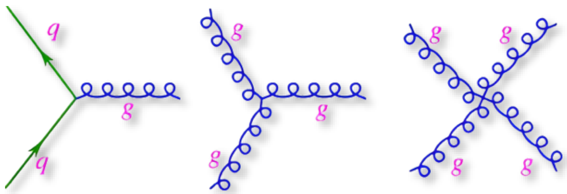
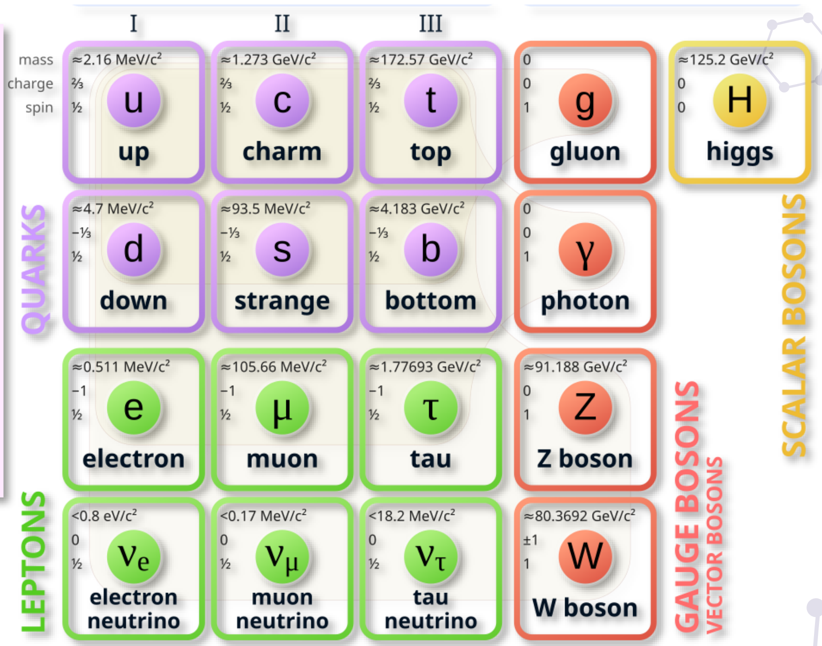
1970: Quantum Chromodynamics

- QCD is a non-Abelian gauge theory with SU(3) color symmetry that describes the strong interaction.

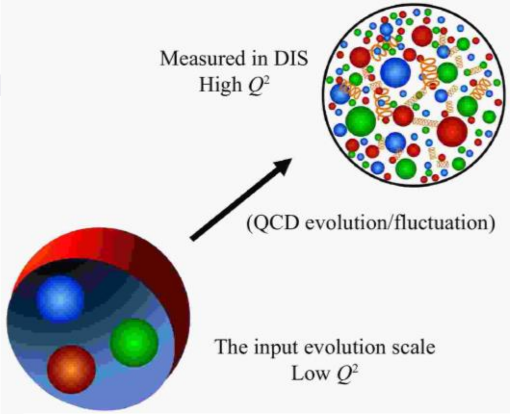
- **Quarks**
Six flavors: up, down, charm, strange, top, bottom
Each quark carries color charge (red, blue, green)

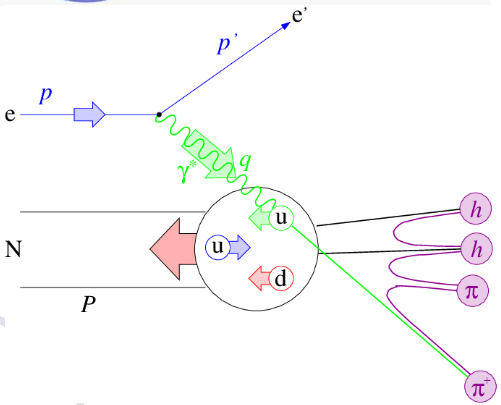
- **Gluons**
Eight gauge fields mediate the interaction
They also carry color charge (self-interactions)





The Central Problem of QCD



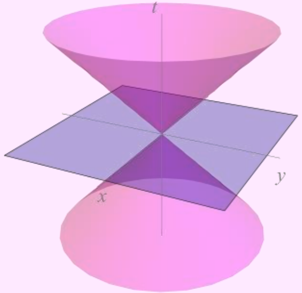


- QCD is highly nonperturbative at low energies.
- Understanding hadron structure from quarks and gluons
- → major challenge.
- Lepton–nucleon DIS provides direct access to quarks and gluons.
- Nonperturbative distributions are required.
- Processes are described in terms of hadron light-front wave functions.
- Phenomenological tools: PDFs, FFs, and GPDs.

CANONICAL QUANTIZATION

Quantum field theory (QFT) provides a quantum-mechanical description of a physical system in four-dimensional Minkowski spacetime

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$



With canonical coordinates:

$$x^\mu = (x^0, x^1, x^2, x^3) = (t, \mathbf{x})$$

$\psi(t, x)$ evolves along the time direction and is solved by fixing boundary conditions $\psi(t_0, x_0)$ on a spacelike hypersurface at fixed time $t = 0$.

$$i\frac{\partial}{\partial t}\psi(t, \mathbf{x}) = P_0\psi(t, \mathbf{x})$$

LIGHT-FRONT QUANTIZATION

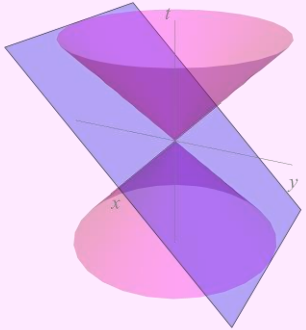
- The concepts of "time" and "space" are arbitrary.
- A new parameterization of spacetime is introduced through generalized coordinates.
- **Front form:**

$$x^+ = \frac{1}{\sqrt{2}}(x^0 + x^3), \quad x^- = \frac{1}{\sqrt{2}}(x^0 - x^3), \quad \boldsymbol{x}_\perp = (x^1, x^2)$$

Light-cone time *Light-cone space*

The new metric is:

$$g_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & \frac{1}{2} \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \frac{1}{2} & 0 & 0 & 0 \end{pmatrix}$$

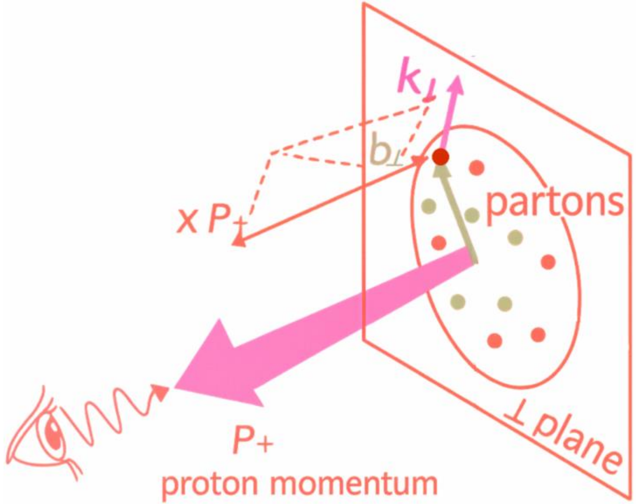


Light-front wave function

In the light-cone Fock decomposition, a pion with momentum P = (P^+, $P\perp$) is described by

$$|\pi : \underline{P}\rangle = \sum_{n,\lambda_i} \int \overline{\prod_i} \frac{dx_i\, d^2\vec{k}_{\perp i}}{\sqrt{x_i}\,16\pi^3} \left| n : x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i \right\rangle \psi_{n/\pi}(x_i, \vec{k}_{\perp i}, \lambda_i)$$

- $\psi(x_i, k\perp_i, \lambda_i)$ is the light-front wave function.
- $x_i = k_i^+/P^+$ is the longitudinal momentum fraction carried by the ith parton.
- k_i^+ is the longitudinal momentum.
- $k\perp_i = p\perp_i - x_i P\perp$ is the transverse momentum relative to the meson direction.
- λ_i is the light-front helicity of the ith parton.



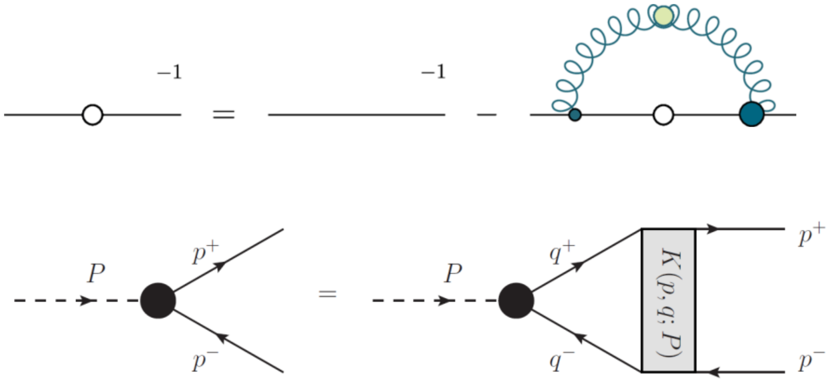
$\psi(x_i, \mathbf{k}\perp, \lambda_i)$ is the probability amplitude for finding partons (quarks and gluons) with momenta k^+ and $p\perp$ inside a hadron with momentum P^+ and transverse momentum $\mathbf{P}\perp$.

Light-front wave function

$$\psi_M^q(x,k_\perp^2) = \mathrm{Tr}\int \frac{\mathrm{d}^2 k_\parallel}{\pi}\delta(n\cdot k - x n\cdot P)\gamma_5\gamma\cdot n\chi_M(k_-,P)$$

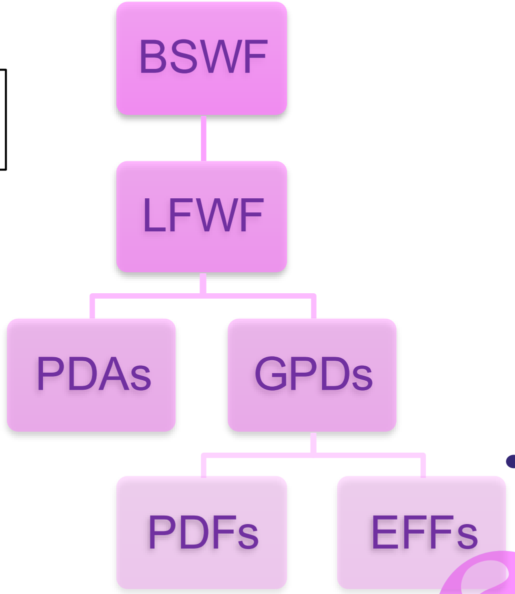
Bethe-Salpeter wave function

$$S_q(k)\Gamma_M(k_-,P)S_{\bar{h}}(k-P)$$

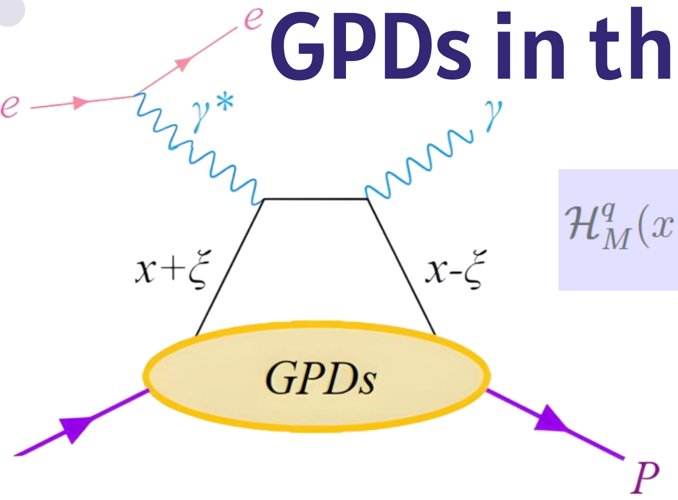


Inputs:
Solutions from
quark **DSE**
and meson **BSE**

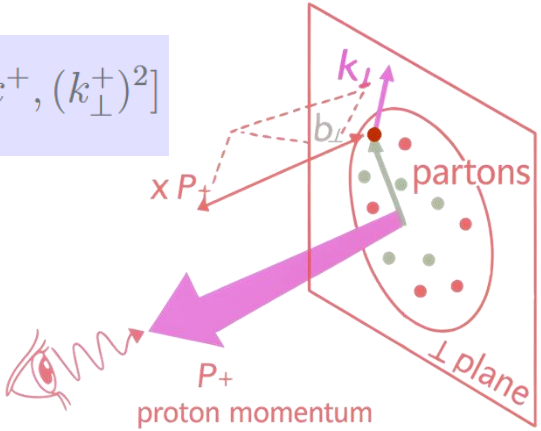
Idea:
Compute **everything**
from the **LFWF**.



GPDs in the Light-Front Formalism



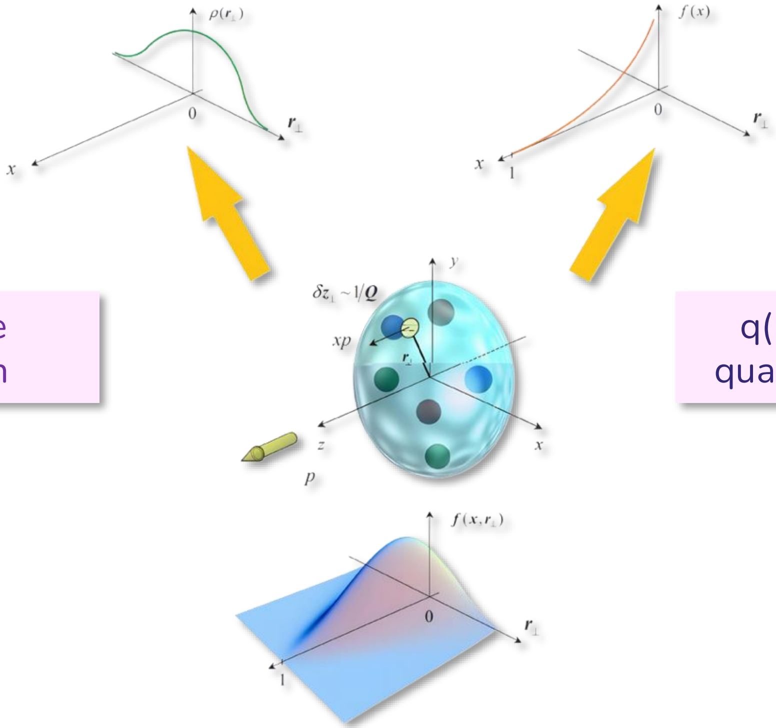
$$\mathcal{H}^q_M(x,\xi,t) = \int_{dk_\perp} \psi^{q*}_M[x^-,(k^-_\perp)^2]\psi^q_M[x^+,(k^+_\perp)^2]$$



- ψ are the parton LFWFs in the hadronic state.
- x_i and $k_{\perp i}$ are the partons' longitudinal and transverse momentum variables.
- ξ is the skewness.
- $t = \Delta^2$ is the momentum transfer.

Probability amplitude for finding a parton at a given position in the transverse plane carrying a fraction x of the hadron momentum

Generalized Parton Distributions

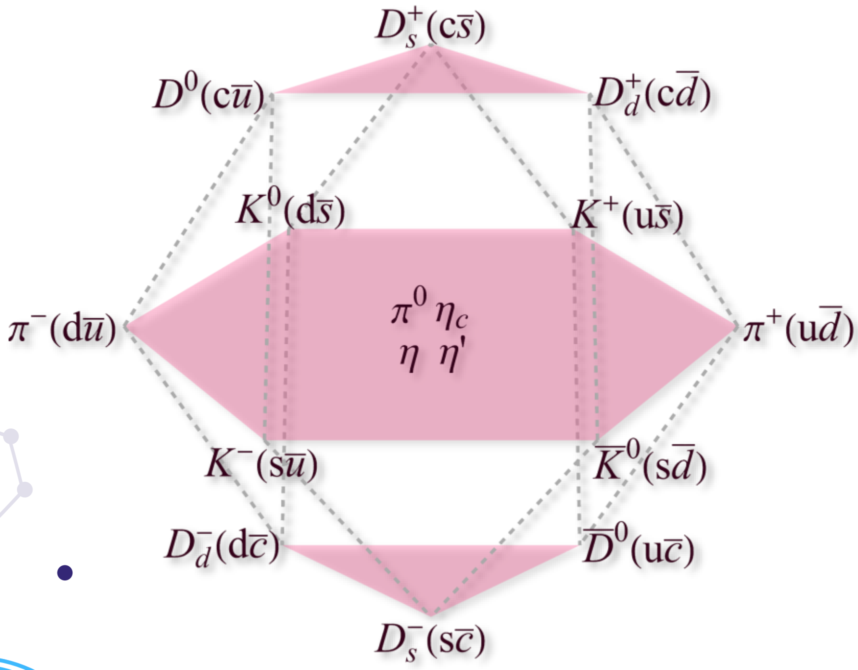


F(t) ⇒ encode the charge distribution in the hadron

q(x) ⇒ probability of finding a quark with momentum fraction x

H(x, ξ, t) ⇒ unify PDFs and FFs

Pseudoscalar Mesons



- Mesons with spin 0
- **Negative parity ($J^P = 0^-$)**
- Composed of a quark and an antiquark
- Composed of light (u, d, s) and heavy (c, b) quarks.
- **Relevance to internal structure:** all allow us to explore PDFs, FFs, and GPDs, although heavy mesons exhibit more pronounced momentum asymmetries.

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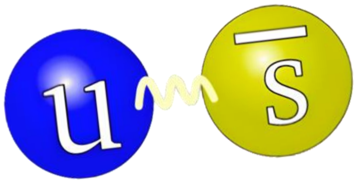
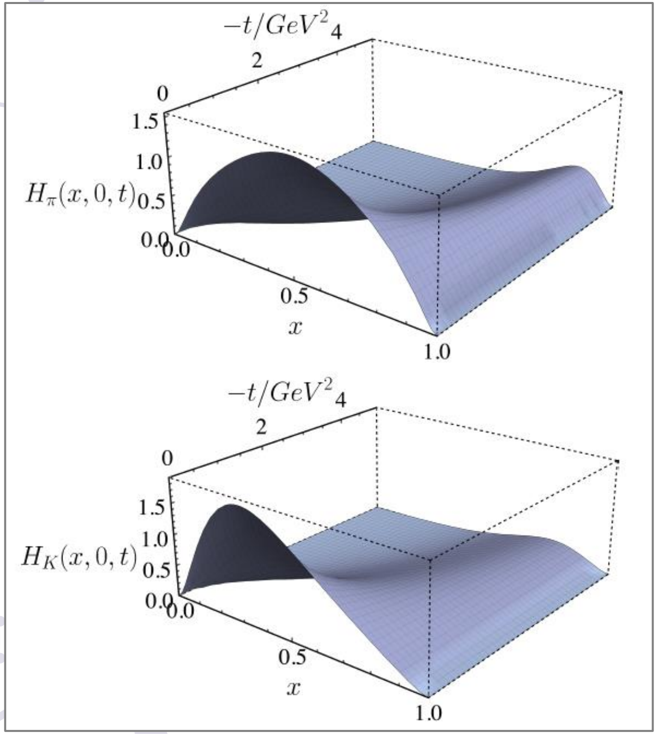
Pion and Kaon

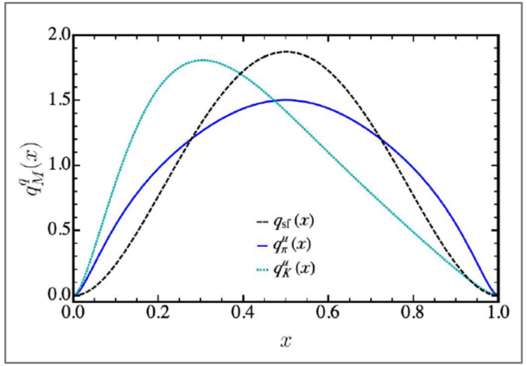


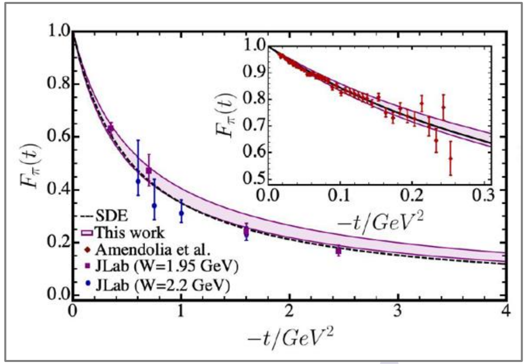


Forward limit:
$\xi = 0, t = 0$
PDF

Zeroth moment:
(integral over x)
EFFs

$r_\pi = 0.660\ fm$
$r_K = 0.560\ fm$





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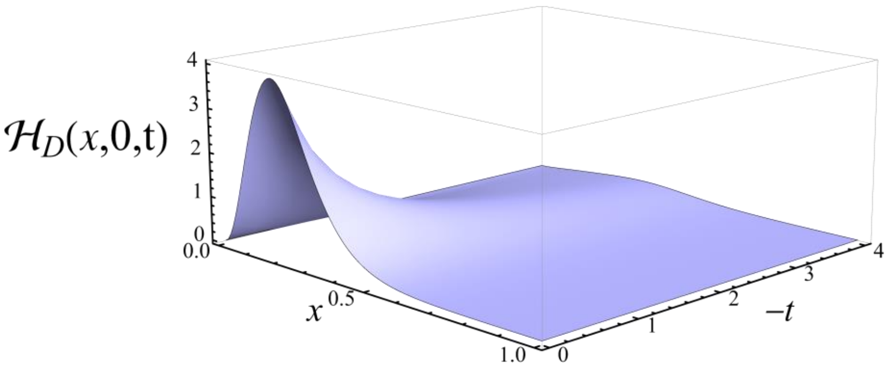
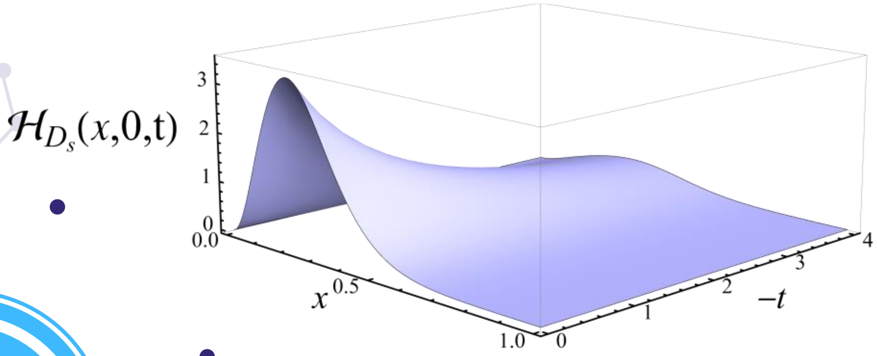
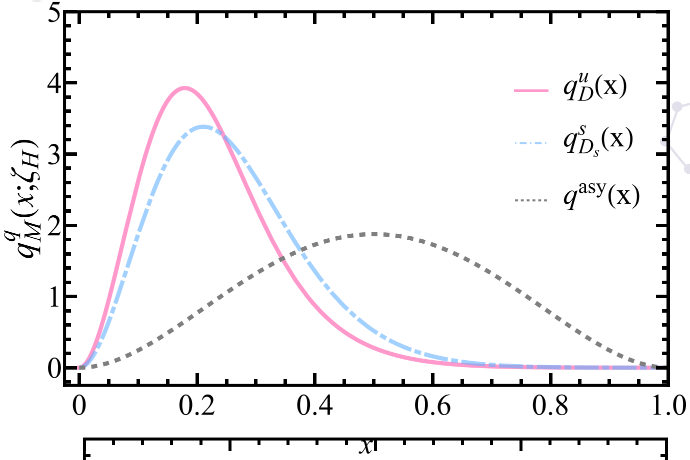
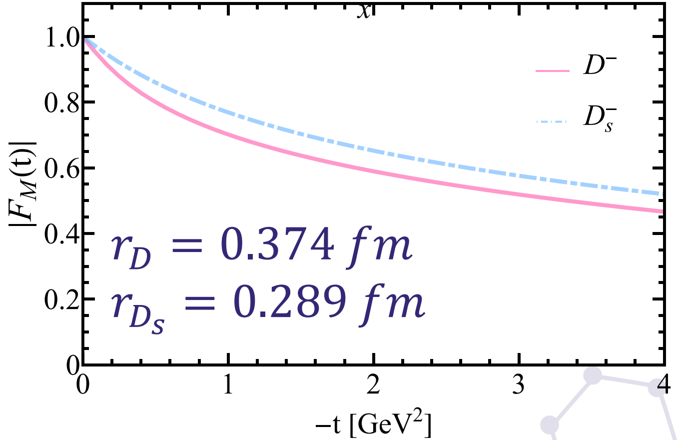
D Mesons: GPDs, PDFs, and EFFs









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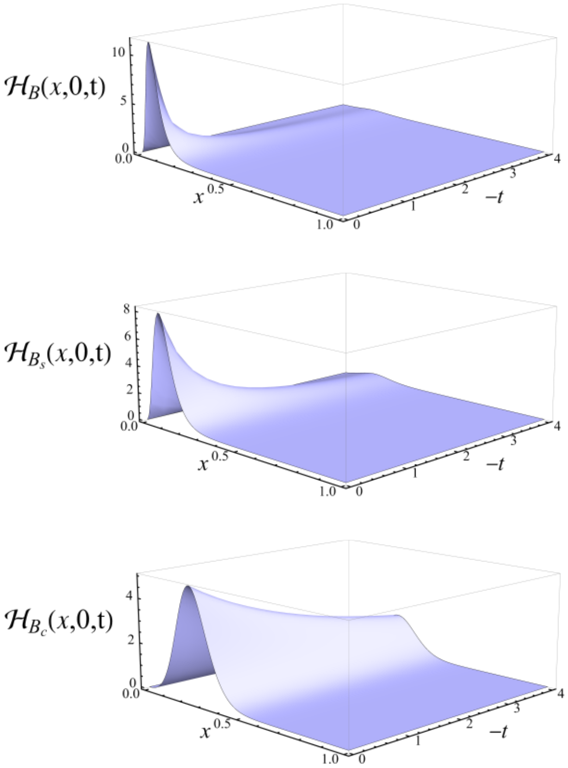
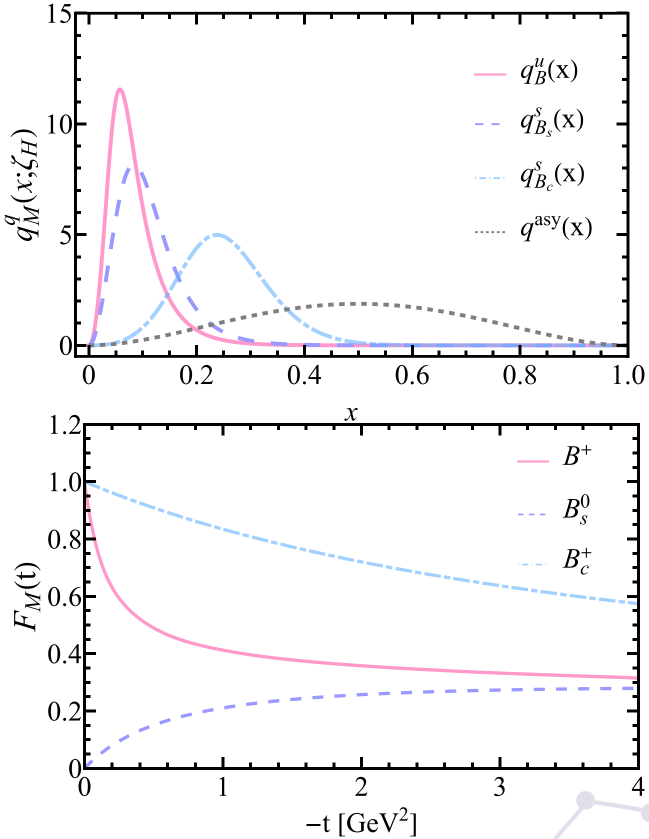
B Mesons: GPDs, PDFs, and EFFs



$$r_B = 0.478\ fm$$
$$r_{B_s} = 0.264\ fm$$
$$r_{B_c} = 0.217\ fm$$



Charge radii: Comparison with Other

		D^-	D_s^-	B^+	B_s^0	B_c^+
$\lvert r_{0^-} \rvert$		0.374	0.289	0.478	0.264	0.217
Covariant CQM	[97]	0.505	0.377	–	–	–
PM	[98]	–	0.460	0.730	0.460	–
LFQM	[99]	0.429	0.352	0.615	0.345	0.208
CI	[100]	–	0.260	0.340	0.240	0.170
Lattice	[101]	0.450(24)	0.465(57)	–	–	–
Lattice	[102]	0.390(33)	–	–	–	–

- Our predictions follow the general trends obtained with other theoretical approaches.
- A similar hierarchy is observed: $r_D > r_{D_s}$ and $r_B > r_{B_s} > r_{B_c}$.

Summary

- Hadron structure is governed by nonperturbative QCD dynamics.
- The light-front formalism provides a natural framework to describe the internal structure of hadrons.
- Light-front wave functions give access to different observables, such as PDFs, GPDs and electromagnetic form factors.
- GPDs connect information on the longitudinal momentum and spatial distribution of partons.
- Heavy-light pseudoscalar mesons exhibit strong momentum asymmetries due to the large difference between the quark masses.
- Within each meson family, heavier quark content leads to smaller charge radii.
- These results follow the same general trends found in other theoretical approaches.

Thank you.