

The Game of Hadron Physics

Seminar for the End of the First Year of PhD

PhD Student

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Supervisors

Professor Barbara Pasquini^{1,2}

Doctor Simone Rodini³(¹ starting October)

¹Università degli Studi di Pavia

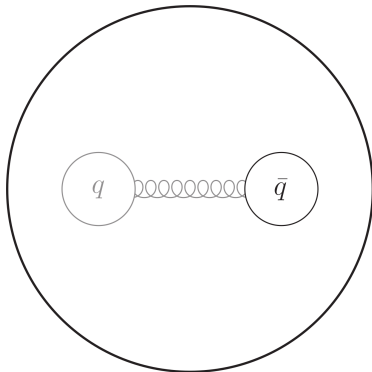
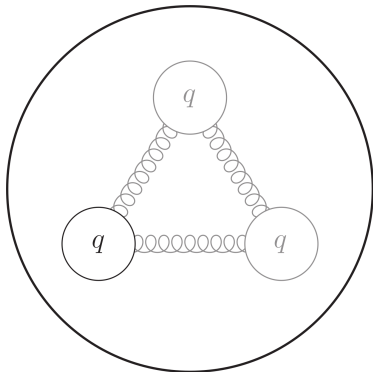
²Istituto Nazionale di Fisica Nucleare INFN, Sezione di Pavia

³Deutsches Elektronen-Synchrotron DESY

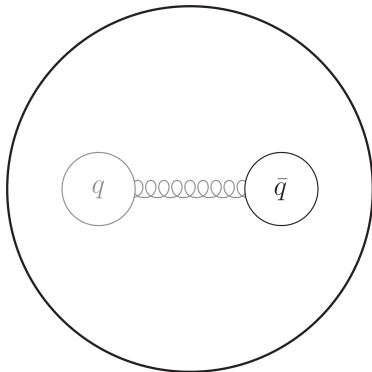
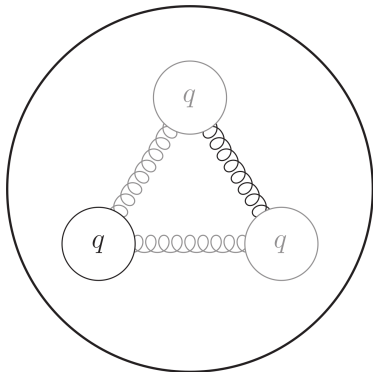
17 September 2025

What is an hadron?

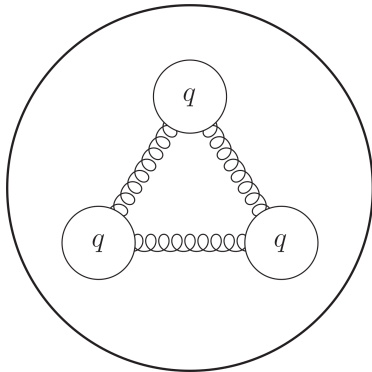
What is an hadron?



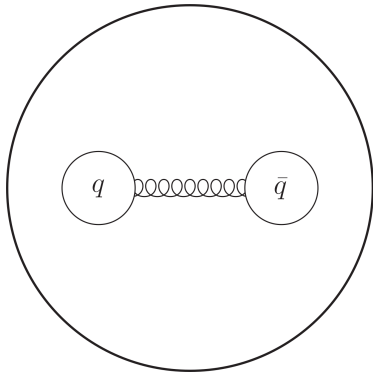
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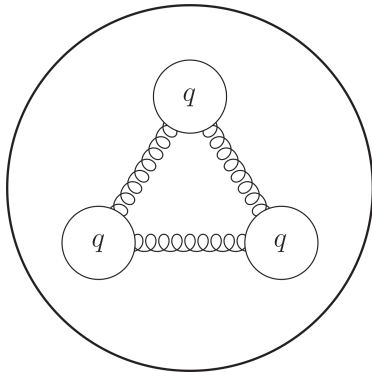


Baryon

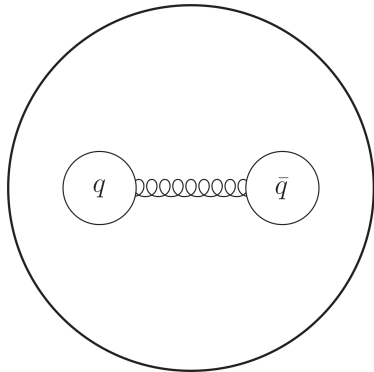


Meson

What is an hadron?



Baryon: proton, neutron, ...



Meson: π^0 , $\pi^\pm$, ...

A Picture of Quantum ChromoDynamics

A Picture of Quantum ChromoDynamics

$$A(x) \quad , \quad \psi(x) \quad \bar{\psi}(y)$$

$$x = (x^0 = t_x, x^1, x^2, x^3), \quad y = (y^0 = t_y, y^1, y^2, y^3)$$

A Picture of Quantum ChromoDynamics

$$A(x) \text{ ~~~~~~ } A(y), \quad \psi(x) \text{ --- } \longleftarrow \bar{\psi}(y)$$

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A Picture of Quantum ChromoDynamics

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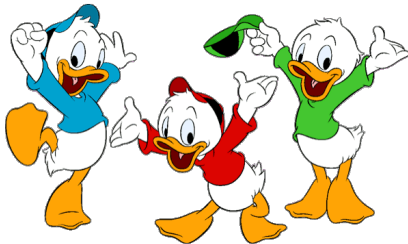
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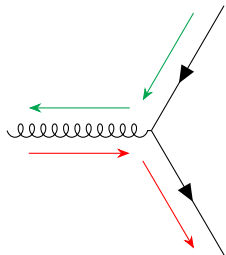
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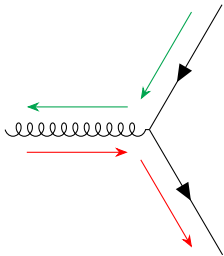


QCD, Now Interactive

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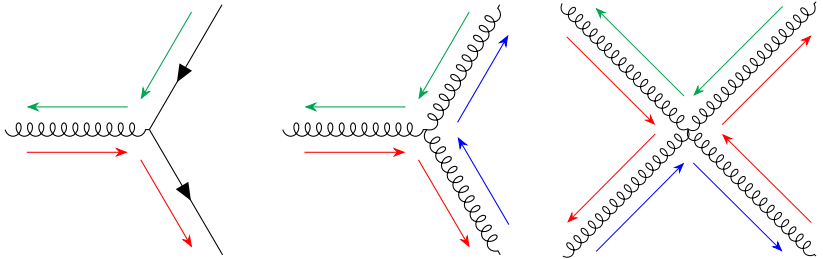


QCD, Now Interactive



Like Quantum Electrodynamics, but...

QCD, Now Interactive



Like Quantum Electrodynamics, but... Gluons can also interact!

The Confines of the Problem

The Confines of the Problem

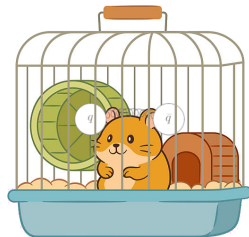


- Asymptotic freedom at small distances

The Confines of the Problem



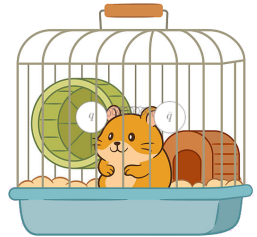
- Asymptotic freedom at small distances
- Confinement of color charges



The Confines of the Problem



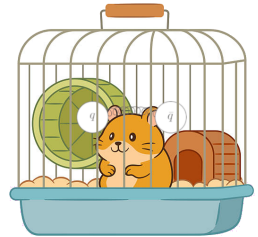
- Asymptotic freedom at small distances
- Confinement of color charges
- Emergent hadronic structure



The Confines of the Problem

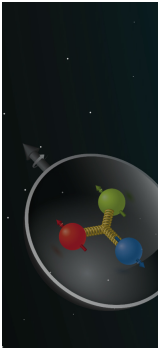


- Asymptotic freedom at small distances
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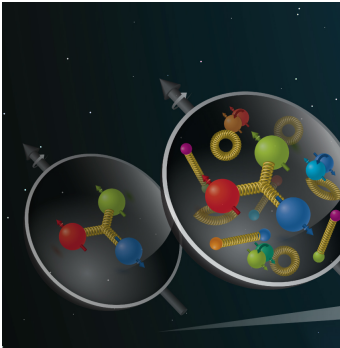


Scaling an Hadron

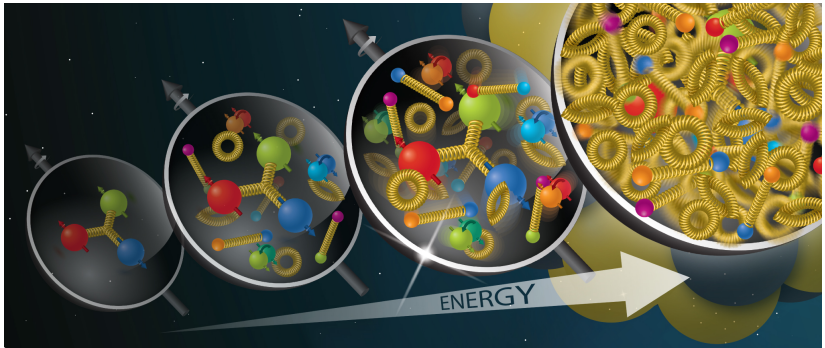
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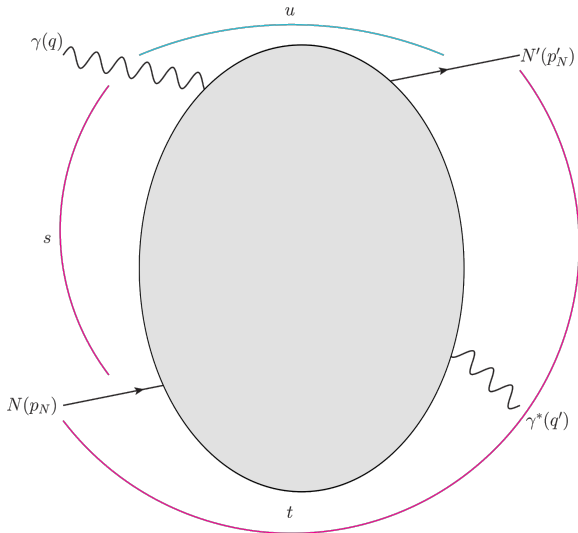


Scaling an Hadron



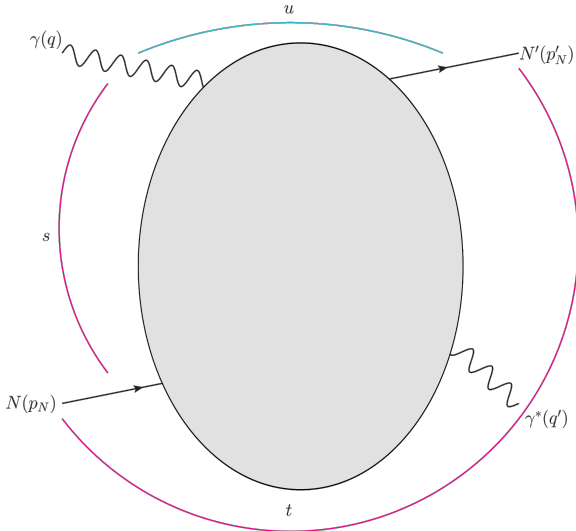
Factorin' Scales

Factorin' Scales



$$\begin{aligned}
 &\gamma(q) + N(p_N) \\
 &\quad \downarrow \\
 &\gamma^*(q') + N'(p'_N) \\
 &\quad \downarrow \\
 &I^-(p_{I-}) + I^+(p_{I+}) \\
 &\quad + N'(p'_N)
 \end{aligned}$$

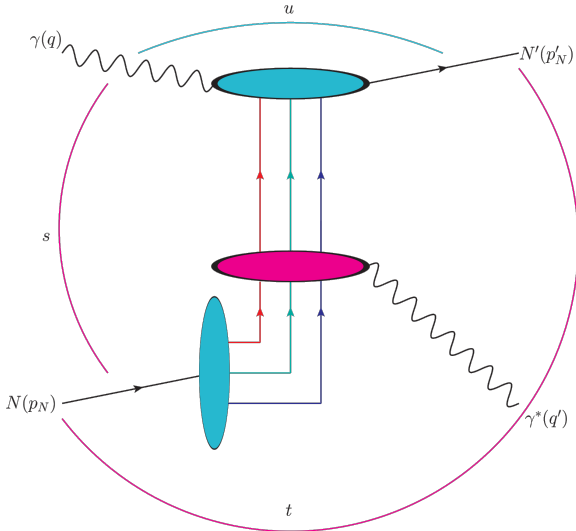
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 \end{aligned}$$

$$\begin{aligned}
 &\frac{q'^2, s, |t| \gg |u|}{u = (p'_N - q)^2} \\
 &t = (p'_N - p_N)^2 \\
 &s = (q + p_N)^2
 \end{aligned}$$

Factorin' Scales



$$\gamma(q) + N(p_N)$$

$$\downarrow$$

$$\gamma^*(q') + N'(p'_N)$$

$$\downarrow$$

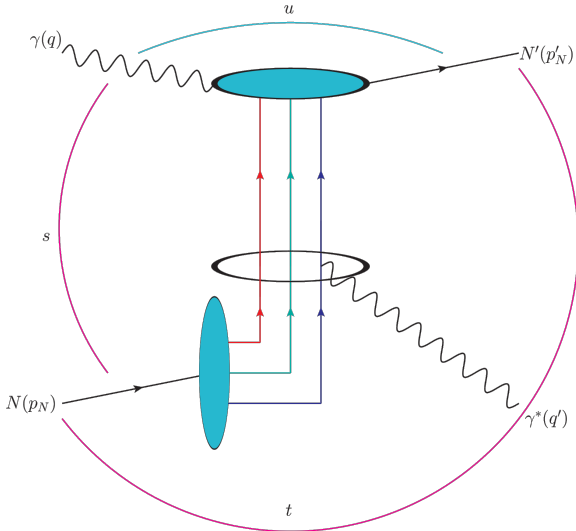
$$I^-(p_{I-}) + I^+(p_{I+}) + N'(p'_N)$$

$$\frac{q'^2, s, |t| \gg |u|}{u = (p'_N - q)^2}$$

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$$\downarrow$$

$$I^-(p_{I-}) + I^+(p_{I+}) + N'(p'_N)$$

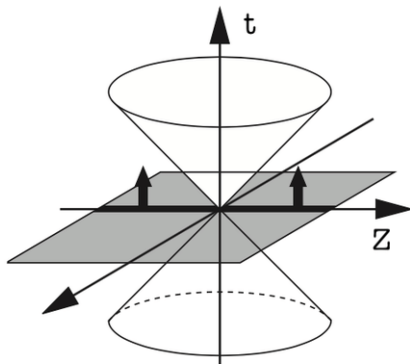
$$\frac{q'^2, s, |t| \gg |u|}{u = (p'_N - q)^2}$$

$$t = (p'_N - p_N)^2$$

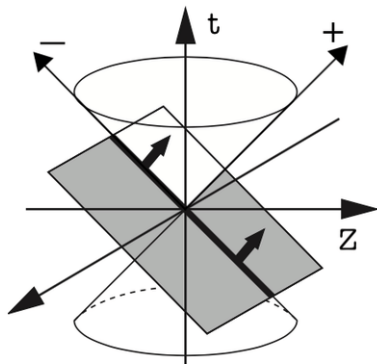
$$s = (q + p_N)^2$$

Going into the Light Front

Going into the Light Front

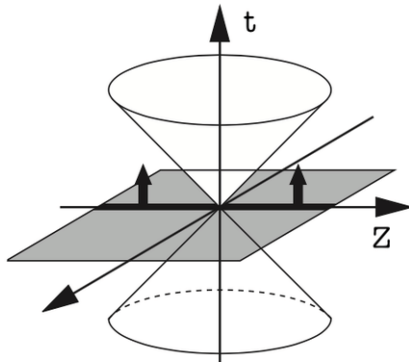


The Instant
Form

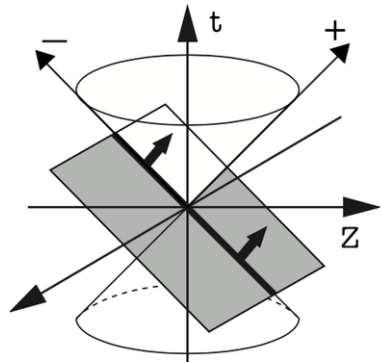


The Front
Form

Going into the Light Front



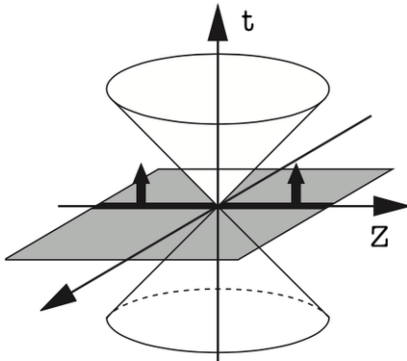
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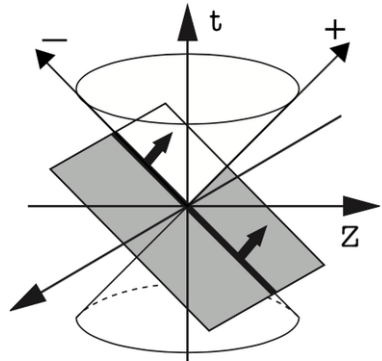
The Front
Form

$$|N\rangle = \psi_{qqq}|qqq\rangle + \psi_{qqqg}|qqqg\rangle + \psi_{qqqq\bar{q}}|qqqq\bar{q}\rangle + \dots$$

Going into the Light Front



The Instant
Form



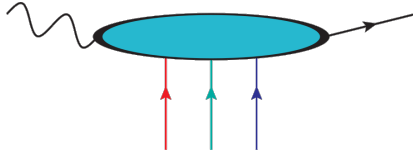
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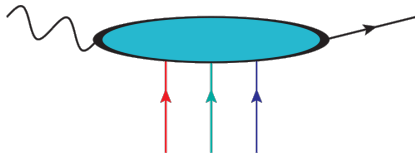
Light-front wave functions give the overlap with multiparton states.

Distributing through Light-Front Wave Functions

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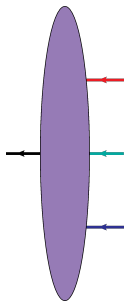
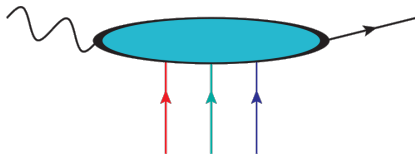


Distributing through Light-Front Wave Functions

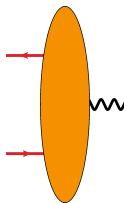


$$\langle N'_P | \bar{\psi}_1(z_1) \bar{\psi}_2(z_2) \bar{\psi}_3(z_3) | \gamma \rangle$$

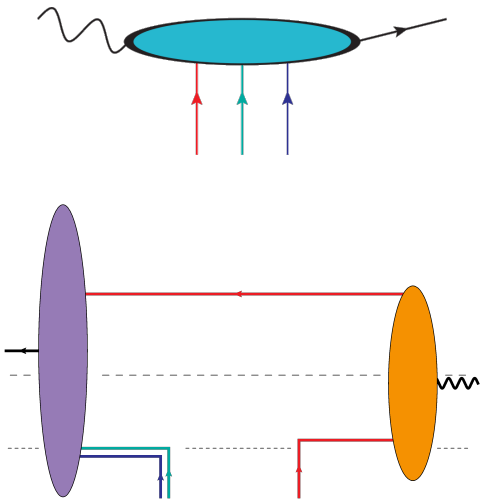
Distributing through Light-Front Wave Functions



$$\bar{\psi}_1(z_1) \bar{\psi}_2(z_2) \bar{\psi}_3(z_3)$$

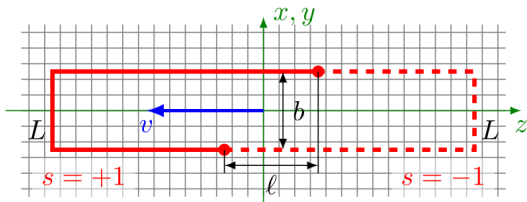
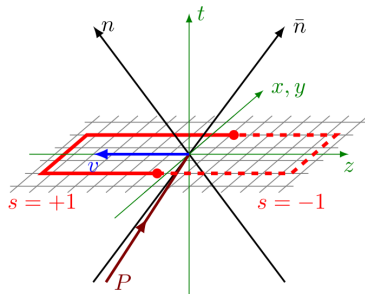


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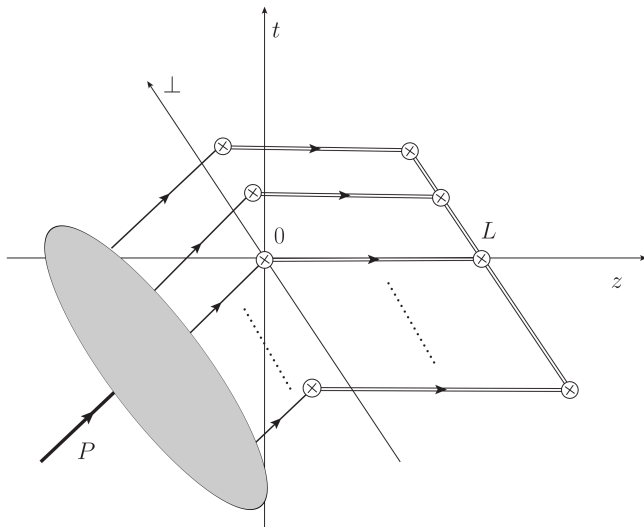
Connecting to the Lattice

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All Together Now!

All Together Now!



Xiangdong Ji and Yizhuang Liu, arXiv:2106.05310