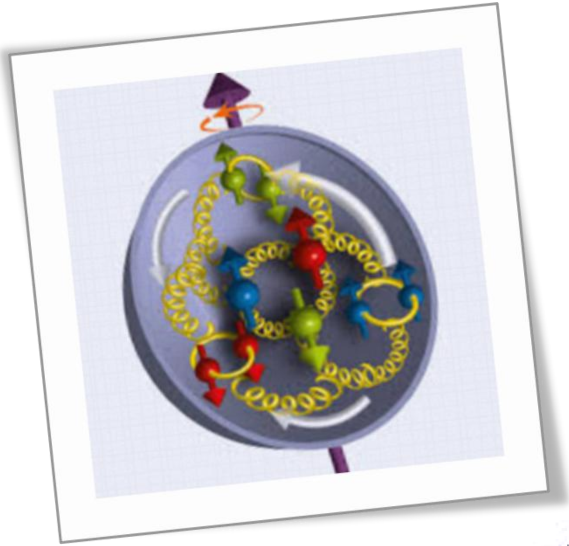
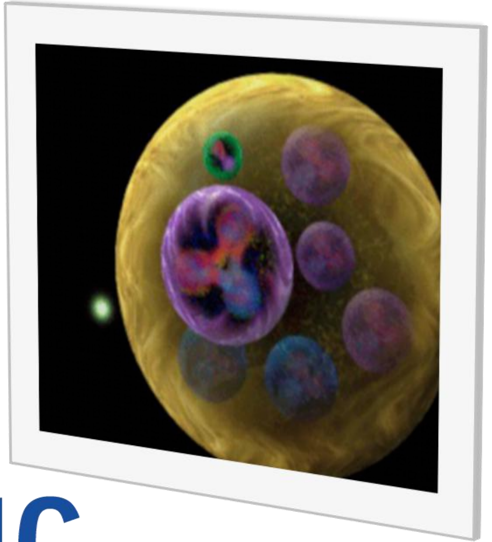
STRUTTURA 3D DI ADRONI LEGATI E LIBERI



Matteo Rinaldi



Perugia, Dipartimento di Fisica e Geologia
30/05/2020

Non siamo soli (anche se a distanza di sicurezza)

Il Gruppo di Fisica teorica Nucleare a Perugia:

Professore Associato: Sergio Scopetta
RTD-A: Matteo Rinaldi
Dottoranda: Sara Fucini

Il gruppo fa parte:
- NINPHA, commisione IV dell' INFN
- del progetto euorpeo STRONG2020

Colleghi con i quali abbiamo collaborato e ancora collaboriamo:

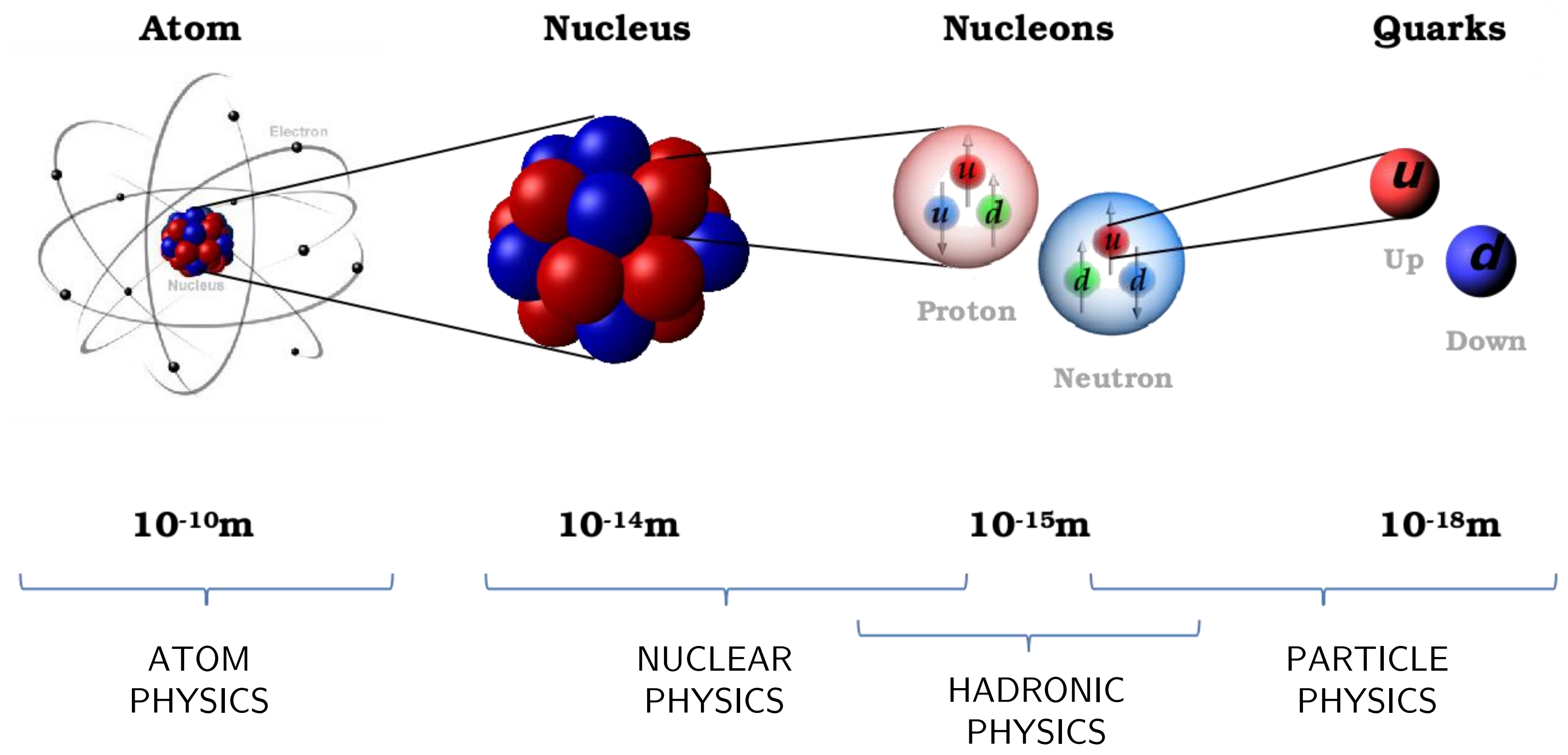
Roma: Giovanni Salmè, Emanuele Pace e A. Del Dotto
Valencia (Spagna): Santiago Noguera & Vicente Vento
Dubna (Russia): Leonid Kaptari
Liegi (Belgio), Haifa (Israele): Federico Alberto Ceccopieri
Mexico: Aurore Courtoy
Orsay Parigi (Francia): Raphael Duprè; Samuel Wallon, J. P. Lansberg
Trento: Marco Claudio Traini, F. Pederiva
Trieste: Daniele Treleani
Mainz (Germania): Tomas Kasemets
Pisa: Michele Viviani
Argonne NL, Chicago (USA): Kawtar Hafidi e Whitney Armstrong
Buenos Aires (Argentina): Daniel Gomez Dumm e Norberto Scoccola
Varsavia (Polonia): Lech Szimanowsky

Indice

- Introduzione
- Le distribuzioni partoniche generalizzate di nucleoni e nuclei leggeri
- Le distribuzioni partoniche doppie di protoni e mesoni
- Glueballs studiate con modelli olografici
- Conclusioni: prospettive e aggiornamenti

ARGOMENTI PRINCIPALI DEI MIEI LAVORI

1 INTRODUZIONE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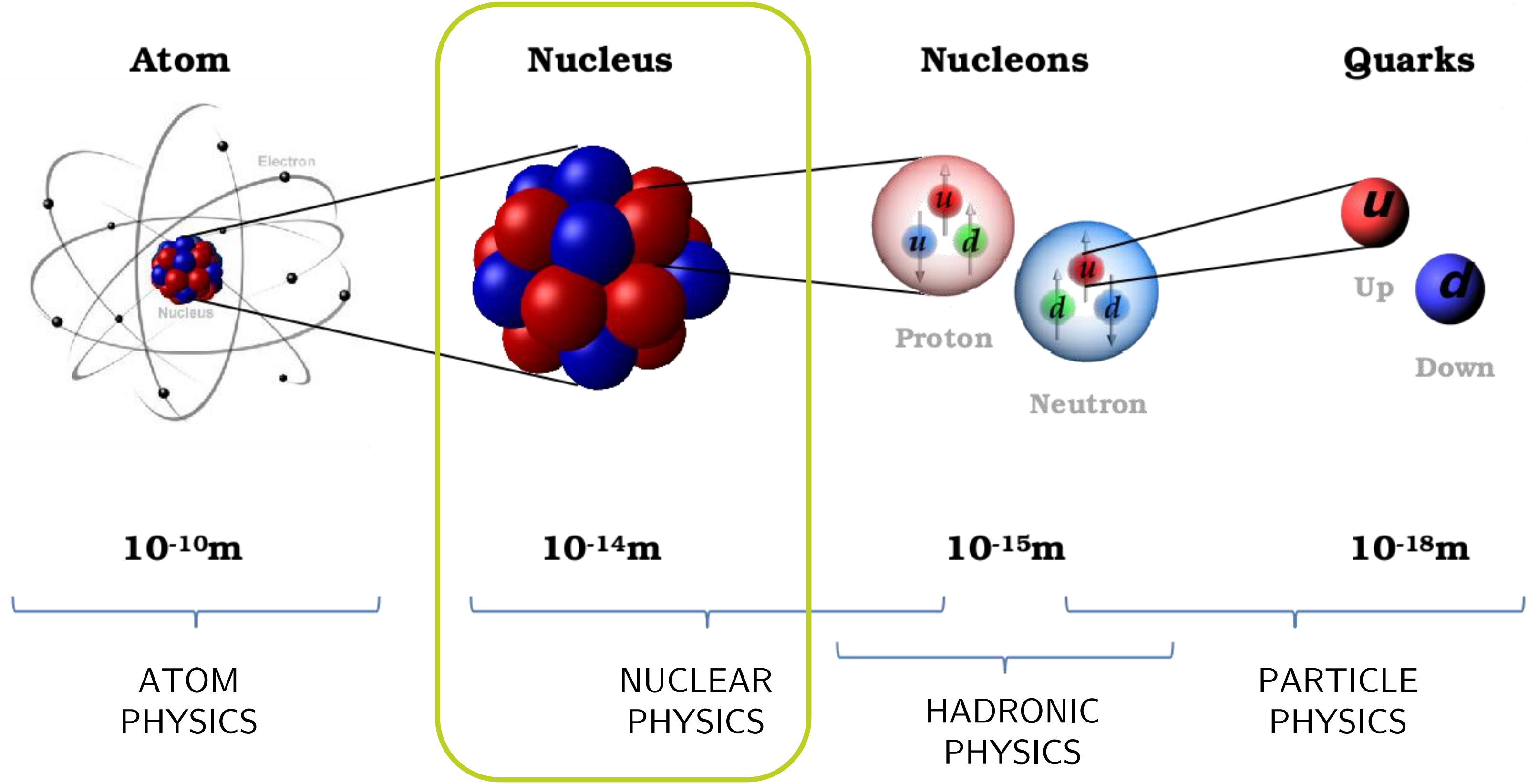
PARTICLE PHYSICS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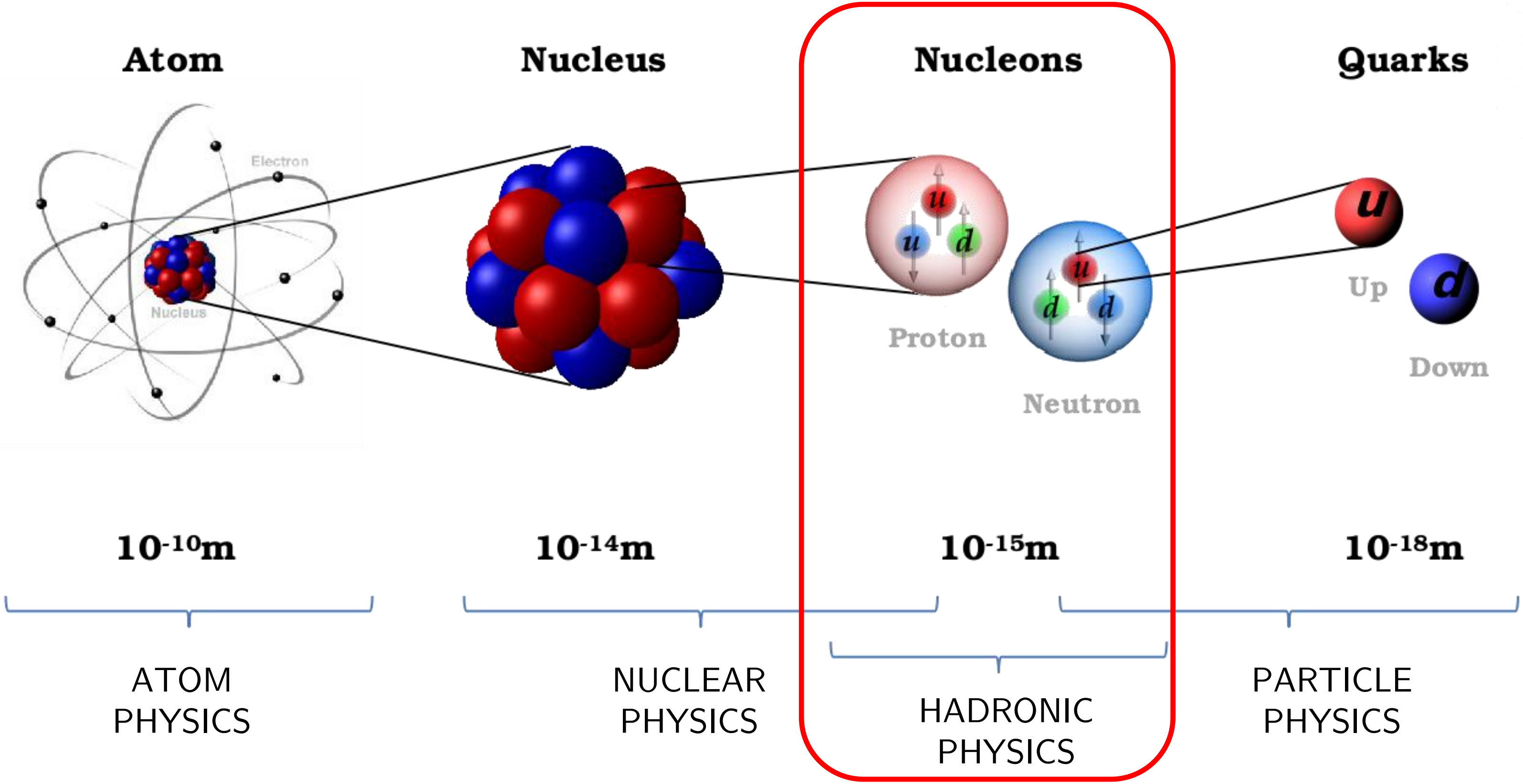
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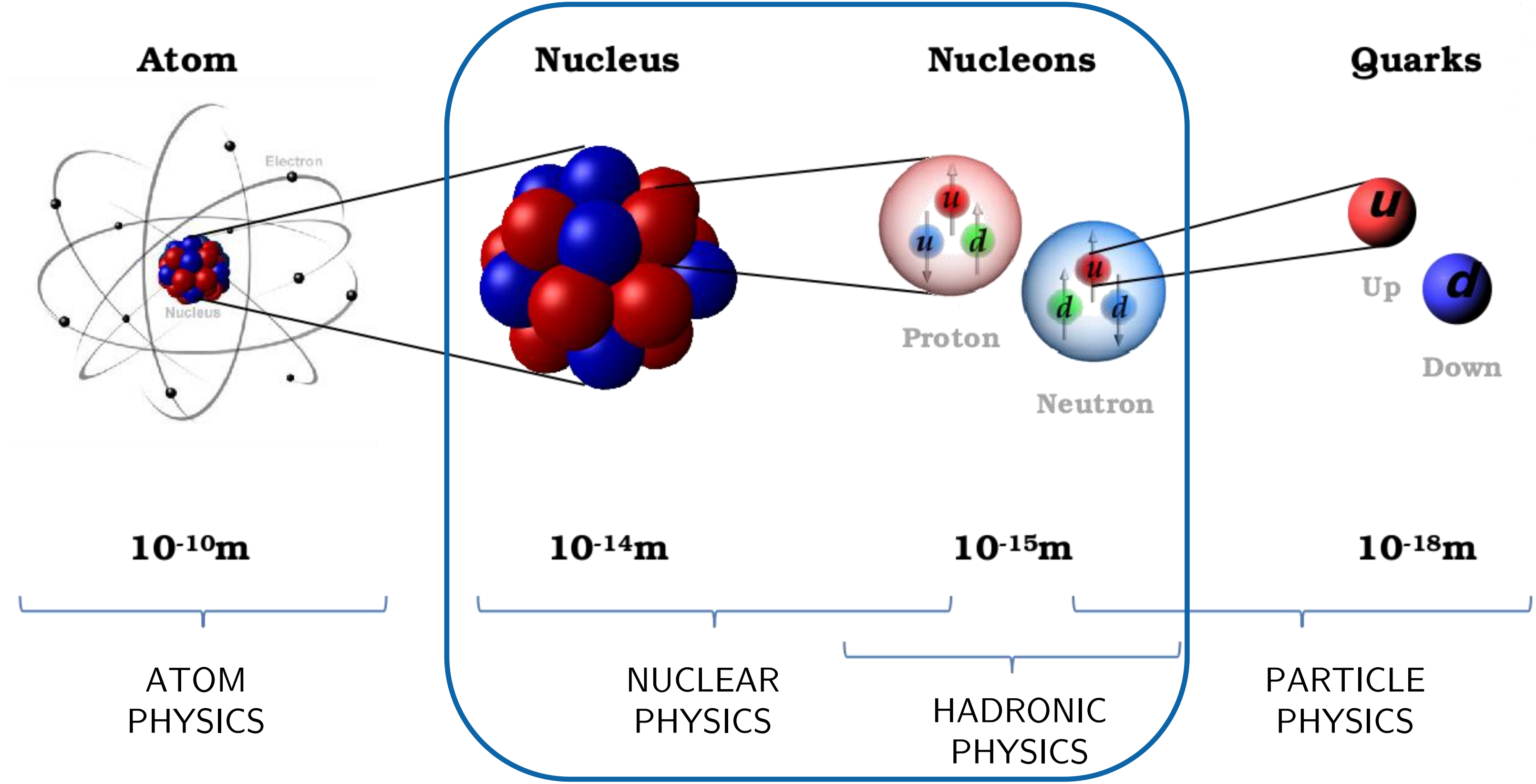
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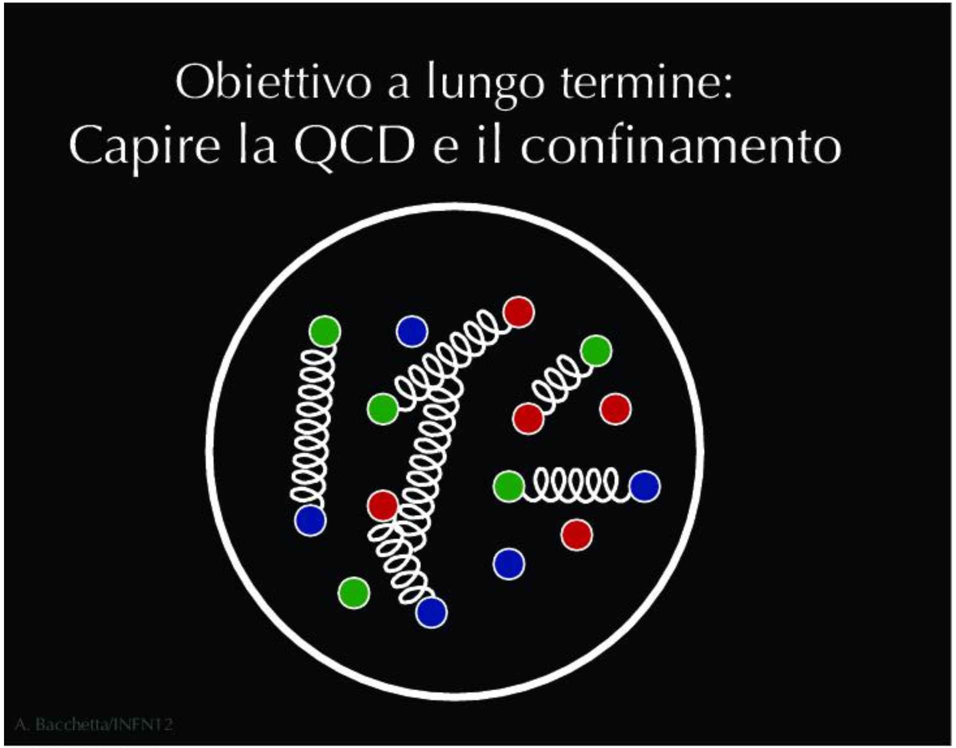
ALCUNI PROBLEMI APERTI



day, 13 November 12

※ Massa di protoni & neutroni (nucleoni)

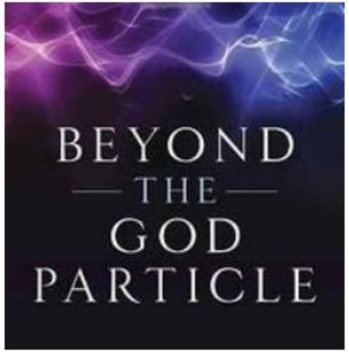
※ SPIN

※ Come cambia la struttura quando protoni e neutroni sono legati per formare i nuclei?

LA MASSA DEGLI ADRONI?

Origin of Mass

- LHC has NOT found the "God Particle" because the Higgs boson is NOT the origin of mass
  - Higgs-boson only produces a little bit of mass
  - Higgs-generated mass-scales explain neither the proton's mass nor the pion's (*near*-)masslessness
  - Hence LHC has, as yet, taught us very little about the origin, structure and nature of the nuclei whose existence support the Cosmos
- Strong interaction sector of the Standard Model, *i.e.* Quantum ChromoDynamics (QCD), is the key to understanding the origin, existence and properties of (almost) all known matter



$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Dirac} + \mathcal{L}_{\rm mass} + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm gauge/\psi}\ .$$

Here,

$$\mathcal{L}_{\rm Dirac} = i\bar{e}^i_{\rm L}\partial\!\!\!/ e^i_{\rm L} + i\bar{\nu}^i_{\rm L}\partial\!\!\!/ \nu^i_{\rm L} + i\bar{e}^i_{\rm R}\partial\!\!\!/ e^i_{\rm R} + i\bar{u}^i_{\rm L}\partial\!\!\!/ u^i_{\rm L} + i\bar{d}^i_{\rm L}\partial\!\!\!/ d^i_{\rm L} + i\bar{u}^i_{\rm R}\partial\!\!\!/ u^i_{\rm R} + i\bar{d}^i_{\rm R}\partial\!\!\!/ d^i_{\rm R}\ ;$$

$$\mathcal{L}_{\rm mass} = -v\left(\lambda^i_e\bar{e}^i_{\rm L}e^i_{\rm R} + \lambda^i_u\bar{u}^i_{\rm L}u^i_{\rm R} + \lambda^i_d\bar{d}^i_{\rm L}d^i_{\rm R} + {\rm h.c.}\right) - M^2_{\rm W}W^+_\mu W^{-\mu} - \frac{M^2_{\rm W}}{2\cos^2\theta_{\rm W}}Z_\mu Z^\mu\ ;$$

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_{WZA}\ ,$$

where

$$\begin{aligned} G^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_3 f^{abc}A^b_\mu A^c_\nu \\ W^\pm_{\mu\nu} &= \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu \\ Z_{\mu\nu} &= \partial_\mu Z_\nu - \partial_\nu Z_\mu \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu\ , \end{aligned}$$

and

$$\begin{aligned} \mathcal{L}_{WZA} = &\ ig_2\cos\theta_{\rm W}\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu Z^\nu + W^+_{\mu\nu}W^{-\mu}Z^\nu - W^-_{\mu\nu}W^{+\mu}Z^\nu\right] \\ &+ie\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu A^\nu + W^+_{\mu\nu}W^{-\mu}A^\nu - W^-_{\mu\nu}W^{+\mu}A^\nu\right] \\ &+g_2^2\cos^2\theta_{\rm W}\left(W^+_\mu W^-_\nu Z^\mu Z^\nu - W^+_\mu W^{-\mu}Z_\nu Z^\nu\right) \\ &+g_2^2\left(W^+_\mu W^-_\nu A^\mu A^\nu - W^+_\mu W^{-\mu}A_\nu A^\nu\right) \\ &+g_2 e\cos\theta_{\rm W}\left[W^+_\mu W^-_\nu\left(Z^\mu A^\nu + Z^\nu A^\mu\right) - 2W^+_\mu W^{-\mu}Z_\nu A^\nu\right] \\ &+\frac{1}{2}g_2^2\left(W^+_\mu W^-_\nu\right)\left(W^{+\mu}W^{-\nu} - W^{+\nu}W^{-\mu}\right)\ ; \end{aligned}$$

and

$$\mathcal{L}_{\rm gauge/\psi} = -g_3 A^a_\mu J^{\mu a}_{(3)} - g_2\left(W^+_\mu J^\mu_{W^+} + W^-_\mu J^\mu_{W^-} + Z_\mu J^\mu_Z\right) - eA_\mu J^\mu_A\ ,$$

where

$$\begin{aligned} J^{\mu a}_{(3)} &= \bar{u}^i\gamma^\mu T^a_{(3)}u^i + \bar{d}^i\gamma^\mu T^a_{(3)}d^i \\ J^\mu_{W^+} &= \frac{1}{\sqrt{2}}\left(\bar{\nu}^i_{\rm L}\gamma^\mu e^i_{\rm L} + V^{ij}\bar{u}^i_{\rm L}\gamma^\mu d^j_{\rm L}\right) \\ J^\mu_{W^-} &= (J^\mu_{W^+})^* \\ J^\mu_Z &= \frac{1}{\cos\theta_{\rm W}}\left[\frac{1}{2}\bar{\nu}^i_{\rm L}\gamma^\mu\nu^i_{\rm L} + \left(-\frac{1}{2} + \sin^2\theta_{\rm W}\right)\bar{e}^i_{\rm L}\gamma^\mu e^i_{\rm L} + (\sin^2\theta_{\rm W})\bar{e}^i_{\rm R}\gamma^\mu e^i_{\rm R}\right. \\ &\quad + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm L}\gamma^\mu u^i_{\rm L} + \left(-\frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm R}\gamma^\mu u^i_{\rm R} \\ &\quad \left. + \left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm L}\gamma^\mu d^i_{\rm L} + \left(\frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm R}\gamma^\mu d^i_{\rm R}\right] \\ J^\mu_A &= (-1)\bar{e}^i\gamma^\mu e^i + \left(\frac{2}{3}\right)\bar{u}^i\gamma^\mu u^i + \left(-\frac{1}{3}\right)\bar{d}^i\gamma^\mu d^i\ . \end{aligned}$$

STANDARD MODEL

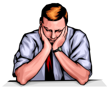
Espressione molto compatta di alcune interazioni fondamentali che governano la composizione della maggior parte della materia nell'universo!

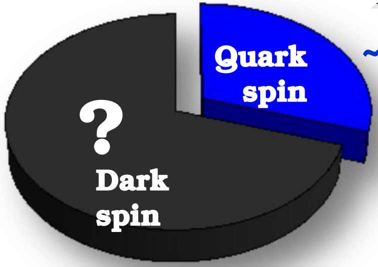
Questo "piccolissimo termine", che descrive la self-interaction tra i bosoni di gauge della QCD (gluoni) è responsabile per quasi il 98% della materia visibile!

Tuttavia,la **QCD** nel regime non perturbativo non è risolvibile. Dopo quasi 50 anni dalla scoperta dei quarks siamo ancora agli inizi per comprendere come dai quark e gluoni si "costruiscono" pioni, protoni, neutroni e nuclei!

Per esempio, infatti, ancora oggi non è chiaro come lo SPIN del protone si ottiene a partire dai suoi costituenti (SPIN CRISIS)

LO SPIN DEL PROTONE: UN PUZZLE IRRISOLTO



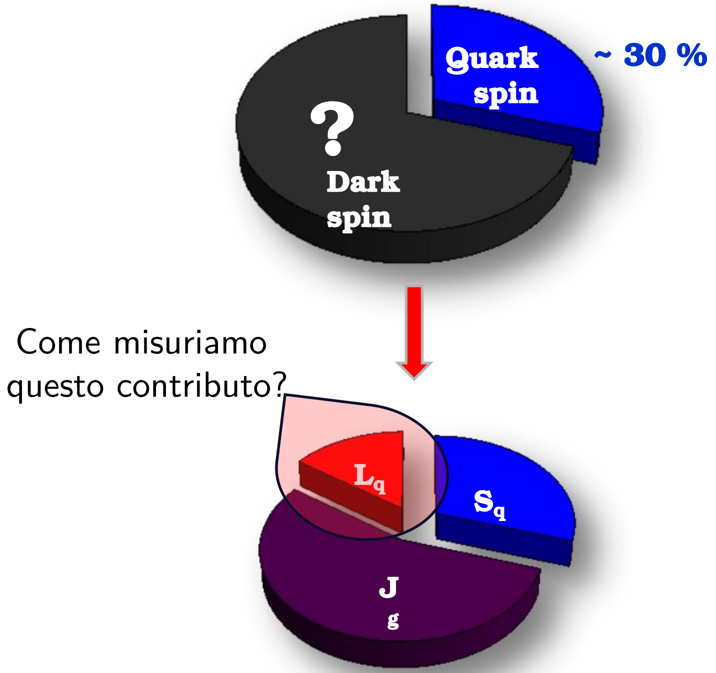


~ 30 %

$$\frac{1}{2} = S_q + L_q + S_g + L_g$$

Dai modelli ci si aspettava
che questi contributi fossero piccoli

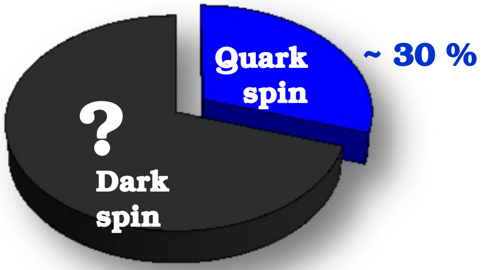
LO SPIN DEL PROTONE: UN PUZZLE IRRISOLTO



$$\frac{1}{2} = S_q + \boxed{L_q} + S_g + L_g$$

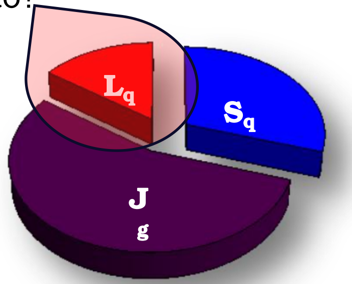
L_q = Orbital Angular Momentum (OAM)

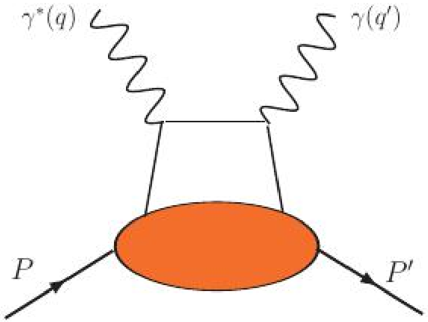
LO SPIN DEL PROTONE: UN PUZZLE IRRISOLTO



$$\frac{1}{2} = S_q + \boxed{L_q} + S_g + L_g$$

Come misuriamo
questo contributo?



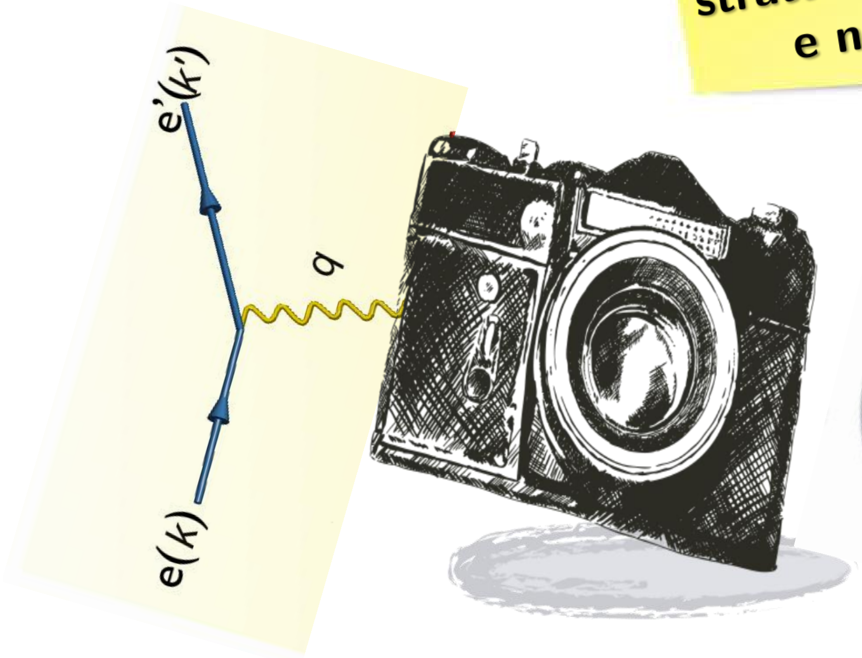


Deeply Virtual
Compton Scatering
DVCS

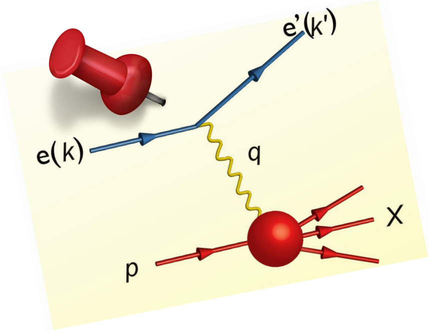
Protoni e Neutroni in 3D

IL NOSTRO APPROCCIO:

Ottenere delle immagini della struttura di protoni e neutroni!



Protoni e Neutroni in 3D



Consideriamo la diffusione profondamente anelastica (DIS): $A(e,e')X$, se il bersaglio A ha spin $J_A = 1/2$, nel sistema del laboratorio (LAB) allora $q=(\nu,0,0,-q)$, Nel limite di Bjorken, $Q^2 = -q^2$, $\nu \longrightarrow \infty$, allora il rapporto Q^2/ν finito

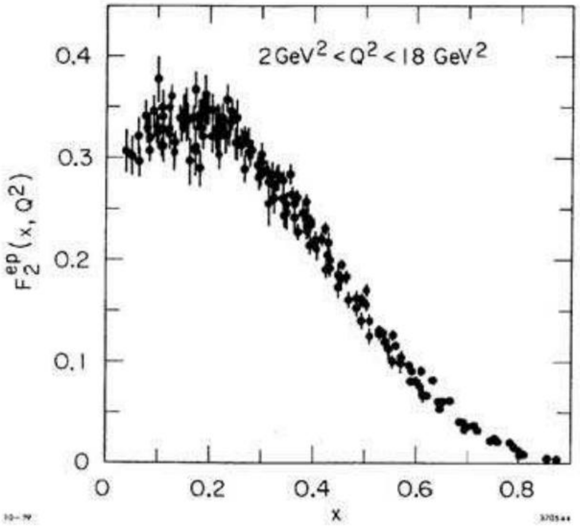
$$\frac{d^2\sigma}{d\Omega dE'} \propto F_2(x) \simeq \sum_q e_q^2 x f_q(x)$$

$F_2(x)$ = funzione di struttura

$f_q(x)$ = distribuzione partonica (PDF)

$x = \frac{Q^2}{2P_A \cdot q}$ è uno scalare:

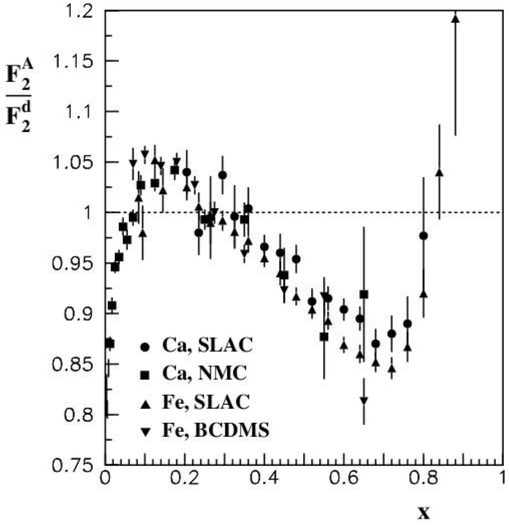
- $x = \frac{Q^2}{2M_A \nu}$ (LAB);
- x = frazione di momento del bersaglio portata dal quark. nell' *Infinite Momentum Frame* (IMF) $(p_z \to \infty)$



In generale, F_2 dipende da Q^2. Nel limite di Bjorken, F_2 scala in x: diffusione incoerente su costituenti puntiformi, i partoni (Al LO in QCD, solo i quark contribuiscono ad F_2).

Un problema aperto: effetto EMC

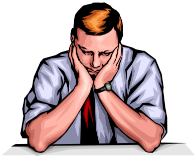
Consideriamo un processo DIS su un nucleo A (EMC coll., CERN 1983) e studiamo il rapporto tra le sezioni d'urto per un nucleone legato in un nucleo e per un nucleone libero. Si vide:



Se il rapporto fosse 1, allora il nucleone libero e legato sarebbero UGUALI.

Il rapporto....non è 1

Dopo tanti anni ancora non sappiamo perché.

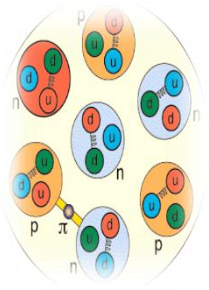


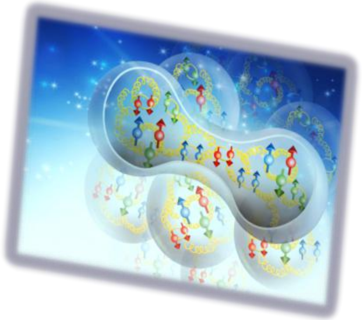
Abbiamo tante ipotesi e per avere una risposta chiara servono nuovi esperimenti, come il DVCS

Misure più difficili e descrizioni teoriche più complesse

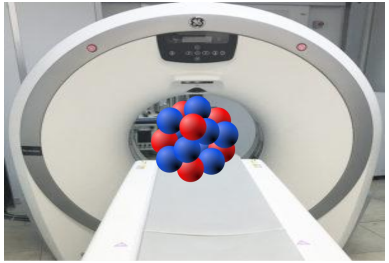
Effetto EMC: come ne usciamo?

Per rispondere al problema dell'effetto EMC, dobbiamo arrivare, essenzialmente, a capire a quale dei due spaccati i nuclei assomigliano:



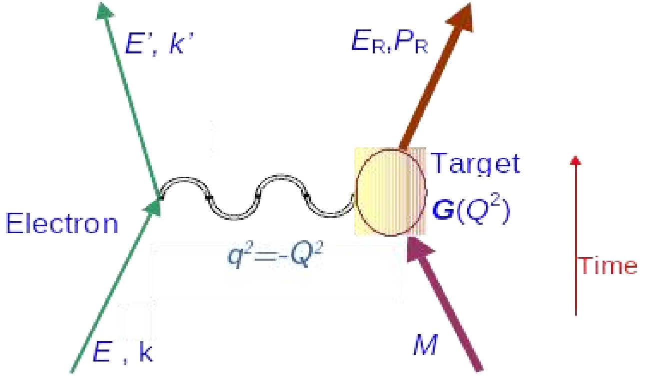


Per rispondere serve fargli una **TOMOGRAFIA.**



Si può fare! Possiamo studiare processi come:
Deeply Virtual Compton Scattering (DVCS)
e ottenere info riguardo le
distribuzioni partoniche generalizzate (GPDs).
Difficili misure ed analisi ma oggi possibile in vari laboratori!

ELASTIC processes

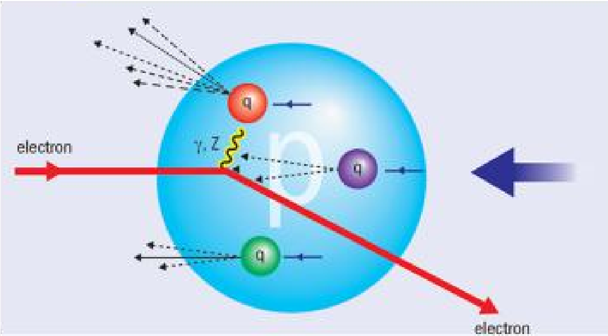


$$\langle N(P')|J^{\mu}_{EM}(0)|N(P)\rangle =$$

$$\bar{u}(P')\left[\gamma^{\mu}F_1(Q^2)+i\sigma^{\mu\nu}\frac{q_\nu}{2M}F_2(Q^2)\right]u(P)$$

DIRAC Form Factor (F_1) — PAULI Form Factor (F_2)

DEEP INELASTIC processes

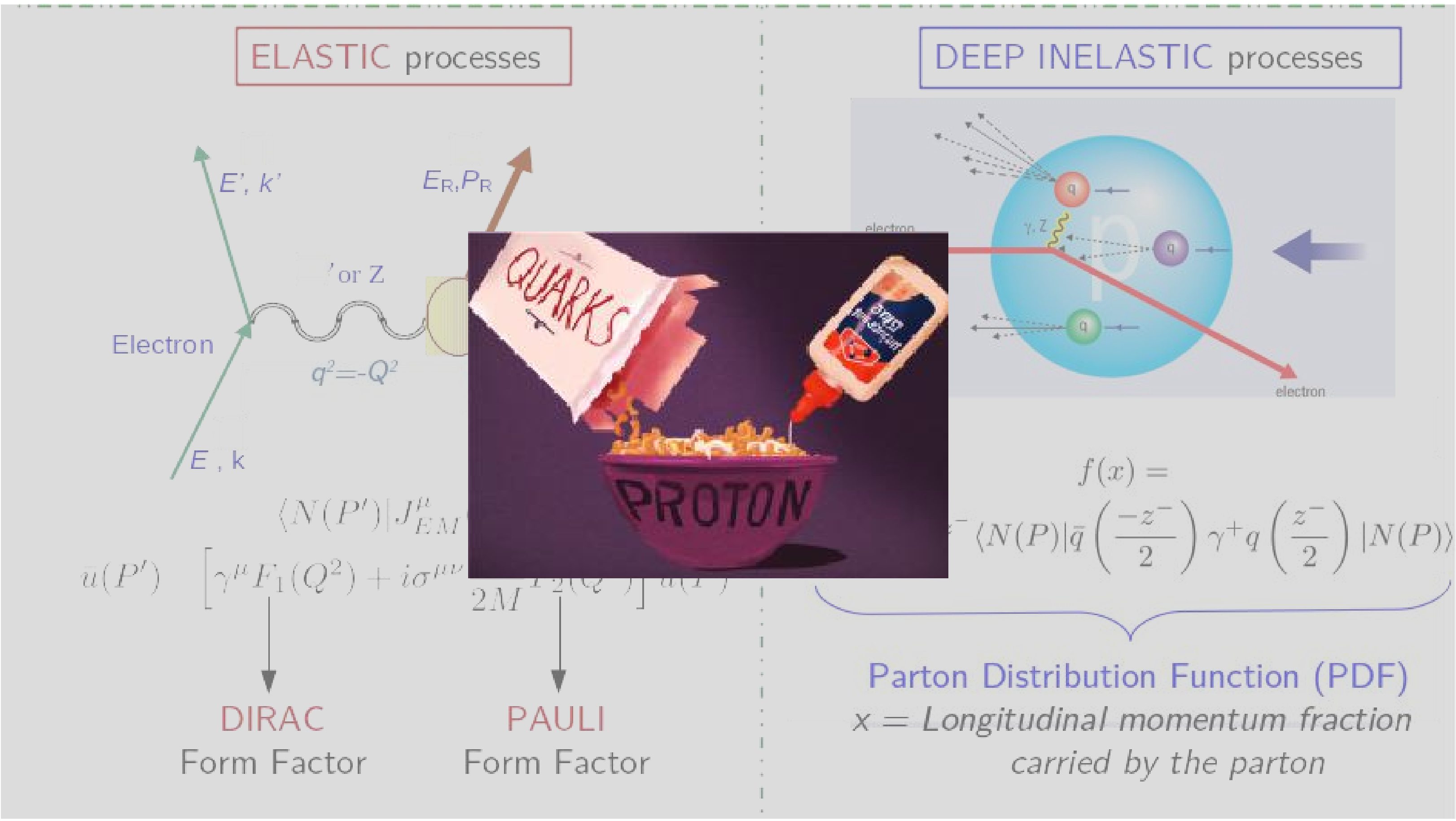


$$f(x) = \int dz^- e^{ixP^+z^-}\langle N(P)|\bar{q}\left(\frac{-z^-}{2}\right)\gamma^+ q\left(\frac{z^-}{2}\right)|N(P)\rangle$$

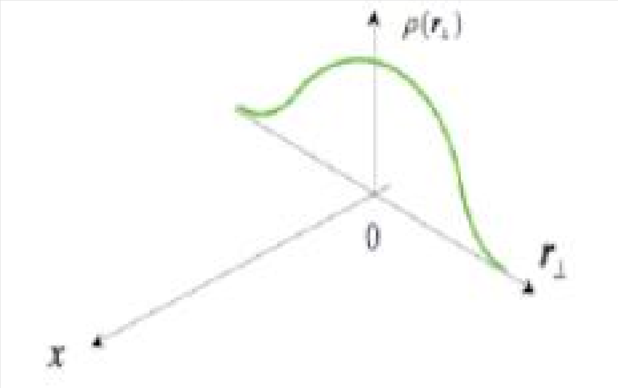
Parton Distribution Function (PDF)

x = *Longitudinal momentum fraction carried by the parton*

PROCESSI AD ALTA ENERGIA



ELASTIC processes



ime

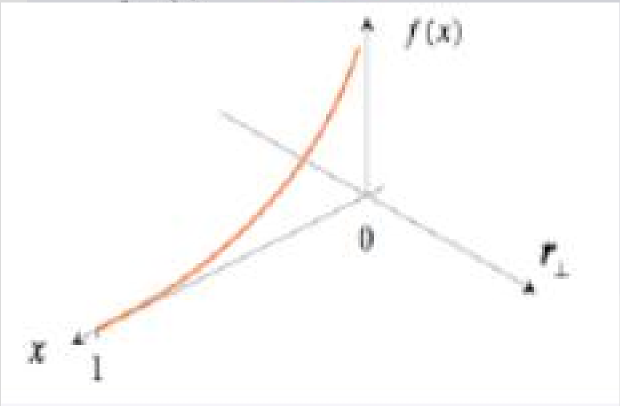
$$\langle N(P')|J^{\mu}_{EM}(0)|N(P)\rangle =$$

$$u(P') \quad \left[\gamma^{\mu}F_1(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M}F_2(Q^2)\right] u(P)$$

DIRAC Form Factor

PAULI Form Factor

DEEP INELASTIC processes

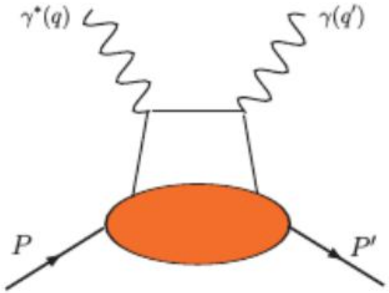


$$\int dz^- e^{ixP^+z^-}\langle N(P)|\bar{q}\left(\frac{-z^-}{2}\right)\gamma^+ q\left(\frac{z^-}{2}\right)|N(P)\rangle$$

x = Longitudinal momentum fraction carried by the parton

1-DIMENSIONAL INFORMATION!

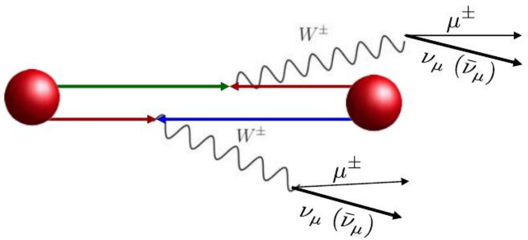
DEEPLY VIRTUAL COMPTON SCATTERING



$$\int dz^- e^{ixP^+z^-}\langle N(P')|\bar{q}\left(\frac{-z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right)|N(P)\rangle = \bar{u}(P')\left[\gamma^+ H(x,\xi,\Delta^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M}E(x,\xi,\Delta^2)\right]u(P)$$

GENERALIZED PARTON DISTRIBUTION FUNCTIONS (GPDs)

Double Parton Scattering



dPDF

Momentum scale

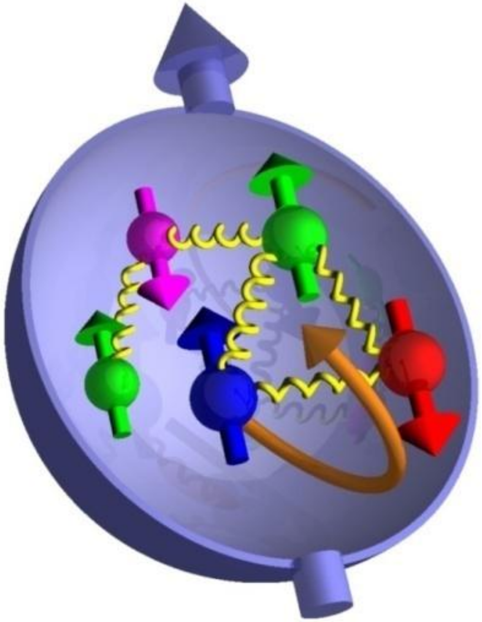
$$d\sigma = \frac{1}{S}\sum_{i,j,k,l}\hat{\sigma}_{ij}(x_1, x_3, \mu_A)\hat{\sigma}_{kl}(x_2, x_4, \mu_B)\int d^2z_\perp F_{ik}(x_1, x_2, z_\perp, \mu_A, \mu_B)F_{jl}(x_3, x_4, z_\perp, \mu_A, \mu_B)$$

Momentum fraction carried by the parton inside the hadron

Transverse distance between the two partons

dPDF= double parton distribution functions

Lo zoo delle distribuzioni



Da molti processi si ottengono un gran numero di distribuzioni, ognuna che fornisce informazioni diverse sulla struttura non-perturbativa di un adrone

Lo zoo delle distribuzioni

$$\frac{1}{2P^+}\langle p^+,\vec{0}_\perp,\Lambda'|\overline{\psi}(0)\Gamma\psi(0)|p^+,\vec{0}_\perp,\Lambda\rangle$$

Depends on :

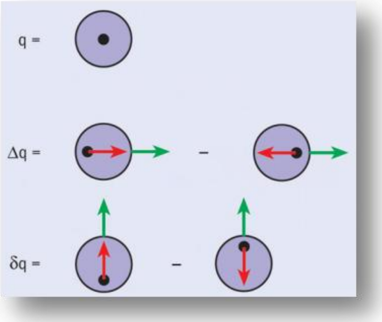
$\Lambda, \Lambda', \Gamma$

- **Polarization**

Vector
Parton number

Axial
Parton helicity

Tensor
Parton transversity



Charges

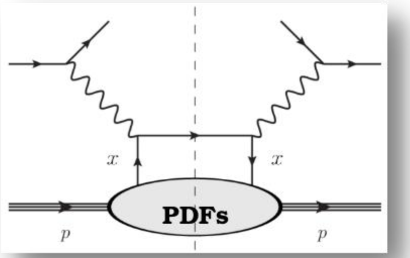
Lo zoo delle distribuzioni

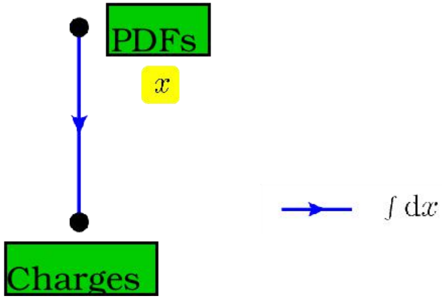
$$\frac{1}{2}\int\frac{\mathrm{d}z^-}{2\pi}\,e^{ik^+z^-}\langle p^+,\vec{0}_\perp,\Lambda'|\overline{\psi}(-\tfrac{z^-}{2})\Gamma\mathcal{W}\psi(\tfrac{z^-}{2})|p^+,\vec{0}_\perp,\Lambda\rangle$$

Depends on :

- $\Lambda, \Lambda', \Gamma$ **Polarization**
- $x = \frac{k^+}{P^+}$ **Longitudinal momentum (fraction)**

DIS





Lo zoo delle distribuzioni

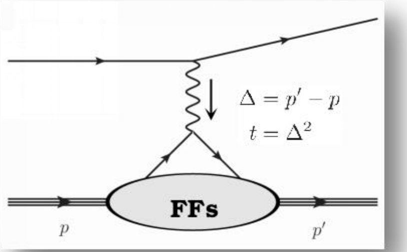
$$\frac{1}{2P^+}\langle p^+, \frac{\vec{\Delta}_\perp}{2}, \Lambda'|\overline{\psi}(0)\Gamma\psi(0)|p^+, -\frac{\vec{\Delta}_\perp}{2}, \Lambda\rangle$$

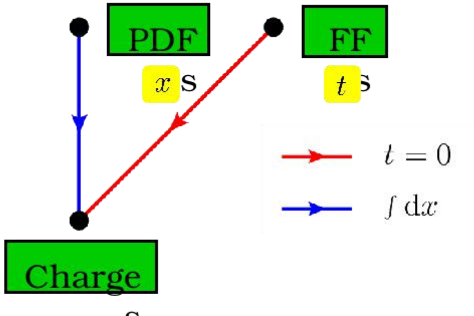
Depends on :

$\Lambda, \Lambda', \Gamma$
- **Polarization**
- **Longitudinal momentum (fraction)**

Δ
- **Momentum transfer**

Elastic scattering





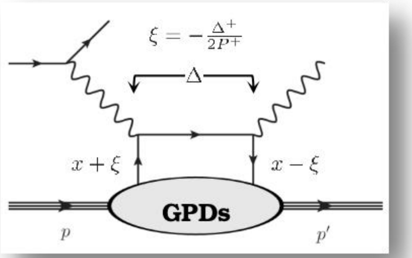
Lo zoo delle distribuzioni

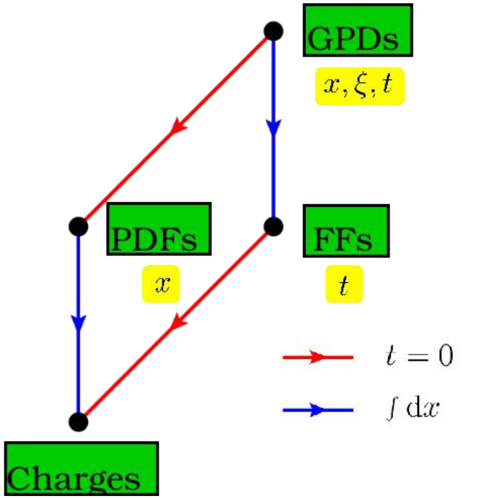
$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ik^+z^-} \langle p'^+, -\frac{\vec{\Delta}_\perp}{2}, \Lambda' | \overline{\psi}(-\frac{z^-}{2}) \Gamma \mathcal{W} \psi(\frac{z^-}{2}) | p^+, \frac{\vec{\Delta}_\perp}{2}, \Lambda \rangle$$

Depends on :

- $\Lambda, \Lambda', \Gamma$ — **Polarization**
- $x = \frac{k^+}{P^+}$ — **Longitudinal momentum (fraction)**
- Δ — **Momentum transfer**

DVCS





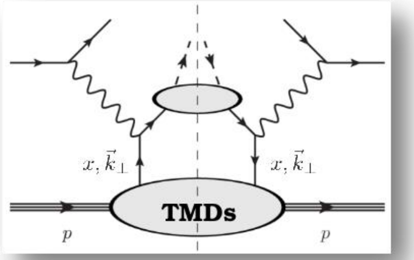
Lo zoo delle distribuzioni

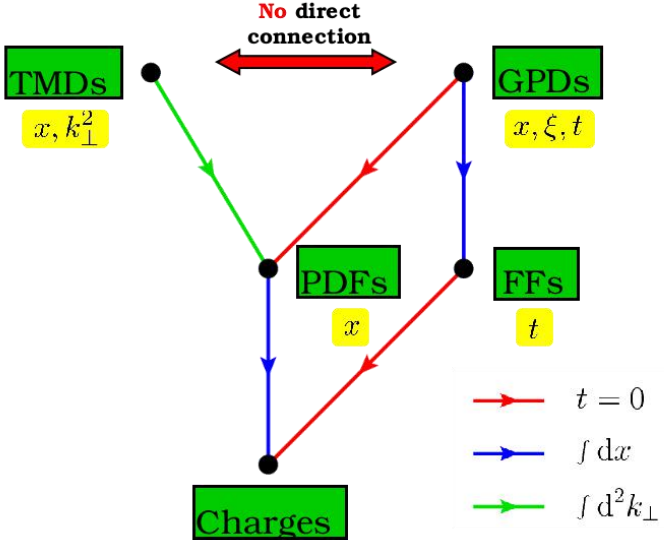
$$\frac{1}{2}\int \frac{\mathrm{d}z^- \,\mathrm{d}^2 z_\perp}{(2\pi)^3}\, e^{ik\cdot z}\, \langle p^+, \vec{0}_\perp, \Lambda' | \overline{\psi}(-\tfrac{z}{2})\Gamma \mathcal{W} \psi(\tfrac{z}{2}) | p^+, \vec{0}_\perp, \Lambda\rangle \Big|_{z^+=0}$$

Depends on :

- $\Lambda, \Lambda', \Gamma$ **Polarization**
- $x = \frac{k^+}{P^+}$ **Longitudinal momentum (fraction)**
- **Momentum transfer**
- $\vec{k}_\perp$ **Transverse momentum**

SIDIS





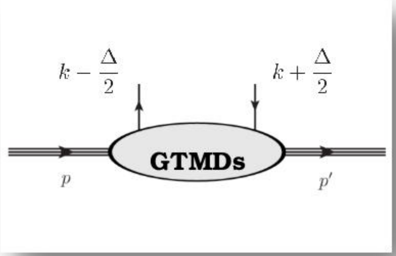
Lo zoo delle distribuzioni

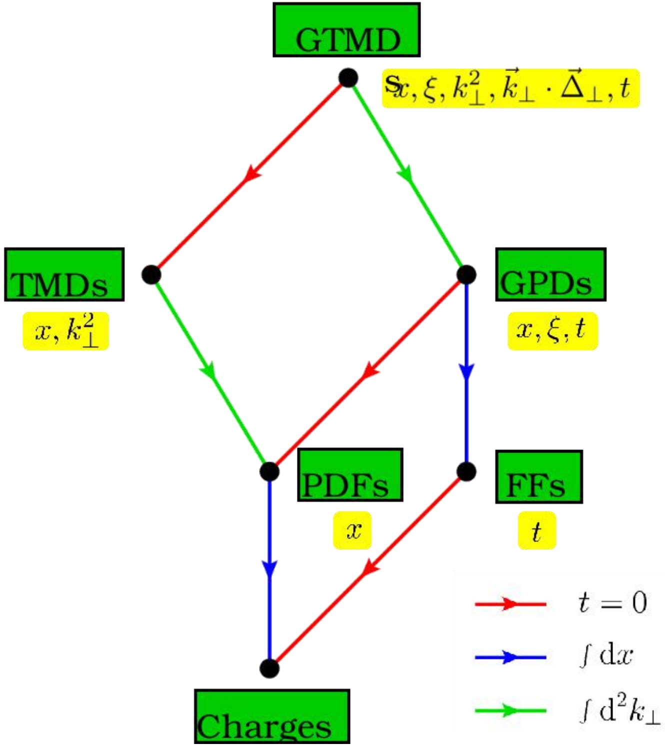
$$\frac{1}{2}\int \frac{\mathrm{d}z^-\,\mathrm{d}^2 z_\perp}{(2\pi)^3}\, e^{ik\cdot z}\, \langle p'^+, \frac{\vec{\Delta}_\perp}{2}, \Lambda' | \overline{\psi}(-\tfrac{z}{2})\Gamma\mathcal{W}\psi(\tfrac{z}{2}) | p^+, -\frac{\vec{\Delta}_\perp}{2}, \Lambda\rangle\Big|_{z^+=0}$$

Depends on :

- $\Lambda, \Lambda', \Gamma$ — **Polarization**
- $x = \frac{k^+}{P^+}$ — **Longitudinal momentum (fraction)**
- Δ — **Momentum transfer**
- $\vec{k}_\perp$ — **Transverse momentum**

???





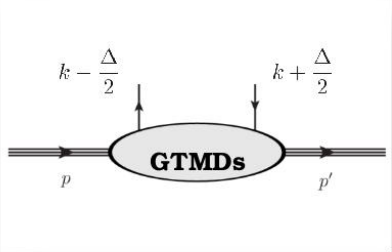
Lo zoo delle distribuzioni

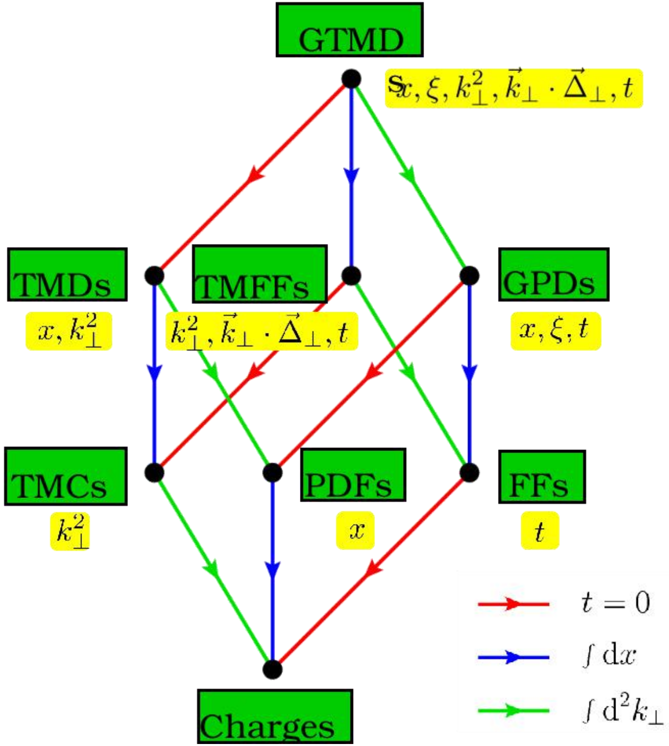
$$\frac{1}{2}\int \frac{\mathrm{d}z^- \, \mathrm{d}^2 z_\perp}{(2\pi)^3} \, e^{ik\cdot z} \, \langle p'^+, \frac{\vec{\Delta}_\perp}{2}, \Lambda' | \overline{\psi}(-\tfrac{z}{2}) \Gamma \mathcal{W} \psi(\tfrac{z}{2}) | p^+, -\frac{\vec{\Delta}_\perp}{2}, \Lambda \rangle \Big|_{z^+=0}$$

Depends on :

- $\Lambda, \Lambda', \Gamma$ — **Polarization**
- $x = \frac{k^+}{P^+}$ — **Longitudinal momentum (fraction)**
- Δ — **Momentum transfer**
- $\vec{k}_\perp$ — **Transverse momentum**

???



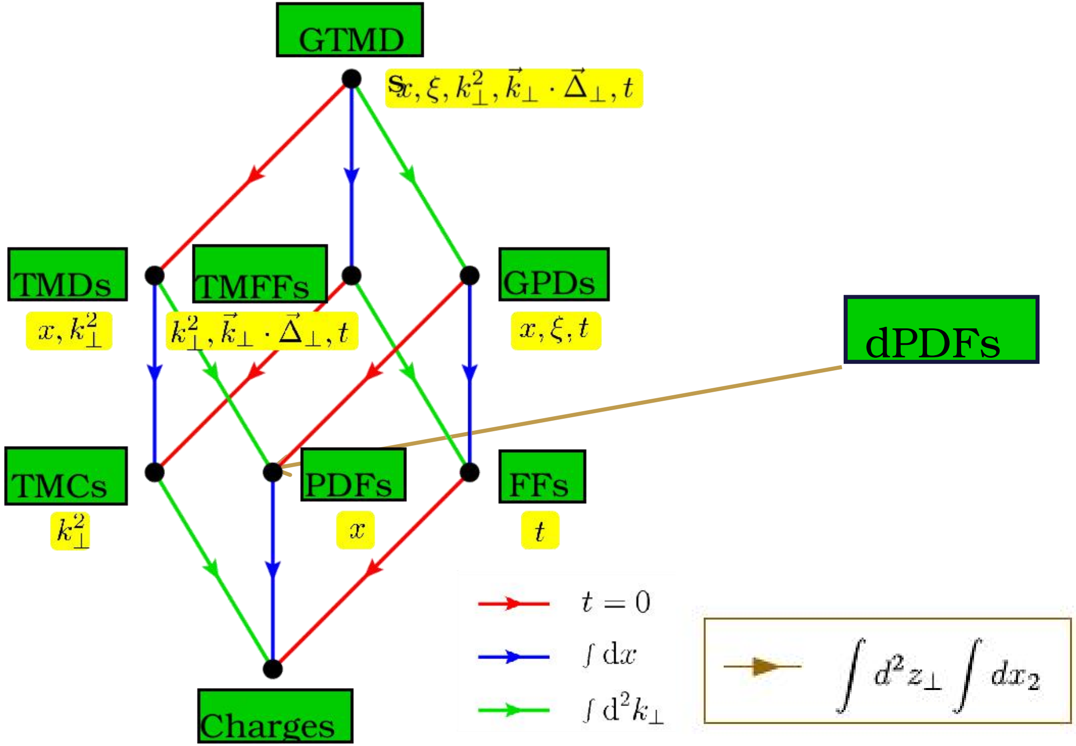


Lo zoo delle distribuzioni

$$\frac{1}{2}\int \frac{dz^- \, d^2 z_\perp}{(2\pi)^3} e^{ik\cdot z} \langle p'^+, \frac{\vec{\Delta}_\perp}{2}, \Lambda' | \overline{\psi}(-\tfrac{z}{2}) \Gamma \mathcal{W} \psi(\tfrac{z}{2}) | p^+, -\frac{\vec{\Delta}_\perp}{2}, \Lambda \rangle \Big|_{z^+=0}$$

Depends on :

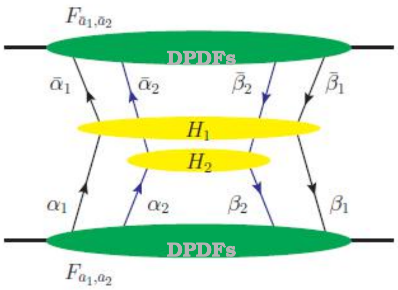
- $\Lambda, \Lambda', \Gamma$ — **Polarization**
- $x = \frac{k^+}{P^+}$ — **Longitudinal momentum (fraction)**
- Δ — **Momentum transfer**
- $\vec{k}_\perp$ — **Transverse momentum**
- $z_\perp$ — **Transverse distance**

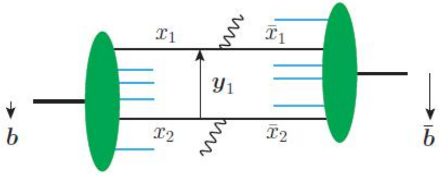


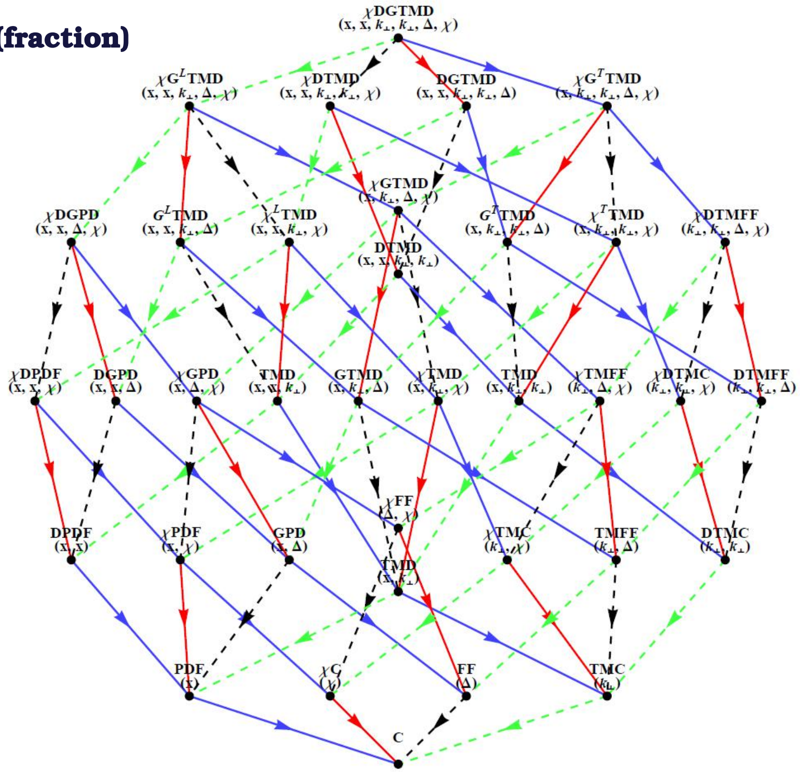
Lo zoo delle distribuzioni

Depends on :

$\Lambda, \Lambda', \Gamma$	**Polarization**
$x = \frac{k^+}{P^+}$	**Longitudinal momentum (fraction)**
Δ	**Momentum transfer**
$\vec{k}_\perp$	**Transverse momentum**
$\vec{y}_\perp$	**Inter-parton distance**





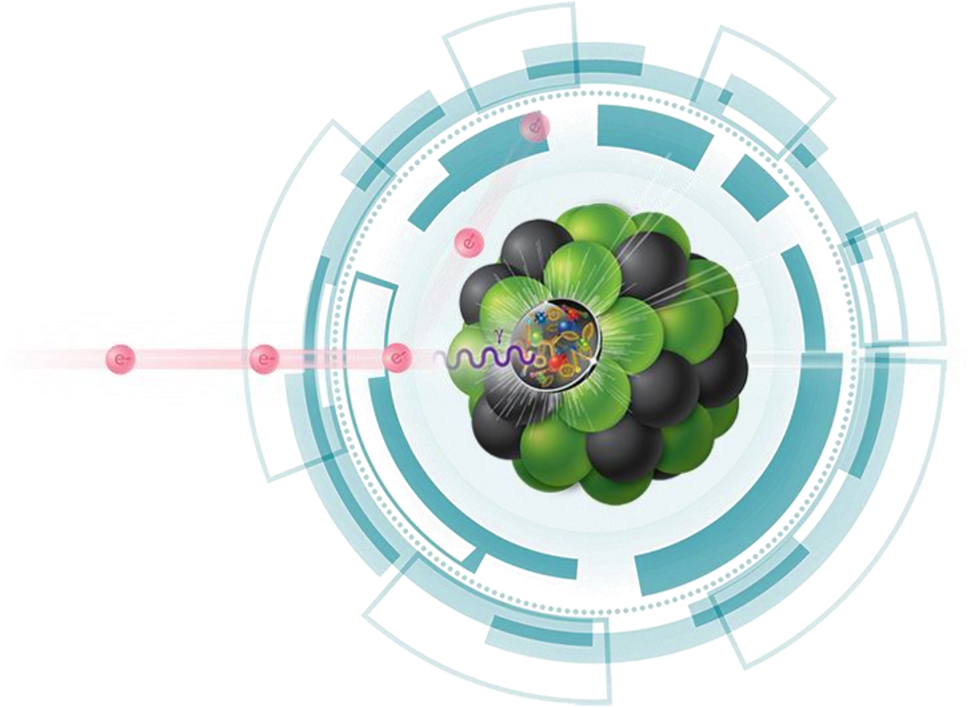


[Diehl, Ostermeier, Schäfer (2012)]

[Thürman, Master thesis (2012)]

Electron Ion Collider (EIC)

"A machine that will unlock the secrets of the strongest force in Nature"



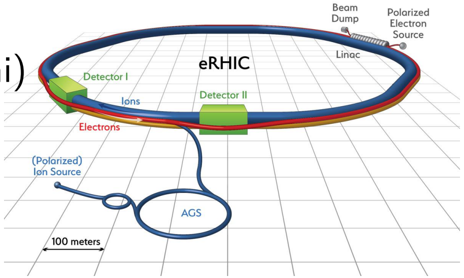
Electron Ion Collider (EIC)

"A machine that will unlock the secrets of the strongest force in Nature"

- Nel prossimo decennio, l'unico acceleratore attivo negli USA sarà l' EIC.
  Servirà per capire la QCD nella sua anima non perturbativa:
  adronizzazione, confinamento... passi fondamentali per la ricerca di nuova Fisica!

- Oltre 2 miliardi di dollari di investimento

- 1055 users, 216 istituzioni (PG rappresentata da me, Sergio Scopetta e Sara Fucini)



- La partecipazione italiana è la più consistente in Europa. Inoltre,
  l' EIC è considerato un esempio di iniziativa extra-Europea supportata anche dal CERN.

- L'EIC è il luogo naturale dove si faranno esperimenti che riguardano la linea di ricerca del gruppo teorico nucleare di Perugia. In quest'ultimo periodo sono aumentati notevolmente inviti e richieste di calcoli. È il momento per proporre misure. Il nostro gruppo è coinvolto nella stesura dello "Yellow report" dove si raccolgono queste idee! DOBBIAMO CONTINUARE A LAVORARE IN QUESTA DIREZIONE e ci sono molti temi caldi da studiare!

2

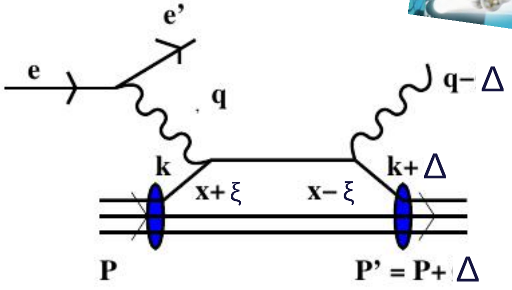
LE GPDs DI NUCLEONI E NUCLEI LEGERI

Lavori ed articoli prodotti:

- Tesi di laurea magistrale
- **M. R. and S. Scopetta, PRC 87 (2013) no.3, 035208**
- **M. R. and S. Scopetta, PRC 85 (2012) no.3, 062201**
- **M. R., PLB 771 (2017), 563-567**

GPDs definizione e proprietà

For a $J = \frac{1}{2}$ target, in a hard-exclusive process, ($Q^2, \nu \to \infty$, Q^2/ν *finite*) such as DVCS:



- * $\Delta = P' - P$, $q^\mu = (q_0, \vec{q})$, and $\bar{P} = (P + P')^\mu/2$
- * $x = k^+/P^+$; ξ = "skewness" = $-\Delta^+/(2\bar{P}^+)$

GPDs $H_q(x, \xi, \Delta^2)$ and $E_q(x, \xi, \Delta^2)$ are introduced:

$$F^{\mu,q}_{H',H}(x, \Delta^2, \xi) = \int \frac{dz^-}{2\pi} e^{ixz^- P^+} \langle P'H'|\bar{\psi}_q\left(-\frac{z}{2}\right)\gamma^\mu \psi_q\left(\frac{z}{2}\right)|PH\rangle|_{z^+=z_\perp=0} =$$

$$= \frac{1}{2P^+}\left[H^q(x, \Delta^2, \xi)\bar{U}'\gamma^\mu U + E^q(x, \Delta^2, \xi)\bar{U}'\frac{i\sigma^{\mu\nu}\Delta_\nu}{2M}U\right] + \ldots$$

- $P' = P$, i.e., $\Delta^2 = \xi = 0$, one recovers the usual PDFs: $H^q(x, 0, 0) = q(x)$; $E^q(x, 0, 0)$ *unknown*
- the x–integration yields Form Factors (F.F.) $\int dx\, \tilde{G}^q_M(x, \Delta^2, \xi) = G^q_M(\Delta^2)$ where here: $\tilde{G}^q_M = H^q + E^q$

Ji Sum Rule

$$\langle J^z_{q,g}\rangle = \frac{1}{2}\int_{-1}^{1} dx\, x[H^{q,g}(x, 0, 0) + E^{q,g}(x, 0, 0)]$$

$\Longrightarrow$ Access to *OAM*

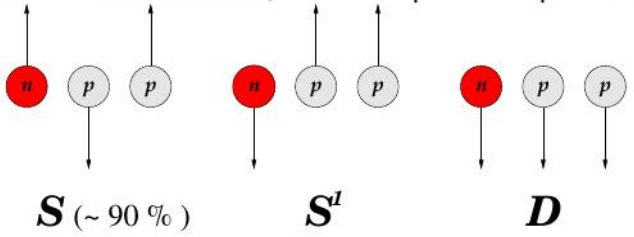
GPDs Nucleari: ^{3}He

Nuclear targets are crucial to obtain:

- *the nuclear short range structure, at quark level* , can be accessed and the reaction mechanism of DIS off nuclei, e.g. the validity of I.A. and the relevance of effects beyond it (non nucleonic degrees of freedom, nucleon modifications...) can be investigated... origin of the EMC effect...;
- information on the Neutron.

To this aim ^{3}He is an ideal nucleus (**and we are proposing an experiment at JLab**):

- ^{3}He is theoretically well known. Even a relativistic treatment may be implemented;
- ^{3}He has been used extensively as an effective neutron target, especially to unveil the spin content of the free neutron, due to its peculiar spin structure



In $S-$wave
$^3\vec{He} = \vec{n}$!

To what extent for OAM and $\tilde{G}^q_M$? The answer here.

- To this aim, ^{3}He is a unique target:
  - **^{2}H has a very small GPD E_q, crucial to access OAM;**
  - **^{4}He is scalar and has no E_q GPD;**
  - **heavier targets do not allow refined theoretical treatments.**

GPDs Nucleari: ^{3}He

coherent DVCS in I.A.
(^{3}He does not break-up $\Delta^2 \ll M^2, \xi^2 \ll 1,$):

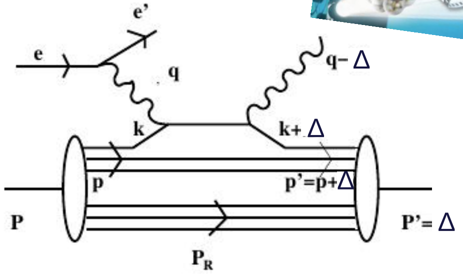
In a symmetric frame $\overline{P} = (P' + P)/2, \; a^{\pm} = a^0 \pm a^3$

$$k^+ = (x + \xi)\overline{P} = (x' + \xi')\overline{p}, \quad \xi' = -\frac{\Delta^+}{2\overline{p}}$$

$$k'^+ = (x - \xi)\overline{P} = (x' - \xi')\overline{p}, \quad x' = \frac{\xi'}{\xi}x$$

Impulse Approximation

- * the nucleus, A, is described by $A - 1$ interacting nucleons and an off-shell free nucleon, a kinematical condition;
- * the virtual photon interacts only with the off-shell nucleon;



$$F^{3,q,\mu}_{S,S'}(x,\Delta^2,\xi) = \int \frac{dz^-}{4\pi} e^{ix\bar{P}^+ z^-} {}_3\langle P'S' \sum\!\!\!\!\!\!\int_{\beta} |\alpha_\beta\rangle\langle\alpha_\beta|\hat{O}^\mu_q \sum\!\!\!\!\!\!\int_{\beta'} |\alpha'_{\beta'}\rangle\langle\alpha'_{\beta'}||PS\rangle_3|_{z^+=0,z_\perp=0} \,.$$

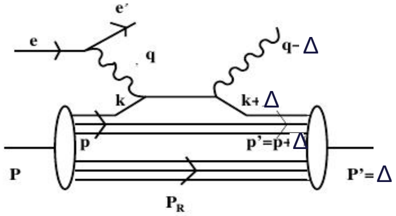
where here: $|\alpha_\beta\rangle = |\vec{P}_R\, S_R\rangle|\vec{t}\, s_t\rangle|\vec{p}\, s\rangle \Rightarrow \beta = \vec{P}_R, S_R, \vec{t}, s_t, \vec{p}, s$

2-body state in CM | 2-body intrinsic state | Nucleon state

$$\langle \vec{P}_R S_R|\langle \vec{t} s_t|\langle \vec{p}\, s|\vec{P} S\rangle = \langle \vec{p}\, s, \vec{t}\, s_t|\vec{P} S\rangle (2\pi)^3 \delta^3(\vec{P} - \vec{P}_R - \vec{p})\delta_{S,S_R,s,s_t}$$

$$\hat{O}^\mu_q = \overline{\Psi}_q(0, -\frac{z^-}{2}, 0)\gamma^\mu \Psi_q(0, \frac{z^-}{2}, 0)$$ "One body operator acting on the nucleon state"

GPDs Nucleari: ³He



H_q^A, with the correct behavior, can be obtained in terms of H_q^N:

$$H_q^A(x,\xi,\Delta^2) = \sum_N \int dE \int d\vec{p} \overline{\sum_S} \sum_s P^N_{SS,ss}(\vec{p},\vec{p}\,',E) \frac{\xi'}{\xi} H_q^N(x',\Delta^2,\xi')$$

Nucleonic input: GPDs

Radyushkin PRD 61, 074027 (2000)

and $\tilde{G}_M^{3,q}$ in terms of $\tilde{G}_M^{N,q}$ (**M. R, S.Scopetta PRC 85, 062201(R) (2012)**):

$$\tilde{G}_M^{3,q}(x,\Delta^2,\xi) = \sum_N \int dE \int d\vec{p} \left[P^N_{+-,+-} - P^N_{+-,-+}\right](\vec{p},\vec{p}\,',E) \frac{\xi'}{\xi} \tilde{G}_M^{N,q}(x',\Delta^2,\xi'),$$

where $P^N_{SS,ss}(\vec{p},\vec{p}\,',E)$ is the one-body, spin-dependent, off-diagonal spectral function for the nucleon N in the nucleus,

$$P^N_{SS',ss'}(\vec{p},\vec{p}\,',E) = \frac{M\sqrt{ME}}{2(2\pi)^6} \int d\Omega_t \sum_{s_t} \langle \vec{P}'S'|\vec{p}\,'s',\vec{t}s_t\rangle^N \langle \vec{p}s,\vec{t}s_t|\vec{P}S\rangle^N$$

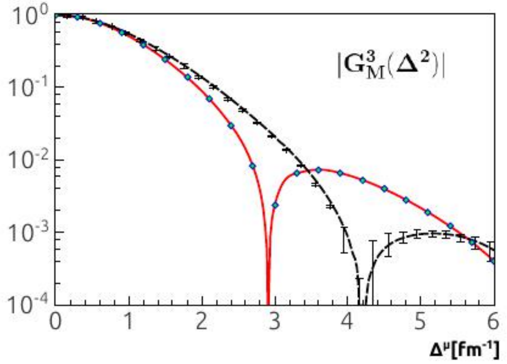
Nuclear input: Overlap

A. Kievsky *et. al*, PRC 56, 64 (1997)

For $\tilde{G}_M^{3,q}$ the only possibile check is the magnetic F.F.:

$\sum_q \int dx \tilde{G}_M^{3,q}(x,\Delta^2,\xi) = G_M^3(\Delta^2)$; $\Delta^\mu = \sqrt{-\Delta^2}$

- ∗ in perfect agreement with previous IA, Av18 calculations (**L.E. Marcucci et al. PRC 58 (1998)**)
- ∗ in good agreement with data in the region relevant to the coherent process, $-\Delta^2 \ll 0.15$ GeV^2
- ∗ To have agreement at higher Δ^2, effects beyond IA are necessary: not important for the coherent channel!

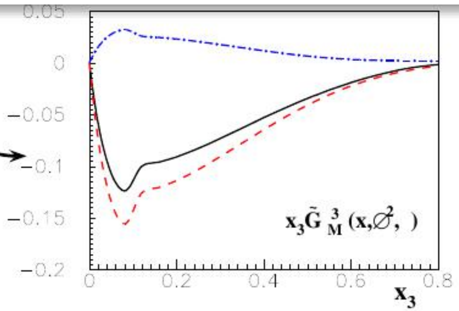


GPDs Nucleari: ^{3}He

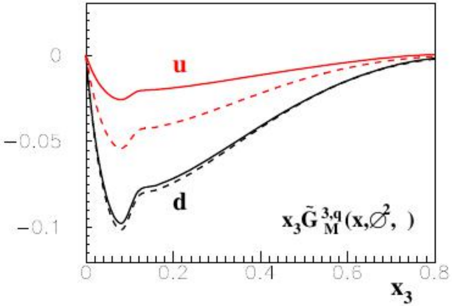
Results of numerical evaluation of GPDs show that in the forward limit the neutron contribution largely dominates ^{3}He and the proton one is almost negligible.
(**M. R, S.Scopetta PRC 85, 062201(R) (2012)**)

Beyond the forward limit, as shown: $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$

The neutron contribution to ^{3}He still dominates
The proton contribution to ^{3}He gets sizable



It is theoretically possible to separate the flavor contributions in the same case:
For the u flavor, the neutron contribution (dashed) to ^{3}He (full) is less important than for the d flavor:



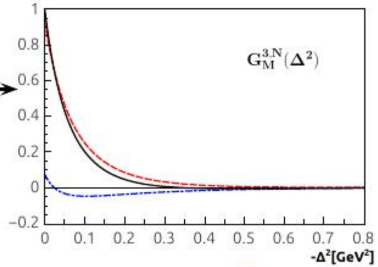
Understandable, sketching the formula:

$$\tilde{G}_M^{3,q} \approx P_p^3 \otimes \tilde{G}_M^{p,q} + P_n^3 \otimes \tilde{G}_M^{n,q} \,,$$

where $P^3_{p(n)}$ describes the proton (neutron) dynamics in ^{3}He.

As already explained, due to the spin structure of ^{3}He,
$P_n^3 >> P_p^3 \longrightarrow$ neutron dominates in the forward limit.

For this purpose it is useful to show the proton and the neutron contribution to the ^{3}He F.F.



With increasing Δ^2, for the u flavor,
$\tilde{G}_M^{p,u} >> \tilde{G}_M^{n,u} \longrightarrow$ the proton contribution grows.

Not for d! Besides, 1/2 of the d content of ^{3}He comes from the neutron, only 1/5 of the u one comes from it.

GPDs Nucleari: ^{3}He

The convolution formula can be written as

$$\tilde{G}_M^{3,q}(x,\Delta^2,\xi) = \sum_N \int_{x_3}^{\frac{M_A}{M}} \frac{dz}{z} g_N^3(z,\Delta^2,\xi) \tilde{G}_M^{N,q}\left(\frac{x}{z},\Delta^2,\frac{\xi}{z}\right),$$

where $g_N^3(z,\Delta^2,\xi)$ is a "light cone off-forward momentum distribution":

$$g_N^3(z,\Delta^2,\xi) = \int dE \int d\vec{p}\, \tilde{P}_N^3(\vec{p},\vec{p}\,',E)\,\delta\left(z + \frac{M_A}{M}(\xi - p^+/\overline{P}^+)\right)$$

Where:

$$\tilde{P}_N^3(\vec{p},\vec{p}\,',E) = P^N_{+-,+-}(\vec{p},\vec{p}\,',E) - P^N_{+-,-+}(\vec{p},\vec{p}\,',E)$$

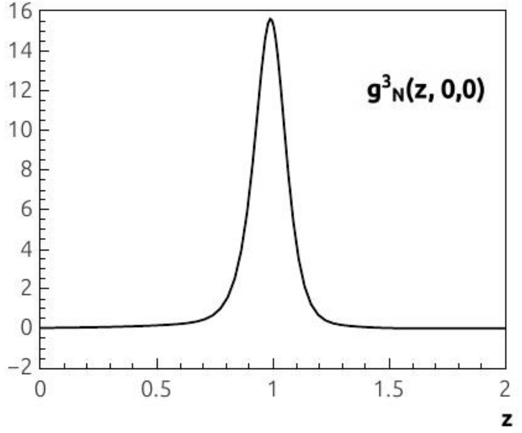
which, close to the forward limit, is strongly peaked around $z = 1$, so that:

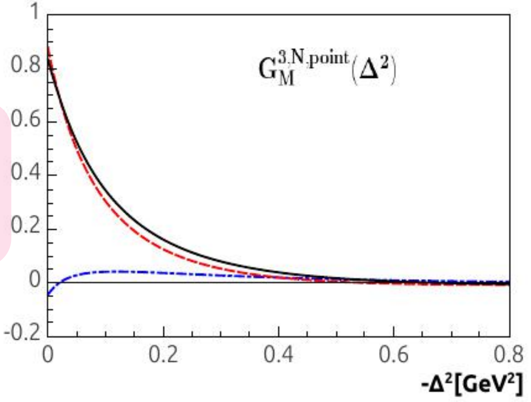
$$\tilde{G}_M^{3,q}(x,\Delta^2,\xi) \underset{low\ \Delta^2}{\simeq} \sum_N \tilde{G}_M^{N,q}(x,\Delta^2,\xi) \int_0^{\frac{M_A}{M}} dz\, g_N^3(z,\Delta^2,\xi)$$

$$= G_M^{3,p,point}(\Delta^2)\tilde{G}_M^p(x,\Delta^2,\xi) + G_M^{3,n,point}(\Delta^2)\tilde{G}_M^n(x,\Delta^2,\xi),$$

where the magnetic point like ff has been introduced

$$G_M^{3,N,point}(\Delta^2) = \int dE \int d\vec{p}\, \tilde{P}_N^3(\vec{p},\vec{p}+\vec{\Delta},E) = \int_0^{\frac{M_A}{M}} dz\, g_N^3(z,\Delta^2,\xi).$$





GPDs Nucleari: ^{3}He

The Validity of the approximated formula:

full: IA calculation, $G_M^3(x, \Delta^2, \xi)$ and proton and neutron contributions to it,

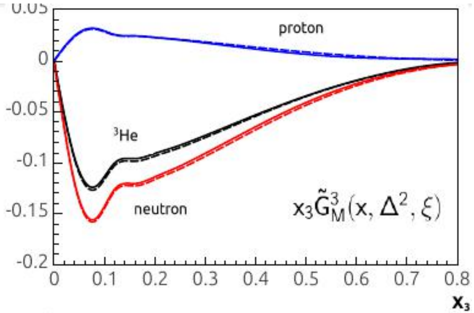
at $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$;

dashed: same quantities, with the approximated formula:

$$\tilde{G}_M^{3,q}(x, \Delta^2, \xi) \simeq G_M^{3,p,point}(\Delta^2)\tilde{G}_M^p(x, \Delta^2, \xi) + G_M^{3,n,point}(\Delta^2)\tilde{G}_M^n(x, \Delta^2, \xi)$$

Impressive agreement!

The only Nuclear Physics ingredient in the approximated formula is the magnetic point like ff, which is under good theoretical control.



The approximated relation can now be solved to extract the neutron contribution:

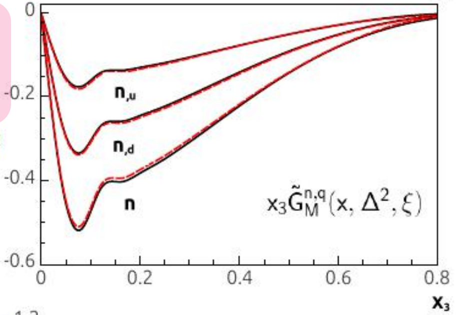
$$\tilde{G}_M^{n,extr}(x, \Delta^2, \xi) \simeq \frac{1}{G_M^{3,n,point}(\Delta^2)} \left\{ \tilde{G}_M^3(x, \Delta^2, \xi) - G_M^{3,p,point}(\Delta^2)\tilde{G}_M^p(x, \Delta^2, \xi) \right\}$$

from data for $\tilde{G}_M^3(x, \Delta^2, \xi)$ and $\tilde{G}_M^p(x, \Delta^2, \xi)$, using as theoretical ingredients the magnetic point

full : the neutron model for $\tilde{G}_M^n(x, \Delta^2, \xi)$ and the different flavor contributions to it;

dashed: the neutron extracted using the IA calculation for $\tilde{G}_M^3(x, \Delta^2, \xi)$

and the model used in it for $\tilde{G}_M^p(x, \Delta^2, \xi)$ together with the magnetic point like ffs.

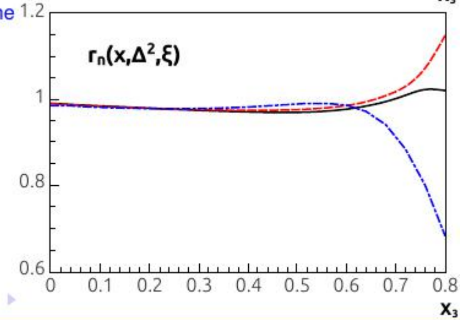


The validity of the extraction procedure is emphasized showing the following ratio, which would be one if the procedure were perfect:

$$r_n(x, \Delta^2, \xi) = \frac{\tilde{G}_M^{n,extr}(x, \Delta^2, \xi)}{\tilde{G}_M^n(x, \Delta^2, \xi)}$$

full: forward limit; dashed: $\Delta^2 = -0.1$ GeV^2, $\xi = 0$; dot-dashed: $\Delta^2 = -0.1$ GeV^2, $\xi = 0.1$.

at $x_3 < 0.7$, in all the kinematical range relevant for coherent DVCS at JLab, the error in the extraction is a few percents.



3

LE dPDFs DI PROTONI E MESONI

Lavori ed articoli prodotti:

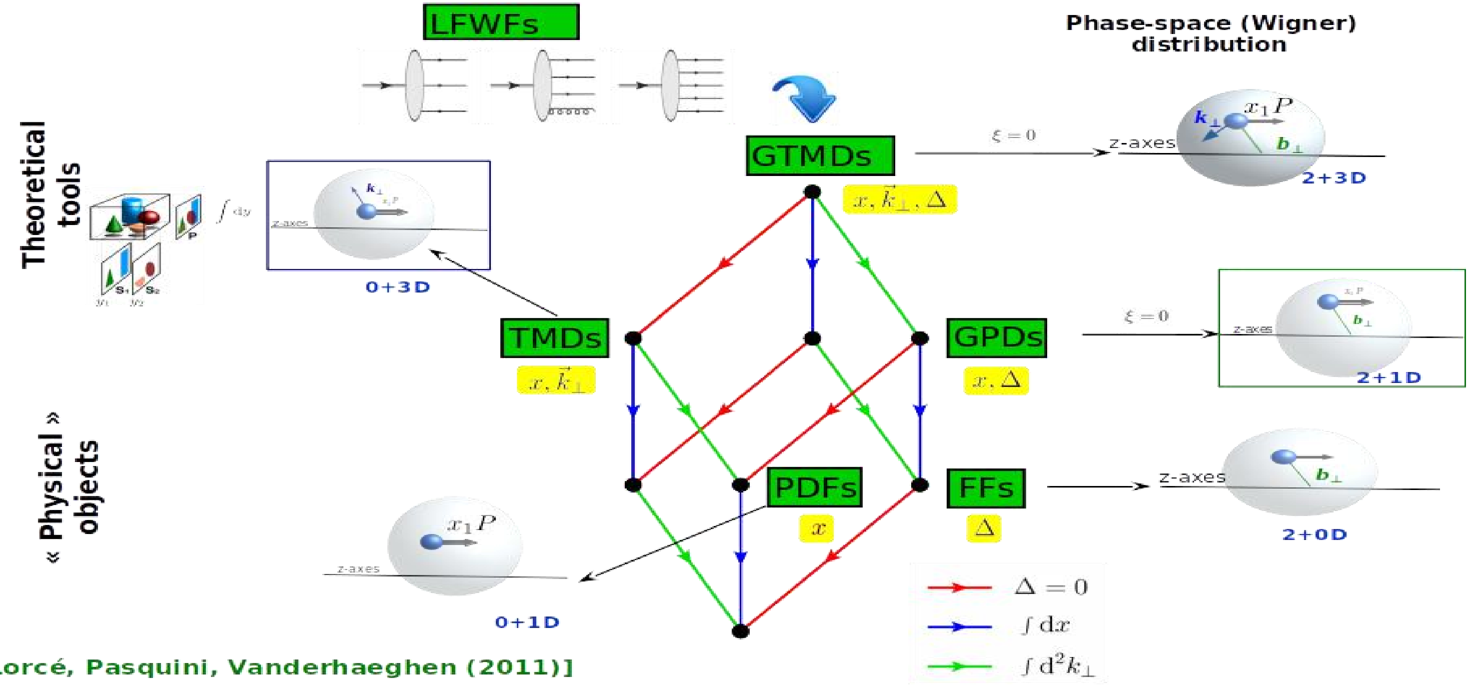
- M. R., S. Scopetta and V. Vento, PRD 87 (2013) 114021
- M. R., S. Scopetta, M. Traini and V. Vento, JHEP 12 (2014) 028
- M. R., S. Scopetta, M. Traini and V. Vento, JHEP 10 (2016) 063
- F. A. Ceccopieri, M. R. and S. Scopetta, PRD 95 (2017), no.11, 114030
- M. R., S. Scopetta, M. Traini and V. Vento, PLB 752 (2016), 40-45
- M. Traini, M. R., S. Scopetta and V. Vento, PLB 768 (2017), 270-273
- M. R., F. A. Ceccopieri, PRD 95 (2017), no.3, 034040
- M. R., F. A. Ceccopieri, PRD 97 (2018), no.7, 071501
- M. R., S. Scopetta, M. Traini and V. Vento, EPJC 78 (2018), no.9, 781
- M. R., F. A. Ceccopieri, JHEP 09 (2019) 097
- M. R., arXiv:2003.09400, sottomesso a EPJC, richieste correzioni minori

Voglio menzionare che l'interesse per questo argomento è nato grazie alla collaborazione con CMS, rappresentato a Perugia dal professore Livio Fanò, del Dipartimento di Fisica e Gelogia, Università degli Studi di Perugia.

Grazie a questa collaborazione il sottoscritto è entrato nella comunità che studia le Multi Parton Interactions, facendo anche parte dei conveners di un Workshop tenutosi a Perugia nel 2018.

Double Parton Distribution Functions

The 3D structure of a strongly interacting system (e.g. nucleon, nucleus..) could be accessed through different processes (e.g. SIDIS, DVCS ...), measuring different kind of parton distributions, providing different kind of information. The parton distribution puzzle is:



[Lorcé, Pasquini, Vanderhaeghen (2011)]

Double Parton Distribution Functions

The 3D structure of a strongly interacting system (e.g. nucleon, nucleus..) could be accessed through different processes (e.g. SIDIS, DVCS ...), measuring different kind of parton distributions, providing different kind of information. The parton distribution puzzle is:

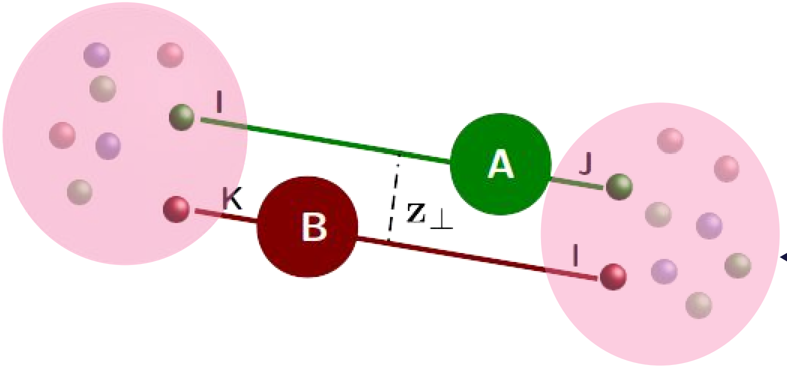
All these distributions are ONE-BODY functions!

How can we access new information as two particle correlations?

[Lorcé, Pasquini, Vanderhaeghen (2011)]

Risposta: Multi Parton Interactions

Multiparton interaction (MPI) can contribute to the, pp and pA, cross section @ the LHC:



The cross section for a double parton scattering (DPS) event can be written in the following way:

N. Paver, D. Treleani, Nuovo Cimento 70A, 215 (1982)

dPDF

Momentum scales

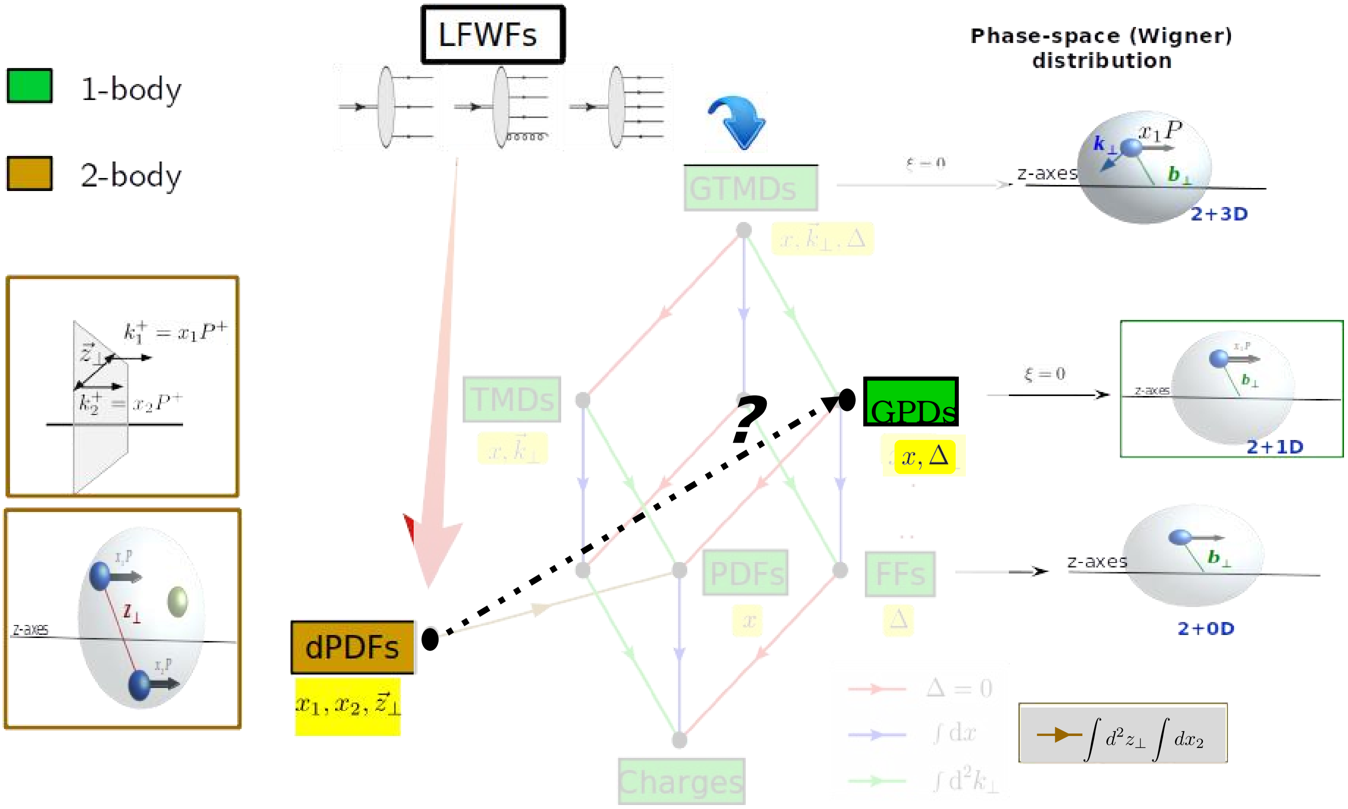
$$d\sigma = \frac{1}{S} \sum_{i,j,k,l} \hat{\sigma}_{ij}(x_1, x_3, \mu_A)\hat{\sigma}_{kl}(x_2, x_4, \mu_B) \int d^2 z_\perp F_{ik}(x_1, x_2, z_\perp, \mu_A, \mu_B) F_{jl}(x_3, x_4, z_\perp, \mu_A, \mu_B)$$

Momentum fractions carried by the parton inside the proton

Transverse distance between partons

DPS processes are important for fundamental studies, e.g. the background for the research of new physics and to grasp information on the 3D PARTONIC STRUCTURE OF THE PROTON

Double Parton Distribution Functions



Double Parton Distribution Functions

@ LHC kinematics it is often used a factorized form of the dPDFs: $(\mathbf{x_1}, \mathbf{x_2}) - \mathbf{z}_\perp$ factorization:

* Here and in the following: $\mu = \mu_A = \mu_B$

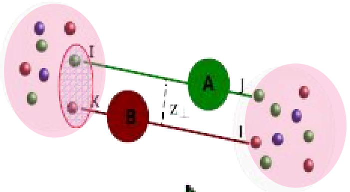
$$F_{ij}(x_1, x_2, \vec{z}_\perp, \mu) = F_{ij}(x_1, x_2, \mu) T(\vec{z}_\perp, \mu)$$

and x_1, x_2 factorization:

$$\underbrace{F_{ij}(x_1, x_2, \mu)}_{\text{dPDF (2-Body), unknown}} = \underbrace{q_i(x_1, \mu)}_{\text{PDF (1-Body)}} \; q_j(x_2, \mu) \, \theta(1 - x_1 - x_2)(1 - x_1 - x_2)^n \quad f(x_1, x_2, \mu)$$

$f(x_1, x_2, \mu)$ → To fulfill sum rules

NO DYNAMICAL CORRELATIONS? →



In this scenario, dynamical parton correlations inside the proton are neglected → NO NEW INFORMATION!

BUT:

- Correlations are present
- dPDFs are non perturbative in QCD and DPCs cannot be directly evaluated within QCD

HOW CAN WE BE SURE OF THE ACCURACY OF SUCH APPROXIMATION

WHAT CAN WE LEARN ABOUT dPDFs AND THE PROTON STRUCTURE?

Ingredienti del Calcolo

- **CONSTITUENT QUARK MODELS (CQMs)**
  - Effective potential and particles strongly bound and correlated
  - Predictions are related to low energy scales and valence region

- **RELATIVISTIC IMPLEMENTATION: LIGHT-FRONT APPROACH**

$$F_{ij}(x_1, x_2, k_\perp) = 3(\sqrt{3})^3 \int \prod_{i=1}^{3} d\tilde{k}_i \delta\left(\sum_{i=1}^{3} \tilde{k}_i\right) \Phi^*(\{\tilde{k}_i\}, k_\perp)\Phi(\{\tilde{k}_i\}, -k_\perp)\delta\left(x_1 - \frac{k_1^+}{M_0}\right)\delta\left(x_2 - \frac{k_2^+}{M_0}\right)$$

Conjugate to $z_\perp$

LF wave function
(we need a CQMs)

GOOD SUPPORT

$$M_0^2 = \sum_{i=1}^{3} \frac{m_i^2 + \tilde{k}_{i\perp}^2}{x_i}$$

Free proton mass

- **pQCD EVOLUTION OF dPDFs**

i) dPDF evaluated at the initial scale of the model

→ **pQCD evolution of dPDFs** →

ii) dPDF evaluated at high generic scale. We can compare with experimental analyses.

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→ **GOOD SUPPORT**

Conjugate to $Z_\perp$

LF wave function (we need a CQMs)

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Free proton mass

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→ **GOOD SUPPORT**

Conjugate to $z_\perp$ ($k_\perp$)

LF wave function (we need a CQMs) (Φ)

$$M_0^2 = \sum_{i=1}^{3} \frac{m_i^2 + \tilde{k}_{i\perp}^2}{x_i}$$

Free proton mass

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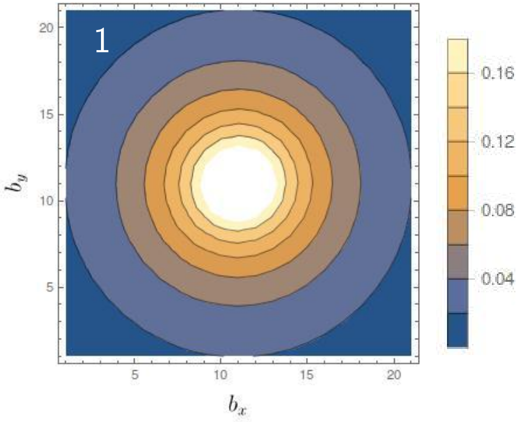
COSA POSSIAMO OTTENERE: LA DISTANZA MEDIA TRA DUE PARTONI

M. R. and F. A. Ceccopieri, JHEP 1909 (2019) 097

Since, in coordinates space, dPDFs get a number density interpretation, in principle one can calculated the mean distance between partons!

For example, for 2 gluons perturbatively generated:

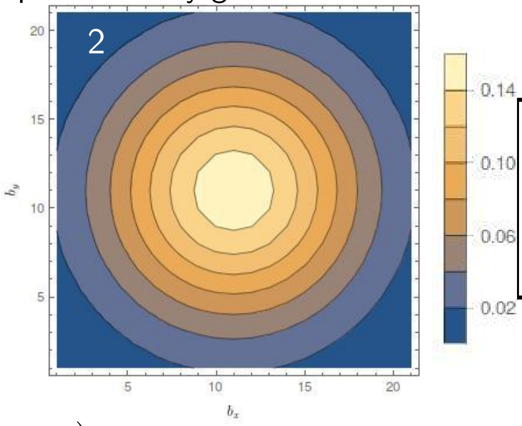


1) HP model

2) HO model

$x_1 = 10^{-4}$ and $x_2 = 10^{-2}$

$$\vec{d}_\perp = \vec{b}_\perp = \vec{z}_\perp$$



M. Traini *et al*, Nucl. Phys. A 656, 400-420 (1999), non relativistic Hyper-Central CQM (potential by M. Ferraris *et al*, PLB 364 (1995)) (HP)

The harmonic oscillator (HO)

One can also define the mean transverse distance $(x_1 - x_2)$ distribution as follows:

$$\langle d_\perp^2 \rangle^{ij}_{x_1,x_2} = \frac{\int d^2b_\perp \; b_\perp^2 F_{ij}(x_1, x_2, b_\perp, Q^2 = M_W^2)}{\int d^2b_\perp \; F_{ij}(x_1, x_2, b_\perp, Q^2 = M_W^2)}$$

For example, for 2 gluons and two different models, one gets:

$$\sqrt{\langle d_\perp^2 \rangle_{10^{-2},10^{-2}}} = \begin{cases} 0.404 \text{ fm} & \text{HP} \\ 0.365 \text{ fm} & \text{HO} \end{cases}$$

$$\sqrt{\langle d_\perp^2 \rangle_{10^{-4},10^{-4}}} = \begin{cases} 0.391 \text{ fm} & \text{HP} \\ 0.393 \text{ fm} & \text{HO} \end{cases}$$

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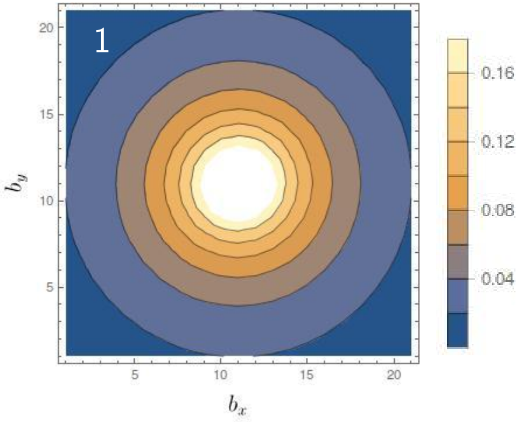

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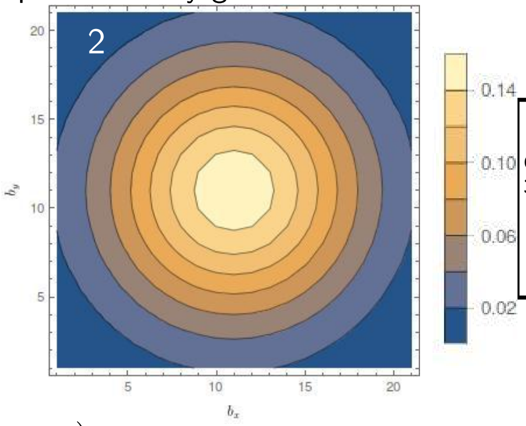

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Are two slow partons closer (in $\perp$ plane) then two fast partons?

COSA OTTENUTO: EFFETTI DELLE CORRELAZIONI

M. R. and F. A. Ceccopieri, JHEP 1909 (2019) 097

The dPDF is formally defined through the Light-cone correlator:

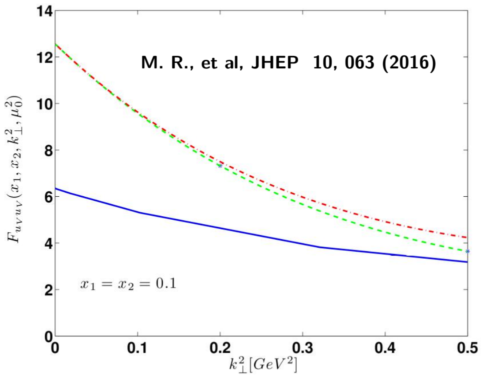
$$F_{12}(x_1,x_2,\vec{z}_\perp) \propto \sum_X \int dz^- \left[\prod_{i=1}^{2} dl_i^- e^{i x_i l_i^- p^+}\right] \langle p|O(z,l_1)|X\rangle\langle X|O(0,l_2)|p\rangle \Big|_{l_1^+=l_2^+=z^+=0}^{\vec{l}_{1\perp}=\vec{l}_{2\perp}=0}$$

Approximated by the proton state!

$$\int \frac{dp'^+ d\vec{p}'_\perp}{p'^+} |p'\rangle\langle p'|$$

GPDs

$$F_{12}(x_1,x_2,\vec{k}_\perp) \sim f(x_1,0,\vec{k}_\perp) f(x_2,0,\vec{k}_\perp)$$



dPDF = GPD x GPD

dPDF

Violation due to:

- Correlation between (x_1, x_2)
  - M. R., et al, PRD 87, 114021 (2013)
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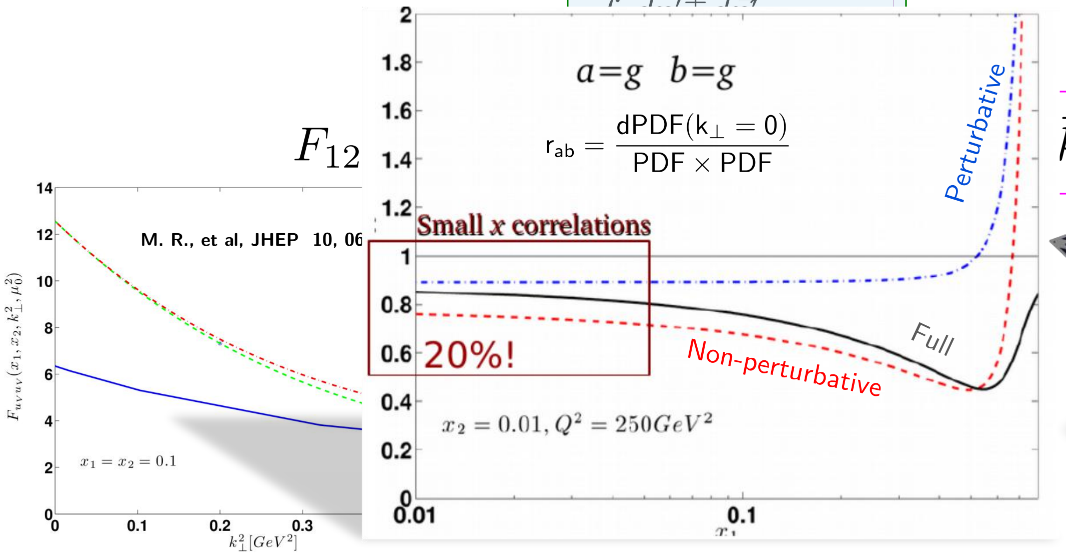

F_{12} … $\vec{k}_\perp)$

GPDs

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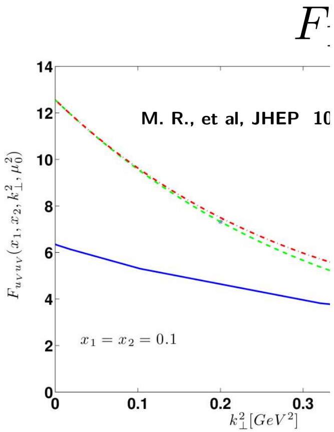
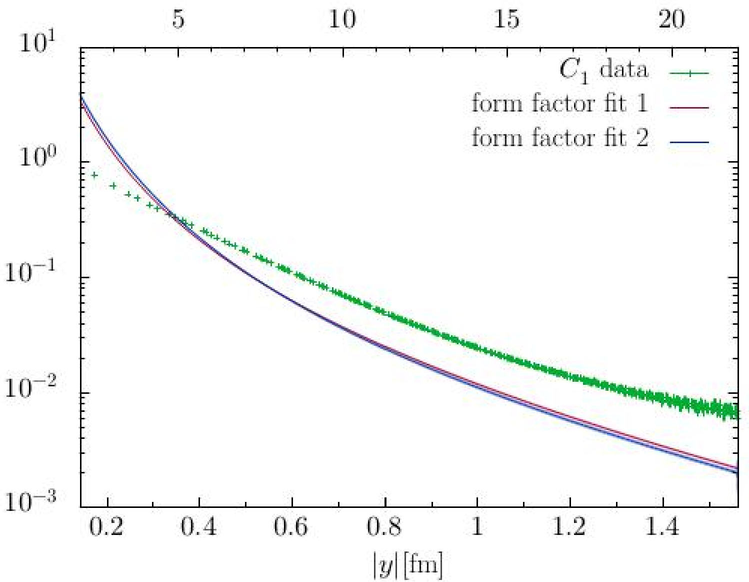
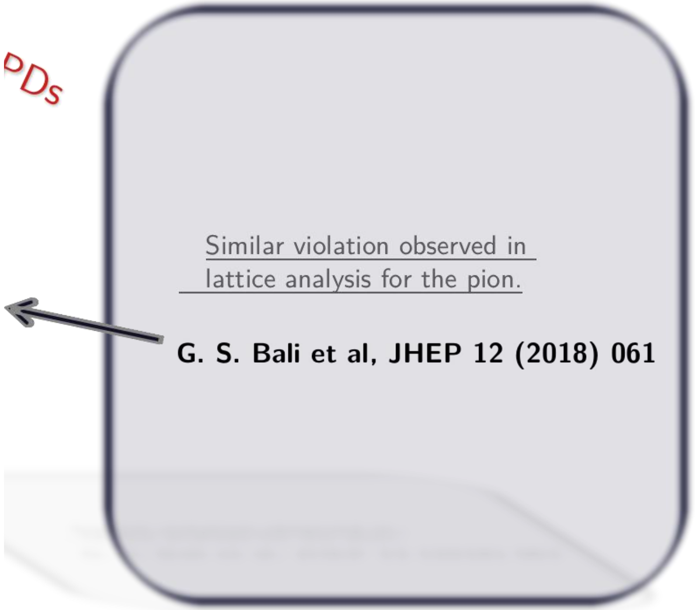






LA SEZIONE D'URTO EFFICACE

A fundamental tool for the comprehension of the role of DPS in hadron-hadron collisions is the so called "effective X-section".

This object can be defined through a "pocket formula":

$$\sigma_{eff} = \frac{m}{2} \frac{\sigma_A^{pp'} \sigma_B^{pp'}}{\sigma_{double}^{pp}}$$

Sensitive to correlations

Combinatorial factor

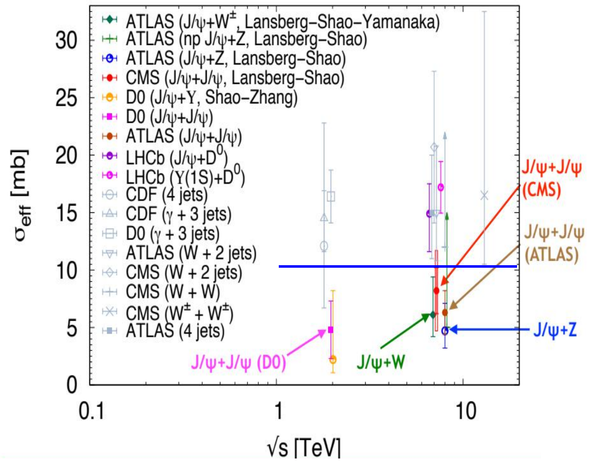
Differential cross section for the process: $\mathrm{pp'} \to A(B) + X$

Differential cross section for a DPS event: $\mathrm{pp'} \to A + B + X$

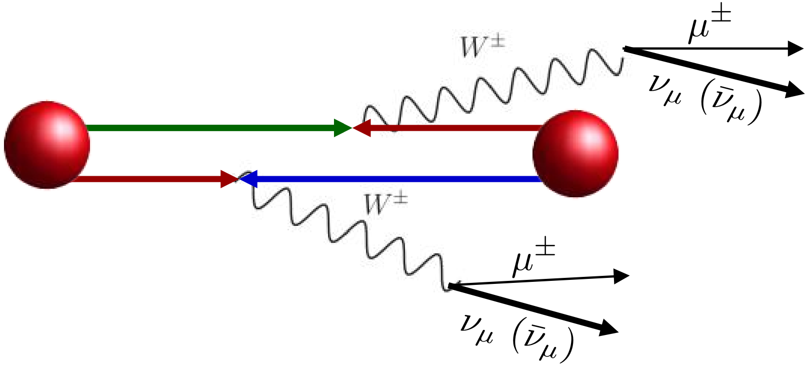
….EXPERIMENTAL STATUS:

- Difficult extraction, approved analysis for the same
- the model dependent extraction of σ_{eff} from data is almost consistent with a "constant" (within errors) (uncorrelated ansatz usually assumed!)…Some inconistencies in production
- different ranges in x_i accessed in different experiments.

Within our CQM framework, we can calculate $\sigma_{\mathbf{eff}}$ without any approximations!



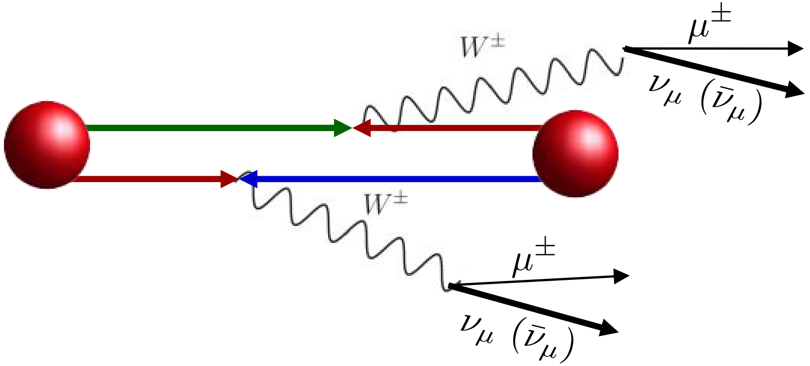
PRODUZIONE DI DUE MESONI W DELLO STESSCO SEGNO AD LHC



In this channel, the single parton scattering (usually dominant w.r.t to the double one) starts to contribute to higher order in strong coupling constant.

"Same-sign W boson pairs production is a promising channel to look for signature of double Parton interactions at the LHC."

PRODUZIONE DI DUE MESONI W DELLO STESSCO SEGNO AD LHC



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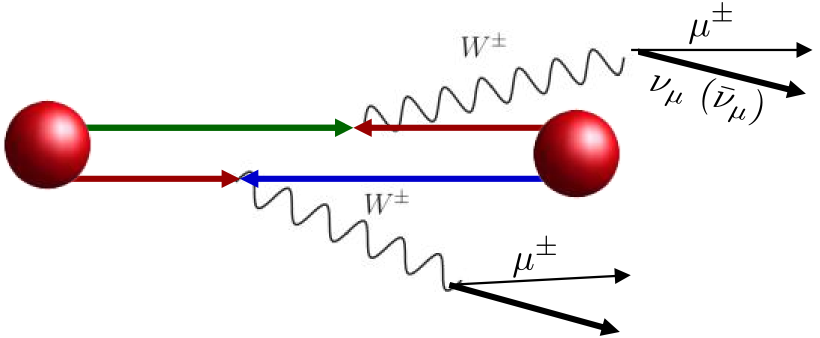
Can double parton correlations be observed for the first time in the next LHC run ?

PRODUZIONE DI DUE MESONI W DELLO STESSCO SEGNO AD LHC



Kinematical cuts

$pp,\ \sqrt{s} = 13$ TeV
$p_{T,\mu}^{leading} > 20$ GeV, $p_{T,\mu}^{subleading} > 10$ GeV
$\lvert p_{T,\mu}^{leading}\rvert + \lvert p_{T,\mu}^{subleading}\rvert > 45$ GeV
$\lvert\eta_\mu\rvert < 2.4$
20 GeV $< M_{inv} <$ 75 GeV or $M_{inv} >$ 105 GeV

DPS cross section:

$$\frac{d^4\sigma^{pp\to\mu^\pm\mu^\pm X}}{d\eta_1 dp_{T,1} d\eta_2 dp_{T,2}} = \sum_{i,k,j,l} \frac{1}{2} \int d^2\vec{b}_\perp F_{ij}(x_1, x_2, \vec{b}_\perp, M_W) F_{kl}(x_3, x_4, \vec{b}_\perp, M_W) \frac{d^2\sigma_{ik}^{pp\to\mu^\pm X}}{d\eta_1 dp_{T,1}} \frac{d^2\sigma_{jl}^{pp\to\mu^\pm X}}{d\eta_2 dp_{T,2}} \mathcal{I}(\eta_i, p_{T,i})$$

M_W ⟶ Momentum scale

In order to estimate the role of double parton correlations we have used as input of dPDFs:

1) Longitudinal and transverse correlations arise from the relativistic CQM model describing three valence quarks

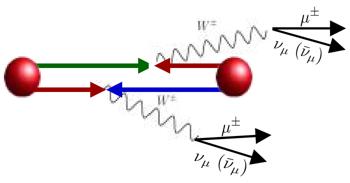
2) These correlations propagate to sea quarks and gluons through pQCD evolution

PRODUZIONE DI DUE MESONI W DELLO STESSCO SEGNO AD LHC

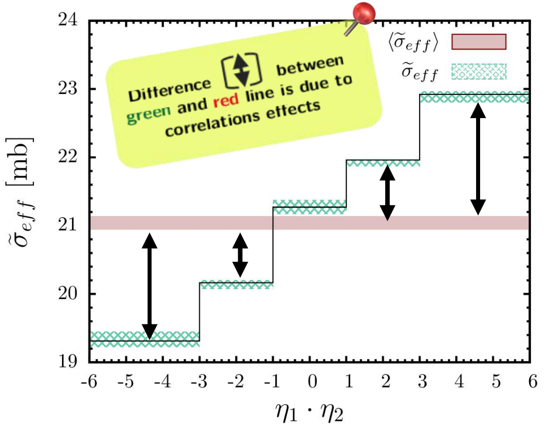
In order to understand whether correlations can be accessed in experimental observations, using dPDF evaluated within the QM model, the effective cross section has been calculated for this process and compared with its mean value:

$$\langle \tilde{\sigma}_{eff} \rangle = 21.04\ ^{+0.07}_{-0.07}\,(\delta Q_0)\ ^{+0.06}_{-0.07}(\delta \mu_F)\ \text{mb}\ .$$

$$\tilde{\sigma}_{eff} = \frac{m}{2} \frac{\sigma_A^{pp'}\ \sigma_B^{pp'}}{\sigma_{double}^{pp}}$$



$$\eta_1 \cdot \eta_2 \simeq \frac{1}{4} ln\frac{x_1}{x_3} ln\frac{x_2}{x_4}$$



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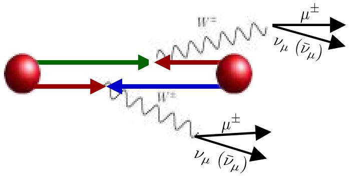

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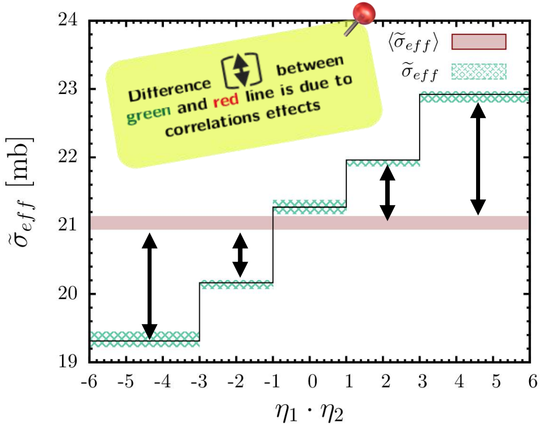

x- dependence of effective x-section consistent with analyses:

M.Rinaldi et al PLB 752,40 (2016)

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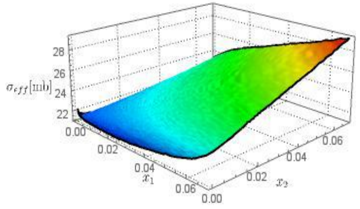
M.R. and F. A. Ceccopieri JHEP 1909 (2019) 097



Gluons ⊗ Gluons

"Assuming that the results of the first and the last bins can be distinguished if they differ by 1 sigma, we estimated that

$$\mathcal{L} = 1000\ \text{fb}^{-1}$$

is necessary to observe correlations"

PRODUZIONE DI DUE MESONI W DELLO STESSCO SEGNO AD LHC

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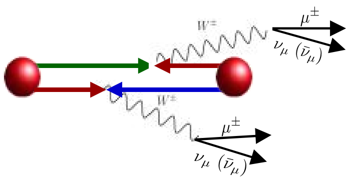

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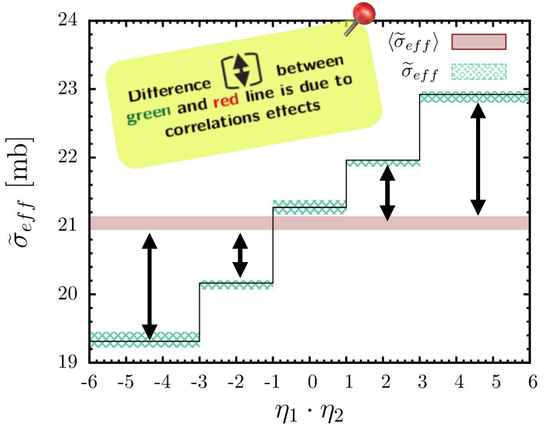

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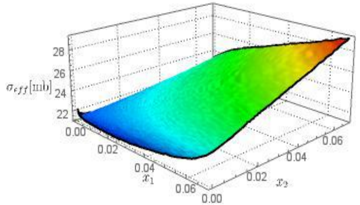

Gluons ⊗ Gluons

To observe correlations, $\mathcal{L} = 1000\ \text{fb}^{-1}$ is needed! ➡ REACHABLE IN THE PLANNED LHC RUN

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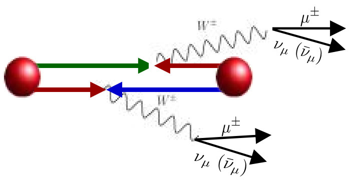

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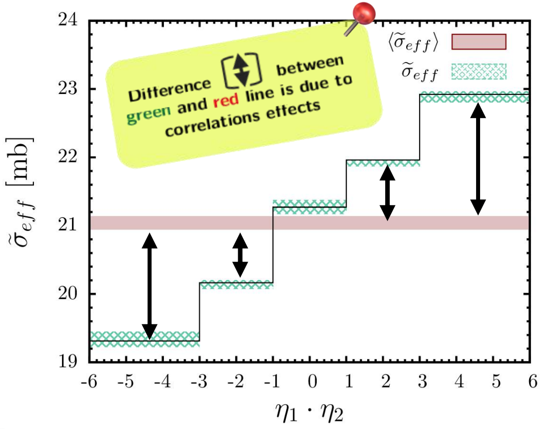

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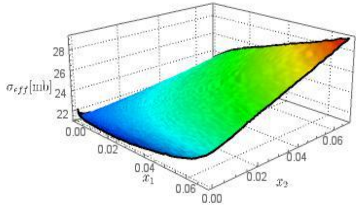

Gluons ⊗ Gluons

IN THIS CHANNEL, WE ESTABLISHED THE POSSIBILITY TO OBSERVE, FOR THE FIRST TIME, TWO-PARTON CORRELATIONS IN THE NEXT LHC RUN!

QUALCHE INDIZIO DAI DATI

Considering the factorization ansatz, for which some estimates of σ_{eff} are available, one has:

$$\sigma_{eff} = \left[\int \frac{d\vec{k}_\perp}{(2\pi)^2} \tilde{T}(\vec{k}_\perp) \tilde{T}(-\vec{k}_\perp) \right]^{-1}$$

$\tilde{T}(-\vec{k}_\perp)$ → Effective form factor (Eff)

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Effective form factor (Eff)

Eff can be formally defined as **FIRST MOMENT** of dPDF (like for GPDs) through the proton wave function:

$$\tilde{T}(k_\perp) = \frac{1}{2} \int dx_1 dx_2 F(x_1, x_2, k_\perp) = \int d\vec{k}_1 d\vec{k}_2 \Psi(\vec{k}_1 + \vec{k}_\perp, \vec{k}_2) \Psi^\dagger(\vec{k}_1, \vec{k}_2 + \vec{k}_\perp)$$

From the above quantity the mean distance in the transverse plane (<u>not necessary close to the proton radius</u>) between two partons can be defined:

$$\langle b^2 \rangle \sim -2 \frac{d}{k_\perp dk_\perp} \tilde{T}(k_\perp) \Big|_{k_\perp = 0}$$

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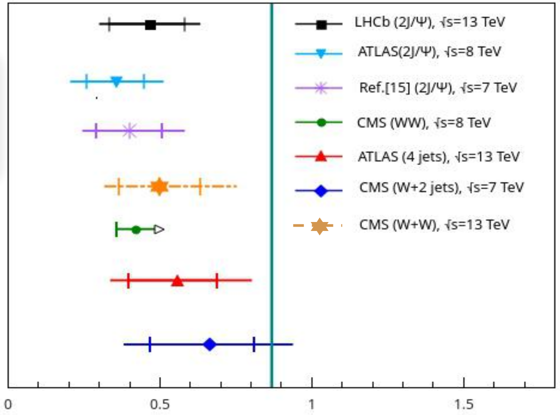
$$\frac{\sigma_{eff}}{3\pi} \leq \langle b^2 \rangle \leq \frac{\sigma_{eff}}{\pi}$$

DPS processes:

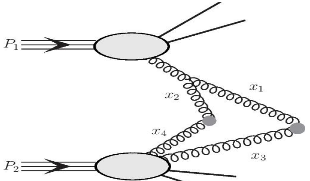


The vertical line stands for the transverse proton radius

We also:

M. R. and F. A. Ceccopieri, JHEP 1909 (2019) 097

- Extended the approach including splitting term



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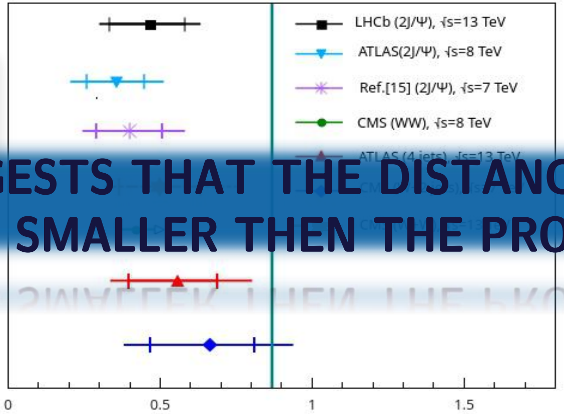

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DATA SUGGESTS THAT THE DISTANCE OF THESE PARTONS IS SMALLER THEN THE PROTON RADIUS

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M. R. and F. A. Ceccopieri, JHEP 1909 (2019) 097

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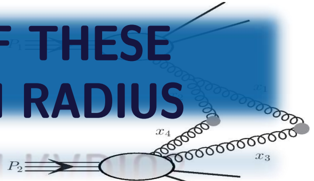

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Altri risultati ottenuti

- dPDFs of the pion within holographic models:
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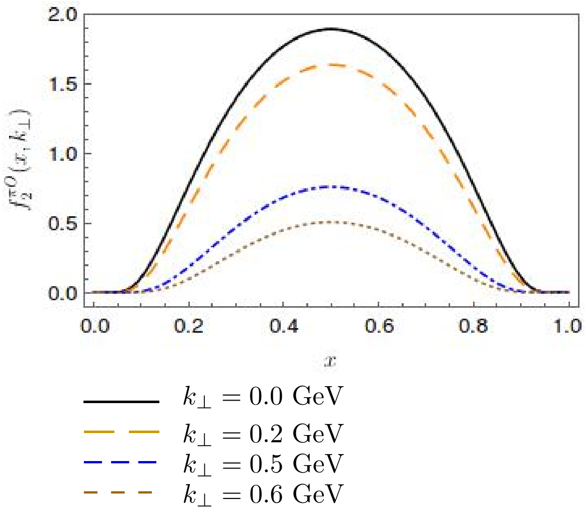
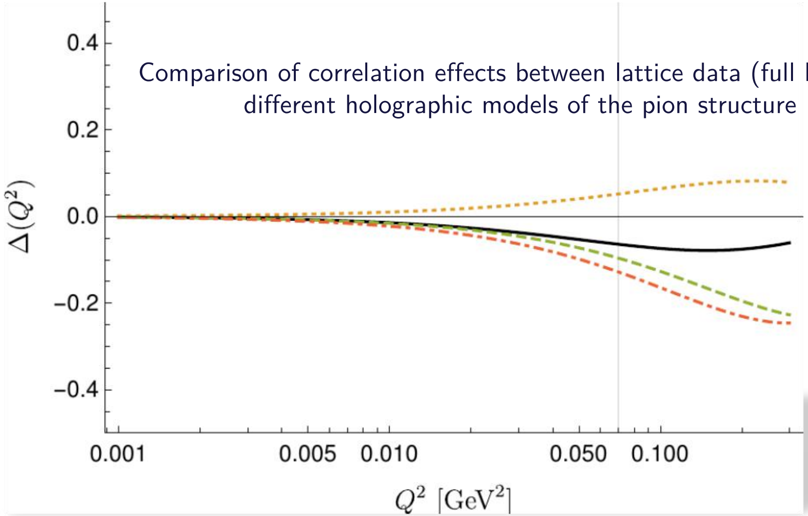


Pion: w.f. calculated within the AdS/QCD soft-wall model

S. J. Brodsky et al, PRD 77, 056007 (2008)



Comparison of correlation effects between lattice data (full line) and different holographic models of the pion structure

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- Relativistic effects in dPDFs calculations:
  - M. R. and F. A. Ceccopieri, PRD 95 (2017) 034040
  - M. R. and F. A. Ceccopieri, JHEP 09 (2019) 097

$$\overbrace{F_{ij}(x_1, x_2, k_\perp; Q^2)}^{\text{pheno}} = \underbrace{q_i(x_1; Q^2) q_j(x_2; Q^2)}_{\text{phenomenology from PDFs}} \overbrace{\theta(1 - x_1 - x_2)}^{\text{good support}} \underbrace{f(x_1, x_2, Q^2)}_{\text{sum rules}} \quad \overbrace{R(x_1, x_2, k_\perp)}^{\text{Melosh effects}} \underbrace{F(k_\perp)}_{}$$

correlations!

To be modeled:
CQMs, GPDs...

4

GLUEBALLS STUDIATE CON MODELI OLOGRAFICI

Lavori ed articoli prodotti:

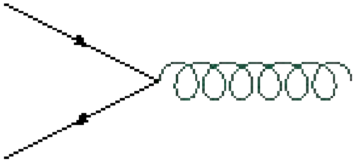
- M. R. and V. Vento, EPJA 54 (2018) 151
- M. R. and V. Vento, J. Phys. G 47 (2020) no.5, 055104
- M. R. and V. Vento, arXiv: 2002.11720, sottomesso a J. Phys. G

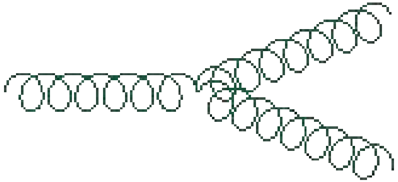
GLUEBALLS

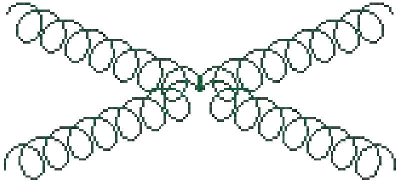
The QCD, the gauge theory describing strong interactions

$$\mathcal{L} = -\frac{1}{4}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} + \sum \bar{\Psi}\left(i\gamma \cdot D - m\right)\Psi$$

gluon field strength tensor: $$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abs} A^b_\mu A^c_\nu$$







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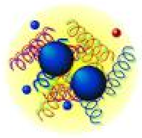
Mesons

$$\mathbf{3} \otimes \bar{\mathbf{3}}$$



Baryons

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Exotic states

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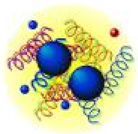

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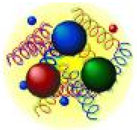

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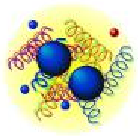

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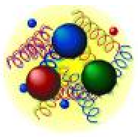

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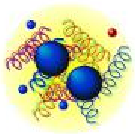

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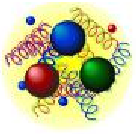

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GLUEBALLS

Why Glueballs?

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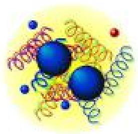

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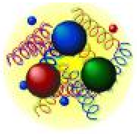

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GLUEBALLS

Glueball spectroscopy is a unique laboratory to test non perturbative QCD and CONFINEMENT

However :

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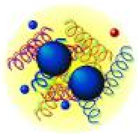

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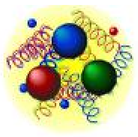

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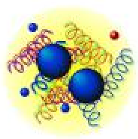

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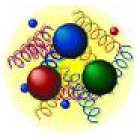

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Why Glueballs?

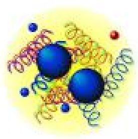
GLUEBALLS

The QCD, the gauge theory describing strong interactions

$$\mathcal{L} = -\frac{1}{4}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} + \sum \bar{\Psi}(i\gamma \cdot D - m)\Psi \qquad G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abs} A^b_\mu A^c_\nu$$

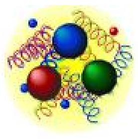
Mesons

$\mathbf{3} \otimes \bar{\mathbf{3}}$



Baryons

$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3}$



Exotic states

$\mathbf{3} \otimes \bar{\mathbf{3}} \otimes \mathbf{8}$ — **HYBRIDS**

$\mathbf{8} \otimes \mathbf{8}$

$\mathbf{8} \otimes \cdots\cdots \otimes \mathbf{8}$ } **GLUEBALLS**

Why Glueballs?

Glueball spectroscopy is a unique laboratory to test non perturbative QCD and CONFINEMENT

However :

1) several mesons have similar mass and quantum number ⟶ MIXING
2) Their measurements represent a very hard task
3) Theoretical calculations of decay are very difficult! Models could help!

GLUEBALLS: LO SPETTRO

So far, data have been obtained from Lattice QCD! BUT also in this framework we have problems:

MP: **C.J. Morningstar et al, PRD 60, 034509 (1999)** YC: **Y. Chen et al, PRD 73, 014516 (2006)** LTW: **B. Lucini et al, JHEP 06, 012 (2004)**

	0^{++}	2^{++}	0^{++}	2^{++}	0^{++}	0^{++}
MP	1730 ± 94	2400 ± 122	2670 ± 222			
YC	1719 ± 94	2390 ± 124				
LTW	1475 ± 72	2150 ± 104	2755 ± 124	2880 ± 164	3370 ± 180	3990 ± 277

The mass of the lightest state is very hard to estimate

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Could model help in this scenario?
We used AdS/QCD models!

GLUEBALLS: LO SPETTRO

One of the main difficulties in the observation of glueballs is related to their mixing with mesons!

For example:

J^{PC}	0^{++}	2^{++}	0^{++}
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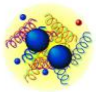
PDG	475 ± 75	990 ± 20	1350 ± 150	1504 ± 6	1723 ± 6	1992 ± 16	2101 ± 7	2189 ± 13



Mixing?

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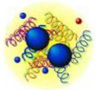


Mixing?

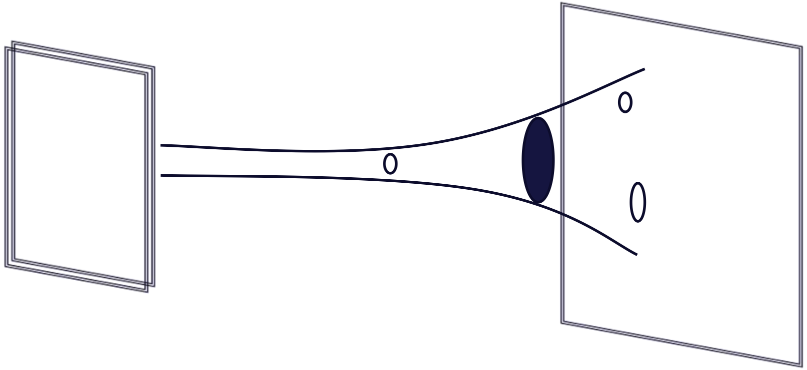
We use AdS/QCD models to study the MIXING problems and "predict" the kinematic conditions where pure glueball states could be observed.

INTRODUZIONE: AdS/QCD

From Maldacena conjecture: AdS/CFT

N=4 SU(N) SYM ⟷ String theory on $AdS_5 \times S_5$

Isometries between group symmetries



$$g_{YM}^2 N \underset{N\to\infty}{=} \frac{R^4}{l^4}$$

R= radius of the manifold

l = length

INTRODUZIONE: AdS/QCD

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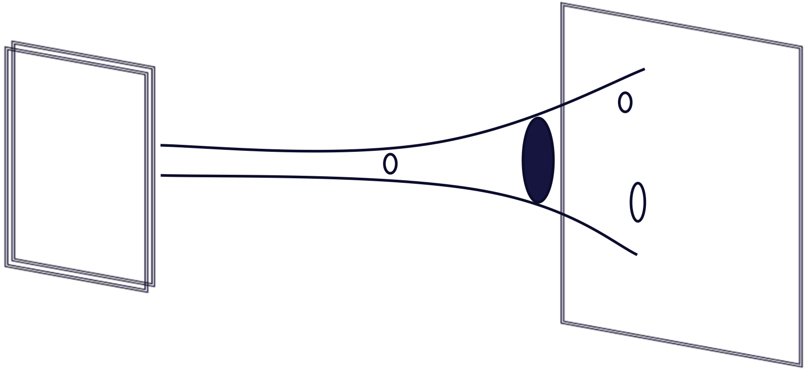
Isometries between group symmetries

This is not QCD!
- No supersymmetry
- Confinement
- Conformal symmetry broken
- N is finite



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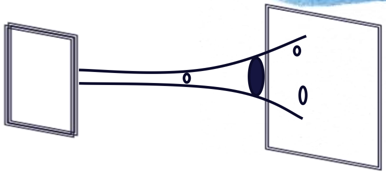


The dream is to understand QCD using its dual gravity theory!

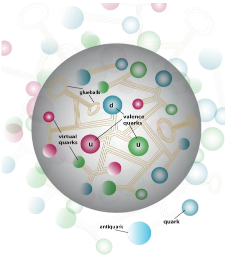
- No supersymmetry
- Confinement
- Conformal symmetry broken
- N is finite

Top-down Approach:
Find a gravitational theory dual to QCD

Bottom-up Approach:
Starts from QCD and attempts to construct a five dimensional holographic dual

Confinement

Confinement



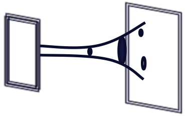
Hard-wall model

Compattification of the 5° dimension by hand. AdS geometry cut by two branes: UV and IR.

Soft-wall model

Soft cutoff of AdS space by introducing a dilaton field. $e^{-\varphi}$

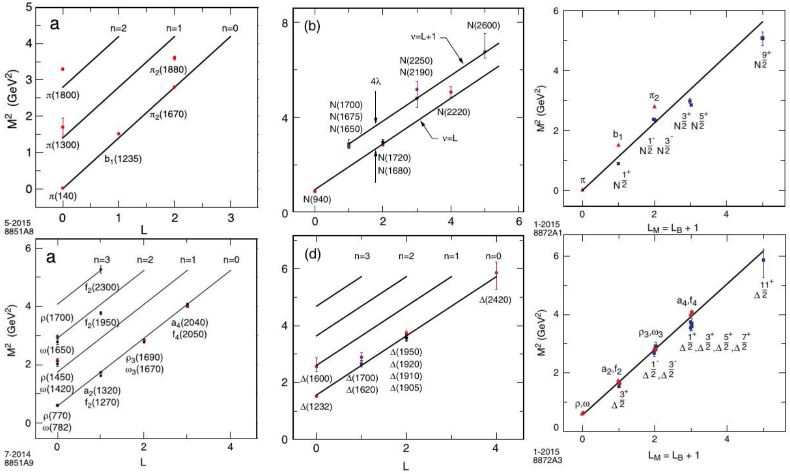
AdS/QCD: PREDIZIONI



HADRON SPECTRUM:

S.J. Brodsky et al, Phys. Rep. 584 (2015)
H.G. Dosh et al PRD 91, 045040 (2015), 085016 (2015)

see Brodsky's talk on Thursday



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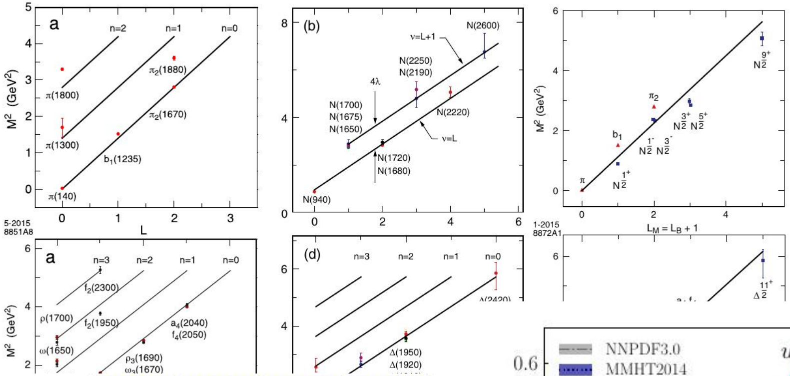

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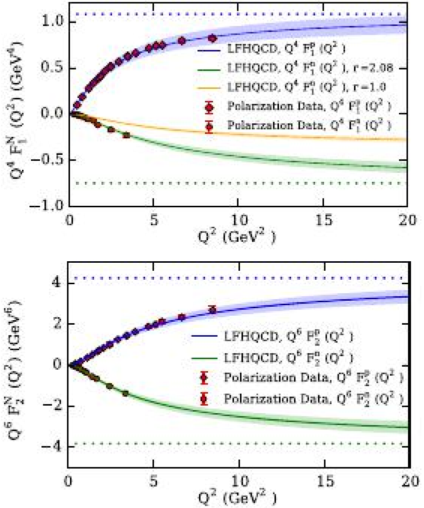
FORM FACTORS, PDFs & GPDs

R.S. Sufian et al PRD 95, 014011 (2017)



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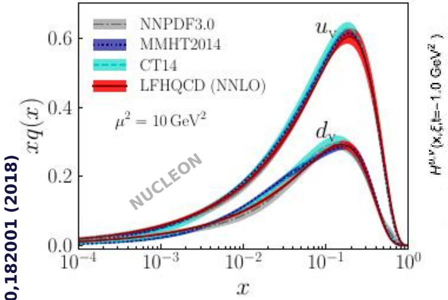
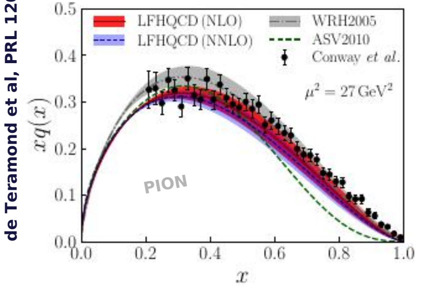
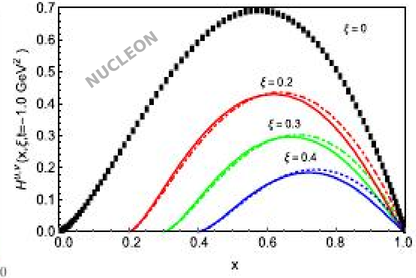
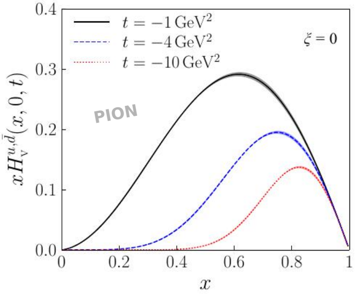




M. Rinaldi, PLB 771 (2017)





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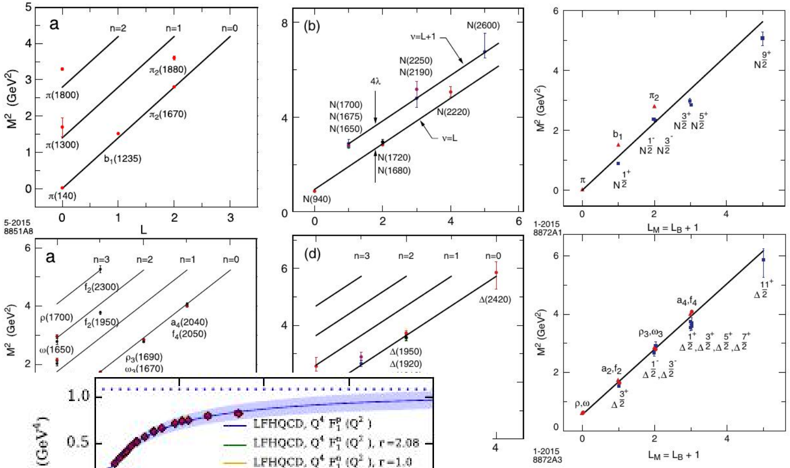

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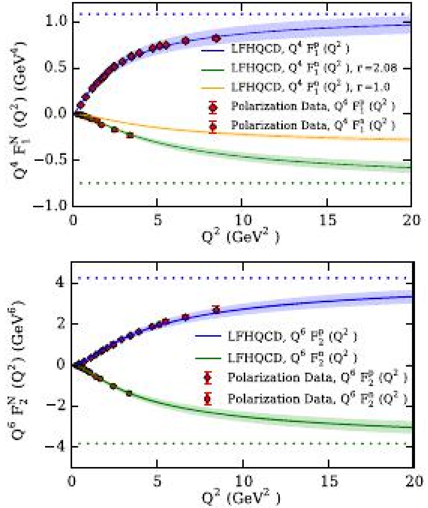
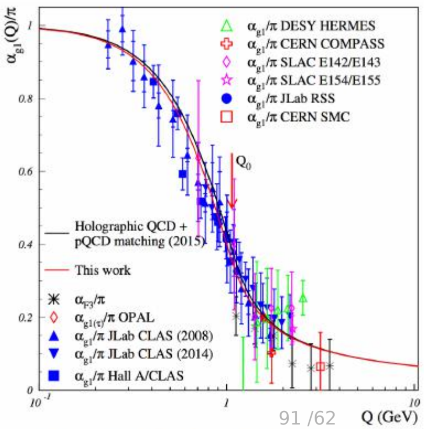


MATCHING THE RUNNING COUPLING



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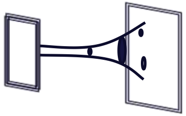

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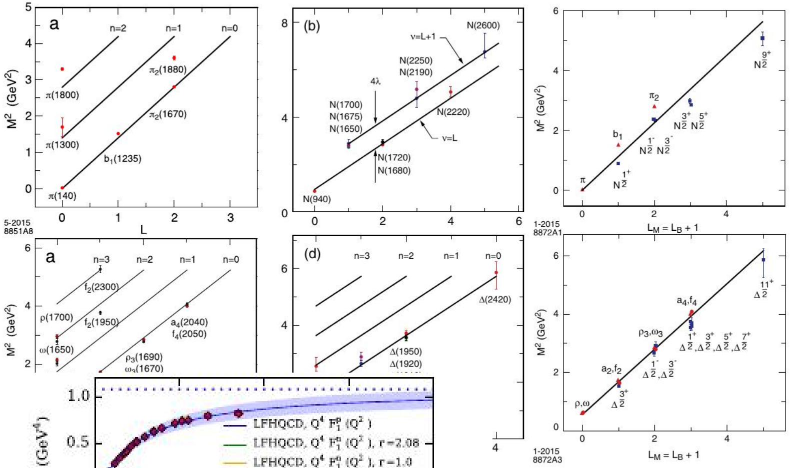

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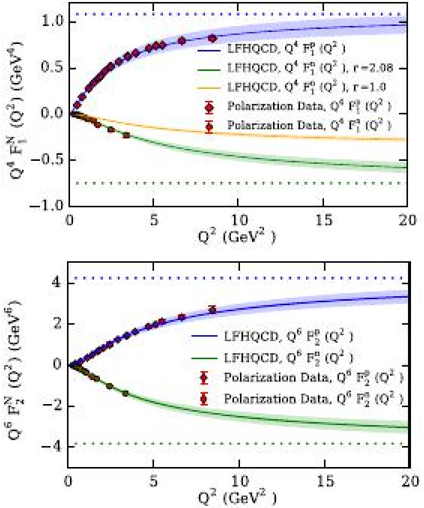

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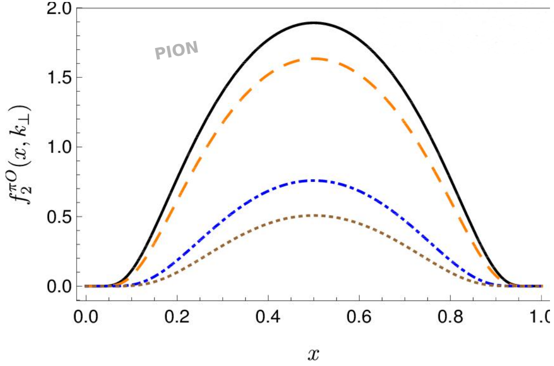

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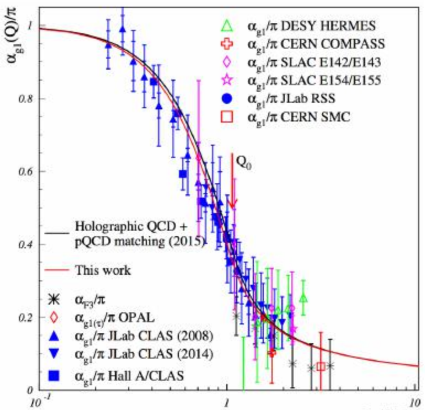

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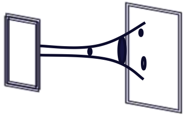

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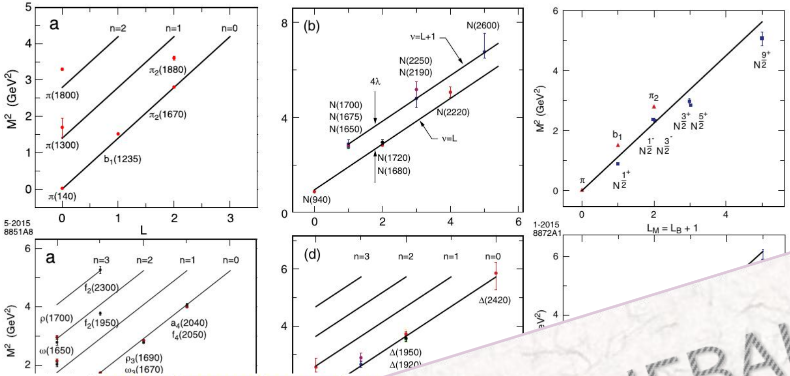

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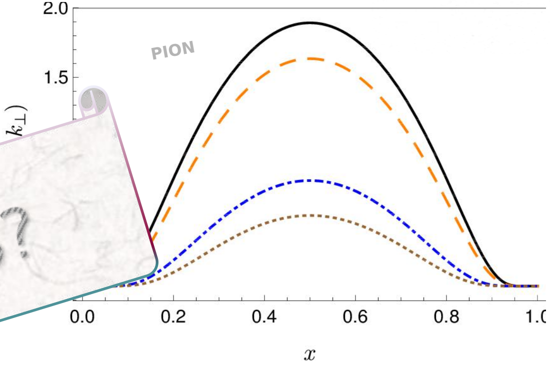
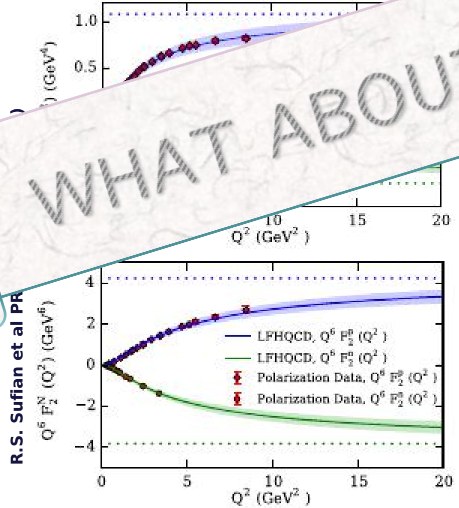


WHAT ABOUT GLUEBALLS?

FORM FACTORS, PDFs & GPDs



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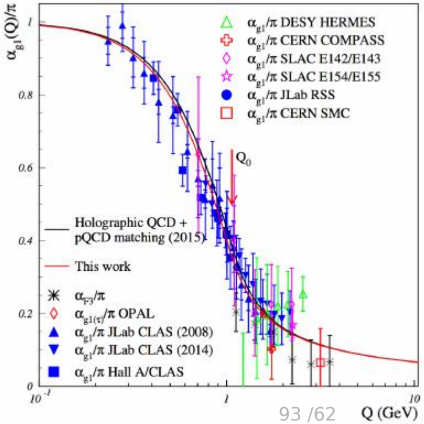
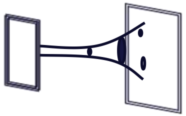


de Teramond et al, PRL 120,182001 (2018)

AdS/QCD: THE HARD WALL

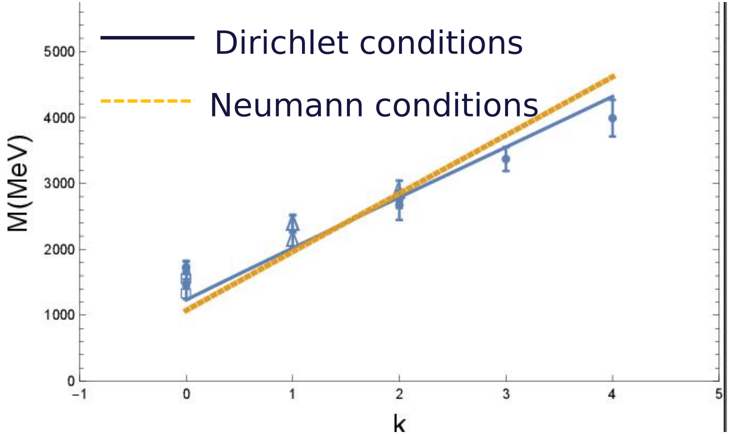


In this case we have the following $AdS_5 \times S_5$ metric : $ds^2 = g_{MN}dx^M dx^N + R^2 d\Omega_5 = \frac{R^2}{z^2}\left(dz^2 + \eta_{\mu\nu}dx^\mu dx^\nu\right) + R^2 d\Omega_5$

In the hard-wall (HW) model confinement is implemented by imposing the following IR cutoff: $0 \leq z \leq z_{max} = \frac{1}{\Lambda_{QCD}}$

0^{++} $\otimes$ 2^{++} GLUEBALL SPECTRA

M.Rinaldi and V. Vento EPJA 54 (2018)

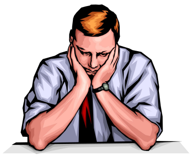


Good agreement!

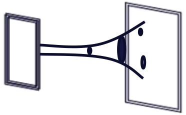
However the HW model does not reproduce the meson spectrum.

$$M_n^2 \sim n^2$$

In order to have a unified view we need another model, i.e.: the Soft-wall model!



AdS/QCD: THE SOFT WALL



karch et al, PRD 74, 015005 (2006)

In the original model we have: $g_{MN}dx^M dx^N = \frac{R^2}{z^2}\left(dz^2 + \eta_{\mu\nu}dx^\mu dx^\nu\right)$

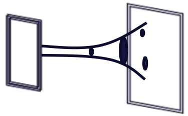
but a soft **cutoff** to space-time is obtained by adding a **dilaton** field in the action:

$$\mathcal{I} = \int d^5x\,\sqrt{-g}\,e^{-\varphi(x)}\mathcal{L}$$

Successful in describing the Regge behavior of the spectrum: $M^2_{n,J} \sim n + j, \qquad j \geq 0$

WHAT ABOUT GLUEBALLS?

AdS/QCD: THE SOFT WALL



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We consider the profile function: $\varphi(z) = \kappa z^2$

SCALR FIELD EQUATION:

Equation of motion of the scalar glueball can be obtained:

$$I = \int d^5x \sqrt{g}\, e^{-\varphi(z)}\left[g^{MN}\partial_M \mathcal{G}\partial_N \mathcal{G} + M_5^2 \mathcal{G}^2\right] \quad \Delta = \text{conformal dimension}$$

Dilaton field

$$\Delta = 2 + \sqrt{4 + M_5^2 R^2}$$

1) scalar glueball state 0^{++} is represented by: $\mathcal{O}_{\Delta=4} = \mathrm{Tr}\left(F^{\mu\nu}F_{\mu\nu}\right)$
2) For example for even spin J: $\mathcal{O}_{\Delta=4+j} = FD_{\{\mu 1 \dots}D_{\mu j\}}F$

The equation of motion for the scalar is:

$$-\Psi''(z) + \left[z^2 + \frac{15}{4z^2} + 2\right]\Psi(z) = M^2\Psi(z)$$

where:

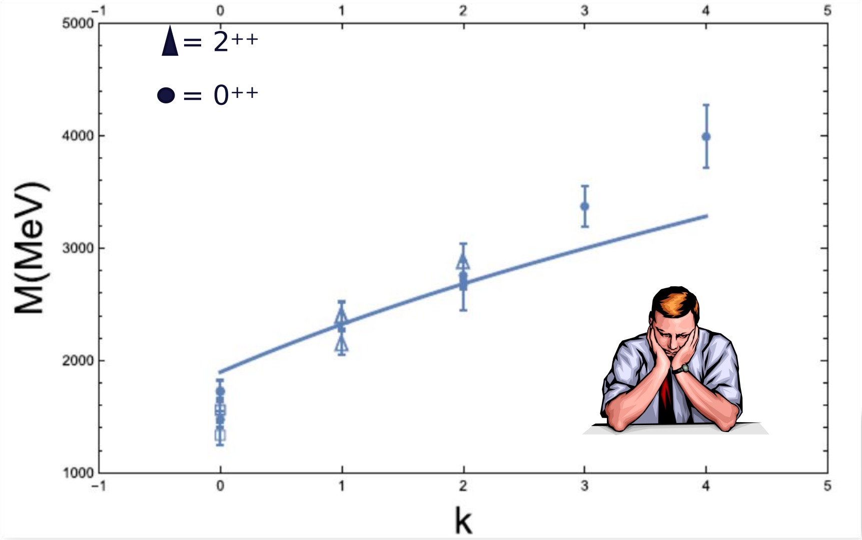
$$\mathcal{G}(x,z) = e^{iP_\mu x^\mu}\left(\frac{z}{R}\right)^{3/2} e^{\kappa^2 z^2/2}\Psi(z), \qquad P^2 = -M^2$$

Eduardo Folco Capossoli et al, PLB 753 (2019) 419-423

SCALAR GLUEBALL SPECTRUM:

$$M_J^2 = 4k + 4 + 2\sqrt{4 + J(J+4)} = 4k + 8$$

→ $k = 0, 1 \dots$ **scalar**
→ $k = 1, 2 \dots$ **tensor**



AdS/QCD: THE GRAVITON SOFT WALL

In **M.Rinaldi and V. Vento EPJA 54 (2018)** we propose to use a soft-wall graviton (GSW) model.
In this case a dilatonic cutoff is incorporated in the metric:

$$\tilde{g}_{MN}dx^M dx^N = e^{-\alpha\varphi(z)}\frac{R^2}{z^2}\left(dz^2 + \eta_{\mu\nu}dx^\mu dx^\nu\right)$$

However, a dilatonic contribution in the action can still be kept:

$$\tilde{\mathcal{I}} = \int d^5x\, \sqrt{-\tilde{g}}\; e^{-\beta\varphi(x)}\mathcal{L}$$

In order to preserve the good description of the hadronic spectrum we require:

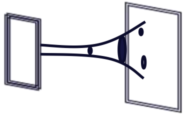
$$\int d^5x\, \sqrt{-\tilde{g}}\; e^{-\beta\varphi(x)}\mathcal{L} \sim \int d^5x\, \sqrt{-g}\; e^{-\varphi(x)}\mathcal{L}$$

kinetic term

$$\frac{3\alpha}{2} + \beta = 1$$

WHAT ABOUT GLUEBALLS?

AdS/QCD: THE GRAVITON SOFT WALL



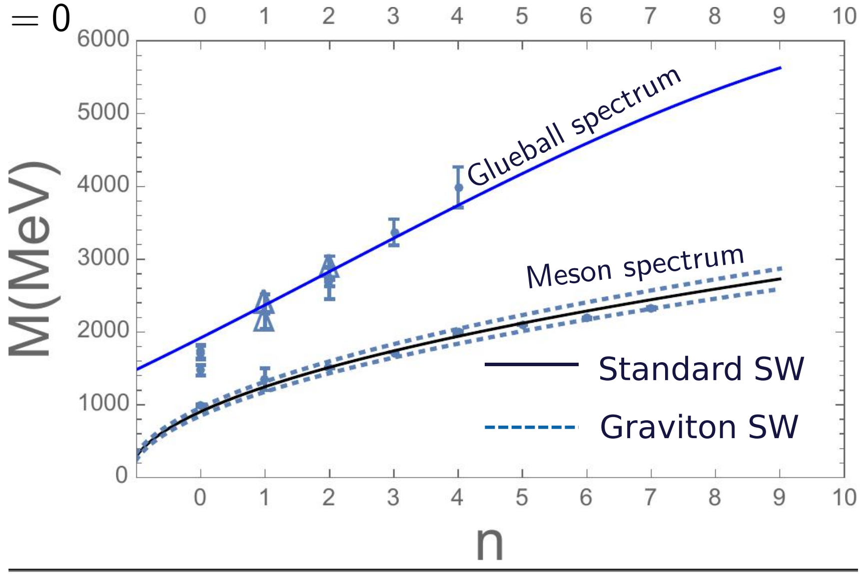
In this case we have the following AdS$_5$ metric : $\tilde{g}_{MN}dx^M dx^N = \underbrace{e^{-\alpha\varphi(z)}}\frac{R^2}{z^2}\left(dz^2 + \eta_{\mu\nu}dx^\mu dx^\nu\right)$

In **M.Rinaldi and V. Vento EPJA 54 (2018)** we consider $\alpha\kappa^2$ as the only **one parameter!**

GRAVITON EoM and SPECTRUM

$$-\frac{1}{2}\tilde{h}_{ab;c}^{;c} - \frac{1}{2}\tilde{h}^{c}_{c;ab} + \frac{1}{2}\tilde{h}_{ac;b}^{;c} + \frac{1}{2}\tilde{h}_{bc;a}^{;c} + 4\tilde{h}_{ab} = 0$$

Also in this case we have a good description of data, but now (w.r.t. the HW model):
we have a complete description of the meson and glueball spectra



IL MIXING

Glueball and meson states could mix!

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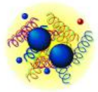
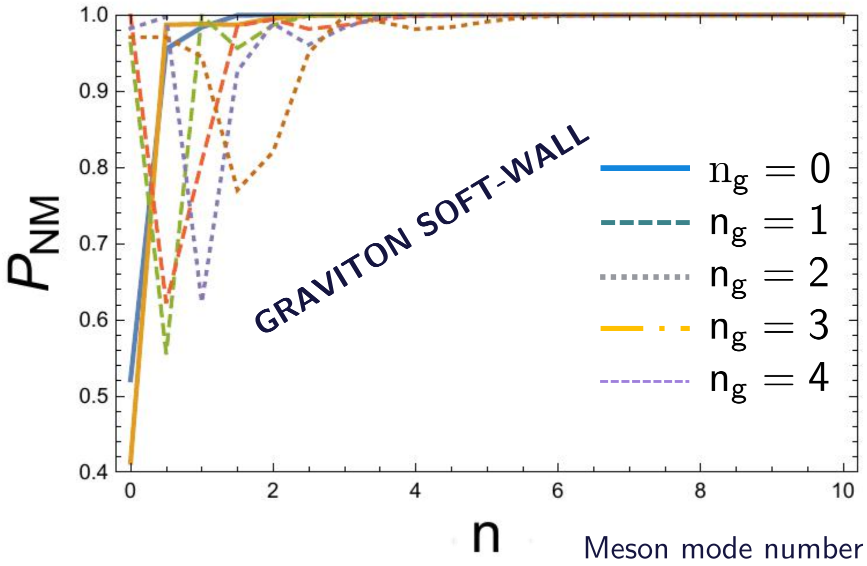


We define the probability for NO MIXING as: $P_{mg} \equiv 1 - |\langle \Psi^g | \Psi^m \rangle|^2$

Meson wave function

Gluon wave function

M.Rinaldi and V.Vento arXiv:1803.05738



Meson mode number

Within the Soft-Wall AdS/QCD models (standard and with graviton) pure glueballs in the scalar sector exist in the mass range above 2 GeV!

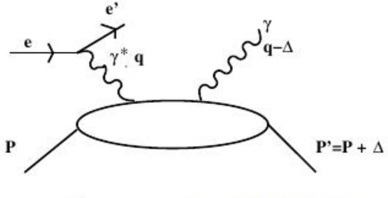
5

CONCLUSIONI: AGGIORNAMENTI E PROSPETTIVE

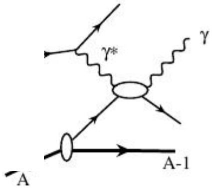
DVCS SU ^{4}HE

In seguito ai lavori di successo di Sergio Scopetta e Sara Fucini, riguardo il calcolo e il confronto con i dati delle asimmetrie (combinazioni e rapporti di sezioni d'urto) del processo DVCS su ^{4}He, ho iniziato a provare interesse per questo argomento:

- Coherent case **S. Fucini, S. Scopetta and M. Viviani, PRC98 (2018), no.1, 093001**
  - I.A. calculation of the GPD H within a non-diagonal spectral function based on the AV18 + UrbanaIX interaction, realistic only in the ground part; Nucleonic model: GK
  - Forward limit and nuclear FFs recovered, momentum SR slightly violated
  - Numbers for CFFs, X-sections, BSA



- Incoherent case **S. Fucini, S. Scopetta and M. Viviani, PRD101 (2020) no.7, 071501**
  - I.A. calculation of cross sections within a diagonal spectral function based on the AV18 + UrbanaIX interaction, realistic only in the ground part; cross section developed for a bound proton; Nucleon model: GK, MMS; numbers for X-sections, BSA



DVCS SU ^{4}HE

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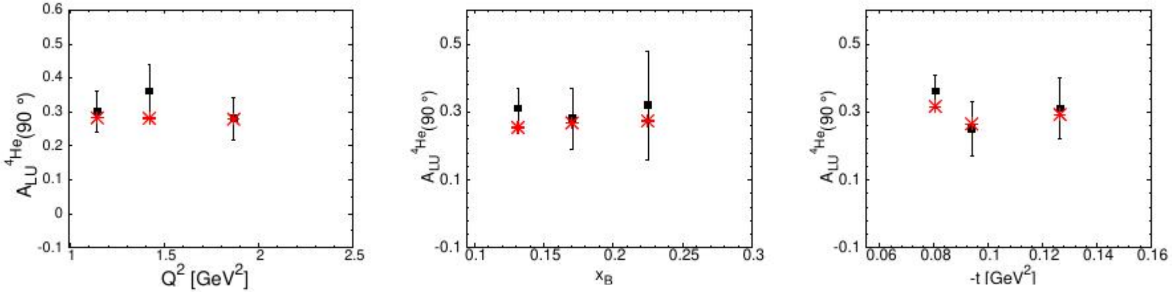
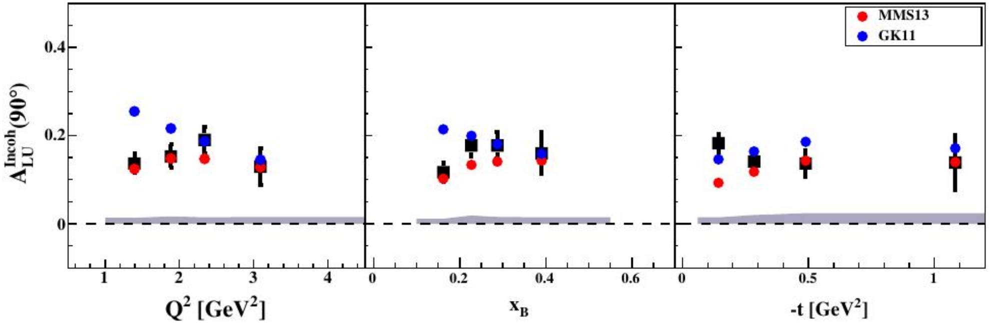


$$A_{LU}(\phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

INCOERENTE
S. Fucini, S. Scopetta and M. Viviani, PRD101 (2020) no.7, 071501



DVCS SU ^{4}HE

Dati i positivissimi risultati, è in corso una collaborazione con i colleghi sperimentali di Orsay per costruzione un **generatore Monte Carlo di eventi**! Questo passo è fondamentale perché:

- Mandatory for the EIC setup
- To realize the feasibility of relevant measurements (e.g., at ξ and $-t$ high enough, look for non-nucleonic degrees of freedom at parton level (**Berger, Cano, Diehl and Pire PRL 2002**))
- Very useful in general (JLAb @ 12 GeV!)
- Ultimate Goal:
  a *new* event generator, based on the FOAM library, *flexible* (different light nuclei (d, ^{3}He, ^{4}He... ^{7}Li?); different setups (fixed target, collider)), *open* (different available models to be implemented), *accessible* to interested colleagues for their studies
- Medium term (weeks? Months?):
  – introduce shadowing in the description
  (a discussion with M. Strikman has started);
  – introduce other nuclei
  (^{3}He cross section evaluation in progress from our GPDs (with M. Rinaldi));
  – incoherent channels **(S. Fucini, S.S., M. Viviani, Phys. Rev. C101 (2020) no.7, 071501)**
  – other people's models for the cross sections

Progetti futuri: Fisica Nucleare

- Calcolo sezioni d’urto ed asimmetrie per il processo DVCS su ^3He

- Implementazione del generatore Monte Carlo per la simuzione di dati per il processo DVCS su ^3He.

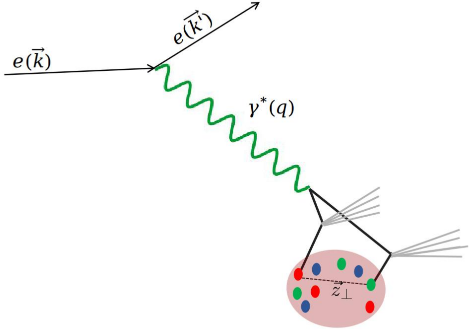
- Introduzione degli effetti dei gluoni nel calcolo delle GPDs nucleari in collaborazione con Sergio Scopetta, Michele Viviani e Mark Strikman

- Studio dell’effetto EMC attraverso la funzione spettrale di ^3He includendo formalmente effetti relativistici tramite l’approccio Light-Front, in collaborazione con Sergio Scopetta, Emanuele Pace e Giovanni Salmè.

Progetti futuri: dPDFs

- Confronto con i dati di lattice per il nucleone: C. Zimmermann, arXiv:1911.05051

- Studio del DPS ad EIC via processi iniziati da Fotoni.



Questo progetto è finanziato dai "Fondi Ricerca di Base" dell'Università degli Studi di Perugia:

"Photon initiated double parton scattering: illuminating the proton parton structure"

PI: Matteo Rinaldi
Collaborators: Sergio Scopetta, Livio Fanò, Simone Pacetti ed Alessandro Rossi

GRAZIE PER L'ATTENZIONE!!