Andrea Signori

University of Turin and INFN

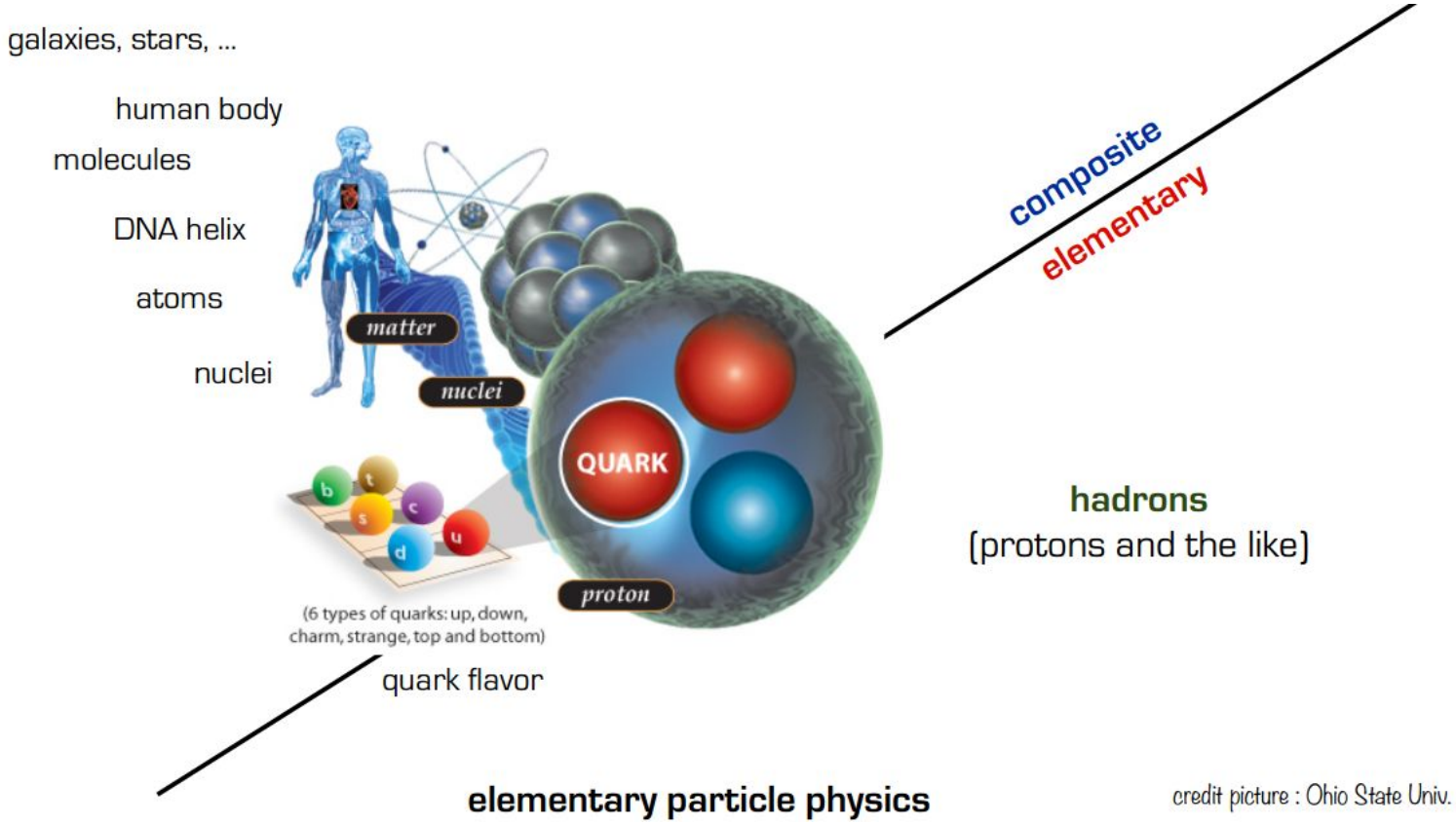
Theory retreat 2023
Santo Stefano Belbo

Studying hadrons in 3D
(via TMDs)

UNIVERSITÀ
DI TORINO

Istituto Nazionale di Fisica Nucleare

The core of matter

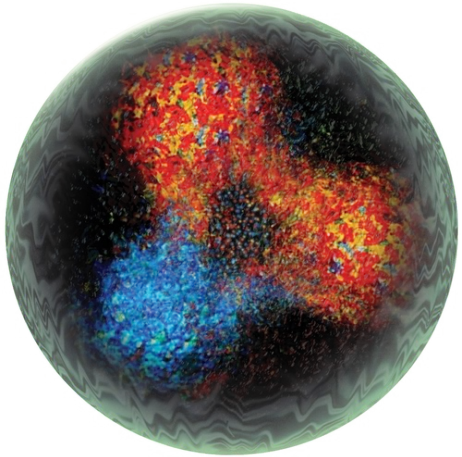


Protons and neutrons: > **99 % of the visible mass** in our world

Hadronic physics

Two macro areas to investigate:

1. **Hadron *structure*** : “hadron → parton(s)” transition



Hadronic physics

Two macro areas to investigate:

1. **Hadron *structure*** : “hadron → parton(s)” transition

2. **Hadron *formation*** : “parton → hadron(s)” transition *(hadronization)*

UniTOhadron

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THEORETICAL HADRON PHYSICS @ TORINO

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RESEARCH INTERESTS

Our group works at the forefront of QCD phenomenology, hadron structure, and hadronization

Learn more on our research interests and international collaborations

See Elena Boglione's talk (NINPHA)

https://sites.google.com/view/unitohadron

Hadron physicists in Turin

Mariaelena Boglione

J. Osvaldo Gonzalez

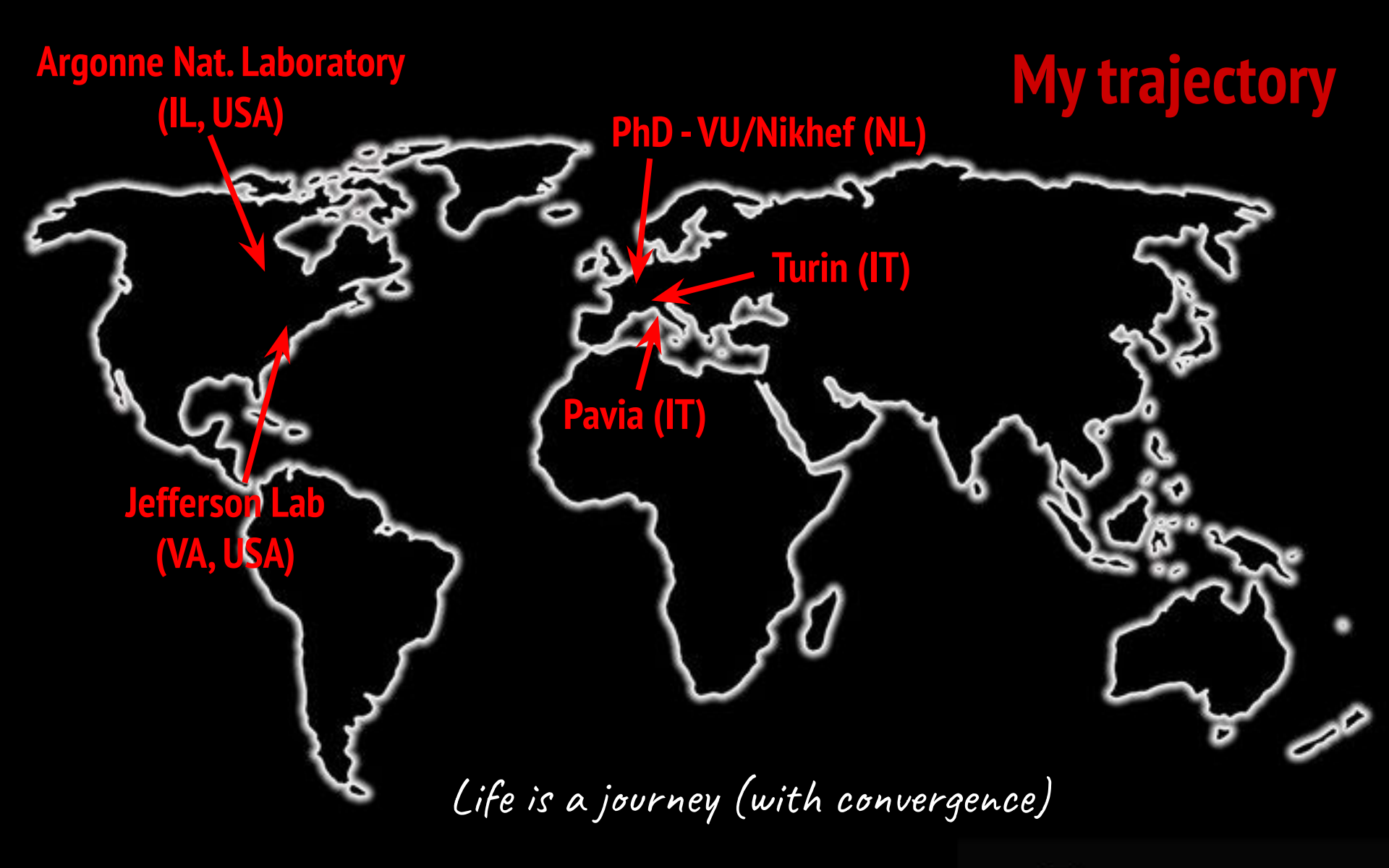
Emanuele R. Nocera

Andrea Signori

Carlo Flore

Tanishq Sharma

Tetiana Yushkevych


Argonne Nat. Laboratory
(IL, USA)
My trajectory
PhD - VU/Nikhef (NL)
Turin (IT)
Pavia (IT)
Jefferson Lab
(VA, USA)
Life is a journey (with convergence)

Quantum Chromodynamics (QCD)

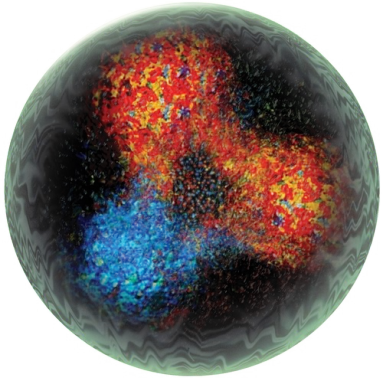
Quarks and **gluons** (or, “partons”) are the degrees of freedom, but they are **confined** within hadrons

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^{a,\mu\nu} F_{a,\mu\nu} + \overline{\psi}(i\not{D} - m)\psi$$

quark field

$$D_\mu = \partial_\mu - igT^a A^a_\mu$$

gluon field



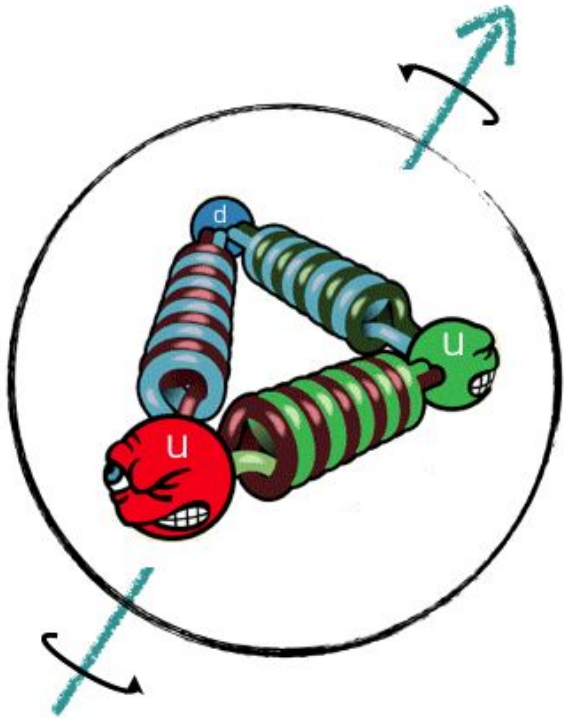
Can we understand the properties of hadrons in terms of quarks and gluons?

Global properties

Can we explain the

mass, spin, size of hadrons

working with quarks and gluons?



Confinement

Can we explain

confinement

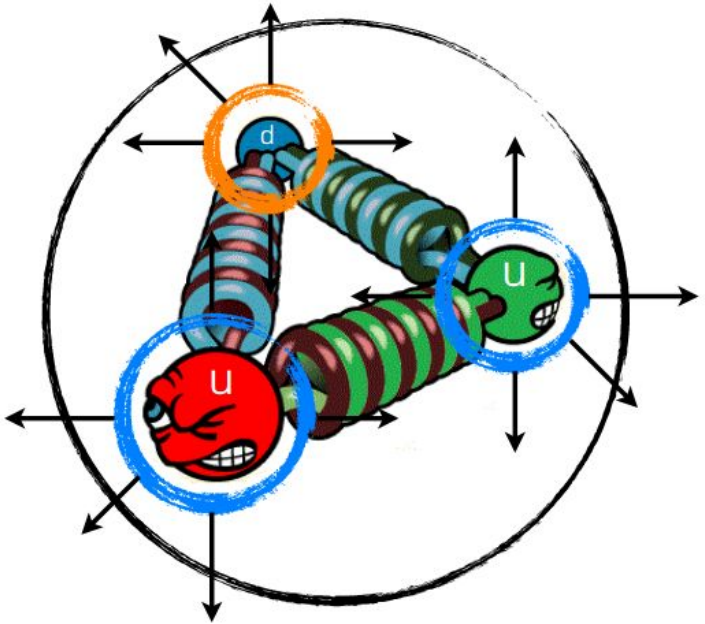
working with quarks and gluons?

Internal structure

Can we explain

the internal structure of hadrons

working with quarks and gluons?

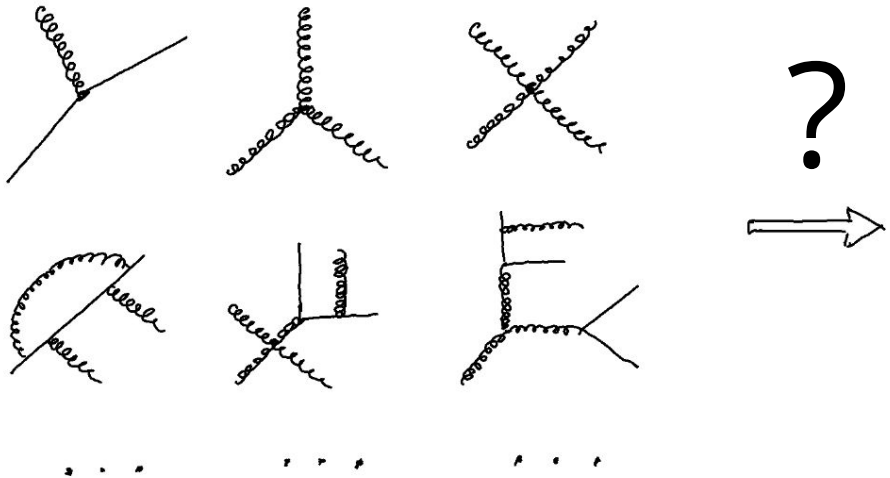


Not really...

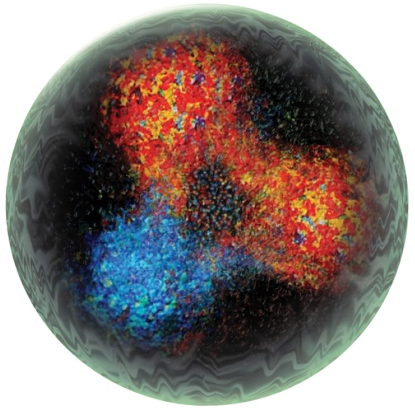
Where is the problem ?

"Perturbative" calculations of the quark-gluon interactions
(α governs the "strength" of the interaction)

$$\mathcal{O}(Q) \sim \mathcal{O}^{(0)} + \alpha_s^1(Q)\,\mathcal{O}^{(1)} + \alpha_s^2(Q)\,\mathcal{O}^{(2)} + \alpha_s^3(Q)\,\mathcal{O}^{(3)} \ldots = ??$$



?



$Q \sim M_N \sim 1\ \mathrm{GeV}$

Where is the problem ?

"Perturbative" calculations of the quark-gluon interactions
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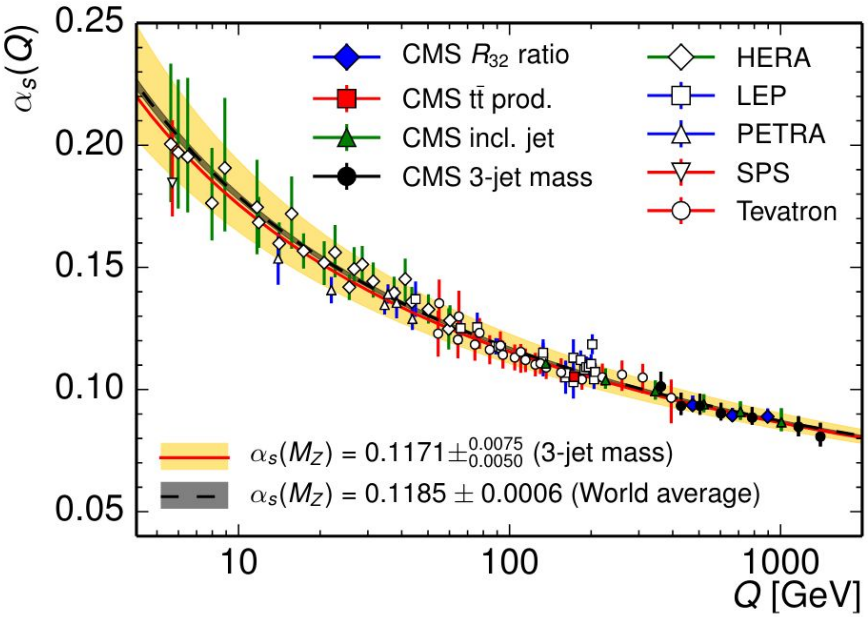
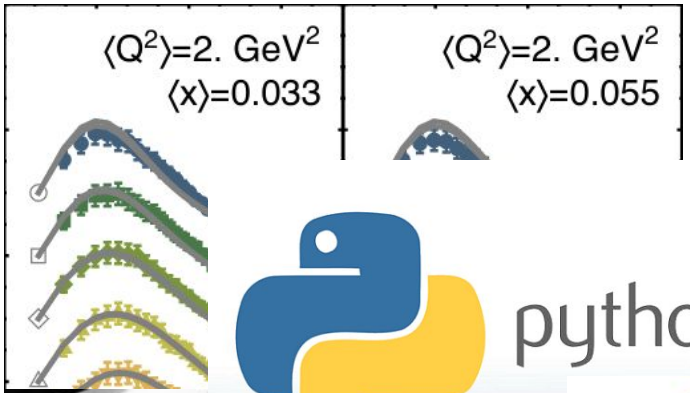


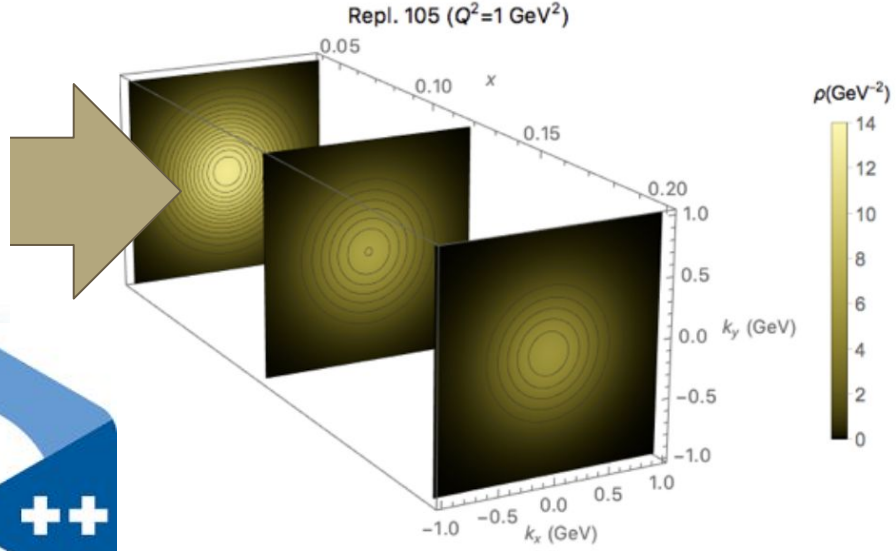
High energy → convergence
→ perturbative QCD

Low energy (hadronic scales)
→ non-perturbative QCD

No predictive power...
Any alternative ?

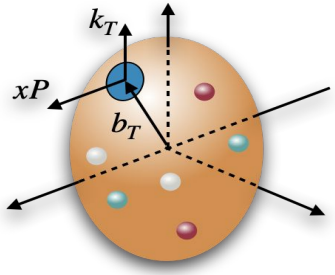
“Imaging”: extracting images of hadrons from data





Hadrons in 3D: TMDs and GPDs

Wigner distributions



Position and momentum of partons

see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Hadrons in 3D: TMDs and GPDs

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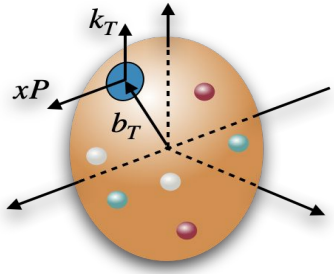
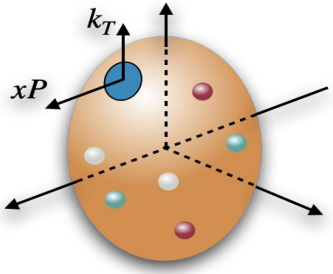


Position and momentum of partons

TMDs



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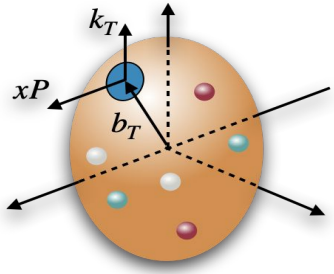

Position and momentum of partons

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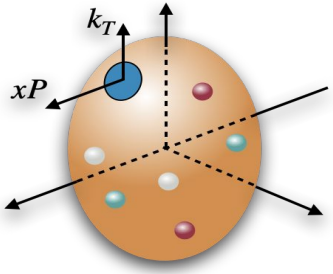
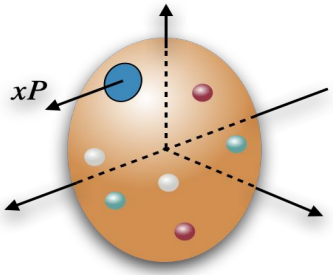


PDFs



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Hadrons in 3D: TMDs and GPDs

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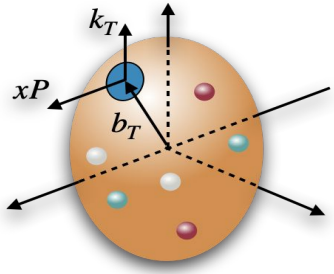
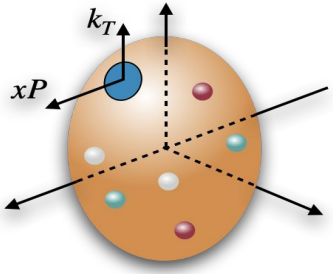
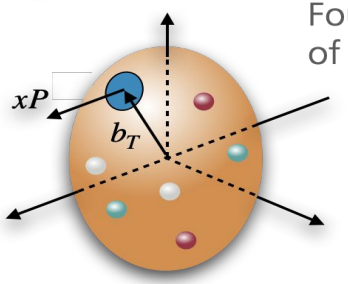


Position and momentum of partons

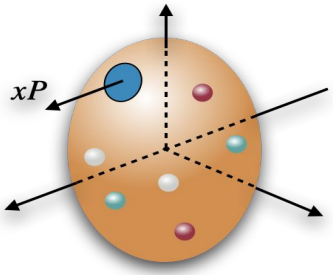
TMDs



Fourier transform of GPDs



PDFs



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Hadrons in 3D: TMDs and GPDs

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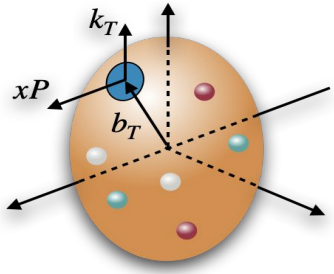
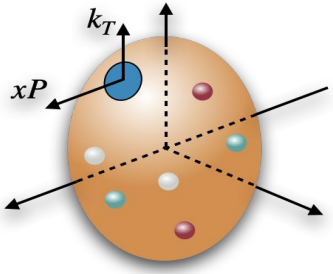


Position and momentum of partons

TMDs



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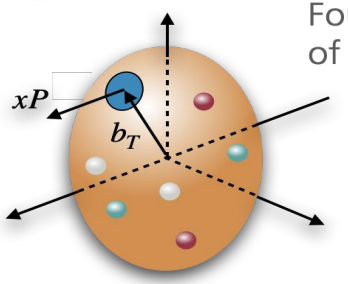
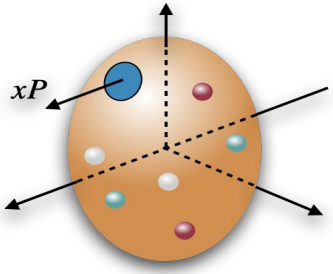
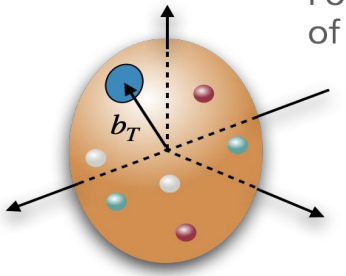


PDFs



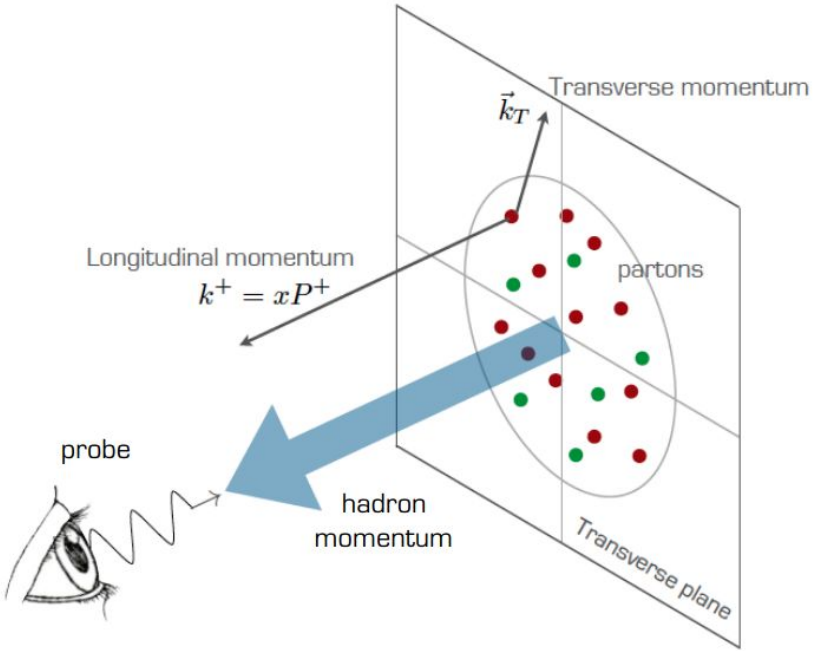
Fourier transform of Form Factors



see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Parton distribution functions

"Maps" of hadron structure in momentum space



Credit picture: A. Bacchetta

$f_1(x)$

1D structure
in momentum space
("collinear")

$f_1(x, k_T^2)$

3D structure
in momentum space
("transverse momentum
dependent")

TMD PDFs for quarks in nucleon

nucleon pol. \ quark pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

$$\Phi_{ij}(k,P) \;=\; \text{F.T.}\,\langle P\big|\,\overline{\psi_j}(0)\,U\,\psi_i(\xi)\,\big|P\rangle$$

At leading twist: 8 TMD PDFs

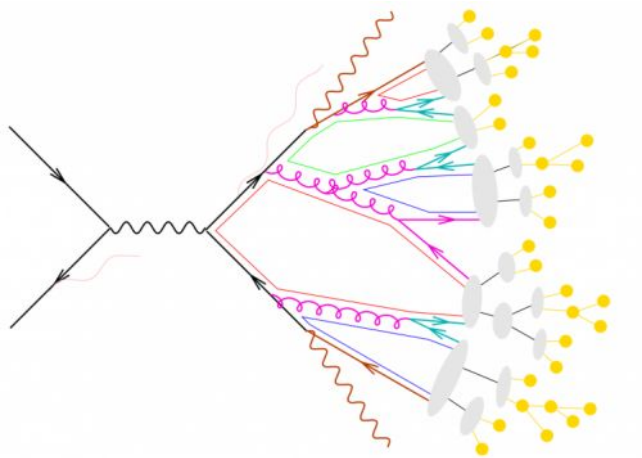
(similar classification for gluons)

- **Black**: time-reversal even AND collinear (see **E. Nocera**'s talk)
- **Blue**: time-reversal even
- **Red**: time-reversal odd (*process dependence*)

The **symmetries of QCD** play a crucial role in this classification

Hadronization and fragmentation functions (FFs)

"Maps" of hadron formation in momentum space



$D_1^h(z)$	single-hadron collinear FF
$D_1^h(z, P_T^2)$	single-hadron TMD FF
$D_1^{h_1 h_2}(z, \zeta)$	di-hadron FF
$J(s)$	inclusive jet FF
$\mathcal{G}^h(s, z)$	in-jet FF

Why studying these maps?

f_1

- Test **factorization** and **universality**
- *Precise* knowledge: impact on **HEP**, e.g. **mW** determination

h_1

- Tensor charge of the nucleon: **CP** violation and access to **BSM** physics

$f_{1T}^{\perp}$, $h_1^{\perp}$

- Test the **symmetries** of QCD

e

- Quark-gluon correlations and quark contribution to hadron **mass**

E

- Quark-gluon correlations and **dynamical** generation of quark mass

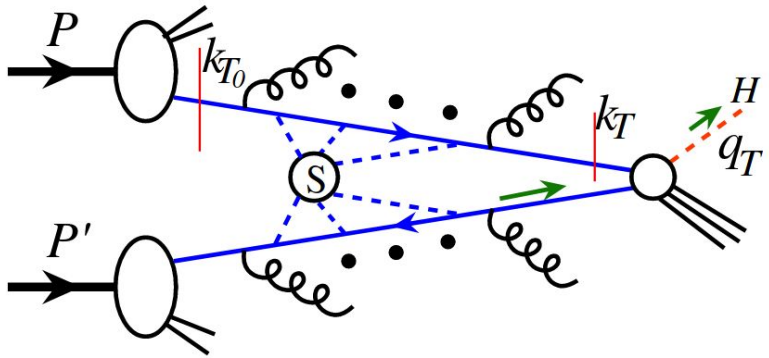
TMD factorization

$q_T \ll Q$

$pp \longrightarrow \gamma^{*} / Z \longrightarrow l\bar{l} + X$

$$\frac{d\sigma}{dq_T} \sim \mathcal{H}\, f_1(x_a, k_{Ta}, Q, Q^2)\, f_1(x_b, k_{Tb}, Q, Q^2)\, \delta^{(2)}\left(q_T - k_{Ta} - k_{Tb}\right) + \mathcal{O}(q_T/Q) + \mathcal{O}(\Lambda/Q)$$

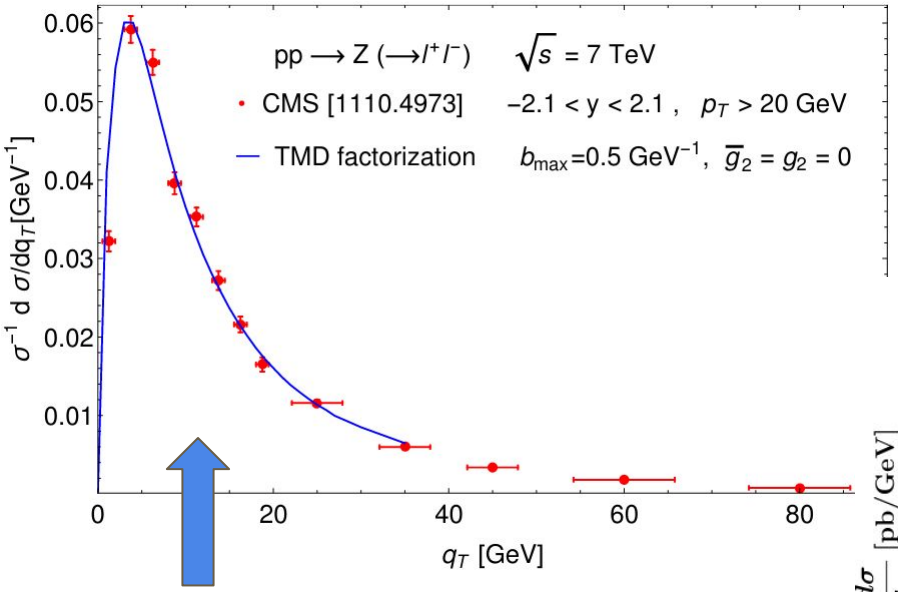
- The TMDs reproduce the structure of the **IR poles** in the cross section (same non-perturbative physics)
- The **observed transverse momentum** is accounted for by the transverse momenta of **quarks**
- The quark transverse momentum has **radiative** (perturbative) and **intrinsic** (non-perturbative) components
- Renormalization = **evolution** equations tell us how to distinguish between the two



My interests: TMD phenomenology

$q_T \ll Q$

https://inspirehep.net/literature/1785810

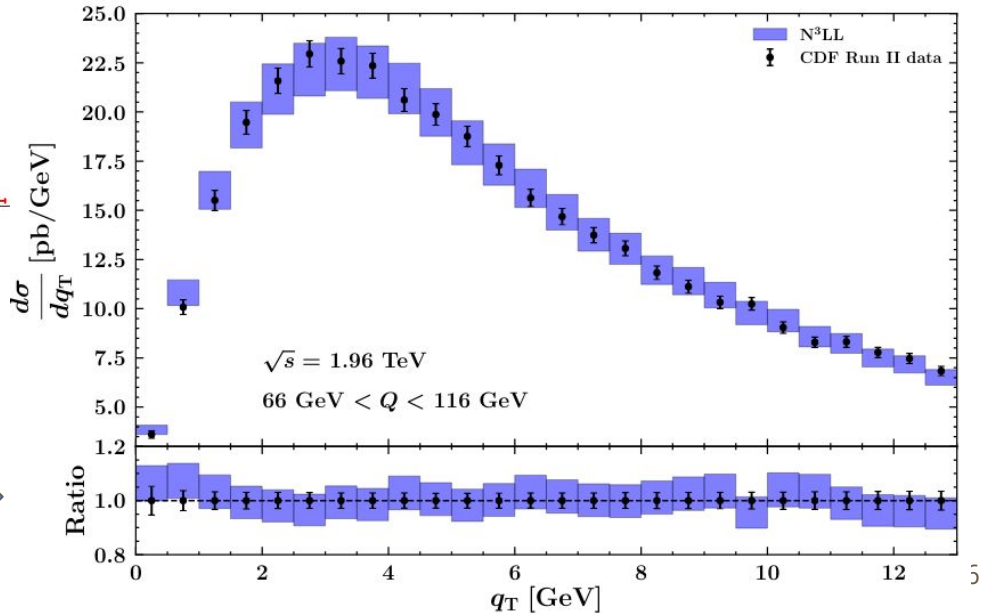


$q_T / Q < 0.3$

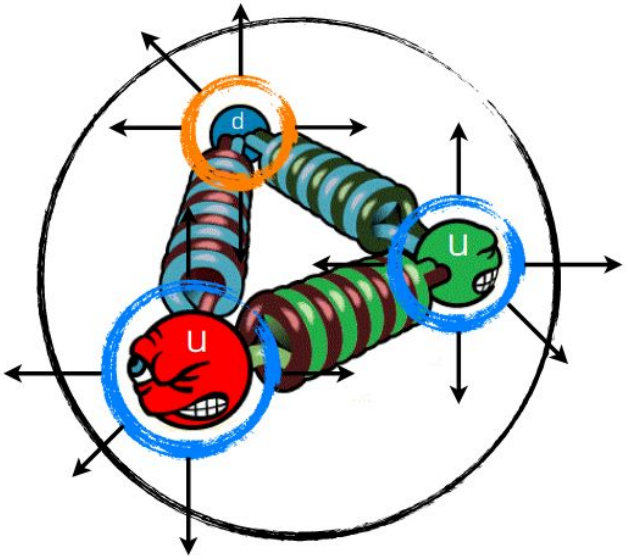
$q_T / Q < 0.2$

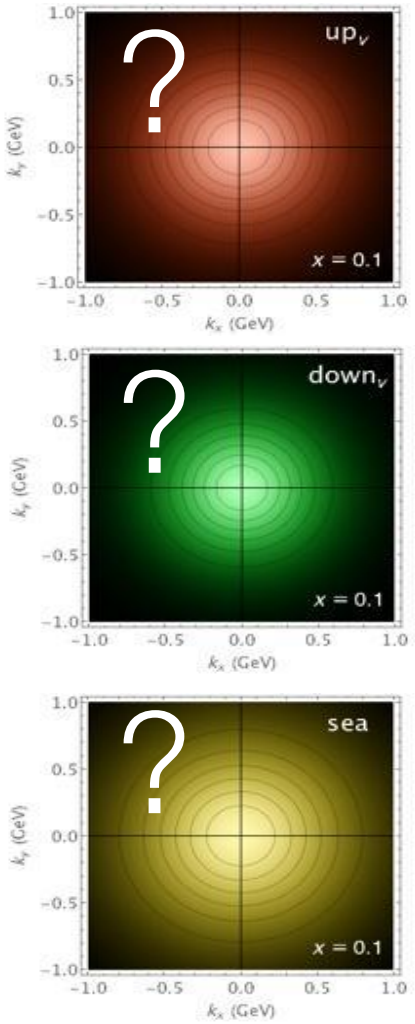
Hadronic collisions

https://inspirehep.net/literature/1771006



My interests: flavor structure





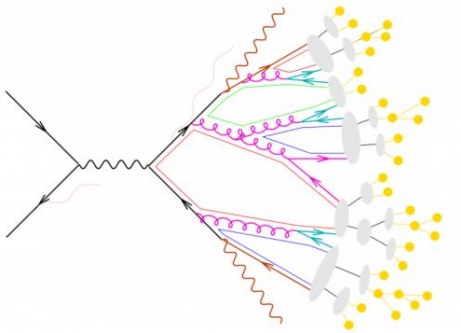
Based on global analyses of experimental data

My interests: hadronization

https://cordis.europa.eu/project/id/795475

For example:

1. Study **unpolarized TMD fragmentation functions (FFs)** in semi-inclusive processes



My interests: hadronization

https://cordis.europa.eu/project/id/795475

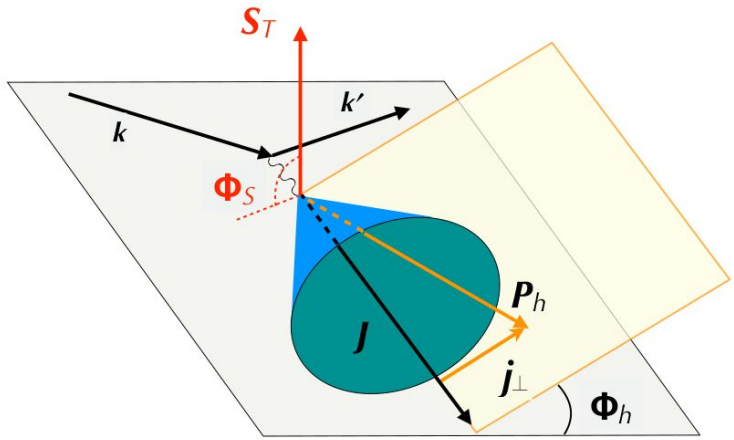
For example:

1. Study **unpolarized TMD fragmentation functions (FFs)** in semi-inclusive processes

$$d\sigma^{l\,N \to l\,jet(h)\,X} \sim h_1\left(x, k_T^2\right) \otimes H_1^{\perp}\left(z_h, j_T^2\right)$$

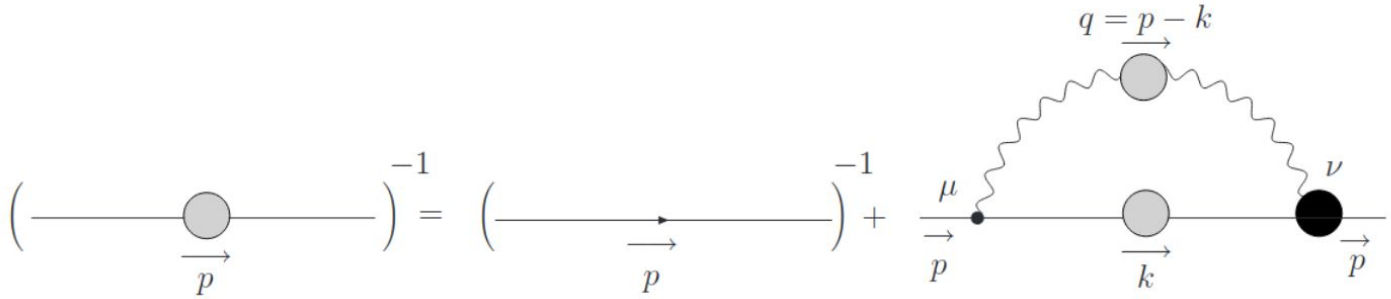
2. Explore the **chiral-odd sector of hadronization** via polarized inclusive jets, in-jet FFs, and FFs

   Crucial to access fundamental mechanisms such as the **dynamical generation of mass** and for the phenomenology of the transversity PDF h1(x)



Credit picture: M. Radici

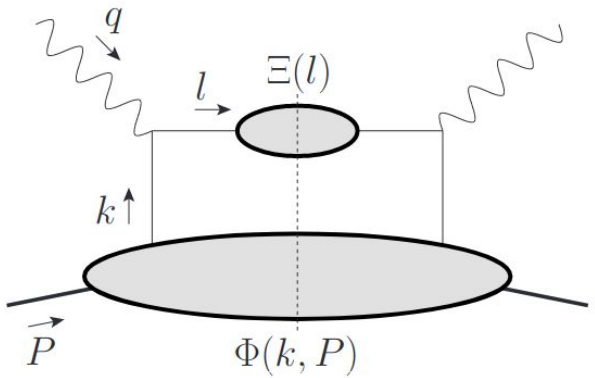
My interests: hadronization and mass generation

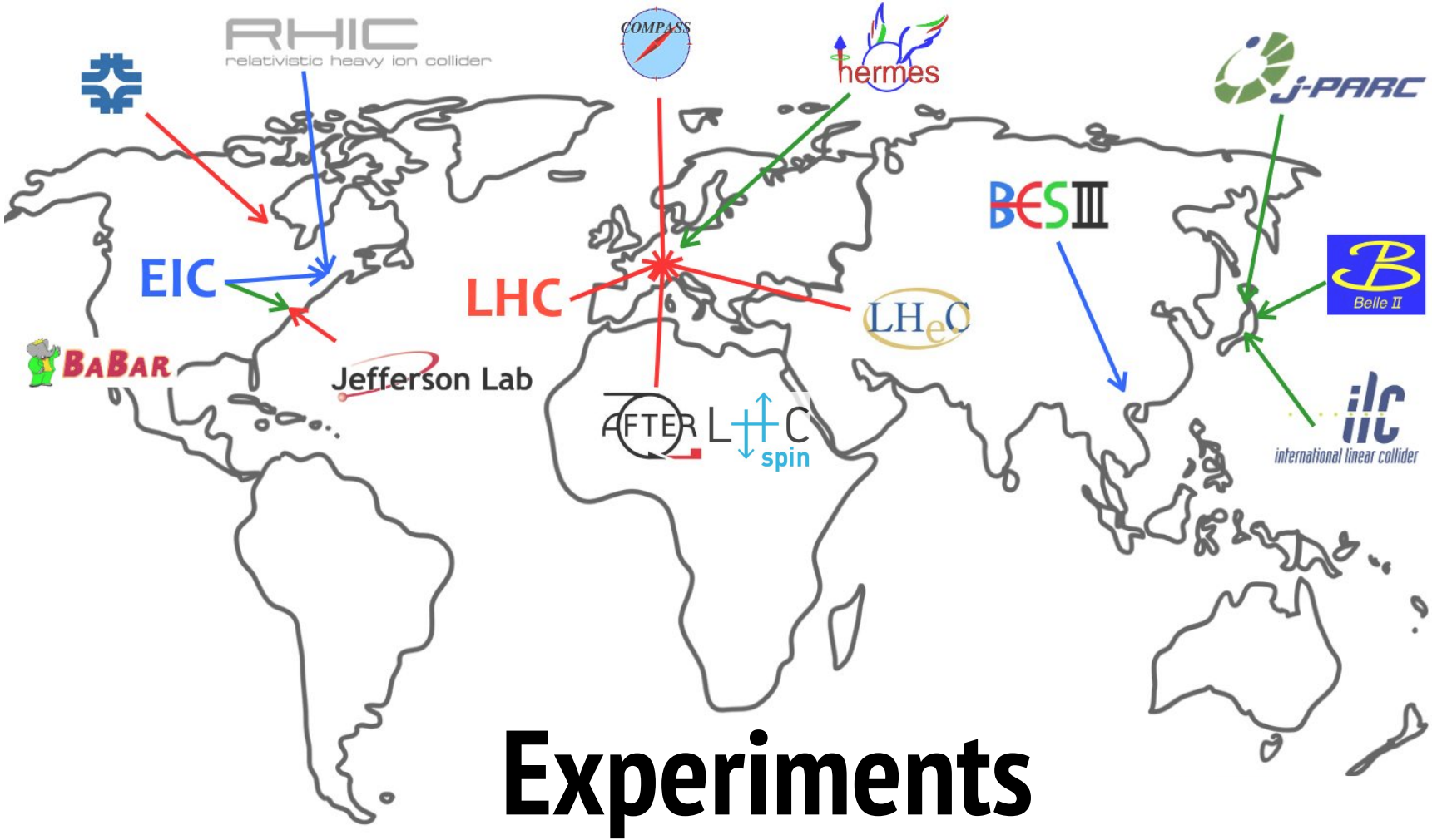


Gap equation for the quark propagator:
dressed "mass function" - how to measure?

Cut propagator = *inclusive limit* of **hadronization**

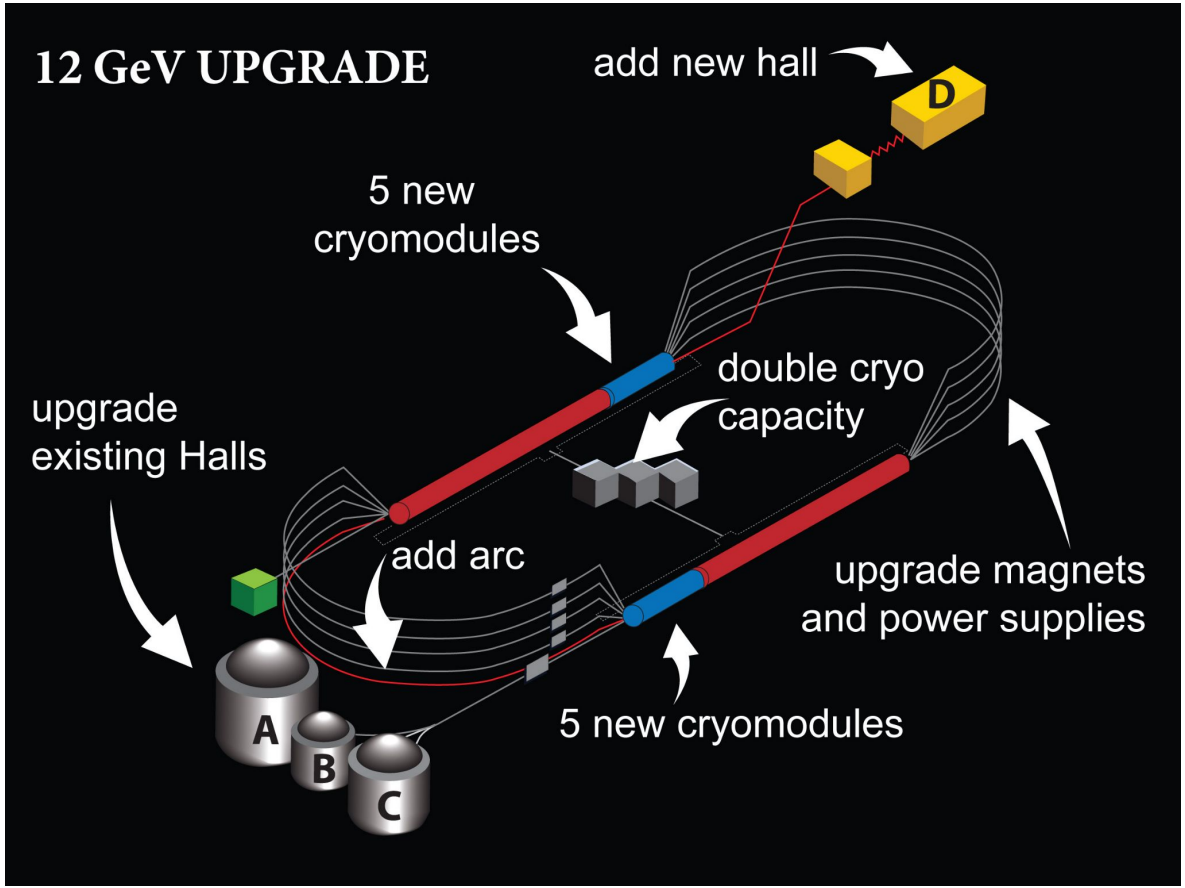
Jet mass with "current" and "dynamical" components: **experimental handle** into **breaking of chiral symmetry**





Experiments

CEBAF at Jefferson Lab



CEBAF:

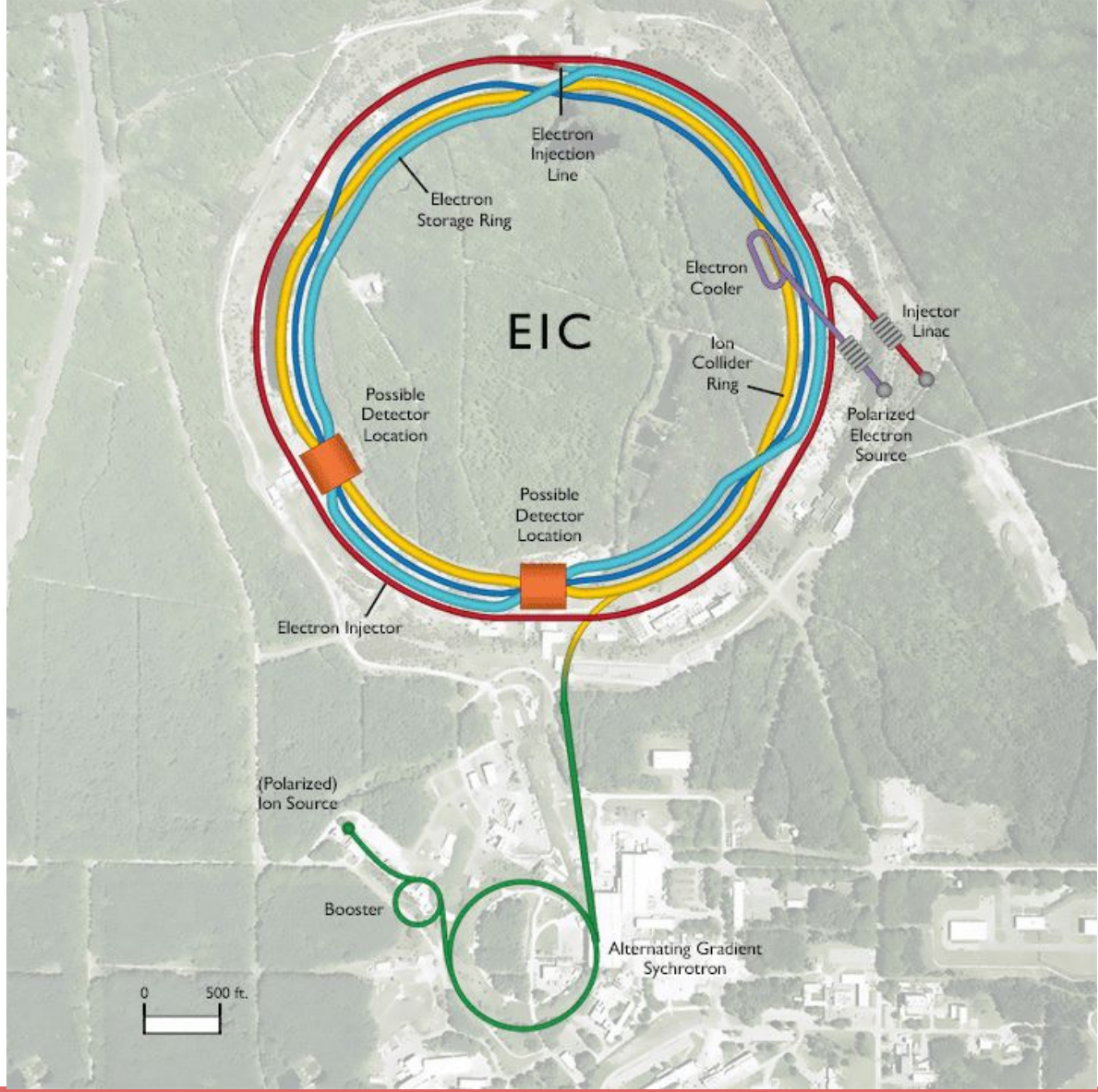
Continuous **E**lectron
Beam
Accelerator **F**acility

Founded in 1984,
recently completed a
major **upgrade**
from 6 GeV to **12 GeV**
+ one new hall

- Hall A & C: hadron structure, high luminosity
- Hall B: hadron structure, 4π coverage
- Hall D: hadron spectroscopy
- … and a Center for Theoretical and Computational Physics

The Electron-Ion Collider

(EIC at BNL)



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Precision 3D imaging of protons and nuclei

An Electron-Ion Collider will take three-dimensional precision snapshots of the internal structure of protons and atomic nuclei.

Solving the Mystery of Proton Spin

An EIC would reveal how the teeming quarks and gluons inside the proton combine their spins to generate the proton's overall spin.

Search for Saturation

A unique form of matter, the color glass condensate, may be produced for study for the first time by an EIC, providing deeper insight into gluons and their interactions.

Quark and Gluon Confinement

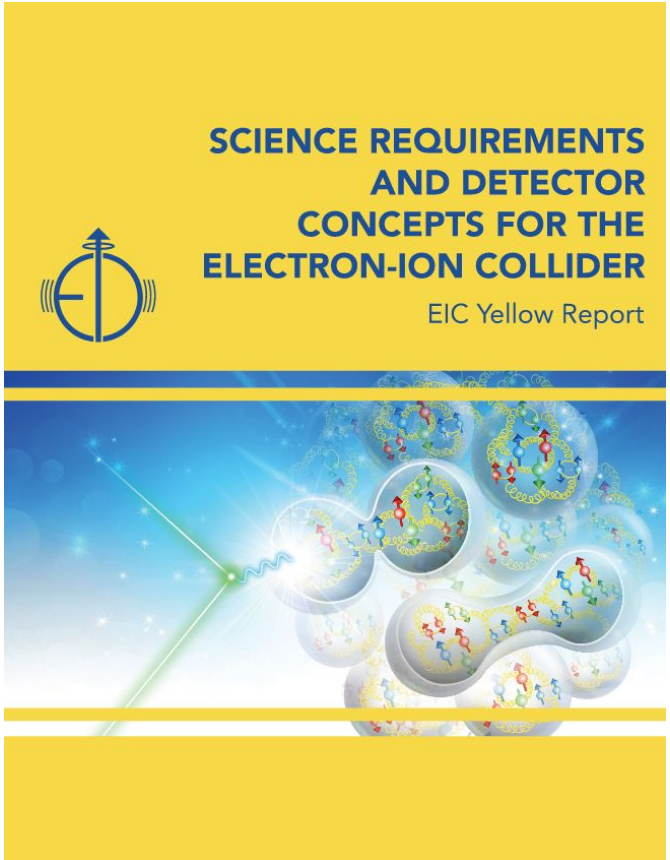
Experiments at an EIC would cast fresh light on the mystery of why quarks or gluons can never be observed in isolation but must remain confined within protons and nuclei.

Electron-Ion Collider (EIC)

https://www.jlab.org/eic

more

The EIC Yellow Report



2021

A **community effort** to line out the science requirements and detector concepts for the EIC

Extensive contribution from the Italian theoretical and experimental communities

More details from the EIC Users Group website: http://eicug.org/

A fixed-target program at the LHC

High-x partonic content of nucleons and nuclei

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/physrep

Spin structure of (un)polarized nucleons

A fi
pro d
astroparticle studies

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Heavy-Ion collisions at large rapidities

C. Hadjidakis [1,a], D. K
M.G. Echevarria [3,4,b],
A. Signori [11,3,12,b], B.
F. Donato [18], E.G. Ferreiro [19,20], I. Hrivnacova [1], A. Klein [17], A. Kurepin [21],
C. Lorcé [22], F. Lyonnet [23], Y. Makdisi [24], S. Porteboeuf Houssais [25], C. Quintans [8],
A. Rakotozafindrabe [26], P. Robbe [1], W. Scandale [27], N. Topilskaya [21], A. Uras [28],
J. Wagner [29], N. Yamanaka [1,32,30,31], Z. Yang [33], A. Zelenski [24]

https://doi.org/10.1016/j.physrep.2021.01.002

Concluding remarks

1. **Hadron structure** and **hadron formation** are **non-perturbative** QCD phenomena, a portion of the Standard Model which has not been explored in great detail yet

2. We are working hard to build "**maps**" of hadron structure and formation: **parton distribution and fragmentation functions** and the like, connected to fundamental properties of QCD

3. **Crucial input** is provided by **experiments**.
   The **Electron-Ion Collider** is the next experimental frontier of QCD and will provide us with a wealth of information: **we have to be ready for that!**

4. But also: 12 GeV upgrade at JLab, RHIC, **LHC** and its proposed **fixed-target mode**, etc

5. A detailed knowledge of 3D hadron structure has an impact on **HEP** too, see the case of the **W boson mass determination**