National Initiative on the Physics of Hadrons

NINPHA

UNIVERSITÀ DI TORINO

INFN

INFN theory retreat 2025

Andrea Signori

NINPHA

National Initiative on the Physics of Hadrons

https://web.infn.it/CSN4/index.php/it/17-esperimenti/135-ninpha-home

National Coordinator: Francesco Murgia (Cagliari)

Local Coordinators:

Umberto D'Alesio (Cagliari)

Elena Santopinto (Genova)

Marco Radici (Pavia)

Matteo Rinaldi (Perugia)

Mariaelena Boglione (Torino)

NINPHA

National Initiative on the Physics of Hadrons

Goals and keywords

"... understanding how **hadron structure** and its **phenomenology** emerge from the underlying dynamics of confined **quarks** and **gluons**.

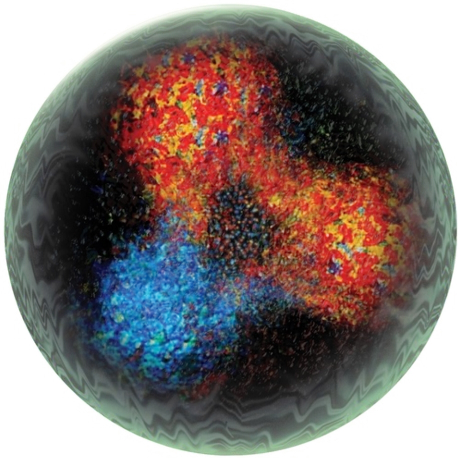
Shedding light on the microscopic mechanisms which lead to the observed **masses** and **spins** of **hadrons** ... will pave the way for a better understanding of **confinement** and **hadronization**."

The physics case

“The Physics of Hadrons”

In particular:

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



“The Physics of Hadrons”

In particular:

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

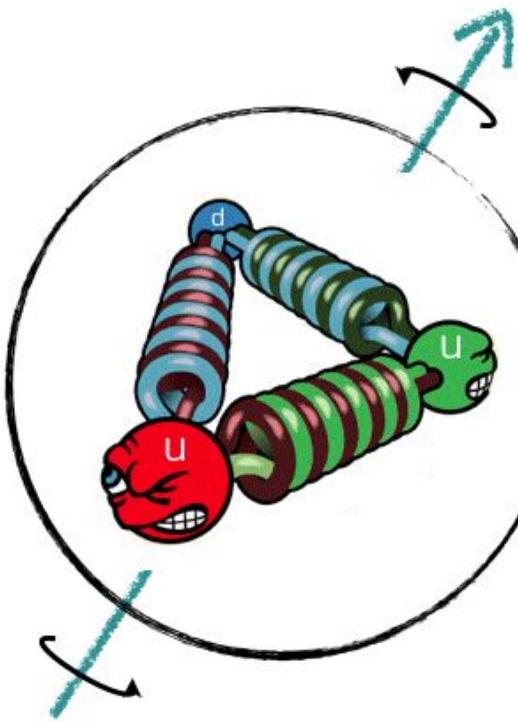
2. **Hadron *formation*** : “parton → hadron(s)” transition
   (hadronization)

Global properties

Can we explain the

mass, spin, size
of hadrons

working with quarks and gluons?



Confinement

Can we explain

confinement

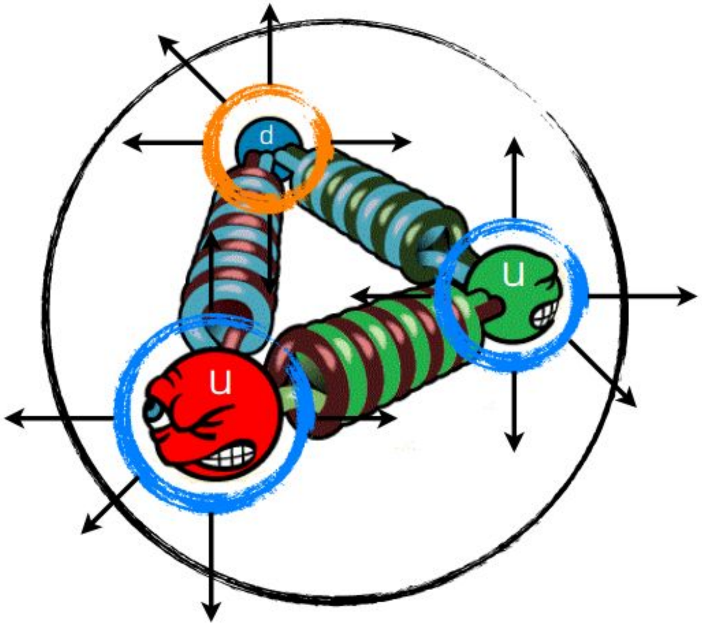
working with quarks and gluons?

Internal structure

Can we explain

the internal structure of hadrons

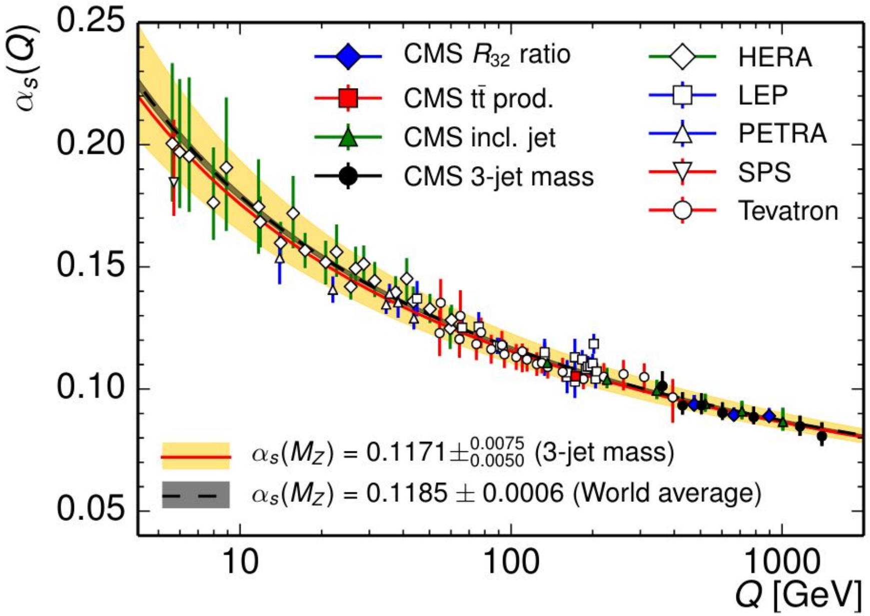
working with quarks and gluons?



Where is the problem ?

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

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

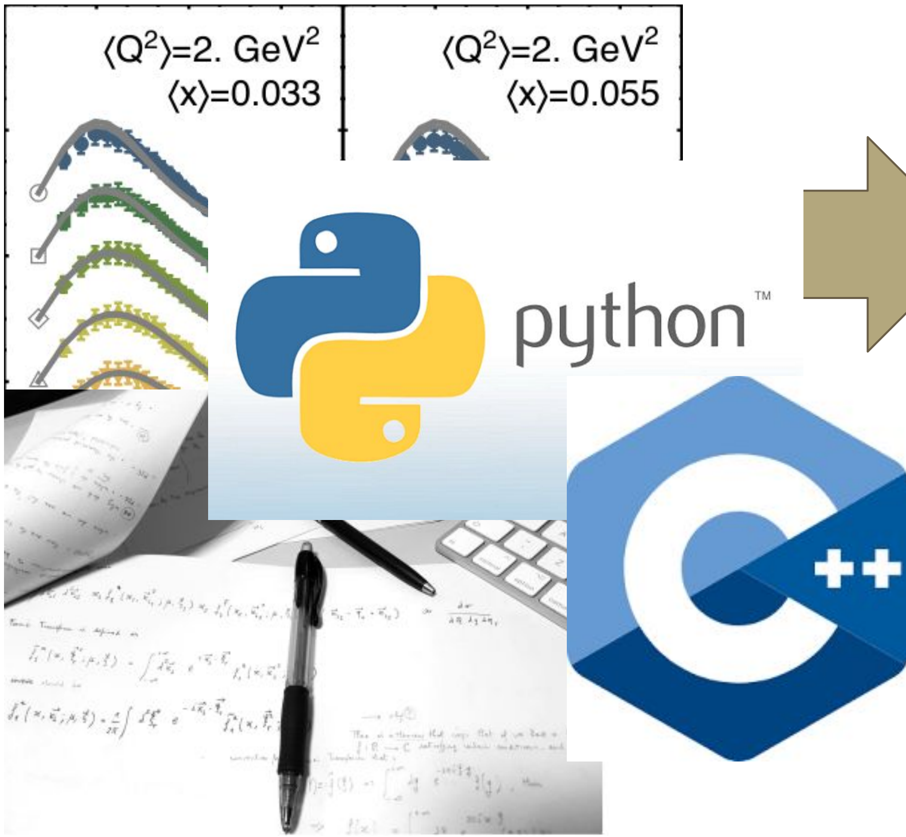


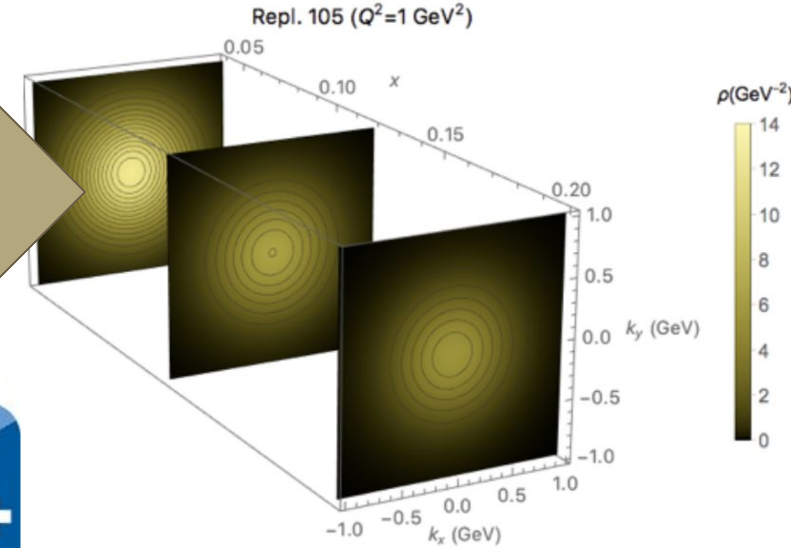
High energy → convergence
→ perturbative QCD

Low energy (hadronic scales)
→ non-perturbative QCD

No predictive power...
Any alternative ?

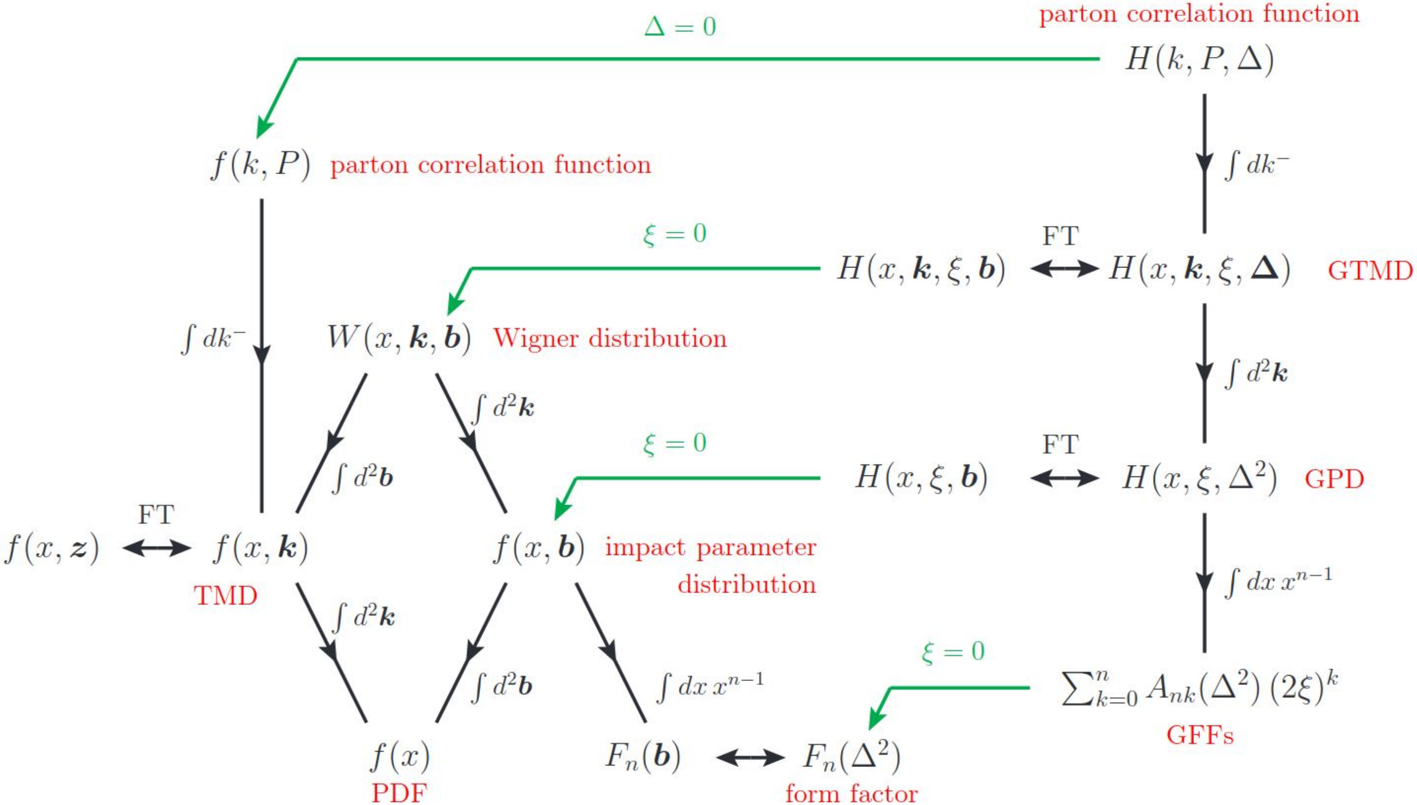
“Imaging”: extracting images of hadrons from data





The “maps”

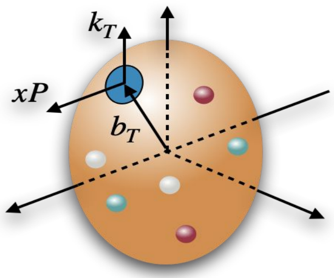
“Maps” of hadron structure



Credit picture: M. Diehl - https://inspirehep.net/literature/1408303

Hadrons in 3D: TMDs and GPDs

Wigner distributions

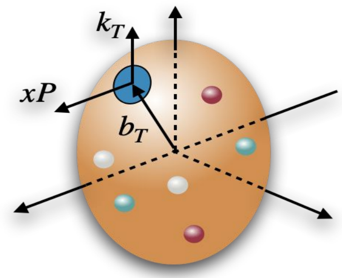


Position and momentum of partons

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

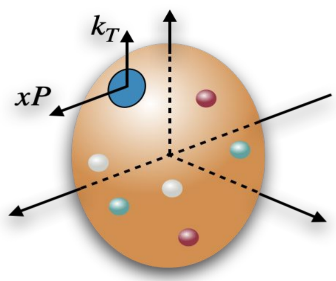
Hadrons in 3D: TMDs and GPDs

Wigner distributions



Position and momentum of partons

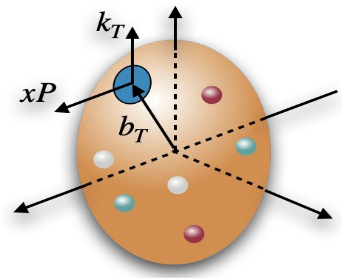
TMDs



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

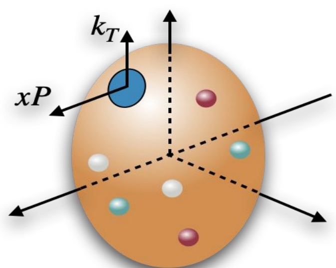
Hadrons in 3D: TMDs and GPDs

Wigner distributions

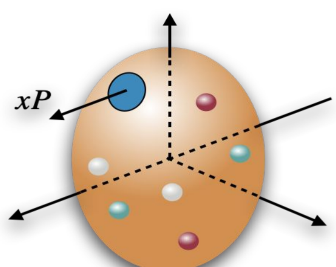


Position and momentum of partons

TMDs



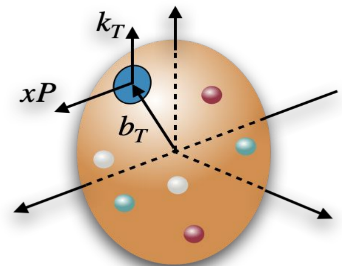
PDFs



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

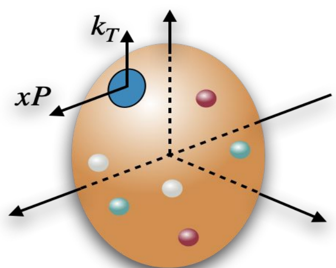
Hadrons in 3D: TMDs and GPDs

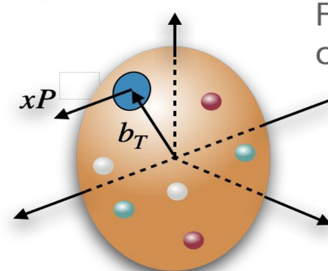
Wigner distributions



Position and momentum of partons

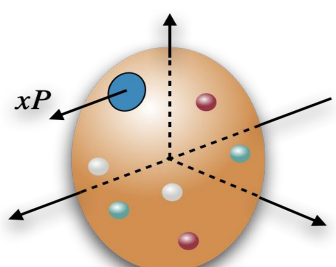
TMDs





Fourier transform
of GPDs

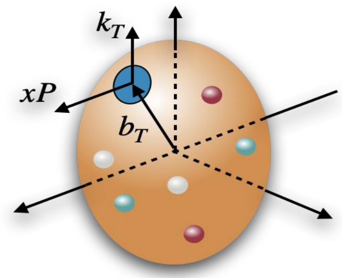
PDFs



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

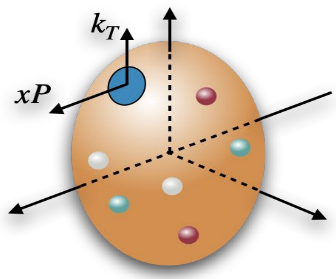
Hadrons in 3D: TMDs and GPDs

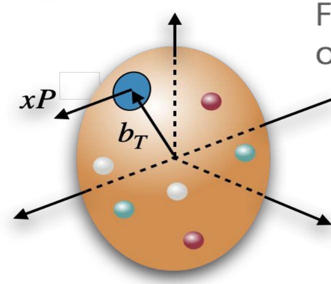
Wigner distributions



Position and momentum of partons

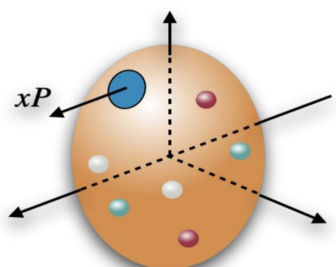
TMDs

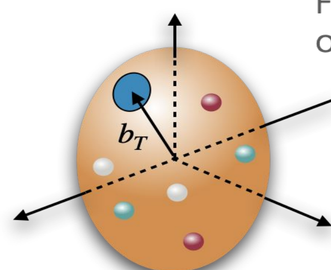




Fourier transform
of GPDs

PDFs



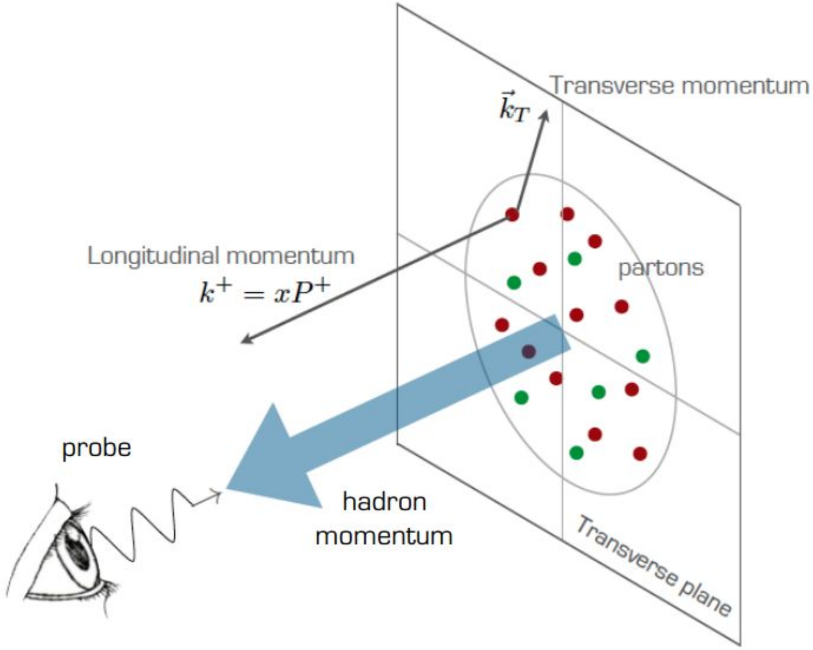


Fourier transform
of Form Factors

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

Parton distribution functions

"Maps" of hadron structure in momentum space



$f_1(x)$

1D structure
in momentum space
("collinear")

$f_1(x, k_T^2)$

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

Credit picture: A. Bacchetta

TMD and collinear 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}	$h_1,\ h_{1T}^\perp$

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

At leading twist: 8 TMD PDFs

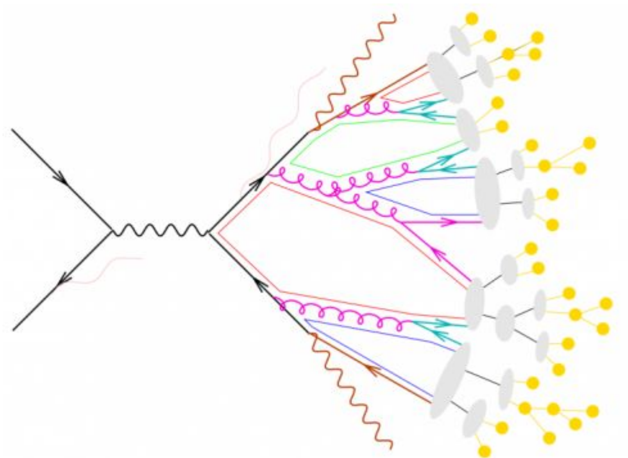
(similar classification for gluons)

- **Black**: time-reversal even AND collinear
- **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

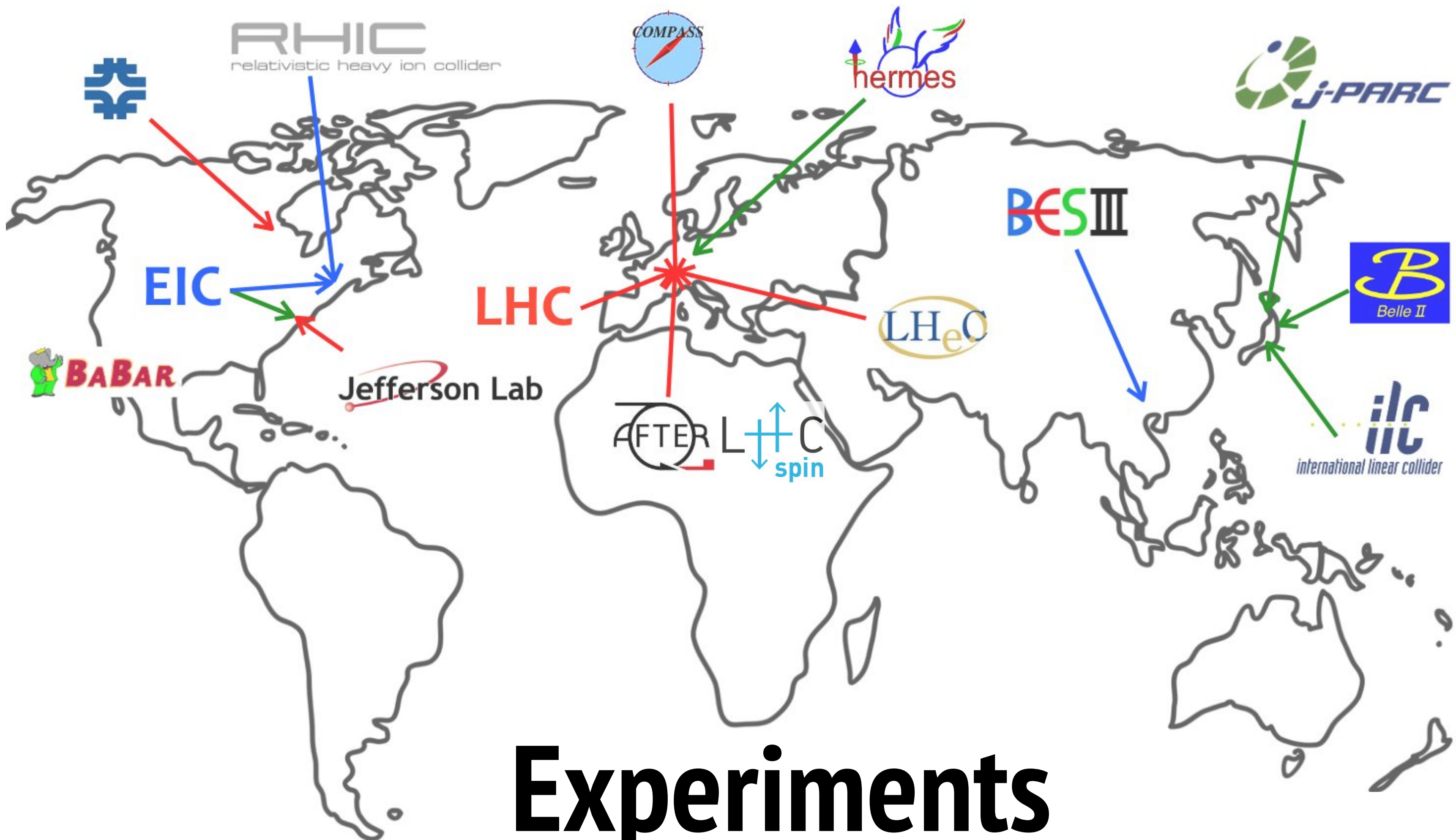


$D_1^h(z)$	single-hadron collinear FF
$D_1^h(z, P_T^2)$	single-hadron TMD FF
$D_1^{h_1\,h_2}(z,\zeta)$	di-hadron FF
$J(s)$	inclusive jet FF
$\mathcal{G}^h(s,z)$	in-jet FF

Why should we study these distributions ?

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**

The data



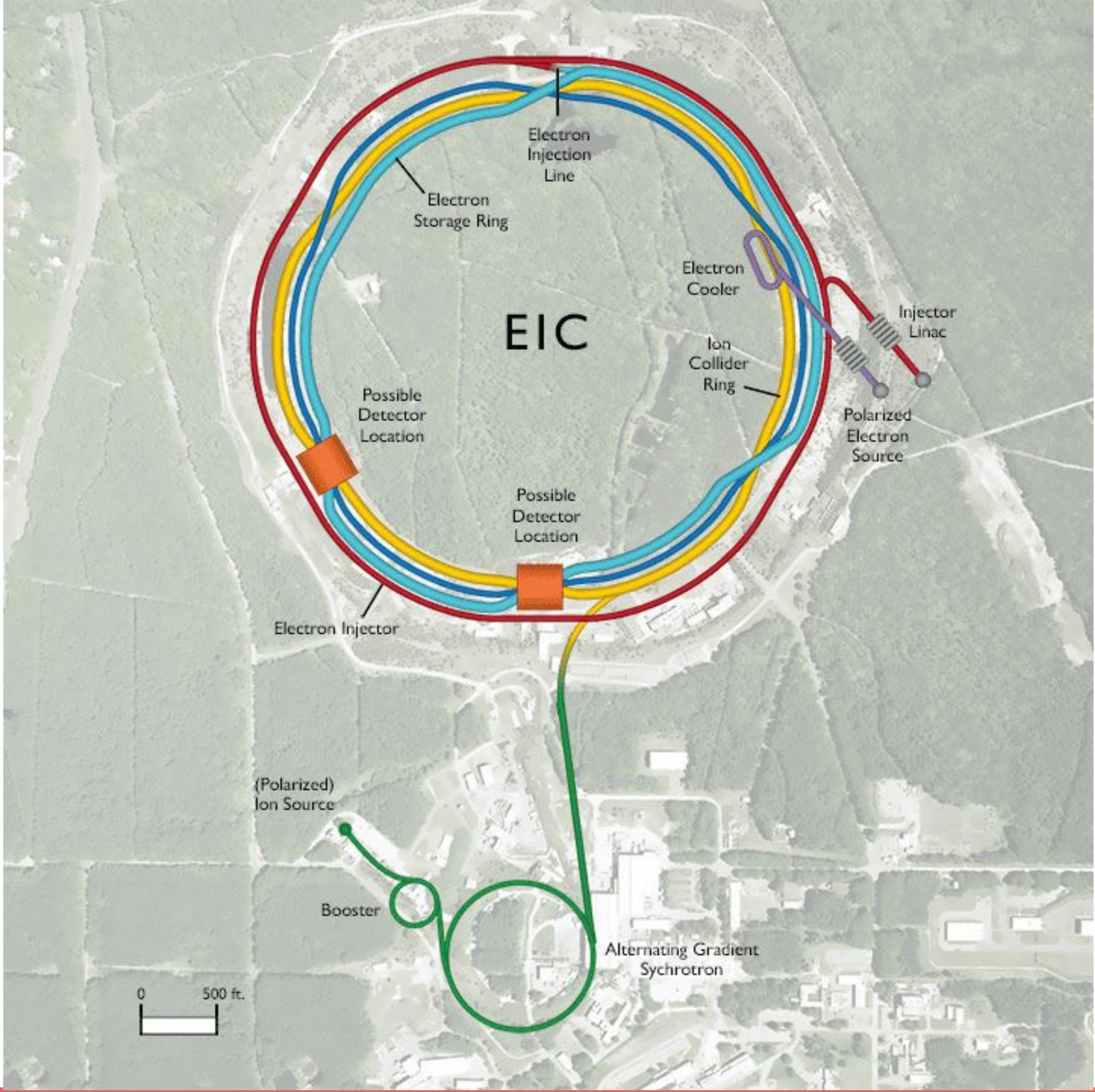
Experiments

The Electron-Ion Collider

(EIC at BNL)

~2.5B$ project

? 2030-2040 ?



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

A fixed-target program at the LHC

Contents lists available at ScienceDirect

ELSEVIER

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

PHYSICS REPORTS

High-x partonic content of nucleons and nuclei

Spin structure of (un)polarized nucleons

Heavy-Ion collisions at large rapidities

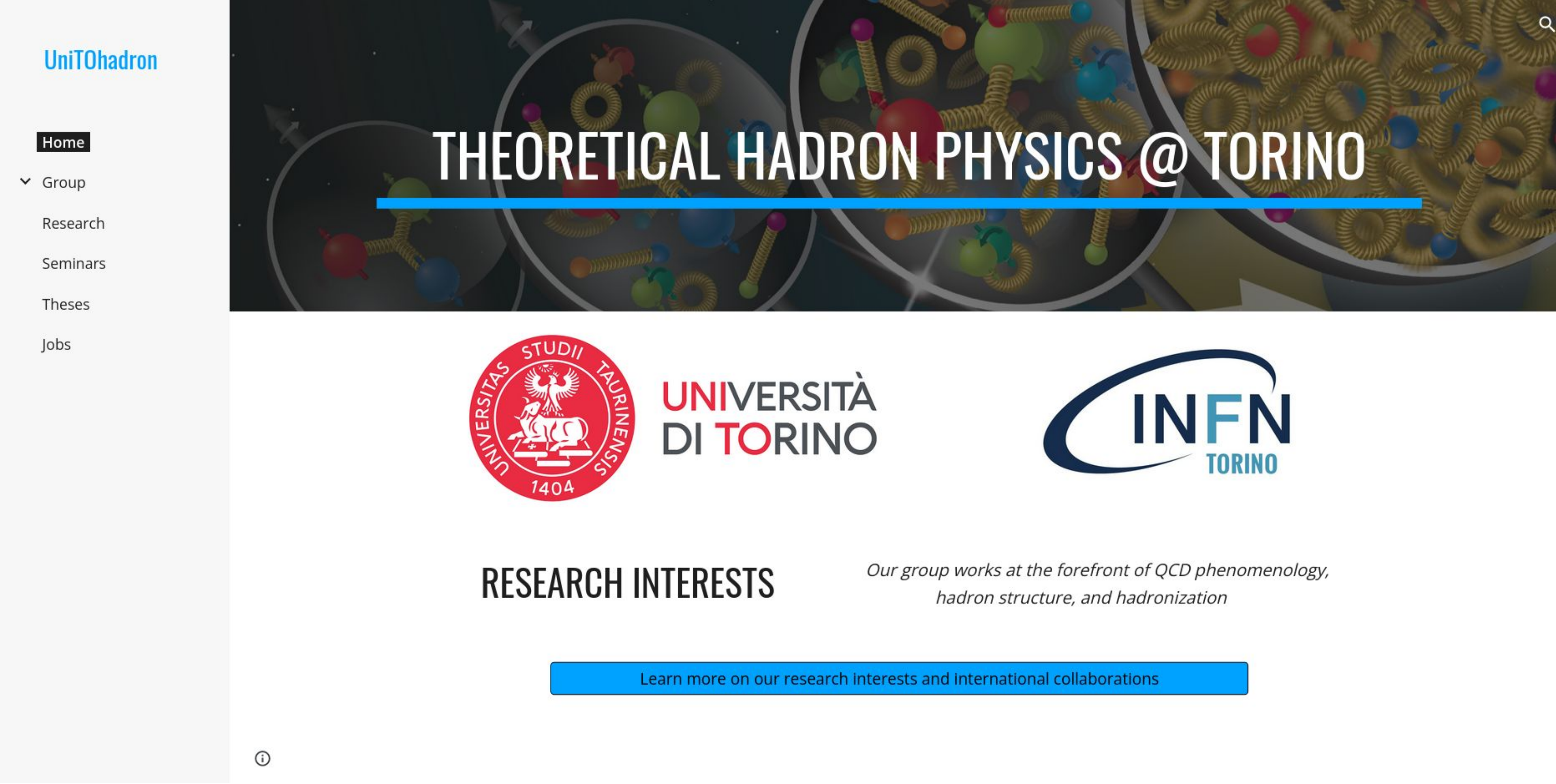
A fi… pro… d astroparticle studies

Check for updates

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

Our group



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

STAFF

Mariaelena Boglione

J. Osvaldo Gonzalez

Emanuele R. Nocera

Andrea Signori

POSTDOCS

Yiyu Zhou

Jennifer Rittenhouse West

Tommaso Giani

GRADUATE STUDENTS

Sara Pontina


Have you tried a closure test first, kiddo..?
Wow … we can study hadrons **in 3D!**
What the …
The more formal theorist
The innocent 3D phenomenologist
The mature 1D phenomenologist

What we do

1D phenomenology

https://nnpdf.mi.infn.it/

Home | The collaboration | Research | For users | Documents | Media | For the public

Research

The NNPDF collaboration has pioneered the use of artificial intelligence and machine learning techniques in the context of high energy physics. More recently, the use of machine learning algorithms in theoretical and experimental high-energy physics has become widespread, with applications from trigger selection to jet substructure classification and detector simulation among many others. Some of the basic machine learning tools used by NNPDF for PDF determination are illustrated here. These include multi-layer feed-forward neural networks for the model-independent parametrization of parton distributions and fragmentation functions, genetic and covariance matrix adaptation algorithms for training and optimization, and closure testing for the systematic validation of the fitting methodology:

> **GLOBAL QCD ANALYSIS AND MACHINE LEARNING**

NNPDF performs determinations of polarized and unpolarized parton distributions (PDFs) and fragmentation functions, using a variety of machine learning tools.

> **GENERAL STRATEGY**

The NNPDF methodology is based on representing the probability in the space of PDFs via the Monte Carlo method, thereby propagating the uncertainty of underlying data.

> **NEURAL NETWORKS**

In the NNPDF approach, parton distribution functions (and fragmentation functions) are parameterized using neural networks as unbiased interpolants.

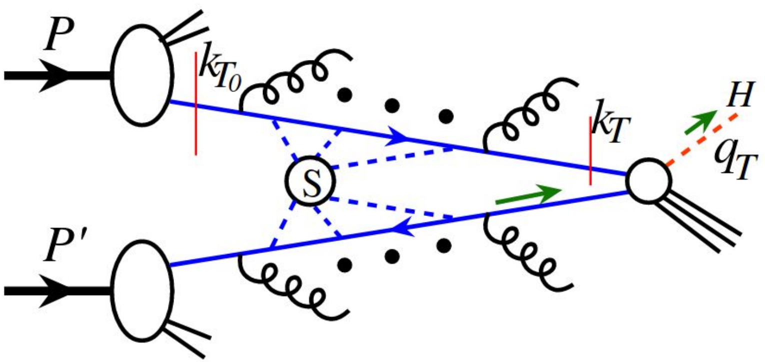
3D phenomenology

$$q_T \ll Q$$

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

$$\frac{d\sigma}{dq_T} \sim \mathcal{H}\, f_1(x_a, k_{T\,a}, Q, Q^2)\, f_1(x_b, k_{T\,b}, Q, Q^2)\, \delta^{(2)}(q_T - k_{T\,a} - k_{T\,b}) \;+ \mathcal{O}(q_T/Q) \;+\; \mathcal{O}(\Lambda/Q)$$

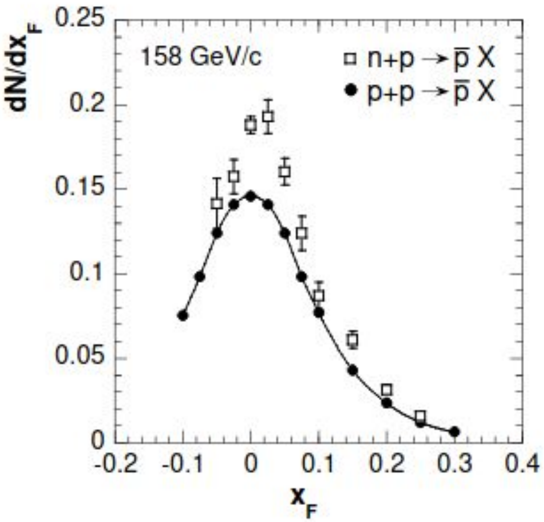
- The TMDs reproduce the structure of the **IR poles** in the cross section (same non-perturbative physics)
- The **observed transverse momentum** is accounted for by the transverse momenta of **quarks**
- The quark transverse momentum has **radiative** (perturbative) and **intrinsic** (non-perturbative)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



Jennifer

$$pp \to \bar{p}X$$

$$pp \to \bar{n}X \to \bar{p}X'$$



NA49 experiment (2002)

The QCD-based calculation estimates a ratio between **1**% and **5**%, contrary to the **30**% result quoted by NA49 (and used in the astro literature)

[**preliminary**]

Intersections between **astrophysics** and **hadron** physics

Yiyu

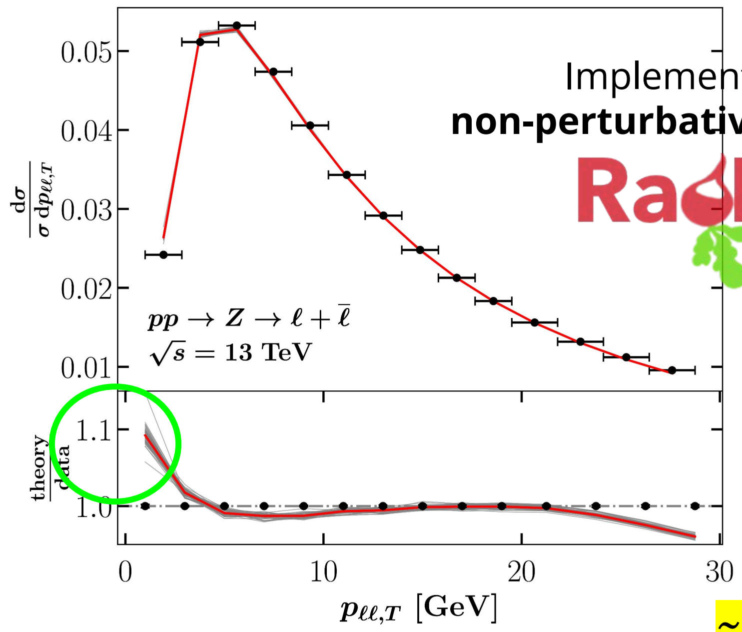
INFN

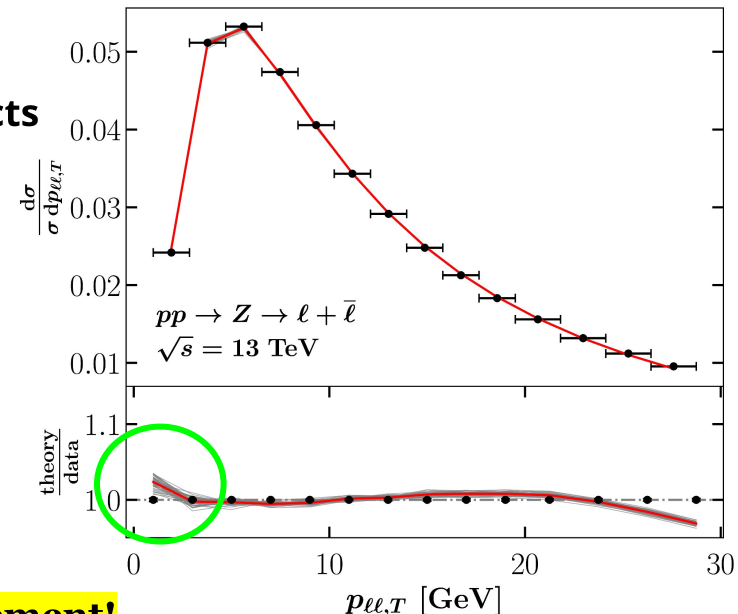
UNIVERSITÀ DI TORINO

Center for Frontiers in Nuclear Science

Implementation of
non-perturbative TMD effects

RadISH





~7% improvement!

Tommaso

UNIVERSITÀ DI TORINO

MARIE CURIE ACTIONS

See also arXiv 2404.07573

BAYHADRON

Marie Sklodowska Curie Action - Postdoc fellowship

2025-2027

Learn more

Sara

UNIVERSITÀ DI TORINO

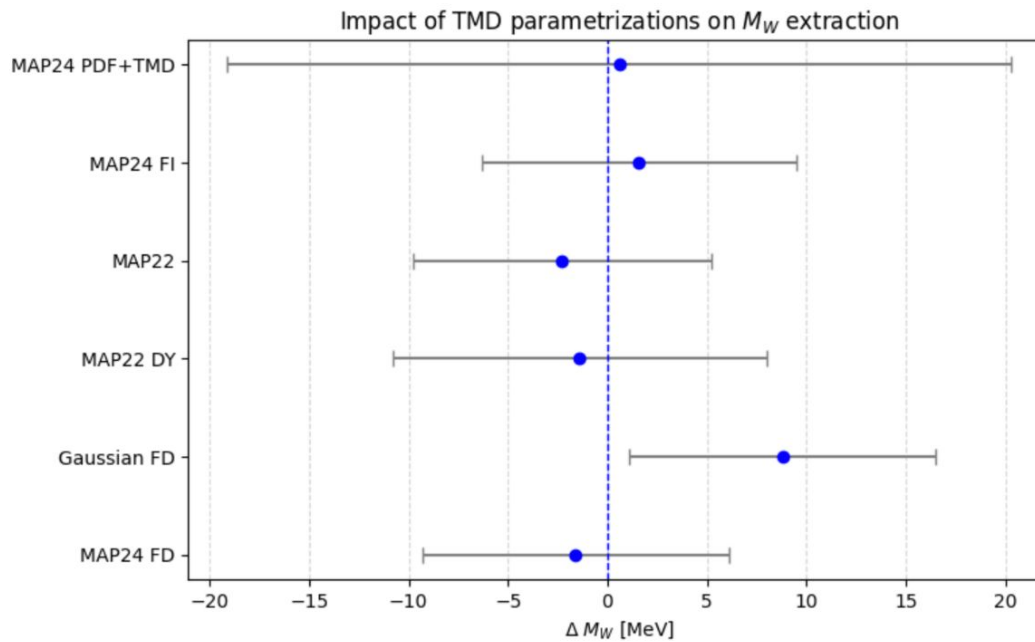
Interplay between **TMD flavor** dependence and **mW** determination

ATLAS measurement

According to the latest ATLAS measurement the result is:

$$M_W = 80366.5 \pm 9.8\ \text{(stat.)} \pm 12.5\ \text{(syst.)}\ \text{MeV}$$

yielding a combined precision of approximately 15.9 MeV.



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!**

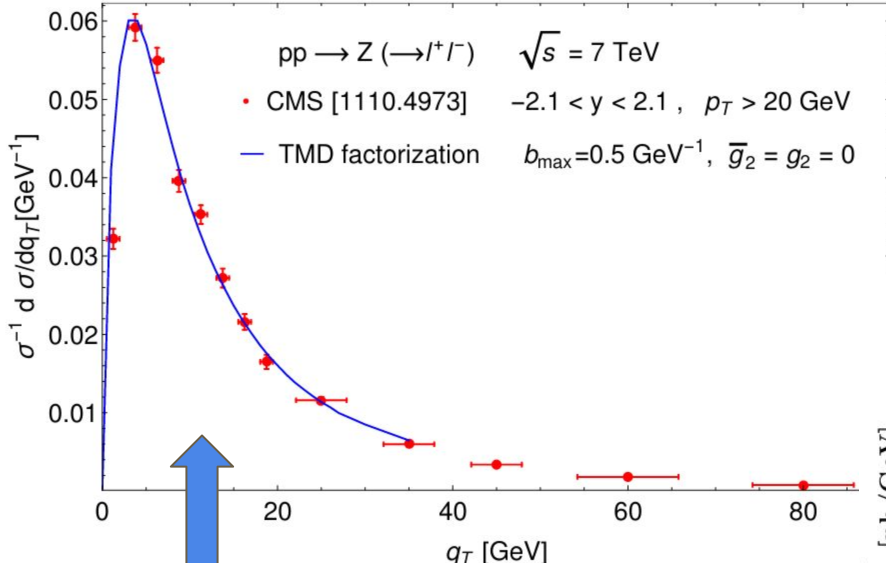
4. A detailed knowledge of hadron structure has an impact on other (sub)fields, for example **HEP** (mW et al.) and **astrophysics**

Backup

TMD phenomenology

$q_T \ll Q$

https://inspirehep.net/literature/1785810

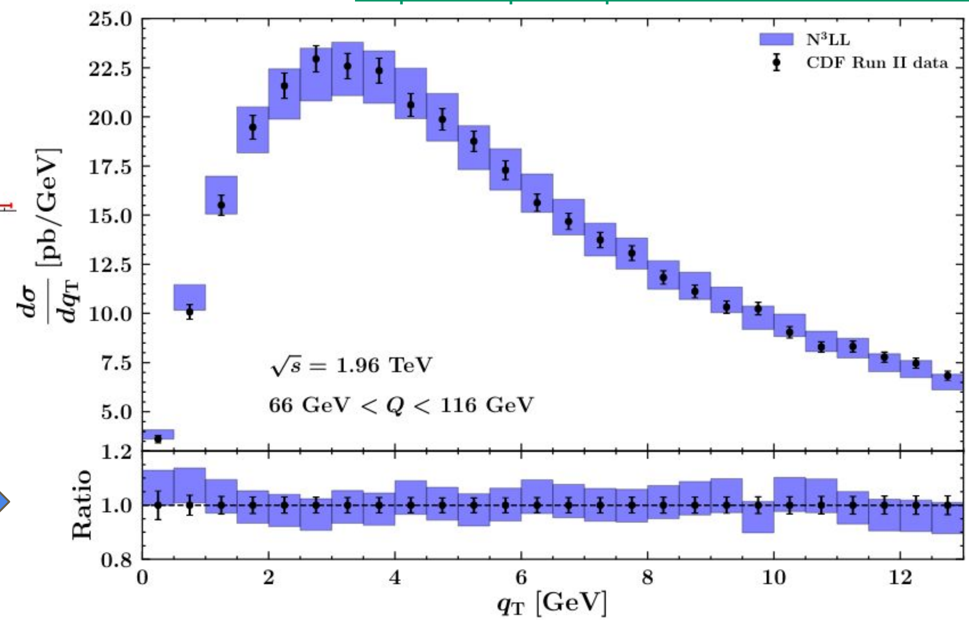


$$q_T \,/\, Q \;<\; 0.3$$

Hadronic collisions

https://inspirehep.net/literature/1771006

$$q_T \,/\, Q \;<\; 0.2$$

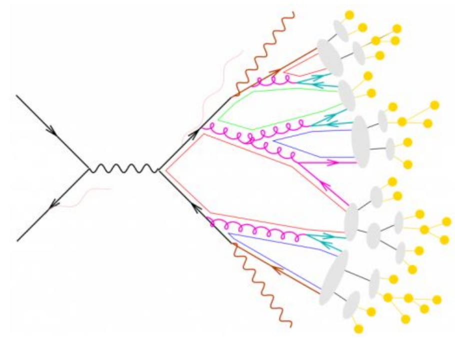


Hadronization

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

For example:

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



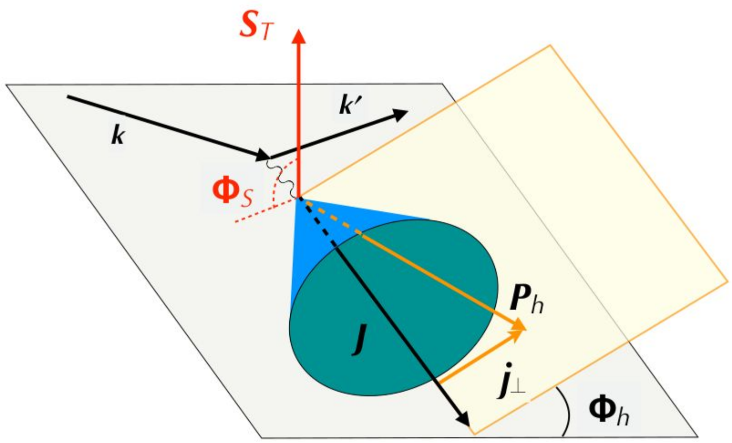
Hadronization

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

For example:

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

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

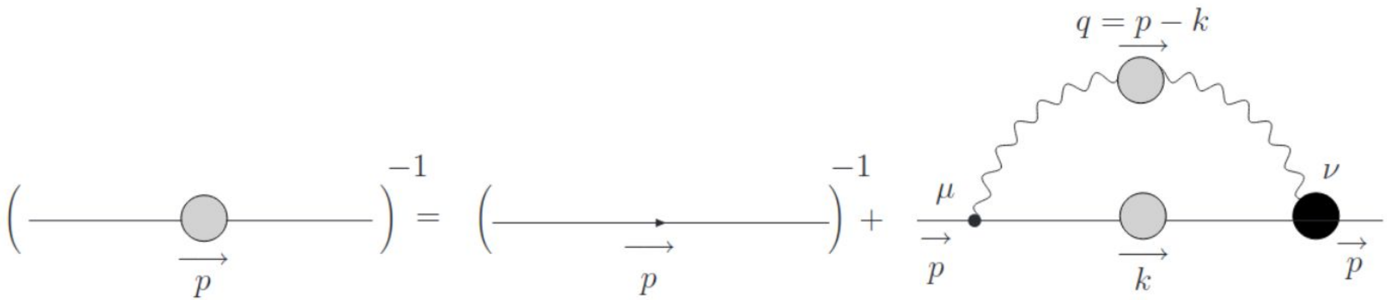


2. Explore the **chiral-odd sector of hadronization** via polarized inclusive jets, in-jet FFs, and FFs

   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

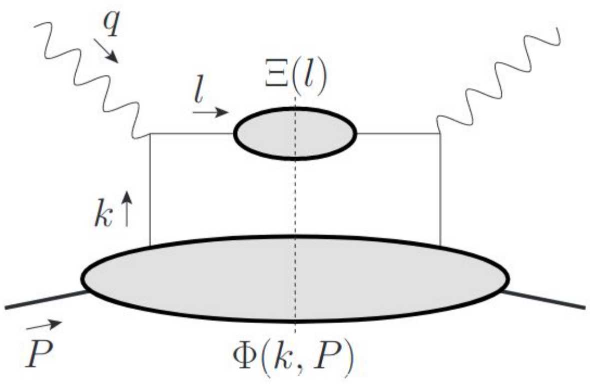
Hadronization and mass generation



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**



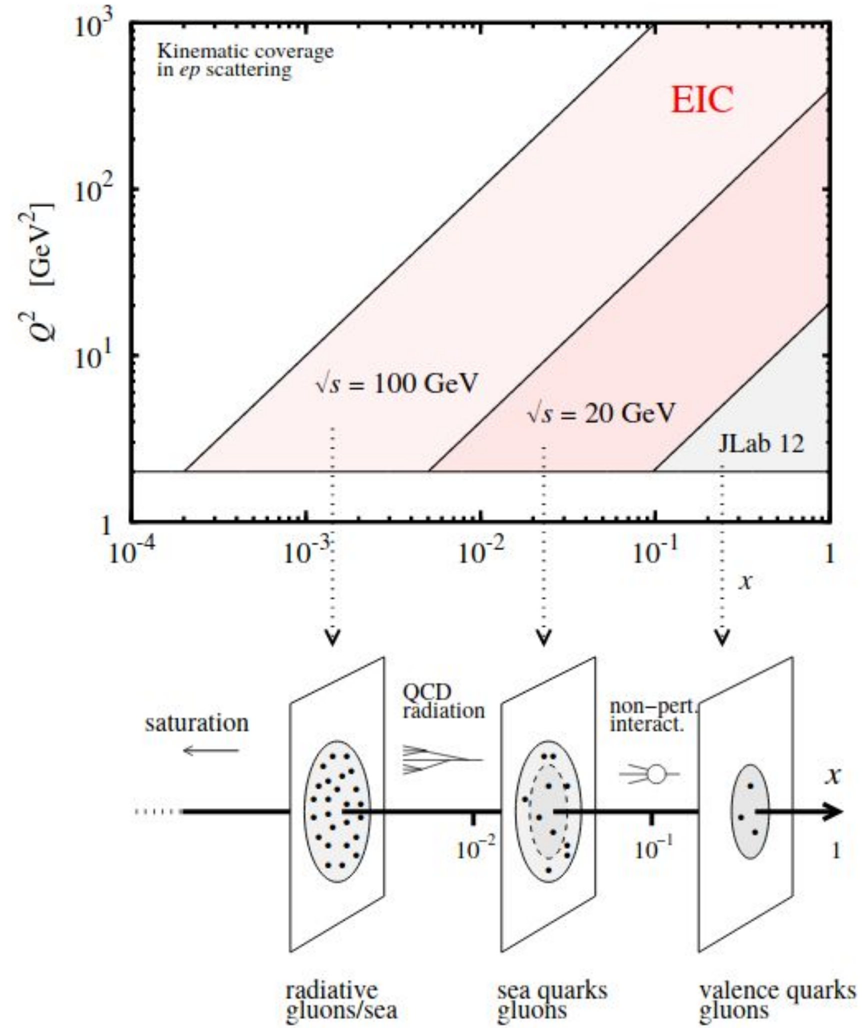
SIDIS coverage

Importance of complementary experiments

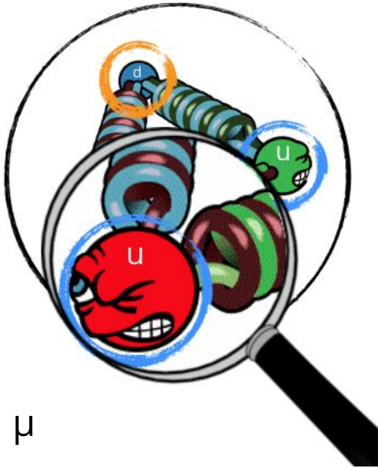
from JLab 12 GeV, Hermes, Compass
to the EIC

zooming into hadron structure

Credit picture: C. Weiss



QCD evolution of a TMD PDF



$$F_a(x, b_T^2; \mu, \zeta) = F_a(x, b_T^2; \mu_0, \zeta_0)$$ → TMD distribution at initial scales

x $$\exp\left[\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \boxed{\gamma_F\left(\alpha_s(\mu'), \frac{\zeta}{\mu'^2}\right)}\right]$$ → evolution in μ

Calculable in pQCD

x $$\left(\frac{\zeta}{\zeta_0}\right)^{-\boxed{D(b_T\mu_0, \alpha_s(\mu_0))}\boxed{+g_K(b_T;\lambda)}}$$ → evolution in ζ

Non-pert. corrections (large bT)

$$F_a(x, b_T^2; \mu_0, \zeta_0) = \sum_b \boxed{C_{a/b}(x, b_T^2, \mu_0, \zeta_0)} \otimes \underline{f_b(x, \mu_0)} \boxed{F_{NP}(b_T; \lambda)}$$

Prior knowledge assumed (?)

See e.g. https://inspirehep.net/literature/1785810 for more details (but also JCC book, etc.)

mW 2019 results

ATLAS - 7 TeV

$$-6 \leq M_{W^+} \leq 9 \text{ MeV}$$

$$-4 \leq M_{W^-} \leq 7 \text{ MeV}$$

The fact that **quark intrinsic transverse momentum** can be **flavor dependent** leads to an **additional uncertainty** on mW, not considered so far

- the four-loop QCD corrections generates a shift of -2.2 MeV
- The expectation from missing higher orders is 4 MeV

Eur.Phys.J. C74 (2014) 3046 ("Global EW fit at NNLO")

Some open questions

A non-exhaustive *personal* list of open questions:

- deepen our understanding of **sea** quarks
- **flavor structure** of TMDs
- experimental confirmation of **sign change** relation
- **gluon** observables and **spin-1** effects
- what can **hadronization** teach us about **confinement**?
- interplay between **nuclear/hadron** and **high-energy** physics
- ..