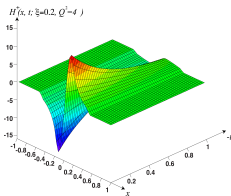
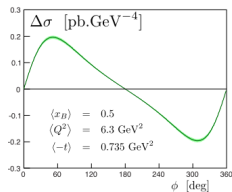
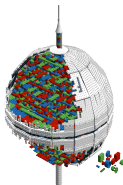
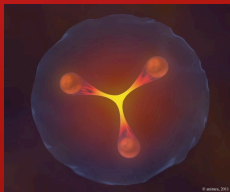


DE LA RECHERCHE À L'INDUSTRIE

cea



Prospects on nucleon tomography



BNL Physics Colloquium | Hervé MOUTARDE

Apr. 3, 2018

www.cea.fr

université
PARIS-SACLAY

Nucleon Tomography

Motivation

Mass without mass
Nucleon structure
Physical content

Phenomenology

Formal definition
Fit status
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DVCS kinematics

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Ergonomics
Examples
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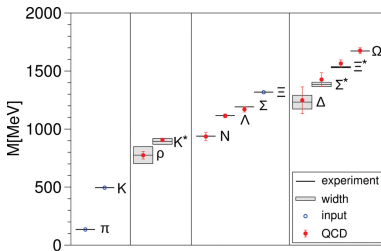
Involvement in PHENIX (2000-10) and sPHENIX

- **Hardware** muon arms electronics
- **Software** Muon tracking, simulation
- **Analysis** J/ψ in dd, d-Au, Au-Au

Today's talk: 3D hadron structure and the need for an EIC

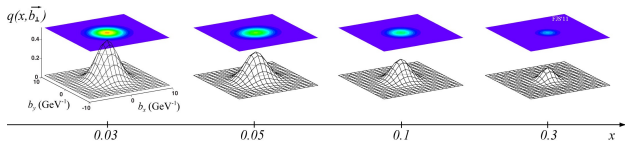
Nucleon Tomography

- Lattice QCD clearly showed that the mass of hadrons is generated by the **interaction**, not by the quark masses.



Durr *et al.*, Science **322**, 1224 (2008)

- Can we **map** the *location of mass* inside a hadron?



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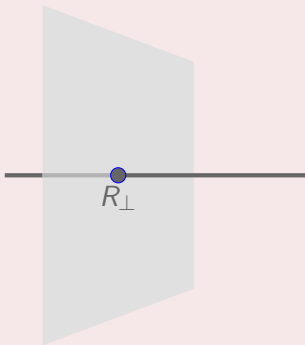
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Manifestation of 3D nucleon structure in scattering processes?



- Transverse center of momentum $R_{\perp} = \sum_i x_i r_{\perp i}$

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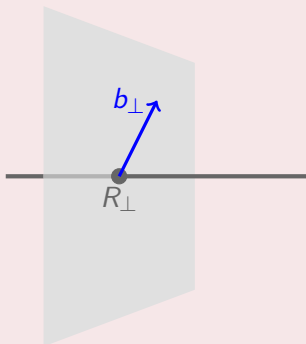
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Manifestation of 3D nucleon structure in scattering processes?



- Transverse center of momentum $R_{\perp} = \sum_i x_i r_{\perp i}$,
- Impact parameter b_{\perp} ,

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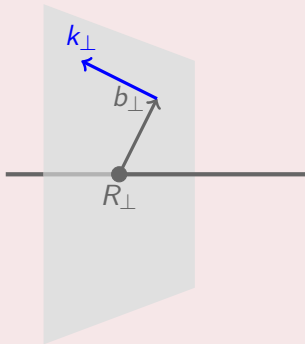
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Manifestation of 3D nucleon structure in scattering processes?



- Transverse center of momentum $R_{\perp} = \sum_i x_i r_{\perp i}$,
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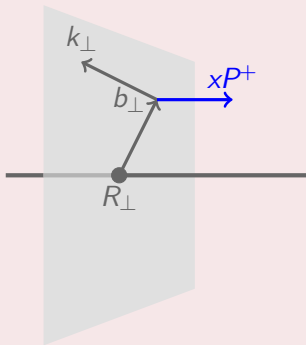
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Manifestation of 3D nucleon structure in scattering processes?



- Transverse center of momentum $R_{\perp} = \sum_i x_i r_{\perp i}$,
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- Transverse momentum k_{\perp} ,
- Longitudinal momentum xP^+ .

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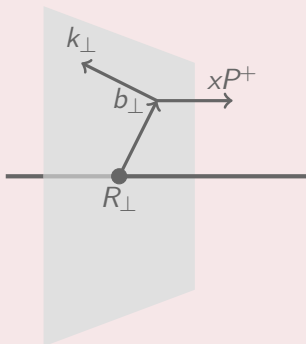
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Manifestation of 3D nucleon structure in scattering processes?



- Transverse center of momentum $R_{\perp} = \sum_i x_i r_{\perp i}$,
- Impact parameter b_{\perp} ,
- Transverse momentum k_{\perp} ,
- Longitudinal momentum xP^+ .
- What is the distortion brought by spin?

Imaging the origin of mass.

Identification of underlying mechanisms from parton distributions.

Nucleon Tomography

How can we recover the well-known characteristics of the nucleon from the properties of its **colored building blocks**?

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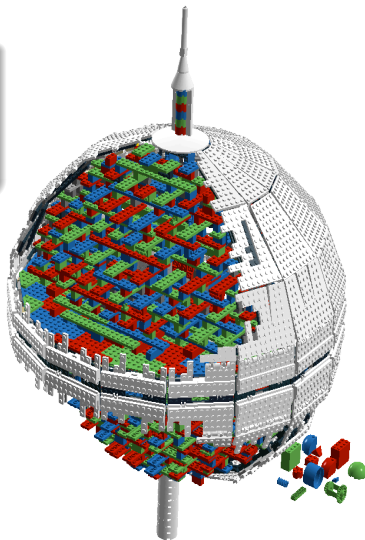
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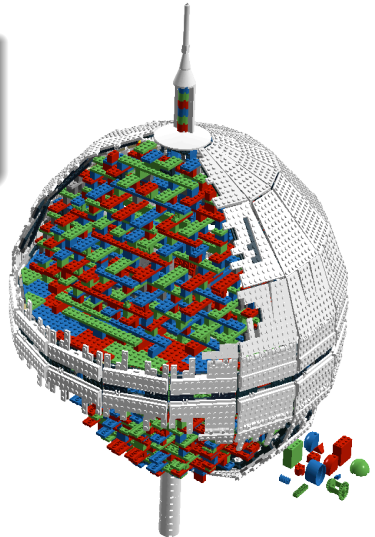
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Mass?



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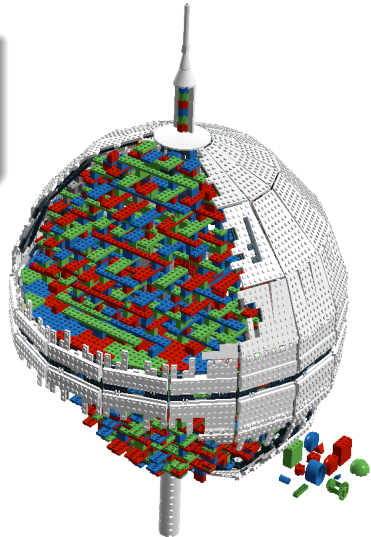
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Mass?
Spin?



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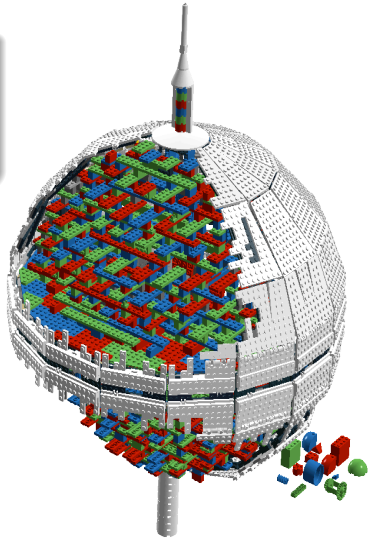
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Spin?
Charge?



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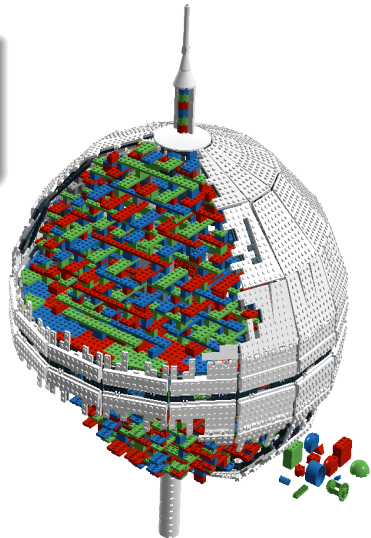
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Spin?
Charge?

...



Nucleon Tomography

How can we recover the well-known characteristics of the nucleon from the properties of its **colored building blocks**?

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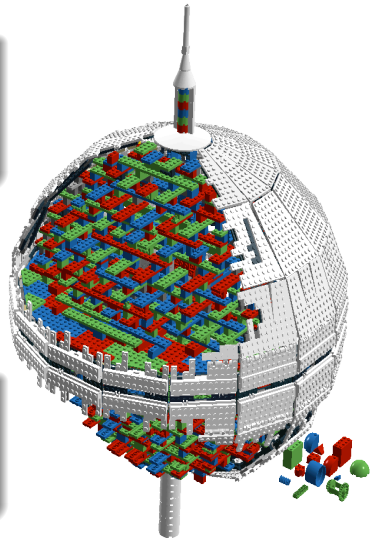
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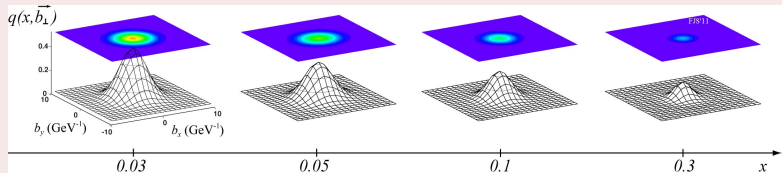
...

What are the relevant **effective degrees of freedom** and **effective interaction** at large distance?



Structuring questions for the hadron physics community

- QCD mechanisms behind the origin of **mass** in the **visible universe**?
- **Cartography** of interactions giving its mass to the nucleon?
- **Pressure** and **density** profiles of the nucleon as a continuous medium?
- **Localization** of quarks and gluons inside the nucleon?
- Possible impact on **initial state** of pp or pA scattering?



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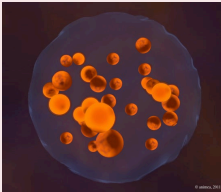
Conclusion

Perturbative and nonperturbative QCD.

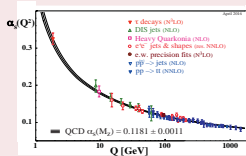
Study nucleon structure to shed new light on nonperturbative QCD.

Nucleon Tomography

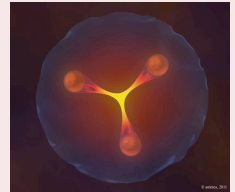
Perturbative QCD



Asymptotic freedom



Nonperturbative QCD



Motivation

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Interface between perturbative and nonperturbative regimes

- Define **universal** objects describing 3D nucleon structure:
Generalized Parton Distributions (GPD).
- Relate GPDs to measurements using **factorization**:
Virtual Compton Scattering (DVCS, TCS),
Deeply Virtual Meson production (DVMP).
- Get **experimental knowledge** of nucleon structure.

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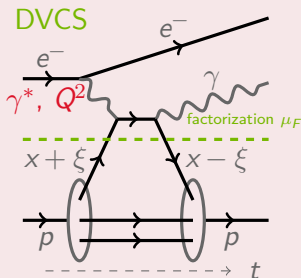
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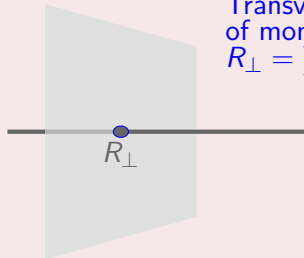
Conclusion

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
- DVCS recognized as the cleanest channel to access GPDs.

Deeply Virtual Compton Scattering (DVCS)



Transverse center of momentum R_\perp

$$R_\perp = \sum_i x_i r_{\perp i}$$


Nucleon Tomography

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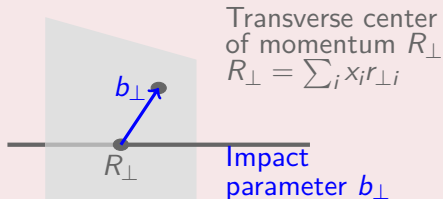
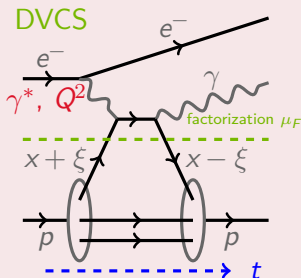
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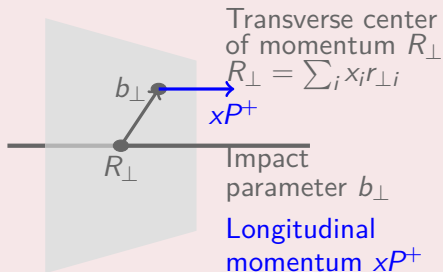
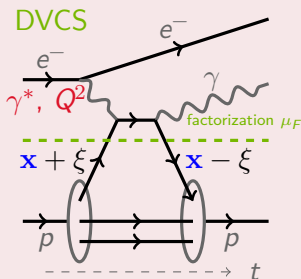
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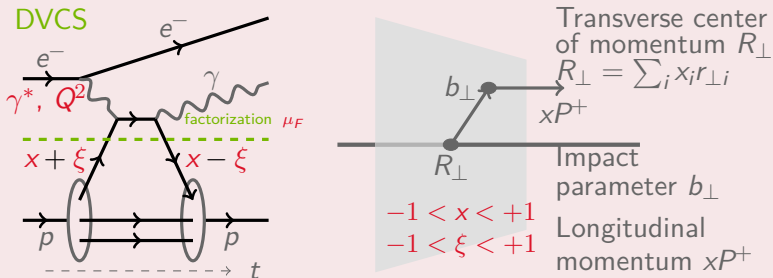
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Deeply Virtual Compton Scattering (DVCS)



- **24 GPDs** $F^i(x, \xi, t, \mu_F)$ for each parton type $i = g, u, d, \dots$ for leading and sub-leading twists.

Nucleon Tomography

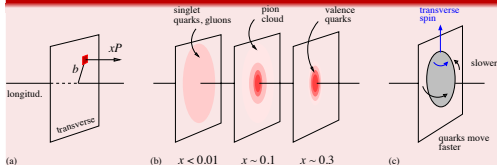
- **Probabilistic interpretation** of Fourier transform of $\text{GPD}(x, \xi = 0, t)$ in **transverse plane**.

$$\rho(x, b_{\perp}, \lambda, \lambda_N) = \frac{1}{2} \left[H(x, 0, b_{\perp}^2) + \frac{b_{\perp}^j \epsilon_{ji} S_{\perp}^i}{M} \frac{\partial E}{\partial b_{\perp}^2}(x, 0, b_{\perp}^2) + \lambda \lambda_N \tilde{H}(x, 0, b_{\perp}^2) \right]$$

- Notations : quark helicity λ , nucleon longitudinal polarization λ_N and nucleon transverse spin S_{\perp} .

Burkardt, Phys. Rev. **D62**, 071503 (2000)

Can we obtain this picture from exclusive measurements?



Weiss, AIP Conf. Proc. **1149**, 150 (2009)

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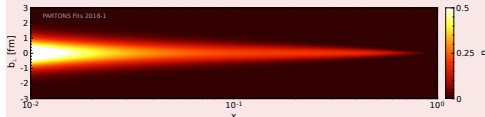
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- Notations : quark helicity λ , nucleon longitudinal polarization λ_N and nucleon transverse spin S_{\perp} .

Burkardt, Phys. Rev. **D62**, 071503 (2000)

Not quite, but close!



Moutarde *et al.*,
Eur. Phys. J. **C78**,
890 (2018)

Nucleon Tomography

- Most general structure of matrix element of energy momentum tensor between nucleon states:

$$\begin{aligned} \left\langle N, P + \frac{\Delta}{2} \right| T^{\mu\nu} \left| N, P - \frac{\Delta}{2} \right\rangle &= \bar{u} \left(P + \frac{\Delta}{2} \right) \left[A(t) \gamma^{(\mu} P^{\nu)} \right. \\ &\quad \left. + B(t) P^{(\mu} i \sigma^{\nu)\lambda} \frac{\Delta_\lambda}{2M} + \frac{C(t)}{M} (\Delta^\mu \Delta^\nu - \Delta^2 \eta^{\mu\nu}) \right] u \left(P - \frac{\Delta}{2} \right) \end{aligned}$$

with $t = \Delta^2$.

- Key observation: **link between GPDs and gravitational form factors**

$$\begin{aligned} \int dx x H^q(x, \xi, t) &= A^q(t) + 4\xi^2 C^q(t) \\ \int dx x E^q(x, \xi, t) &= B^q(t) - 4\xi^2 C^q(t) \end{aligned}$$

Ji, Phys. Rev. Lett. **78**, 610 (1997)

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■ Spin sum rule:

$$\int dx x (H^q(x, \xi, 0) + E^q(x, \xi, 0)) = A^q(0) + B^q(0) = 2J^q$$

Ji, Phys. Rev. Lett. **78**, 610 (1997)

■ Shear and pressure of a hadron considered as a continuous medium:

$$\langle N | T^{ij}(\vec{r}) | N \rangle = s(r) \left(\frac{r^i r^j}{r^2} - \frac{1}{3} \delta^{ij} \right) + p(r) \delta^{ij}$$

Polyakov and Shuvaev, hep-ph/0207153

■ Energy density, tangential and radial pressures of a hadron considered as a continuous medium.

Lorcé *et al.*, Eur. Phys. J. **C79**, 89 (2019)

Mechanical properties of hadrons.

From the nucleon to compact stars (1/3).

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- **Matrix element** in the Breit frame ($a = q, g$):

$$\left\langle \frac{\Delta}{2} \left| T_a^{\mu\nu}(0) \right| - \frac{\Delta}{2} \right\rangle = M \left\{ \eta^{\mu 0} \eta^{\nu 0} \left[A_a(t) + \frac{t}{4M^2} B_a(t) \right] \right. \\ \left. + \eta^{\mu\nu} \left[\bar{C}_a(t) - \frac{t}{M^2} C_a(t) \right] + \frac{\Delta^\mu \Delta^\nu}{M^2} C_a(t) \right\}$$

- Anisotropic fluid in **relativistic hydrodynamics**:

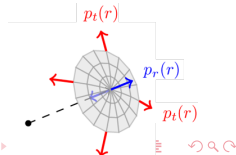
$$\Theta^{\mu\nu}(\vec{r}) = [\varepsilon(r) + p_t(r)] u^\mu u^\nu - p_t(r) \eta^{\mu\nu} + [p_r(r) - p_t(r)] \chi^\mu \chi^\nu$$

where u^μ and $\chi^\mu = x^\mu / r$.

- Define **isotropic pressure** and **pressure anisotropy**:

$$p(r) = \frac{p_r(r) + 2 p_t(r)}{3}$$

$$s(r) = p_r(r) - p_t(r)$$



Nucleon Tomography

- Write dictionary between quantum and fluid pictures:

Motivation

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Nucleon structure

$$\frac{\varepsilon_a(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ A_a(t) + \bar{C}_a(t) + \frac{t}{4M^2} [B_a(t) - 4C_a(t)] \right\}$$

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$$\frac{p_{r,a}(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\bar{C}_a(t) - \frac{4}{r^2} \frac{t^{-1/2}}{M^2} \frac{d}{dt} \left(t^{3/2} C_a(t) \right) \right\}$$

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$$\frac{p_{t,a}(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\bar{C}_a(t) + \frac{4}{r^2} \frac{t^{-1/2}}{M^2} \frac{d}{dt} \left[t \frac{d}{dt} \left(t^{3/2} C_a(t) \right) \right] \right\}$$

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$$\frac{p_a(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\bar{C}_a(t) + \frac{2}{3} \frac{t}{M^2} C_a(t) \right\}$$

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$$\frac{s_a(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\frac{4}{r^2} \frac{t^{-1/2}}{M^2} \frac{d^2}{dt^2} \left(t^{5/2} C_a(t) \right) \right\}$$

Mechanical properties of hadrons.

From the nucleon to compact stars (3/3).

- Evaluate orders of magnitude with naive multiple model:

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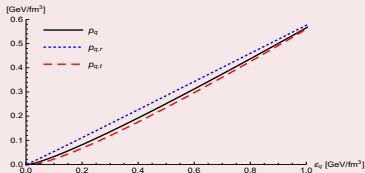
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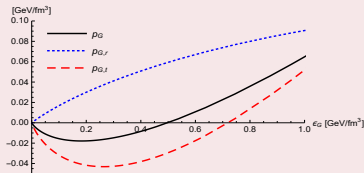
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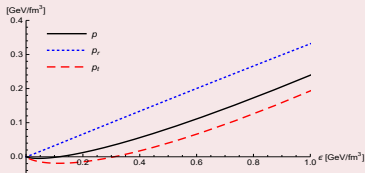
quark



glue

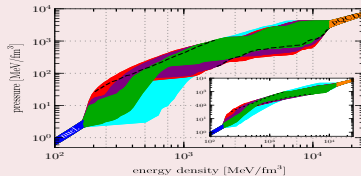


quark + glue



Lorcé et al., Eur. Phys. J.
C79, 89 (2019)

Neutron stars



Annala et al., Phys. Rev.
Lett. **120**, 172703 (2018)

Phenomenology

Spin-0 Generalized Parton Distribution.

Definition and simple properties.

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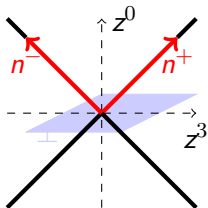
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$$H_{\pi}^q(x, \xi, t) = \frac{1}{2} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P + \frac{\Delta}{2} \left| \bar{q} \left(-\frac{z}{2} \right) \gamma^+ q \left(\frac{z}{2} \right) \right| \pi, P - \frac{\Delta}{2} \right\rangle_{\substack{z^+=0 \\ z_{\perp}=0}}$$

with $t = \Delta^2$ and $\xi = -\Delta^+/(2P^+)$.



■ PDF forward limit

$$H^q(x, 0, 0) = q(x)$$

References

Müller *et al.*, Fortschr. Phys. **42**, 101 (1994)
Ji, Phys. Rev. Lett. **78**, 610 (1997)
Radyushkin, Phys. Lett. **B380**, 417 (1996)

Spin-0 Generalized Parton Distribution.

Definition and simple properties.

Nucleon Tomography

$$H_{\pi}^q(x, \xi, t) = \frac{1}{2} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P + \frac{\Delta}{2} \left| \bar{q} \left(-\frac{z}{2} \right) \gamma^+ q \left(\frac{z}{2} \right) \right| \pi, P - \frac{\Delta}{2} \right\rangle_{z_{\perp}=0}^{z_{\perp}=0}$$

Motivation

Mass without mass
Nucleon structure
Physical content

with $t = \Delta^2$ and $\xi = -\Delta^+/(2P^+)$.

Phenomenology

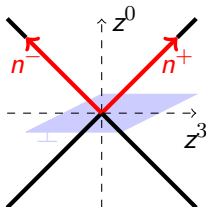
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References

Müller *et al.*, Fortschr. Phys. **42**, 101 (1994)
Ji, Phys. Rev. Lett. **78**, 610 (1997)
Radyushkin, Phys. Lett. **B380**, 417 (1996)

- PDF forward limit
- Form factor sum rule

$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t)$$

Spin-0 Generalized Parton Distribution.

Definition and simple properties.

Nucleon Tomography

$$H_{\pi}^q(x, \xi, t) = \frac{1}{2} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P + \frac{\Delta}{2} \left| \bar{q} \left(-\frac{z}{2} \right) \gamma^+ q \left(\frac{z}{2} \right) \right| \pi, P - \frac{\Delta}{2} \right\rangle_{z_{\perp}=0}^{z_{\perp}=0}$$

Motivation

Mass without mass
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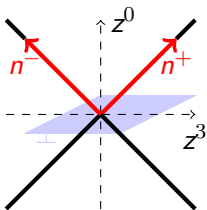
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with $t = \Delta^2$ and $\xi = -\Delta^+/(2P^+)$.



References

Müller *et al.*, Fortschr. Phys. **42**, 101 (1994)
Ji, Phys. Rev. Lett. **78**, 610 (1997)
Radyushkin, Phys. Lett. **B380**, 417 (1996)

- PDF forward limit
- Form factor **sum rule**
- H^q is an **even function** of ξ from time-reversal invariance.

Spin-0 Generalized Parton Distribution.

Definition and simple properties.

Nucleon Tomography

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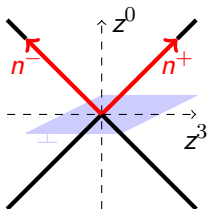
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$$H_{\pi}^q(x, \xi, t) = \frac{1}{2} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P + \frac{\Delta}{2} \left| \bar{q} \left(-\frac{z}{2} \right) \gamma^+ q \left(\frac{z}{2} \right) \right| \pi, P - \frac{\Delta}{2} \right\rangle_{z_{\perp}=0}^{z_{\perp}=0}$$

with $t = \Delta^2$ and $\xi = -\Delta^+/(2P^+)$.



References

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Ji, Phys. Rev. Lett. **78**, 610 (1997)
Radyushkin, Phys. Lett. **B380**, 417 (1996)

- PDF forward limit
- Form factor **sum rule**
- H^q is an **even function** of ξ from time-reversal invariance.
- H^q is **real** from hermiticity and time-reversal invariance.

Spin-0 Generalized Parton Distribution.

Not so simple properties.

Nucleon Tomography

■ Polynomiality

$$\int_{-1}^{+1} dx x^n H^q(x, \xi, t) = \text{polynomial in } \xi$$

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■ Polynomiality

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Not so simple properties.

Nucleon Tomography

■ Polynomiality

Lorentz covariance

Motivation

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■ Positivity

$$H^q(x, \xi, t) \leq \sqrt{q\left(\frac{x+\xi}{1+\xi}\right) q\left(\frac{x-\xi}{1-\xi}\right)}$$

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■ Positivity

Positivity of Hilbert space norm

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Not so simple properties.

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■ Polynomiality

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■ Positivity

Positivity of Hilbert space norm

■ H^q has support $x \in [-1, +1]$.

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Relativistic quantum mechanics

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Not so simple properties.

Nucleon Tomography

■ Polynomiality

Lorentz covariance

■ Positivity

Positivity of Hilbert space norm

■ H^q has support $x \in [-1, +1]$.

Relativistic quantum mechanics

■ Soft pion theorem (pion target)

$$H^q(x, \xi = 1, t = 0) = \frac{1}{2} \phi_\pi^q \left(\frac{1+x}{2} \right)$$

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■ Polynomiality

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■ Positivity

Positivity of Hilbert space norm

■ H^q has support $x \in [-1, +1]$.

Relativistic quantum mechanics

■ Soft pion theorem (pion target)

Dynamical chiral symmetry breaking

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■ H^q has support $x \in [-1, +1]$.

Relativistic quantum mechanics

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■ Soft pion theorem (pion target)

Dynamical chiral symmetry breaking

Conclusion

How can we implement *a priori* these theoretical constraints?

- In the following, focus on **polynomiality** and **positivity**.
- Do not discuss the reduction to form factors or PDFs.

DVCS analysis and fits.

No global GPD fit has been obtained so far.

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- GPD fits **only in the small x_B region** with a **flexible** parameterization (kinematic simplifications).
- Global fits of CFFs in the sea, valence and glue regions.
- Some GPD models with non-flexible parameterizations adjusted to experimental DVCS or DVMP data.

Kumerički *et al.*, Eur. Phys. J. **A52**, 157 (2016)

The situation can be improved!

- GPD parameterizations satisfying *a priori* all theoretical constraints on GPDs.
- Computing framework to go beyond leading order and leading twist analysis.

Exclusive processes of current interest (1/2). Factorization and universality.

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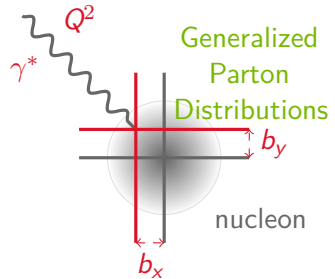
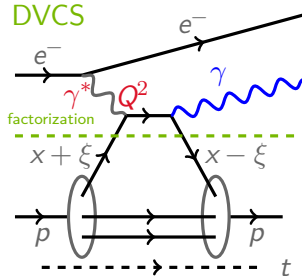
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Exclusive processes of current interest (1/2). Factorization and universality.

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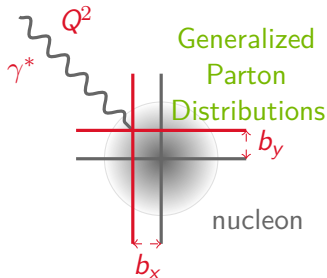
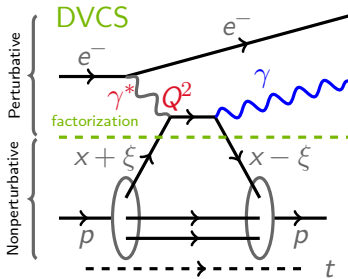
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Exclusive processes of current interest (1/2). Factorization and universality.

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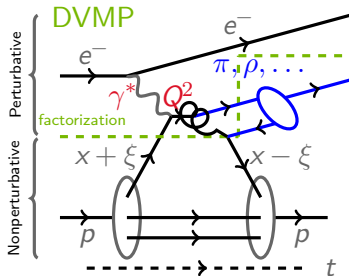
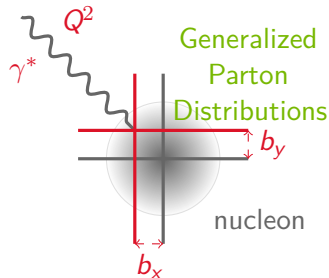
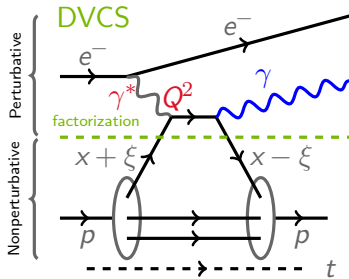
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Exclusive processes of current interest (1/2). Factorization and universality.

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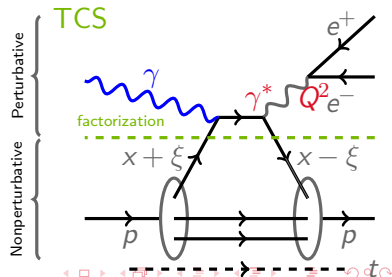
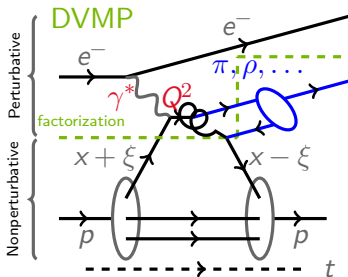
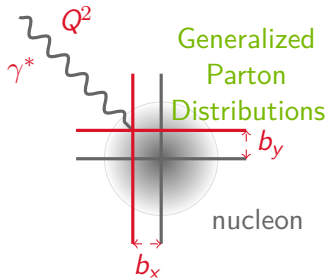
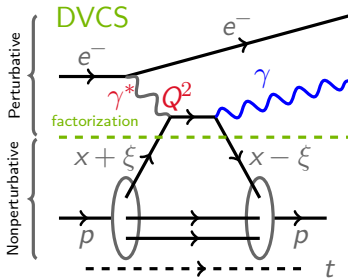
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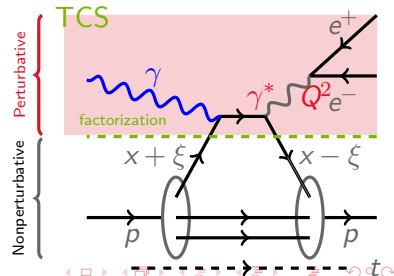
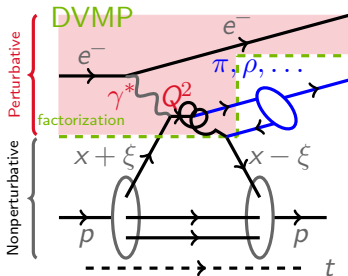
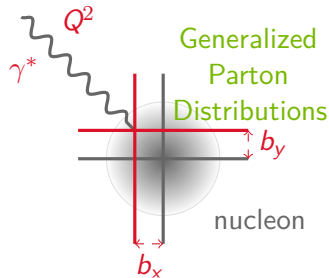
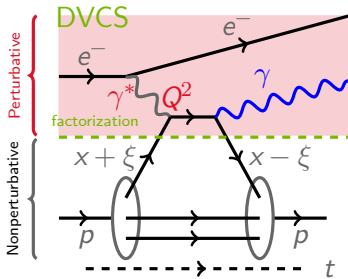
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Exclusive processes of current interest (1/2). Factorization and universality.

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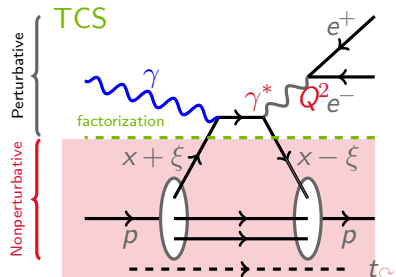
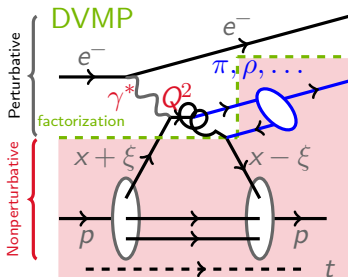
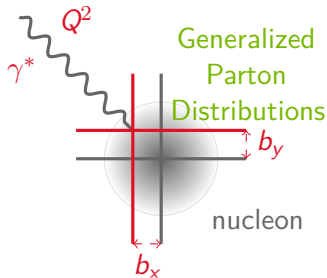
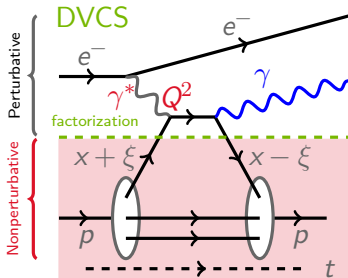
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Bjorken regime : large Q^2 and fixed $x_B \simeq 2\xi/(1+\xi)$

- Partonic interpretation relies on **factorization theorems**.
- All-order proofs for DVCS, TCS and some DVMP.
- GPDs depend on a (arbitrary) factorization scale μ_F .
- **Consistency** requires the study of **different channels**.

- GPDs enter DVCS through **Compton Form Factors** :

$$\mathcal{F}(\xi, t, Q^2) = \int_{-1}^1 dx C\left(x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F}\right) F(x, \xi, t, \mu_F)$$

for a given GPD F .

- CFF \mathcal{F} is a **complex function**.

Need for global fits of world data.

Different facilities will probe different kinematic domains.

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Need for global fits of world data.

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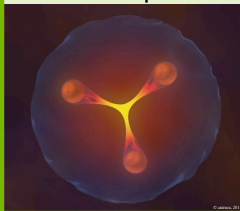
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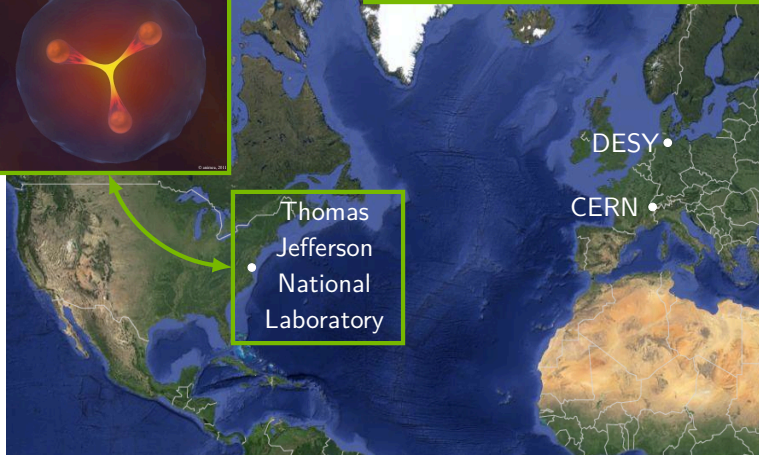
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Valence quarks



Experimental data collected at 3 facilities



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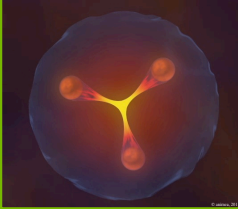
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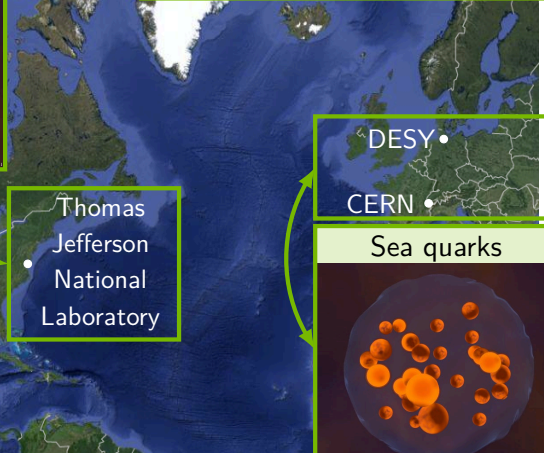
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Experimental data collected at 3 facilities

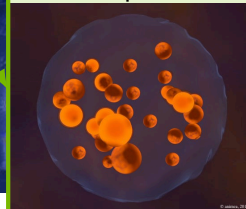


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Sea quarks



Need for global fits of world data.

Different facilities will probe different kinematic domains.

Nucleon Tomography

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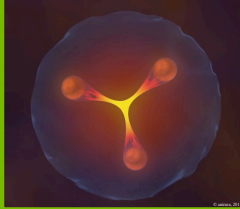
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Experimental data collected at 3 facilities, soon 4: EIC !

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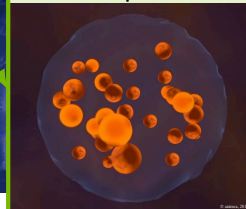
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Thomas Jefferson National Laboratory

Gluons

EIC: a unique probe of the gluon sector

Sea quarks



Need for global fits of world data.

Only a small subset of the (ξ, t, Q^2) space is directly accessed.

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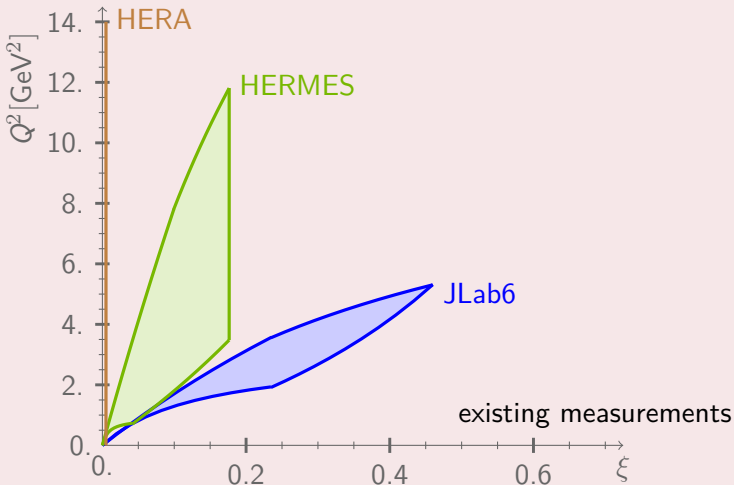
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Kinematic reach of existing or near-future DVCS measurements



Need for global fits of world data.

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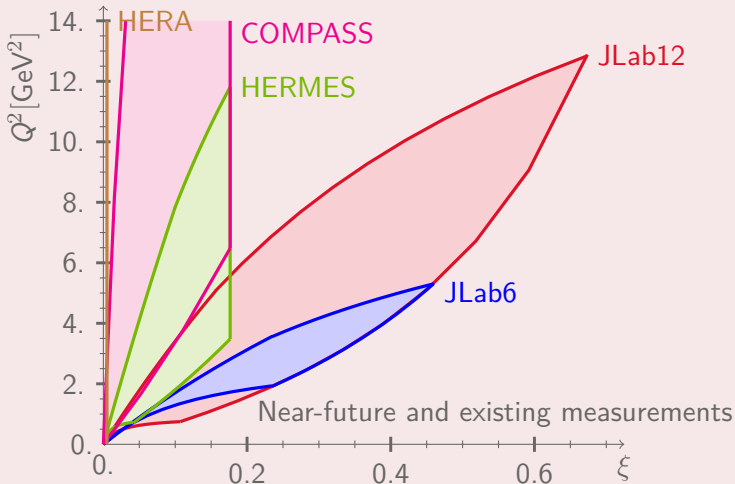
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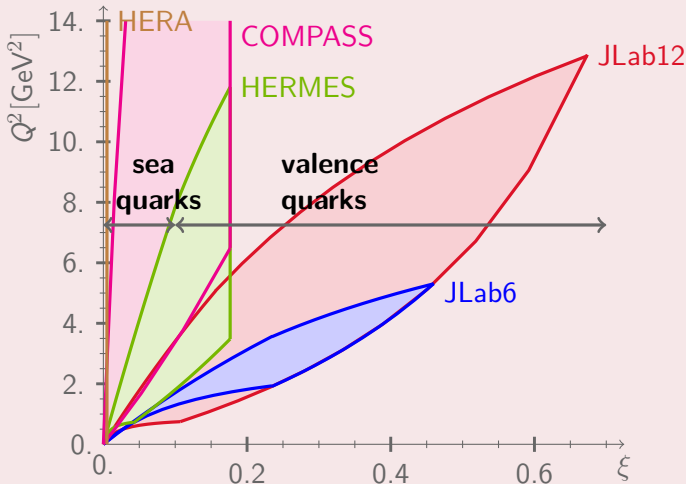
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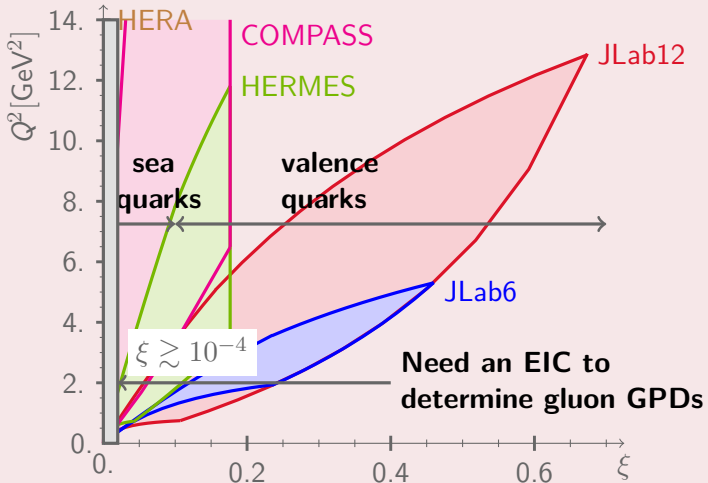
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Need for global fits of world data.

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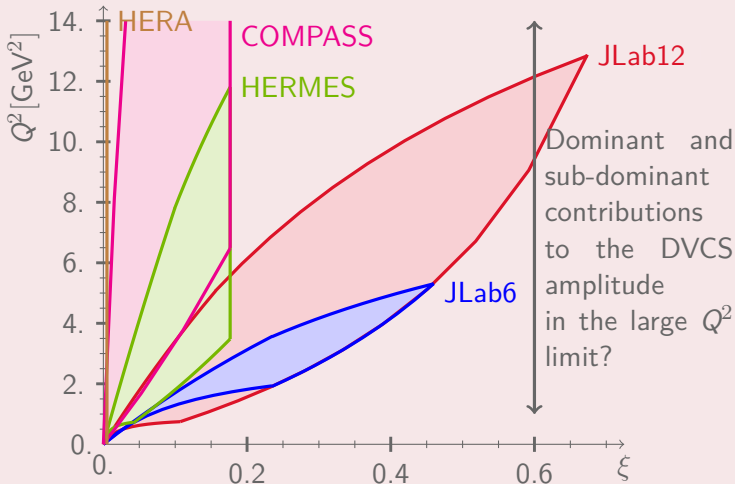
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Software for the phenomenology of GPDs.

Different questions to be answered with the same tools.

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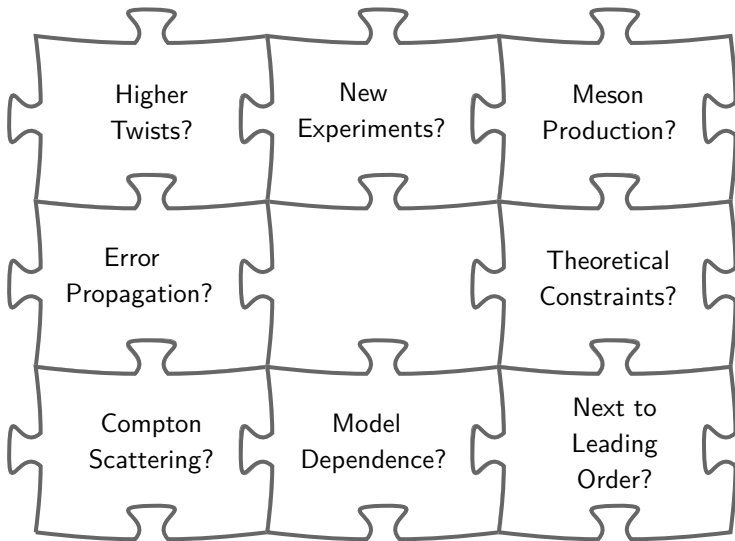
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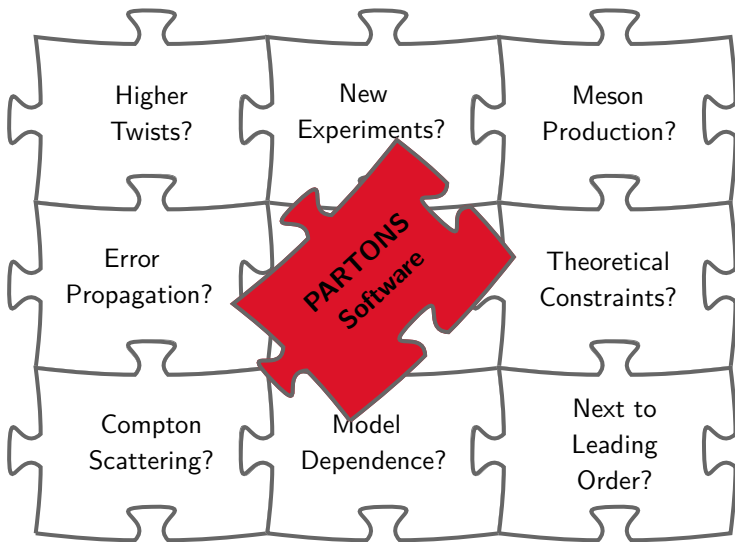
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The PARTONS framework



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Large distance
contributions

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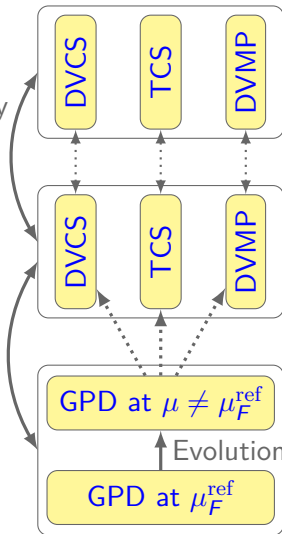
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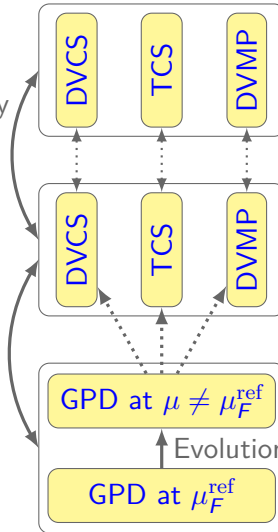
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- Many observables.
- Kinematic reach.

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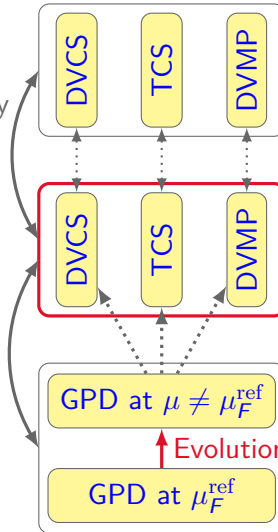
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Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

- **Perturbative approximations.**
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

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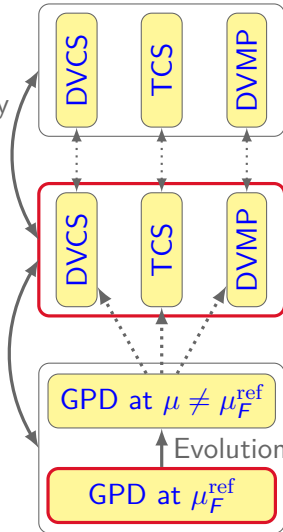
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- Perturbative approximations.
- **Physical models.**
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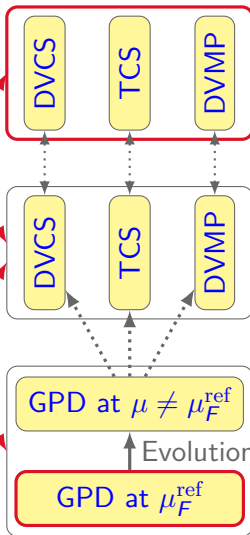
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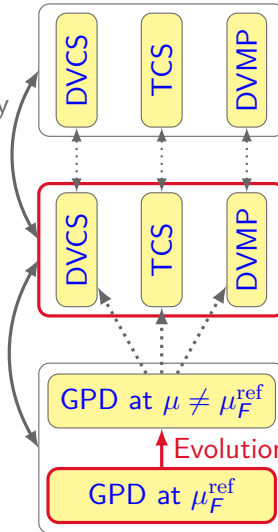
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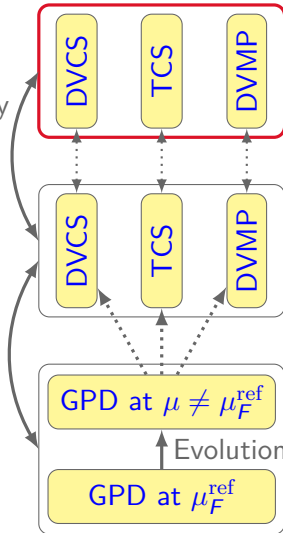
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- 3 stages:
 - 1 Design.
 - 2 Integration and validation.
 - 3 Benchmarking and production.
- 1 new physical development = 1 new module.
- **Aggregate knowledge and know-how:**
 - Models
 - Measurements
 - Numerical techniques
 - Validation
- What *can* be automated *will be* automated.
- Flexible software architecture.

B. Berthou *et al.*, Eur. Phys. J. **C78**, 478 (2018)

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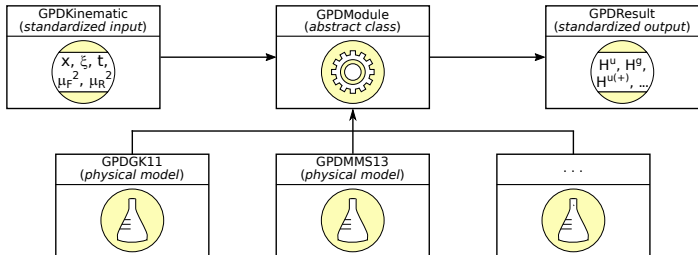
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- Steps of logic sequence in parent class.
- Model description and related mathematical methods in daughter class.

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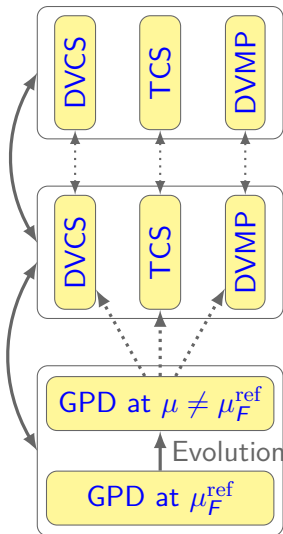
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- A DVCS coefficient function module generically outputs a complex number when provided $(\xi, t, Q^2, \mu_F^2, \mu_R^2)$.

—ConvCoeffFunctionModule.h—

```
1 virtual std::complex<double> compute(  
double xi, double t, double Q2, double MuF2,  
double MuR2, GPDType::Type gpdType) =  
0;
```

- This module can be anything:
 - Constant CFFs for local fits.
 - CFFs for massless quarks.
 - CFFs for heavy quarks.
 - CFFs with TMC.
 - ...

Modularity and layer structure.

Modifying one layer does not affect the other layers.

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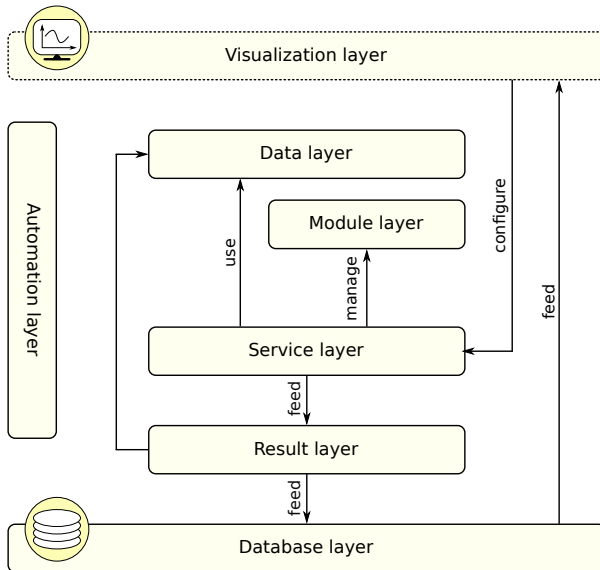
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Modularity and automation.

Parse XML file, compute and store result in database.

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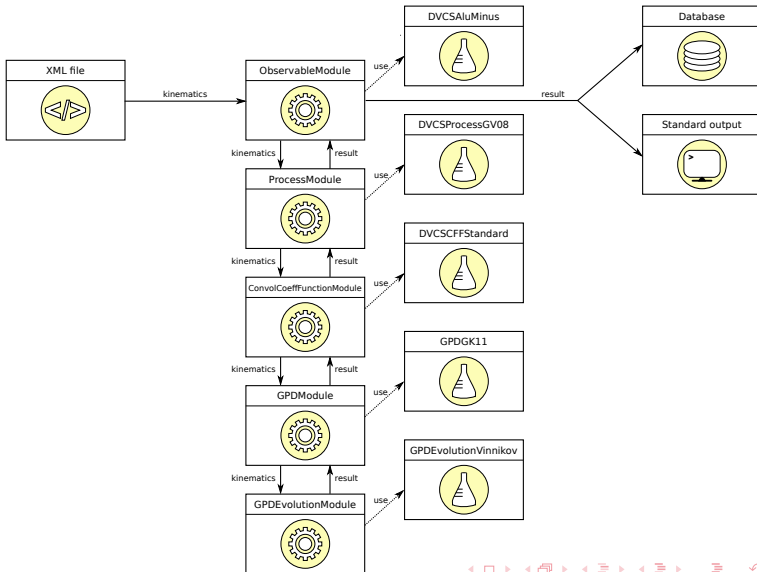
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Automation allows...:

- to run **numerous computations** with various physical assumptions,
- to run **nonregression** tests.
- to perform **fits** with various models.
- physicists to **focus on physics!**

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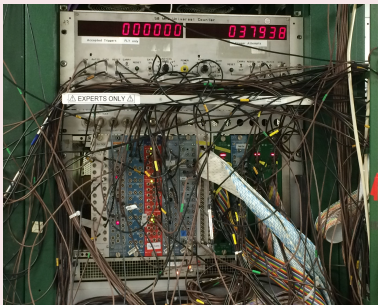
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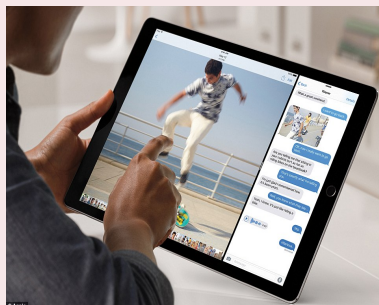
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Without PARTONS



With PARTONS



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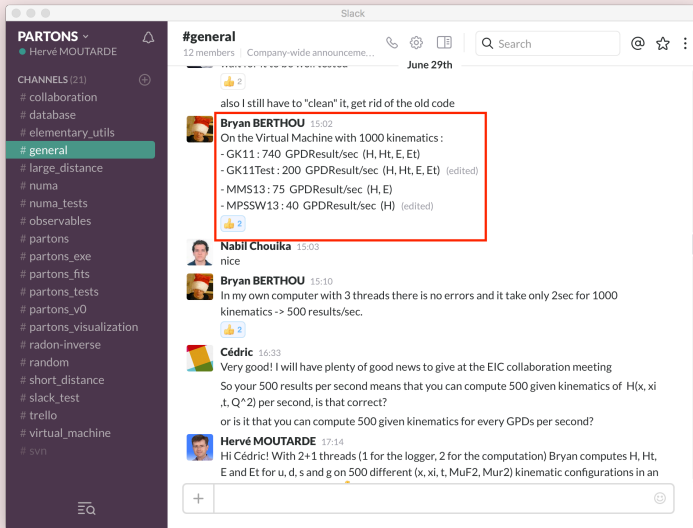
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GPD computations with or without threads



The screenshot shows a Slack channel named #general with 12 members. The channel is part of a workspace named PARTONS, managed by Hervé MOUTARDE. The channel list on the left includes #collaboration, #database, #elementary_utils, #general (selected), #large_distance, #numa, #numa_tests, #observables, #partons, #partons_exe, #partons_fits, #partons_tests, #partons_v0, #partons_visualization, #radon-inverse, #random, #short_distance, #slack_test, #trello, #virtual_machine, and #svn.

The conversation history shows:

- A message from Bryan BERTHOU (15:02) stating: "also I still have to 'clean' it, get rid of the old code".
- A message from Bryan BERTHOU (15:02) listing performance results on a Virtual Machine with 1000 kinematics:
 - GK11: 740 GPDResult/sec (H, Ht, E, Et)
 - GK11Test: 200 GPDResult/sec (H, Ht, E, Et) (edited)
 - MMS13: 75 GPDResult/sec (H, E)
 - MPSSW13: 40 GPDResult/sec (H) (edited)
- A message from Nabil Chouika (15:03) saying "nice".
- A message from Bryan BERTHOU (15:10) stating: "In my own computer with 3 threads there is no errors and it take only 2sec for 1000 kinematics -> 500 results/sec.".
- A message from Cédric (16:33) stating: "Very good! I will have plenty of good news to give at the EIC collaboration meeting. So your 500 results per second means that you can compute 500 given kinematics of $H(x, x_1, t, Q^2)$ per second, is that correct? or is it that you can compute 500 given kinematics for every GPDs per second?"
- A message from Hervé MOUTARDE (17:14) responding to Cédric: "Hi Cédric! With 2+1 threads (1 for the logger, 2 for the computation) Bryan computes H, Ht, E and Et for u, d, s and g on 500 different (x, xi, t, MuF2, Mur2) kinematic configurations in an

Systematic studies made fast.

What can be done from scratch in about 1 hour.

From D. Sokhan's talk, EIC User Group Meeting, ANL, 2016

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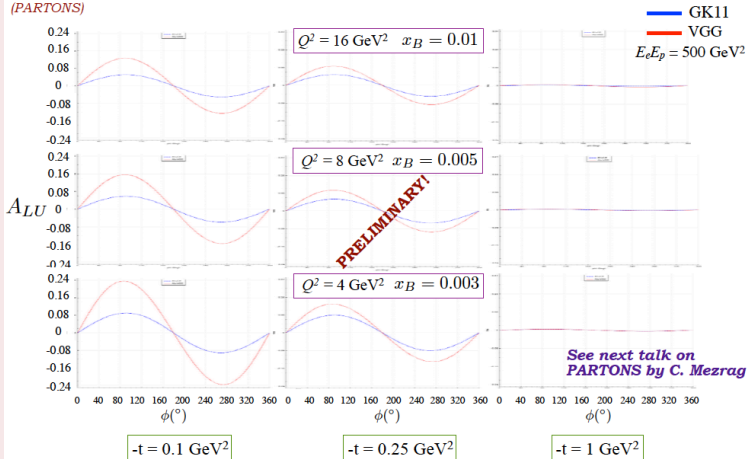
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Luca Colaneri,
Nabil Chouika
(PARTONS)

DVCS beam-spin asymmetries at EIC



First local fit of pseudo DVCS data, Sep. 26th, 2016

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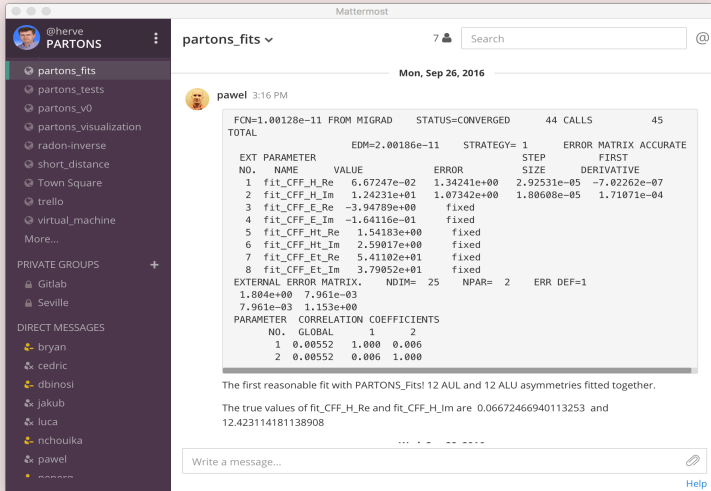
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The screenshot shows a Mattermost chat interface. On the left is a sidebar with a user list and a channel list. The main window shows a chat channel named 'partons_fits'. A message from user 'pawel' is displayed, dated 'Mon, Sep 26, 2016' at '3:16 PM'. The message content is a text-based report of a fit result.

partons_fits 7

Mon, Sep 26, 2016

pawel 3:16 PM

FCN=1.00128e-11 FROM MIGRAD STATUS=CONVERGED 44 CALLS 45
TOTAL EDM=2.00186e-11 STRATEGY= 1 ERROR MATRIX ACCURATE

EXT NO.	PARAMETER NAME	VALUE	ERROR	STEP SIZE	FIRST DERIVATIVE
1	fit_CFF_H_Re	6.67247e-02	1.34241e+00	2.92531e-05	-7.02262e-07
2	fit_CFF_H_Im	1.24231e+01	1.07342e+00	1.80608e-05	1.71071e-04
3	fit_CFF_E_Re	-3.94789e+00	fixed		
4	fit_CFF_E_Im	-1.64116e-01	fixed		
5	fit_CFF_Ht_Re	1.54183e+00	fixed		
6	fit_CFF_Ht_Im	2.59017e+00	fixed		
7	fit_CFF_Et_Re	5.41102e+01	fixed		
8	fit_CFF_Et_Im	3.79052e+01	fixed		

EXTERNAL ERROR MATRIX, NDIM= 25 NPAR= 2 ERR DEF=1
1.804e+00 7.961e-03
7.961e-03 1.153e+00

PARAMETER NO.	GLOBAL	COEFFICIENTS 1	COEFFICIENTS 2
1	0.00552	1.000	0.006
2	0.00552	0.006	1.000

The first reasonable fit with PARTONS_Fits! 12 AUL and 12 ALU asymmetries fitted together.

The true values of fit_CFF_H_Re and fit_CFF_H_Im are 0.06672466940113253 and 12.423114181138908

Write a message... Help

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Parametric global fit of JLab DVCS data, Apr. 5th, 2017

RESULTS

- Kinematic cuts $Q^2 > 1.5 \text{ GeV}^2$ (where we can rely on LO approximation)
 $-t / Q^2 < 0.25$ (where we can rely on GPD factorization)

- χ^2 / ndf 3272.6 / (3433 - 7) ≈ 0.96

- Free parameters $a_{\text{Hsea}}, a_{\text{Hval}}, a_{\text{Hsea}}, C_{\text{sub}}, a_{\text{sub}}, N_E, N_{\bar{E}}$

- χ^2 / ndf per data set

[1] Phys. Rev. C 92, 055202 (2015)
[2] Phys. Rev. Lett. 115, 212003 (2015)
[3] Phys. Rev. D 91, 052014 (2015)

Experiment	Reference	Observables	N points all	N points selected	chi2	chi2 / ndf
Hall A	[1] KINX2	σ_{UU}	120	120	135.0	1.19
Hall A	[1] KINX2	$\Delta\sigma_{\text{LU}}$	120	120	98.9	0.88
Hall A	[1] KINX3	σ_{UU}	108	108	274.8	2.72
Hall A	[1] KINX3	$\Delta\sigma_{\text{LU}}$	108	108	107.3	1.06
CLAS	[2]	σ_{UU}	1933	1333	1089.2	0.82
CLAS	[2]	$\Delta\sigma_{\text{LU}}$	1933	1333	1171.9	0.88
CLAS	[3]	AUL, ALU, ALL	498	305	338.1	1.13

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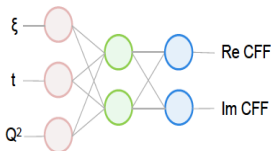
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Neural network global fit of CLAS asymmetries, May 31st, 2017

NEURAL NETWORK



- Our very first attempt to use NN technique → proof of feasibility
- Genetic algorithm (GA) to learn NN
- NN and GA libraries by PARTONS group
- Very simple design of NN
- CLAS asymmetry data only
- $\chi^2 / \text{ndf} = 273.9 / (305 - 68) \approx 1.16$

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- PARTONS architecture allows focusing on **parameterization** and **fitting engine**.
- The **same machinery** is used for local **and** global fits.
- **Fast** and **constant** progress since the first fits.
- More to come in the near future.

See Pawel Sznajder's seminar in Stony Brook tomorrow!

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GPD modules

- GK
- VGG
- Vinnikov (evolution)
- MPSSW13 (NLO study)
- MMS13 (DD study)

DVCS modules

- VGG
- GV
- BMJ

CFF modules

- LO
- NLO
- NLO Noritzsch

Evolution modules

- Vinnikov (LO)

α_s modules

- 4-loop perturbation
- constant value

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The screenshot shows the PARTONS website interface. At the top, the title "PARTONS" is displayed in large blue letters, followed by the subtitle "PARTonic Tomography Of Nucleon Software". A navigation bar contains links: "Main Page", "Download", "Tutorials +", "Reference documentation +", and "About +". A search bar is located on the right of the navigation bar. The main content area starts with the heading "Main Page" and "What is PARTONS?". Below this, a paragraph describes PARTONS as a C++ software framework for Generalized Parton Distributions (GPDs). To the right of the text is a "Table of Contents" sidebar with links to various sections. The bottom of the screenshot shows the heading "Get PARTONS".

PARTONS PARTonic Tomography Of Nucleon Software

Main Page Download Tutorials + Reference documentation + About +

Search

Main Page

What is PARTONS?

PARTONS is a C++ software framework dedicated to the phenomenology of Generalized Parton Distributions (GPDs). GPDs provide a comprehensive description of the partonic structure of the nucleon and contain a wealth of new information. In particular, GPDs provide a description of the nucleon as an extended object, referred to as 3-dimensional nucleon tomography, and give an access to the orbital angular momentum of quarks.

PARTONS provides a necessary bridge between models of GPDs and experimental data measured in various exclusive channels, like Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP). The experimental programme devoted to study GPDs has been carrying out by several experiments, like HERMES at DESY (closed), COMPASS at CERN, Hall-A and CLAS at JLab. GPD subject will be also a key component of the physics case for the expected Electron Ion Collider (EIC).

PARTONS is useful to theorists to develop new models, phenomenologists to interpret existing measurements and to experimentalists to design new experiments.

Get PARTONS

Table of Contents

- What is PARTONS?
- Get PARTONS
- Configure PARTONS
- How to use PARTONS
- Publications and talks
- License
- Contact and newsletter

Berthou et al., Eur. Phys. J. C78, 478 (2018)

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The screenshot shows the GitLab web interface for the 'partons' group. The top navigation bar includes 'Webmail CEA', 'L'intranet de l'Ifnu', 'L'intranet du SPHn', 'herve moutarde', 'GitLab DRF', 'PROPHET - Trac', 'vianavigo', 'Overleaf', and 'http://agenda.... la formation'. The main header features the GitLab logo and navigation tabs: 'Projects', 'Groups', 'Snippets', and 'Help'. A search bar and 'Sign in / Register' button are also present. The left sidebar contains icons for home, code, issues, and users. The main content area displays the 'partons' group details, including a 'core' repository icon. Below this, a table lists the group's projects:

Project Name	Description	Stars
partons	PARTONS project	★ 2
elementary-utils	Utility softwares (logger, parser, threads, string and file manipulation)	★ 0
numa	NumA++: numerical analysis C++ routines	★ 0
partons-example	Running version of PARTONS with examples (C++ code and XML computing scenarios)	★ 0

At the bottom of the page, there are navigation buttons: 'Prev', '1' (selected), and 'Next'.

Berthou et al., Eur. Phys. J. C78, 478 (2018)

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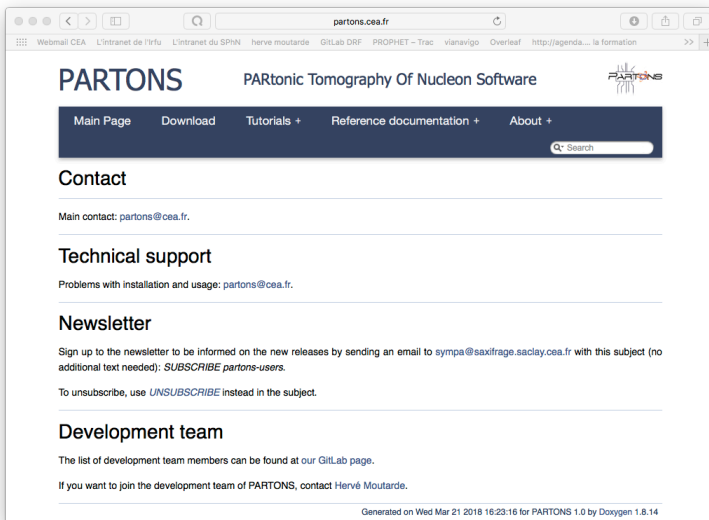
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The screenshot shows the PARTONS website in a browser window. The browser's address bar displays 'partons.cea.fr'. The website has a dark blue header with the title 'PARTONS' and subtitle 'PARTonic Tomography Of Nucleon Software'. A navigation bar below the header contains links: 'Main Page', 'Download', 'Tutorials +', 'Reference documentation +', and 'About +'. A search bar is located on the right side of the navigation bar. The main content area is divided into sections: 'Contact' (with email 'partons@cea.fr'), 'Technical support' (with email 'partons@cea.fr'), 'Newsletter' (with sign-up instructions), and 'Development team' (with a link to the GitLab page and contact information for Hervé Moutarde). The footer indicates the page was generated on Wed Mar 21 2018 16:23:16 for PARTONS 1.0 by Doxygen 1.8.14.

Berthou et al., Eur. Phys. J. C78, 478 (2018)

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Channel modules

- DVMP
- TCS
- γM production
- ???

Other modules

- Mellin moments (EM tensor, lattice QCD)
- ???

Hadron structure modules

- DAs
- DDs
- Form factors
- PDFs
- LFWFs
- ???

Nonperturbative QCD modules

- Gap equation solver
- ???

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A workpackage of the EU-funded STRONG-2020 program

- Mutualize developments for GPD and TMD frameworks.
- Address the question of event generation.
- Open-source release and maintenance of computing codes related to 3D hadron structure.

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- We now have tools to **systematically relate** these models to **experimental data** in **multi-channel** analysis.
- We now have an **operating engine** for global CFF fits.
- We revisit the **mechanical properties** of hadrons to assess how much we can learn from GPD extractions.
- We can now build generic GPD models satisfying *a priori* **all theoretical constraints**.

New studies become possible!

- Global GPD fits.
- Energy-momentum structure of hadrons.
- Quantitative impact of nonperturbative QCD ingredients on 3D hadron structure studies.
- GPD and TMD studies in a common framework.
- ... And probably much more!

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EICUG

Electron-Ion Collider User Group Meeting

2019 JULY 22-26

École Nationale Supérieure de Chimie

The world's most powerful microscope for studying the "glue" that binds the building blocks of visible matter

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3D STRUCTURE OF PROTON AND NUCLEI

GLUON SATURATION AND THE COLOR GLASS CONDENSATE

SOLVING THE MYSTERY OF THE PROTON SPIN

QUARK AND GLUON CONFINEMENT

Local Organizing Committee

Francesco BOSSI: CEA-Saclay
Valérie FROIS: CNRS/IN2P3, Secretary
Carlos MUÑOZ CAMACHO: CNRS/IN2P3
Franck SABATIE: CEA-Saclay

<https://indico.in2p3.fr/event/EICUG2019>

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