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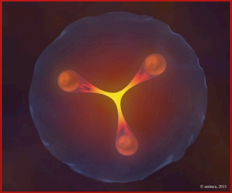

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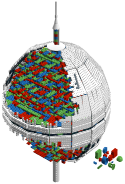
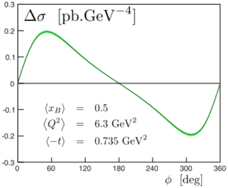
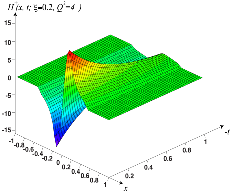
STRONG 2020

PARTONS

Prospects on nucleon tomography







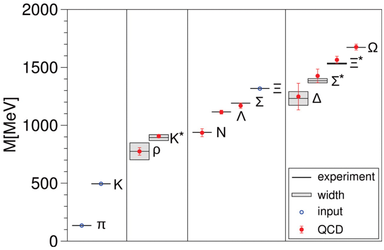
Colloquium of the Department of Fundamental Research (NCBJ) | Hervé MOUTARDE

université PARIS-SACLAY

Nov. 18, 2019

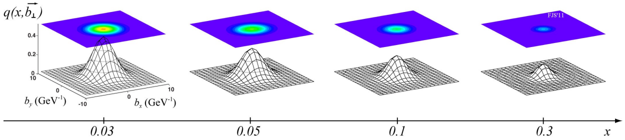
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093.

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

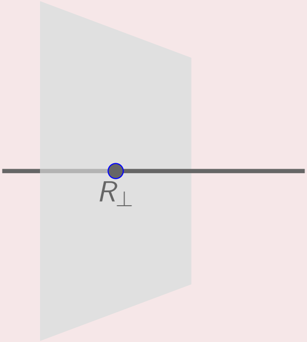


Durr *et al.*, Science **322**, 1224 (2008)

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

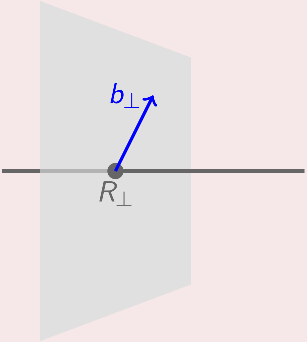


Manifestation of 3D nucleon structure in scattering processes?



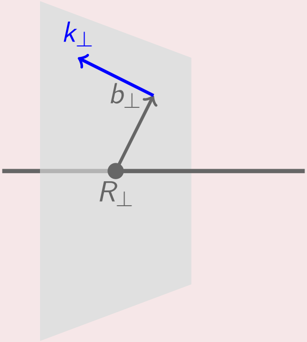
- Transverse center of momentum $R_\perp = \sum_i x_i r_{\perp i}$,

Manifestation of 3D nucleon structure in scattering processes?



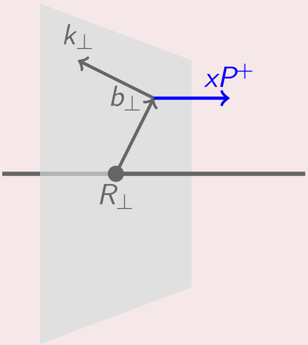
- Transverse center of momentum $R_\perp = \sum_i x_i r_{\perp i}$,
- Impact parameter $b_\perp$,

Manifestation of 3D nucleon structure in scattering processes?



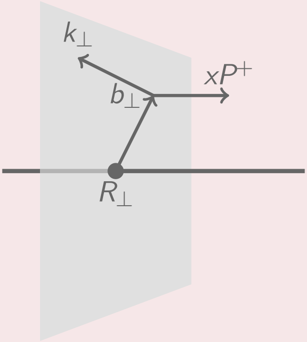
- Transverse center of momentum $R_\perp = \sum_i x_i r_{\perp i}$,
- Impact parameter $b_\perp$,
- Transverse momentum $k_\perp$,

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^+.

Manifestation of 3D nucleon structure in scattering processes?



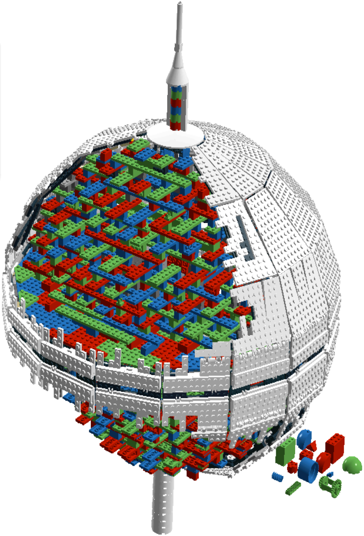
- Transverse center of momentum $R_\perp = \sum_i x_i r_{\perp i}$,
- Impact parameter $b_\perp$,
- Transverse momentum $k_\perp$,
- Longitudinal momentum xP^+.
- What is the distortion brought by spin?

Imaging the origin of mass.

Identification of underlying mechanisms from parton distributions.

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

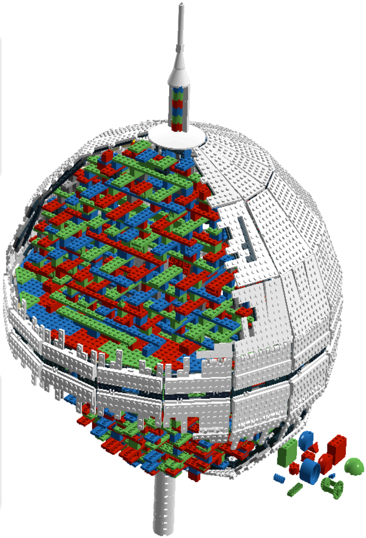
Mass?
Spin?
Charge?
...



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

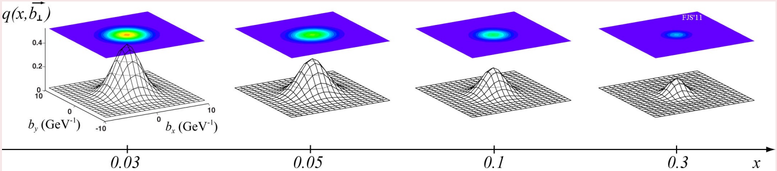
Mass?
Spin?
Charge?
...

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

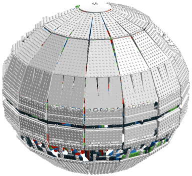


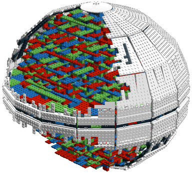
Structuring questions for the hadron physics community

- 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?



Colorless proton $\overset{??}{\leftrightarrow}$ Colorful components

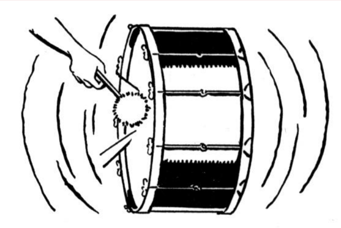




"Can one hear the shape of a drum?"

Kac, Am. Math. Mon. **74**, 1 (1966)

"Can one hear the shape of a drum?"



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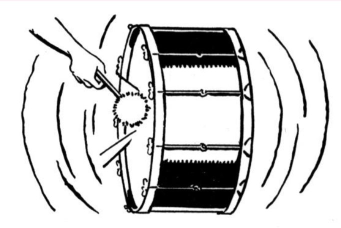
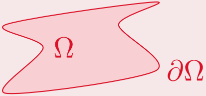


Kac, Am. Math. Mon. **74**, 1 (1966)

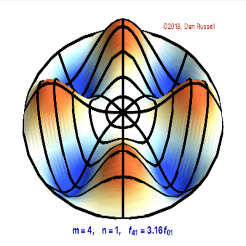
In quantitative terms



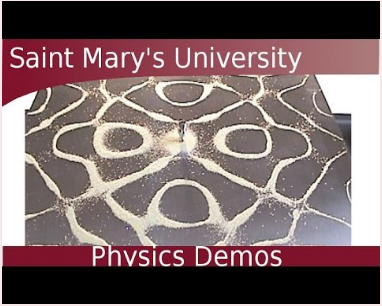
- Dirichlet problem for the Laplacian:

$$\Delta u + \lambda u = 0 \quad \text{and} \quad u_{|\partial\Omega} = 0$$

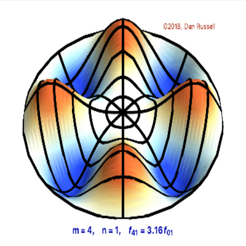
Vibration patterns



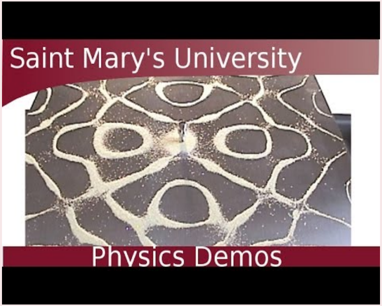
Vibration patterns



Vibration patterns



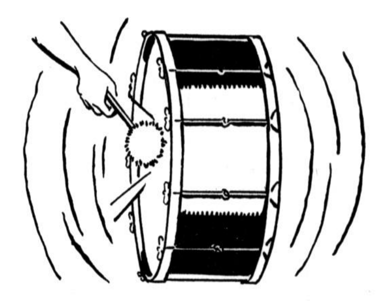
Vibration patterns



What about the proton?

- "Hit" the proton, *e.g.* with a virtual photon:
- "Listen" to the distribution of produced particles:
- "Measure" harmonics:

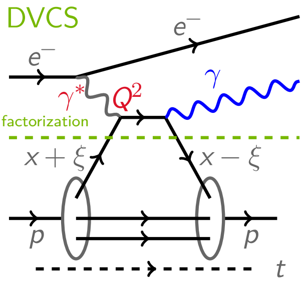
Drum

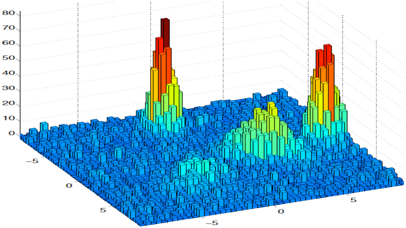


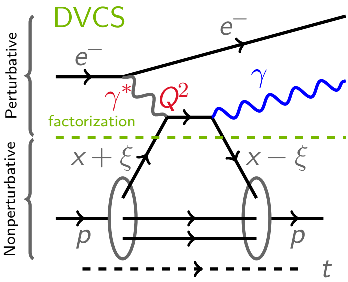
Proton

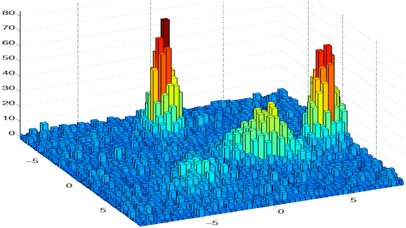
What about the proton?

- "Hit" the proton, *e.g.* with a virtual photon: hard
- "Listen" to the distribution of produced particles: exclusive
- "Measure" harmonics: amplitudes (Compton form factors)


DVCS
e−
e−
γ*
Q2
γ
factorization
x + ξ
x − ξ
p
p
t

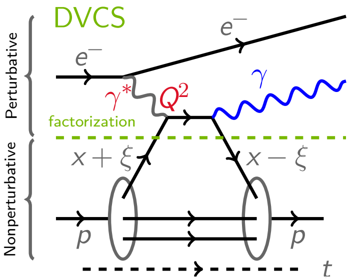


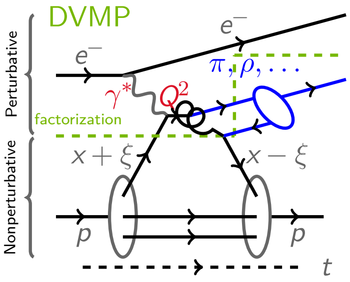

DVCS
Perturbative
Nonperturbative
e^-
e^-
γ^*
Q^2
γ
factorization
$x+\xi$
$x-\xi$
p
p
t

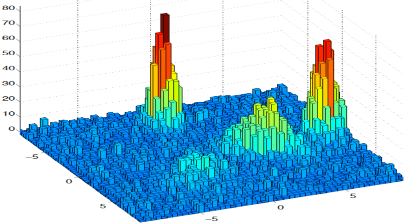


Exclusive processes of current interest.

Factorization and Generalized Parton Distributions (GPDs).







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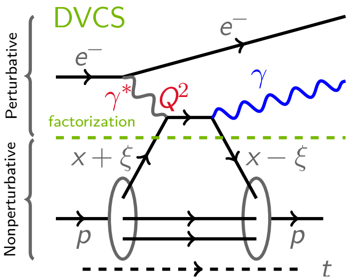

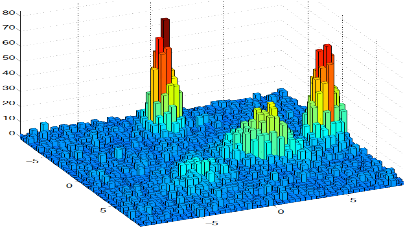

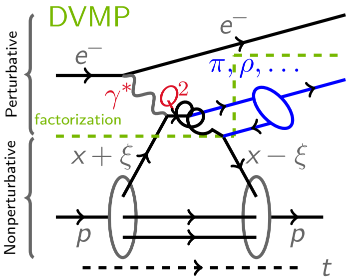

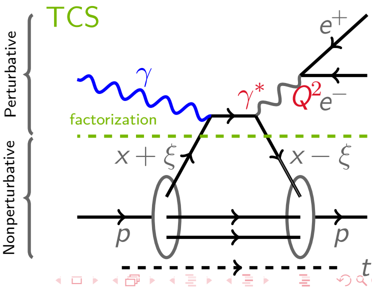

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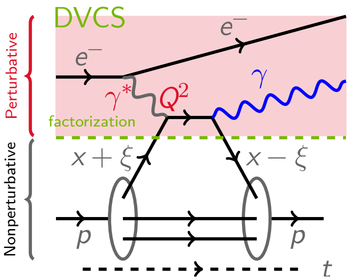

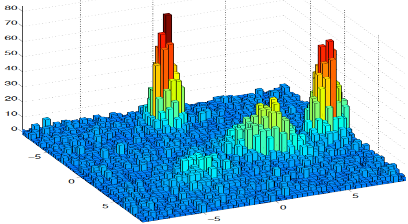

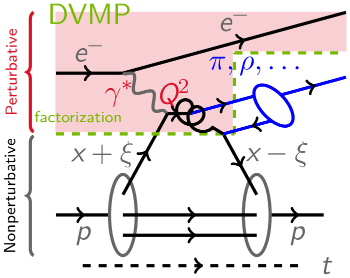

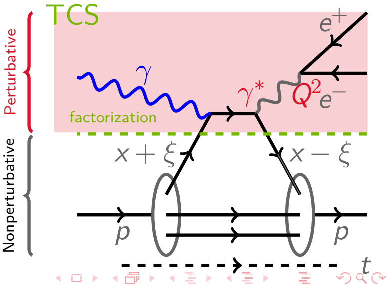

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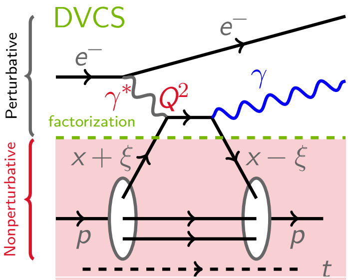
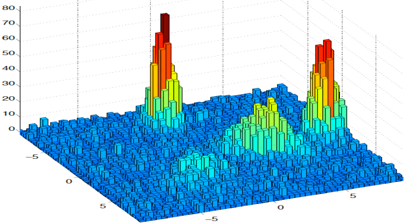
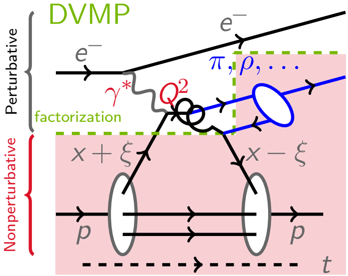
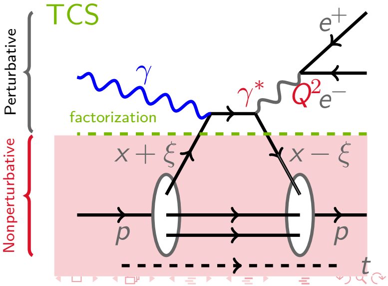








Bjorken regime : large Q^2 and fixed $xB \simeq 2\xi/(1+\xi)$

- 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** :

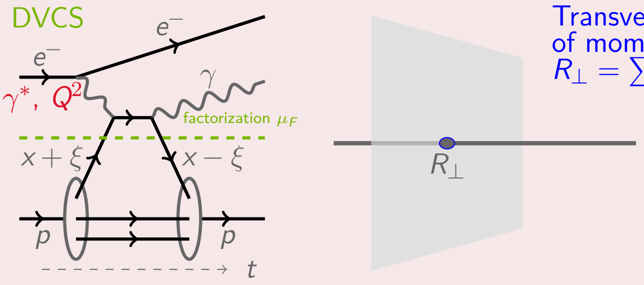
$$\mathcal{F}(\xi, t, Q^2) = \int_{-1}^{1} dx\, C\left(x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F}\right) F(x, \xi, t, \mu_F)$$

  for a given GPD F.
- CFF $\mathcal{F}$ is a **complex function**.

Phenomenology

- 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 $R_\perp$

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

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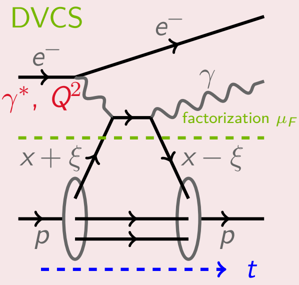

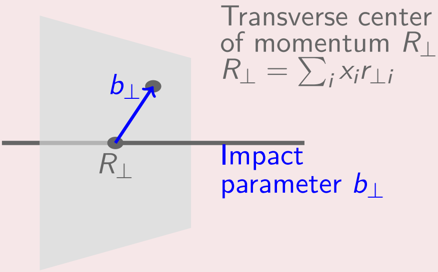

Anatomy of hadrons.

GPDs, 3D hadron imaging, and beyond (1/4).

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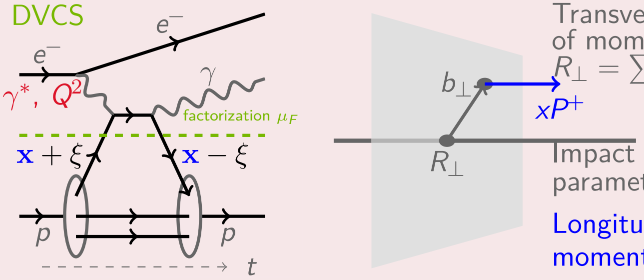
Deeply Virtual Compton Scattering (DVCS)



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

Impact parameter $b_\perp$

Longitudinal momentum xP^+

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
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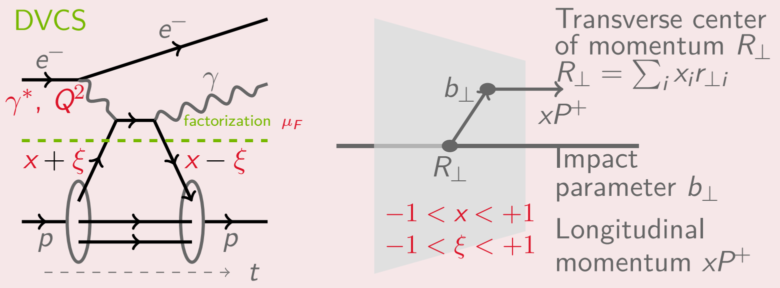
Deeply Virtual Compton Scattering (DVCS)



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

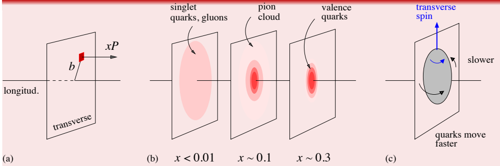
- **Probabilistic interpretation** of Fourier transform of $\mathrm{GPD}(x, \xi = 0, t)$ in **transverse plane**.

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

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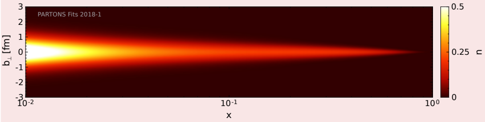
- Notations : quark helicity λ, nucleon longitudinal polarization λ_N and nucleon transverse spin $S_\perp$.

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

Not quite, but close!



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

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

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

with $t = \Delta^2$.

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

$$\int \mathrm{d}x\, xH^q(x,\xi,t) = A^q(t) + 4\xi^2 C^q(t)$$

$$\int \mathrm{d}x\, xE^q(x,\xi,t) = B^q(t) - 4\xi^2 C^q(t)$$

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

- Spin sum rule:

$$\int \mathrm{d}x\, x\big(H^q(x,\xi,0) + E^q(x,\xi,0)\big) = A^q(0) + B^q(0) = 2J^q$$

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

- **Shear** and **pressure** of a hadron considered as a continuous medium:

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

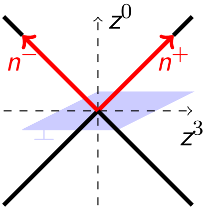
Polyakov and Shuvaev, hep-ph/0207153

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

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

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

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**

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

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

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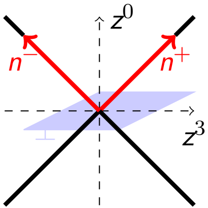

References

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

- PDF **forward limit**
- Form factor **sum rule**

$$\int_{-1}^{+1} dx\, H^q(x, \xi, t) = F^q_1(t)$$

Spin-0 Generalized Parton Distribution.

Definition and simple properties.

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

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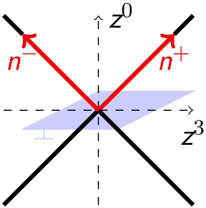

References

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Radyushkin, Phys. Lett. **B380**, 417 (1996)

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

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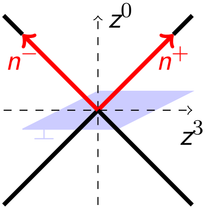


References

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**
- H^q is an **even function** of ξ from time-reversal invariance.
- H^q is **real** from hermiticity and time-reversal invariance.

Polynomiality

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

Polynomiality

Lorentz covariance

- **Polynomiality**

Lorentz covariance

- **Positivity**

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

Spin-0 Generalized Parton Distribution.

Not so simple properties.

- **Polynomiality**

Lorentz covariance

- **Positivity**

Positivity of Hilbert space norm

- **Polynomiality**

Lorentz covariance

- **Positivity**

Positivity of Hilbert space norm

- H^q has support $x \in [-1, +1]$.

- **Polynomiality**

  Lorentz covariance

- **Positivity**

  Positivity of Hilbert space norm

- H^q has support $x \in [-1, +1]$.

  Relativistic quantum mechanics

- **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)

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

- **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)

  Dynamical chiral symmetry breaking

Spin-0 Generalized Parton Distribution.

Not so simple properties.

- **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)

  Dynamical chiral symmetry breaking

Implementing these theoretical constraints is non-trivial!

- Fulfilling **polynomiality** and **positivity**: solved in 2017.
- Reduction to form factors or PDFs underway.

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

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

- Anisotropic fluid in **relativistic hydrodynamics**:

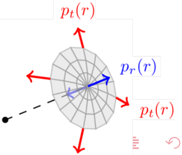
$$\Theta^{\mu\nu}(\vec{r}) = \left[\varepsilon(r) + p_t(r) \right] u^\mu u^\nu - p_t(r) \eta^{\mu\nu} + \left[p_r(r) - p_t(r) \right] \chi^\mu \chi^\nu$$

where u^μ and $\chi^\mu = x^\mu / r$.

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

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

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



- Write dictionary between quantum and fluid pictures:

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

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

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

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

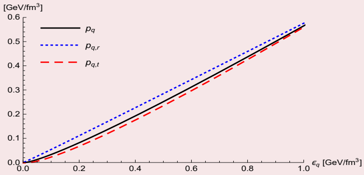
$$\frac{s_a(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta}\cdot\vec{r}} \left\{ -\frac{4}{r^2}\frac{t^{-1/2}}{M^2}\frac{d^2}{dt^2}\left(t^{5/2}\, C_a(t)\right) \right\}$$

Mechanical properties of hadrons.

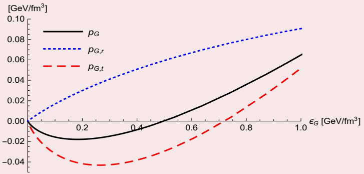
From the nucleon to compact stars (3/3).

- Evaluate orders of magnitude with naive multiple model:

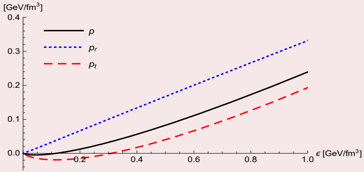
quark



glue

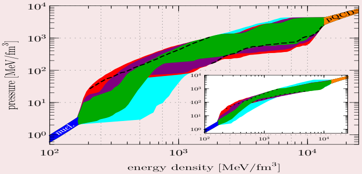


quark + glue



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

Neutron stars



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

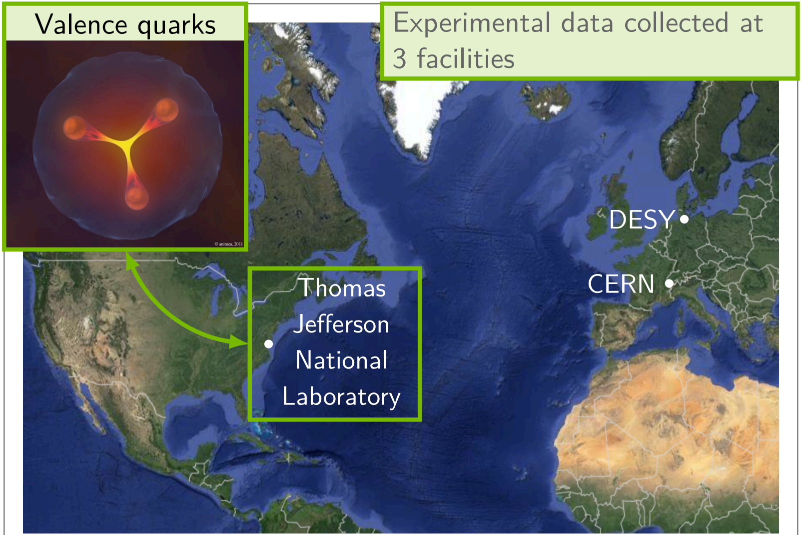
Need for global fits of world data.

Different facilities will probe different kinematic domains.

Experimental data collected at 3 facilities

Need for global fits of world data.

Different facilities will probe different kinematic domains.



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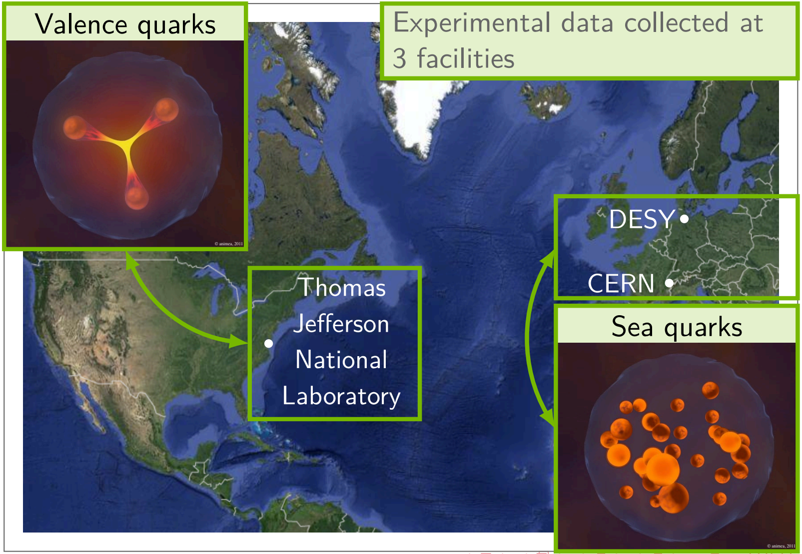

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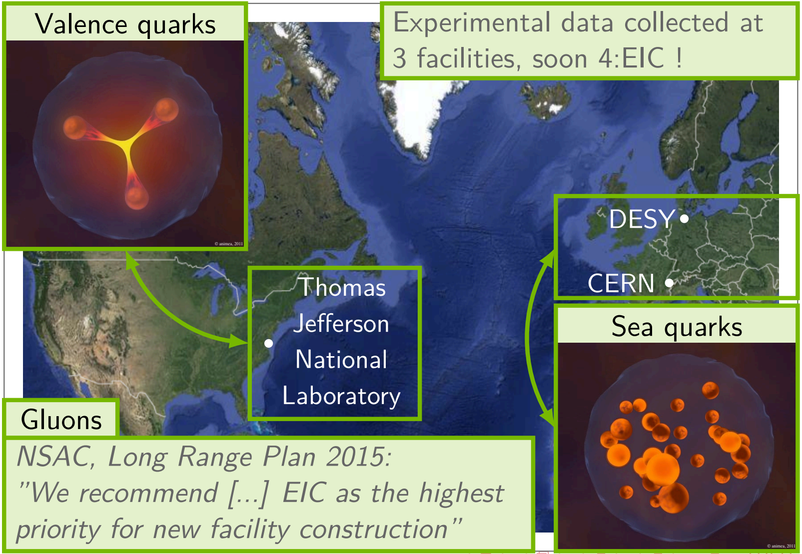


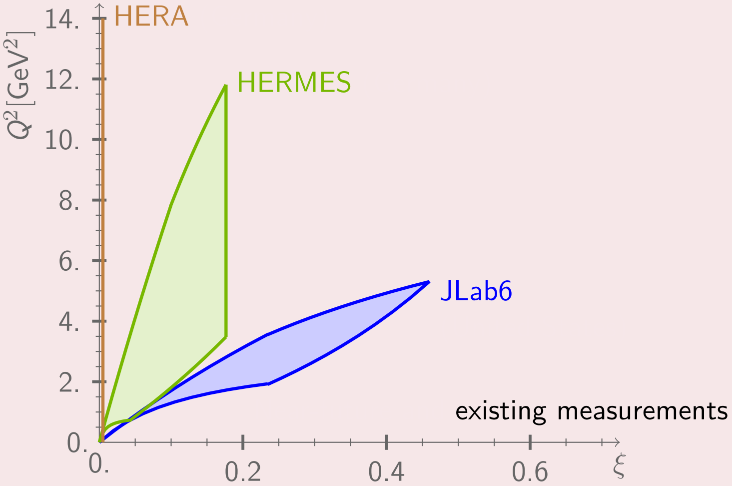
Experimental data collected at 3 facilities, soon 4:EIC !

NSAC, Long Range Plan 2015:
"We recommend [...] EIC as the highest priority for new facility construction"

Need for global fits of world data.

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

Kinematic reach of existing or near-future DVCS measurements



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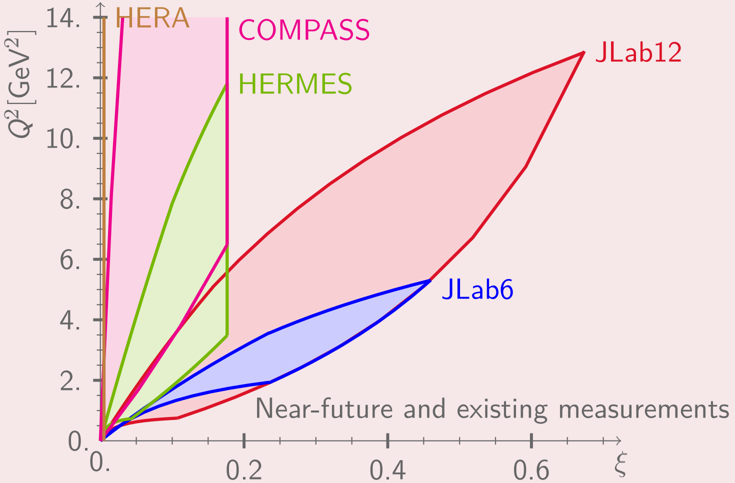

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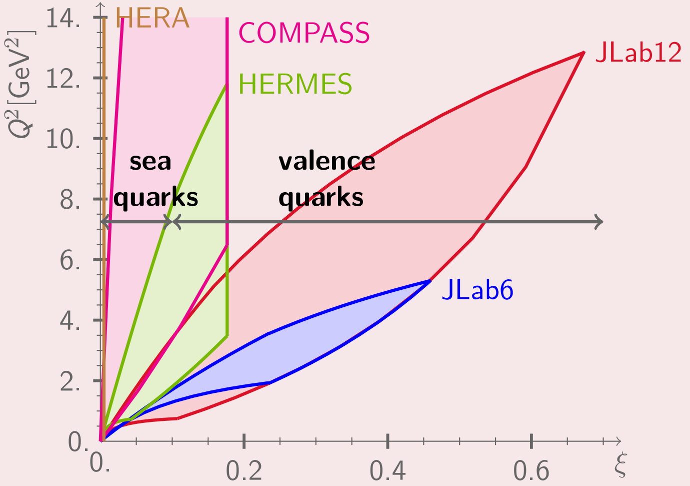

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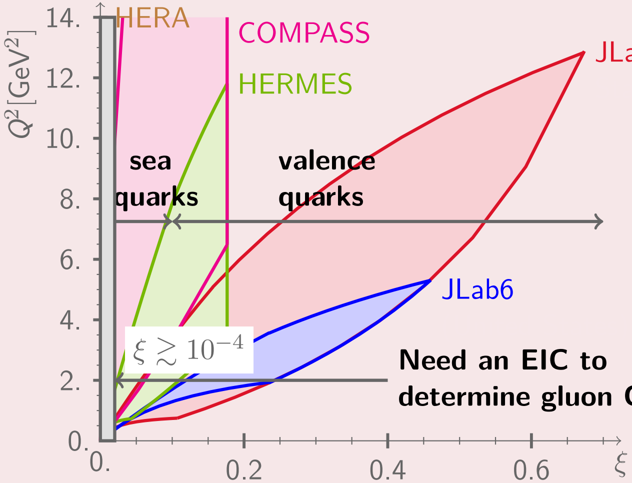
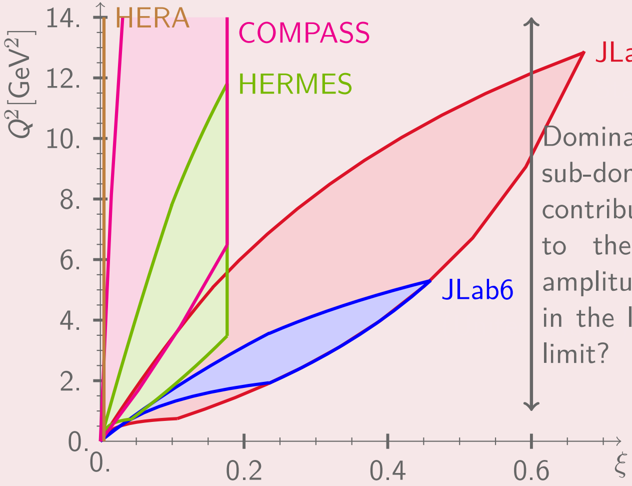


Need an EIC to determine gluon GPDs

Kinematic reach of existing or near-future DVCS measurements



Dominant and sub-dominant contributions to the DVCS amplitude in the large Q^2 limit?

DVCS analysis and fits.

No global GPD fit has been obtained so far.

- 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 is being improved!

- GPD parameterizations satisfying *a priori* all theoretical constraints on GPDs.

Chouika *et al.*, Eur. Phys. J. **C77**, 906 (2017)

- Computing framework to go beyond leading order and leading twist analysis.

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

Neural network global fit of CFFs.

All existing sets except $d^4\sigma^{-}_{UU}$ from Hall A (2015-17).

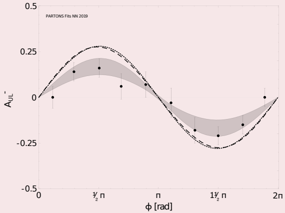
No.	Collab.	Year	Ref.	Observable		Kinematic dependence	No. of points used / all
1	HERMES	2001	[40]	A^{+}_{LU}		ϕ	10 / 10
2		2006	[41]	$A_C^{\cos i\phi}$	$i=1$	t	4 / 4
3		2008	[42]	$A_C^{\cos i\phi}$	$i=0,1$	x_{Bj}	18 / 24
				$A_{UT,\mathrm{DVCS}}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0$		
				$A_{UT,\mathrm{I}}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0,1$		
				$A_{UT,\mathrm{I}}^{\cos(\phi-\phi_S)\sin i\phi}$	$i=1$		
4		2009	[43]	$A_{LU,\mathrm{I}}^{\sin i\phi}$	$i=1,2$	x_{Bj}	35 / 42
				$A_{LU,\mathrm{DVCS}}^{\sin i\phi}$	$i=1$		
				$A_C^{\cos i\phi}$	$i=0,1,2,3$		
5		2010	[44]	$A_{UL}^{+,\sin i\phi}$	$i=1,2,3$	x_{Bj}	18 / 24
				$A_{LL}^{+,\cos i\phi}$	$i=0,1,2$		
6		2011	[45]	$A_{LT,\mathrm{DVCS}}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1$	x_{Bj}	24 / 32
				$A_{LT,\mathrm{DVCS}}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1$		
				$A_{LT,\mathrm{I}}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1,2$		
				$A_{LT,\mathrm{I}}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1,2$		
7		2012	[46]	$A_{LU,\mathrm{I}}^{\sin i\phi}$	$i=1,2$	x_{Bj}	35 / 42
				$A_{LU,\mathrm{DVCS}}^{\sin i\phi}$	$i=1$		
				$A_C^{\cos i\phi}$	$i=0,1,2,3$		
8	CLAS	2001	[47]	$A_{LU}^{-,\sin i\phi}$	$i=1,2$	—	0 / 2
9		2006	[48]	$A_{UL}^{-,\sin i\phi}$	$i=1,2$	—	2 / 2
10		2008	[49]	A^{-}_{LU}		ϕ	283 / 737
11		2009	[50]	A^{-}_{LU}		ϕ	22 / 33
12		2015	[51]	A^{-}_{LU}, A^{-}_{UL}, A^{-}_{LL}		ϕ	311 / 497
13		2015	[52]	$d^4\sigma^{-}_{UU}$		ϕ	1333 / 1933
14	Hall A	2015	[34]	$\Delta d^4\sigma^{-}_{LU}$		ϕ	228 / 228
15		2017	[35]	$\Delta d^4\sigma^{-}_{LU}$		ϕ	276 / 358
16	COMPASS	2018	[36]	$d^3\sigma^{\pm}_{UU}$		t	2 / 4
17	ZEUS	2009	[37]	$d^3\sigma^{+}_{UU}$		t	4 / 4
18	H1	2005	[38]	$d^3\sigma^{+}_{UU}$		t	7 / 8
19		2009	[39]	$d^3\sigma^{\pm}_{UU}$		t	12 / 12
						SUM:	2624 / 3996

Moutarde *et al.*, Eur. Phys. J. **C79**, 614 (2019).

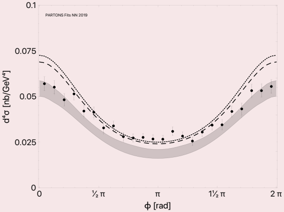
A selection of results.

2600+ measurements of 30 observables published during 2001-17.

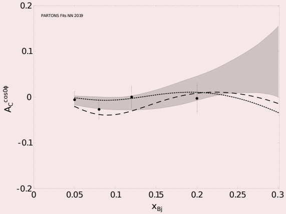
CLAS



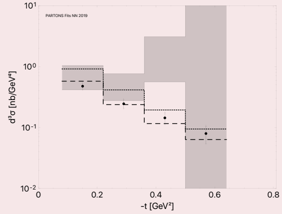
Hall A



HERMES



COMPASS

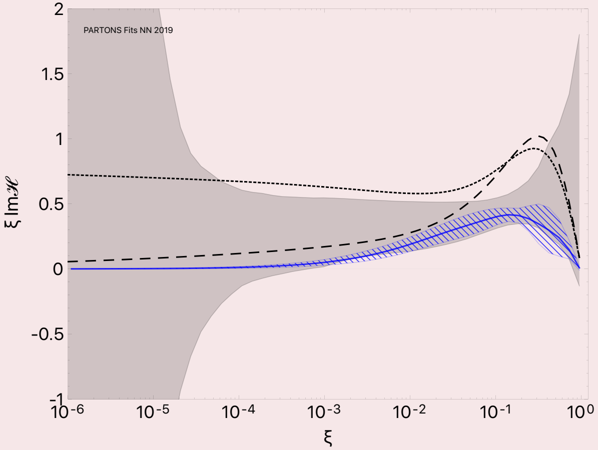


Moutarde *et al.*, Eur. Phys. J. **C79**, 614 (2019)

A selection of results.

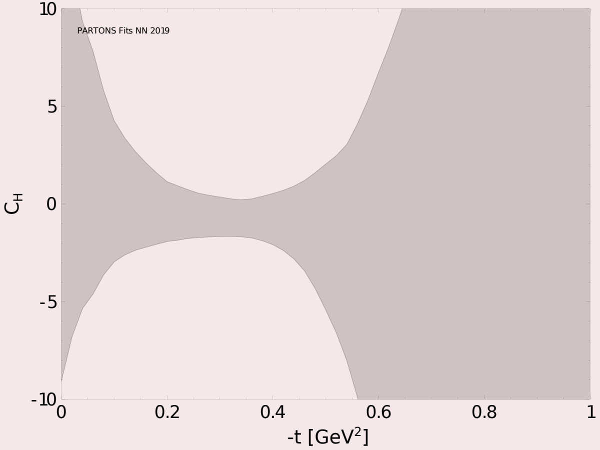
2600+ measurements of 30 observables published during 2001-17.

Compton form factor $\mathrm{Im}\mathcal{H}(\xi, t = -0.3\ \mathrm{GeV}^2, Q^2 = 2.\ \mathrm{GeV}^2)$



Moutarde *et al.*, Eur. Phys. J. **C79**, 614 (2019)

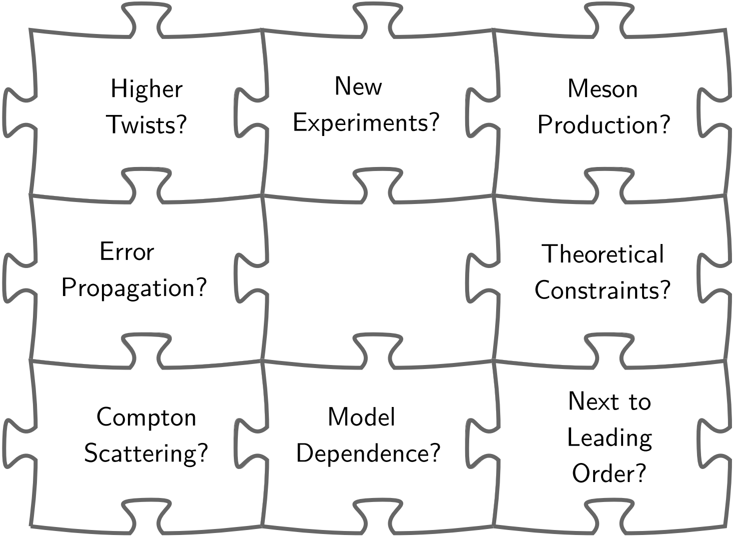
Subtraction constant (related to pressure distribution)



Moutarde *et al.*, Eur. Phys. J. **C79**, 614 (2019)

Software for the phenomenology of GPDs.

Different questions to be answered with the same tools.



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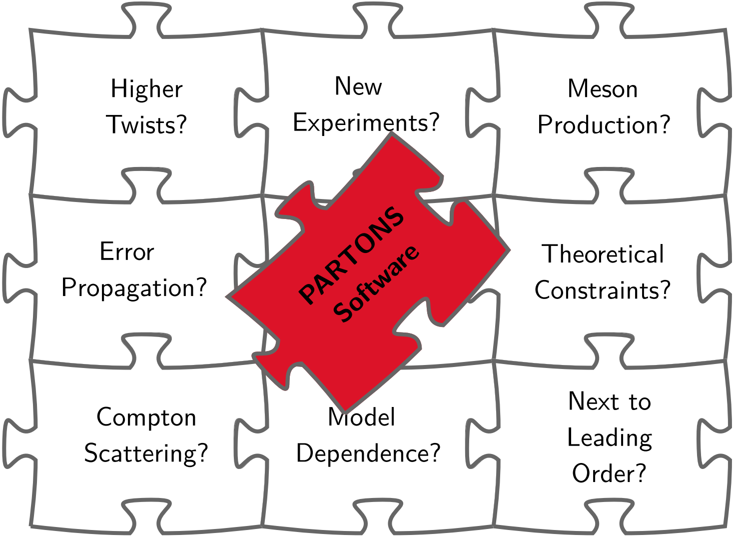


The PARTONS framework

PARtonic
Tomography
Of
Nucleon
Software

Computing chain design.

Differential studies: physical models and numerical methods.

Experimental data and phenomenology	Full processes
Computation of amplitudes	Small distance contributions
First principles and fundamental parameters	Large distance contributions

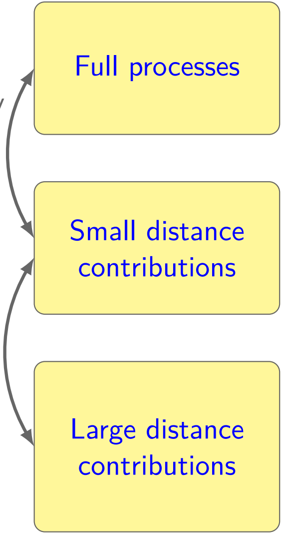
Computing chain design.

Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



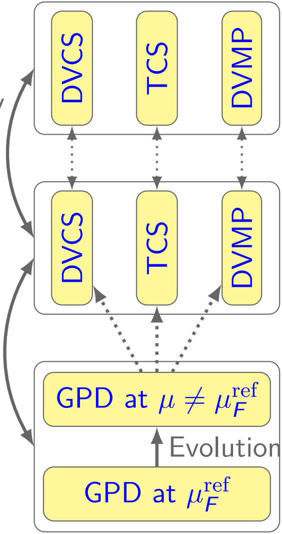
Computing chain design.

Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



Computing chain design.

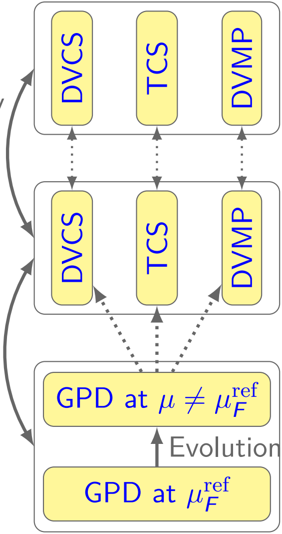
Differential studies: physical models and numerical methods.

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.

A computing framework for physics.

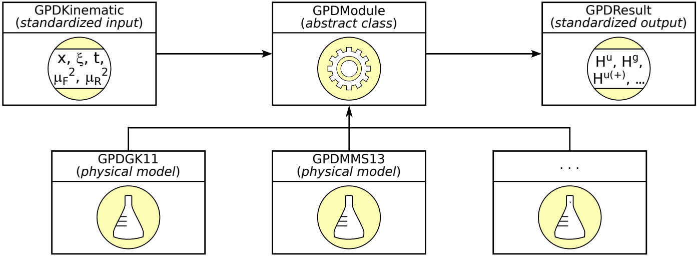
Done: tests, benchmarking, documentation, tutorials.

- Long-term perspective: future users or developers (when EIC takes data!) will not have taken part to the design.
- 3 stages:
  1. Design.
  2. Integration and validation.
  3. Benchmarking and production.
- 1 new physical development = 1 new module.
- *Aggregate* **knowledge** and **know-how** in a robust long-term solution:
  - Models.
  - Measurements.
  - Numerical techniques.
  - Validation.
- What *can* be automated *will be* automated.
- Flexible software architecture.

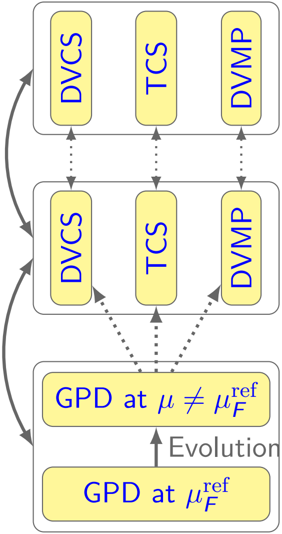
B. Berthou *et al.*, Eur. Phys. J. **C78**, 478 (2018)

Modularity.

Inheritance, standardized inputs and outputs.



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



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

ConvolCoeffFunctionModule.h

```
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.
  - ...

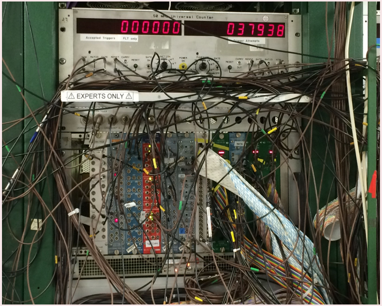
Systematic studies made easy.

A faster and safer way to GPD phenomenology... and beyond?!

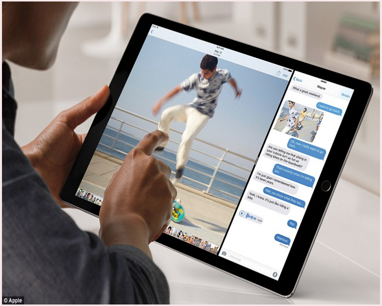
Automation allows...:

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

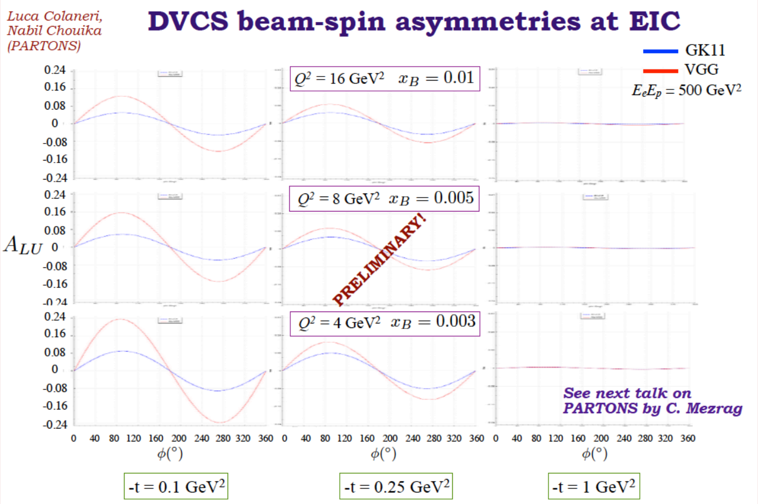
Without PARTONS



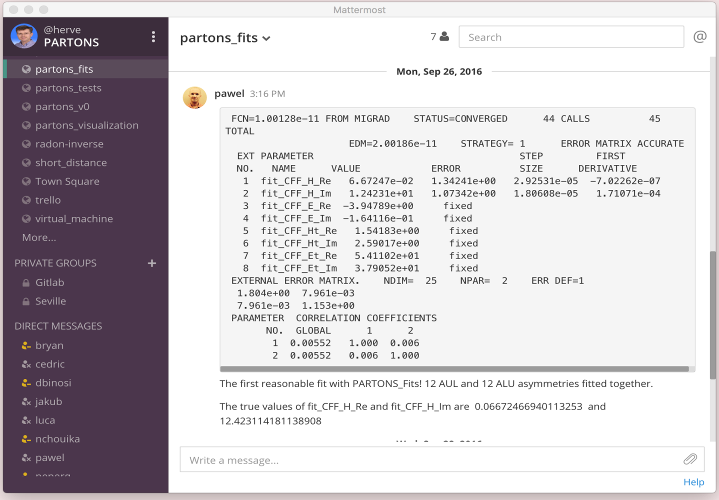
With PARTONS



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



First local fit of pseudo DVCS data, Sep. 26$^{\text{th}}$, 2016



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

RESULTS

- Kinematic cuts $Q^2 > 1.5$ GeV^2 (*where we can rely on LO approximation*)
  $-t / Q^2 < 0.25$ (*where we can rely on GPD factorization*)
- χ^2 / ndf $3272.6 / (3433 - 7) \approx 0.96$
- Free parameters a_{Hsea}, $a_{\tilde{H}val}$, $a_{\tilde{H}sea}$, C_{sub}, a_{sub}, N_E, $N_{\tilde{E}}$
- 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	σUU	120	120	135.0	1.19
Hall A	[1] KINX2	ΔσLU	120	120	98.9	0.88
Hall A	[1] KINX3	σUU	108	108	274.8	2.72
Hall A	[1] KINX3	ΔσLU	108	108	107.3	1.06
CLAS	[2]	σUU	1933	1333	1089.2	0.82
CLAS	[2]	ΔσLU	1933	1333	1171.9	0.88
CLAS	[3]	AUL, ALU, ALL	498	305	338.1	1.13

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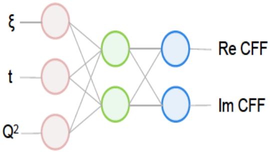
Neural network global fit of CLAS asymmetries, May 31st, 2017

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
- χ^2 / ndf = 273.9 / (305 - 68) ≈ 1.16

Paweł Sznajder Nucleon and Resonance Structure Workshop 2017 23

GPD or CFF fits (4/4).

From local to global fits in 8 months!

- 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.

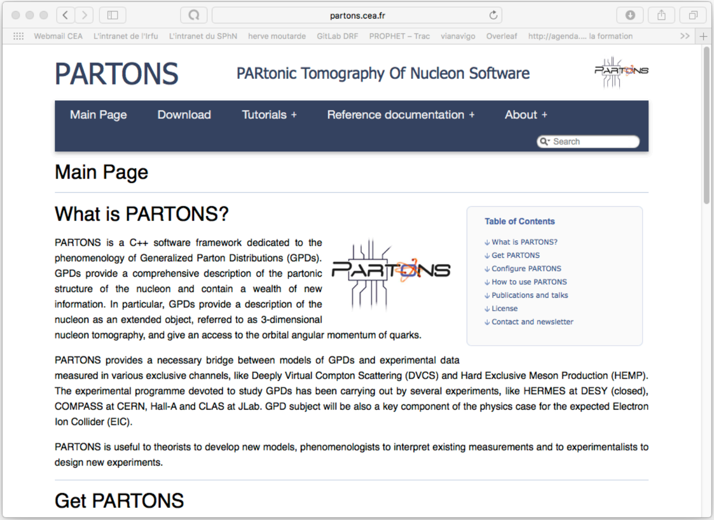
  Moutarde *et al.*, Eur. Phys. J. **C78**, 890 (2018)

  Moutarde *et al.*, Eur. Phys. J. **C79**, 614 (2019)

- More to come in the near future: GPD fits, impact studies!

Open source release.

Publicly available on CEA GitLab server.



PARTONS

PARtonic Tomography Of Nucleon Software

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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.

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

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).

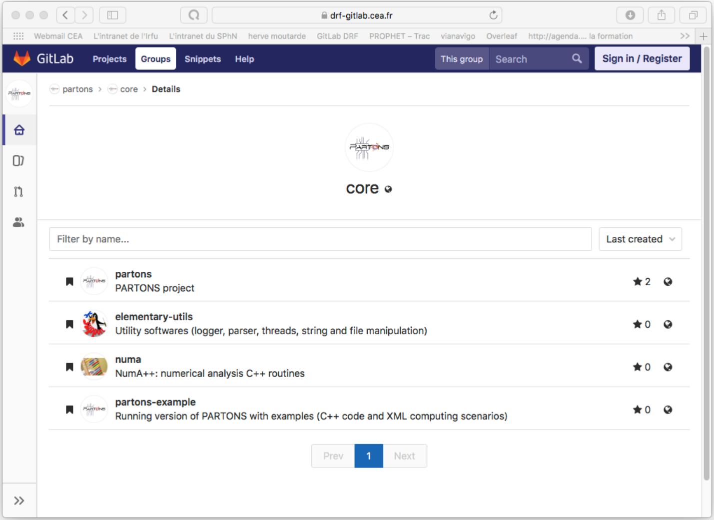
PARTONS is useful to theorists to develop new models, phenomenologists to interpret existing measurements and to experimentalists to design new experiments.

Get PARTONS

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

Open source release.

Publicly available on CEA GitLab server.



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

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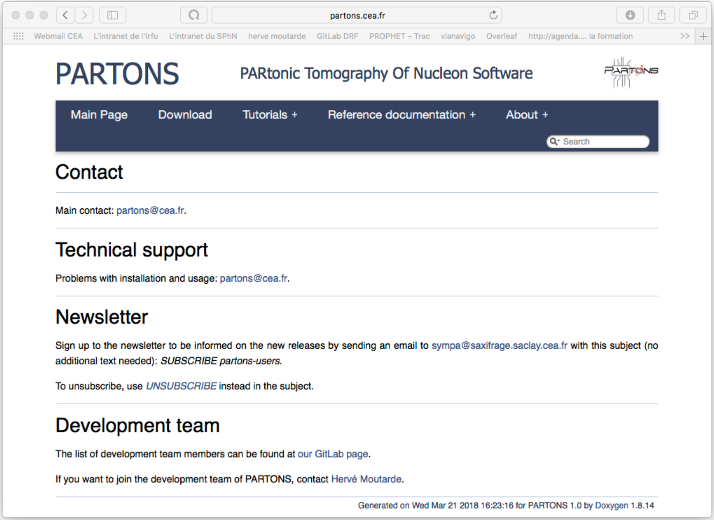
partons.cea.fr

Webmail CEA L'intranet de l'Irfu L'intranet du SPhN herve moutarde GitLab DRF PROPHET – Trac vianavigo Overleaf http://agenda.... la formation

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Contact

Main contact: partons@cea.fr.

Technical support

Problems with installation and usage: partons@cea.fr.

Newsletter

Sign up to the newsletter to be informed on the new releases by sending an email to sympa@saxifrage.saclay.cea.fr with this subject (no additional text needed): *SUBSCRIBE partons-users*.

To unsubscribe, use *UNSUBSCRIBE* instead in the subject.

Development team

The list of development team members can be found at our GitLab page.

If you want to join the development team of PARTONS, contact Hervé Moutarde.

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)

Work Package objectives

- Aggregate, improve and homogenize existing codes written by independent groups from the GPD and TMD communities: **ensure interoperability**.
- Maintain and release robust, flexible, validated and up-to-date open source codes to the 3D hadron structure community: **foster progress**.
- Provide documentation, technical assistance and perform nonregression tests: **facilitate dissemination**.
- Promote Open Data and Open Science: **build on previous research and get new results faster**.

Work Package tasks

- Flexible software architecture for GPD and TMD codes, elaborating on existing libraries and benefiting from experience from the PDF community.
- Generic MC event generators for GPDs and TMDs.
- Associated tools to compare theoretical calculations to experimental data.
- 3DPartons workshops and training schools.
- Webpage, software forge and mailing lists.
- Interact with relevant Work Packages of STRONG-2020.

Conclusion

Conclusion and prospects.

Putting all the pieces together.

- 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**.

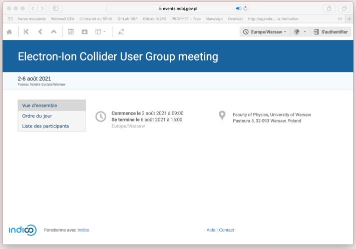
New studies become possible!

- 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!

PARTONS joins the EU effort towards EIC!

Previous European EIC User Group Meeting in Paris

Next European EIC User Group Meeting in Warsaw



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