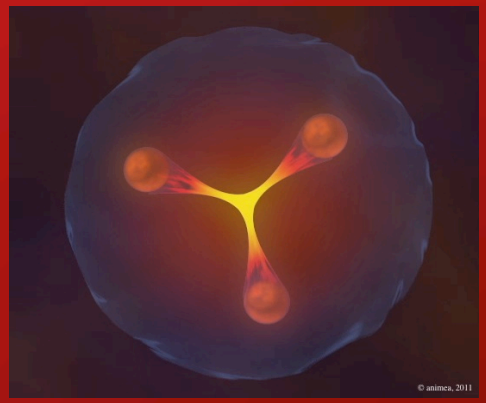
DE LA RECHERCHE À L'INDUSTRIE



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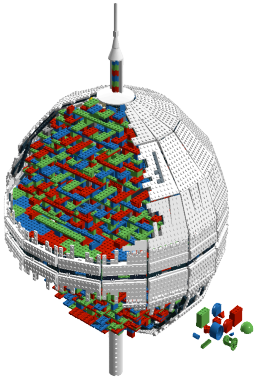
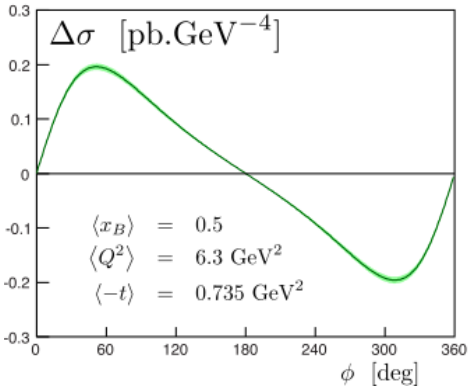
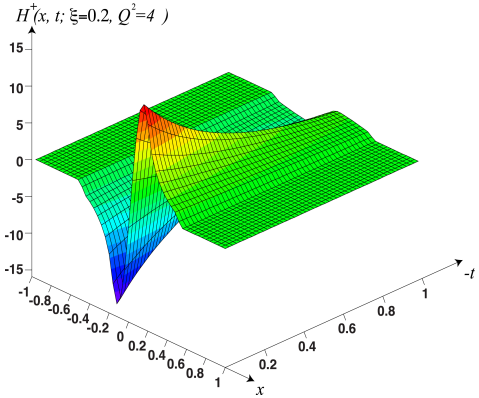
Prospects on nucleon tomography







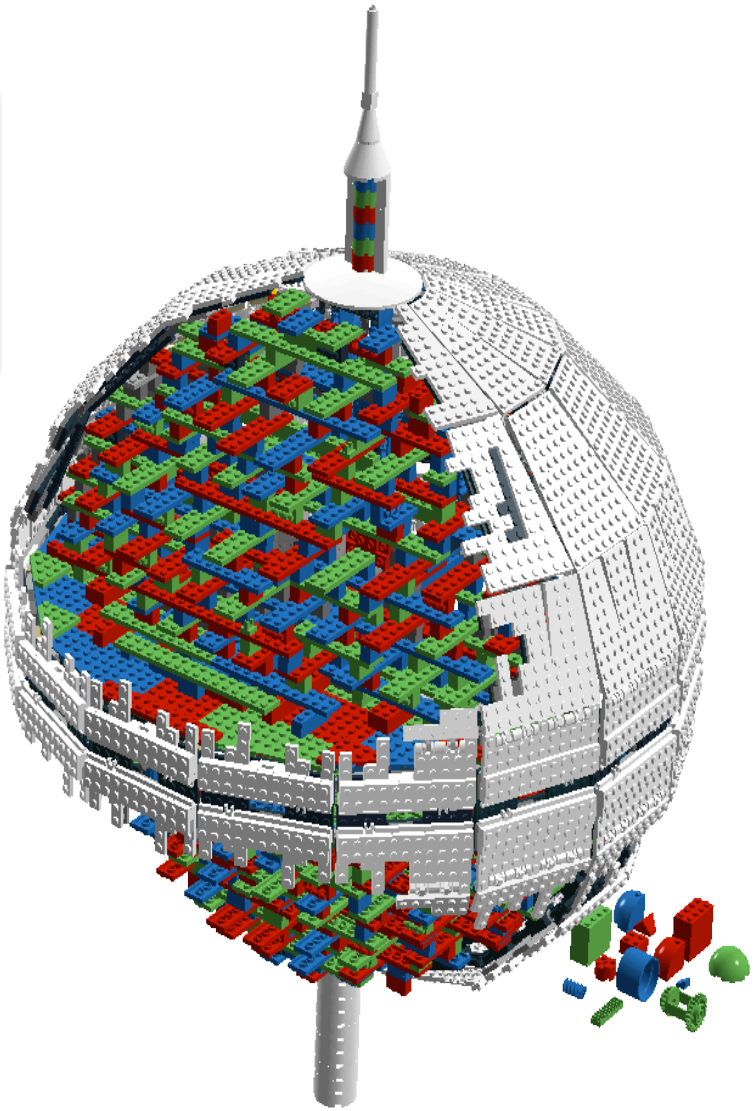
INPC | Hervé MOUTARDE

Jul. 30, 2019

université PARIS-SACLAY

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 characterics of the nucleon from the properties of its **colored building blocks**?

Mass?
Spin?
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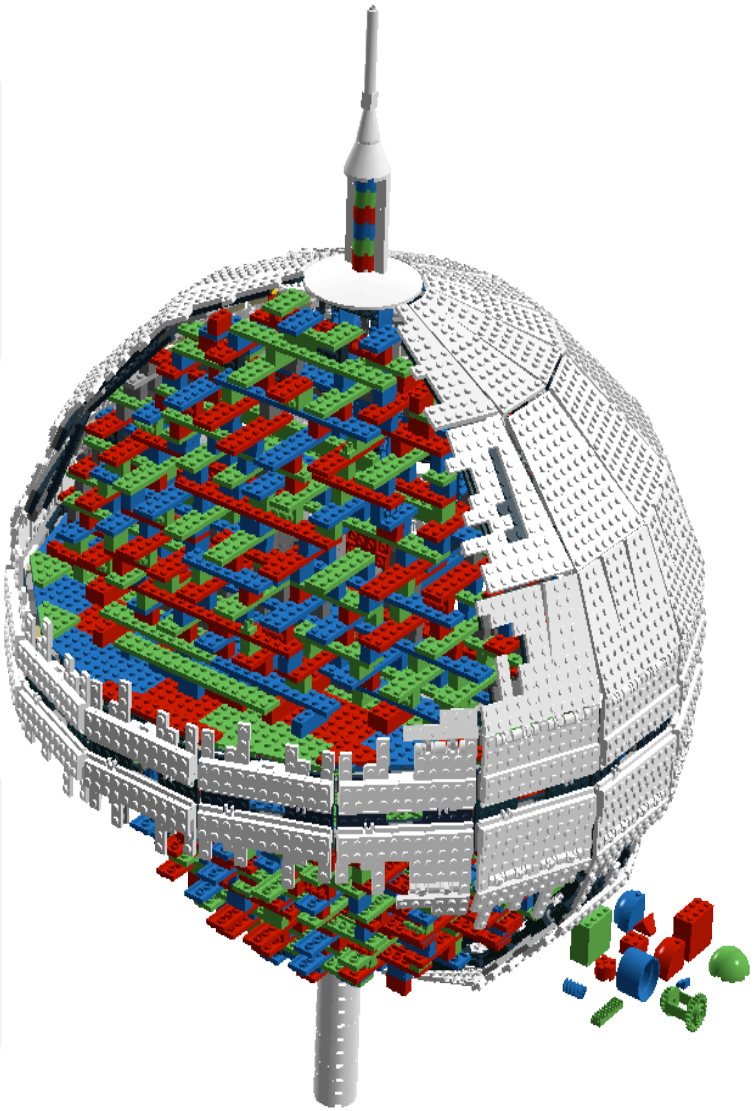
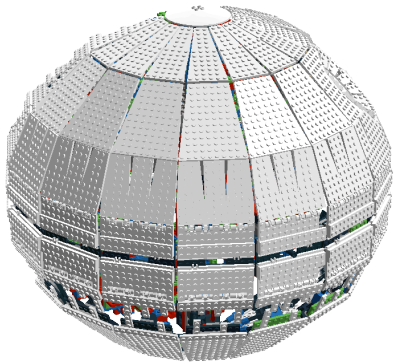
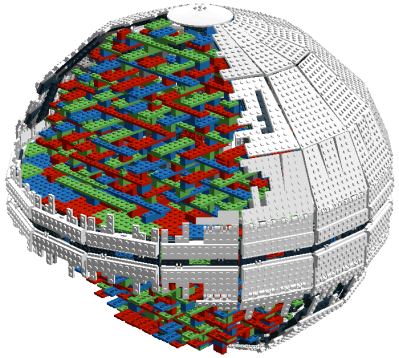
...

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



Colorless proton ?? $\leftrightarrow$ Colorful components





"Can one hear the shape of a drum?"

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

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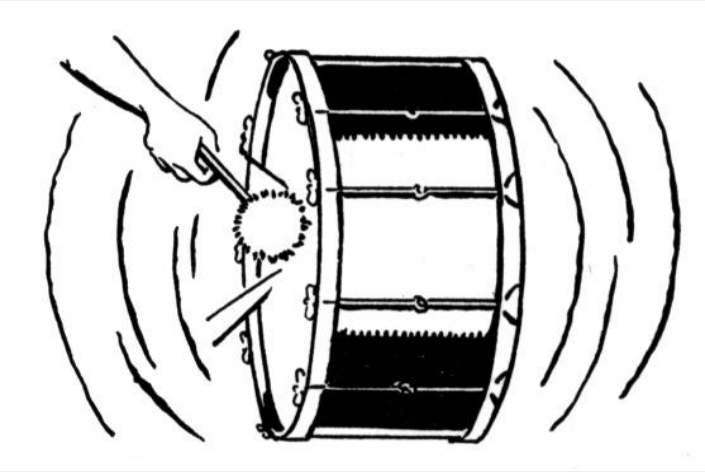

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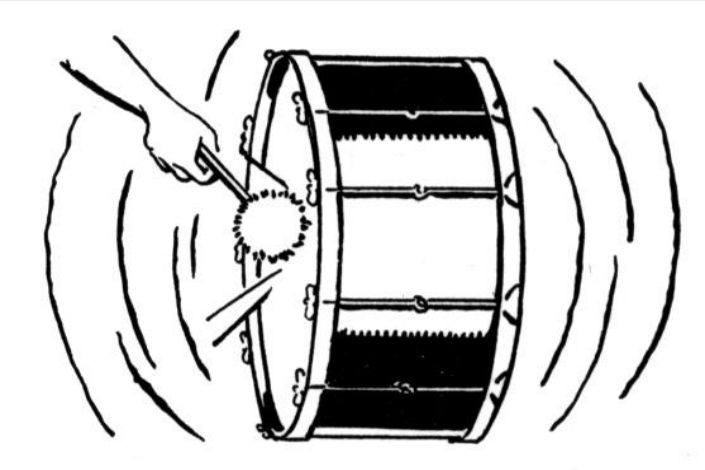

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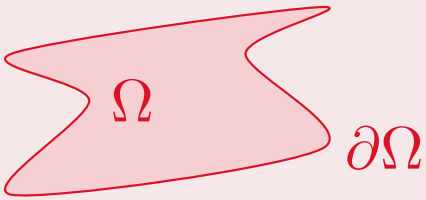
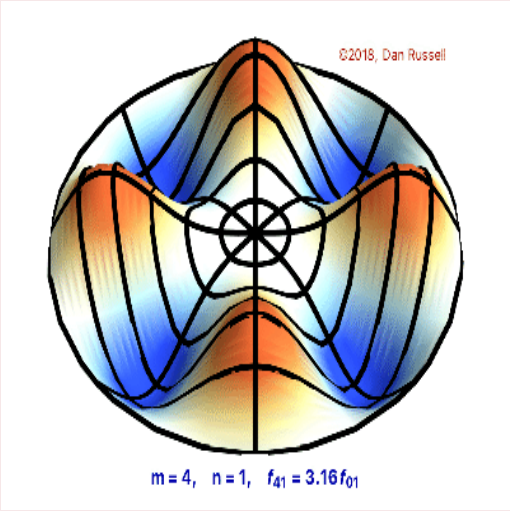
In quantitative terms



- Dirichlet problem for the Laplacian:

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

Vibration patterns



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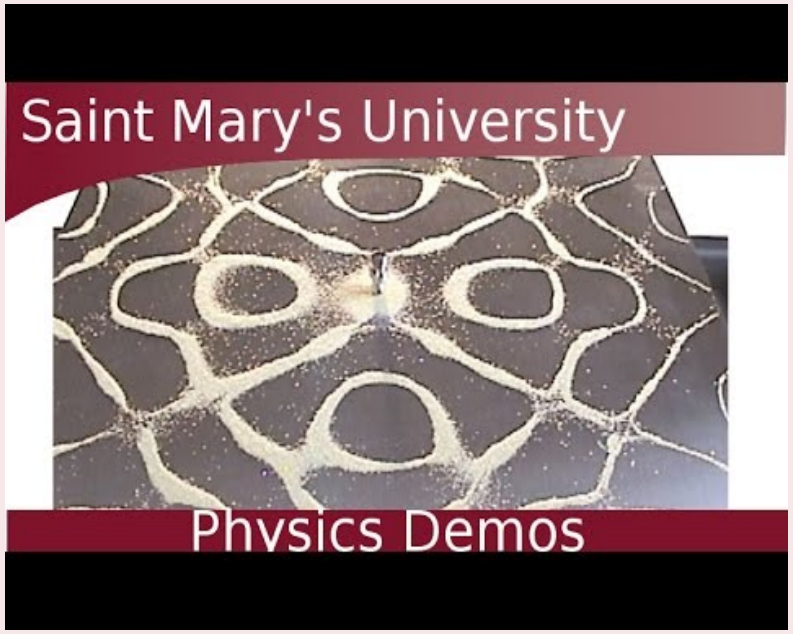
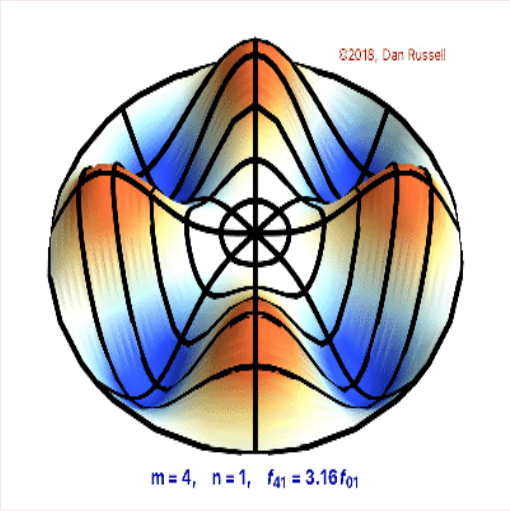


Can one hear the shape of a proton?

Harmonics and patterns.

Vibration patterns



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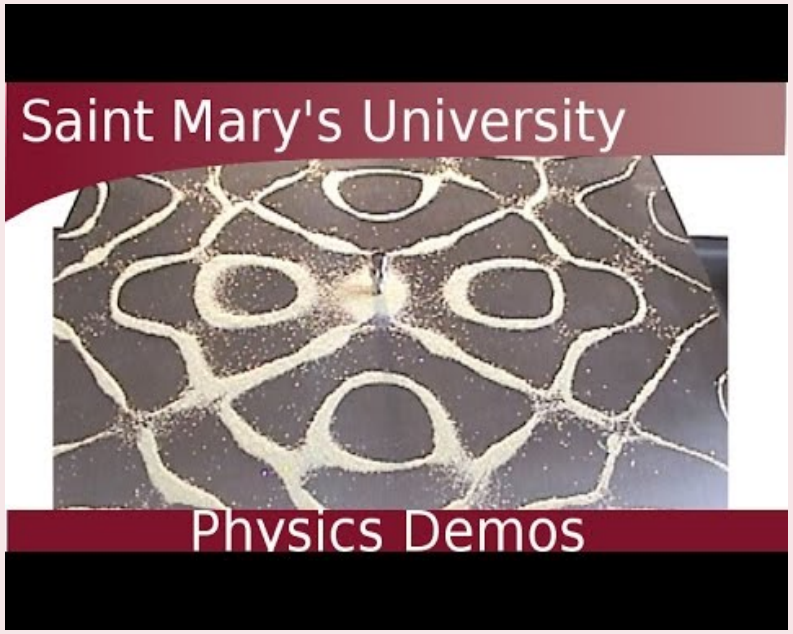


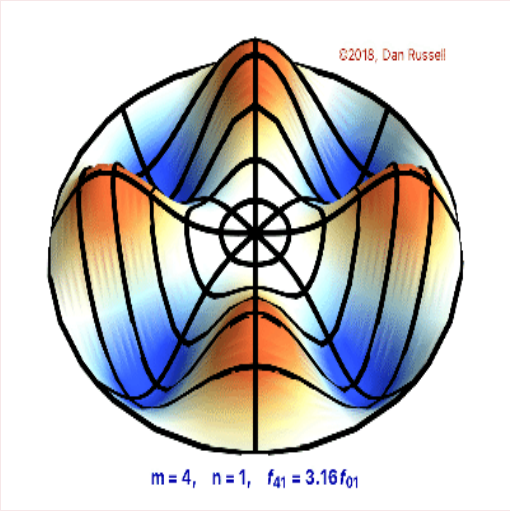
What about the proton?

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

Can one hear the shape of a proton?

Harmonics and patterns.

Vibration patterns



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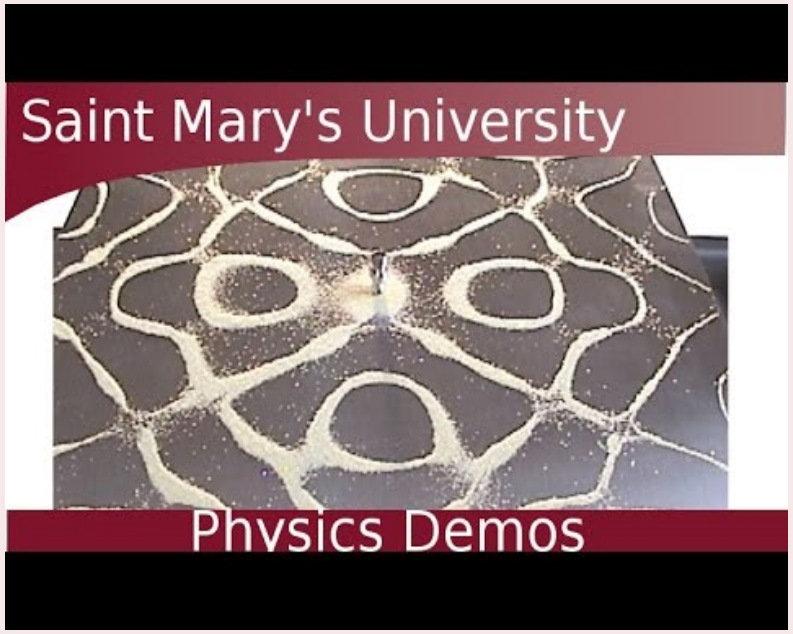
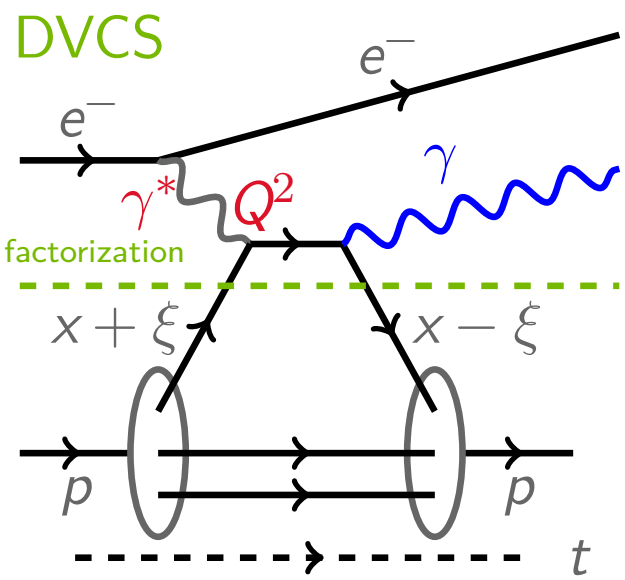


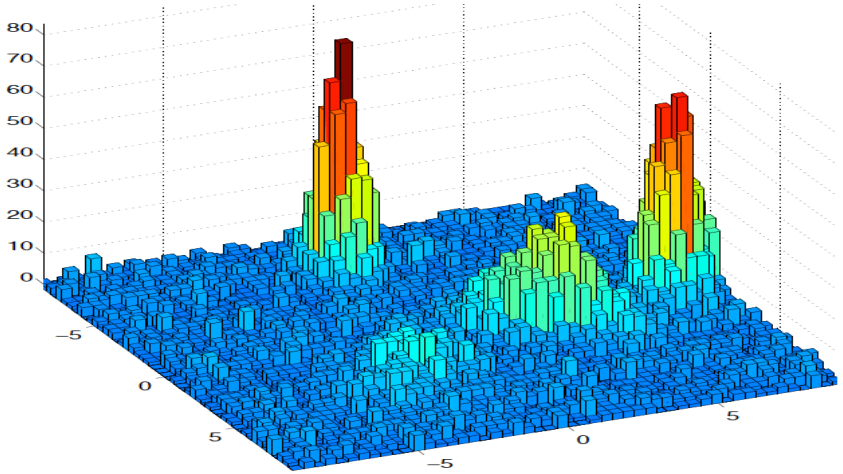
What about the proton?

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

Exclusive processes of current interest.

Factorization, universality and event distributions.





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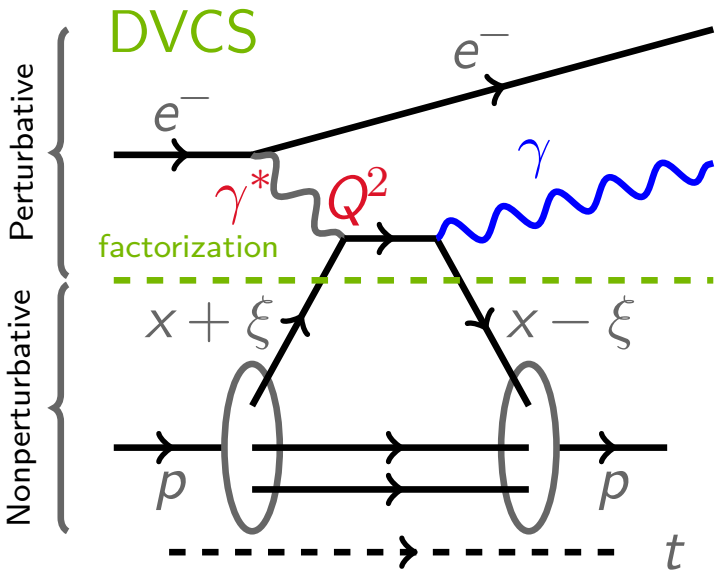

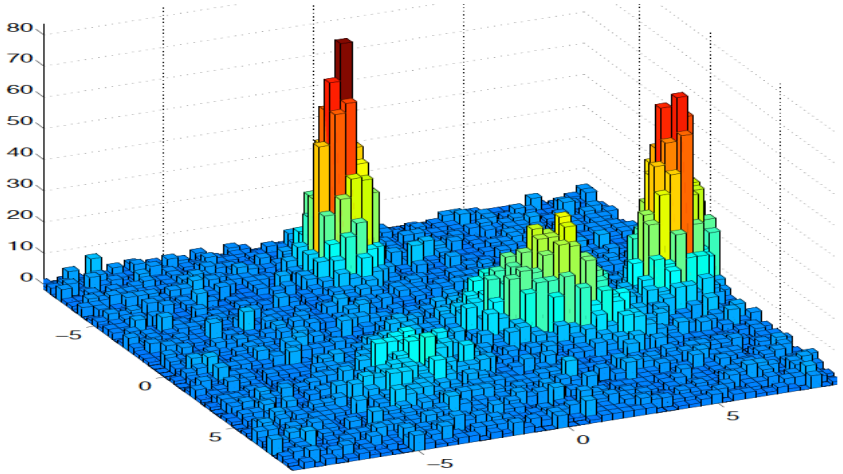

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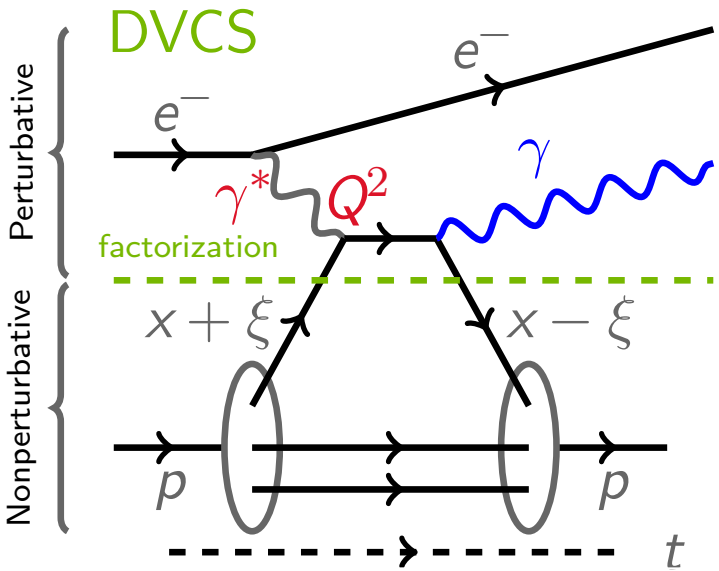

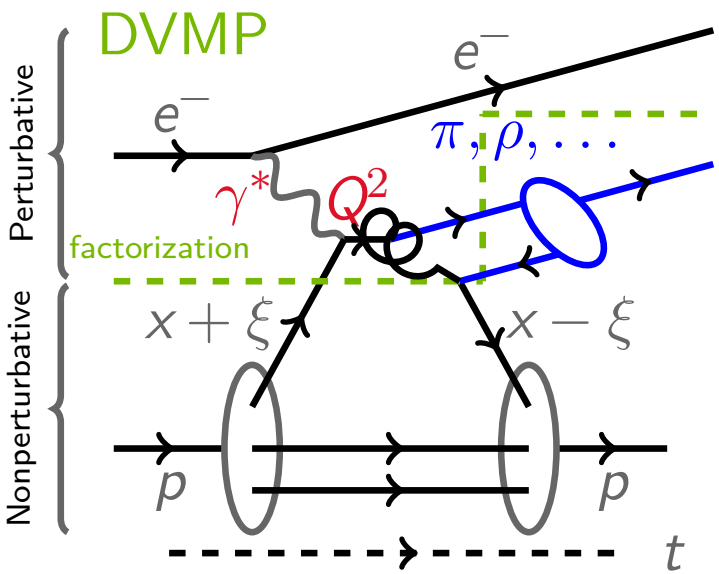

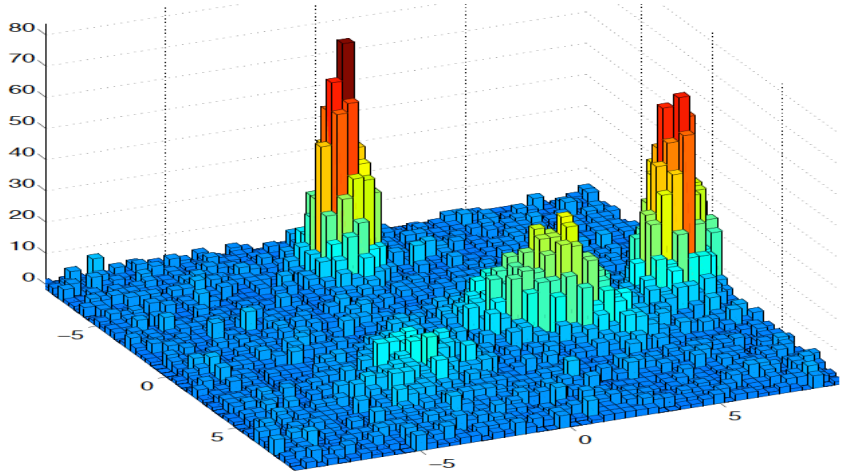

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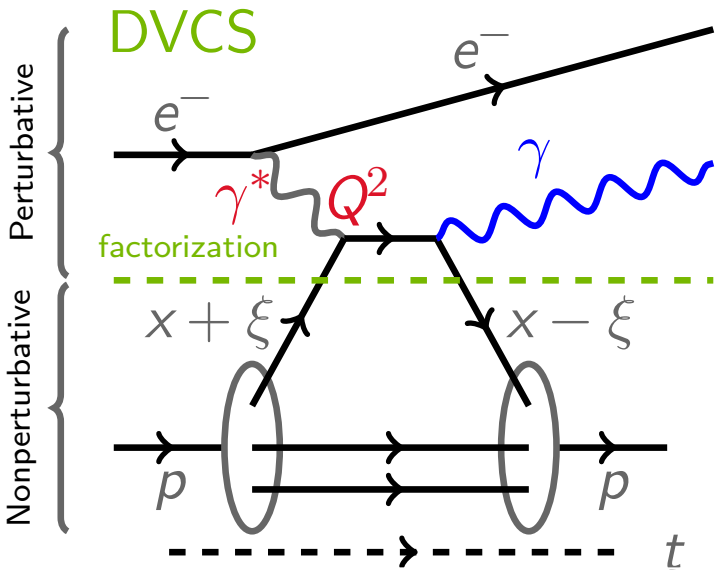

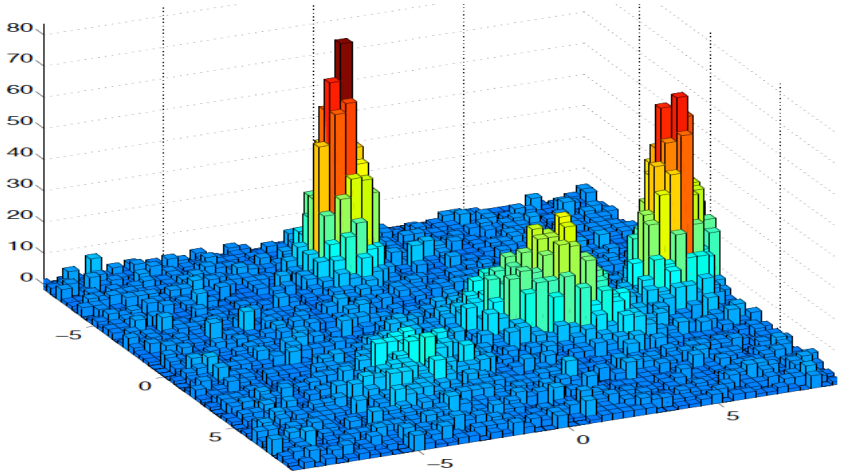

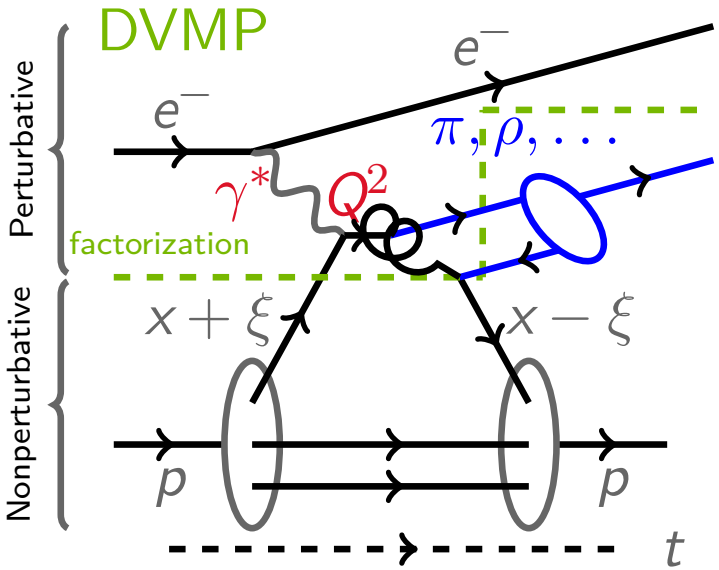

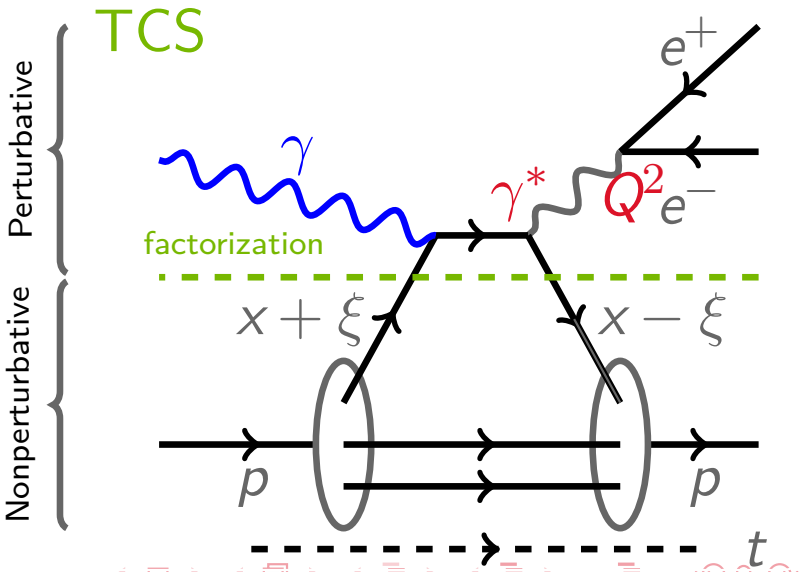

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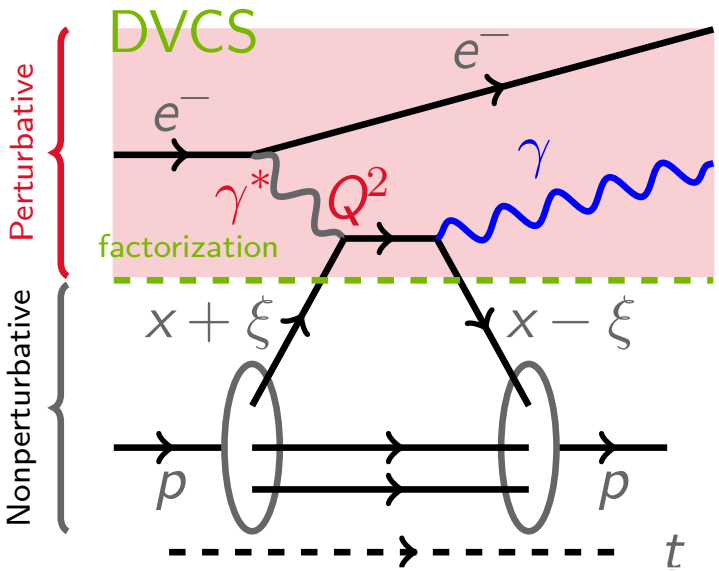

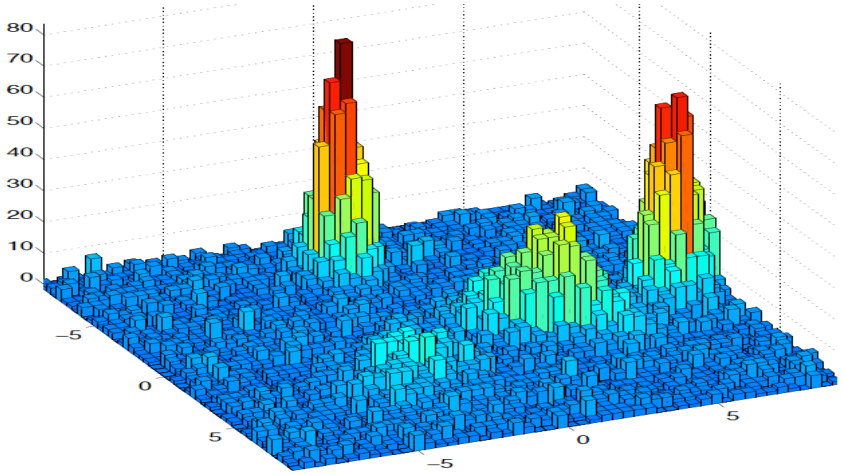

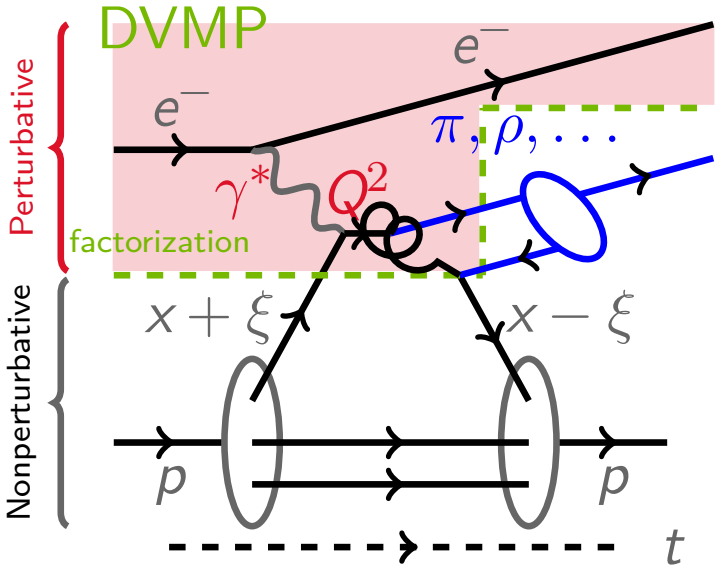

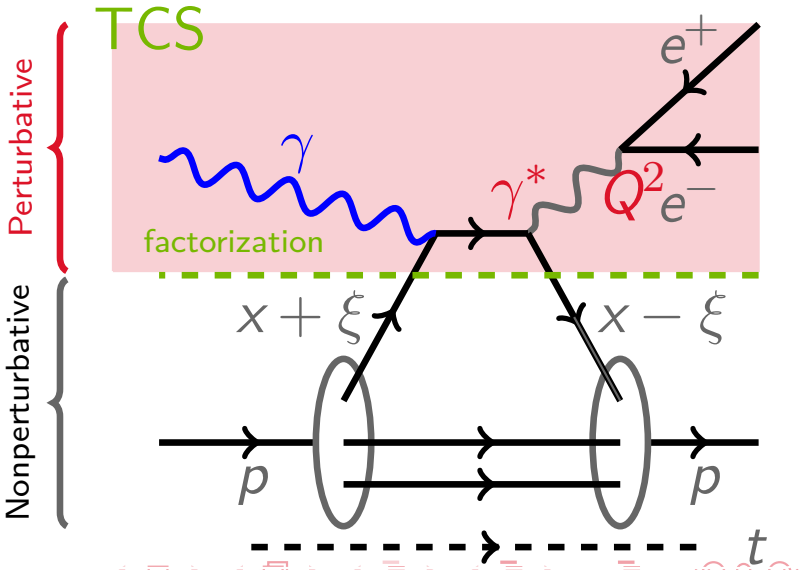

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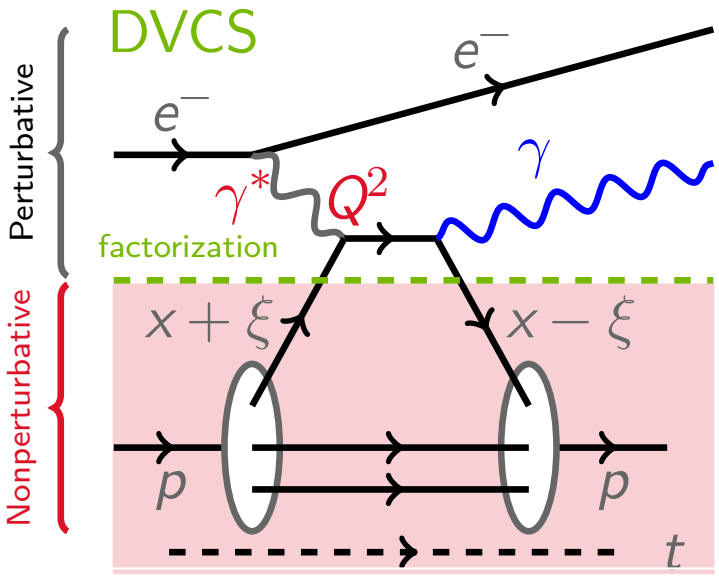
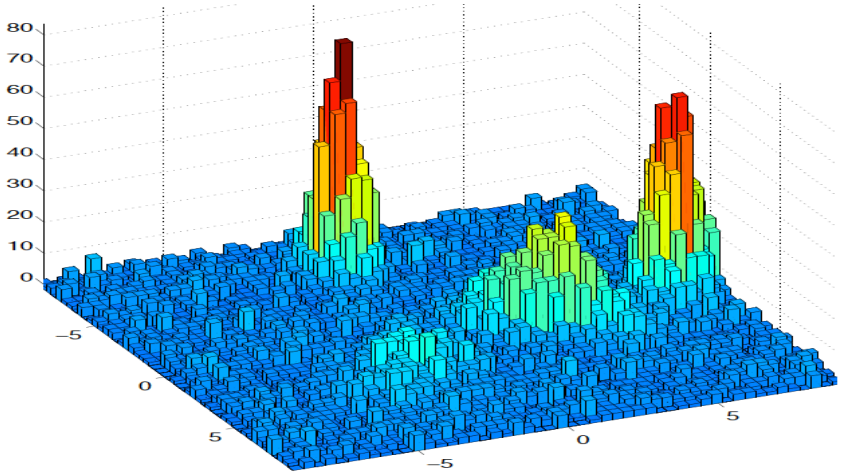
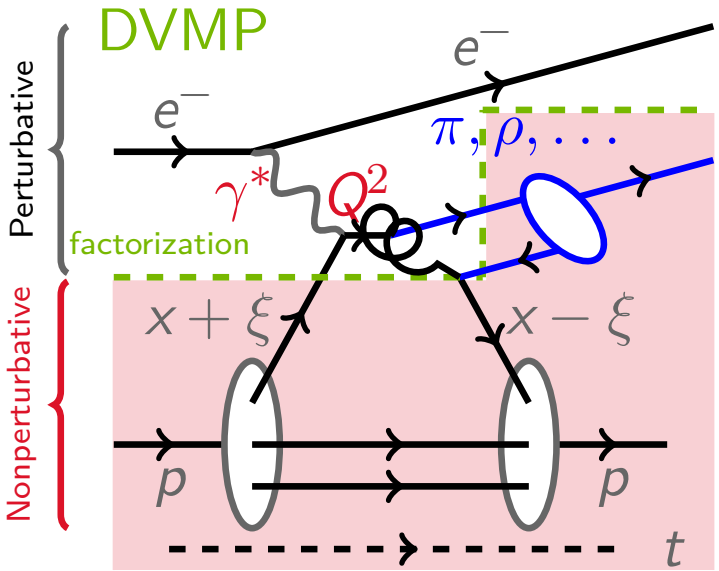
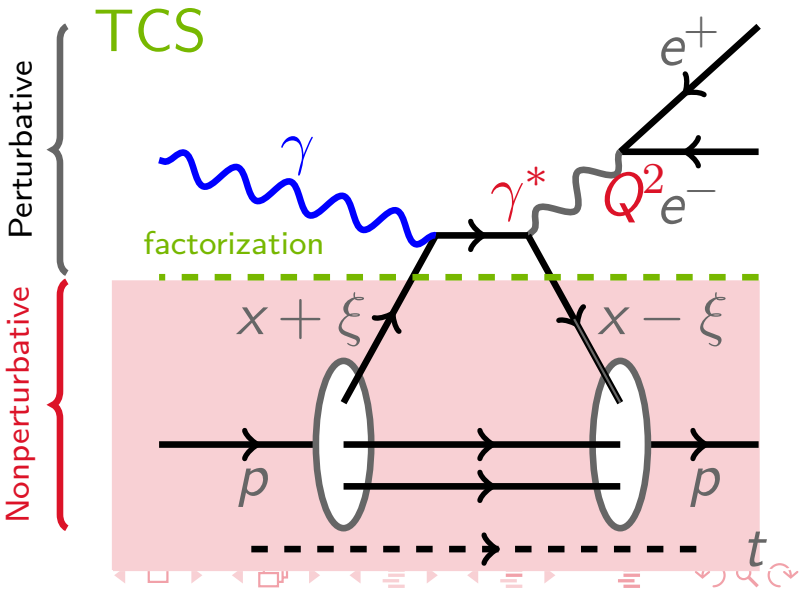


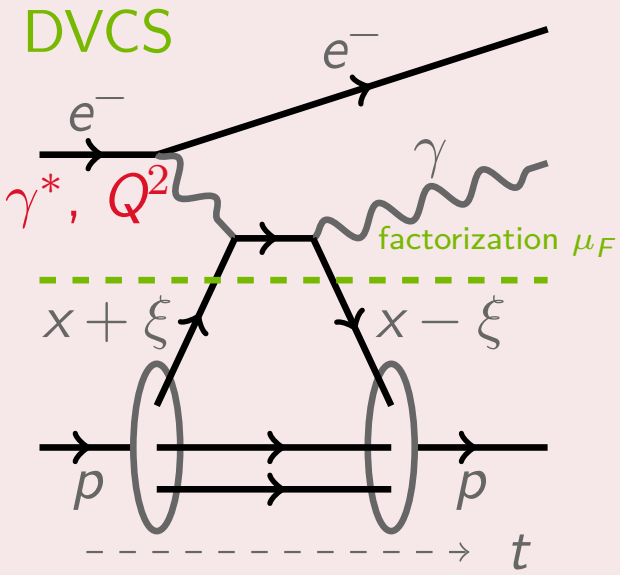


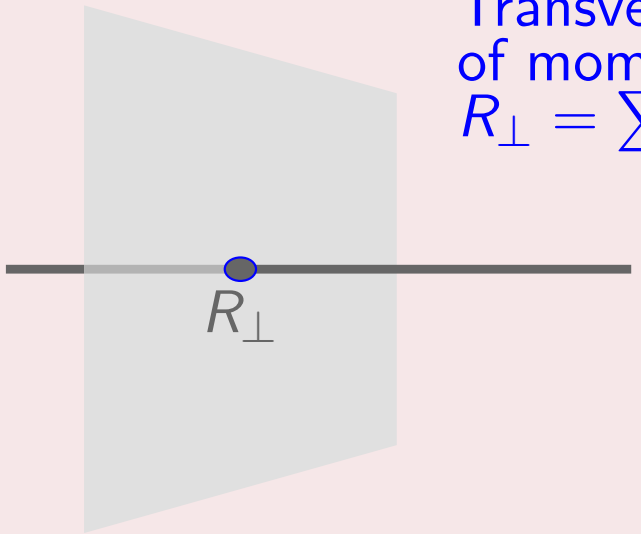




- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
- DVCS recognized as the cleanest channel to access GPDs.

Deeply Virtual Compton Scattering (DVCS)





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

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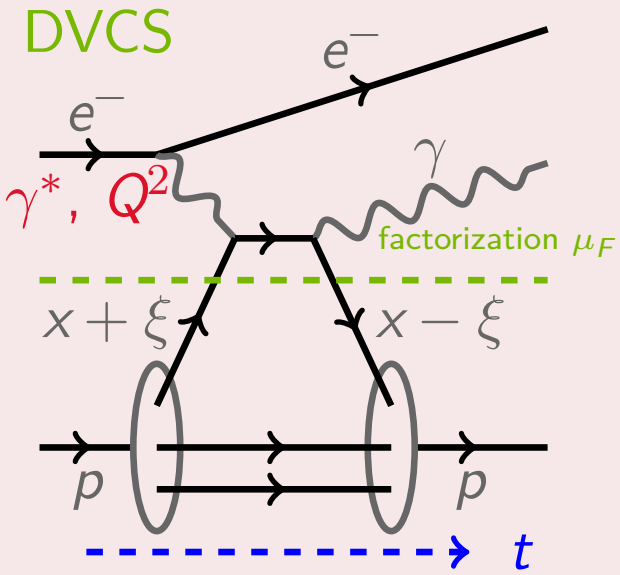

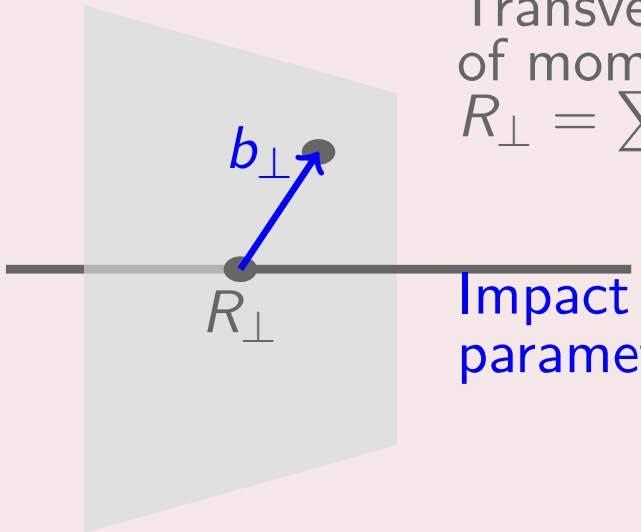

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Impact parameter $b_\perp$

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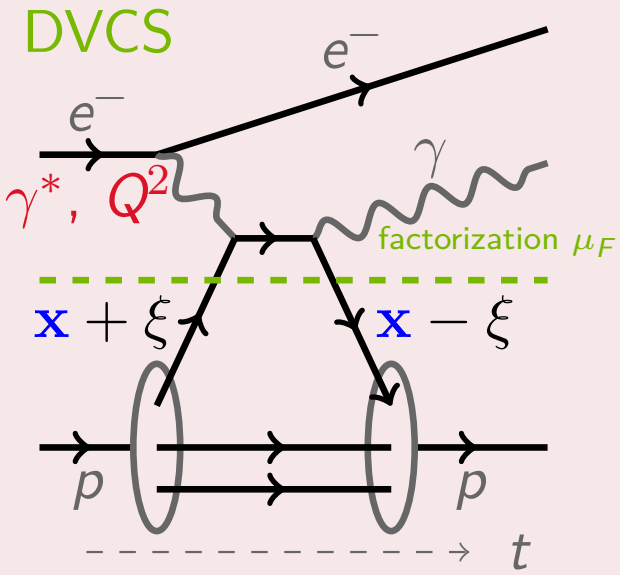

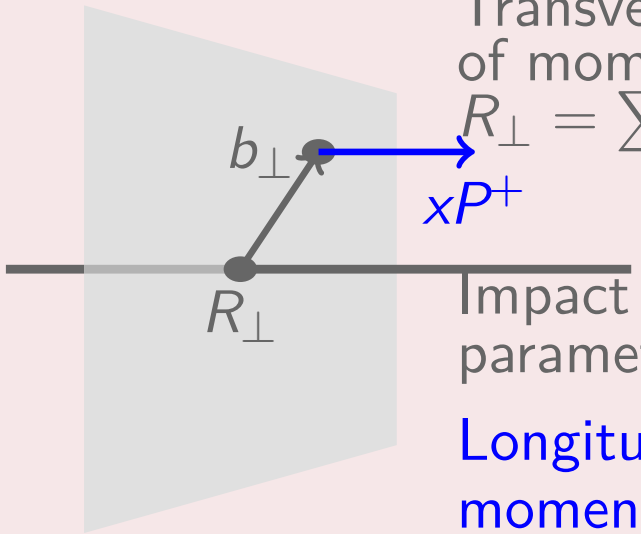

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Longitudinal momentum xP^+

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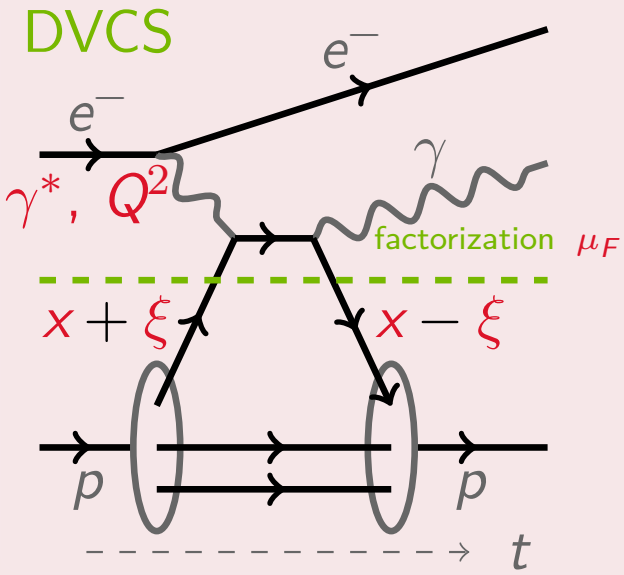

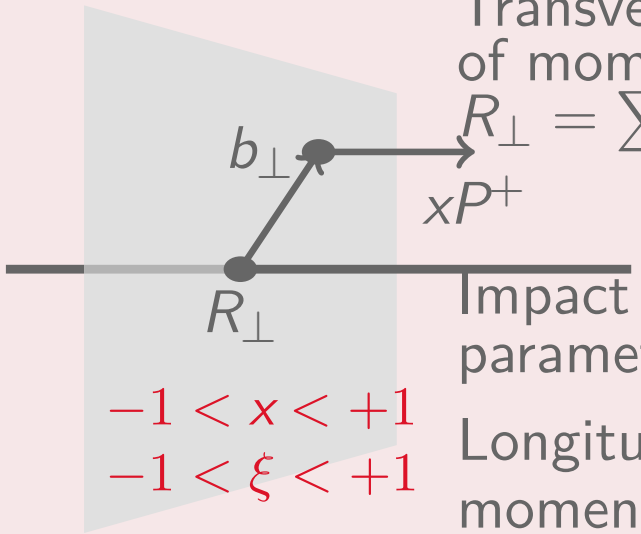

Transverse center of momentum $R_\perp$
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Impact parameter $b_\perp$

Longitudinal momentum xP^+

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

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

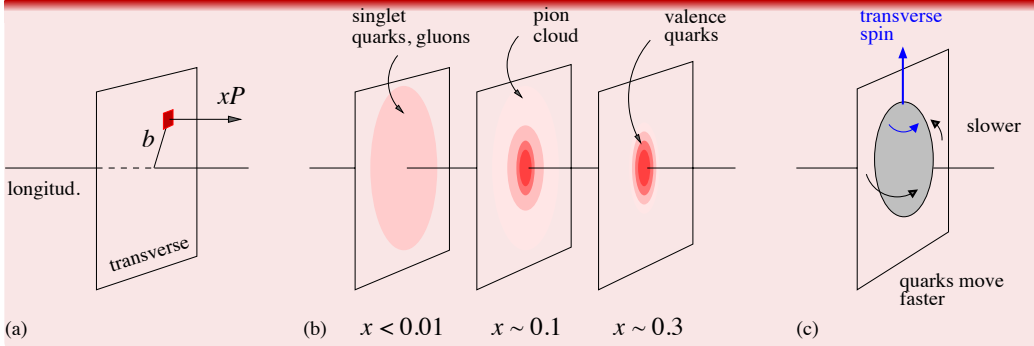
- **Probabilistic interpretation** of Fourier transform of GPD$(x, \xi = 0, t)$ in **transverse plane**.

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

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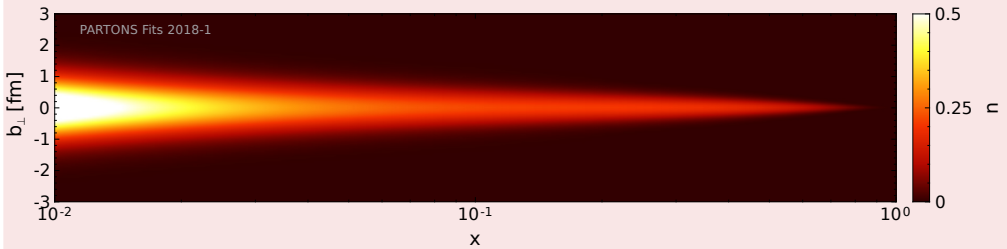
Burkardt, Phys. Rev. **D62**, 071503 (2000)

Not quite, but close!



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

- Energy momentum tensor between nucleon states:

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

with $t = \Delta^2$.

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

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

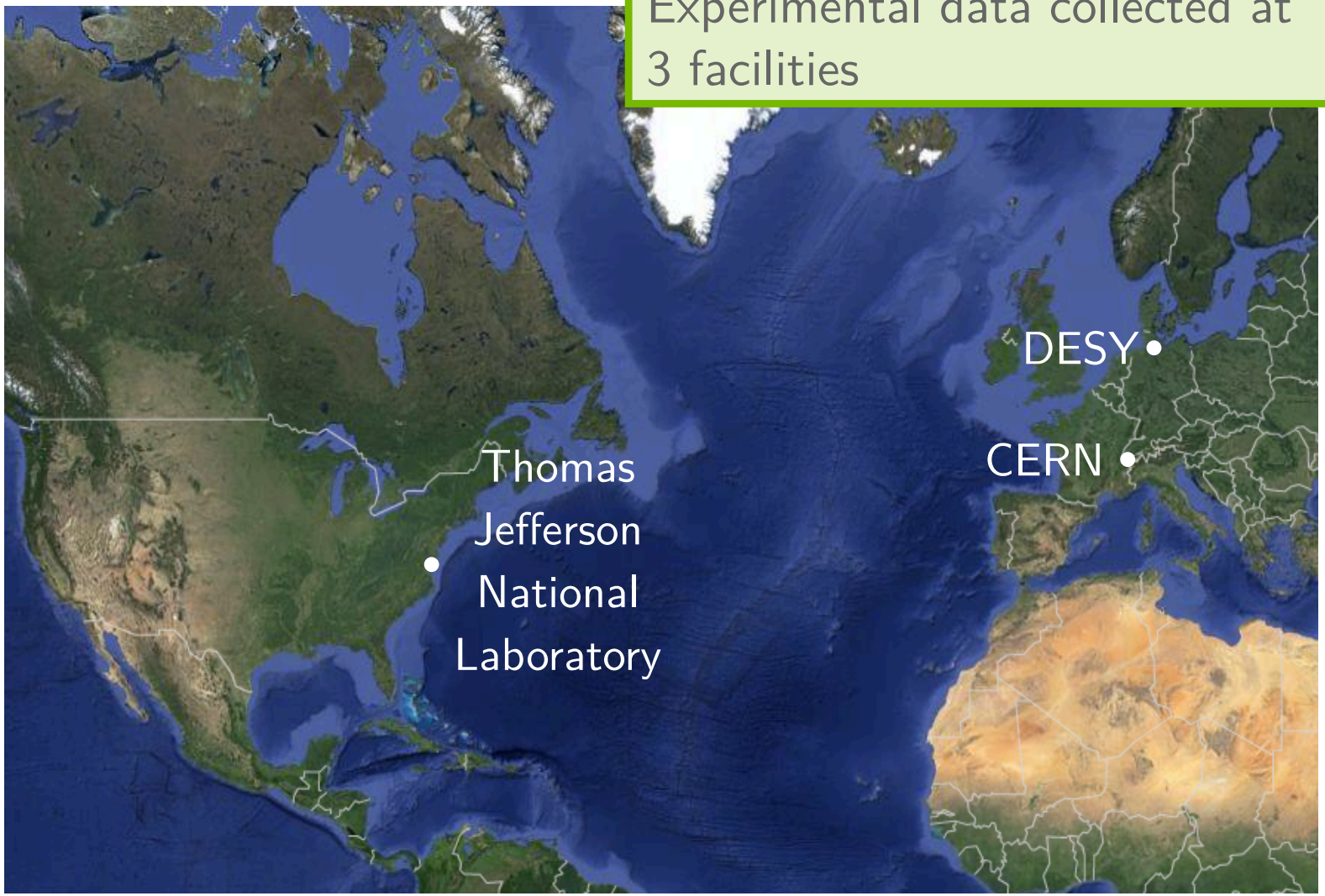
$$\int \mathrm{d}x\, x E^q(x,\xi,t) = B^q(t) - 4\xi^2 C^q(t)$$

Ji, Phys. Rev. Lett. **78**, 610 (1997)
See C. Lorcé's talk today!

Need for global fits of world data.

Different facilities will probe different kinematic domains.

Experimental data collected at 3 facilities



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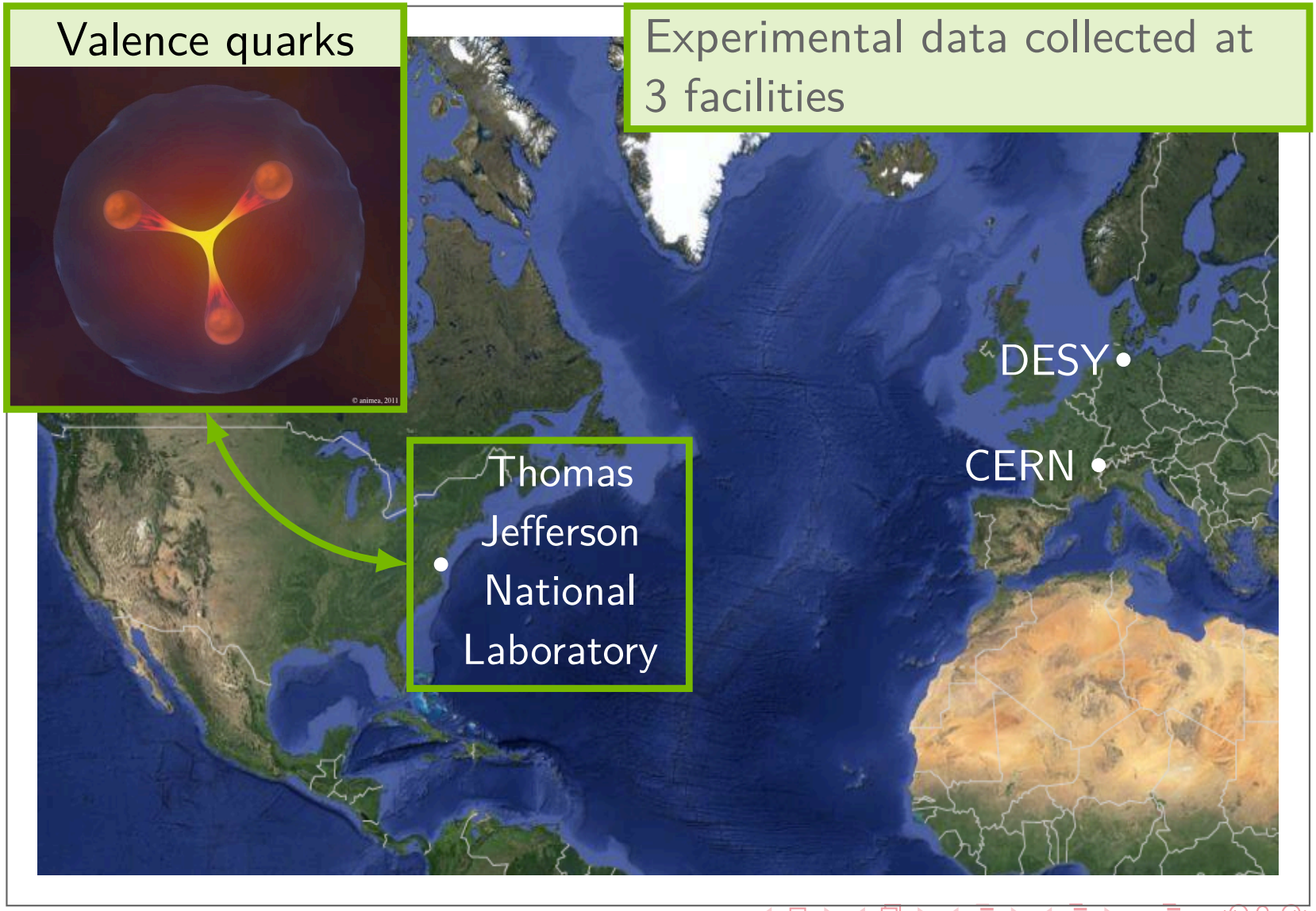

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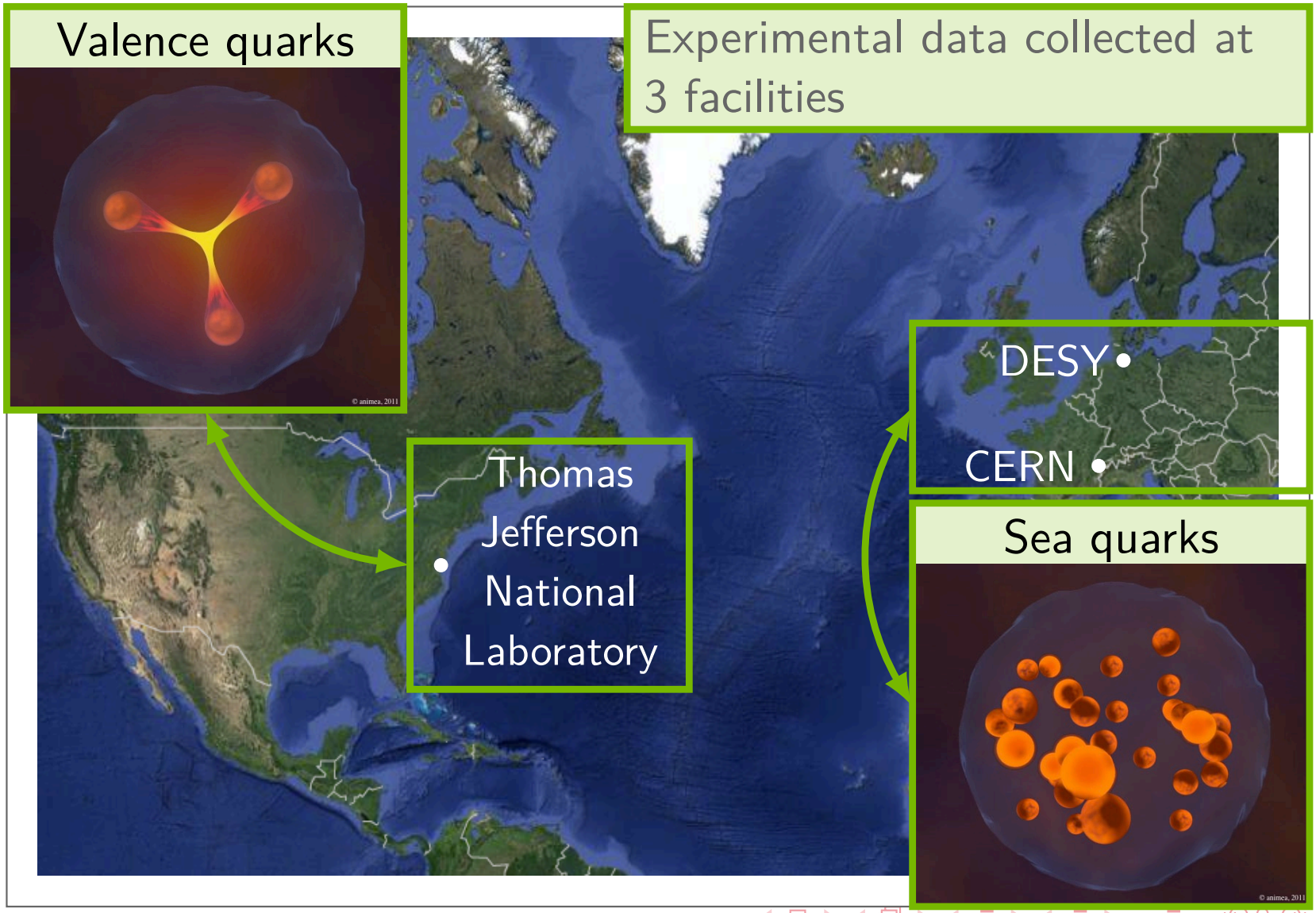
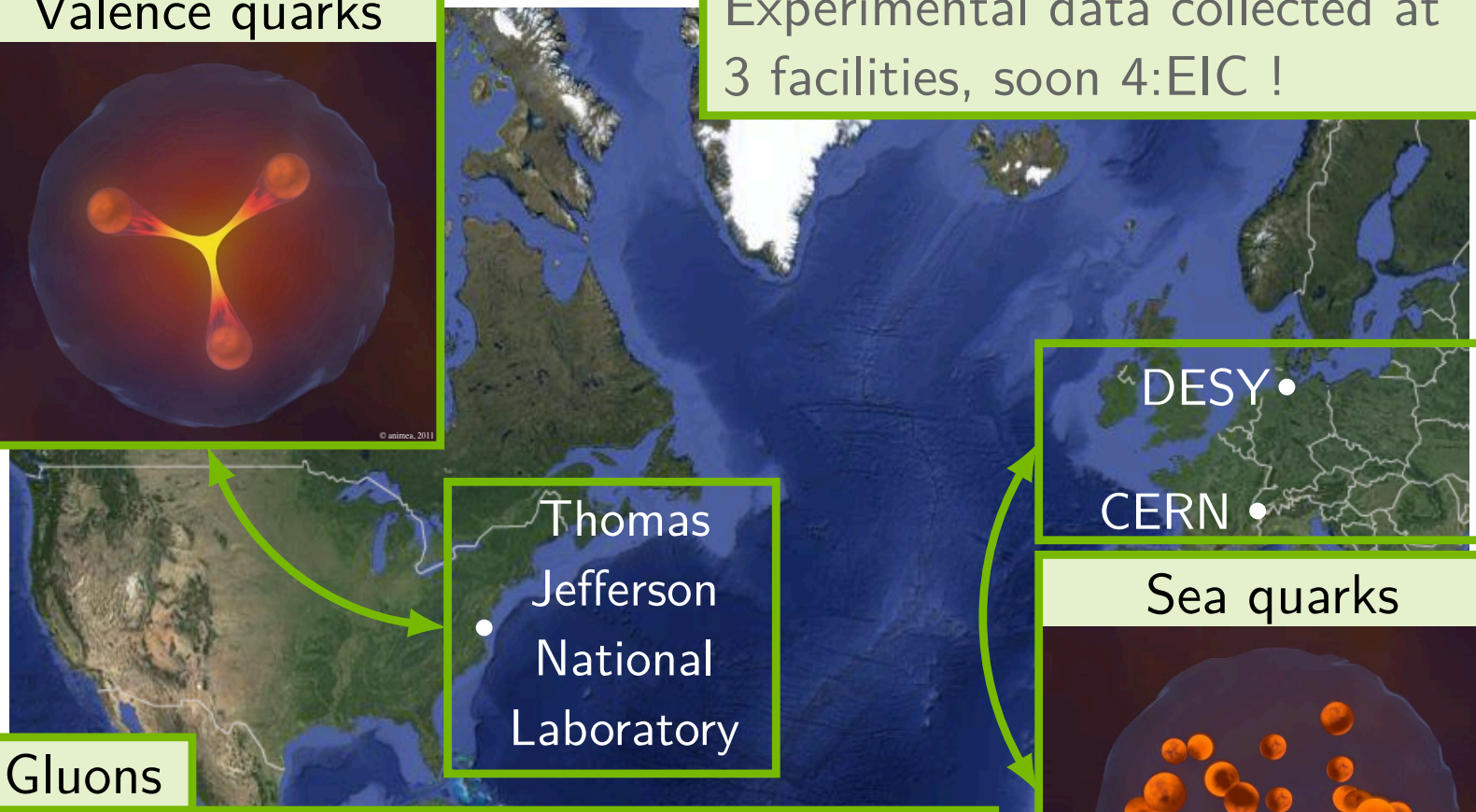


Need for global fits of world data.

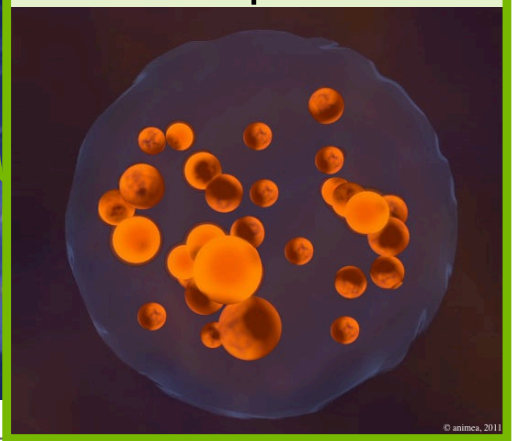
Different facilities will probe different kinematic domains.

Valence quarks

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



Sea quarks



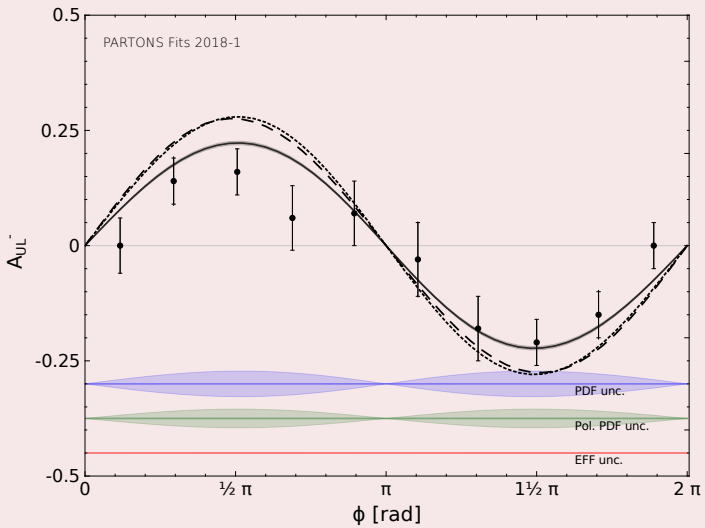
Gluons

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

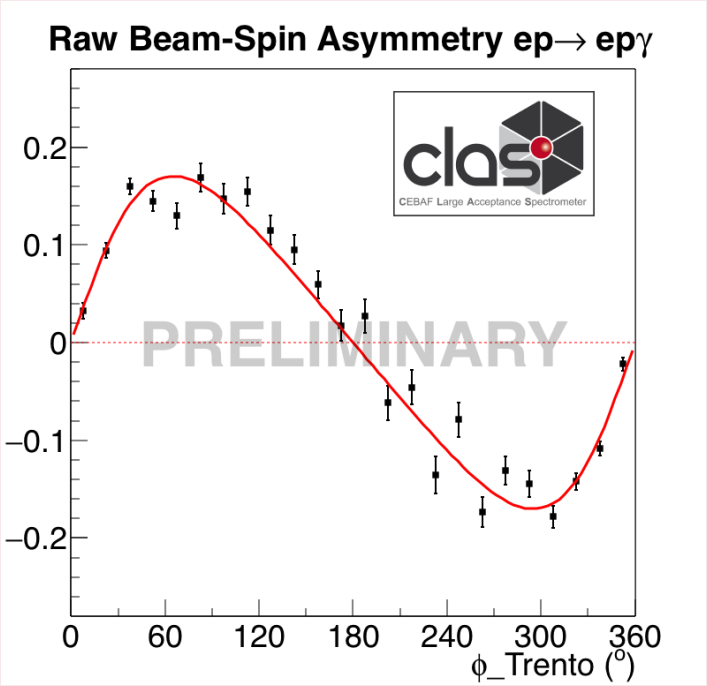
Existing and future DVCS measurements.

The field is changing with new data of unprecedented accuracy.

CLAS: preliminary results with 2% of approved beam time



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



Christiaens, APS DNP'18

See the talks by J. Roche, M. Defurne, G. Christiaens, S. Niccolai, P. Chatagnon and S. Scopetta on Thursday!

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

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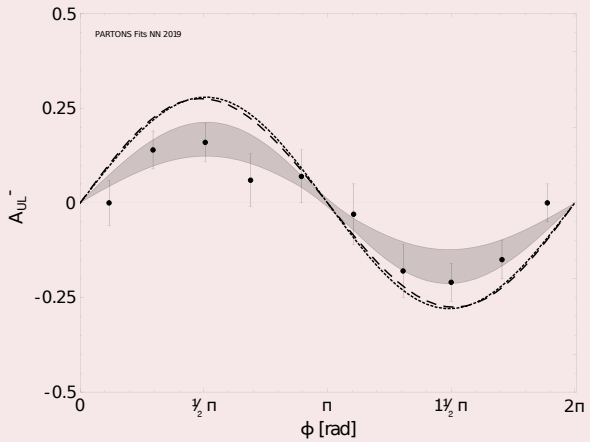
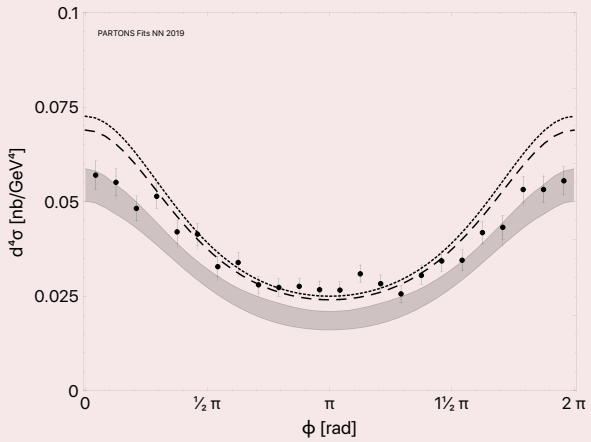
A selection of results.

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

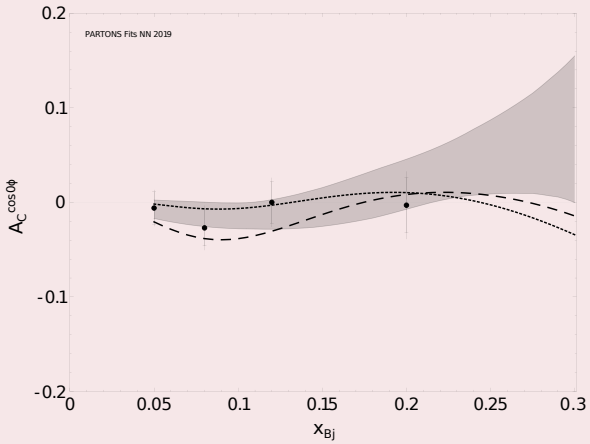
CLAS



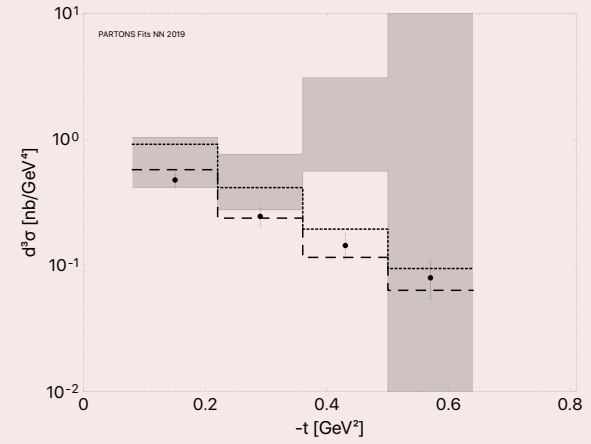
Hall A



HERMES



COMPASS



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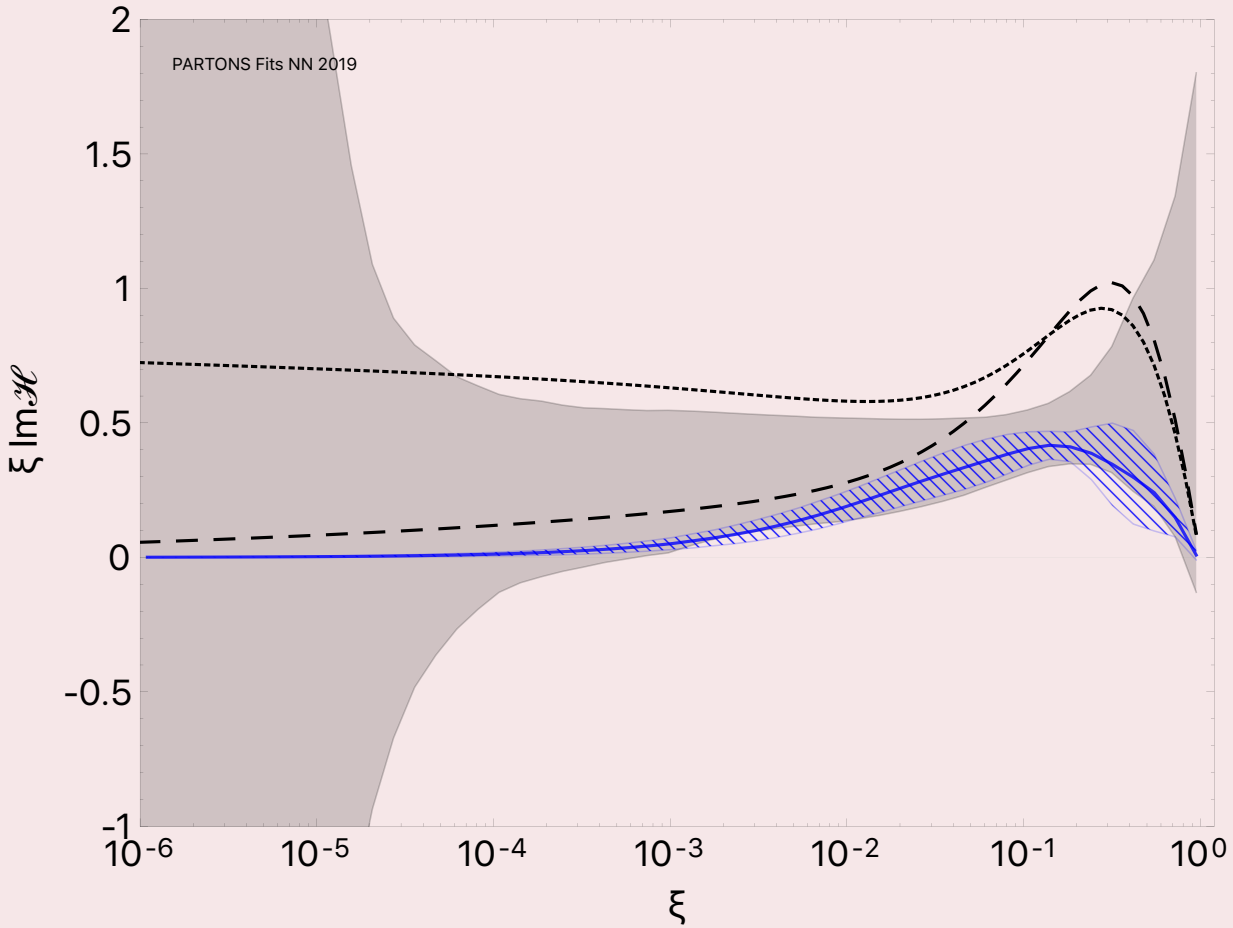
Compton form factor $\mathrm{Im}\mathcal{H}(\xi, t = -0.3\ \mathrm{GeV}^2, Q^2 = 2.\ \mathrm{GeV}^2)$



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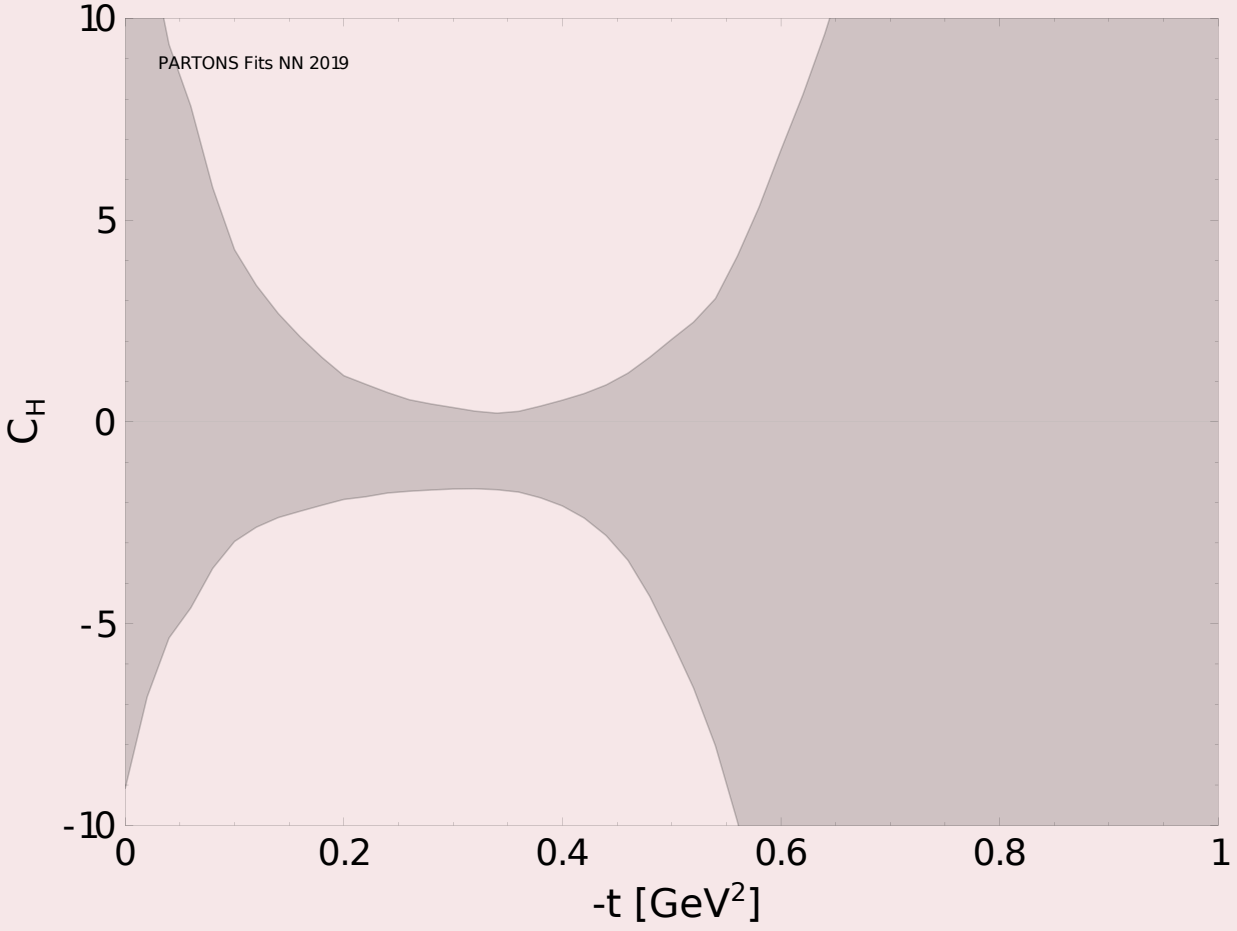
Subtraction constant (related to pressure distribution)



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The PARTONS framework

PARtonic
Tomography
Of
Nucleon
Software

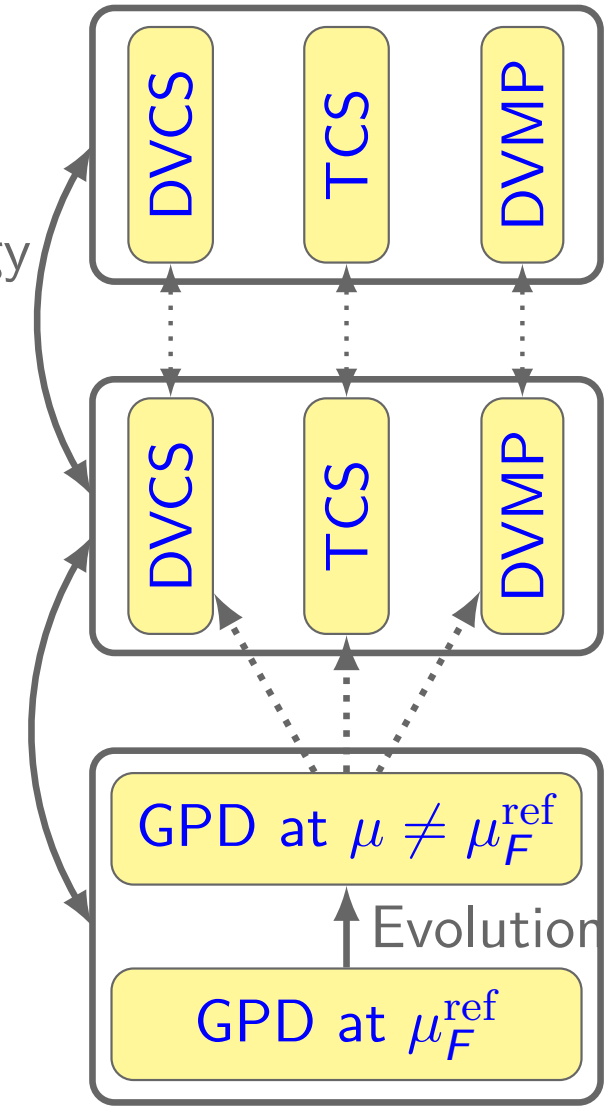
Computing chain design.

Differential studies: physical models and numerical methods.

Full processes
Experimental data and phenomenology

Small distance
Computation of amplitudes

Large distance
First principles and fundamental parameters



PARtonic **T**omography **O**f **N**ucleon **S**oftware

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

A computing framework for physics.

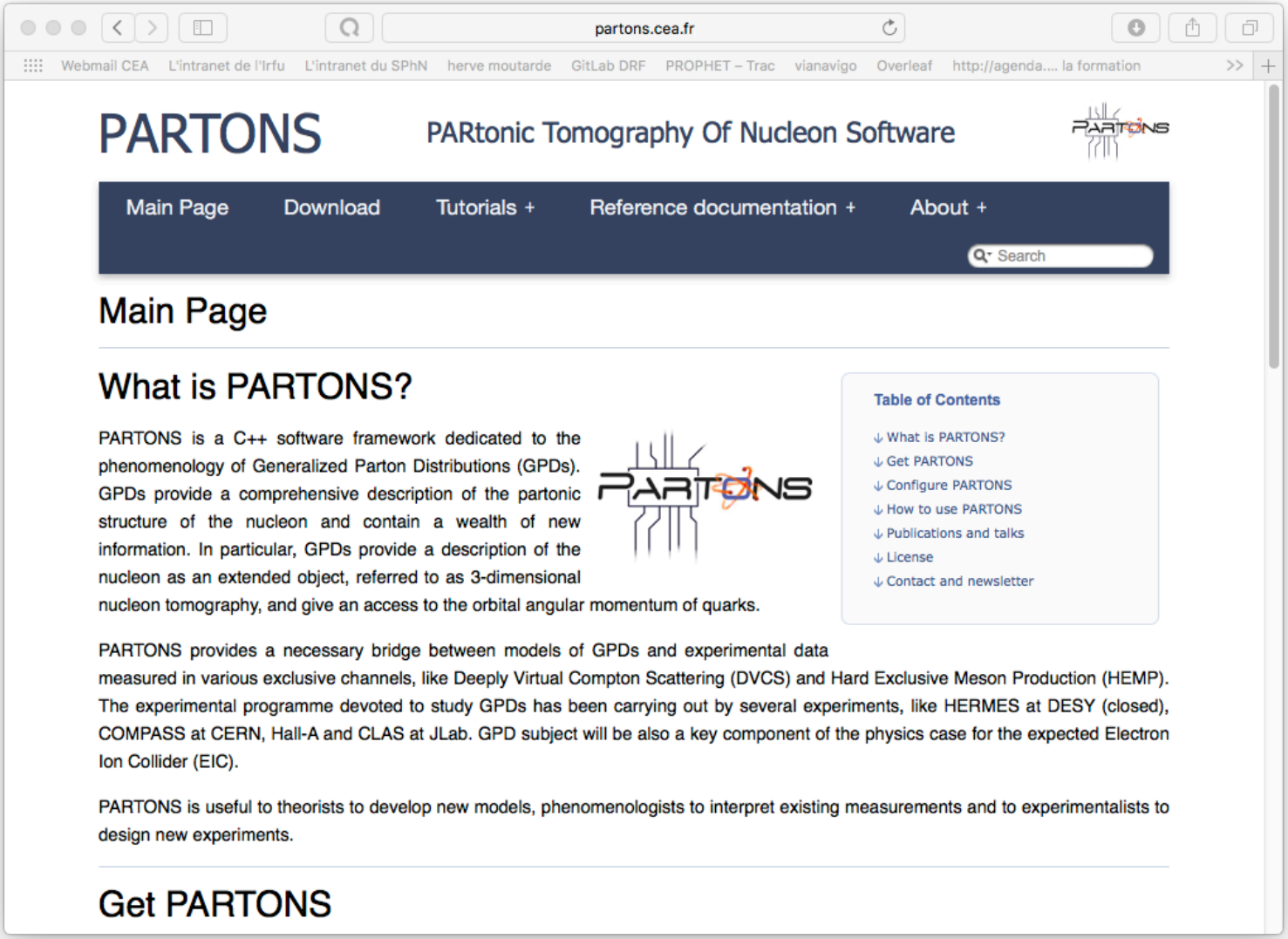
Done: tests, benchmarking, documentation, tutorials.

- 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)

Open source release.

Publicly available on CEA GitLab server.



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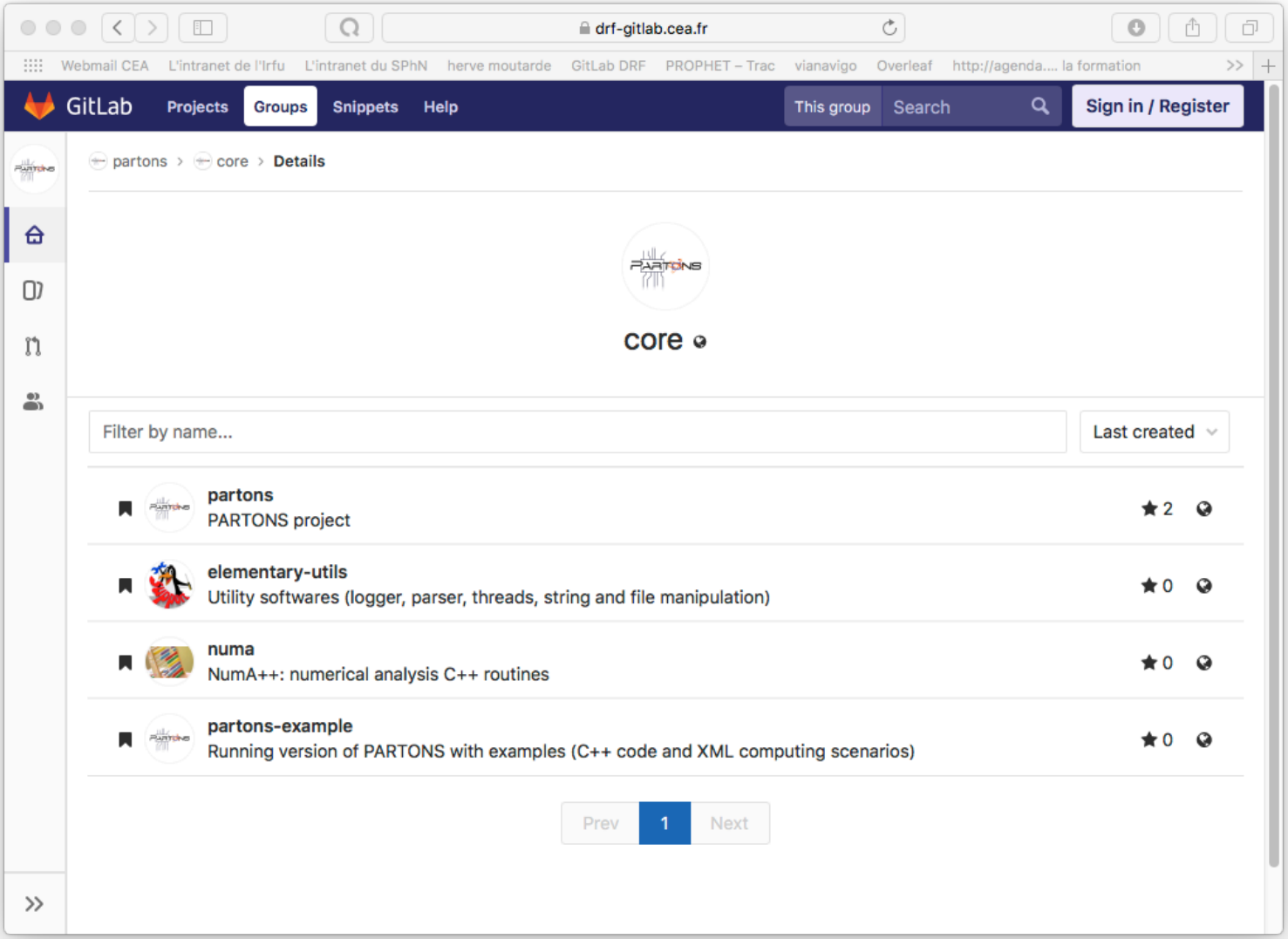

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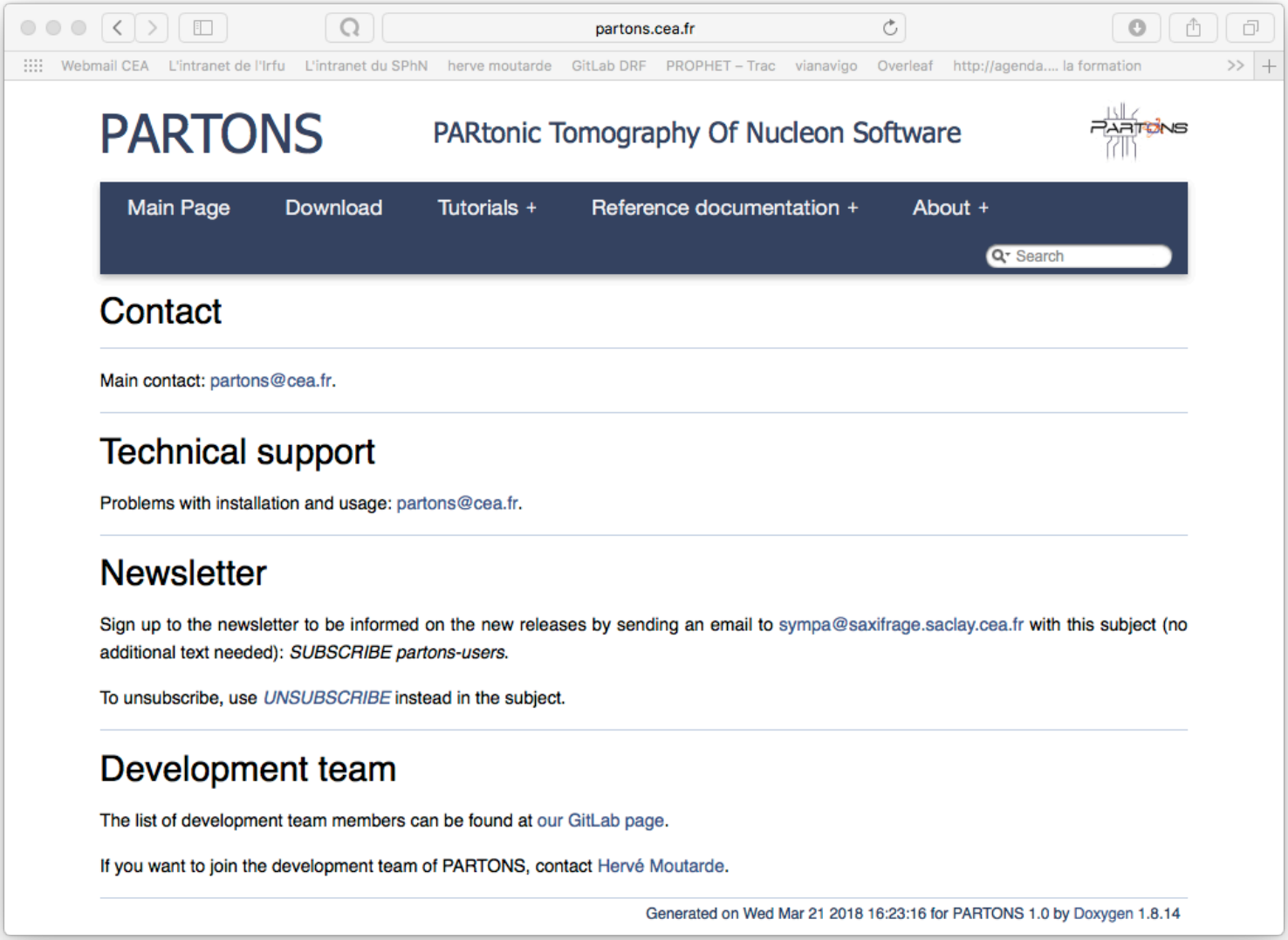

Berthou *et al.*, Eur. Phys. J. **C78**, 478 (2018)

Within the next four years.

Virtual Access Infrastructure 3DPartons in STRONG-2020.

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.

Conclusion

Conclusion and prospects.

Putting all the pieces together.

- We now have tools to **systematically relate** 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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