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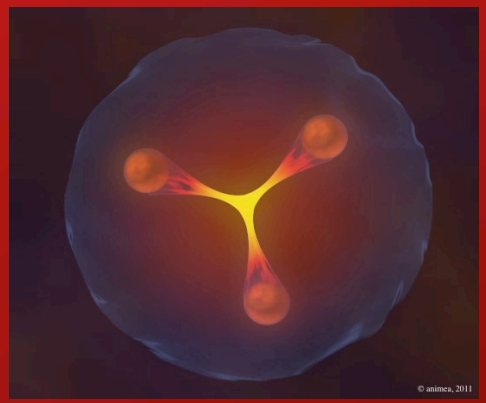


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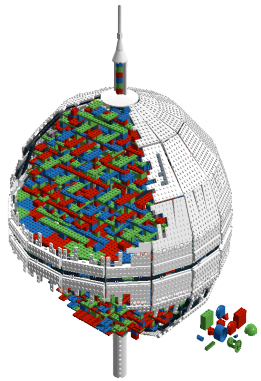
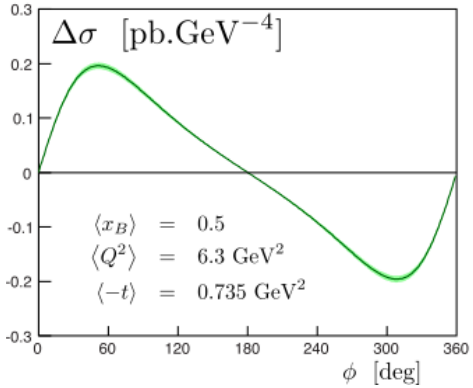
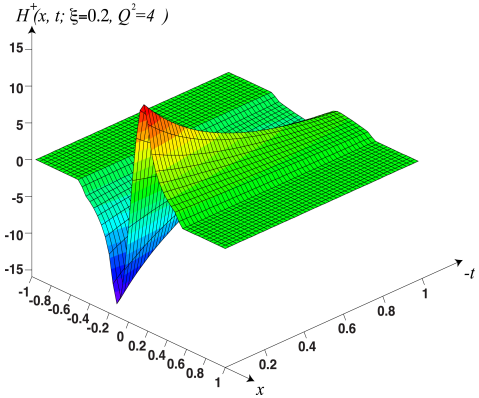
# GPD studies with PARTONS






**Weekly Meeting Excl. Proc. WG | Hervé MOUTARDE**

université PARIS-SACLAY

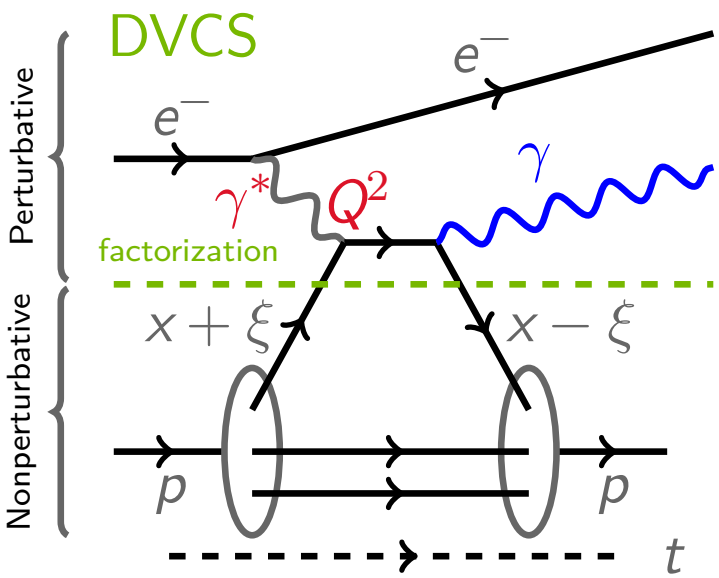
**Apr. 24, 2020**

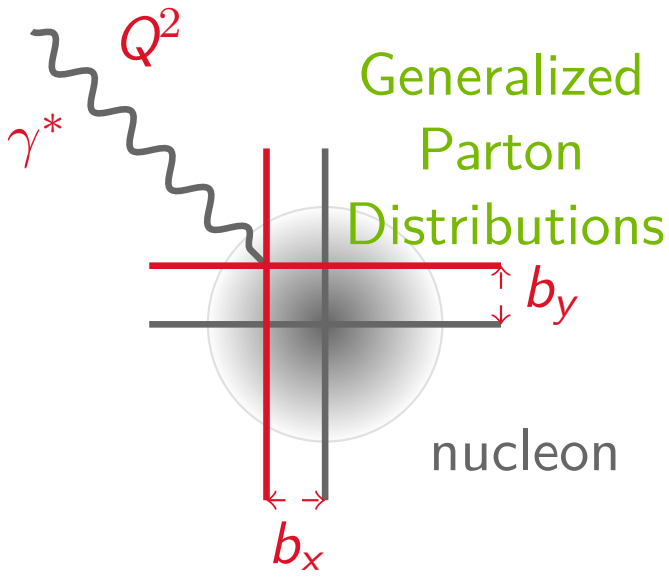
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093.

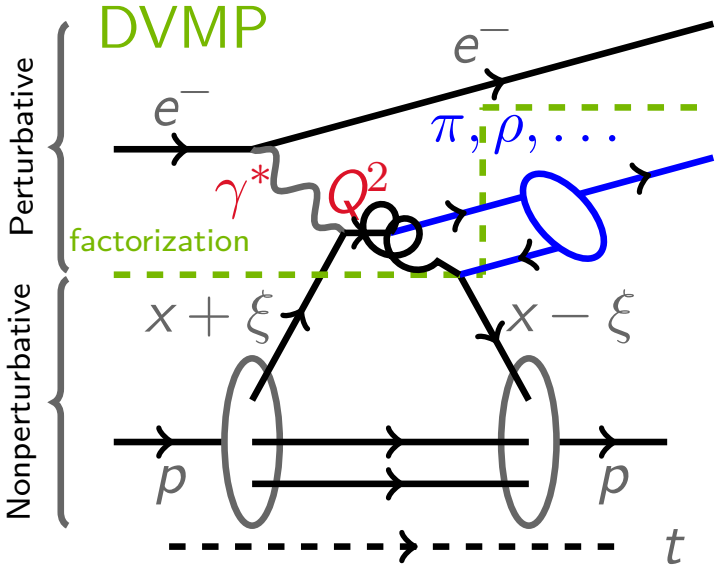
# Exclusive processes of current interest.

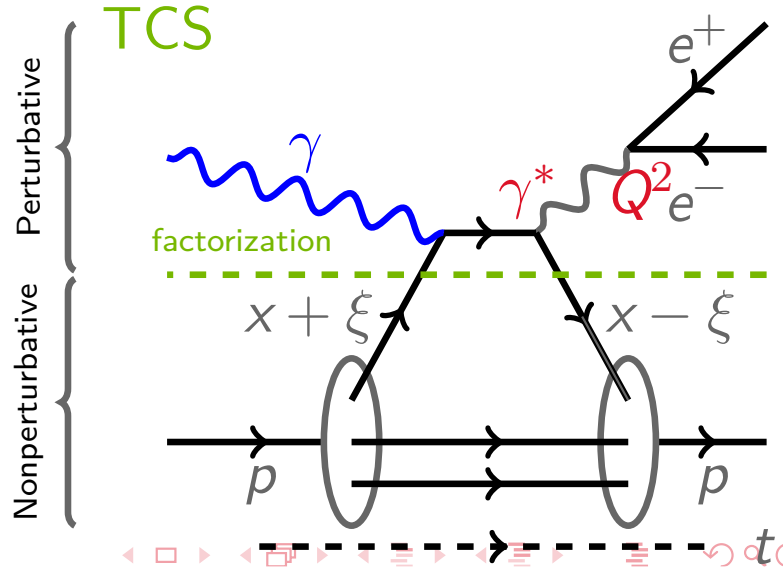
## Factorization and universality.





# Compton Form Factors.

## DVCS amplitude in the Bjorken regime.





### 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 $\mu_F$.
- **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**.

# CFF global fits

# First global CFF fit with PARTONS.

## Assumptions, limits and key ingredients.





- **Leading twist** and **leading order** analysis.
- Focus on the quark sector (intermediate to large $x_B$).
- Dispersion relations: CFF $\mathcal{H}$ depends on **D-term** and **border function** $H(x, \xi = x)$.
- Tomography: model **skewing function** $H(x, x, t)/H(x, 0, t)$ consistently with perturbative QCD.
- Fit to PDFs and elastic form factors.
- Propagate uncertainties by **replica method**.

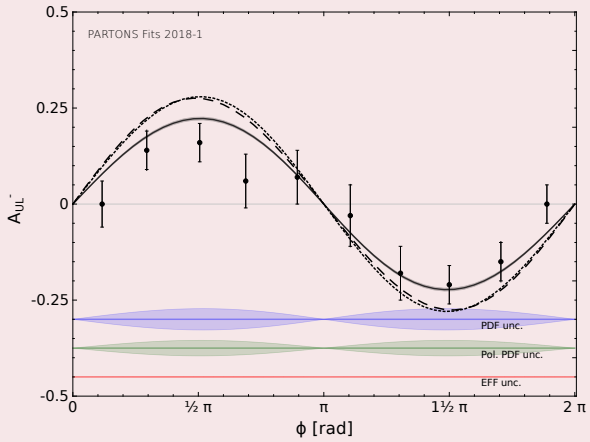
Moutarde *et al.*, Eur. Phys. J. **C78**, 890 (2018)

# A selection of results.

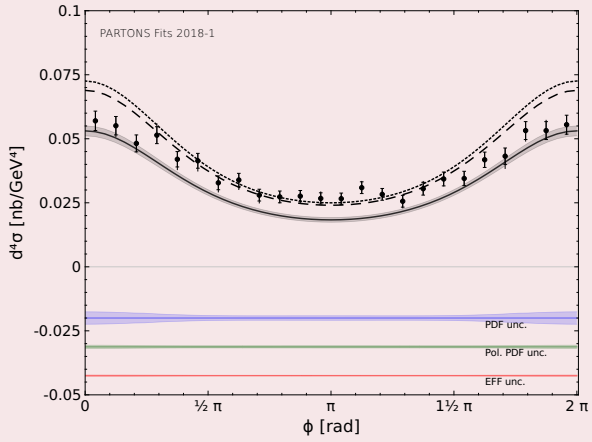
2600 experimental points, 13 free parameters, $\chi^2/\mathrm{dof} \simeq 0.91$.



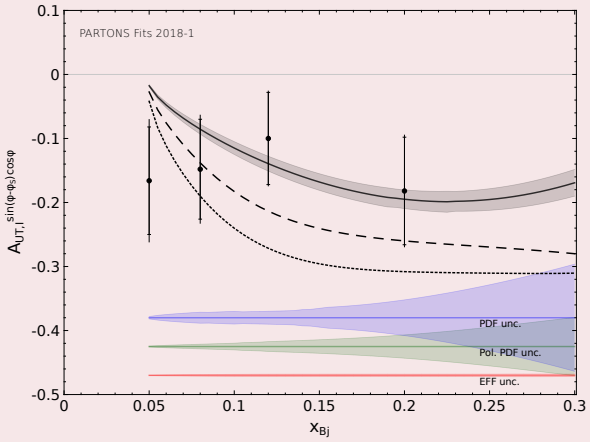
## CLAS



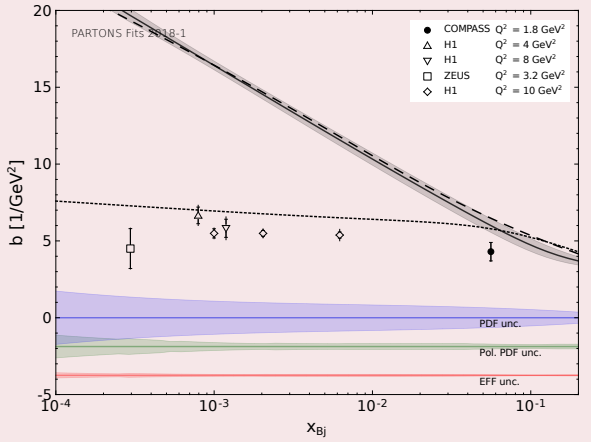

## Hall A




## HERMES




## COMPASS



# 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 | $A^+_{LU}$ | | $\phi$ | 10 / 10 |
| 2 | | 2006 | 41 | $A_C^{\cos i\phi}$ | $i=1$ | $t$ | 4 / 4 |
| 3 | | 2008 | 42 | $A_C^{\cos i\phi}$ | $i=0,1$ | $x_{\rm Bj}$ | 18 / 24 |
| | | | | $A_{UT,\rm DVCS}^{\sin(\phi-\phi_S)\cos i\phi}$ | $i=0$ | | |
| | | | | $A_{UT,\rm I}^{\sin(\phi-\phi_S)\cos i\phi}$ | $i=0,1$ | | |
| | | | | $A_{UT,\rm I}^{\cos(\phi-\phi_S)\sin i\phi}$ | $i=1$ | | |
| 4 | | 2009 | 43 | $A_{LU,\rm I}^{\sin i\phi}$ | $i=1,2$ | $x_{\rm Bj}$ | 35 / 42 |
| | | | | $A_{LU,\rm DVCS}^{\sin i\phi}$ | $i=1$ | | |
| | | | | $A_C^{\cos i\phi}$ | $i=0,1,2,3$ | | |
| 5 | | 2010 | 44 | $A_{UL}^{+,\sin i\phi}$ | $i=1,2,3$ | $x_{\rm Bj}$ | 18 / 24 |
| | | | | $A_{LL}^{+,\cos i\phi}$ | $i=0,1,2$ | | |
| 6 | | 2011 | 45 | $A_{LT,\rm DVCS}^{\cos(\phi-\phi_S)\cos i\phi}$ | $i=0,1$ | $x_{\rm Bj}$ | 24 / 32 |
| | | | | $A_{LT,\rm DVCS}^{\sin(\phi-\phi_S)\sin i\phi}$ | $i=1$ | | |
| | | | | $A_{LT,\rm I}^{\cos(\phi-\phi_S)\cos i\phi}$ | $i=0,1,2$ | | |
| | | | | $A_{LT,\rm I}^{\sin(\phi-\phi_S)\sin i\phi}$ | $i=1,2$ | | |
| 7 | | 2012 | 46 | $A_{LU,\rm I}^{\sin i\phi}$ | $i=1,2$ | $x_{\rm Bj}$ | 35 / 42 |
| | | | | $A_{LU,\rm DVCS}^{\sin i\phi}$ | $i=1$ | | |
| | | | | $A_C^{\cos i\phi}$ | $i=0,1,2,3$ | | |
| 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 | $A^-_{LU}$ | | $\phi$ | 283 / 737 |
| 11 | | 2009 | 50 | $A^-_{LU}$ | | $\phi$ | 22 / 33 |
| 12 | | 2015 | 51 | $A^-_{LU}$, $A^-_{UL}$, $A^-_{LL}$ | | $\phi$ | 311 / 497 |
| 13 | | 2015 | 52 | $d^4\sigma^-_{UU}$ | | $\phi$ | 1333 / 1933 |
| 14 | Hall A | 2015 | 34 | $\Delta d^4\sigma^-_{LU}$ | | $\phi$ | 228 / 228 |
| 15 | | 2017 | 35 | $\Delta d^4\sigma^-_{LU}$ | | $\phi$ | 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 |

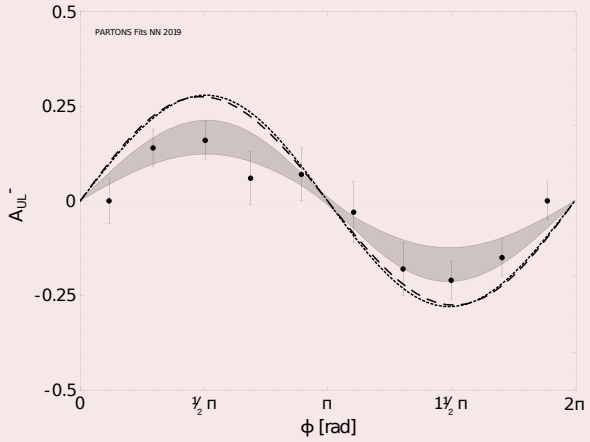
Moutarde *et al.*, Eur. Phys. J. **C79**, 614 (2019)

# A selection of results.

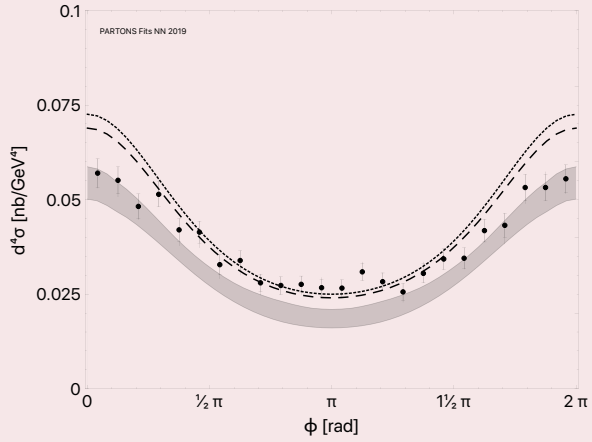
2600+ measurements of 30 observables published during 2001-17.



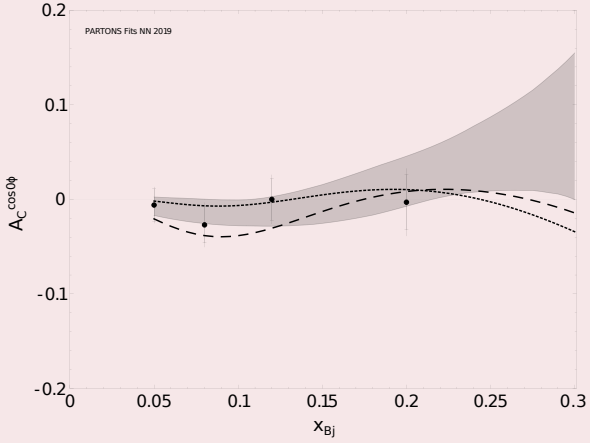
## CLAS



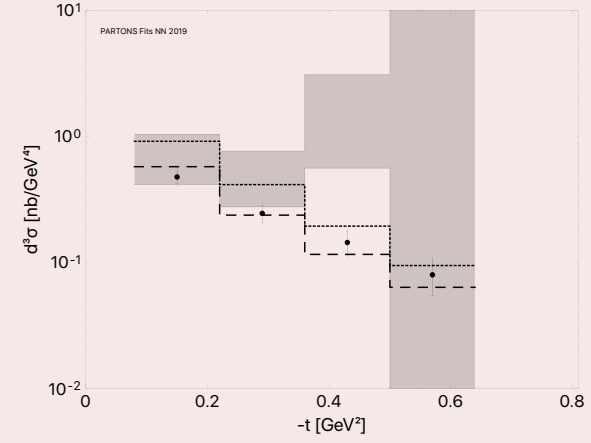

## Hall A




## HERMES




## COMPASS



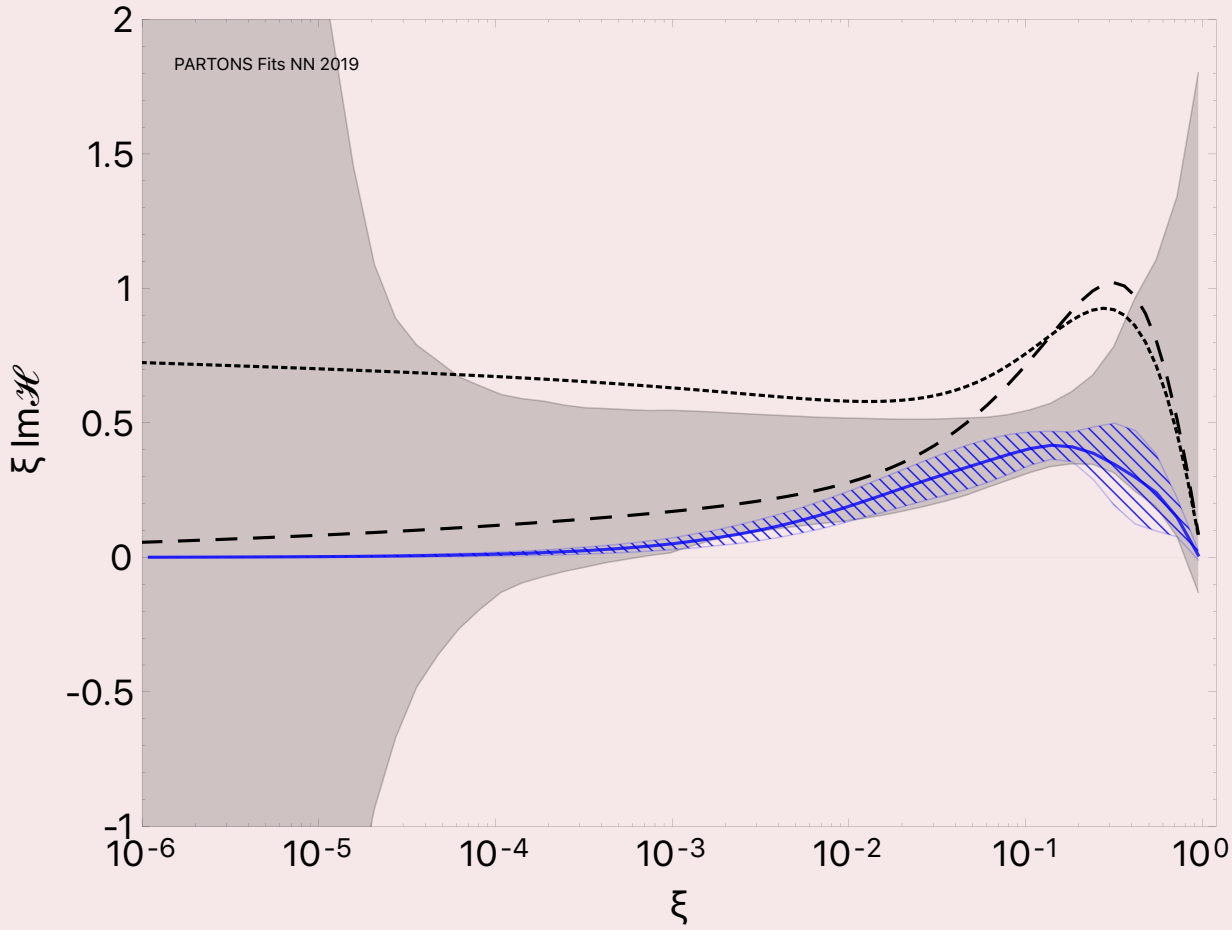

Moutarde *et al.*. Eur. Phys. J. **C79**. 614 (2019)

# 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)

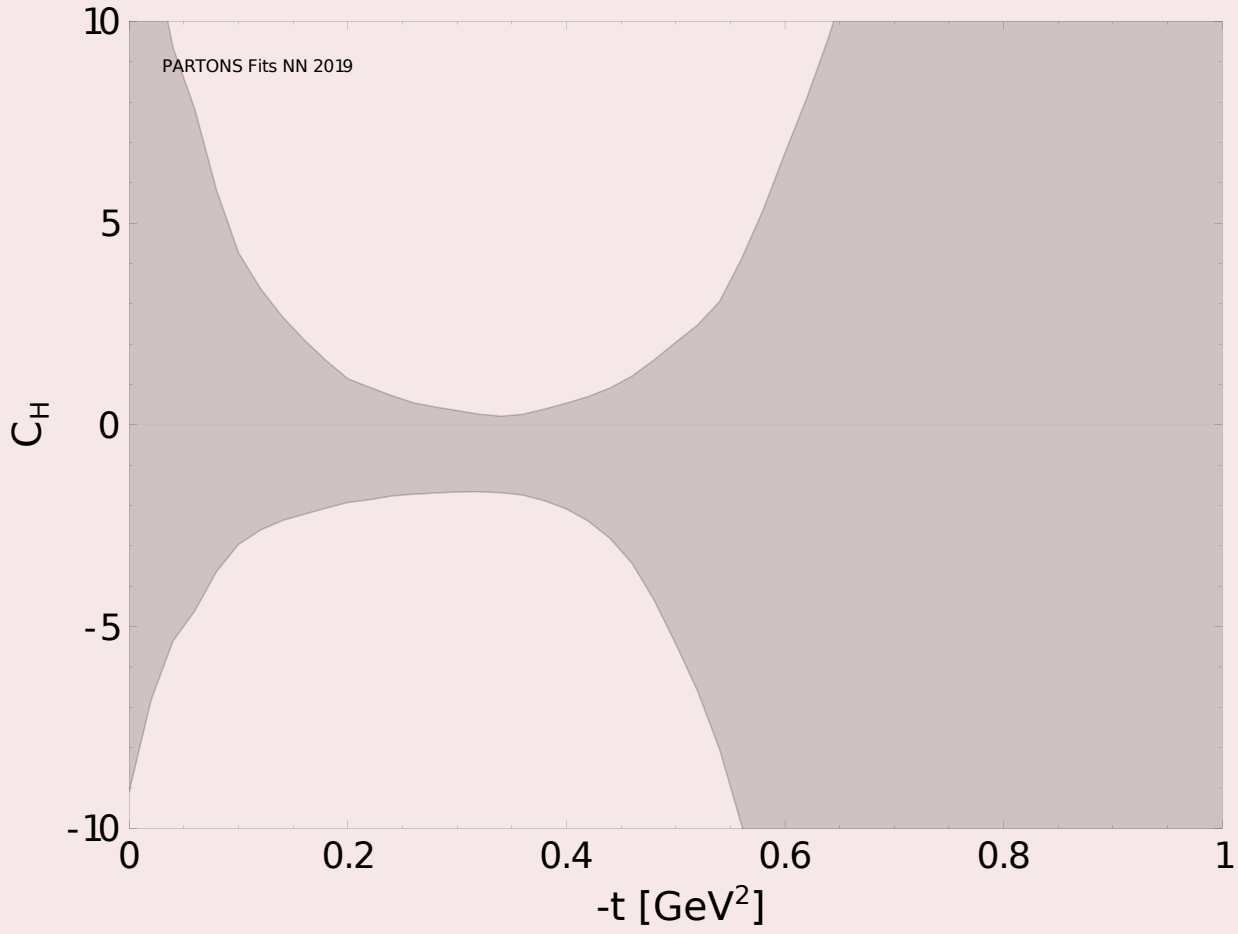
# A selection of results.

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





## Subtraction constant (related to pressure distribution)




See Paweł's talk today!

# Multi-channel analysis

# Assessing the universality of GPDs.

## Intimate relation between TCS and DVCS due to analyticity.





- Relation between **spacelike** (DVCS) and **timelike** (TCS) CFFs worked out at NLO:

$$\mathcal{T}_{\mathcal{H}} \overset{\text{LO}}{=} \mathcal{S}_{\mathcal{H}^*},$$

$$\mathcal{T}_{\mathcal{H}} \overset{\text{NLO}}{=} \mathcal{S}_{\mathcal{H}^*} - i\pi\,\mathcal{Q}^2 \frac{\partial}{\partial \mathcal{Q}^2} \mathcal{S}_{\mathcal{H}^*},$$

with $\mathcal{Q}$ the virtuality of the incoming or outgoing photon.

Müller *et al.*, Phys. Rev. **D86**, 031502 (2012)

- Using a **global CFF fit** to DVCS measurements, the **first multi-channel data-driven** analysis of exclusive processes beyond LO becomes possible!
- First step towards **multi-channel fits** to exclusive processes.

See J. Wagner's talk at the Temple meeting

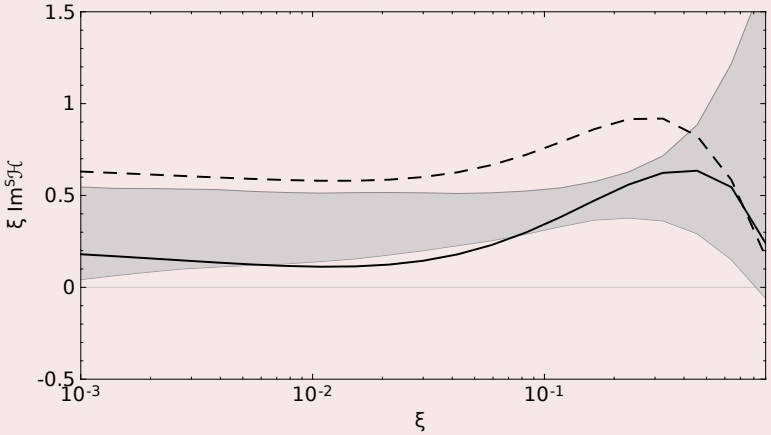
# From DVCS to TCS.

## Prediction of TCS CFF at 68 % confidence level.

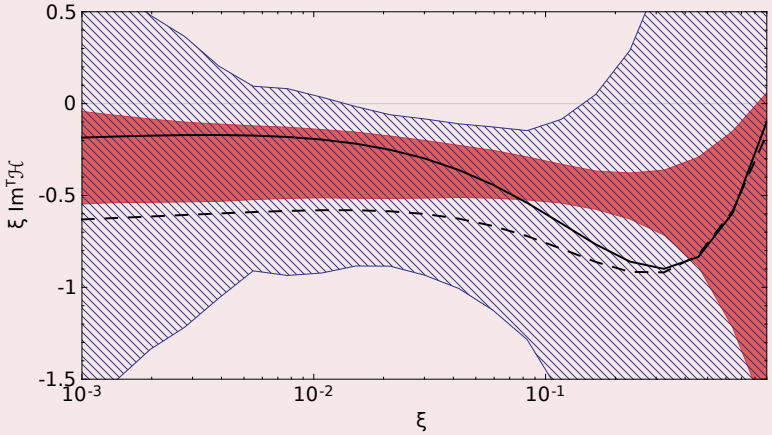


- Spacelike and timelike CFFs depending on $\xi$ at common kinematics: $Q^2 = 2$ GeV$^2$ and $t = -0.3$ GeV$^2$.
- $\xi$ range from EIC to Jefferson Lab kinematics.
- Comparison with phenomenological model at LO (dashed) and NLO (solid).

### DVCS




### TCS




Grocholski *et al.*, Eur. Phys. J. **C80**, 171 (2020)

# The PARTONS framework


**PAR**tonic
**T**omography
**O**f
**N**ucleon
**S**oftware

# Computing chain design.

## Differential studies: physical models and numerical methods.

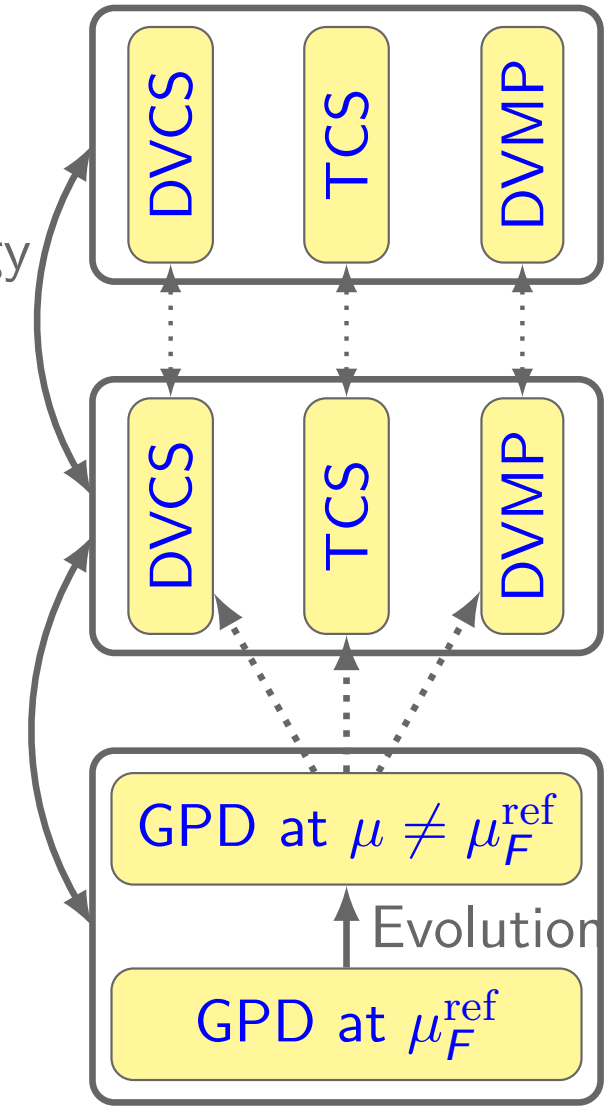




**Full processes**
Experimental data and phenomenology

**Small distance**
Computation of amplitudes

**Large distance**
First principles and fundamental parameters

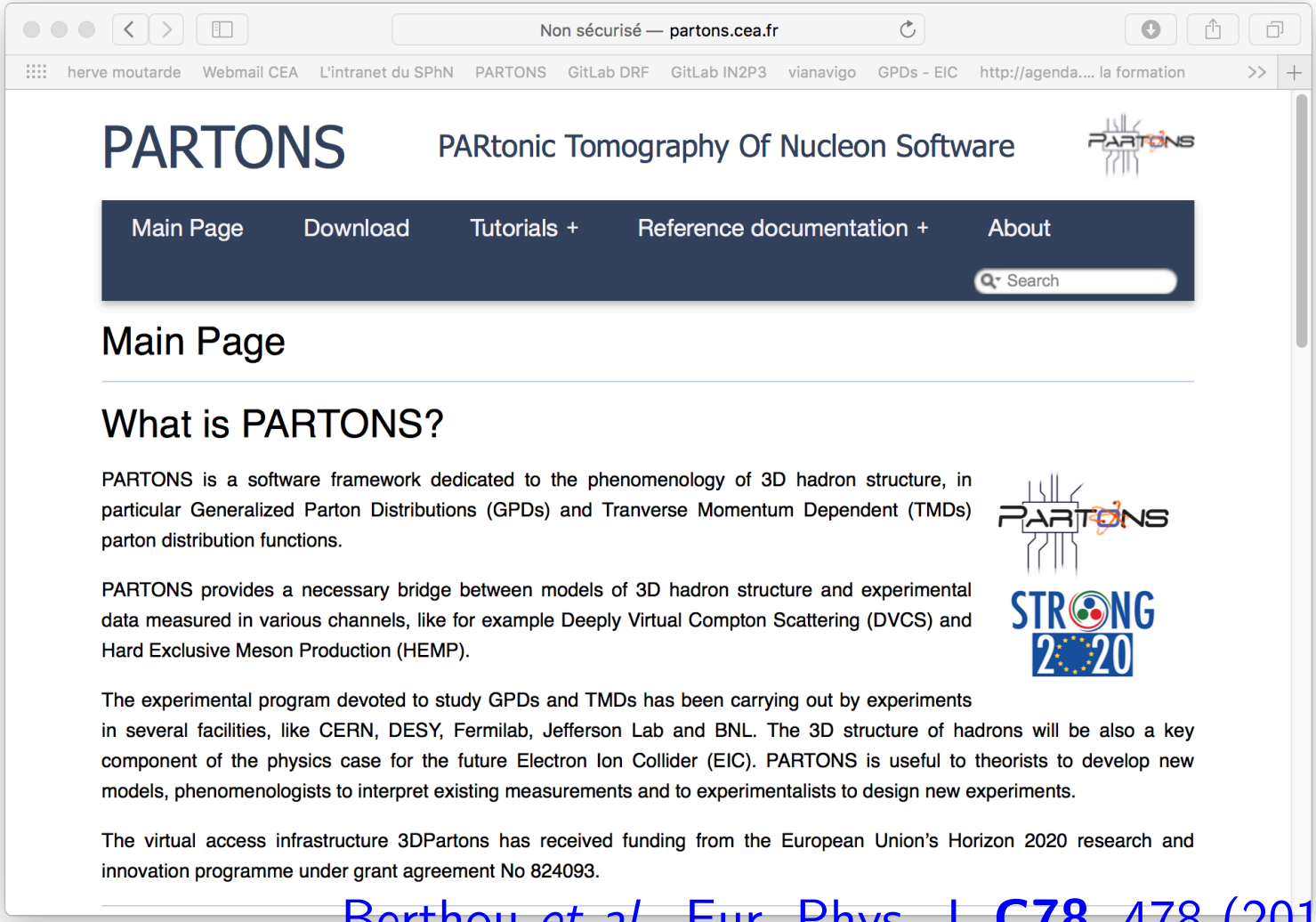



**PAR**tonic **T**omography **O**f **N**ucleon **S**oftware

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

# Open source release.
## Now PARTONSv2: features TCS and more!



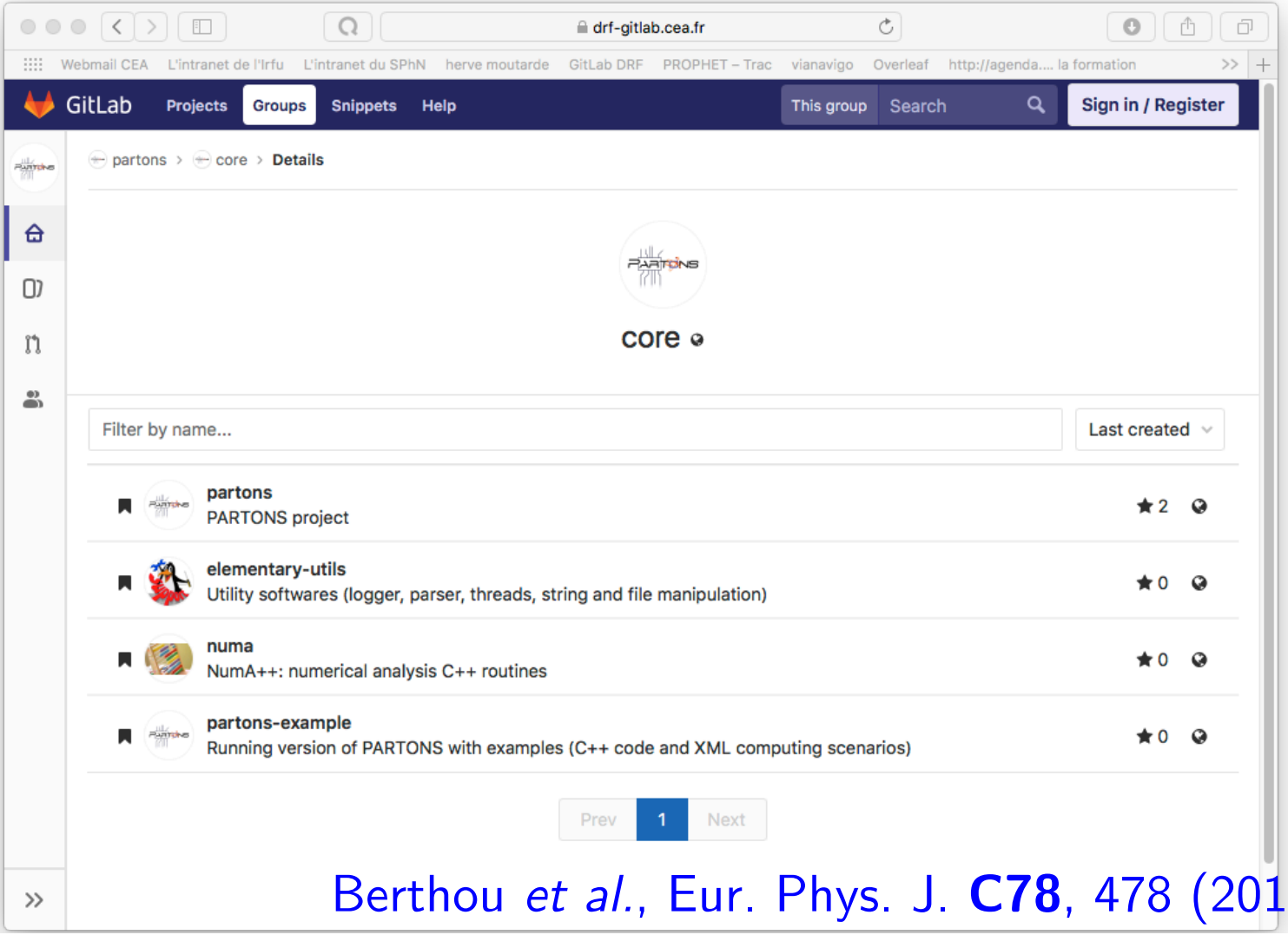



Berthou *et al.*, Eur. Phys. J. **C78**, 478 (2018)

# Open source release.
## Now PARTONSv2: features TCS and more!



## Publicly available on CEA GitLab server




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

# EIC contributions.

## Focus on plausible deliverables within the YR timeline.



- Ongoing work:
  - Cross sections for **exclusive $\pi^0$ production**. See K. Tezgin's talk (WMEP WG 2020/04/13).
  - Various **TCS observables** from several GPD or CFF models under various pQCD assumptions. See J. Wagner's talk (Temple 2020/03/20).
  - Extraction of the **first Gegenbauer coefficient** of the D-term (pressure forces) from global fits to DVCS data. See P. Sznajder's talk today.
  - Integration in the **MILOU MC generator** of tables of CFF output from PARTONS.
  - **GPD evolution** computed with **APFEL**.
- Elements that would help:
  - Realistic DVCS mock observables on EIC kinematics.
  - Manpower for (model-dependent) sensivity studies on the GPD $E$ and Ji sum rule.

## Work Package tasks

- **Flexible software architecture** for GPD and TMD codes, elaborating on existing libraries.
- Generic MC event generators for GPDs and TMDs.
- Associated tools to compare theoretical calculations to experimental data.
- Webpage, software forge and mailing lists.
- Documentation, technical assistance and nonregression tests: **facilitate dissemination**.
- Open Data and Open Science: **build on previous research and get new results faster**.

# Conclusion

# Conclusion and prospects.

Not covering ongoing theoretical work (longer time scale).



- 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.
- Next step: GPD fits.

## Deliverables within the YR timeline

- Cross sections for **exclusive $\pi^0$ production**.
- **TCS observables**.
- Impact of EIC on the extraction of the **first Gegenbauer coefficient** of the D-term from global CFF fits.
- Integration in the **MILOU MC generator** of tables of CFFs output from PARTONS.
- **GPD evolution** computed with **APFEL**.

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