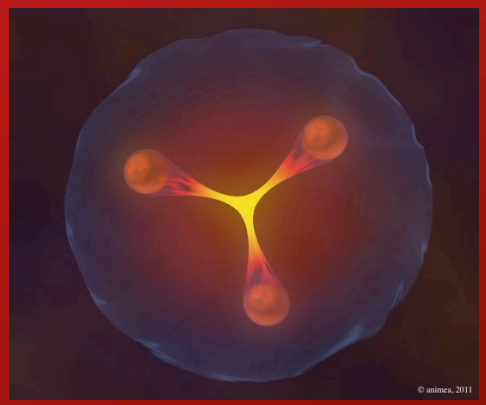
DE LA RECHERCHE À L'INDUSTRIE



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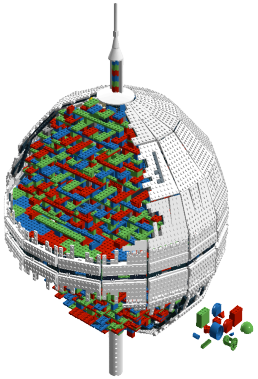
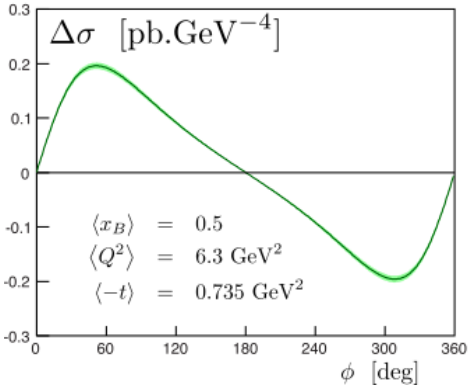
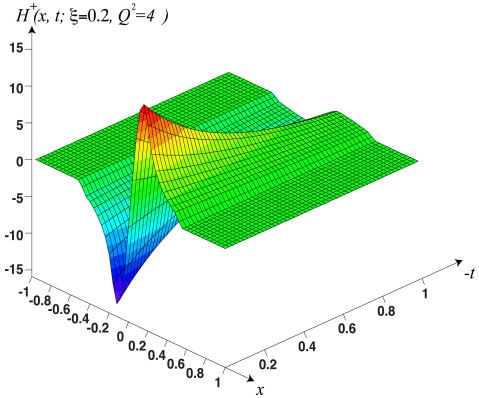
Nucleon tomography: Experimental data fits







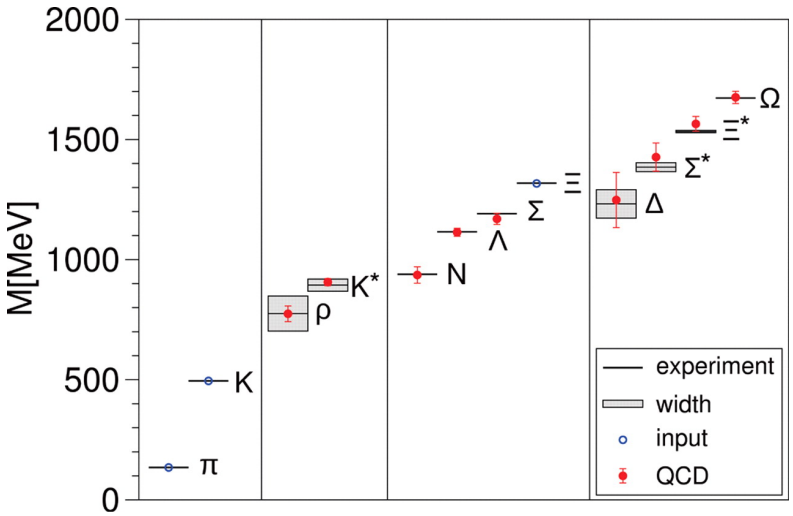
Apr. 28th, 2017

université PARIS-SACLAY

Motivation.

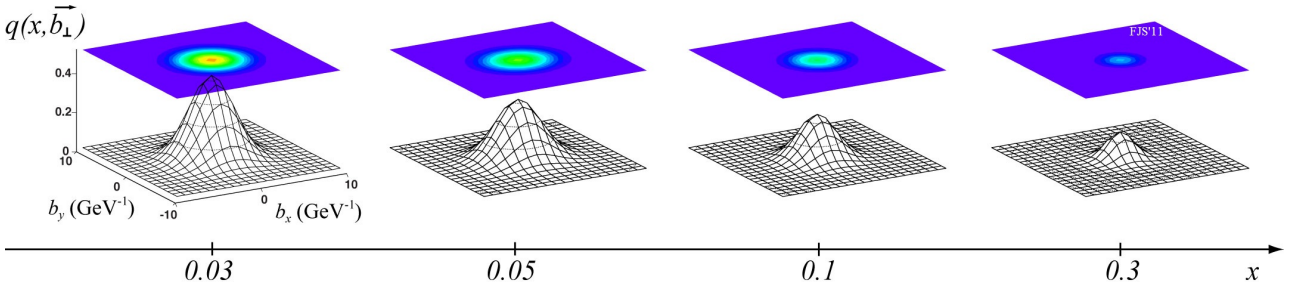
QCD large distance dynamics from the hadron structure viewpoint.

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

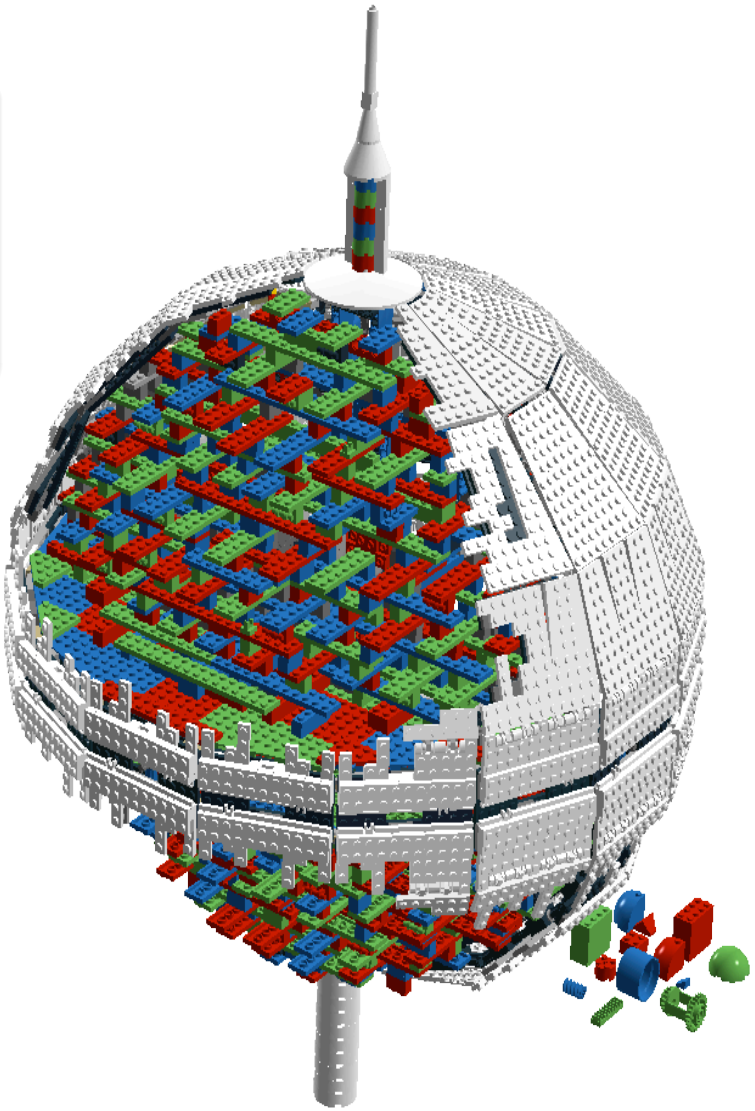


Durr *et al.*, Science **322**, 1224 (2008)

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



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



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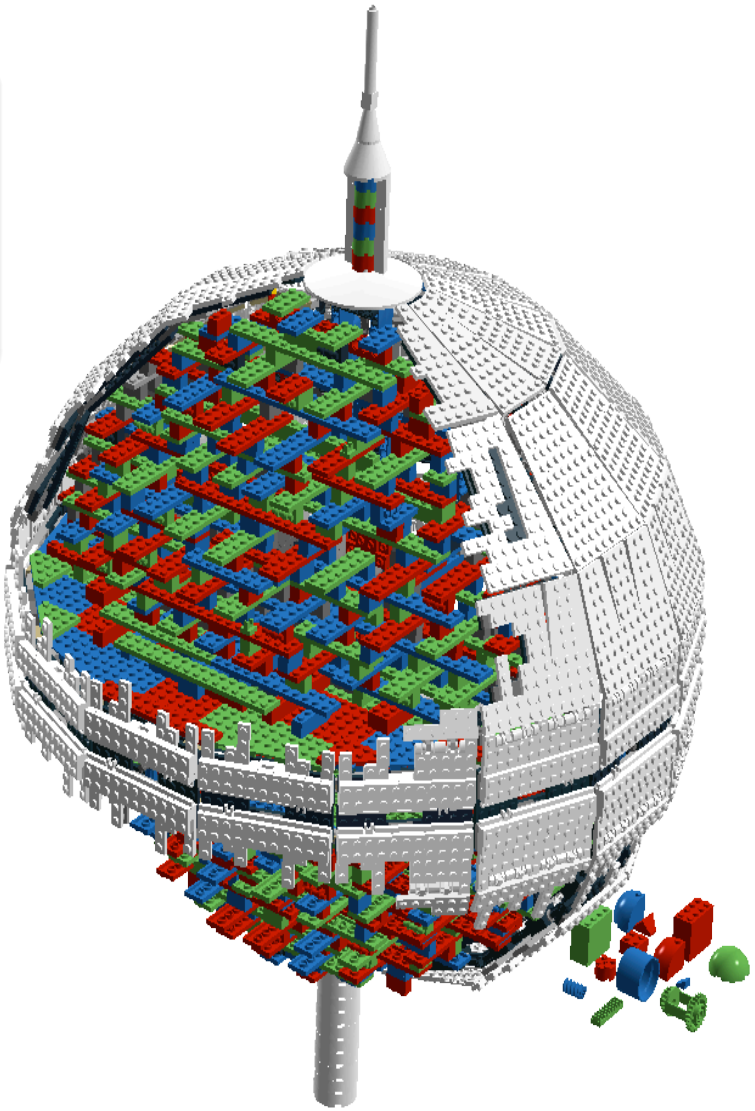
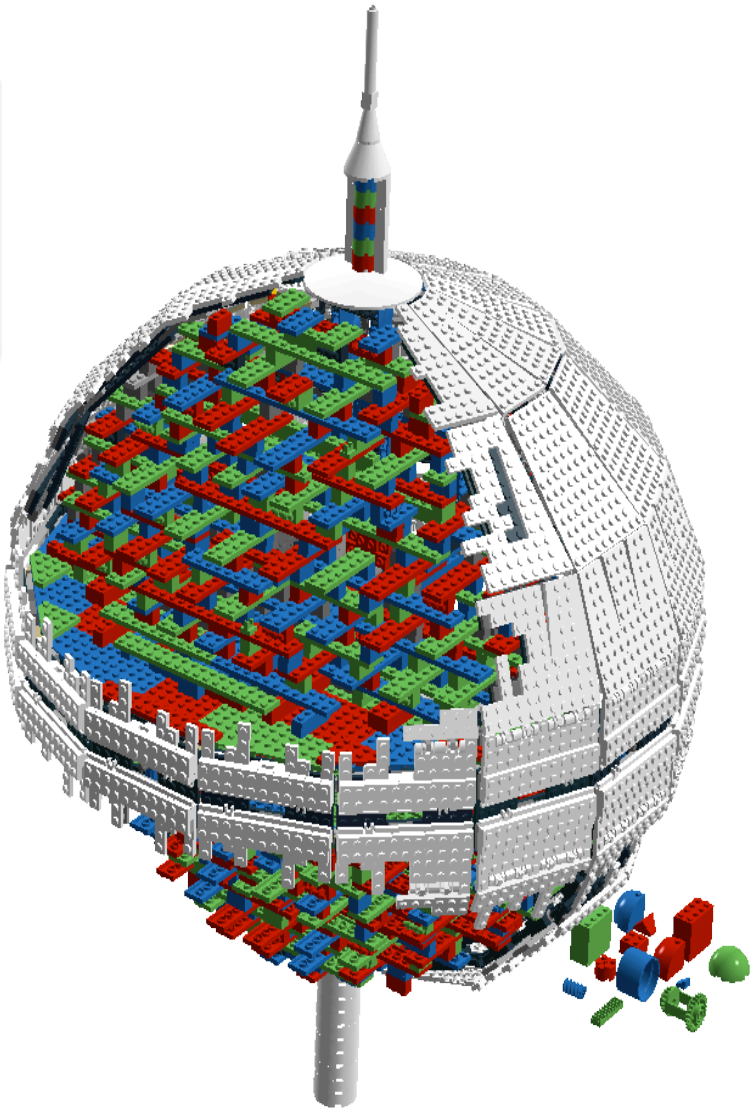
Mass?



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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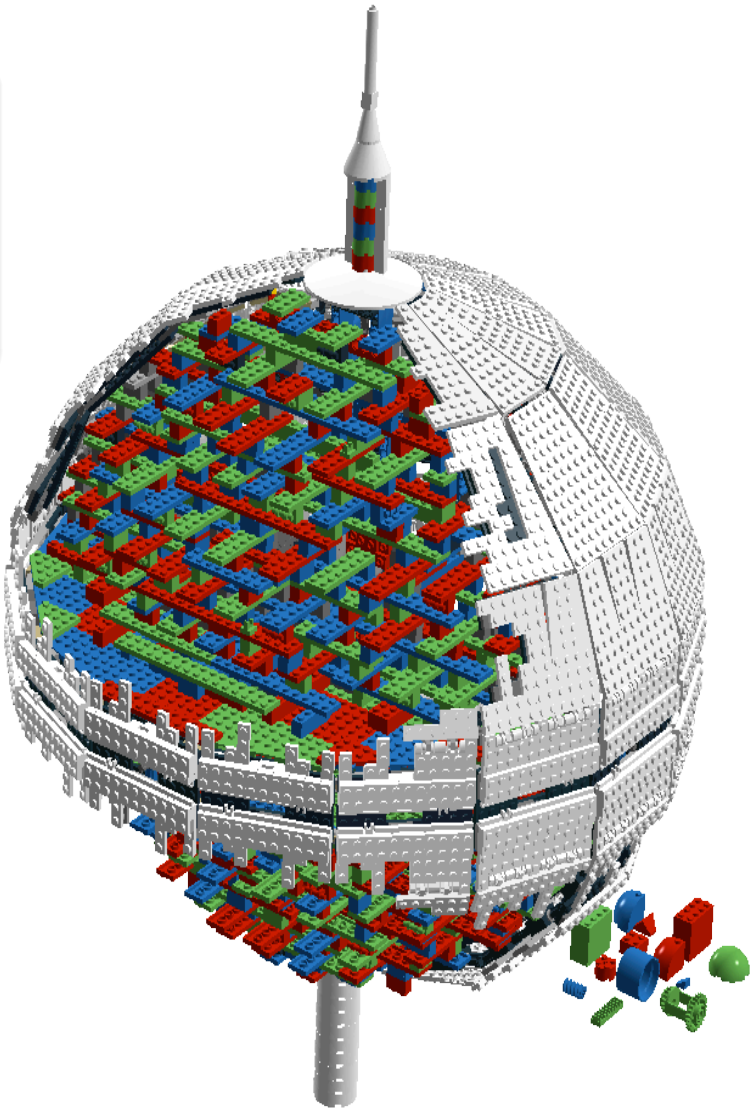
Mass?
Spin?
Charge?



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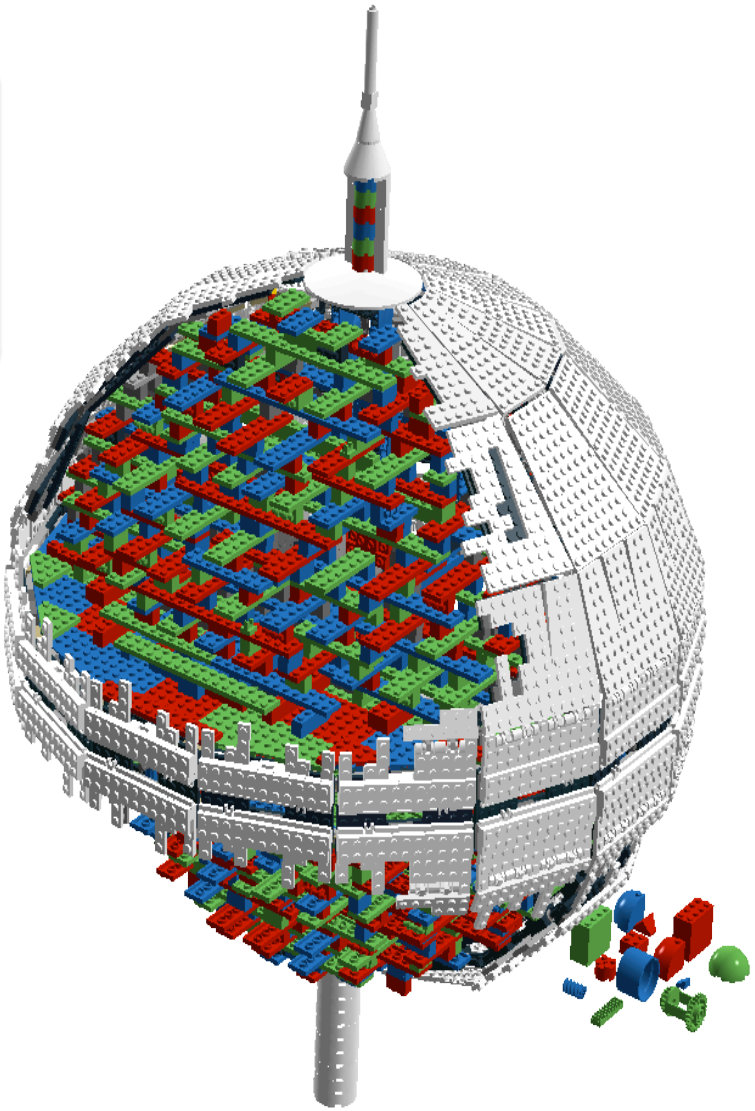
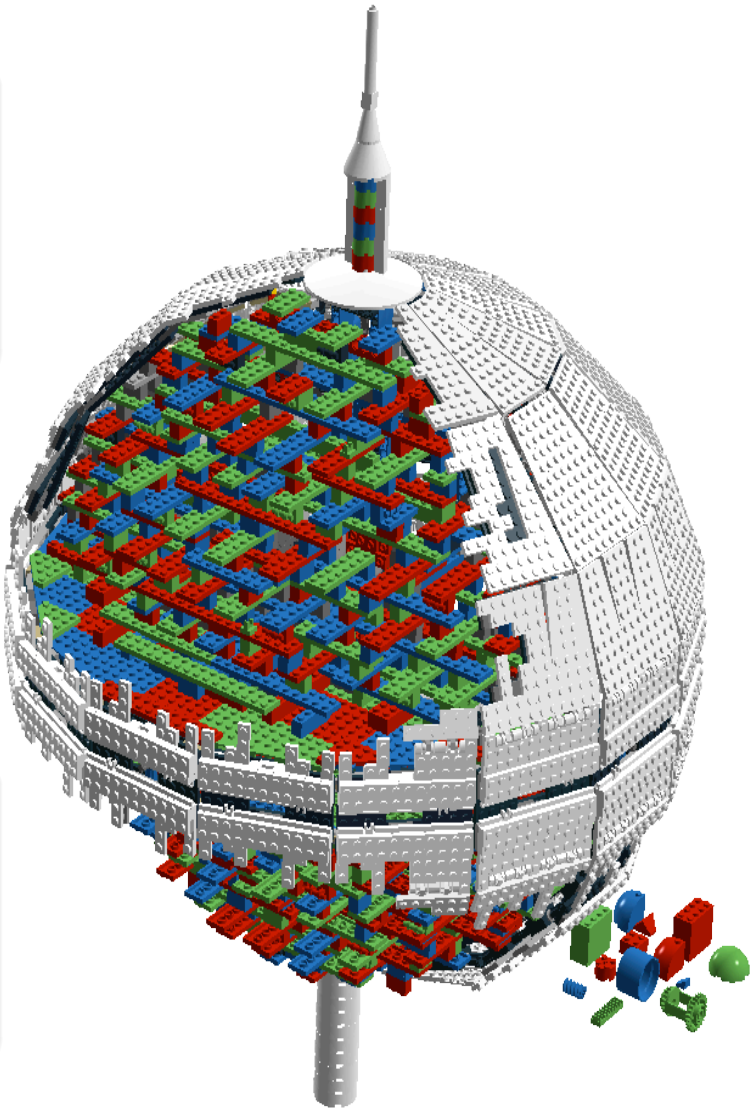


How can we recover the well-known characterics of the nucleon from the properties of its **colored building blocks**?

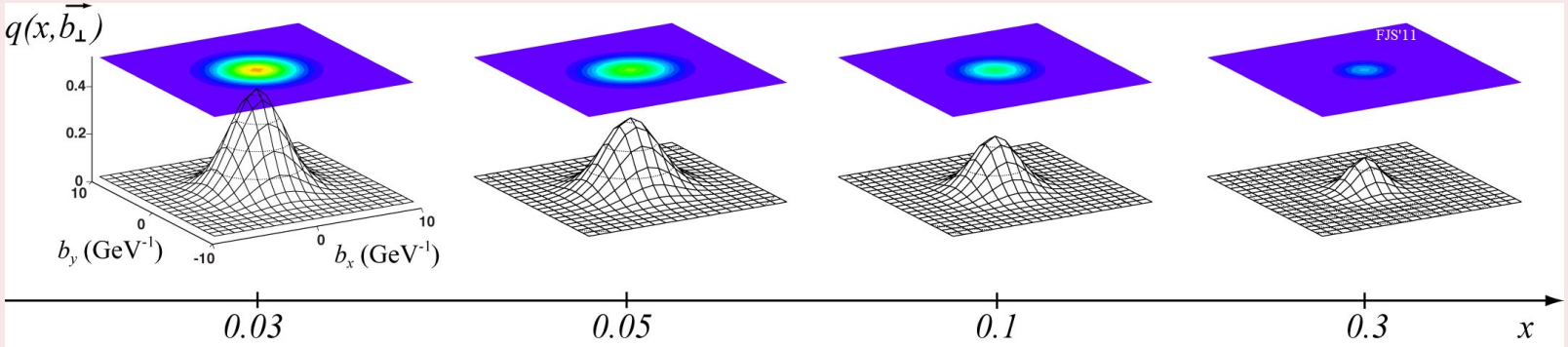
Mass?
Spin?
Charge?
...

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



Structuring questions for the hadron physics community

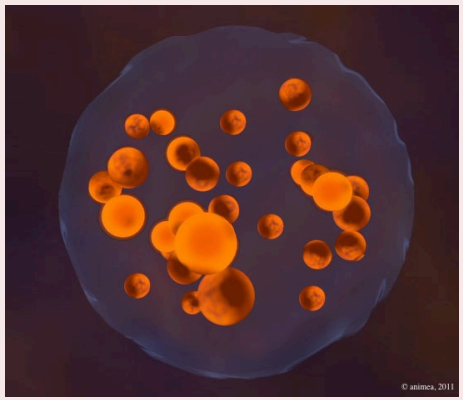
- QCD **mechanisms** behind the origin of **mas** in the **visible universe**?
- **Cartography** of interactions giving its mass to the nucleon?
- **Pressure** and **density** profiles of the nucleon as a continuous medium?
- **Localization** of quarks and gluons inside the nucleon?



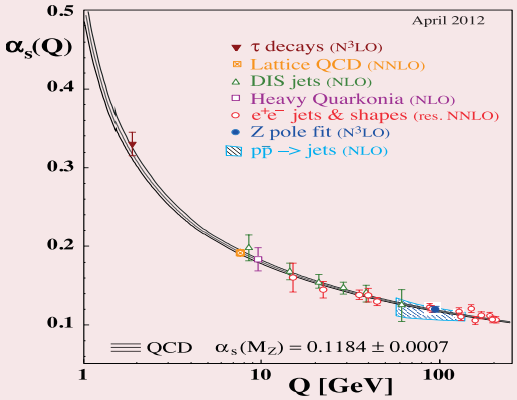
Motivation.

Study nucleon structure to shed new light on nonperturbative QCD.

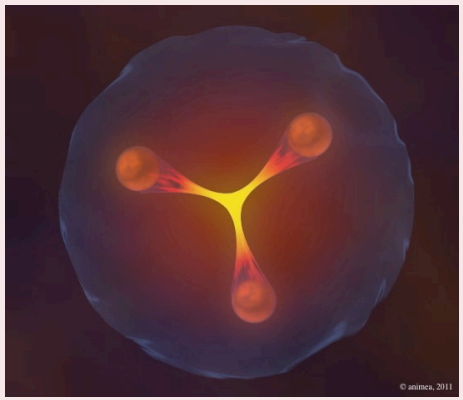
Perturbative QCD



Asymptotic freedom



Nonperturbative QCD

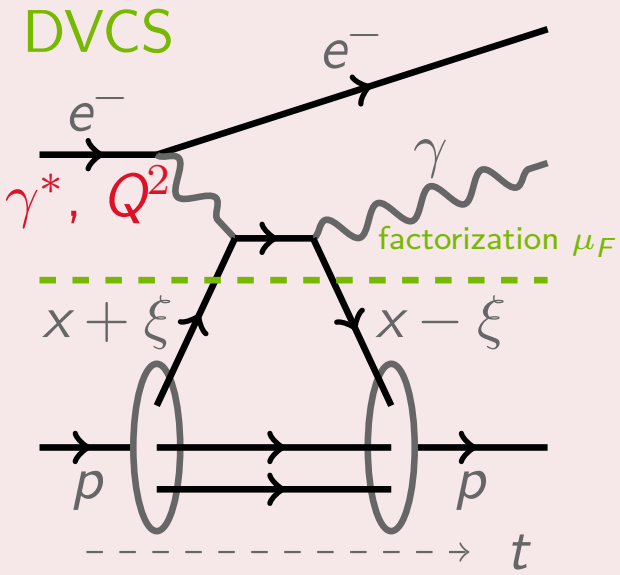


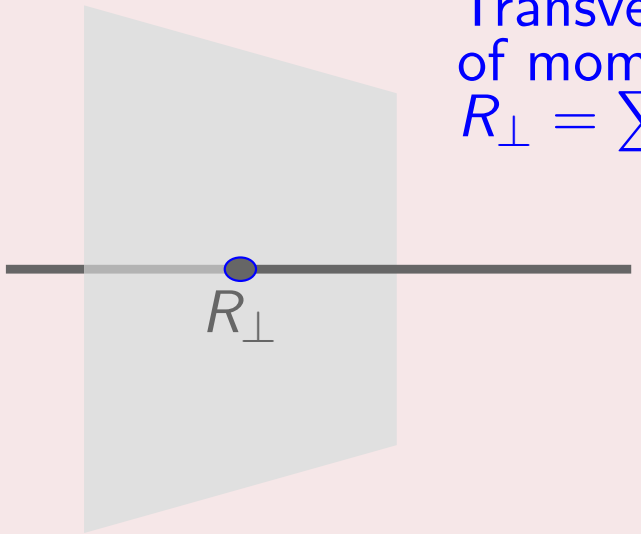
Perturbative AND nonperturbative QCD at work

- 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.

- 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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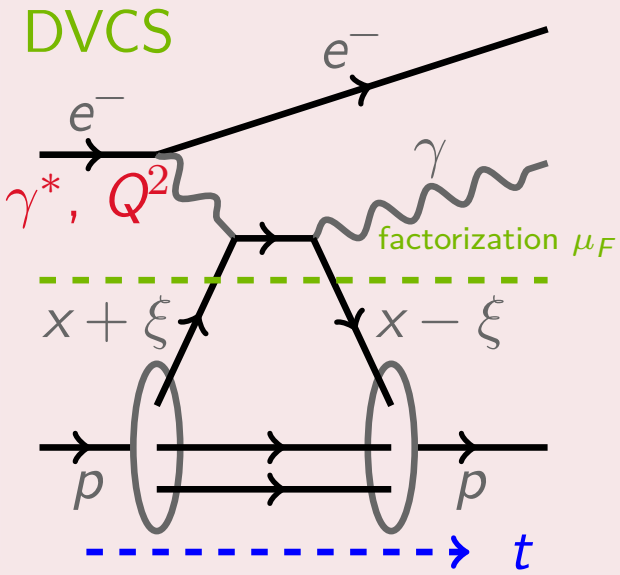

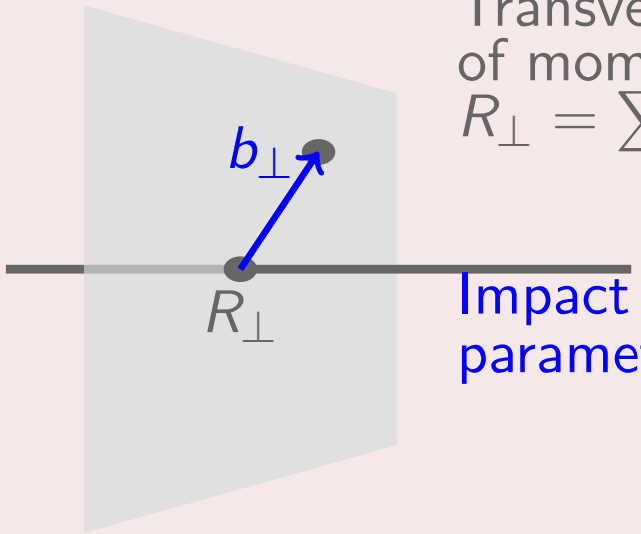

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Impact parameter $b_\perp$

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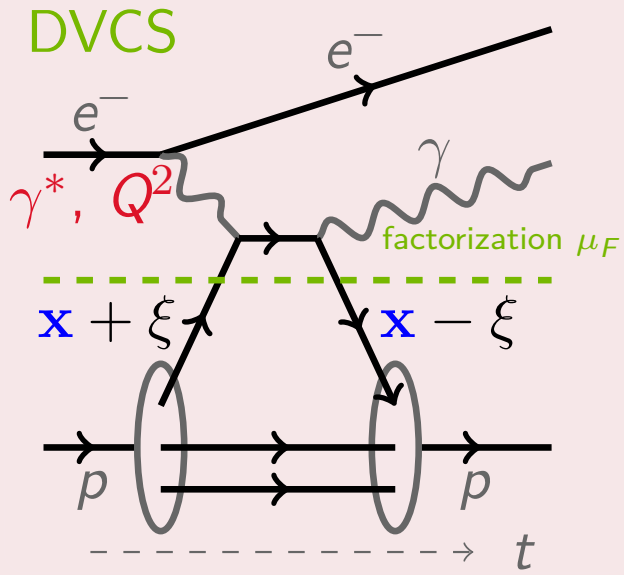

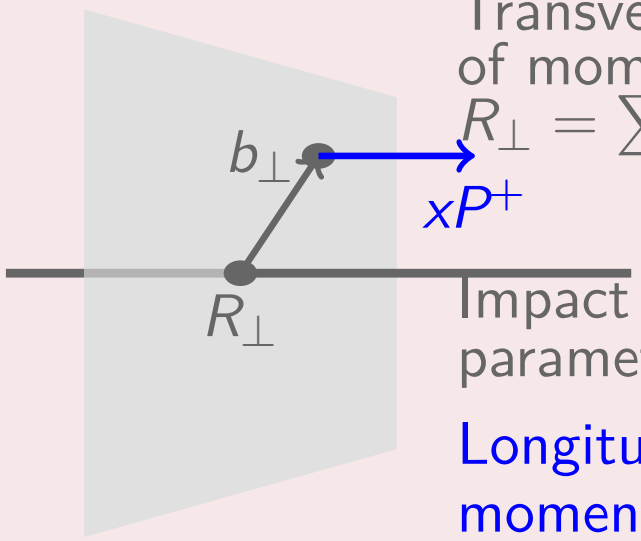

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Impact parameter $b_\perp$

Longitudinal momentum xP^+

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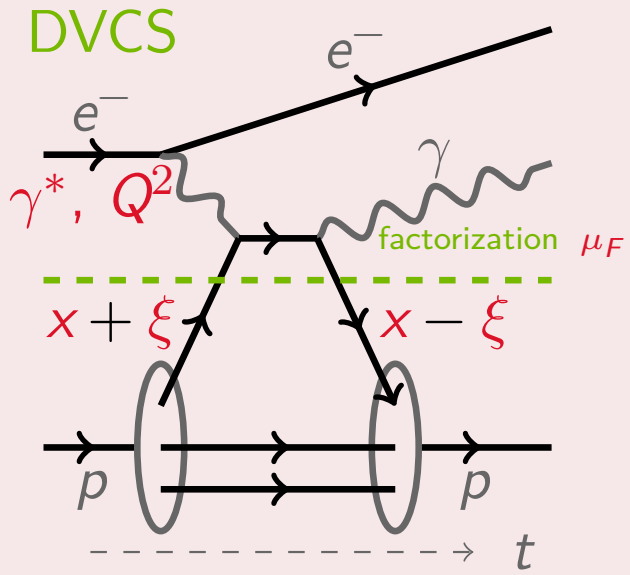
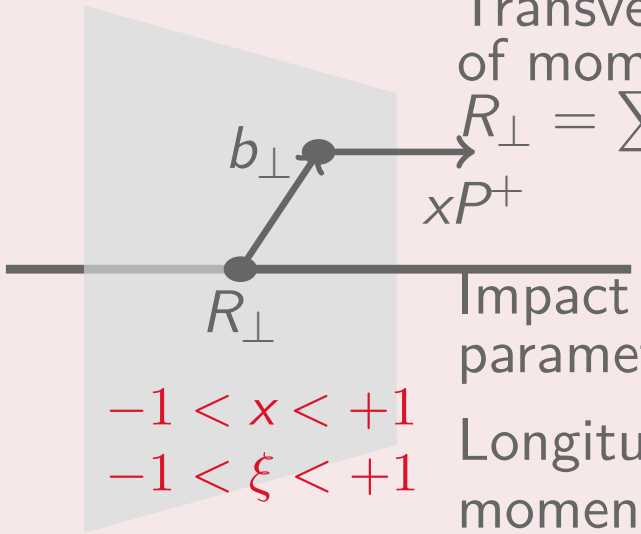
Deeply Virtual Compton Scattering (DVCS)





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

Impact parameter $b_\perp$

Longitudinal momentum xP^+

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

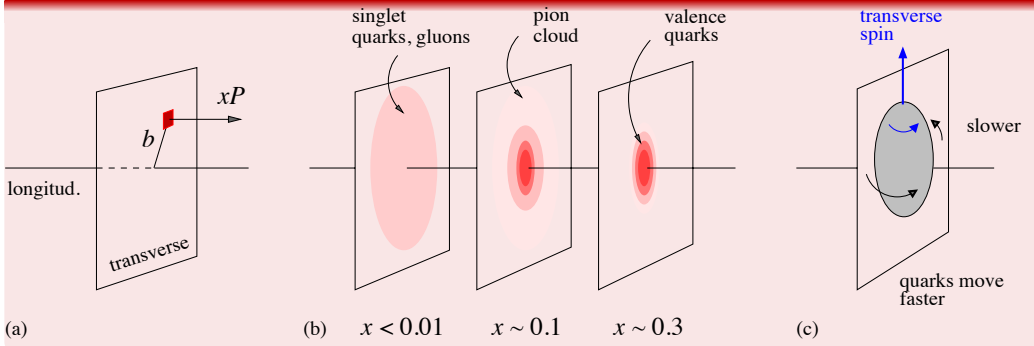
- **Probabilistic interpretation** of Fourier transform of GPD$(x, \xi = 0, t)$ in **transverse plane**.

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

- 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)

- 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**

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

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

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

- 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:

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

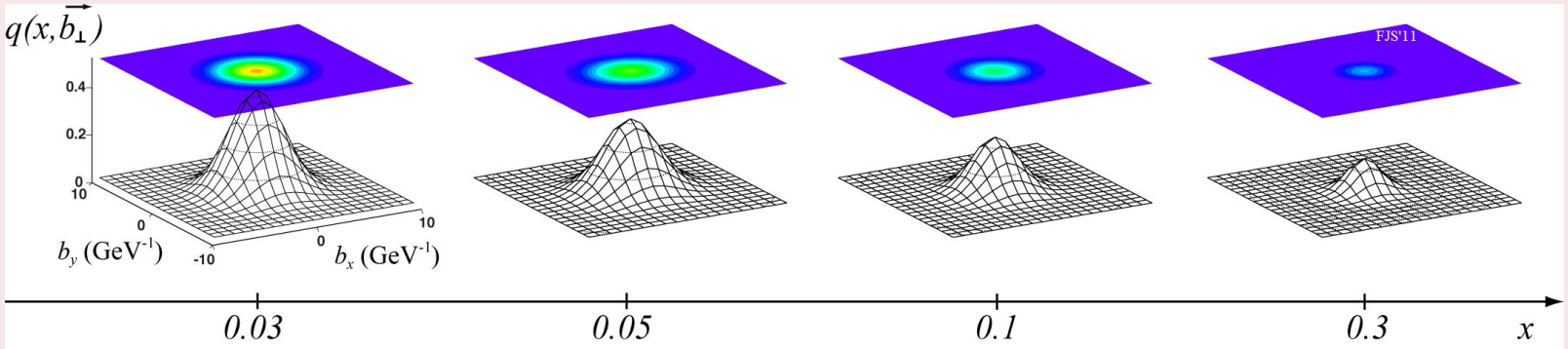
Polyakov and Shuvaev, hep-ph/0207153

Towards hadron tomography.

How can we make the best from experimental data?

1. **Scaling regime:** looking for Bjorken scaling.
2. **Extractions:** strategies to get GPDs or CFFs from data.
3. **PARTONS framework:** tools for GPD phenomenology and theory.

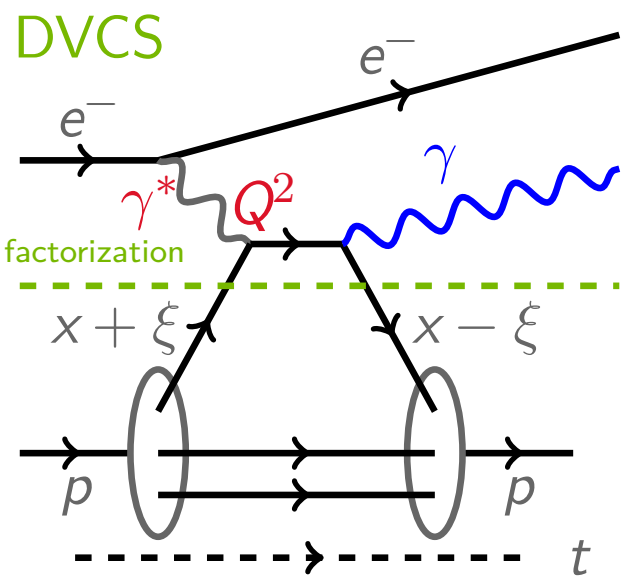
How can we make this picture? What do we learn from it?

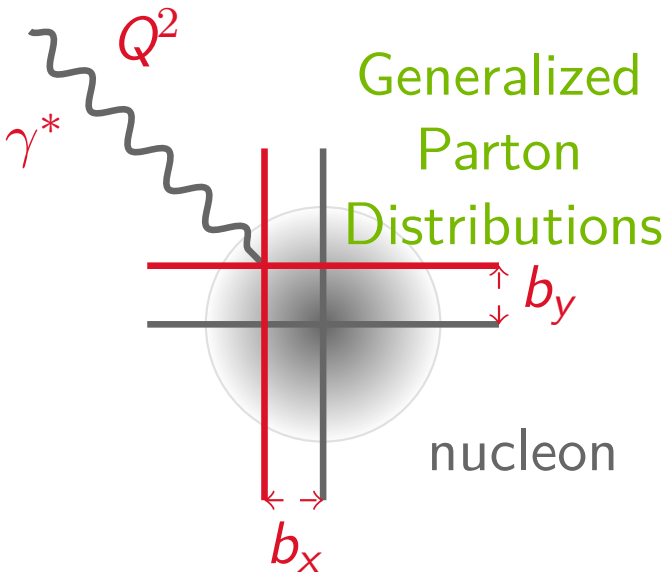


Searching the scaling regime

Exclusive processes of current interest (1/2).

Factorization and universality.





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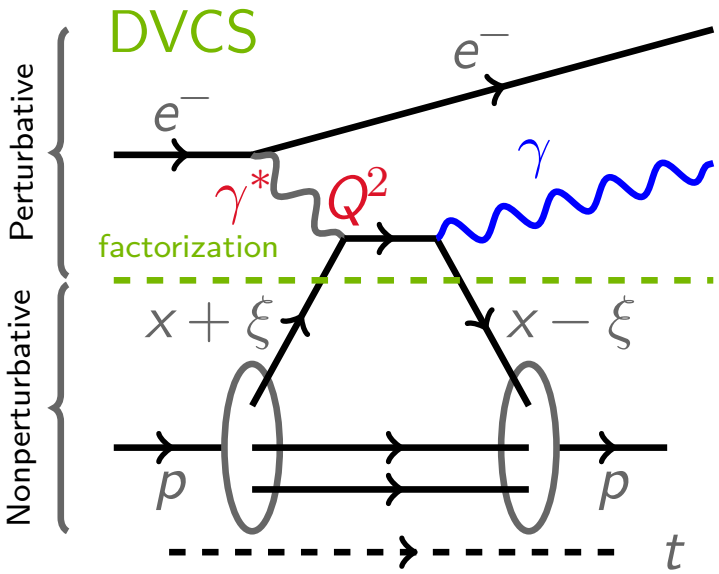

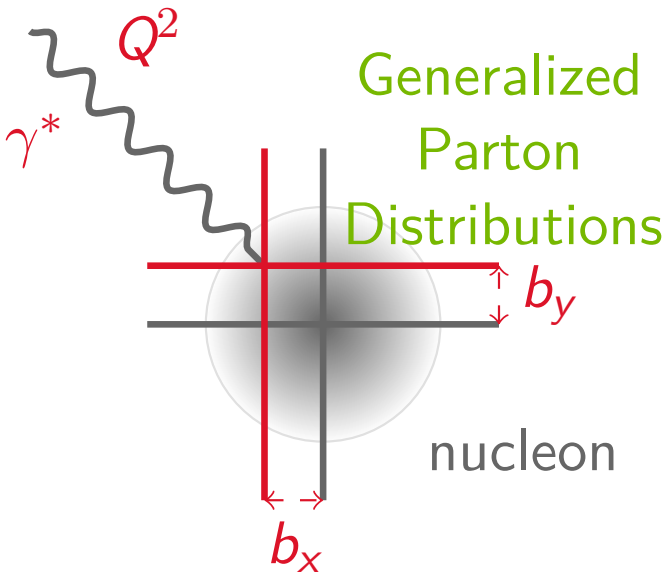

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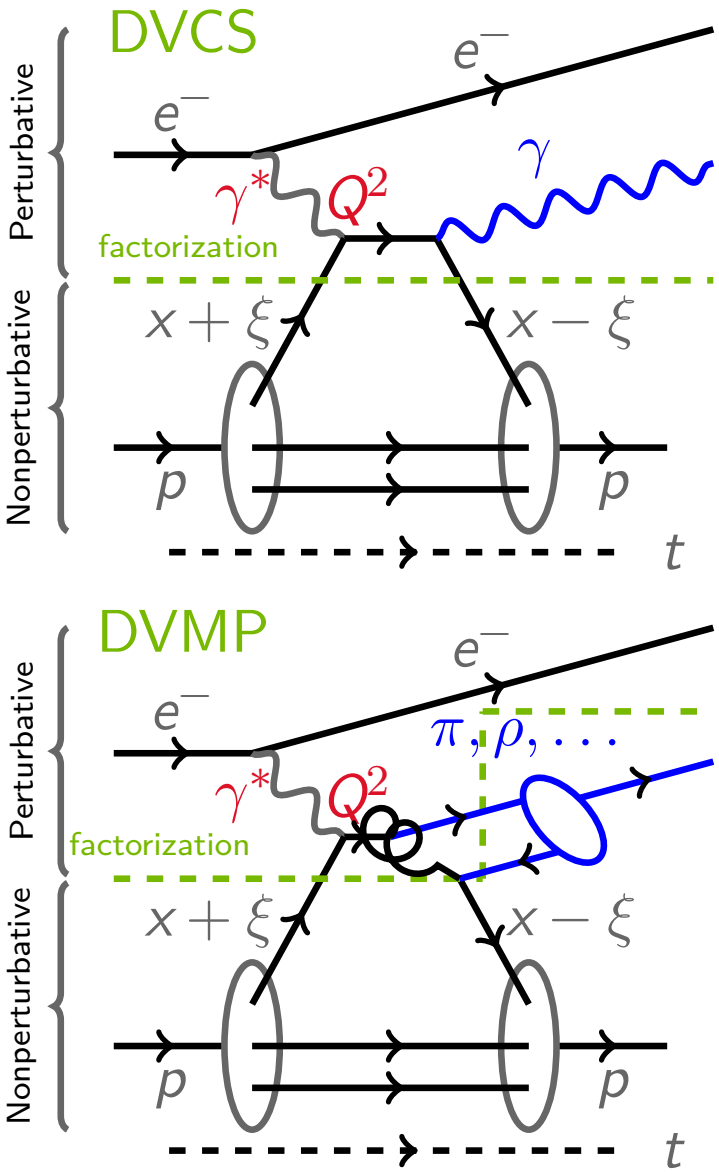

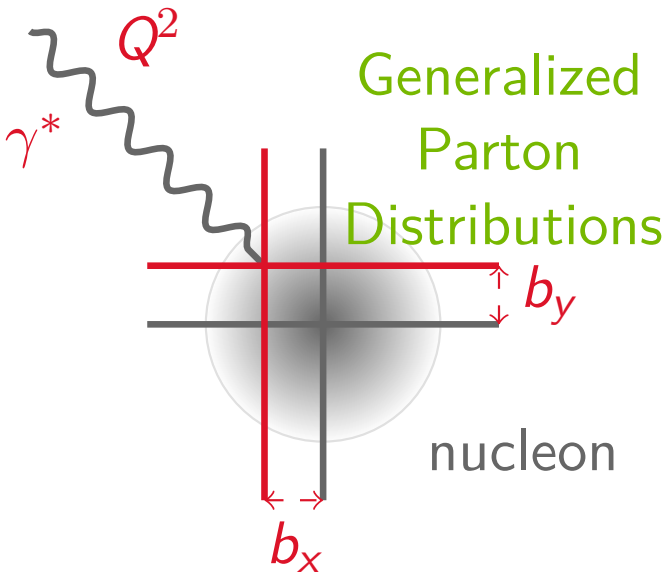

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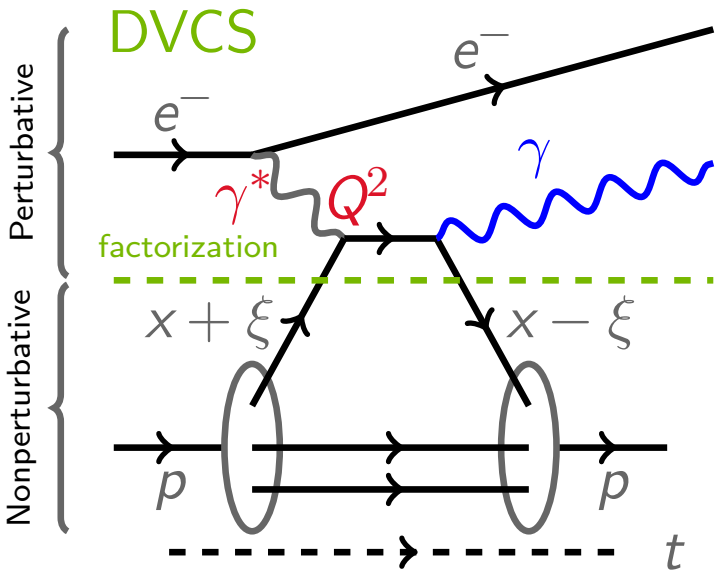

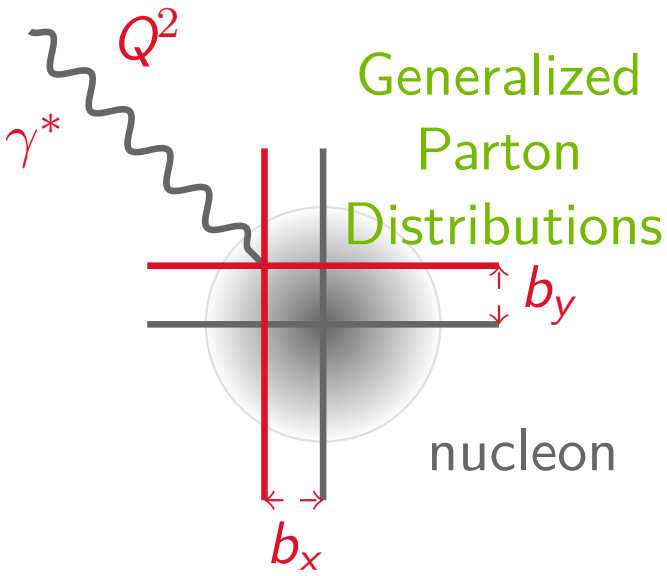

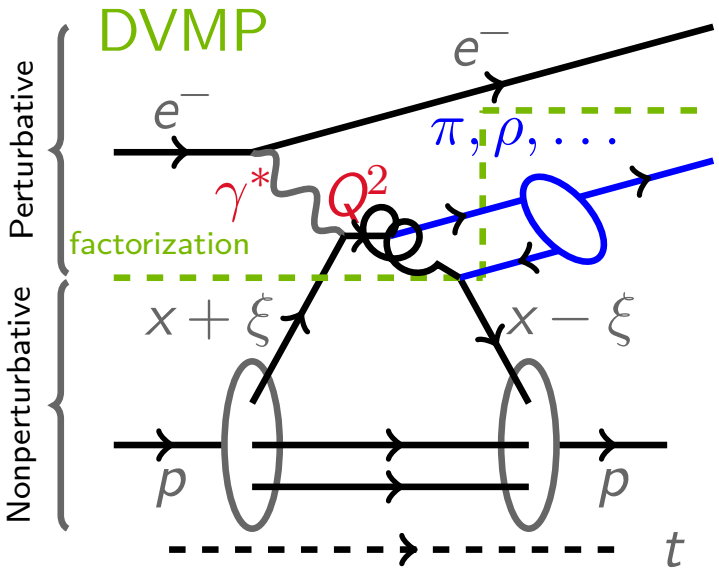

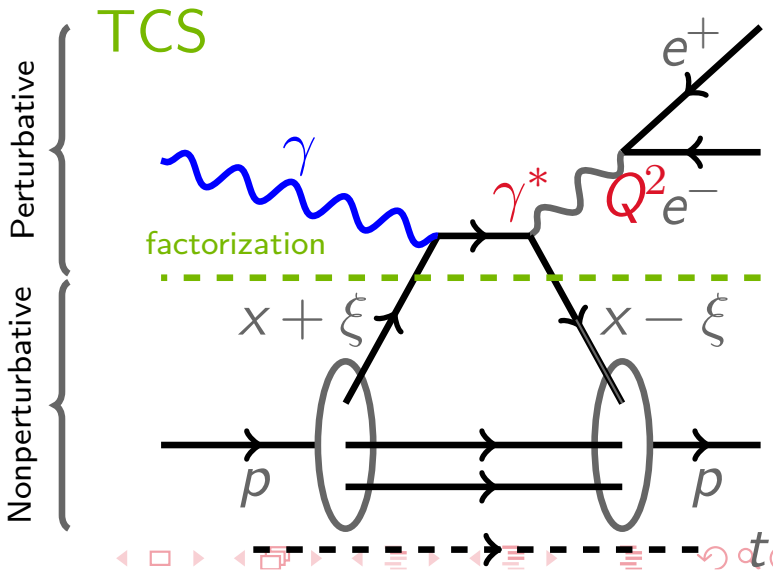

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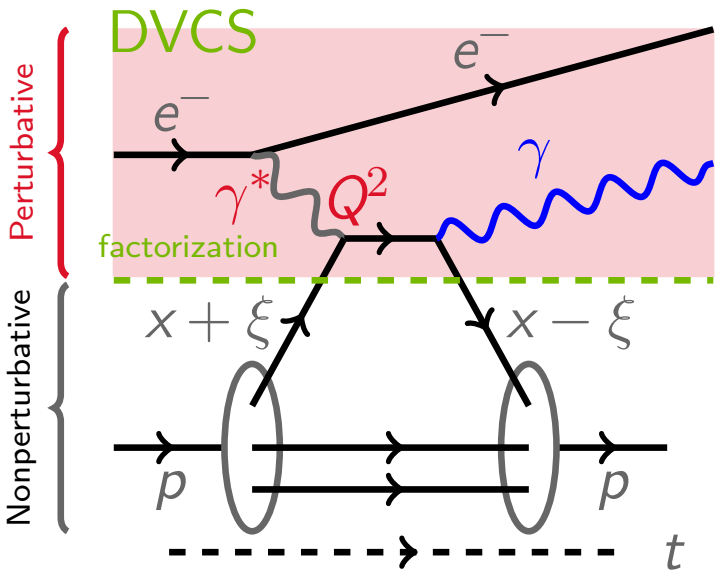

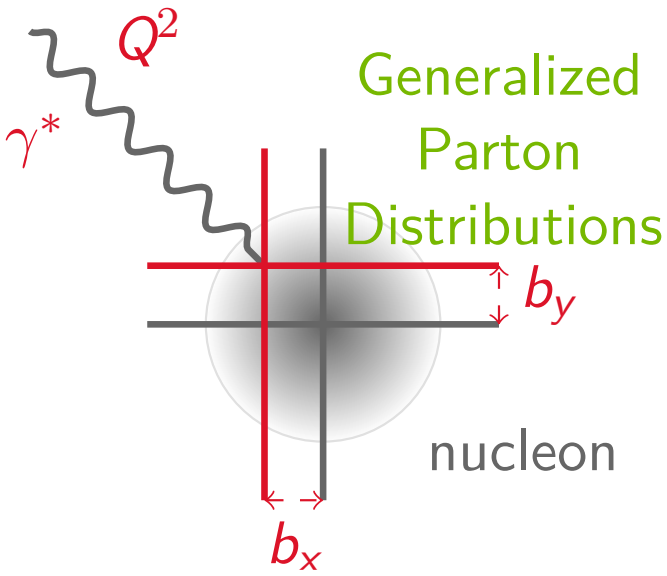

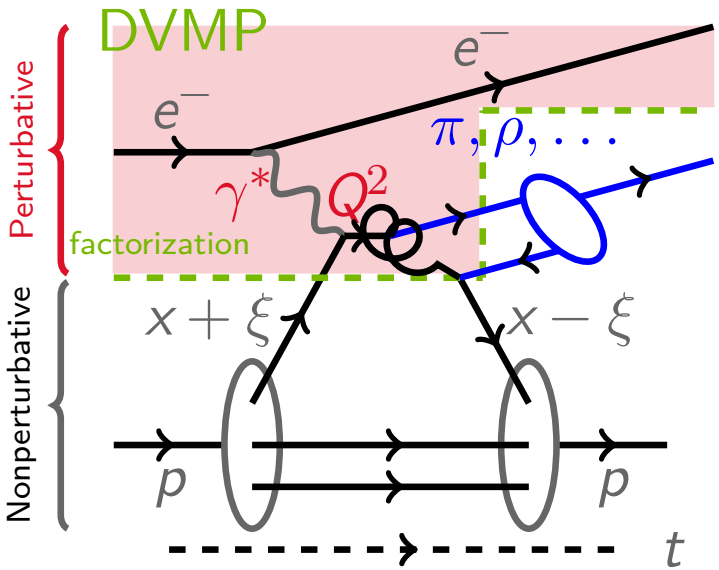

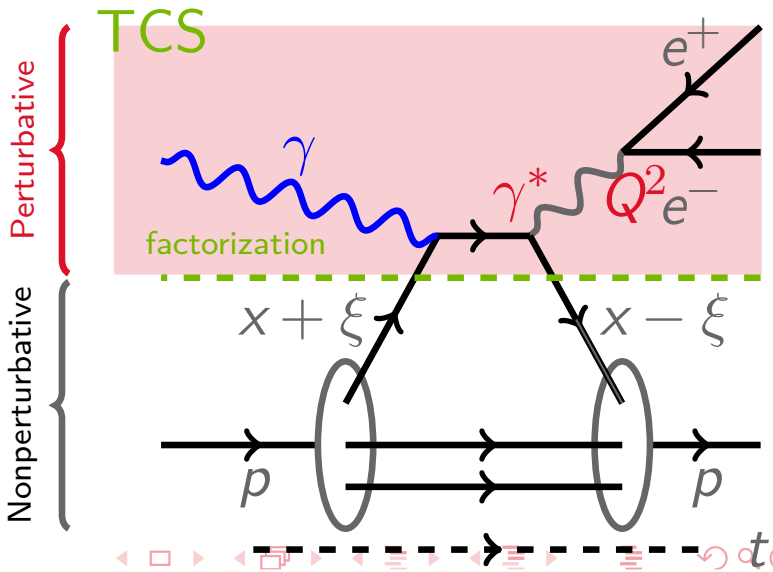

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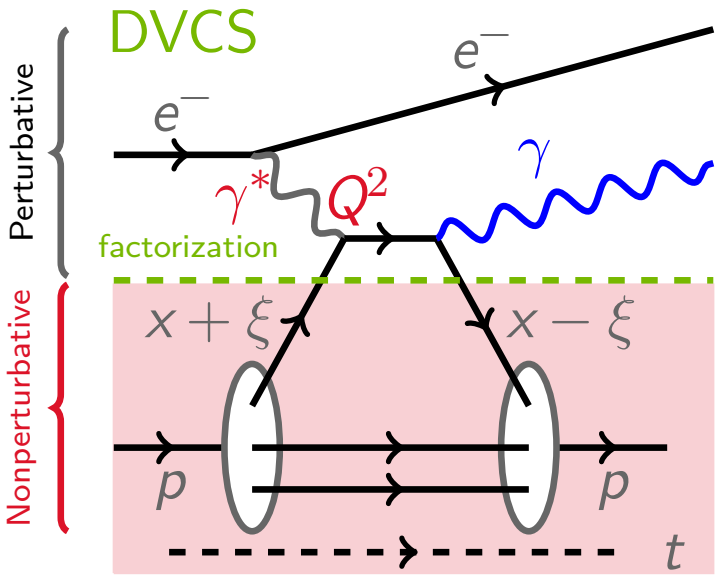
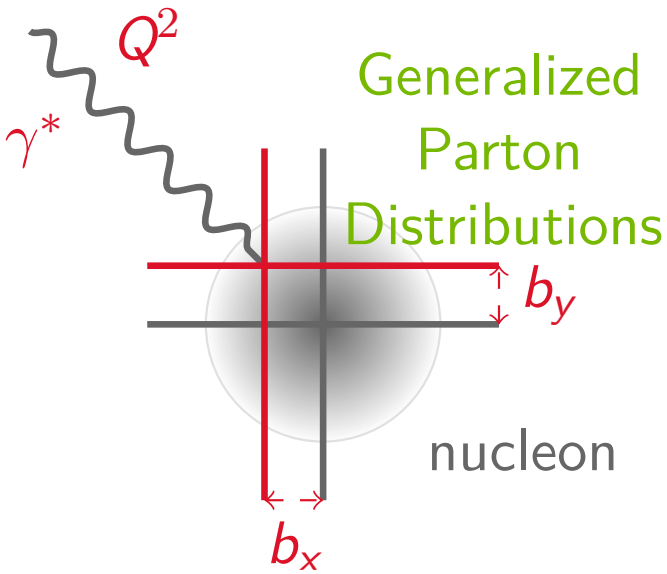
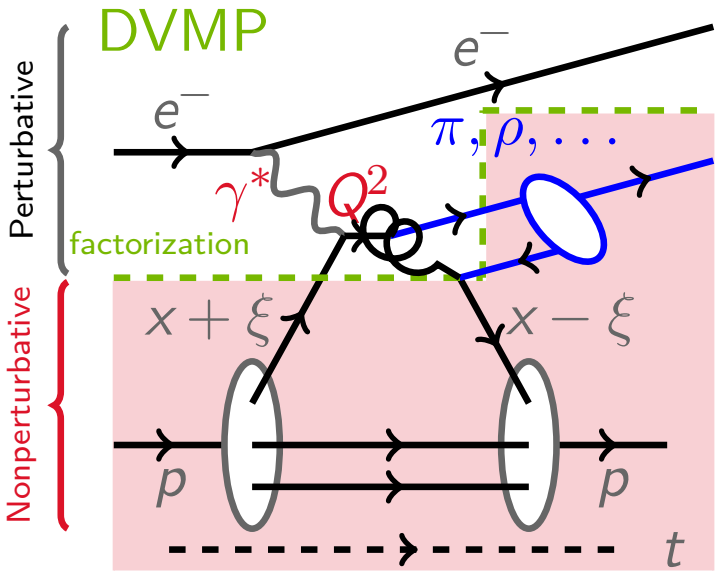
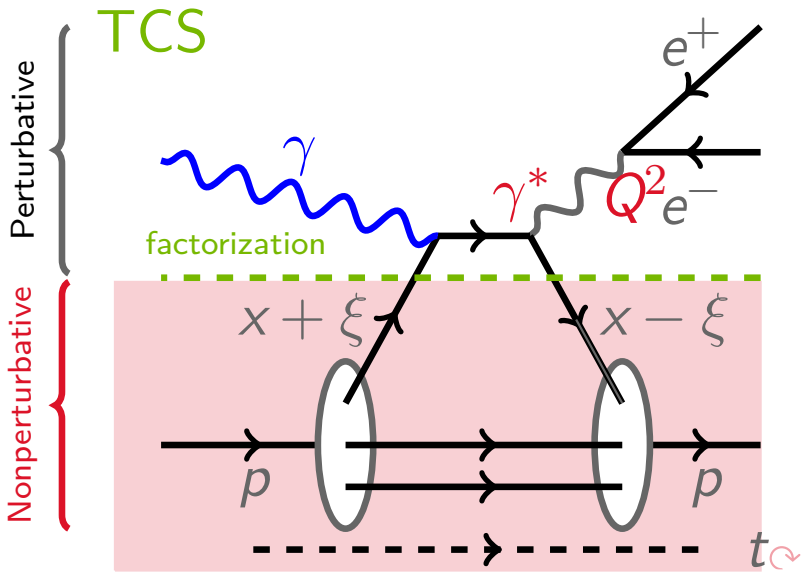








Bjorken regime : large Q^2 and fixed $xB \simeq 2\xi/(1+\xi)$

- 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** :

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

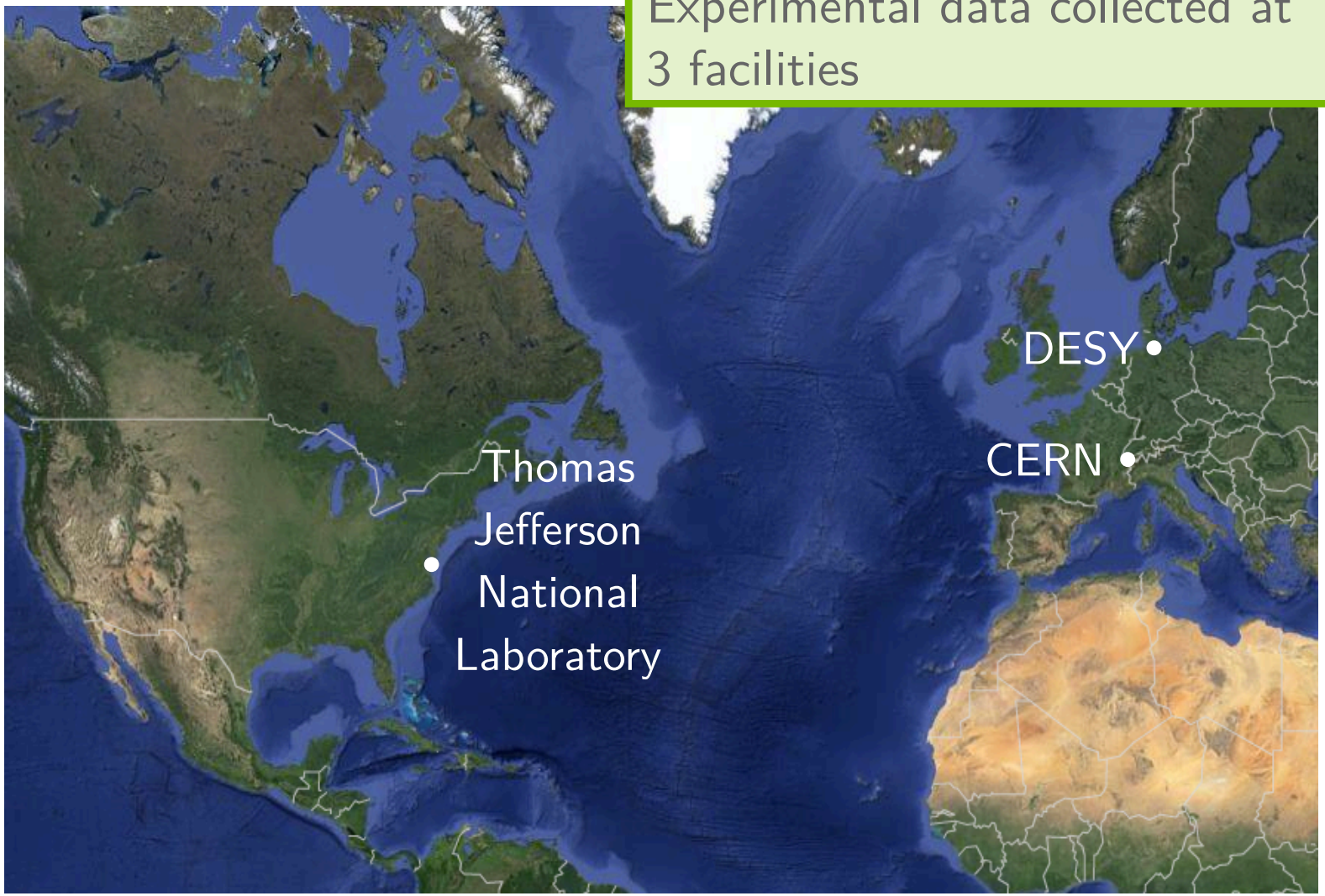
for a given GPD F.

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

Need for global fits of world data.

Different facilities will probe different kinematic domains.

Experimental data collected at 3 facilities



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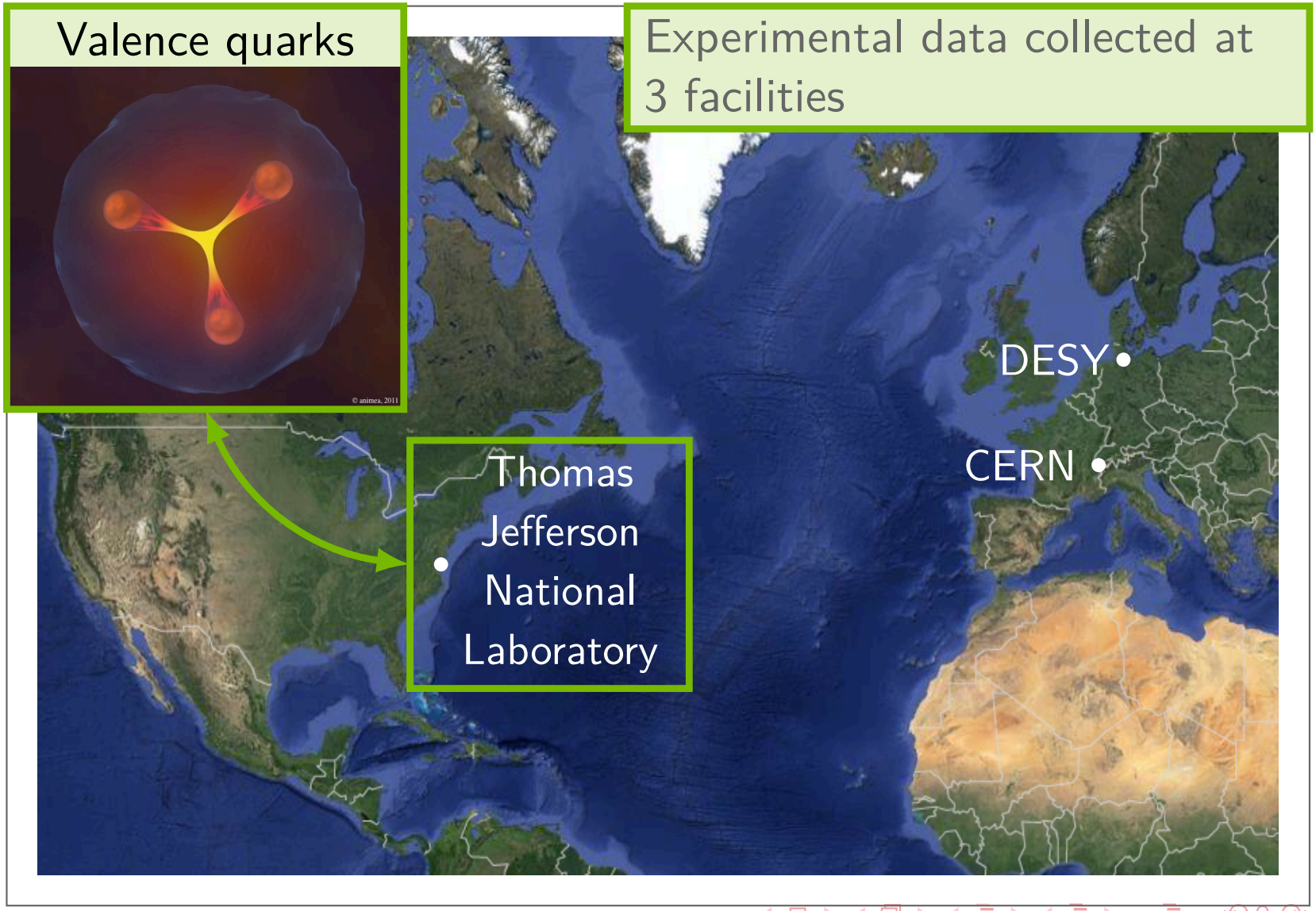

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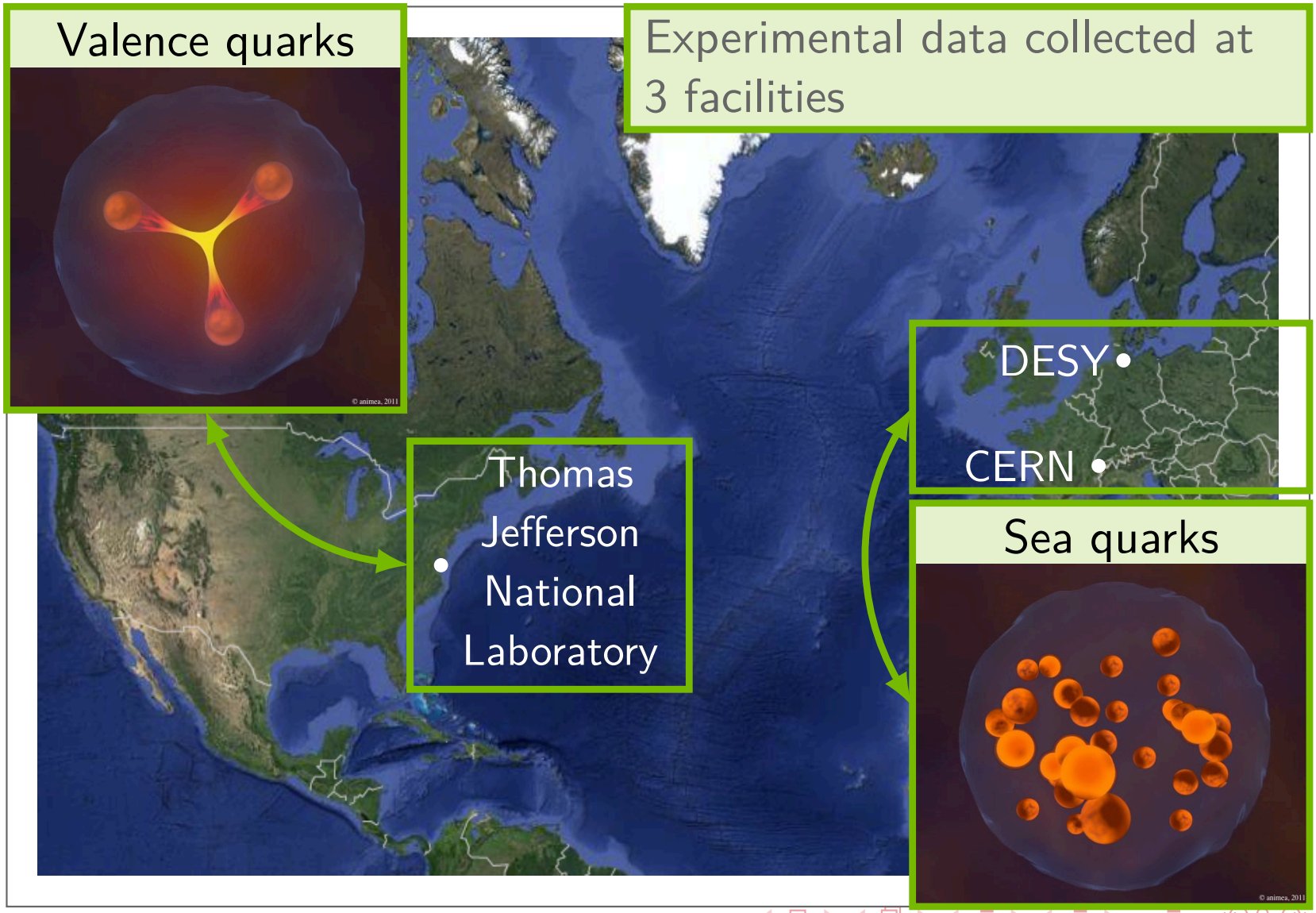
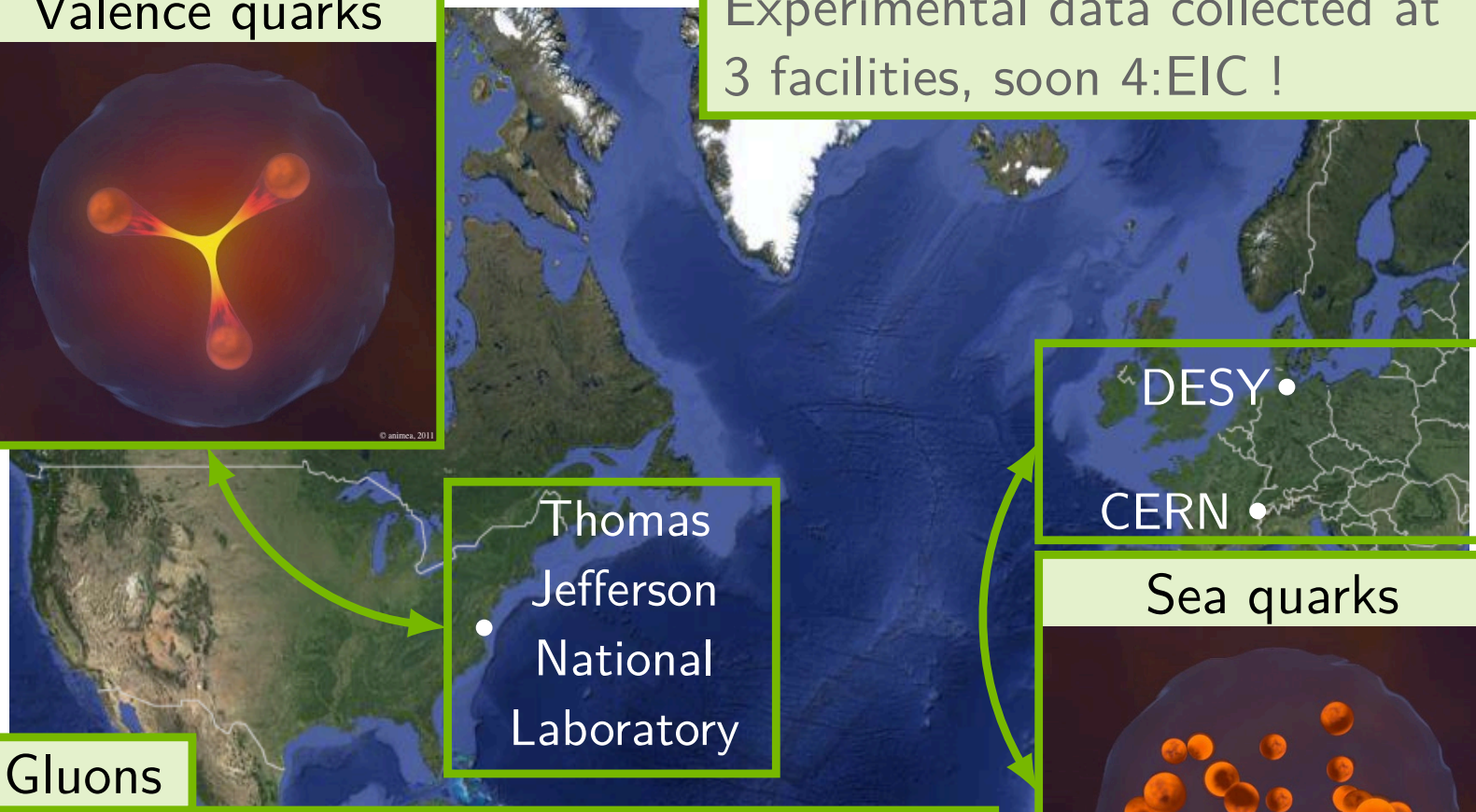


Need for global fits of world data.

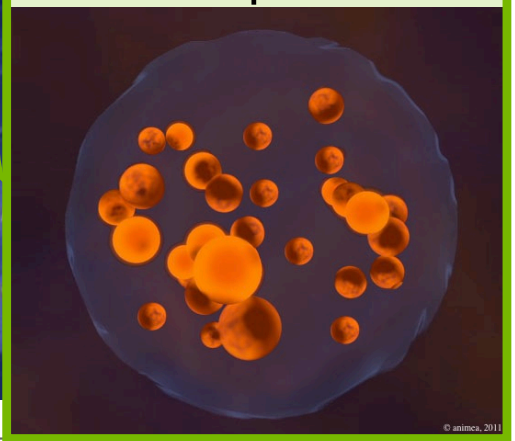
Different facilities will probe different kinematic domains.

Valence quarks

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



Sea quarks



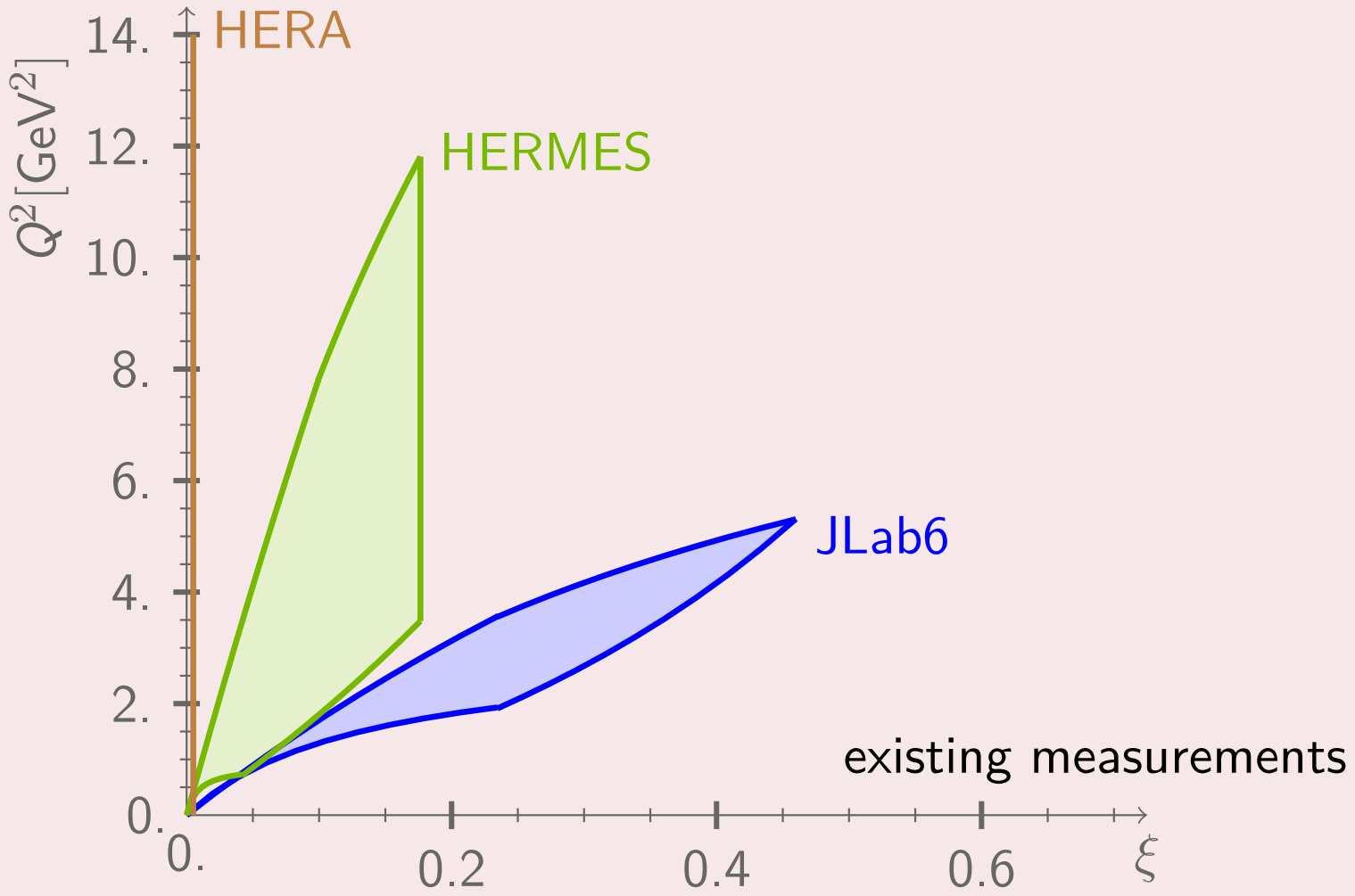
Gluons

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

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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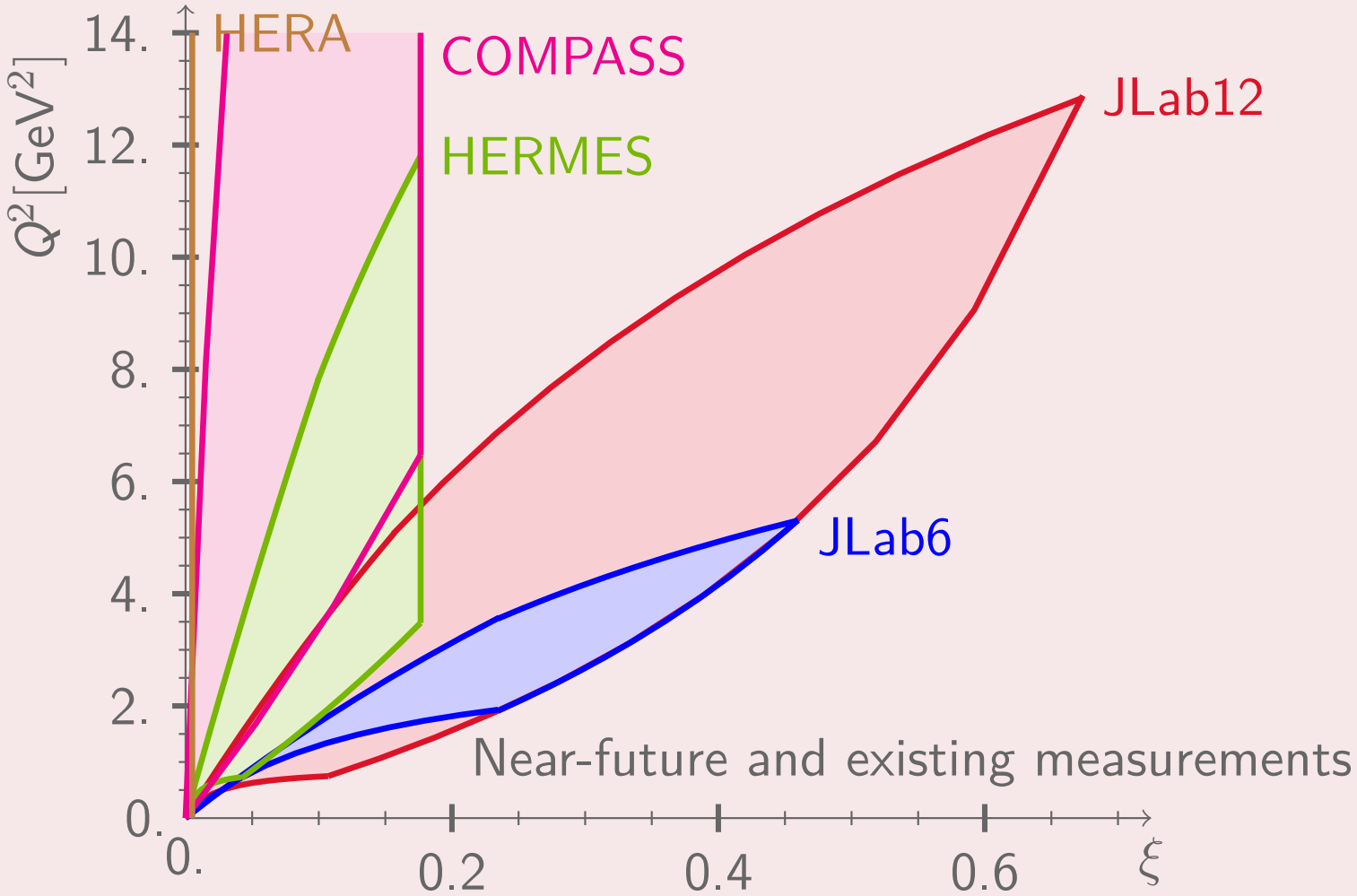

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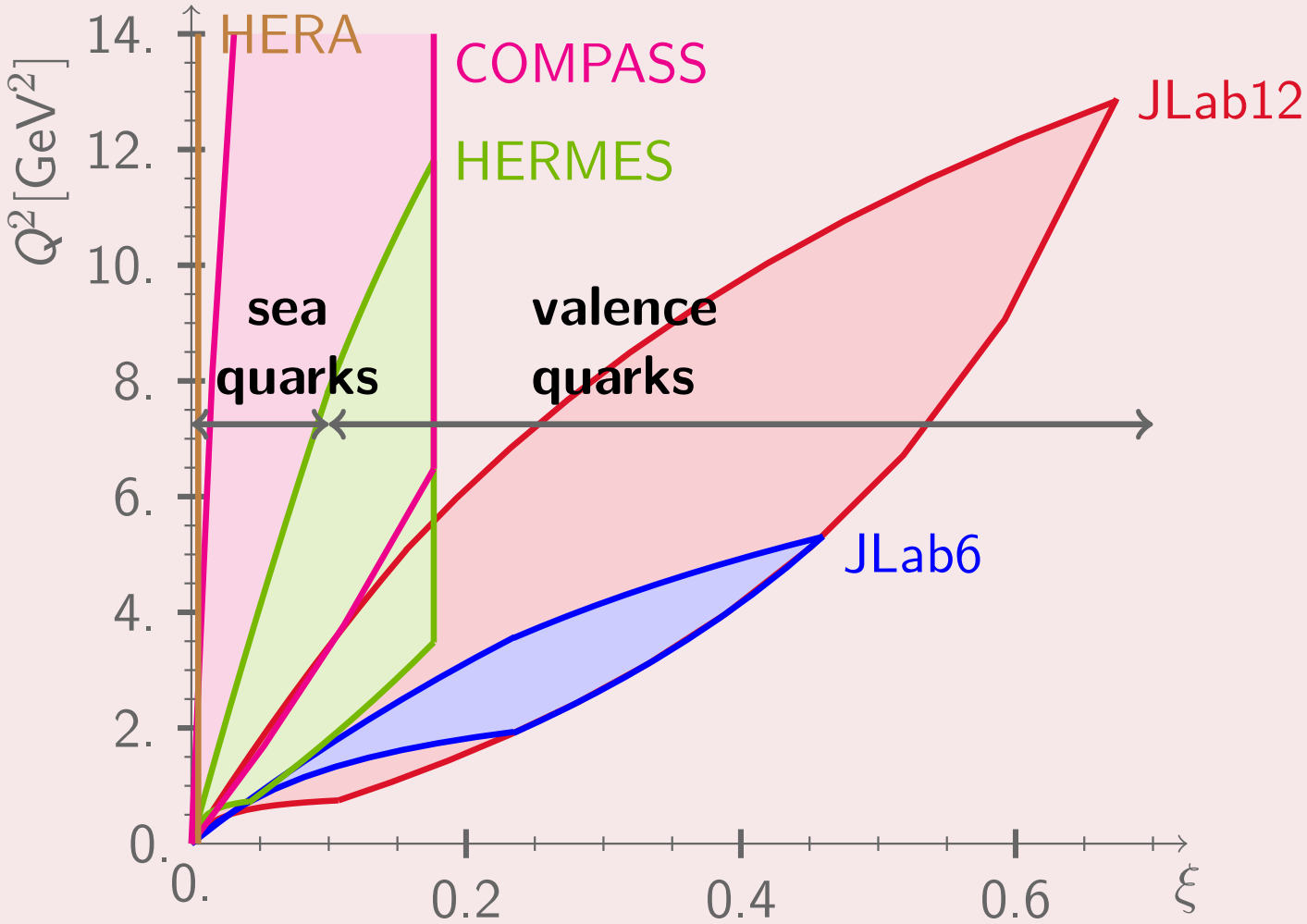

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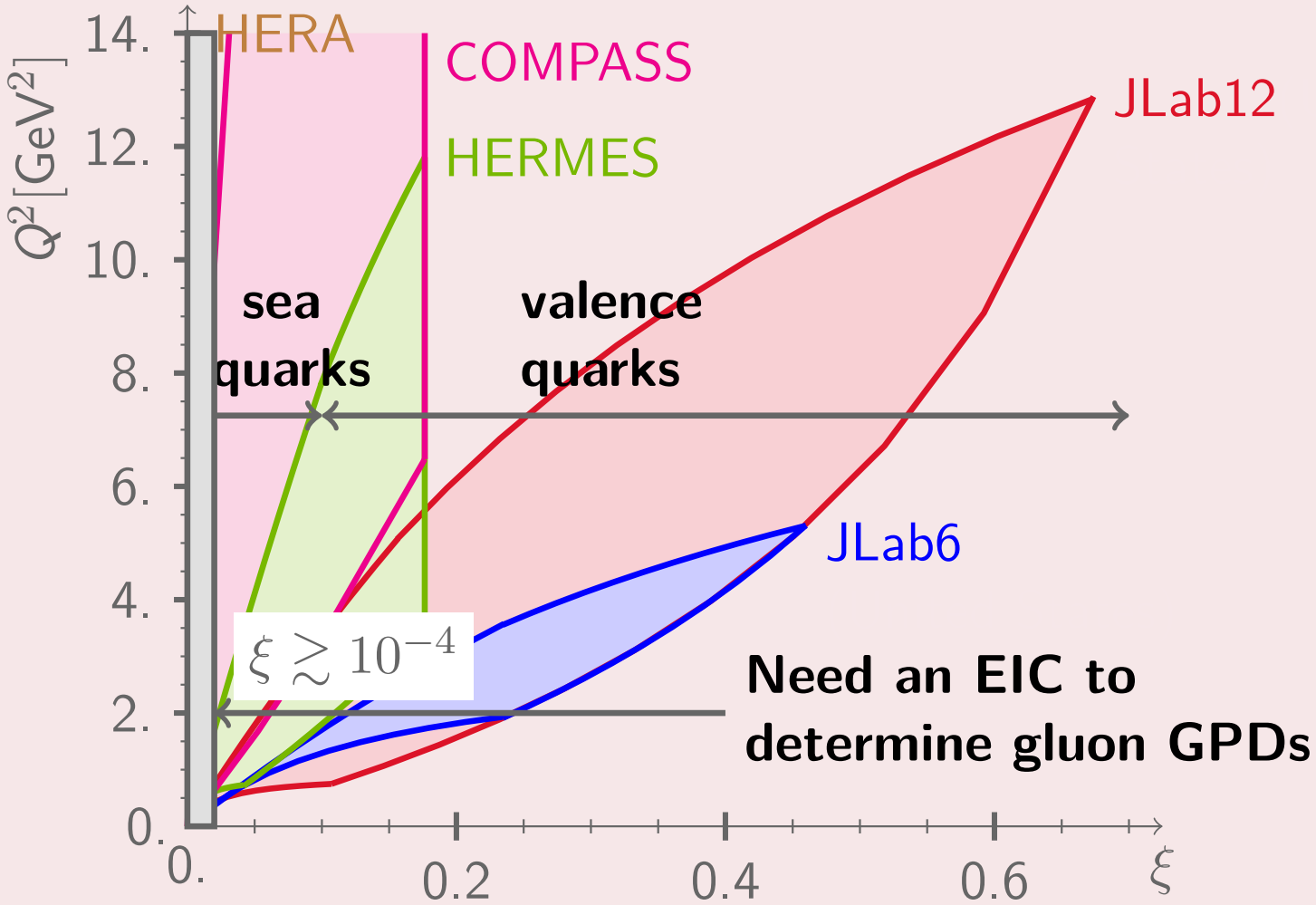

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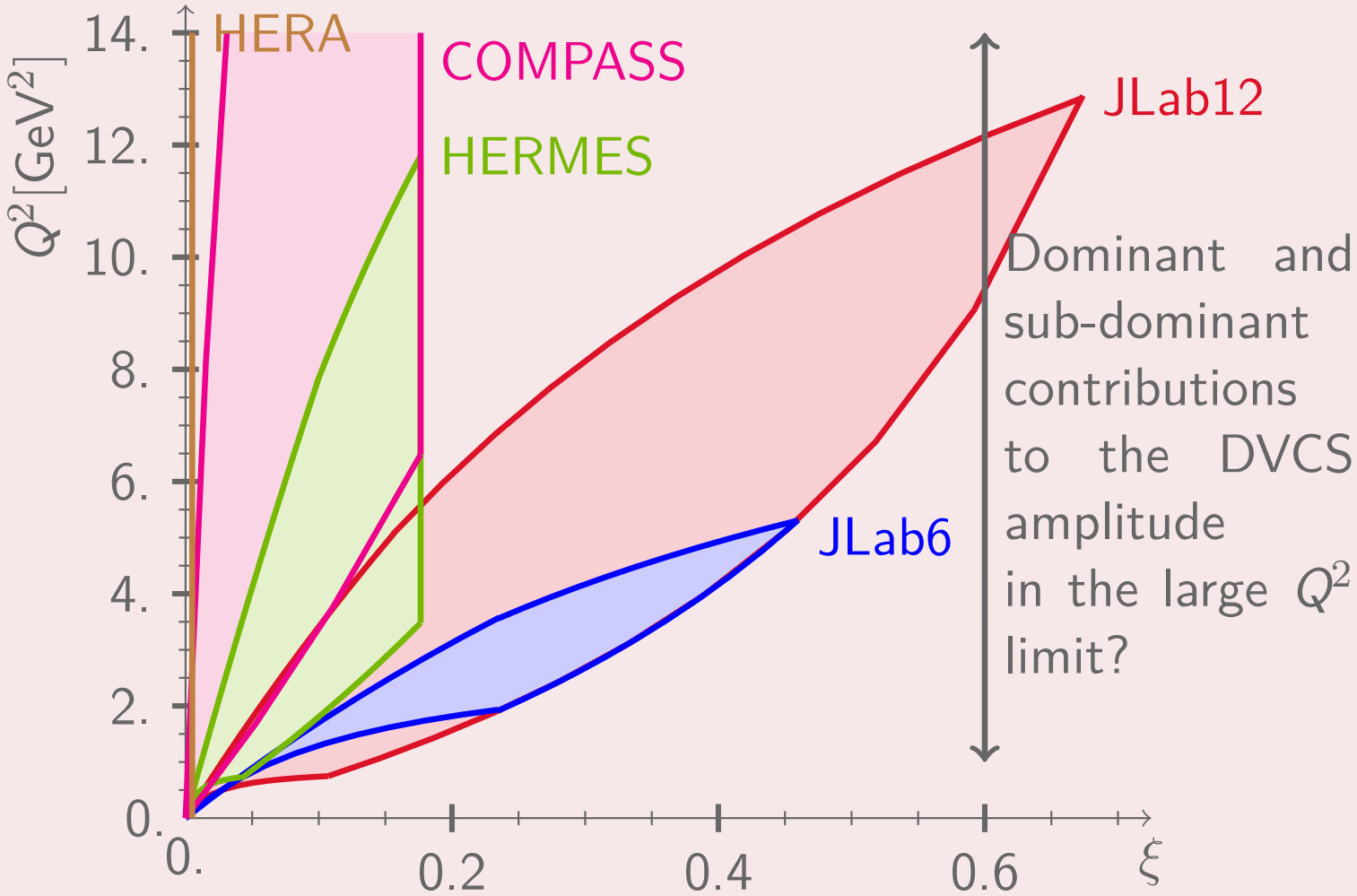
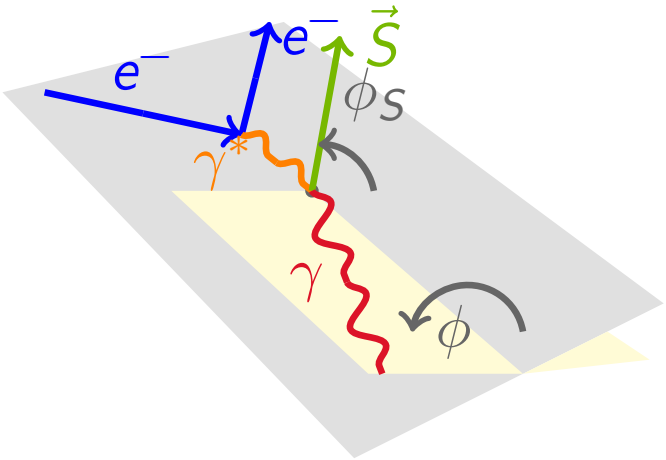


Typical DVCS kinematics.

Probing gluons, sea and valence quarks through DVCS.



- Study the **harmonic structure** of $ep \to ep\gamma$ amplitude.

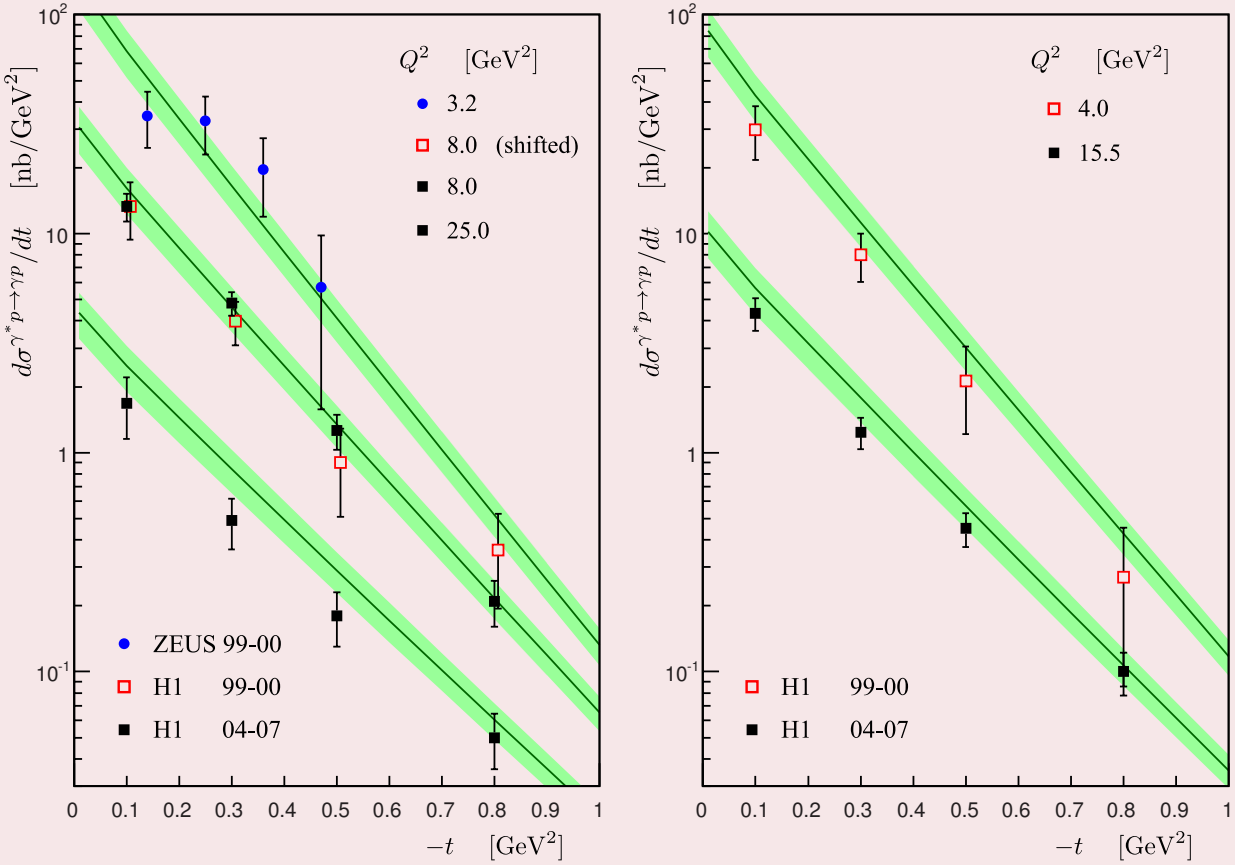
Diehl *et al.*, Phys. Lett. **B411**, 193 (1997)

Experiment	Kinematics		
	x_B	Q^2 [GeV^2]	t [GeV^2]
HERA	0.001	8.00	-0.30
COMPASS	0.05	2.00	-0.20
HERMES	0.09	2.50	-0.12
CLAS	0.19	1.25	-0.19
HALL A	0.36	2.30	-0.23

Goloskokov-Kroll (GK) model on DVCS.

No parameter of the GK model **was tuned** to analyse DVCS.

Differential cross section, HERA



Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

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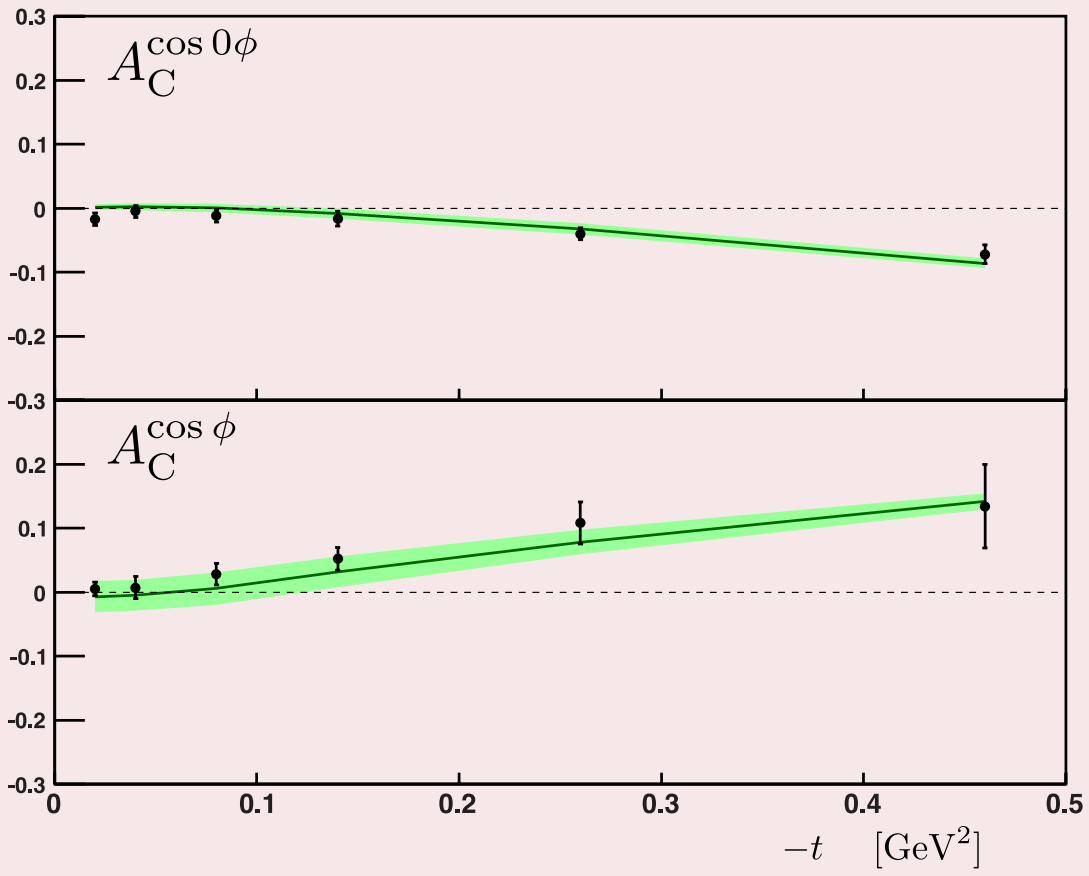
Beam Charge Asymmetry, HERMES



Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

Goloskokov-Kroll (GK) model on DVCS.

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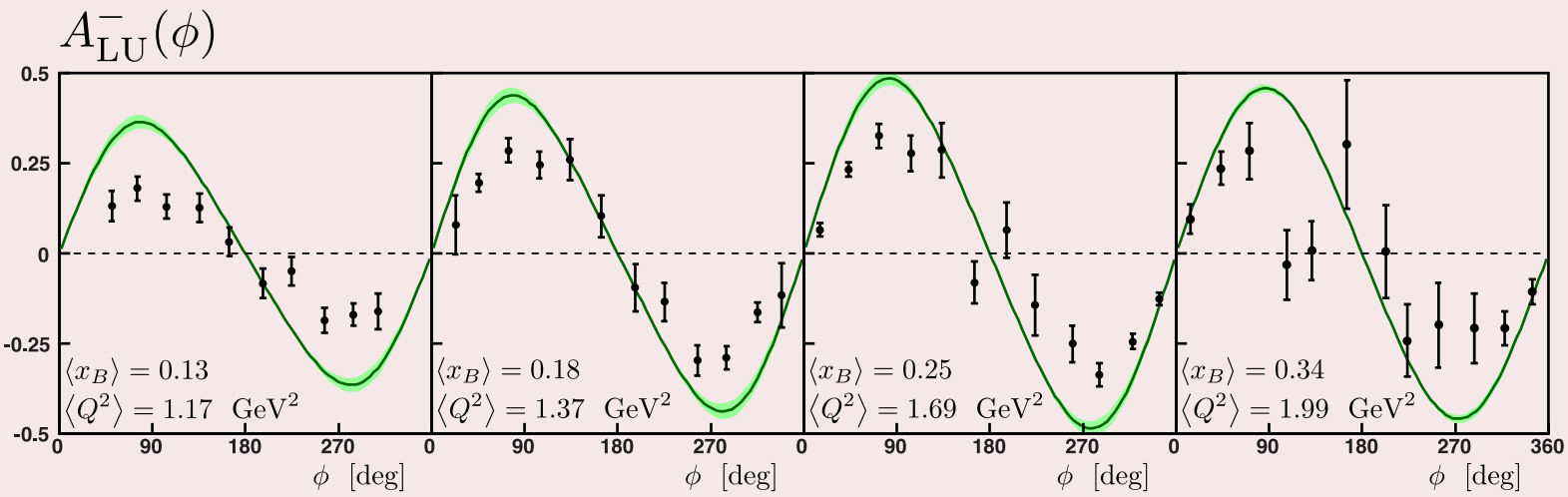
Beam Spin Asymmetry, CLAS

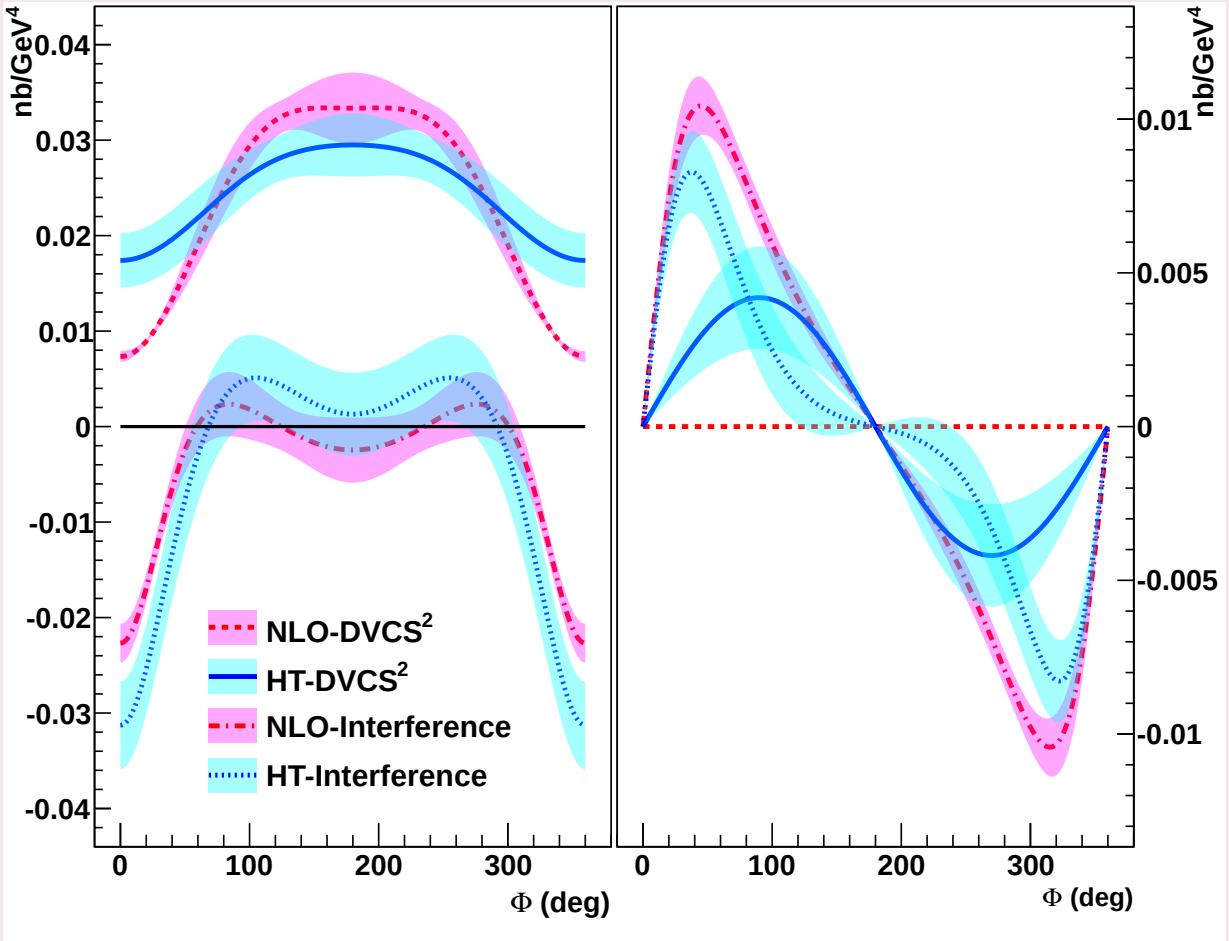


Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

Kinematic contributions.

Evidence for contributions beyond twist or leading order.

t/Q^2 and M^2/Q^2 are not small!



Defurne *et al.*, arXiv:1703.09442 [hep-ex]

Extracting GPDs or CFFs from experimental data

Dispersion relations and the line $x = \xi$.

Existence of a relation between $Re\mathcal{H}(\xi)$ and $H(x, \xi = x)$.

- Write dispersion relation **at fixed** t **and** Q^2:

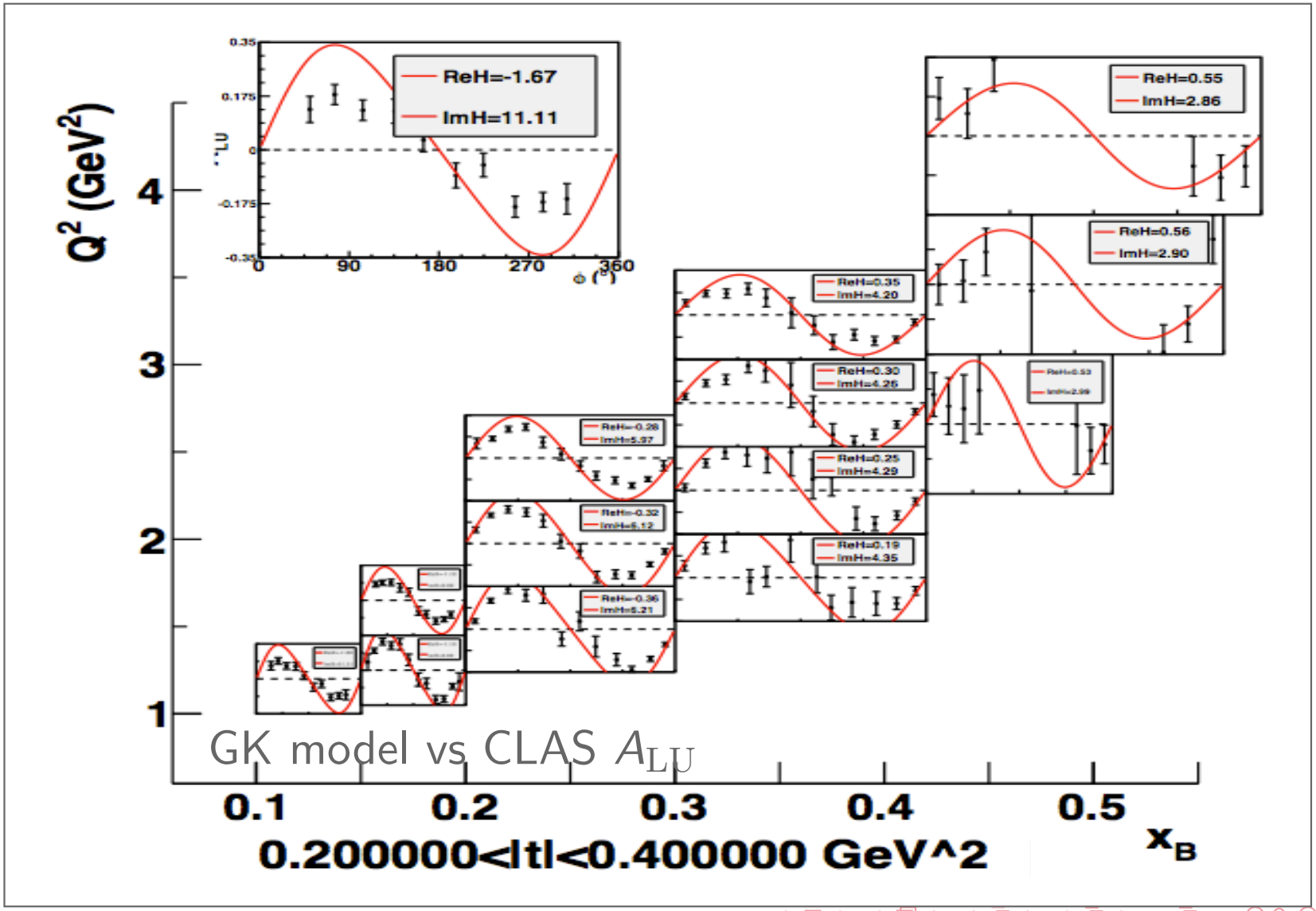
$$Re\mathcal{H}(\xi, t) = \Delta(t) + \frac{2}{\pi}\mathcal{P}\int_0^1 \frac{\mathrm{d}x}{x}\frac{Im\mathcal{H}(x,t)}{\left(\frac{\xi^2}{x^2} - 1\right)}$$

- Use LO relation $Im\mathcal{H}(x,t) = \pi\big(H(x,x,t) - H(-x,x,t)\big)$.
- Up to the D-term form factor $\Delta(t)$, all the information accessible **at LO and fixed** Q^2 is contained on the line $x = \xi$.

Teryaev, hep-ph/0510031
Anikin and Teryaev, Phys. Rev. **D76**, 056007 (2007)
Diehl and Ivanov, Eur. Phys. J. **C52**, 919 (2007)

Dispersion relations and actual data.

Too few kinematic bins to provide model-independent constraints?



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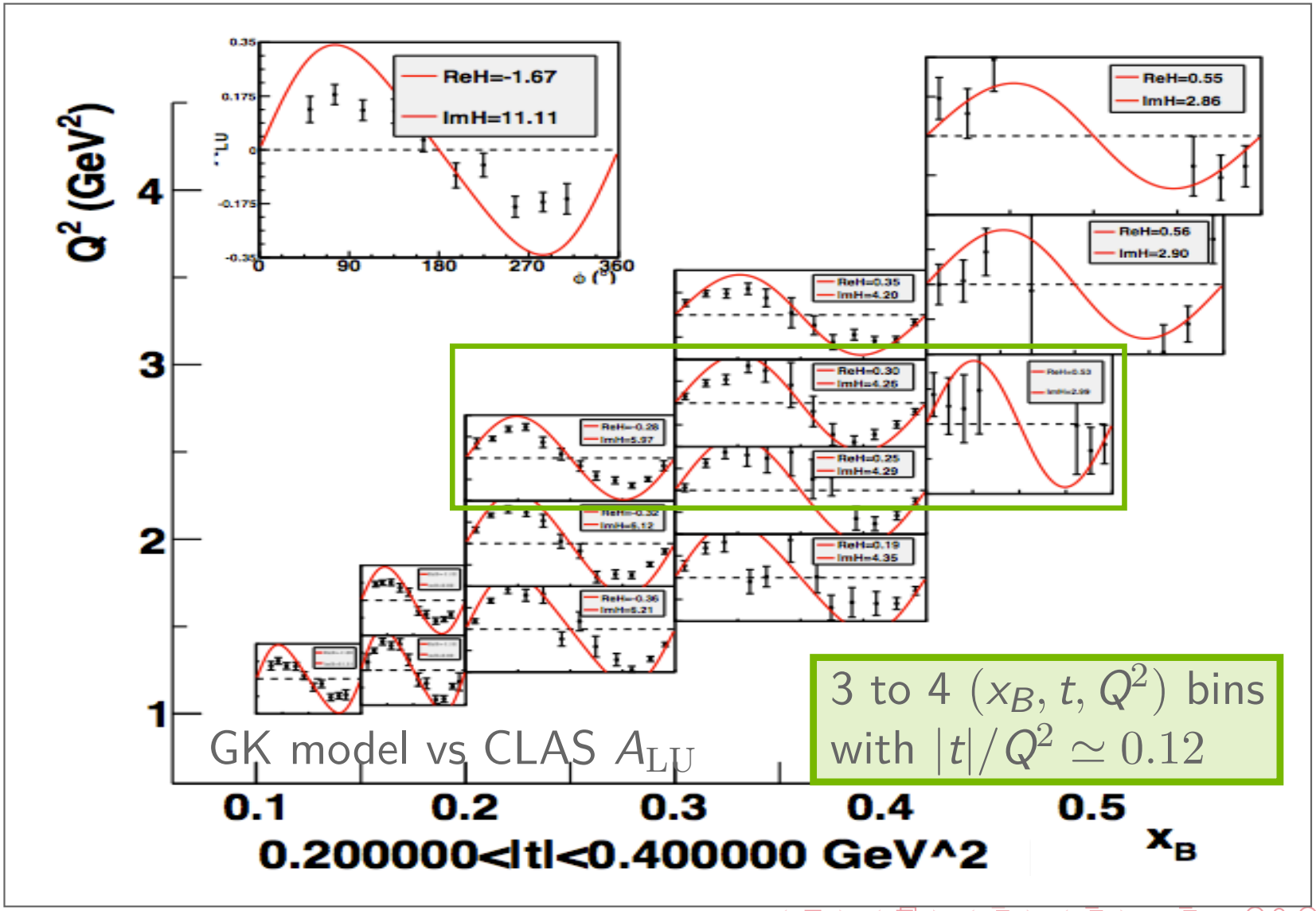

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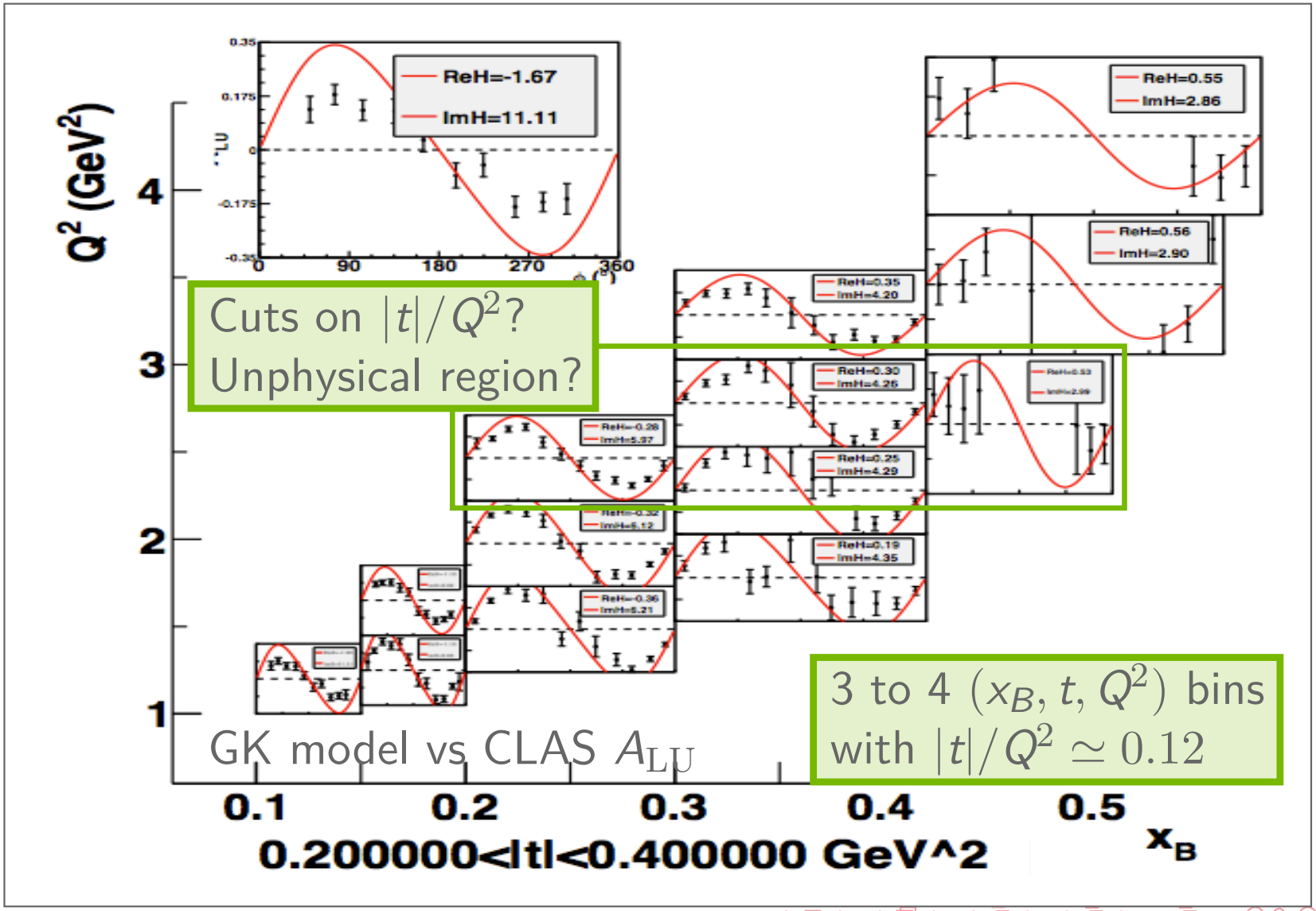


Overview of current extraction methods.

Problems: Model dependence? Uncertainties?

Local fits

Take each kinematic bin independantly of the others.
Extraction of $Re\mathcal{H}$, $Im\mathcal{H}$, ...as independent parameters.

Global fit

Take all kinematic bins at the same time. Use a parametrization of GPDs or CFFs.

Hybrid : Local / global fit

Option 1 Local fits and then smoothness assumption.

Option 2 Local fits and then 1-parameter fit.

Neural networks

Exploratory stage for GPDs.

Local fits

Take each kinematic bin independantly of the others.
Extraction of $Re\mathcal{H}$, $Im\mathcal{H}$, ...as independent parameters.

M. Guidal, Eur. Phys. J. **A39**, 5 (2009)

- **Almost model-independent**: relies on twist-2 dominance assumption and assume bounds for the fitting domain.
- Interpretation of **uncertainties** on extracted quantities? Contributions from measurements uncertainties, correlations between CFFs and fitting domain boundaries.
- Interpretation of **extracted quantities**? *e.g.*mixing of quark and gluon GPDs due to NLO effects.
- **Oscillations** between different (x_B, t, Q^2) bins may happen.
- **Extrapolation** problem left open.

Local fits: What can be achieved in principle?

- Structure of BSA at twist 2 :

$$\mathrm{BSA}(\phi) = \frac{a \sin\phi + b \sin 2\phi}{1 + c\cos\phi + d\cos 2\phi + e\cos 3\phi}$$

where $a = \mathcal{O}(Q^{-1})$, $b = \mathcal{O}(Q^{-4})$, $c = \mathcal{O}(Q^{-1})$, $d = \mathcal{O}(Q^{-2})$, $e = \mathcal{O}(Q^{-5})$.

Local fits: What can be achieved in principle?

- Structure of BSA at twist 2 :

$$\mathrm{BSA}(\phi) = \frac{a \sin\phi + b \sin 2\phi}{1 + c\cos\phi + d\cos 2\phi + e\cos 3\phi}$$

- **Underconstrained** problem (8 fit parameters : real and imaginary parts of 4 CFFs $\mathcal{H}$, $\mathcal{E}$, $\tilde{\mathcal{H}}$ and $\tilde{\mathcal{E}}$).

Local fits: What can be achieved in principle?

- Structure of BSA at twist 2 :

$$\mathrm{BSA}(\phi) = \frac{a \sin\phi + b \sin 2\phi}{1 + c\cos\phi + d\cos 2\phi + e\cos 3\phi}$$

- **Underconstrained** problem.
- Need other asymmetries on **same** kinematic bin to allow extraction of **all CFFs** (or **add** $\simeq$ 5-10 % **systematic uncertainty**).

Local fits: What can be achieved in principle?

- Structure of BSA at twist 2 :

$$\mathrm{BSA}(\phi) = \frac{a \sin\phi + b \sin 2\phi}{1 + c\cos\phi + d\cos 2\phi + e\cos 3\phi}$$

- **Underconstrained** problem.
- Need other asymmetries on **same** kinematic bin to allow extraction of **all CFFs**.
- Add physical input? **Dispersion relations**, etc.

Kumericki *et al.*, Phys. Part. Nucl. **45**, 723 (2014)
Guidal *et al.*, Rept. Prog. Phys. **76**, 066202 (2013)

Global fit

Take all kinematic bins at the same time. Use a parametrization of GPDs or CFFs.

Kumericki, Nucl. Phys. **B841**, 1 (2010)

- **Model-dependent** approach.
- Allows the **implementation of theoretical constraints** on GPDs or CFFs.
- Guideline for **extrapolation** outside the physical domain.
- Compromise between number of parameters and number of described GPDs (flavor dependence, higher-twists, ...)?
- Impact on the **choice of a fitting strategy**?

Hybrid : Local / global fit

Option 1 Local fits and then smoothness assumption.

Moutarde, Phys. Rev. **D79**, 094021 (2009)

- Avoid unphysical oscillations between different (x_B, t, Q^2) bins by comparing to a **global fit by a smooth function**:

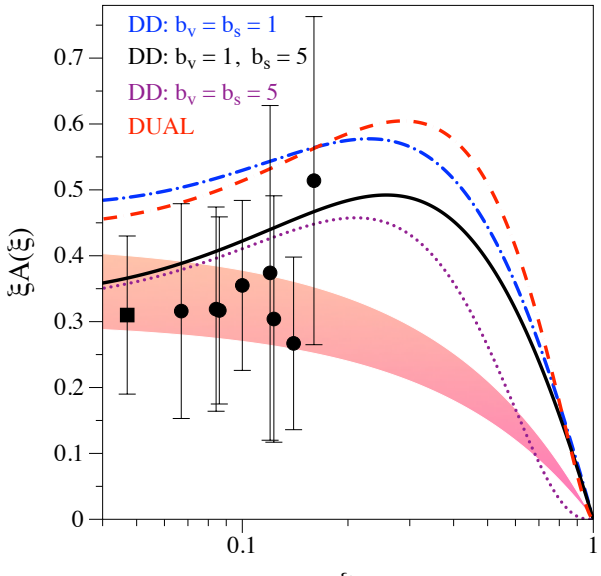
$$H^+ = 2\sum_{n=0}^{N}\sum_{l=0}^{n+1} B_{nl}(t)\theta(|x|<\xi)\left(1-\frac{x^2}{\xi^2}\right) C_{2n+1}^{(3/2)}\left(\frac{x}{\xi}\right) P_{2l}\left(\frac{x}{\xi}\right)$$

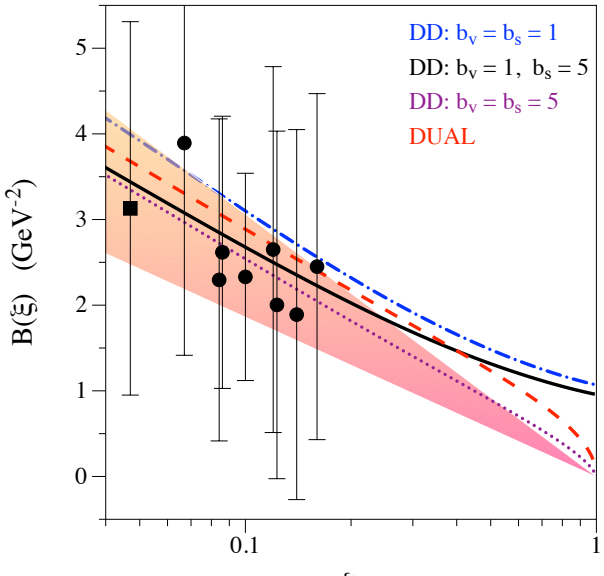
- Number of fit parameters describing the B_{nl} coefficients **increases with** N^2...Extension to other GPDs seems difficult.
- **Extrapolation** problem left open.

Hybrid : Local / global fit

Option 2 Local fits and then 1-parameter fit.

Dupré *et al.*, Phys. Rev. **D95**, 011501 (2017)





- Size of error bars reflects **systematics** of local fits.
- **Extrapolation** problem take care of by model-dependent 1-parameter parameterization.

Neural networks

Exploratory stage for GPDs.

Kumericki *et al.*, JHEP **1107**, 073 (2011)

- Already used for PDF fits.
- **Almost model-independent**: neural network description, twist-2, H-dominance?
- Good agreement between model fit and neural network fit in the fitting domain.
- **More reliable uncertainties** in extrapolations?
- **Overtraining** as a generic feature of (too) flexible models.

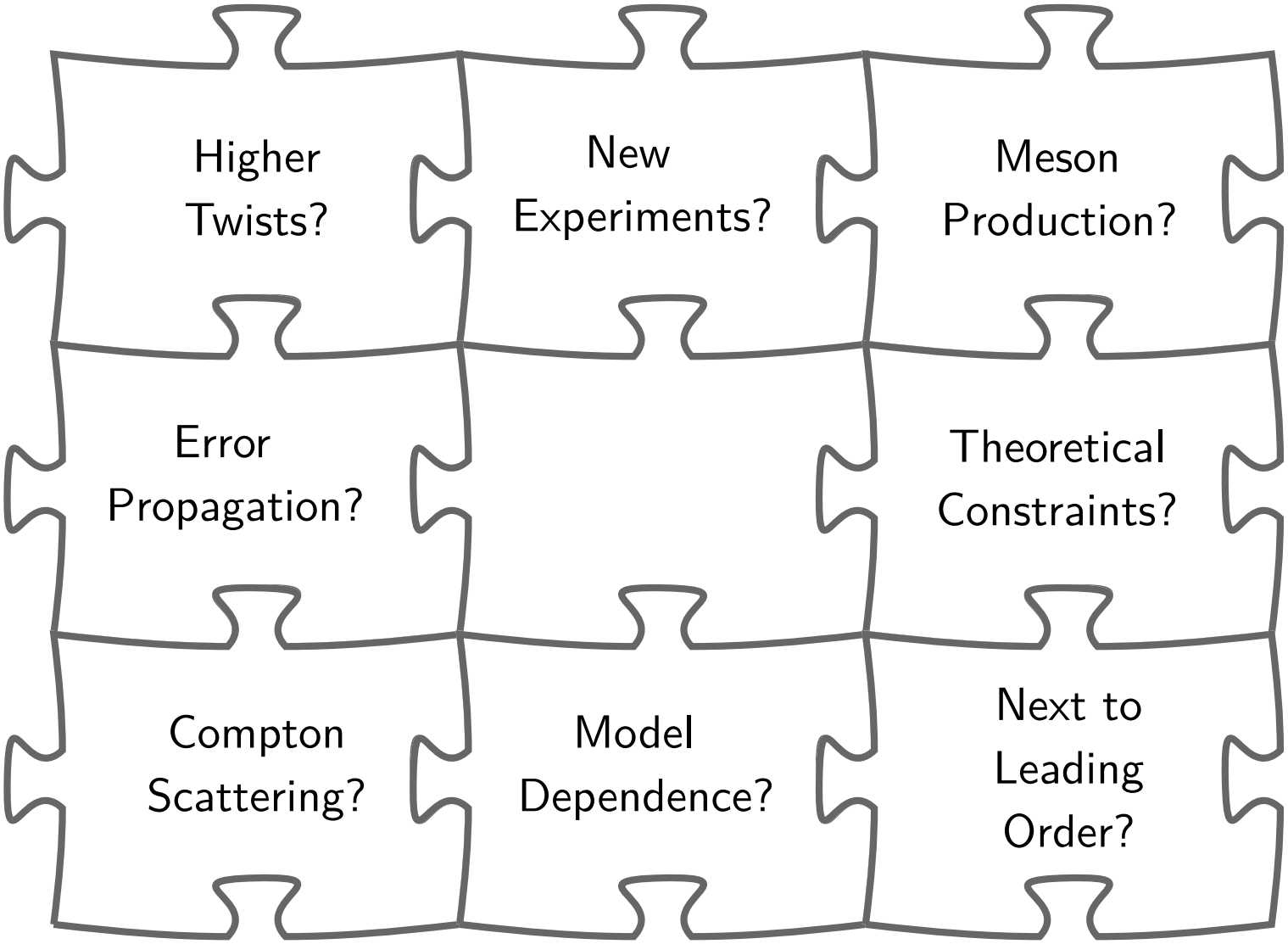
Summary of first extractions.

Feasibility of twist-2 analysis of existing data.

- **Dominance** of twist-2 and **validity** of a GPD analysis of DVCS data.
- $Im\mathcal{H}$ **best determined**. Large uncertainties on $Re\mathcal{H}$.
- However sizable **higher twist contamination** for DVCS measurements.

Software for the phenomenology of GPDs.

Different questions to be answered with the same tools.



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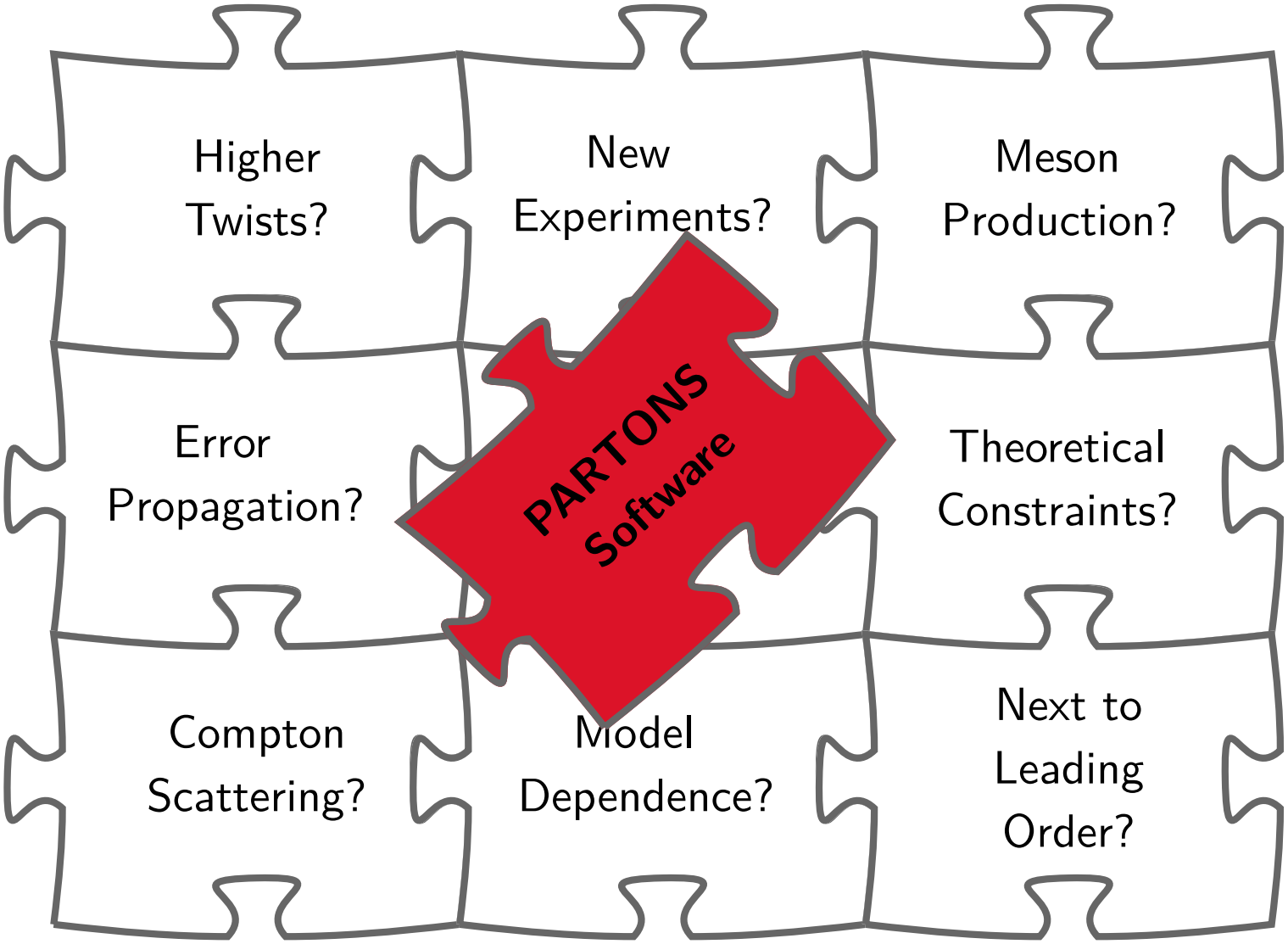


PARTONS framework

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

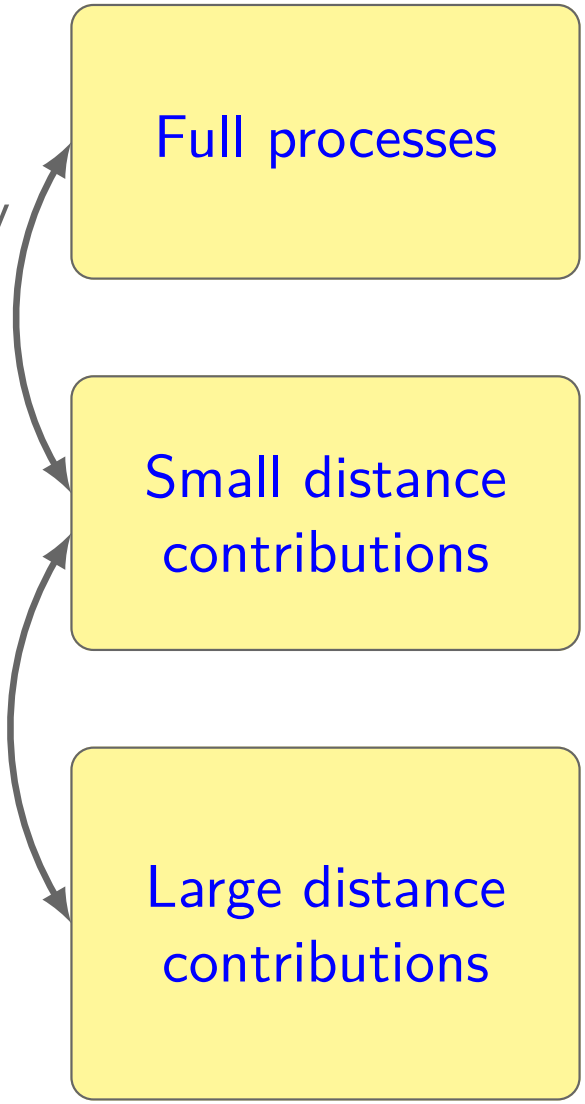
Computing chain design.

Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



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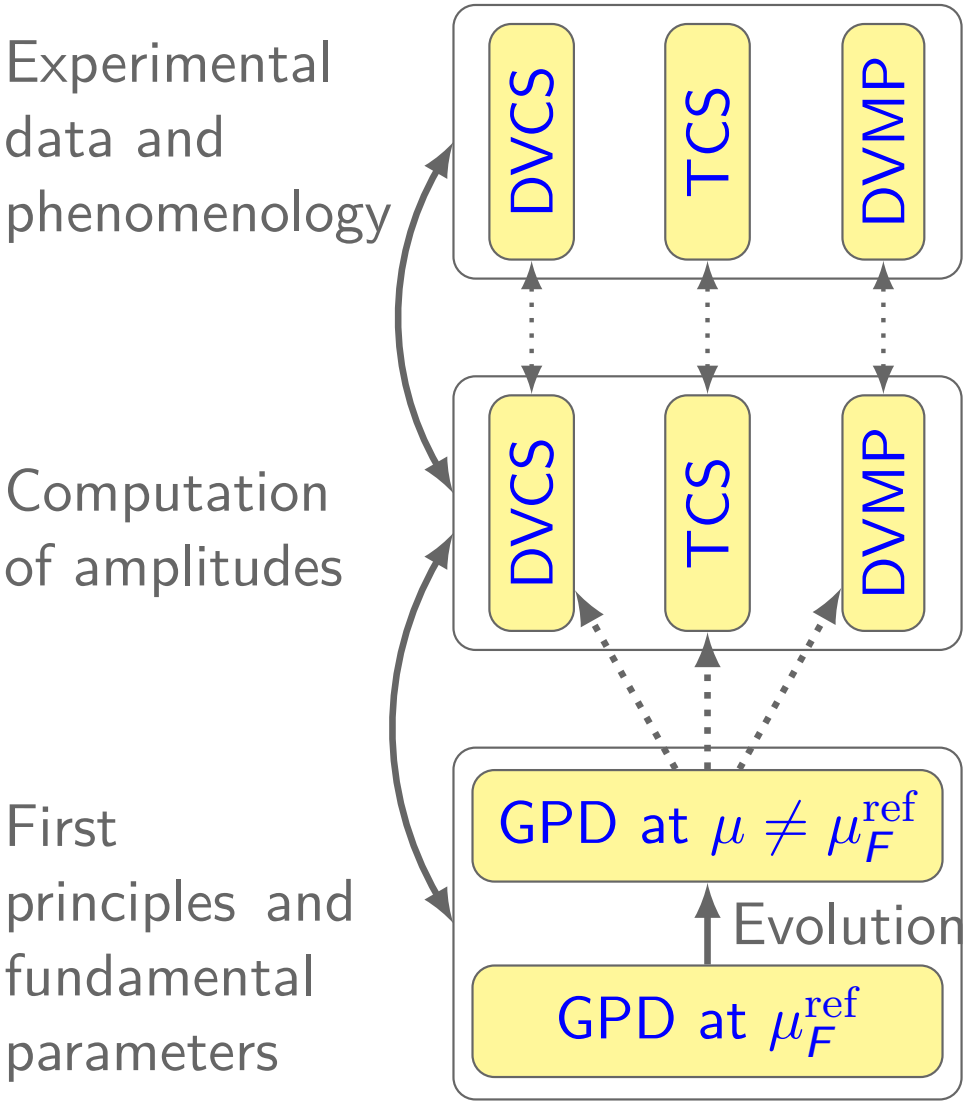
Differential studies: physical models and numerical methods.



Computing chain design.

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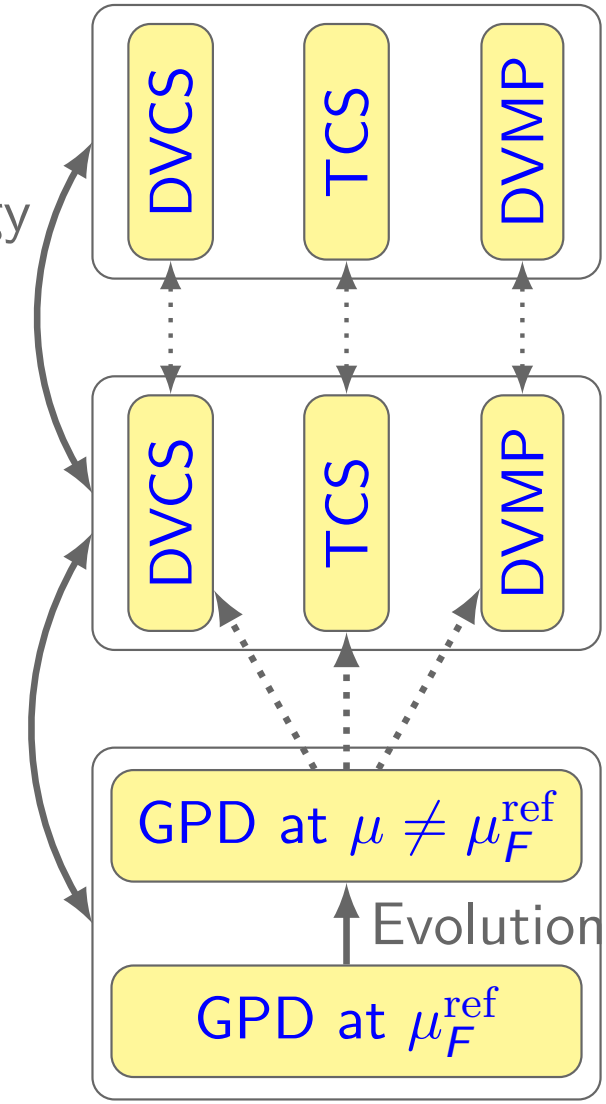
Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

Computing chain design.

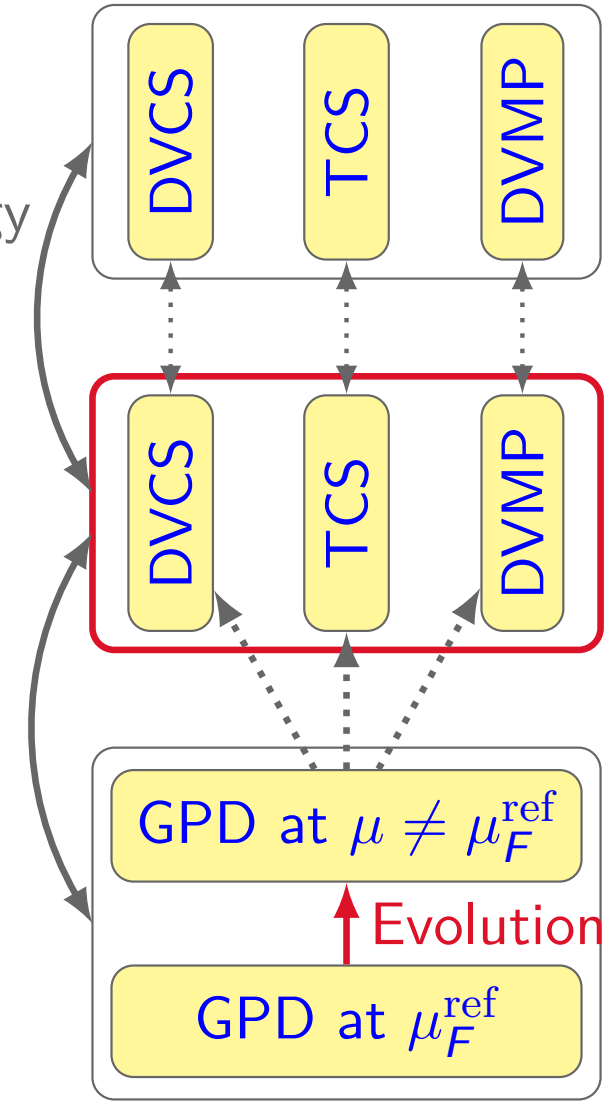
Differential studies: physical models and numerical methods.

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.

Computing chain design.

Differential studies: physical models and numerical methods.

Experimental data and phenomenology

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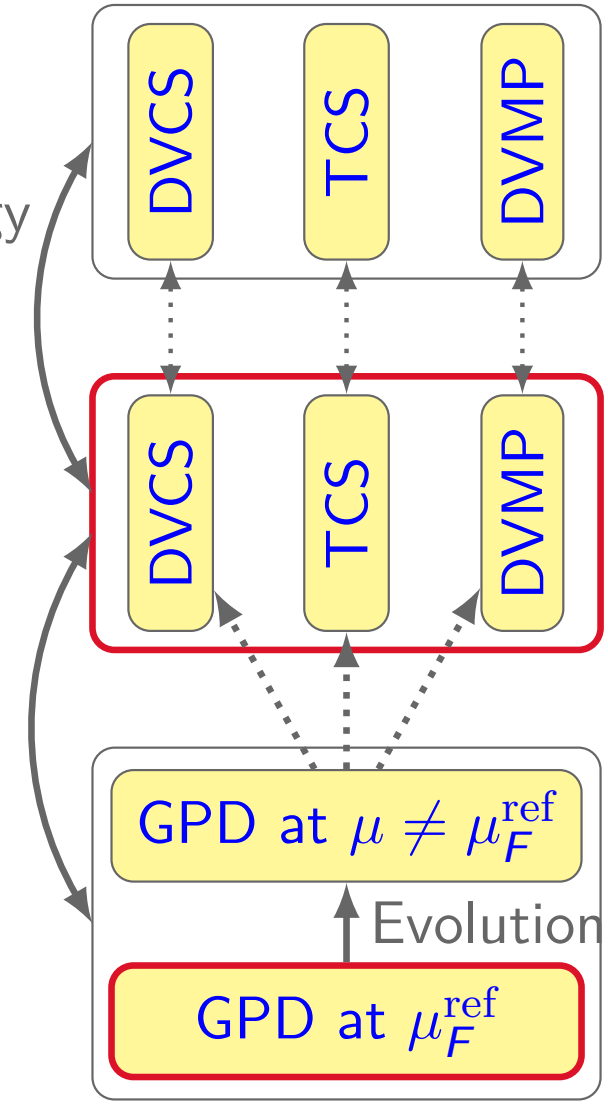

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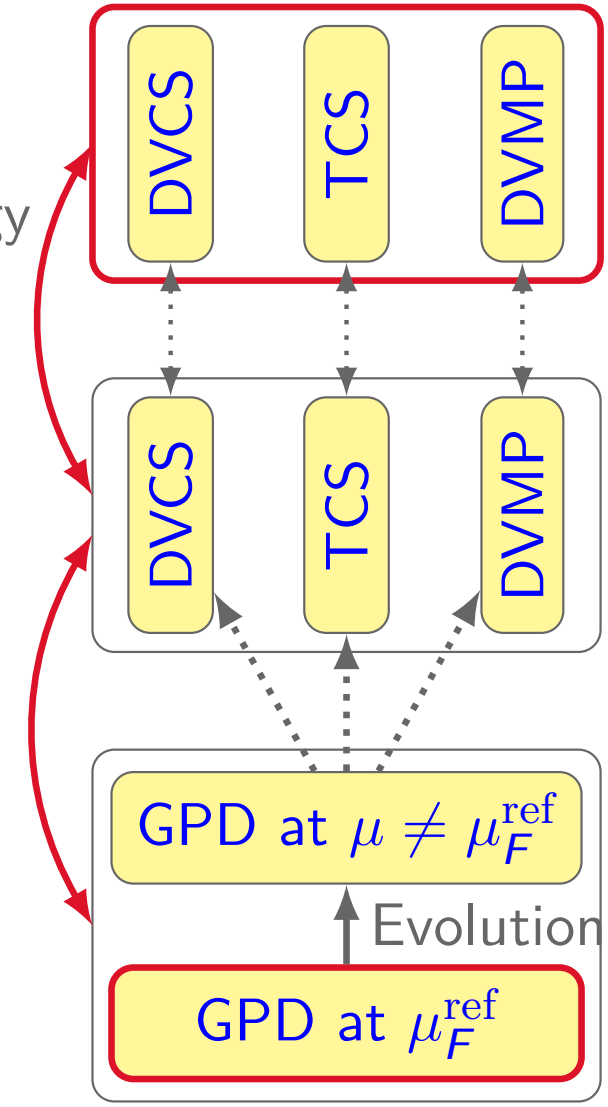

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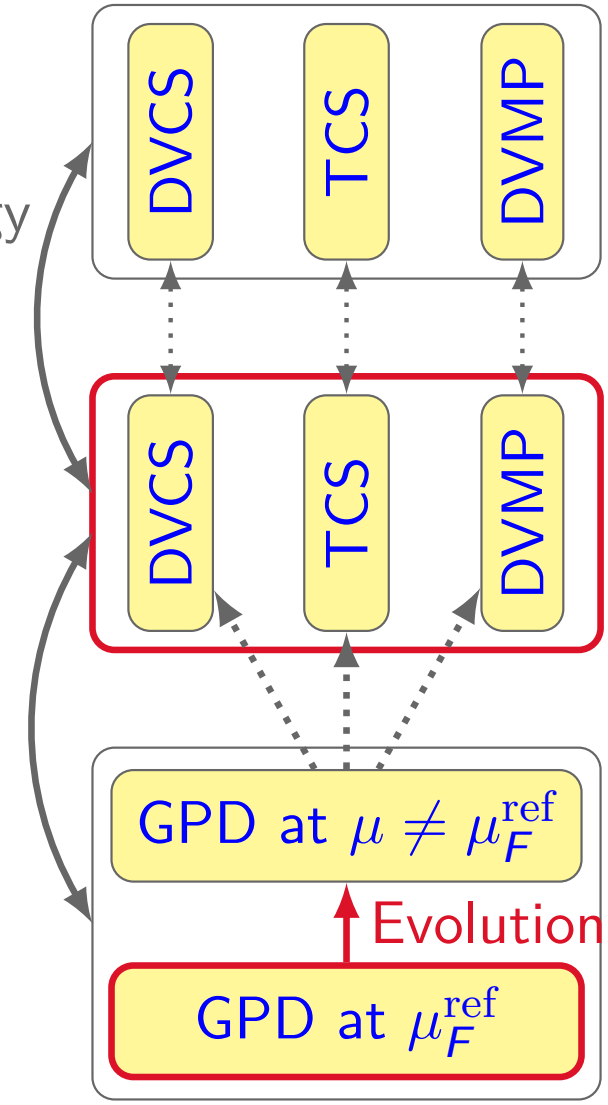

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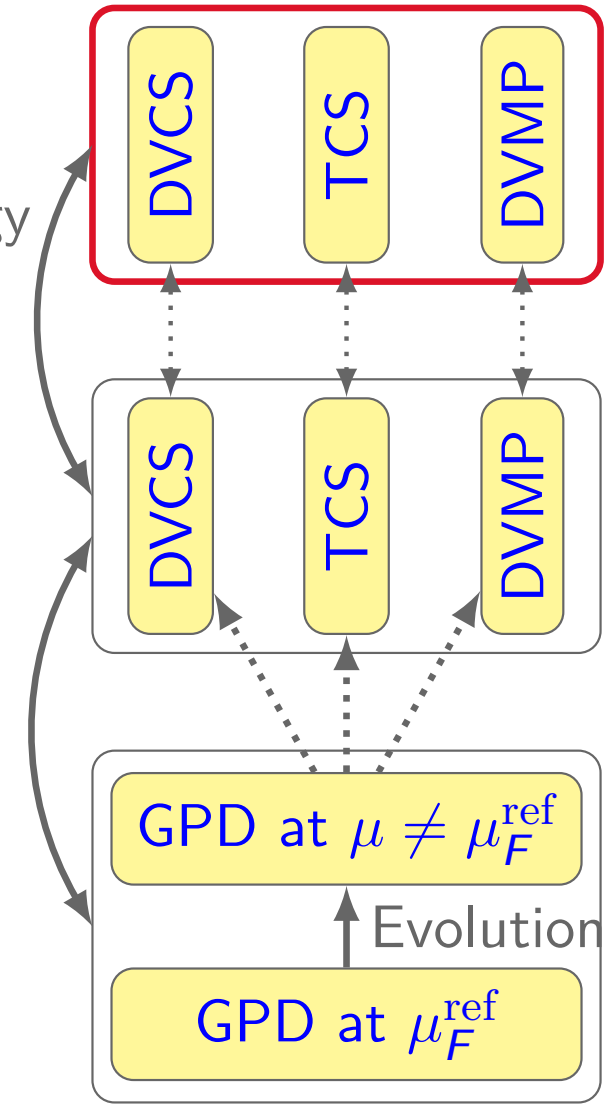


- Many observables.
- Kinematic reach.

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

Towards the first release.

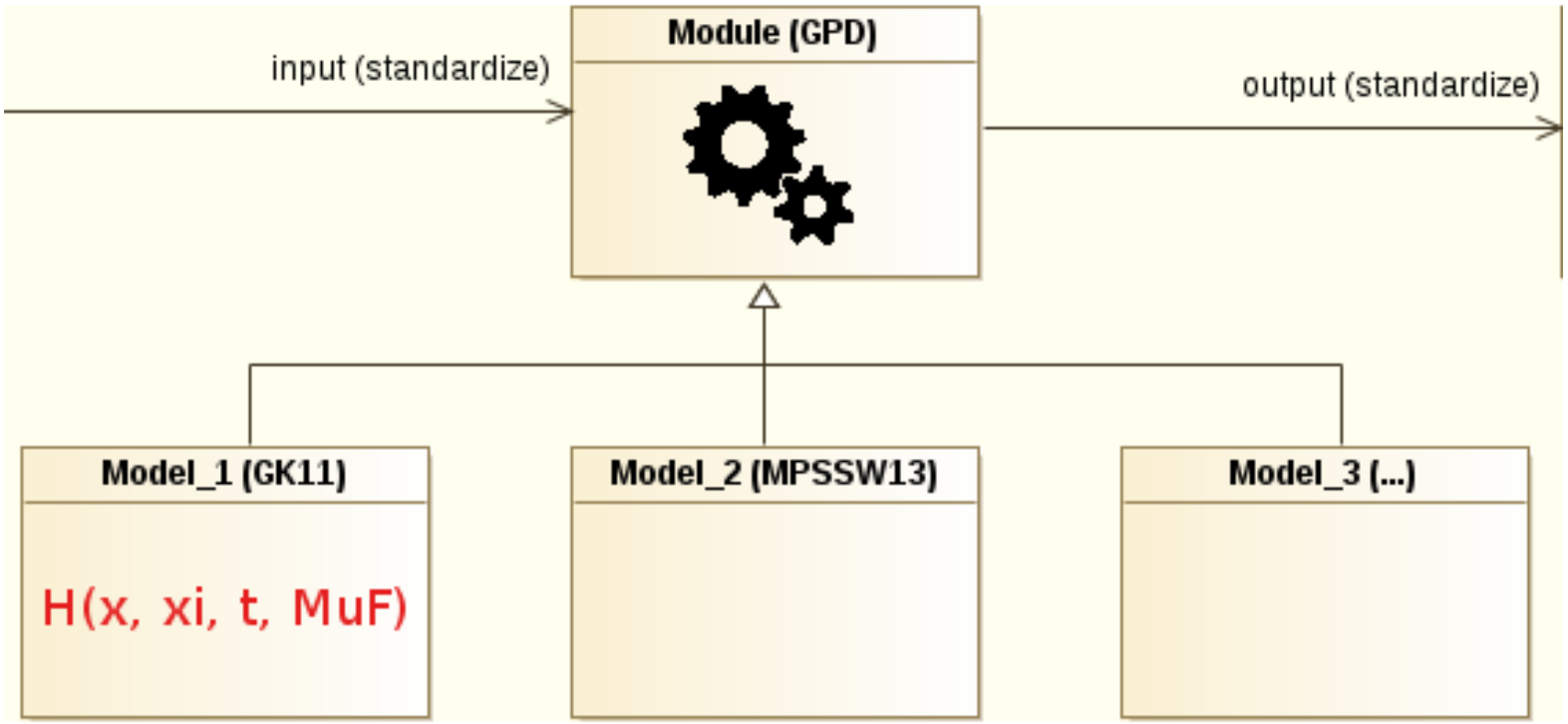
Currently: tests, benchmarking, documentation, tutorials.

- 3 stages:
  1. Design.
  2. Integration and validation.
  3. Benchmarking and production.
- Flexible software architecture.

  B. Berthou *et al.*, *PARTONS: a computing platform for the phenomenology of Generalized Parton Distributions* arXiv:1512.06174, *to appear in Eur. Phys. J. C.*
- 1 new physical development = 1 new module.
- *Aggregate* **knowledge** and **know-how**:
  - Models.
  - Measurements.
  - Numerical techniques.
  - Validation.
- What *can* be automated *will be* automated.

Modularity.

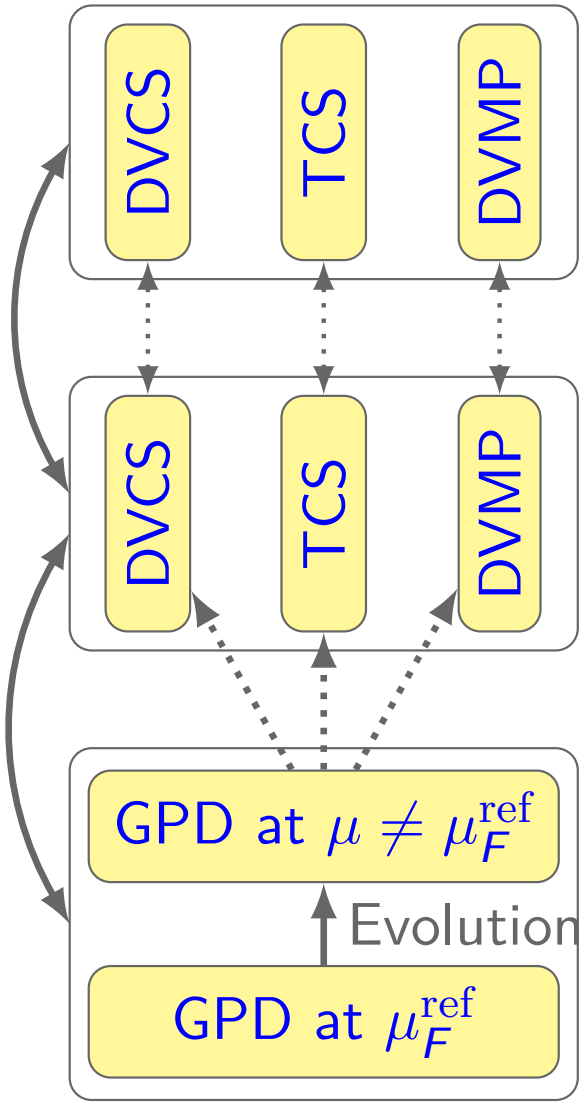
Inheritance, standardized inputs and outputs.



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

Flexibility.

Example: implementation of new coefficient functions.



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

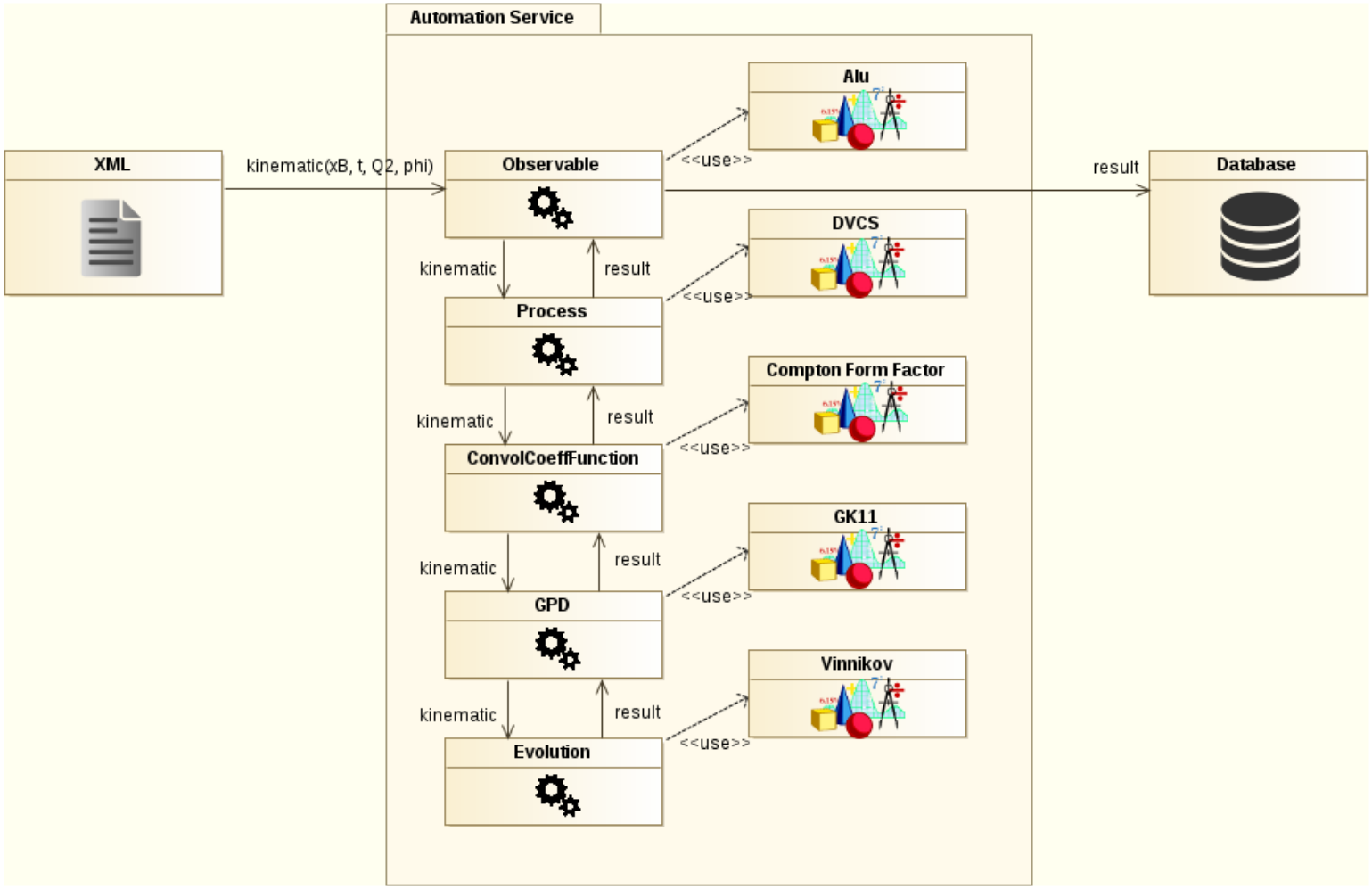
ConvolCoeffFunctionModule.h

```
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.
  - ...

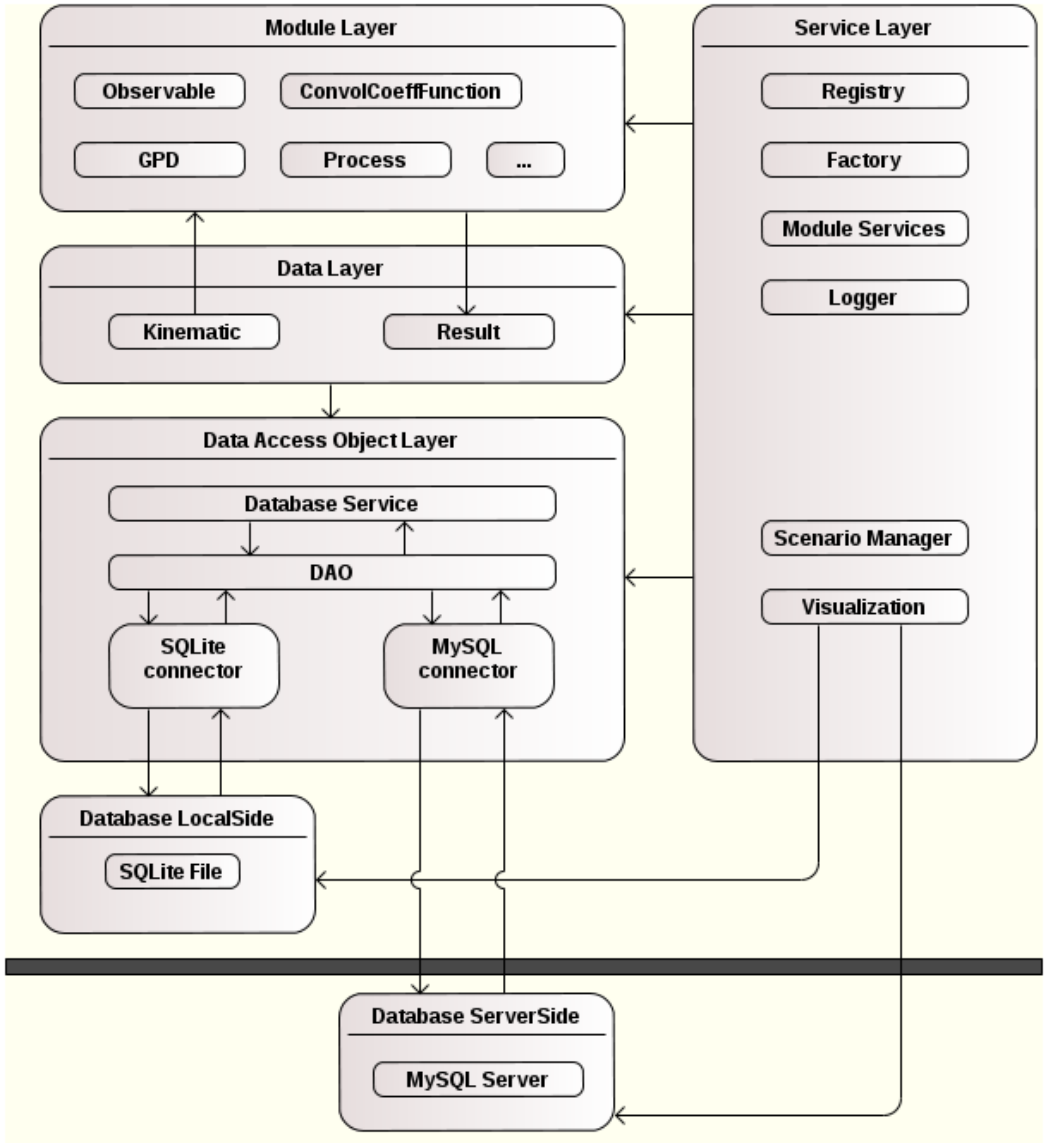
Modularity and automation.

Parse XML file, compute and store result in database.



Modularity and layer structure.

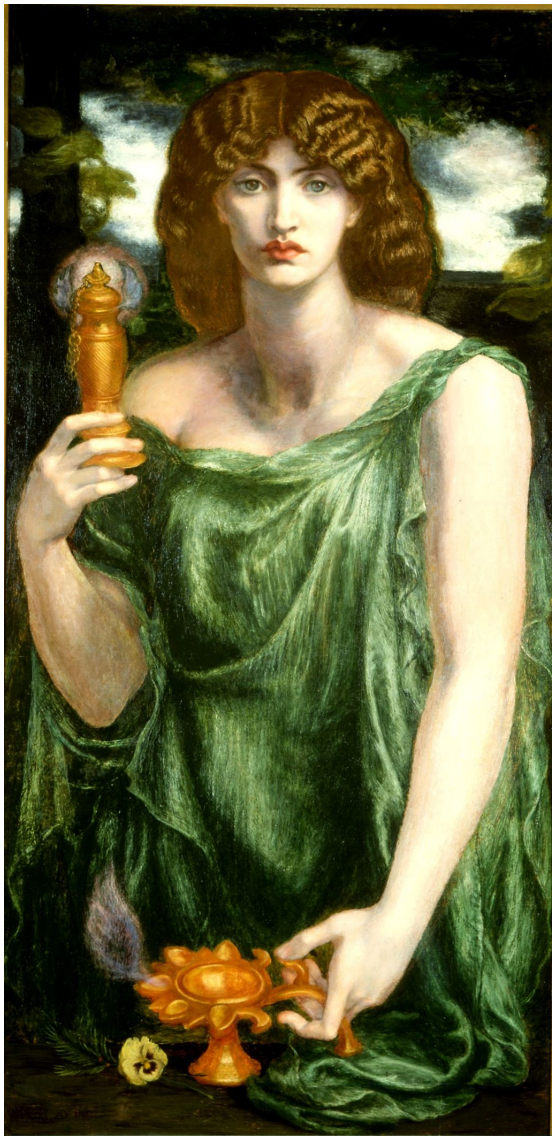
Modifying one layer does not affect the other layers.



Automation and nonregression.

Mnemosyne, the PARTONS project database server.

- Keep track of validated results.
- Systematic nonregression tests.
- Help preparing new releases.
- Store experimental data.
- Store grids of new models.
- Post processing?
- Time consuming fits?



Handling experimental data.

Using the power of SQL for data selections.

- **All fixed-target DVCS data collected at Jefferson Lab** are stored in the database used for fits.
- No data about TCS or DVMP so far.
- Including **all existing DVCS data sets** in Mnemosyne is **a matter of hours**.
- Data selection from SQL requests for fits.

insert_CLAS_asymmetries.sql

```sql
-- Kinematics --
INSERT INTO observable_kinematic (bin_id, xB, t, Q2, E, phi) VALUES(0, 0.19400, -0.11000, 1.68000, 5.93200, 25.00000);
SET @last_observable_kinematic_id = LAST_INSERT_ID();
-- Value and uncertainties --
INSERT INTO observable_result (observable_name, observable_value, stat_error_lb, stat_error_ub, syst_error_lb, syst_error_ub, total_error, observable_kinematic_id) VALUES('Alu', 0.37000, 0.23000, 0.23000, 0.01000, 0.01000, 0.00000, @last_observable_kinematic_id);
```

GPD or CFF fits (1/6).

Local fit of CFFs.

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

Mattermost

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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 PARAMETER                                   STEP         FIRST
  NO.   NAME      VALUE            ERROR          SIZE      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  CORRELATION COEFFICIENTS
       NO.  GLOBAL      1      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

Succesful global fit of Jefferson Lab DVCS data (DIS 2017)

FIT ANSATZ

fitted parameter

GPDs H and H̃:

$$H^q(x,x,t,Q^2) = H^q(x,0,t,Q^2) \times r^q(x)$$

- border function

- composed of GPD at (x, 0, t)
- and skewness function

GPDs H:

$$\mathcal{C}_{\mathcal{H}}(t,Q^2) = C_{\rm sub} \times \exp\left(a_{\rm sub} t\right)$$

- subtraction constant

- so far proposed ad-hoc
- weak sensitivity of data on this term

GPDs E and Ẽ:

$$\mathcal{E}(\xi,t,Q^2) = N_E \times \mathcal{E}_{\rm GK}(\xi,t,Q^2)$$
$$\widetilde{\mathcal{E}}(\xi,t,Q^2) = N_{\widetilde{E}} \times \widetilde{\mathcal{E}}_{\rm GK}(\xi,t,Q^2)$$

- GK CFFs

Paweł Sznajder DIS 2017 9

Data points and fit results

RESULTS

- Kinematic cuts $Q^2 > 1.5\ \mathrm{GeV}^2$ (*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 $a_{H_{sea}}, a_{\tilde{H}_{val}}, a_{\tilde{H}_{sea}}, C_{sub}, a_{sub}, N_E, N_{\tilde{E}}$
- 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

Careful statistical analysis

RESULTS

- Values of parameters and correlation matrix

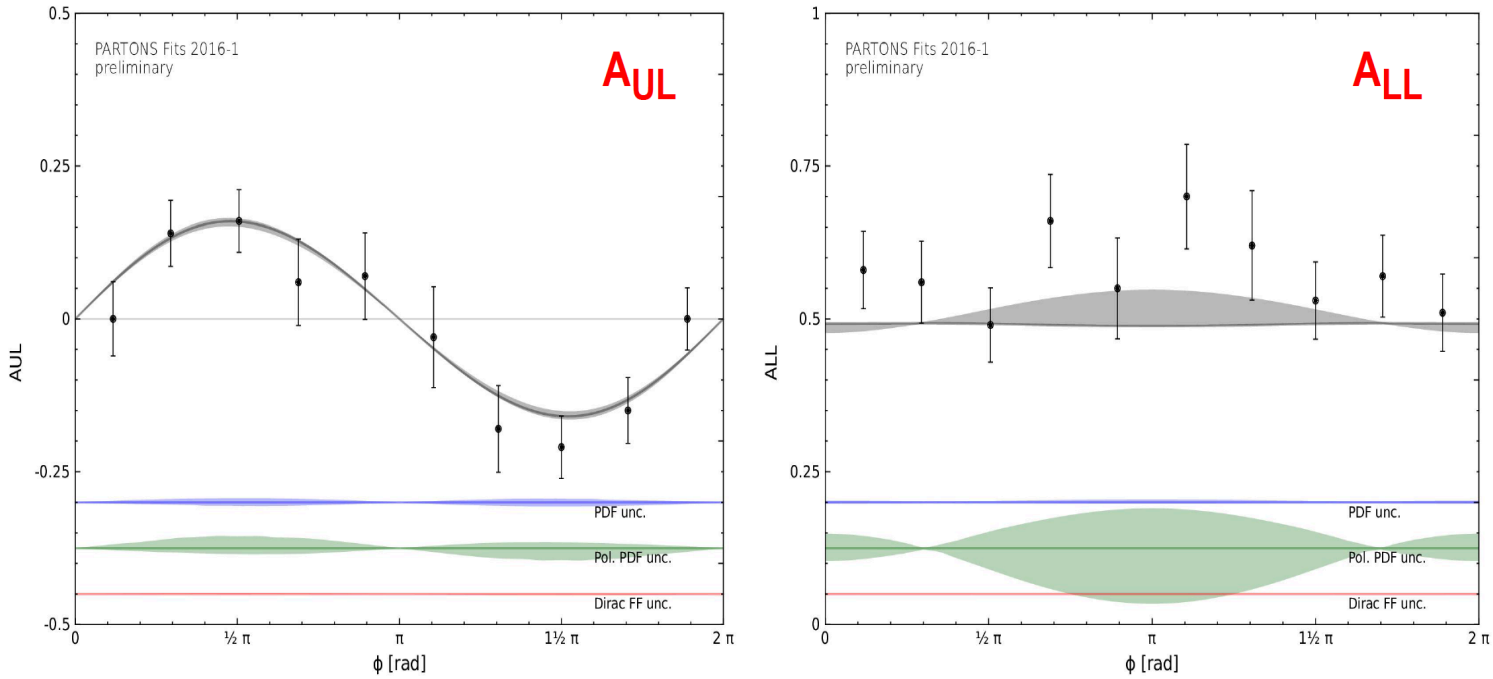
GPD	Parameter	Value	Error
H	Cu val	1.21	-
H	Cu sea	1.27	-
H	Cd val	1.2	-
H	Cd sea	1.27	-
Htilde	Cu val	1.07	-
Htilde	Cu sea	1.06	-
Htilde	Cd val	1.11	-
Htilde	Cd sea	1.07	-
H	a val	0.74	-
H	a sea	52.7	62.2
Htilde	a val	2.51	0.35
Htilde	a sea	0	1.35
H	C sub	-0.81	0.16
H	a sub	-0.39	0.6
E	N	-8.08	0.57
Etilde	N	-0.45	0.07

Comparison to CLAS data

RESULTS

CLAS: A_{UL} and A_{LL}
@ x_B = 0.26, t = -0.23 GeV^2, Q^2 = 2.0 GeV^2, E = 5.9 GeV

0.68 c.l.

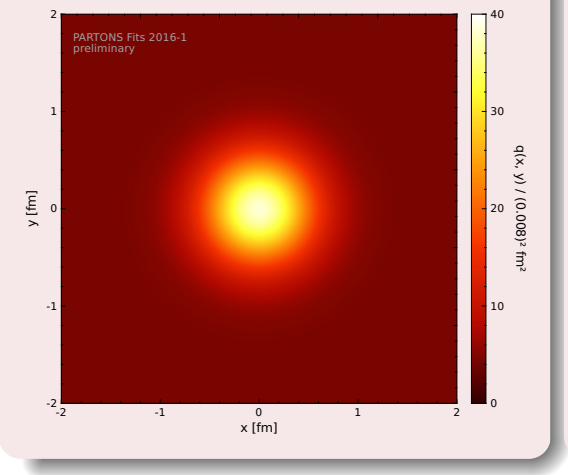


Good description of experimental data, large systematics coming from Δq

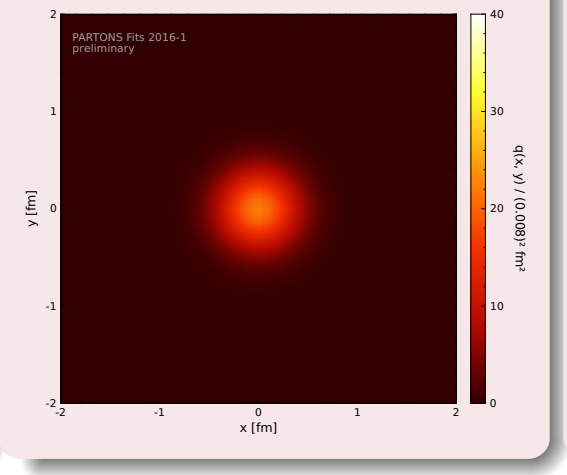
GPD or CFF fits (6/6).

Proton tomography from experimental data.

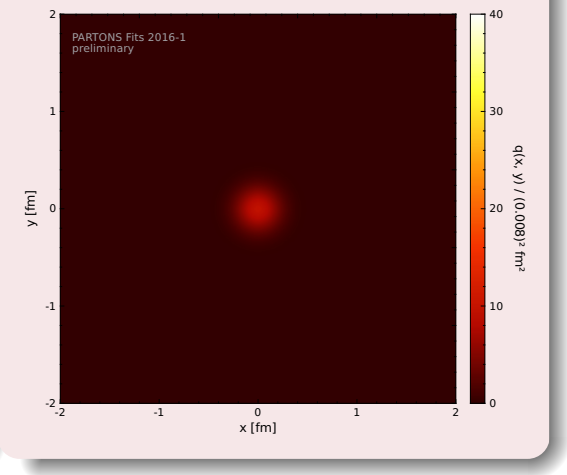
$x = 0.01$

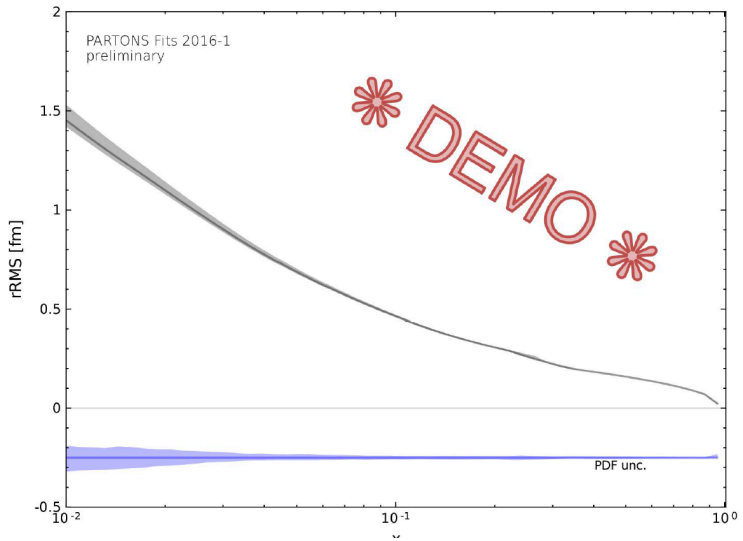


$x = 0.1$



$x = 0.5$





Conclusions

Conclusions and prospects.

Towards a unifying framework for GPD studies.

- **A lot has been achieved in the last few years!**
- **Challenging constraints** expected from Jefferson Lab, COMPASS and EIC.
- **Good theoretical control** on the link between GPD models and experimental data. **High-precision** phenomenology achievable.
- Development of the PARTONS framework for **phenomenology** and **theory** purposes.
- **Fitting engine** ready for global and local fits. **Original global CFF fits** recently achieved, meeting initial aim!
- **First release** of PARTONS... *as soon as possible!*

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