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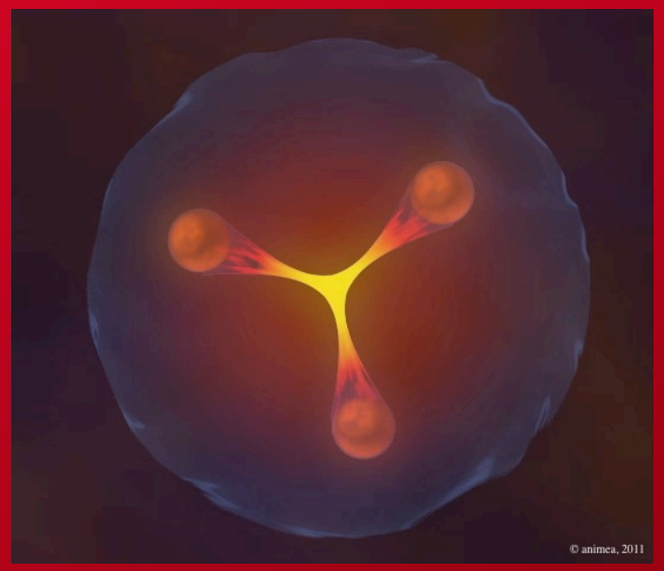
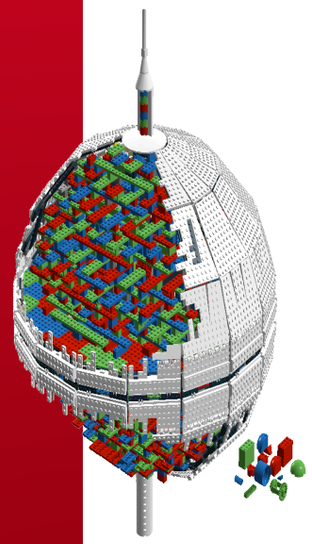
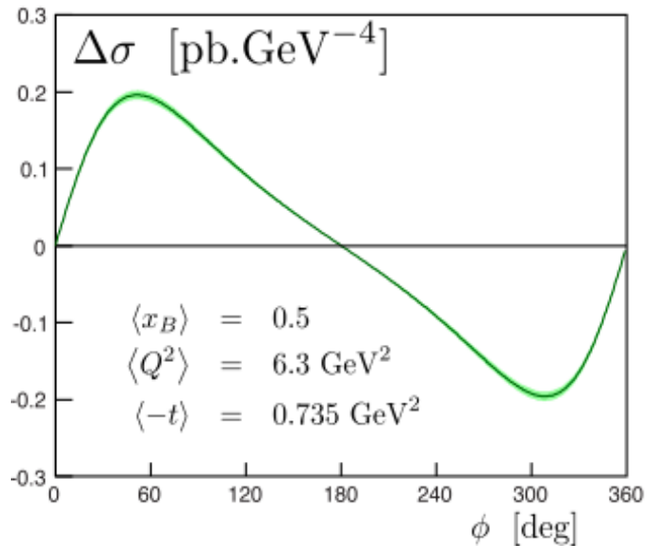
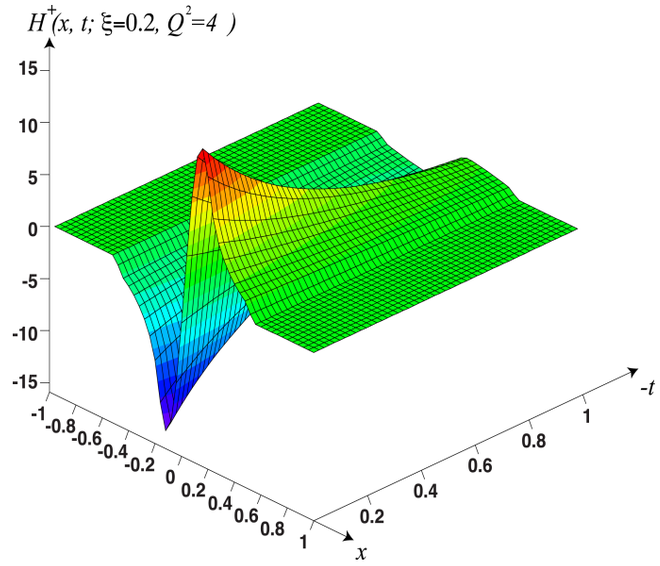


De l'observable aux distributions de partons généralisées en physique hadronique







HERVÉ MOUTARDE

ATELIER LARSIN-ESNT – 19/06/2018

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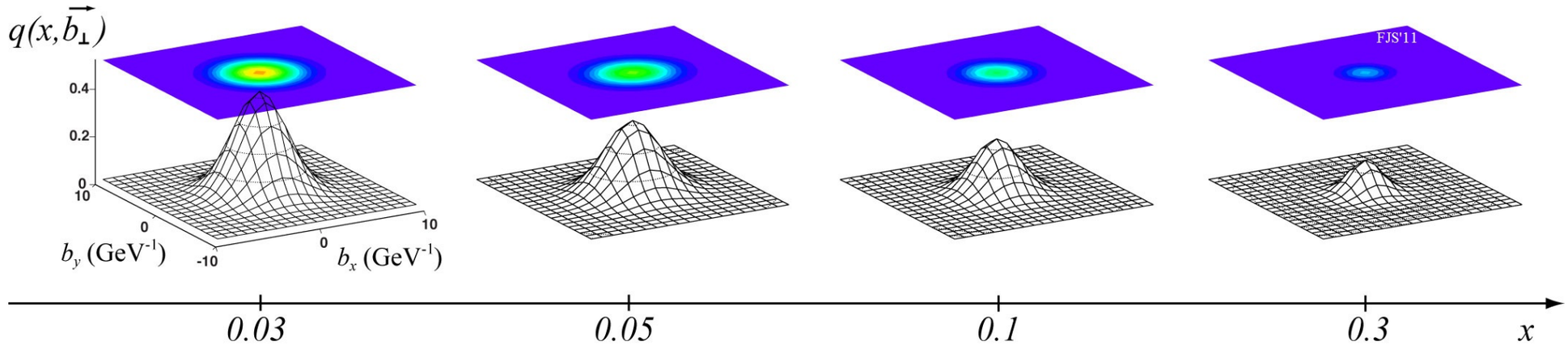
CONTENT.

1. QCD reminder.
2. Parton distribution functions as a paradigm.
3. Elaborating with generalized parton distributions.



Experimental knowledge of hadron structure?

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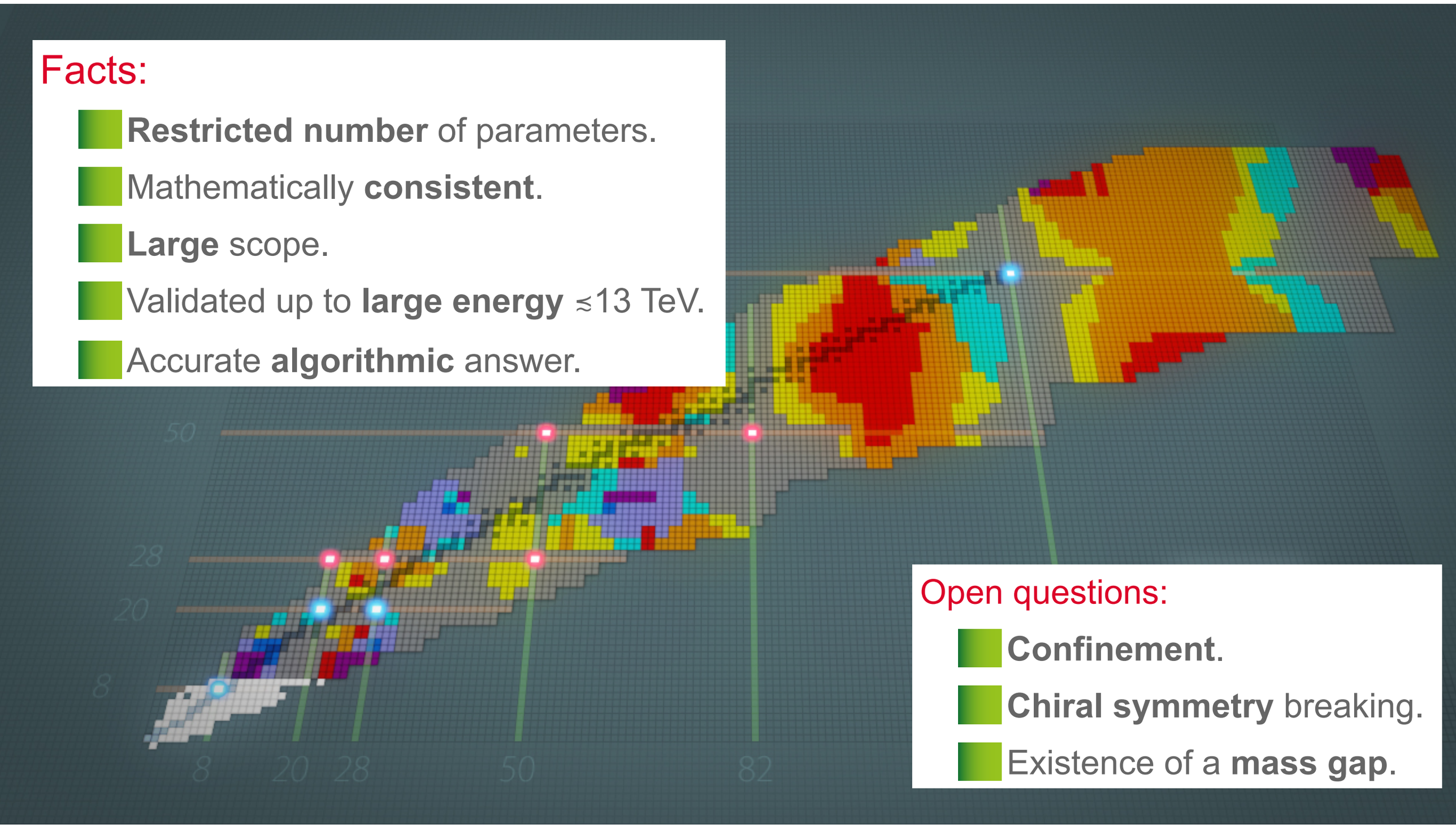
QUANTUM CHROMODYNAMICS

THE UNIQUE FEATURES OF QCD.

Facts:

- **Restricted number** of parameters.
- Mathematically **consistent**.
- **Large** scope.
- Validated up to **large energy** ≲13 TeV.
- Accurate **algorithmic** answer.



Open questions:

- **Confinement**.
- **Chiral symmetry** breaking.
- Existence of a **mass gap**.

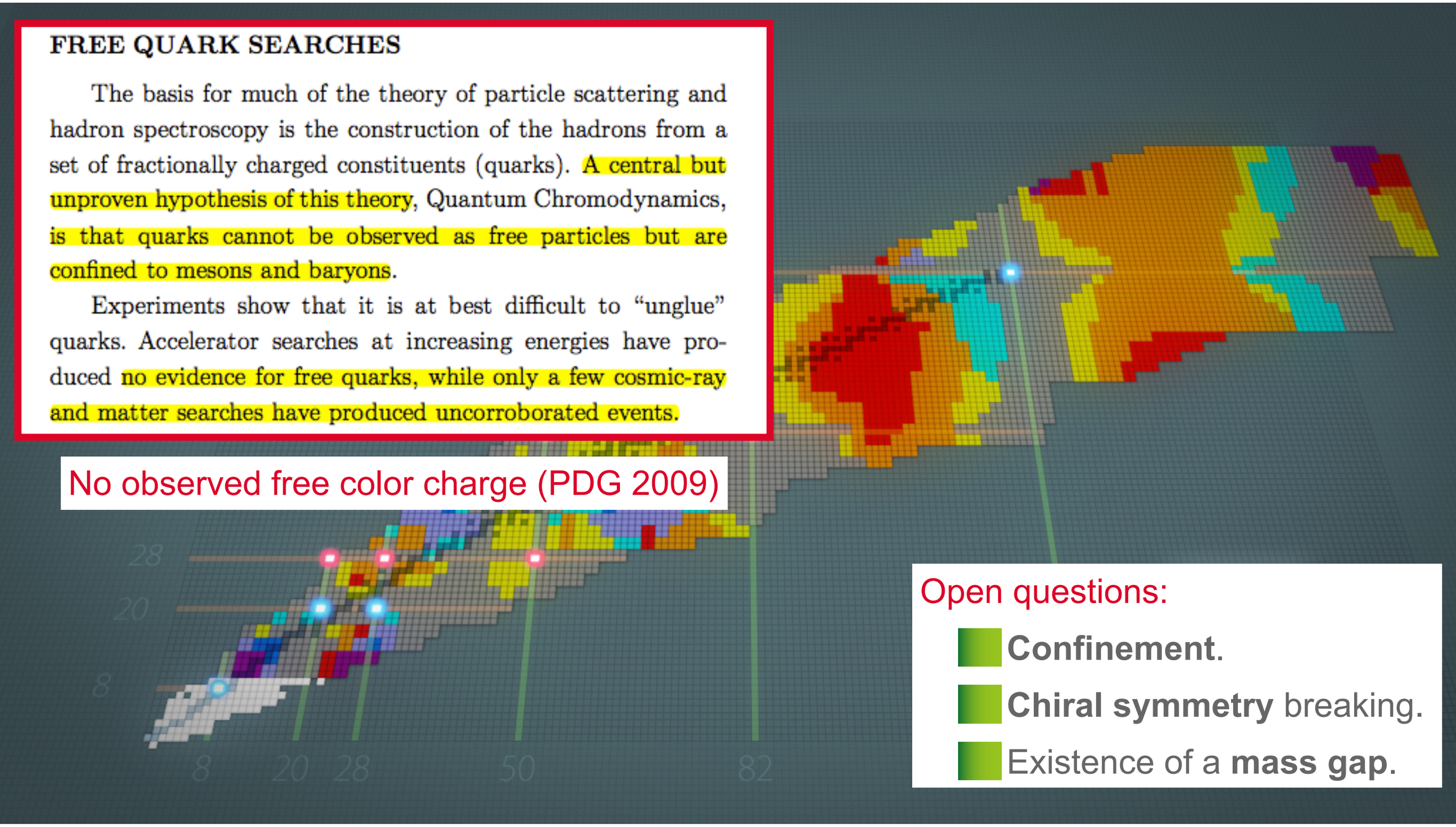
THE UNIQUE FEATURES OF QCD.

FREE QUARK SEARCHES

The basis for much of the theory of particle scattering and hadron spectroscopy is the construction of the hadrons from a set of fractionally charged constituents (quarks). A central but unproven hypothesis of this theory, Quantum Chromodynamics, is that quarks cannot be observed as free particles but are confined to mesons and baryons.

Experiments show that it is at best difficult to "unglue" quarks. Accelerator searches at increasing energies have produced no evidence for free quarks, while only a few cosmic-ray and matter searches have produced uncorroborated events.

No observed free color charge (PDG 2009)



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From quarks to hadrons:

- What are the relevant degrees of freedom?
- What are the effective forces between them?

Open questions:

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THE UNIQUE FEATURES OF QCD.

QUANTUM YANG–MILLS THEORY 5

Finally, QFT is the jumping-off point for a quest that may prove central in 21st century physics—the effort to unify gravity and quantum mechanics, perhaps in string theory. For mathematicians to participate in this quest, or even to understand the possible results, QFT must be developed further as a branch of mathematics. It is important not only to understand the solution of specific problems arising from physics, but also to set such results within a new mathematical framework. One hopes that this framework will provide a unified development of several fields of mathematics and physics, and that it will also provide an arena for the development of new mathematics and physics.

For these reasons the Scientific Advisory Board of CMI has chosen a Millennium problem about quantum gauge theories. Solution of the problem requires both understanding one of the deep unsolved physics mysteries, the existence of a mass gap, and also producing a mathematically complete example of quantum gauge field theory in four-dimensional space-time.

Clay Millenium Prize (Jaffe and Witten)

From quarks to hadrons:

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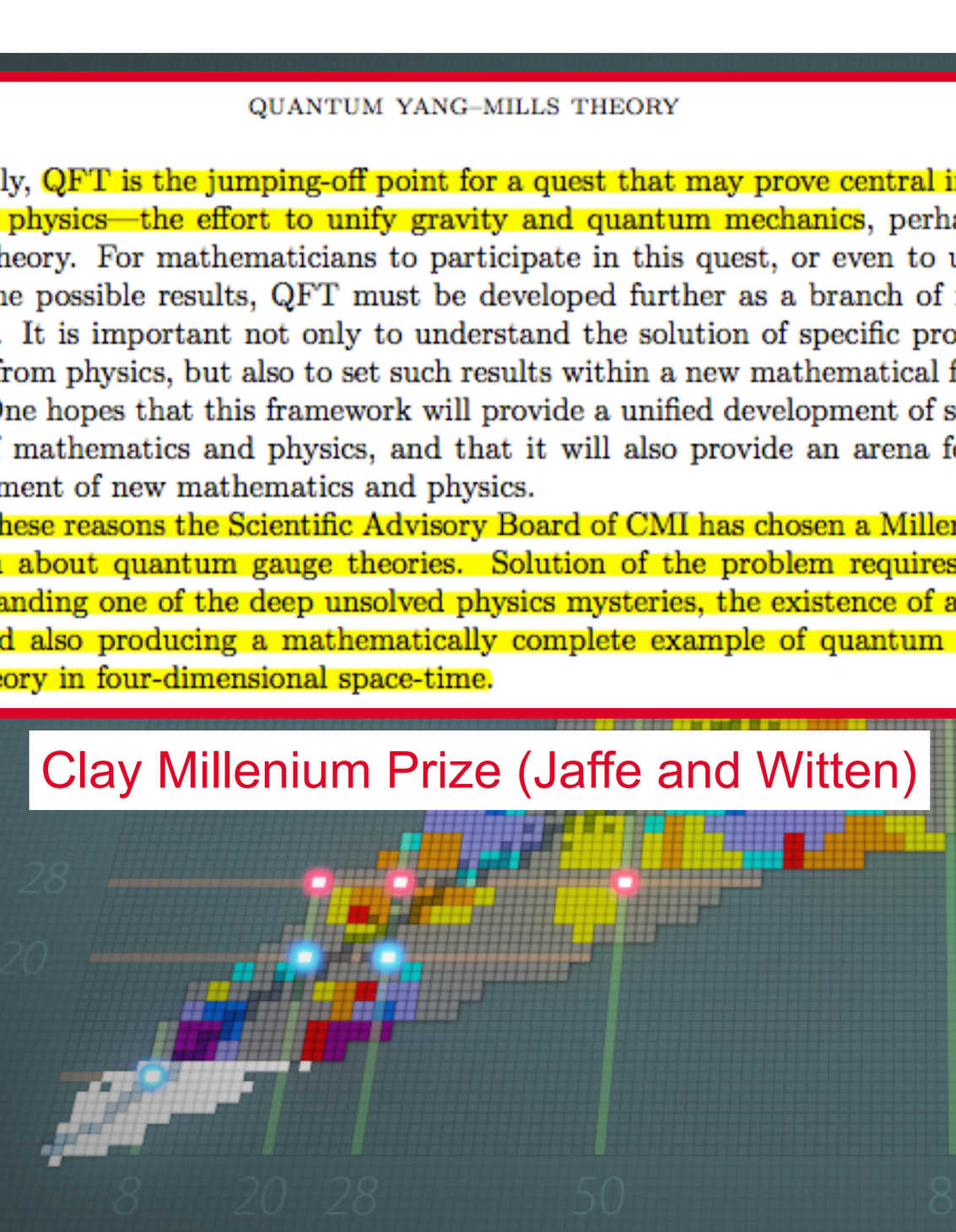

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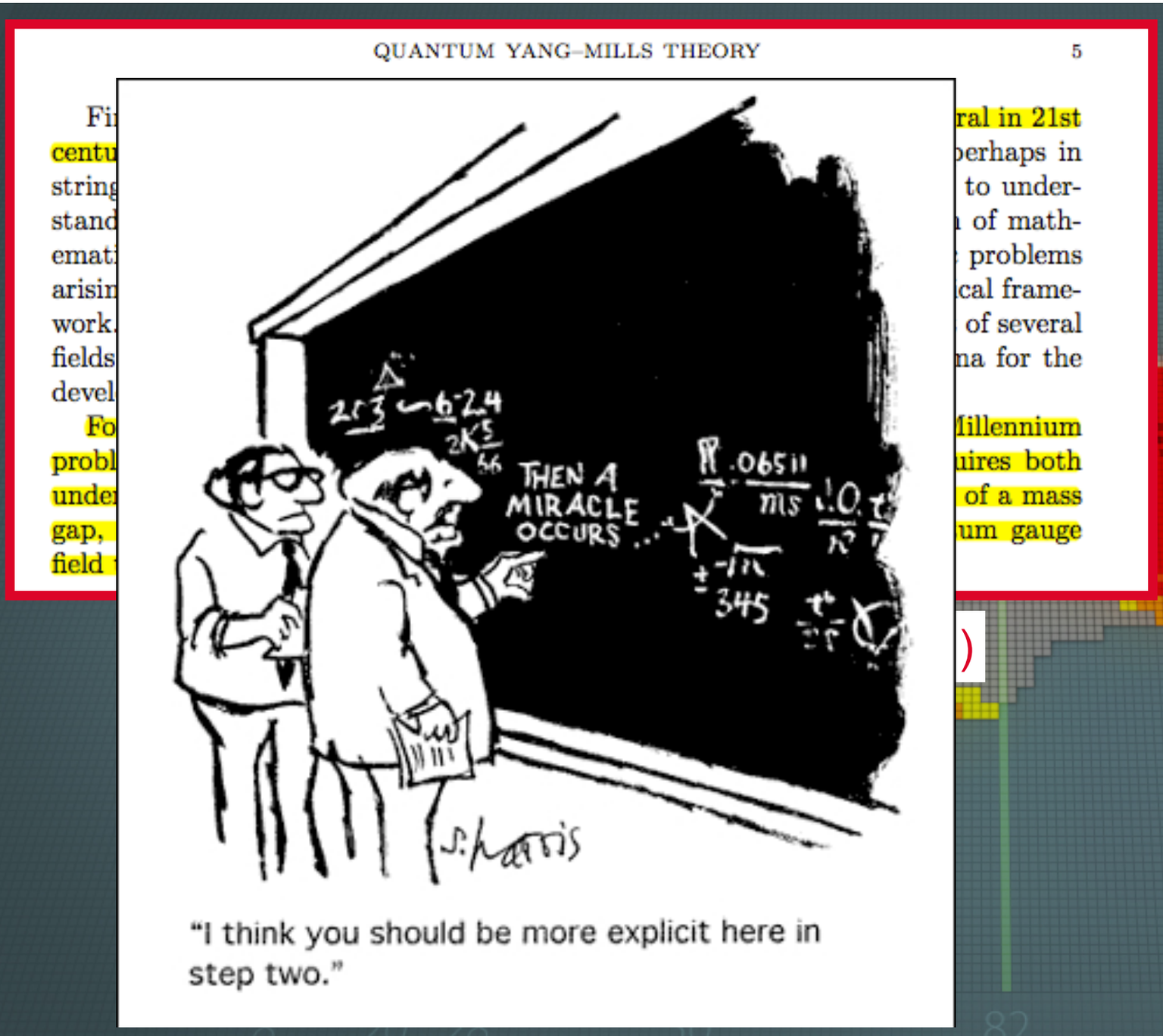

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WHAT ARE THE OBSERVED STATES?!

Particle	$L_{2I\,2J}$	Overall status	Status as seen in — $N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	***			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****	*			****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*	*					
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	**	**	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	e		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r			**		
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*	d					
$\Delta(2390)$	F_{37}	*	*	e					
$\Delta(2400)$	G_{39}	**	**	n					
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

What is the low energy spectrum of QCD?

- In principle resonances are described by QCD.
- Success of quark models but **missing resonances**…
- International experimental and theoretical programs to answer this question.

"Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them!"

ARE QUARKS REAL?!

Birth of the quark model: George Zweig is told it's complete rubbish; Murray Gell-mann says quarks are unphysical; James « B.J » Bjorken has a big idea, which leads to their discovery. Feynman invents the « parton model ». The strong force acting on quarks appears to be a paradox: The closer you look, the feebler it appears to be.

Bjorken

In 1964 Gell-Mann dismissed Zweig airily: « The concrete quark model —that's for blockheads! ».

Close, in The infinity puzzle

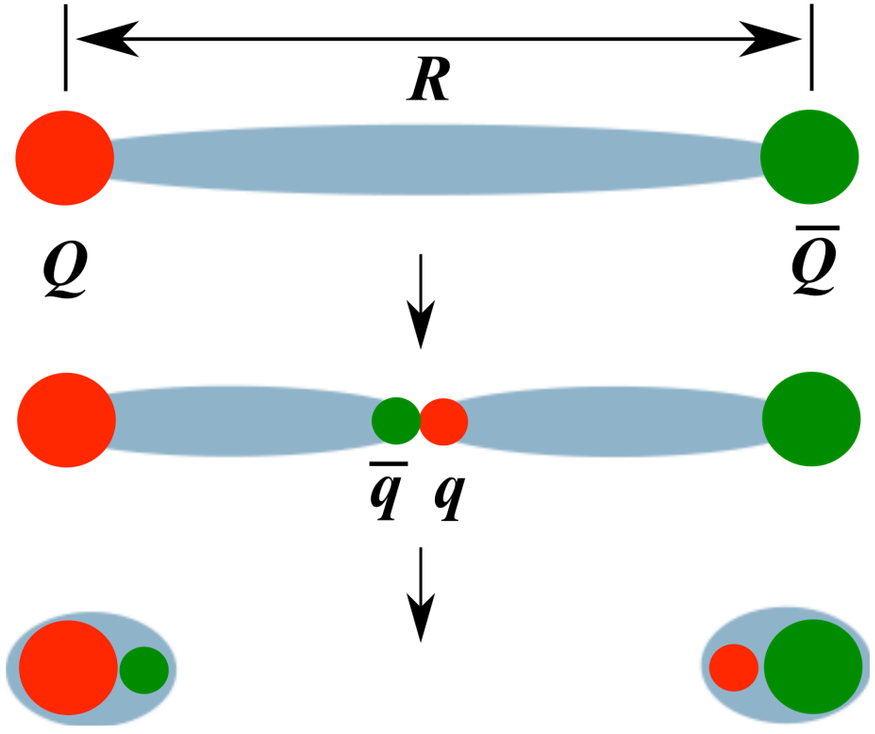
Worries about the existence of quarks in the 1960s

- General disbelief at quarks, « *a convenient way of keeping track of the mathematical group theory* » (Gell-Mann).
- Bjorken's question: how to find quarks?
- Technical (short) paper « Applications of chiral $U(6) \times U(6)$ algebra of current densities » in 1966.
- Exciting results from experiments at SLAC announced at an international conference in Vienna in Summer 1968.

QUARKS ARE REAL AND CONFINED.

Many arguments for quarks:

- Supported by quark model and deep inelastic scattering experiments.
- Mesons ($q\bar{q}$ bound states) can approximately be ordered on lines on the (J, m^2) plane: Regge trajectories.
- Consistent with the image of two particles located at the ends of a rotating string.



- Theory: at large distance the potential between static quarks is **linearly increasing**.
- Supported by heavy meson spectroscopy.
- Supported by lattice QCD simulations.

$$V_{q\bar{q}}(r) = -\frac{4}{3}\frac{\alpha_S(r)}{r} + \sigma r$$

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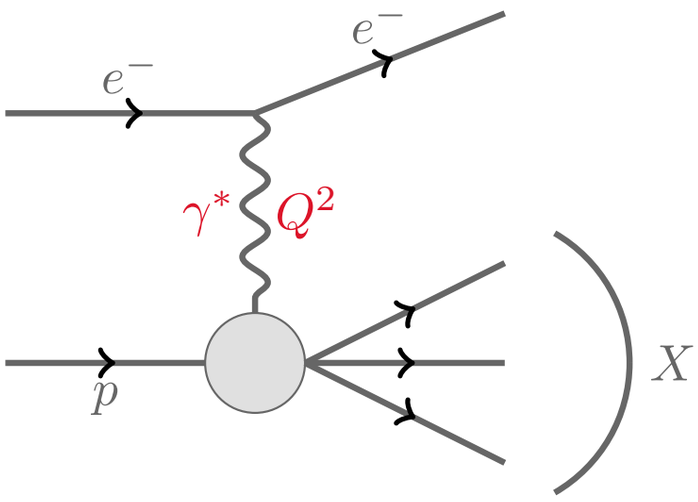
PARTON DISTRIBUTION FUNCTIONS

DEEP INELASTIC SCATTERING.



The golden channel to access parton distribution functions

- First measurements at SLAC following Bjorken's idea: *Bjorken regime*.

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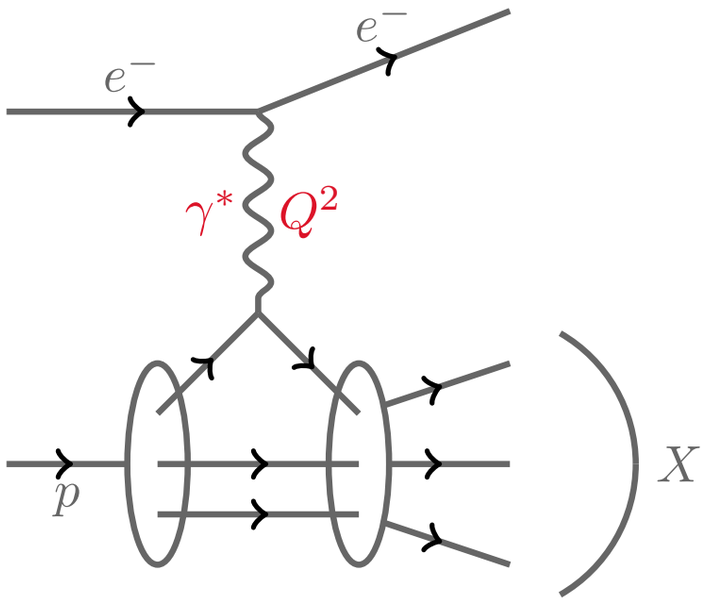

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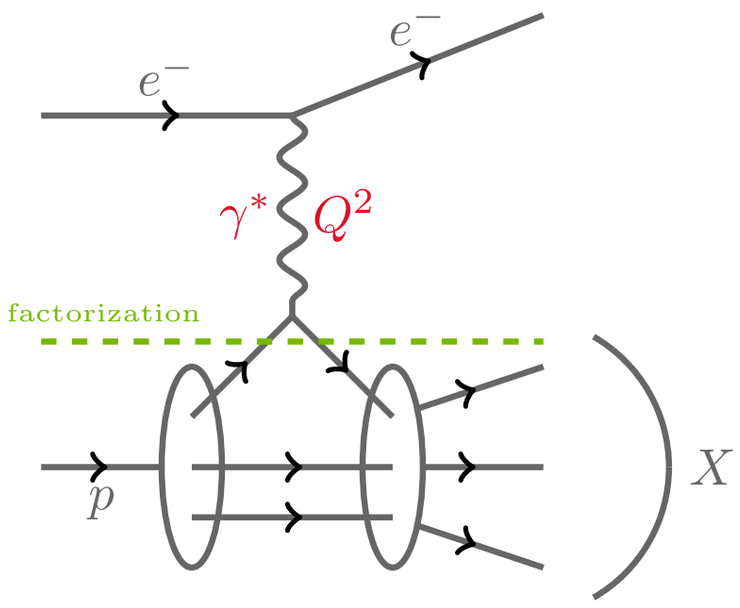

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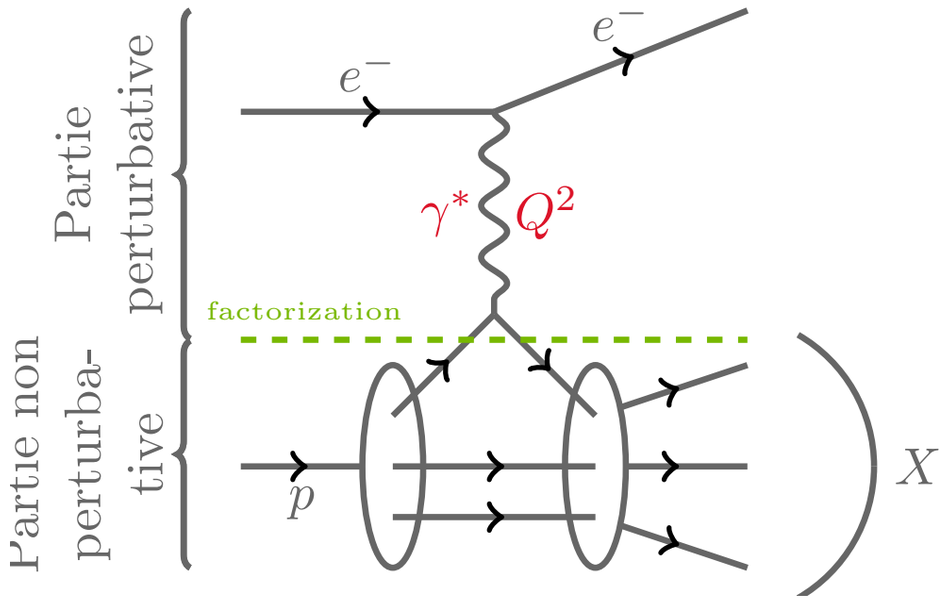

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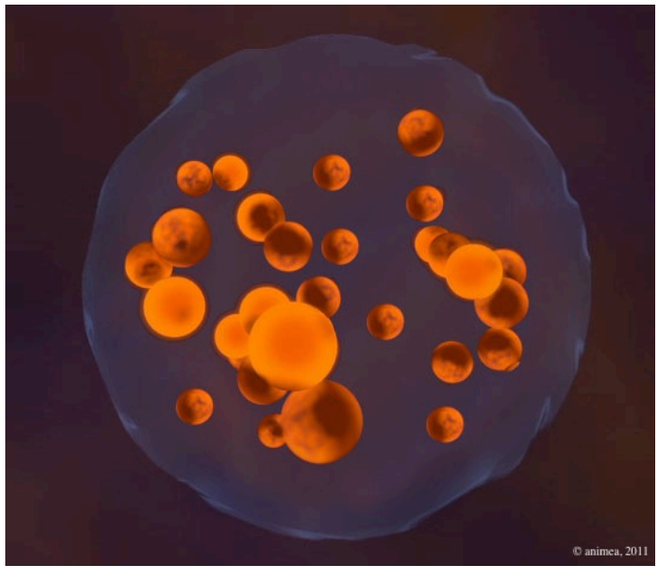
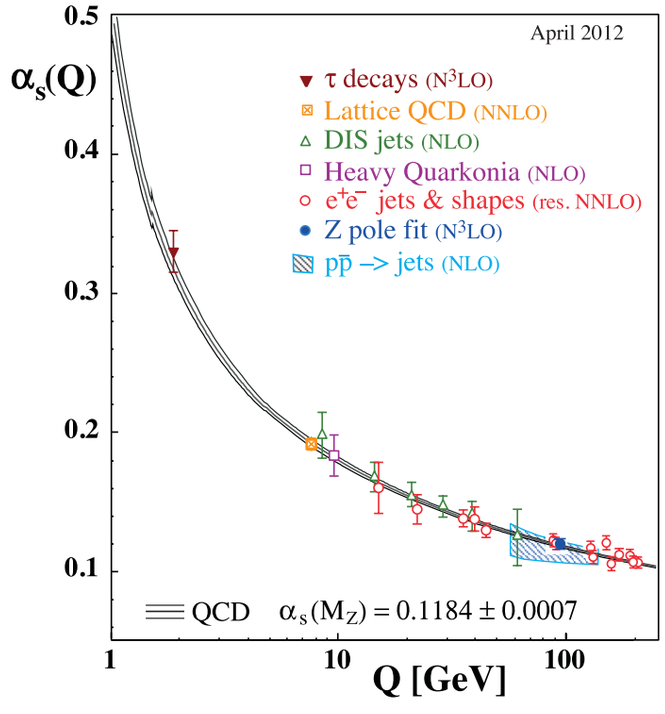
- Interpreted by Feynman in terms of **parton distribution functions** (PDFs).
- Modern QCD treatment by end of 1970s/ beginning of 1980s: **factorization**.
- Paradigm for all subsequent developments in hadron structure.

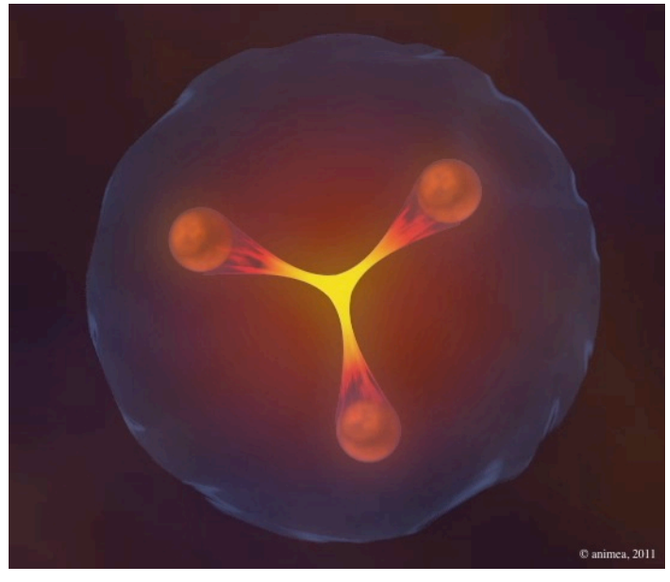
ANALYTIC STRUCTURE.

Parton distribution functions

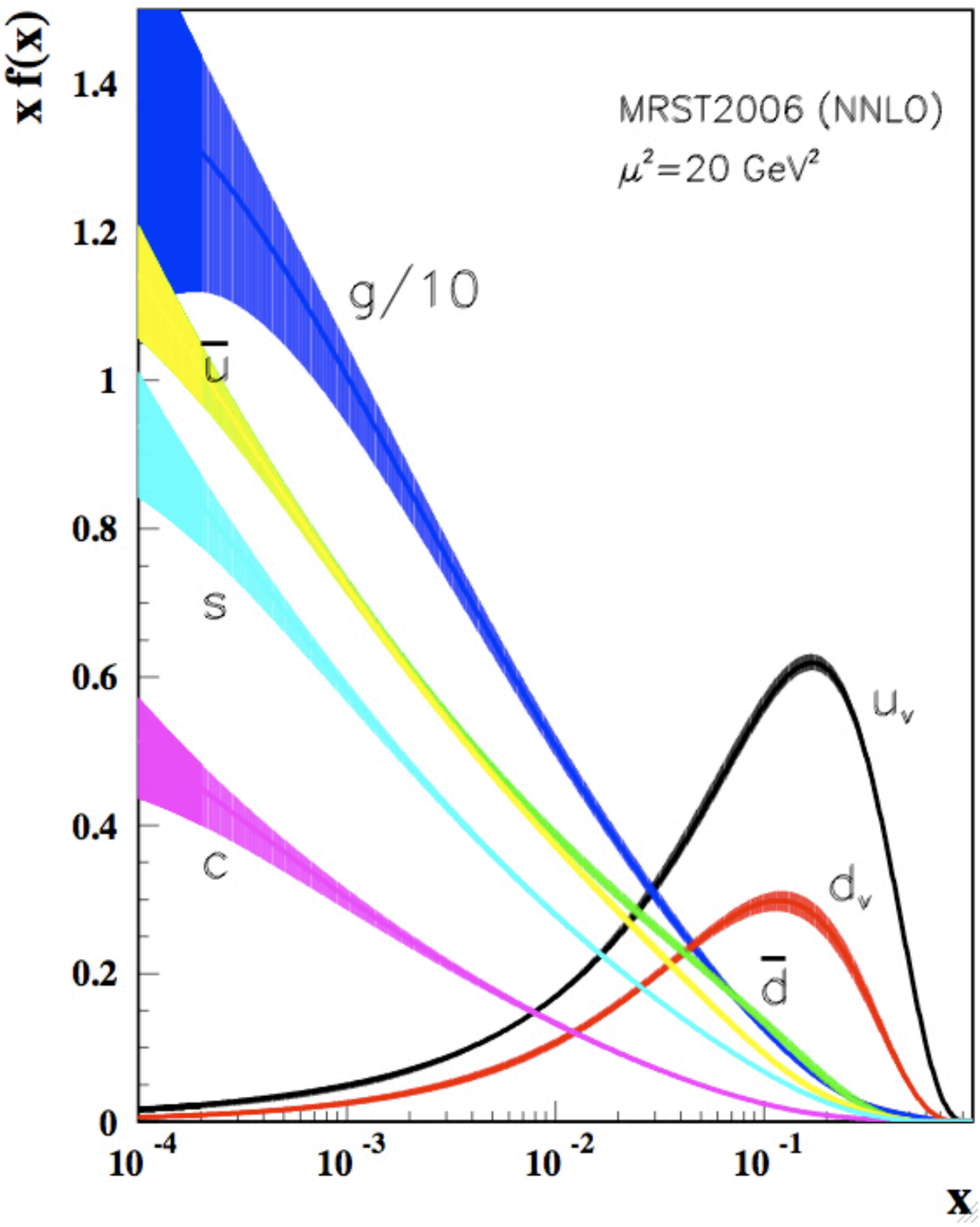
- Naive « definition »: $f(x)\mathrm{d}x$ is the number of partons of a certain type (g, u, d, s, …) carrying a momentum fraction in $[x, x+\mathrm{d}x]$.
- Less naive definition in terms of (renormalized) matrix element of quark (or gluon) field operators.
- In the Bjorken regime, the cross-section of DIS is the convolution of:
  - a hard scattering part, computed in perturbation theory,
  - a soft part, nonperturbative, encoding hadron structure.
- For many cases, factorization can be proved to hold at all orders of perturbation theory.







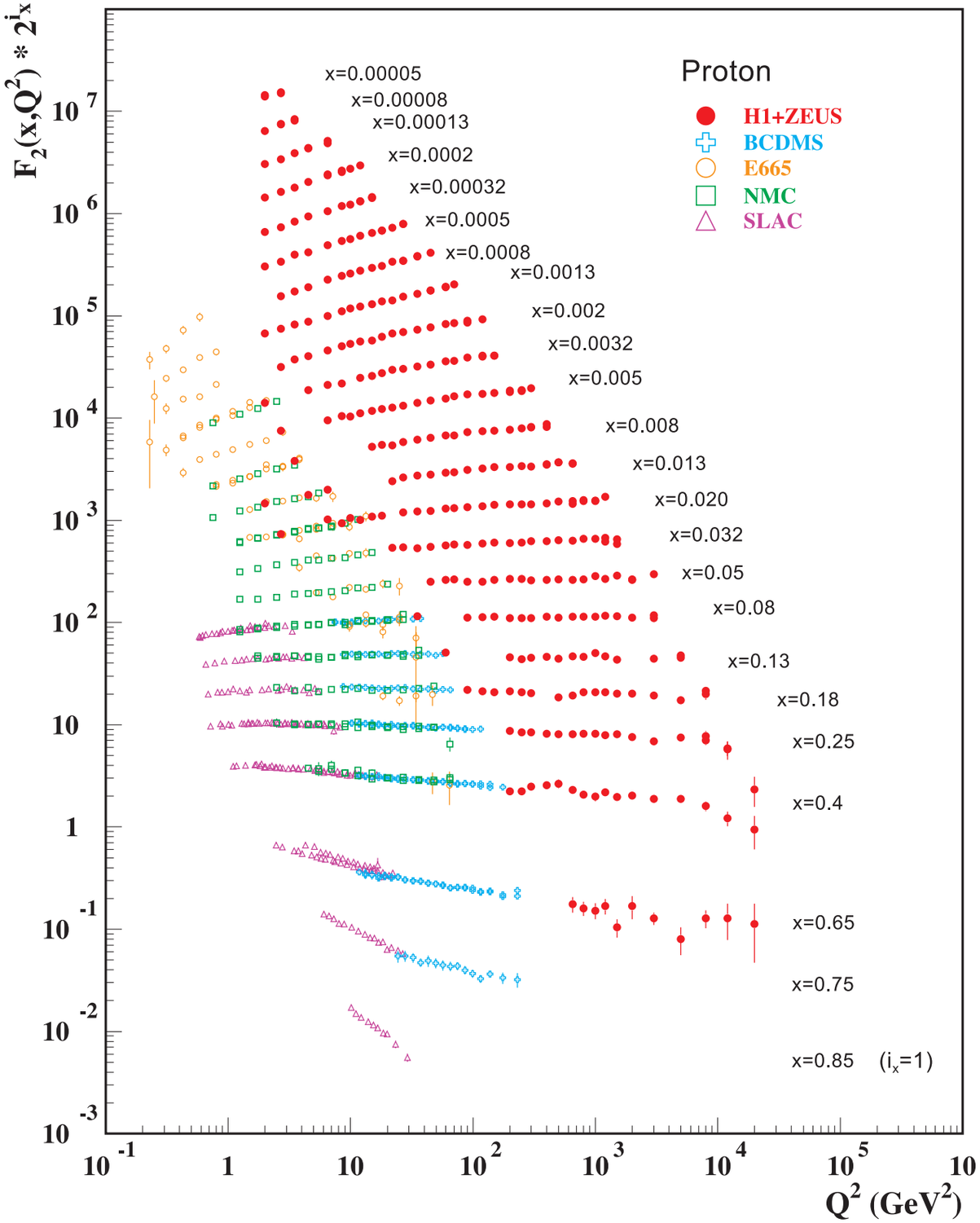
PDF EXTRACTIONS (NOT MEASUREMENTS!).

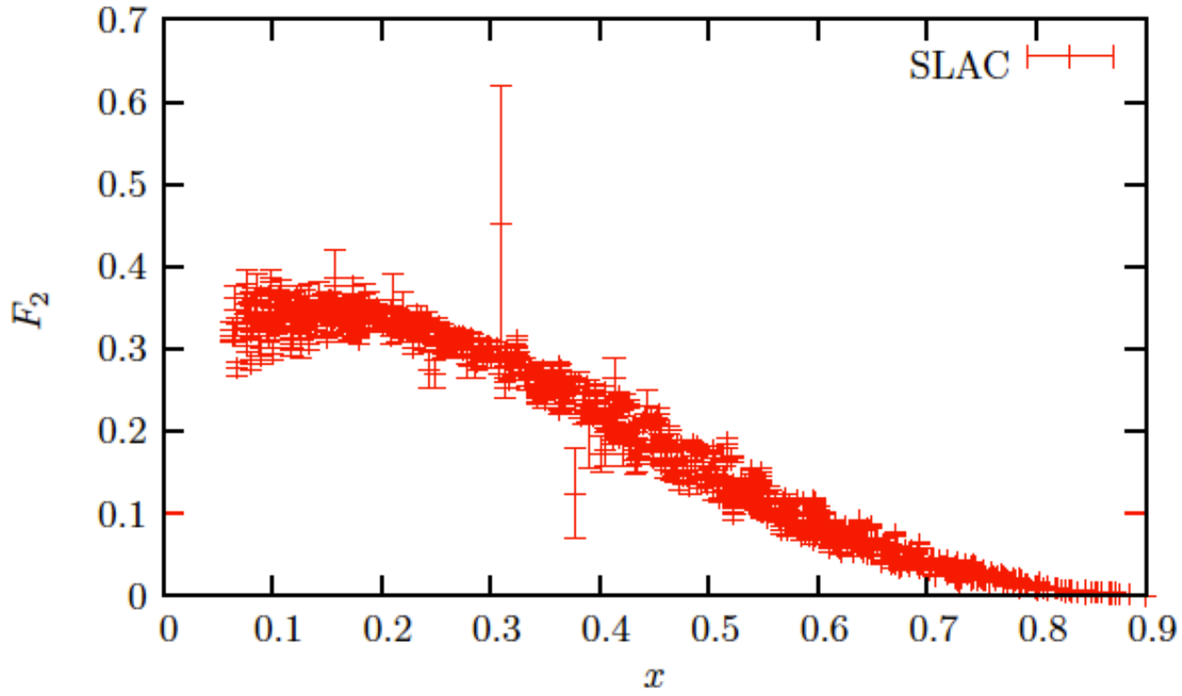


Extraction from experimental data:

- Choose a functional form for PDFs at a **low factorization scale** μ_0 with **free parameters**.
- Use DGLAP equation to **evolve** the PDFs from the scale μ_0 to a scale μ = Q where data are available.
- At this scale Q compute structure functions and compare to data.
- Repeat for all data sets.
- **Adjust free parameters**, typically by least-square fitting.

MORE THAN JUST PDF EXTRACTIONS.





Scaling and scaling violations

- Scaling: **point-like behavior** of active constituants.
- The experimental determination of **anomalous dimensions** was crucial in validating QCD.

UNIVERSALITY.

Beyond the interest of PDFs *per se*

- Universality of PDFs allows the **simultaneous analysis of experimental data** from many different processes:
  - DIS,
  - SIDIS,
  - weak boson production pp collisions,
  - jet production in pp collisions,
  - etc.
- **Precision PDFs** are needed to understand the **structure of QCD bound states** and to compute backgrounds in searches for physics **beyond the Standard Model**.

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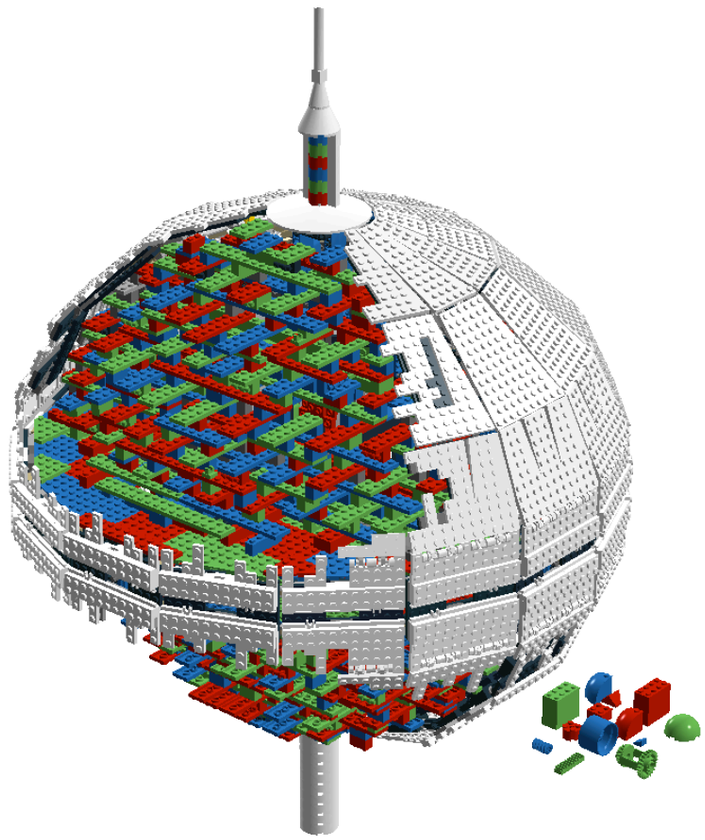
GENERALIZED PARTON DISTRIBUTION FUNCTIONS

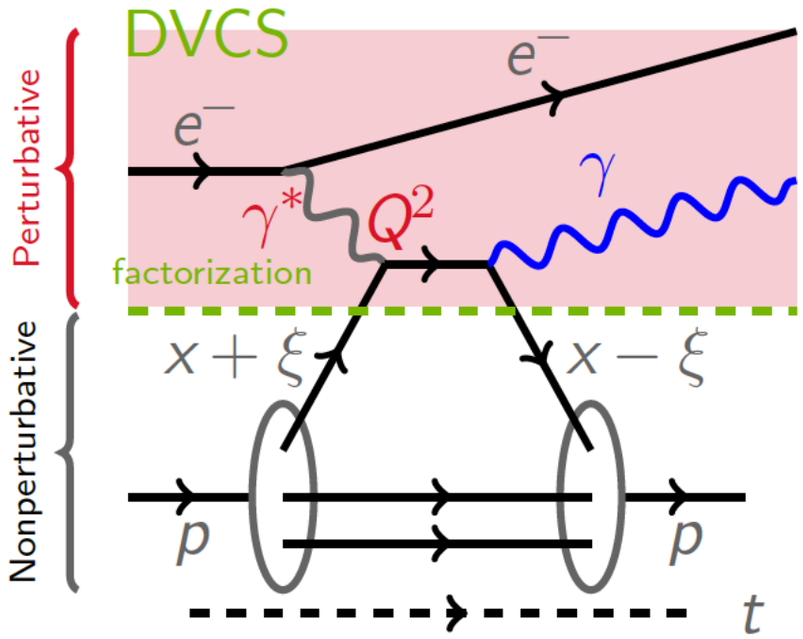
3D HADRON STRUCTURE.

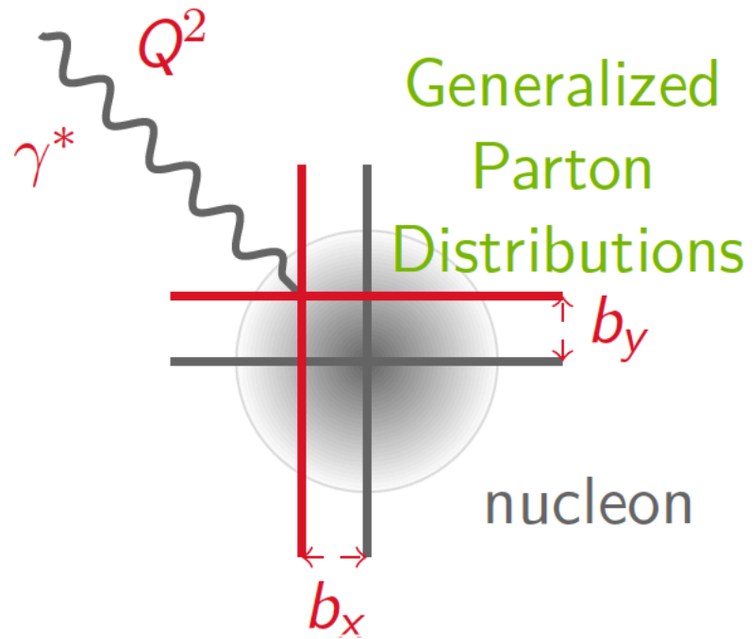
Modern challenges in hadron structure

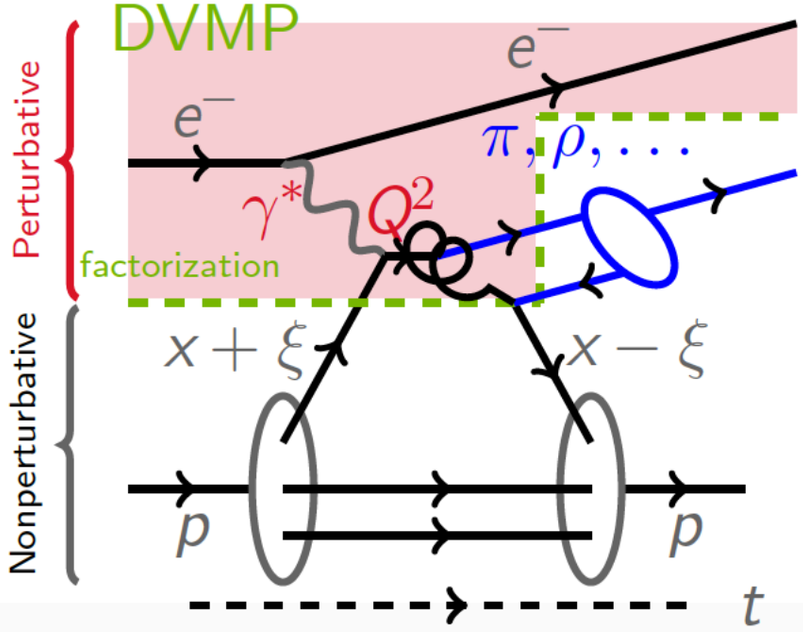
- How can we recover the well-known characteristics of the nucleon from the properties of its **colored building blocks**?
  - Mass?
  - Spin?
  - Charge?
  - etc.
- **Cartography** of the interactions giving its mass to the nucleon?
- **Density profiles** of the nucleon as a continuous medium?

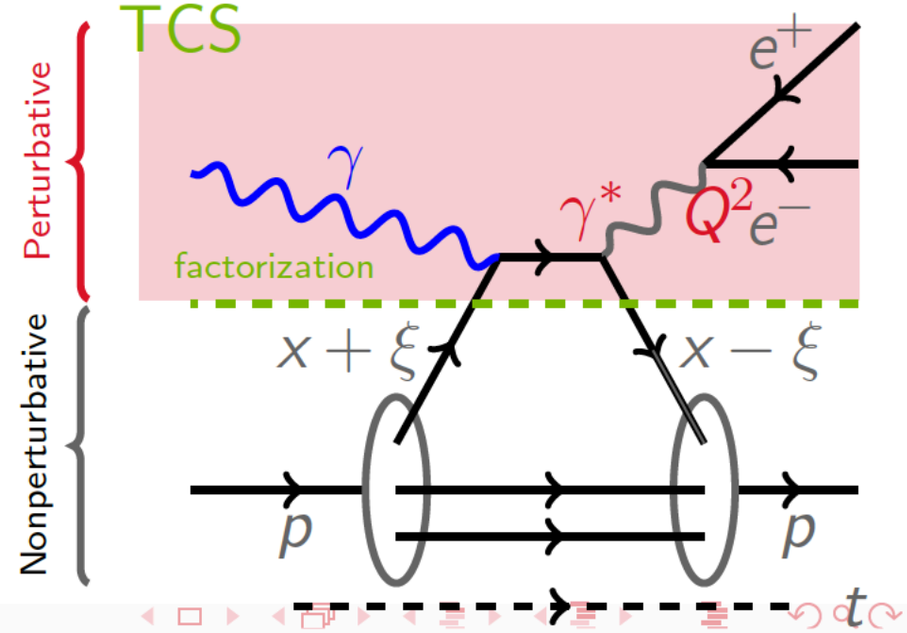


EXCLUSIVE PROCESSES AND FACTORIZATION.









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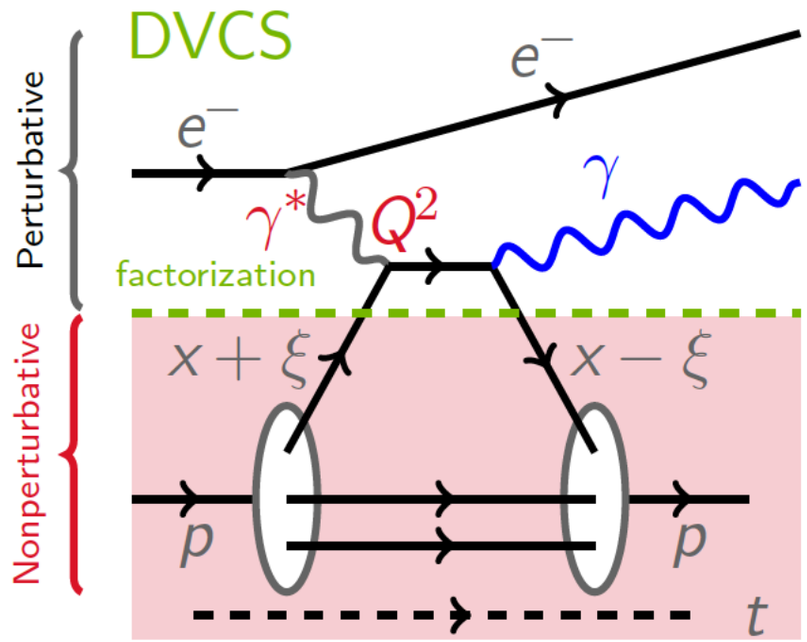

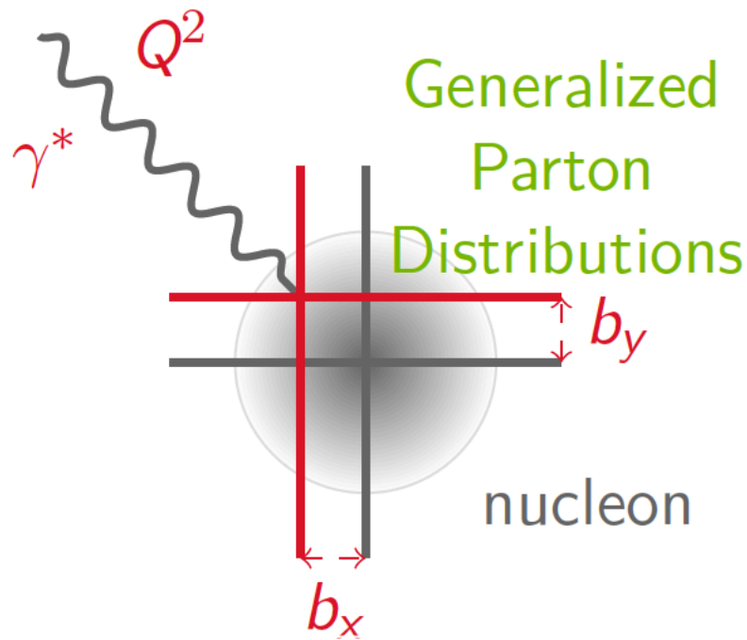

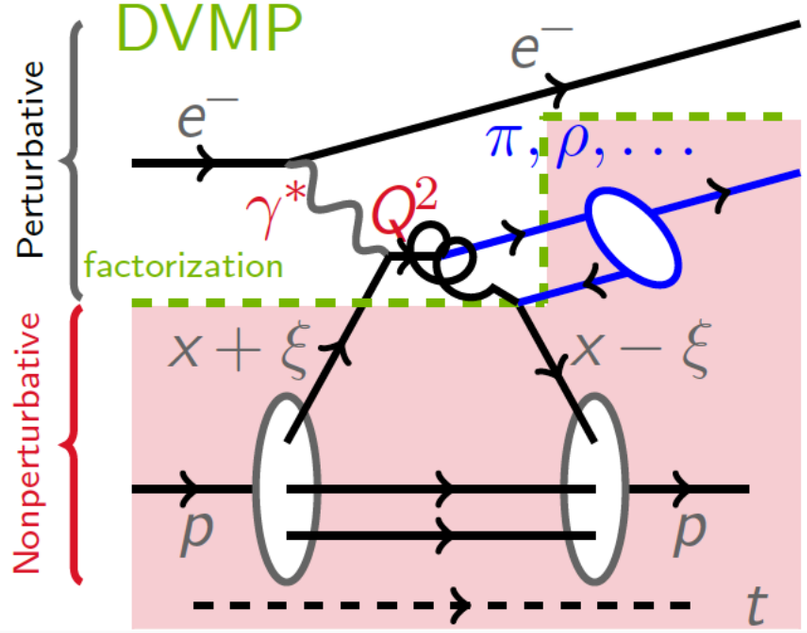

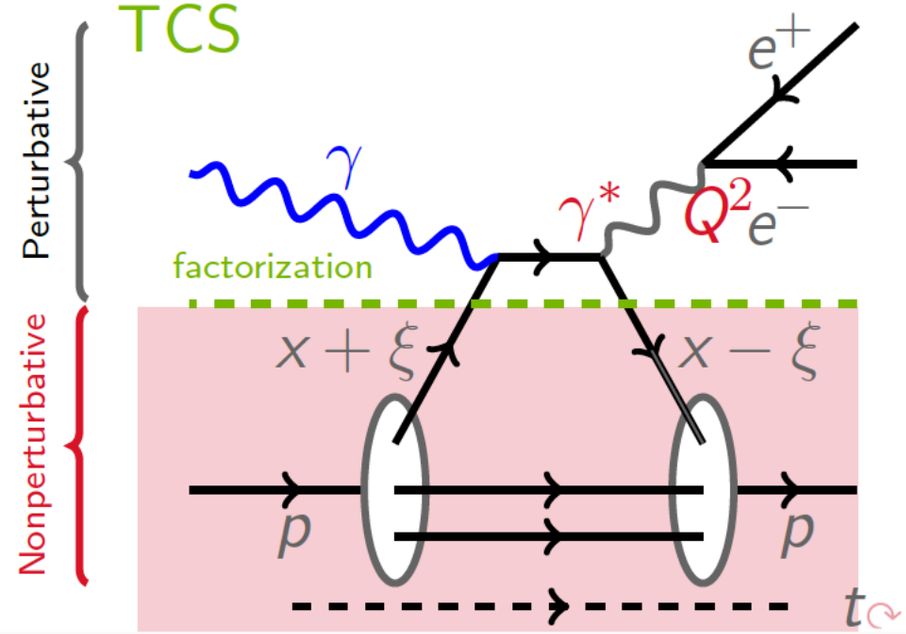

GPD, FACTORIZATION, UNIVERSALITY.

Partonic interpretation and universality

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

Coefficient functions and Compton form factors

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

Partonic interpretation and universality

- Factorization scale dependence compensates between coefficient functions and GPDs.
- Compton form factors do not depend on factorization scale (contrary to GPDs).
- Only Compton form factors have been obtained in global fits so far.
- *This is just the beginning!*