Unveiling the structure of nucleons in high-energy experiments

Physics Colloquium

Hampton University, Feb 2013

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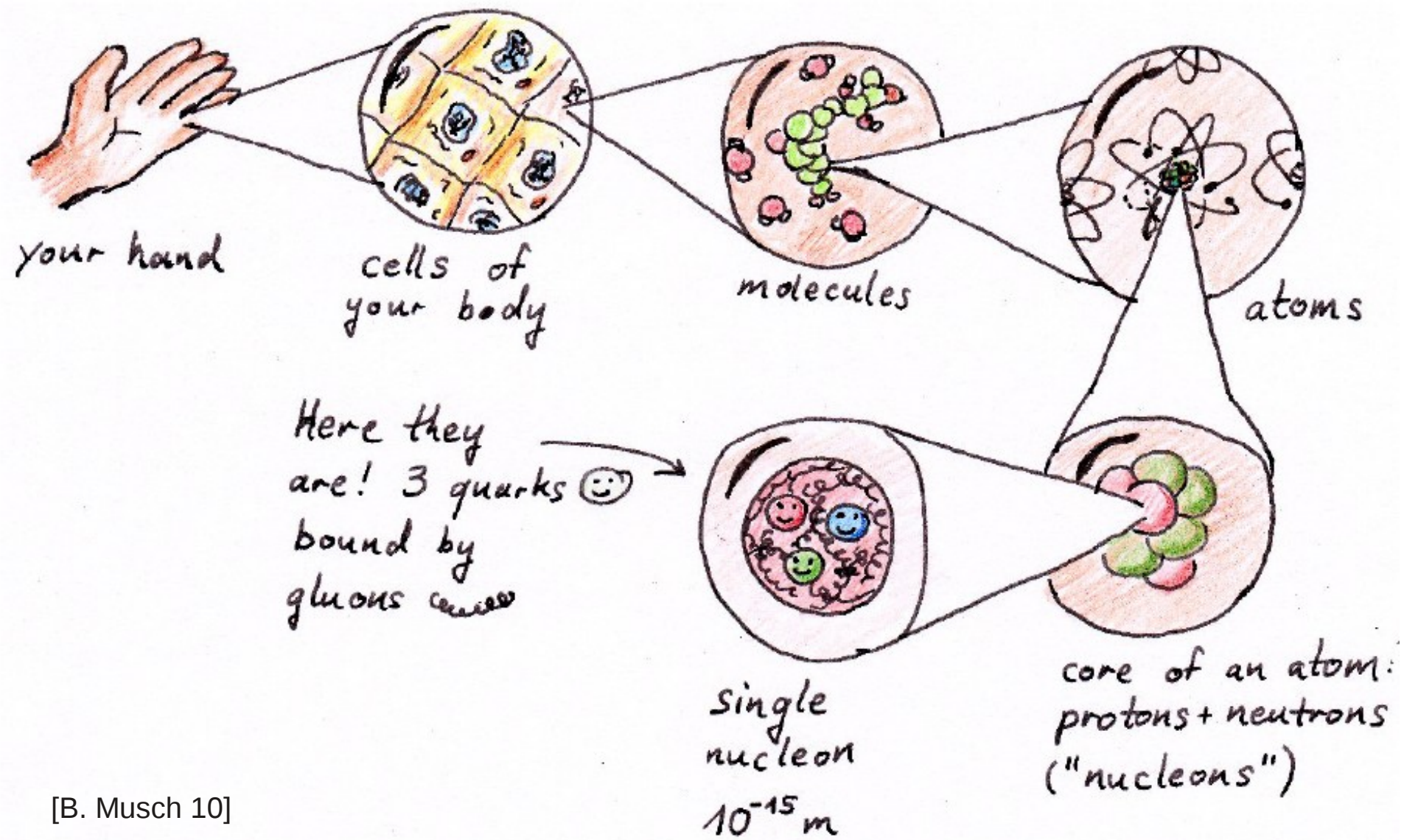
Jefferson Lab

Unveiling the structure of nucleons in high-energy experiments

- Experiments at high-energy particle accelerators
- QCD and the partonic structure of the nucleon
- Global analysis of parton distribution functions

Unveiling the structure of matter



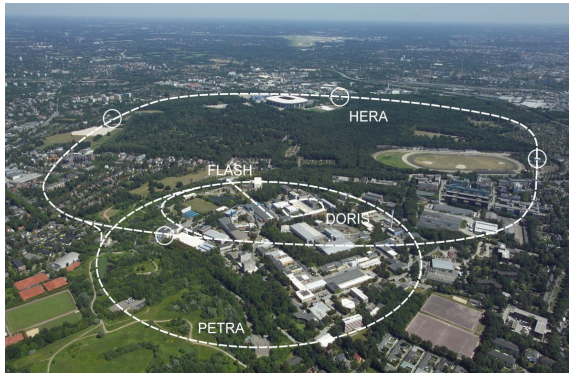
[B. Musch 10]

Plus other hadrons and fundamental particles (and more obscure matters)

Larger particle accelerator laboratories

SLAC

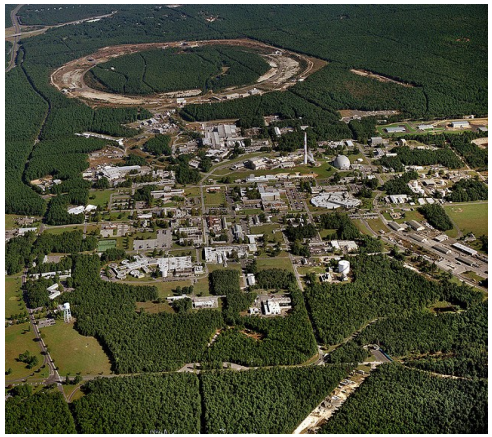
Fermilab

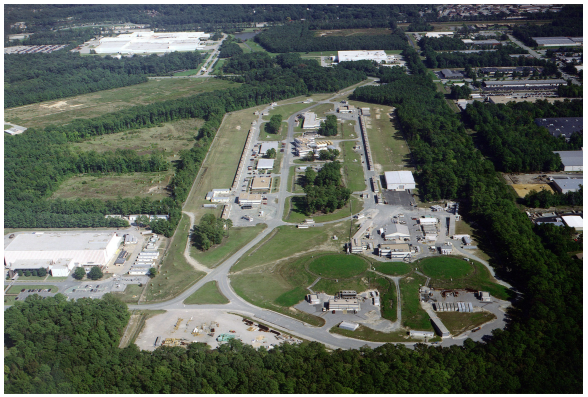


DESY

CERN

BNL



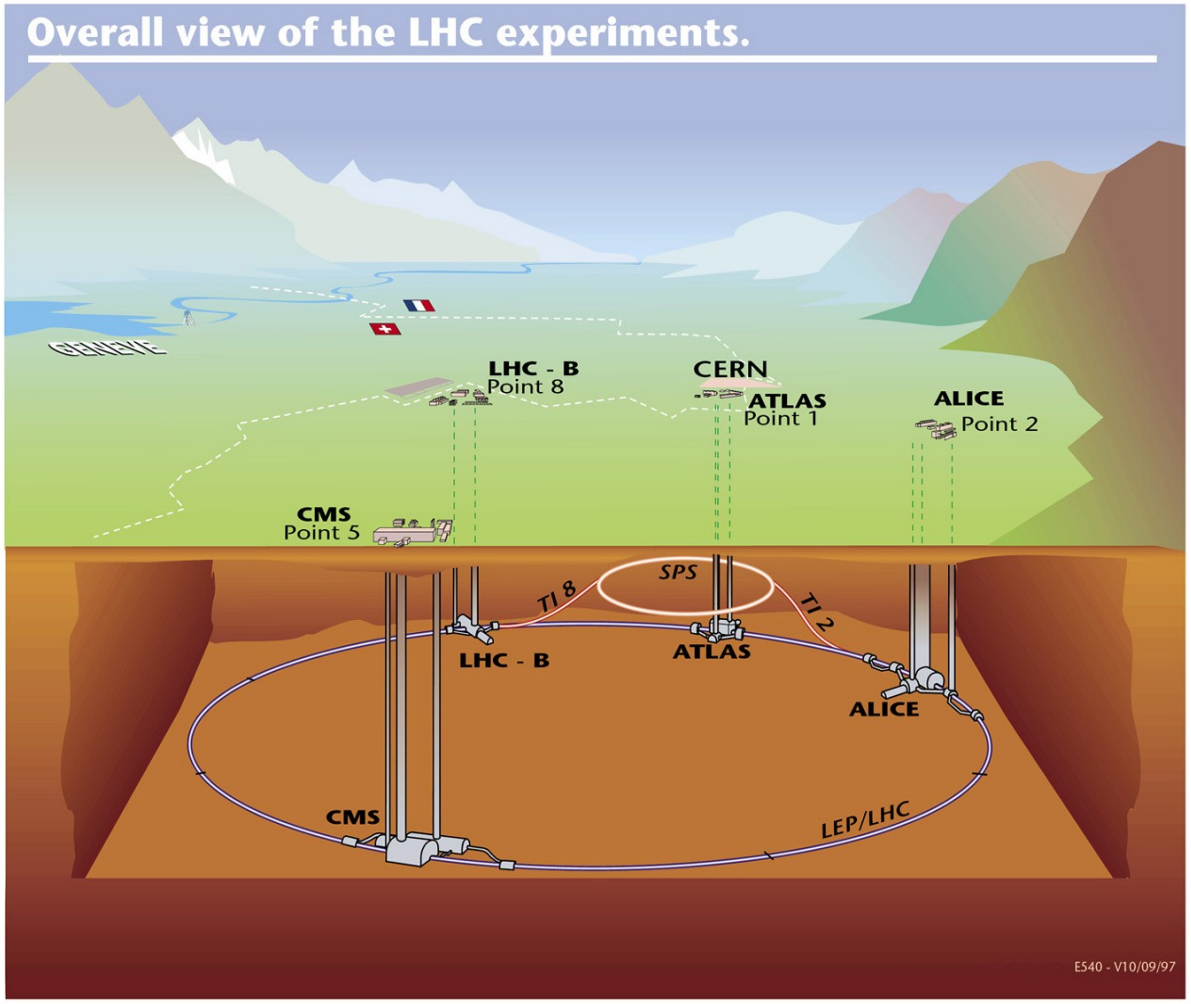


JLab

J-PARC, GSI, ... and more (to come)

We will look at one particular example: *discovery of a new boson at LHC*

Example of particle accelerator: LHC



CERN (near Geneva, CH)

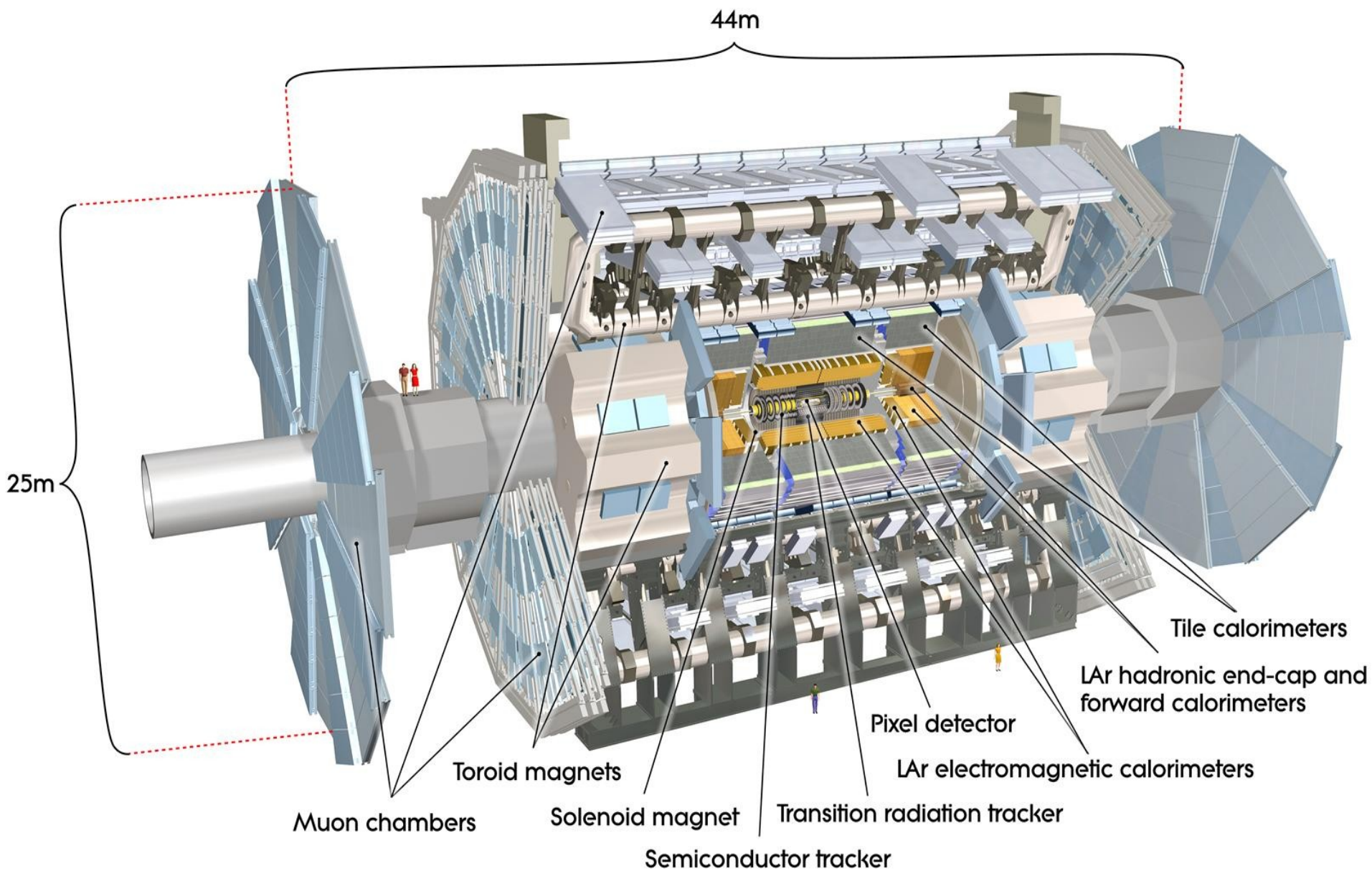
27 km circumference

Built by more than 10.000 people from more than 100 countries

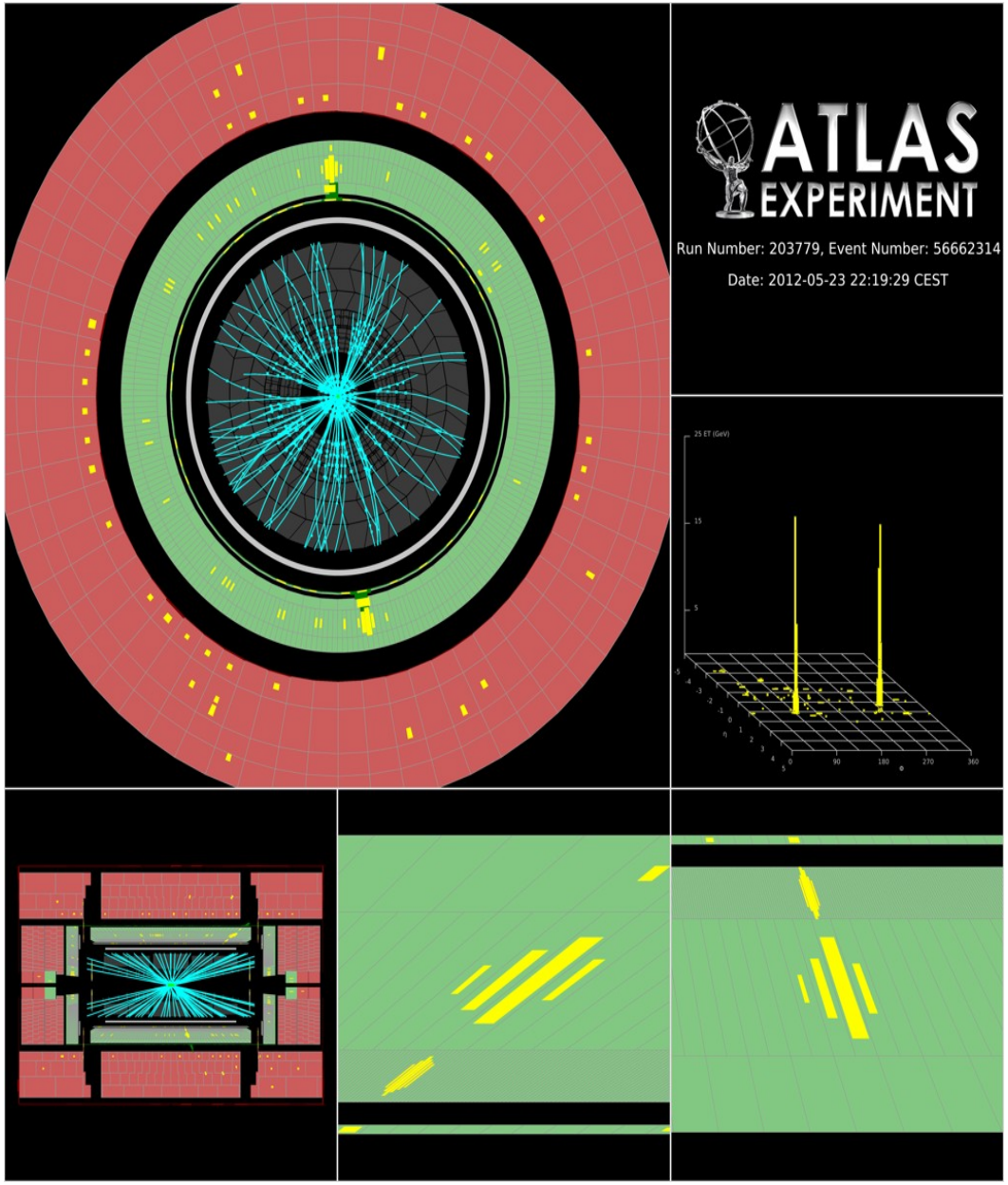
Proton-proton collider (also heavy ions)

Design energy 14 TeV (currently 8 TeV)

Example of particle detector: ATLAS



Relating measurements and theory



Event candidate for Higgs production

<u>Experimental output:</u>

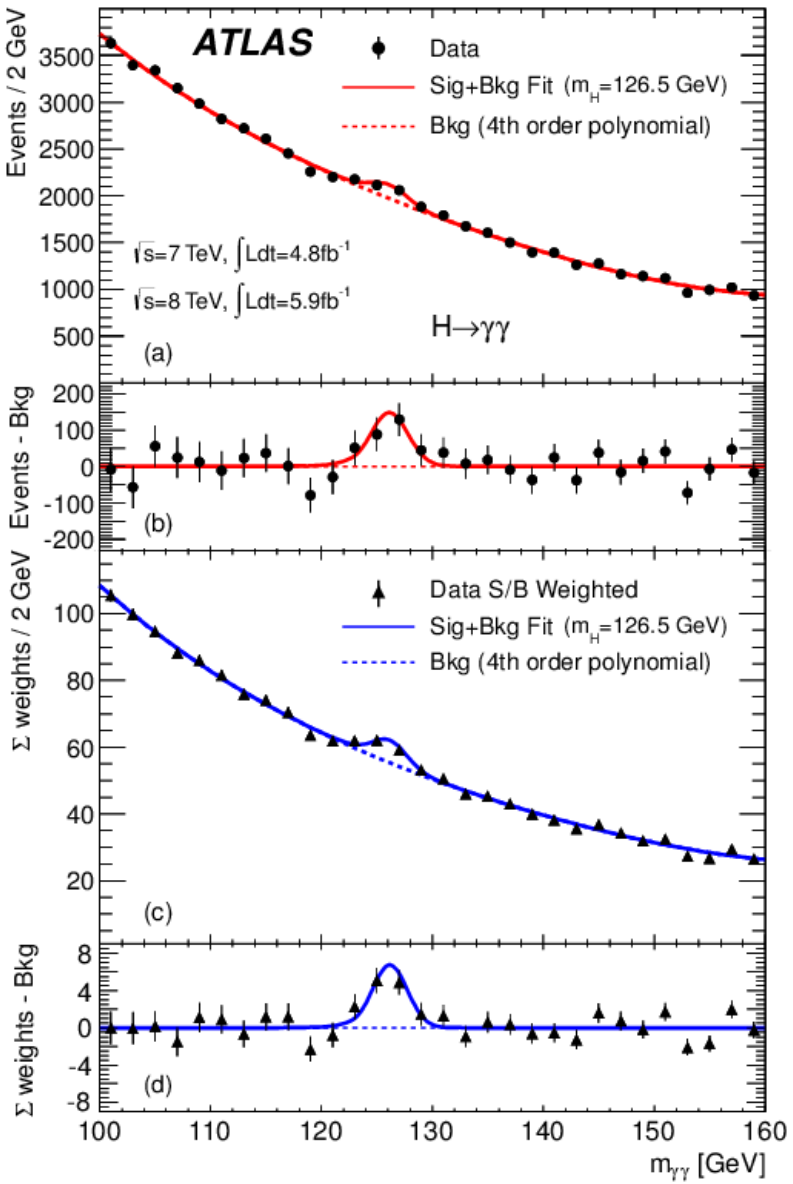
Measurement of ***events*** (particles and momenta)

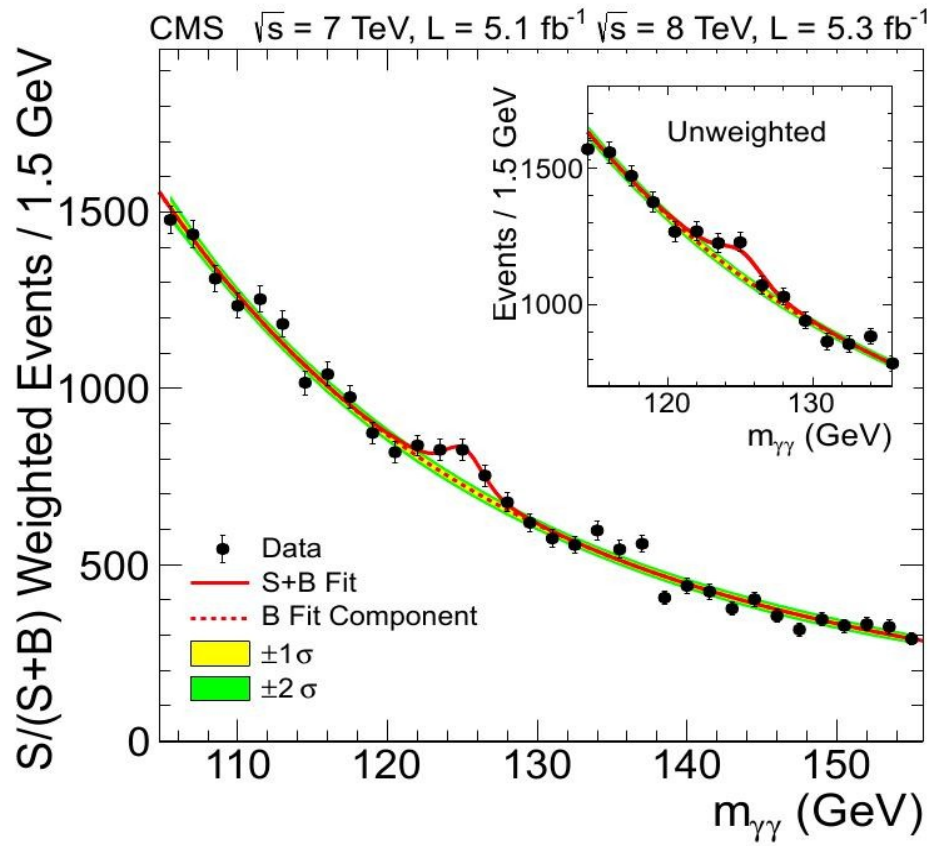
<u>Some current goals:</u>

- Understand origin of particle masses (related to the Higgs)
- Complete the ***Standard Model*** of particle physics
- Explore *New Physics* (beyond the SM): Supersymmetry, extra dimensions, dark matter ...
- Understand ***hadron structure*** and *QCD matter* in general

Discovery of a new boson

Only with *many* events can one discriminate ***signal*** and ***background***





One possibility or *channel*:

$$gg \rightarrow H \rightarrow \gamma\gamma$$

The *Standard Model* of particle physics

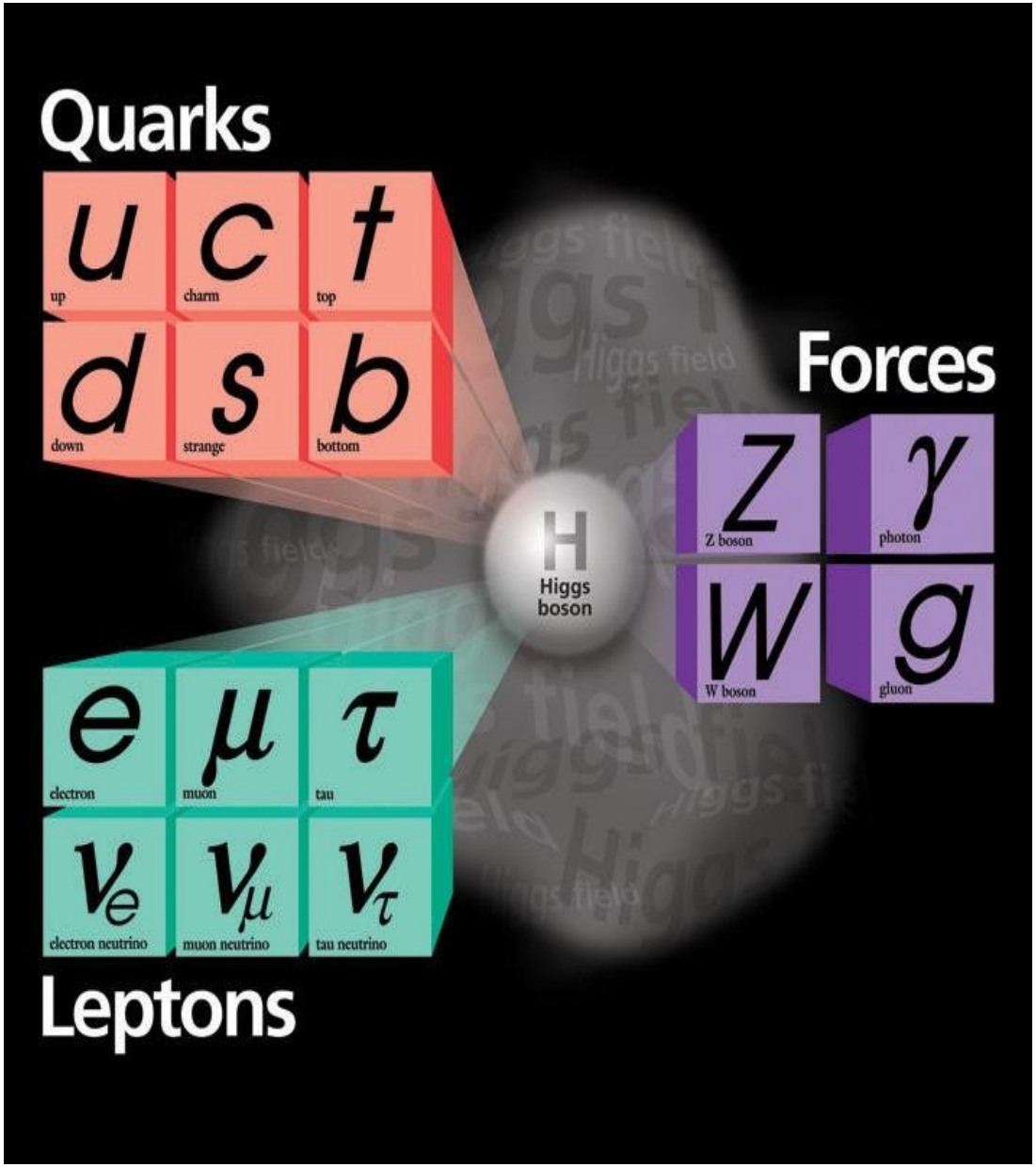
The theory of *almost* everything:

- Quantum Field Theory
- Given particle content
- Local gauge symmetries

⇒ Interactions between particles:

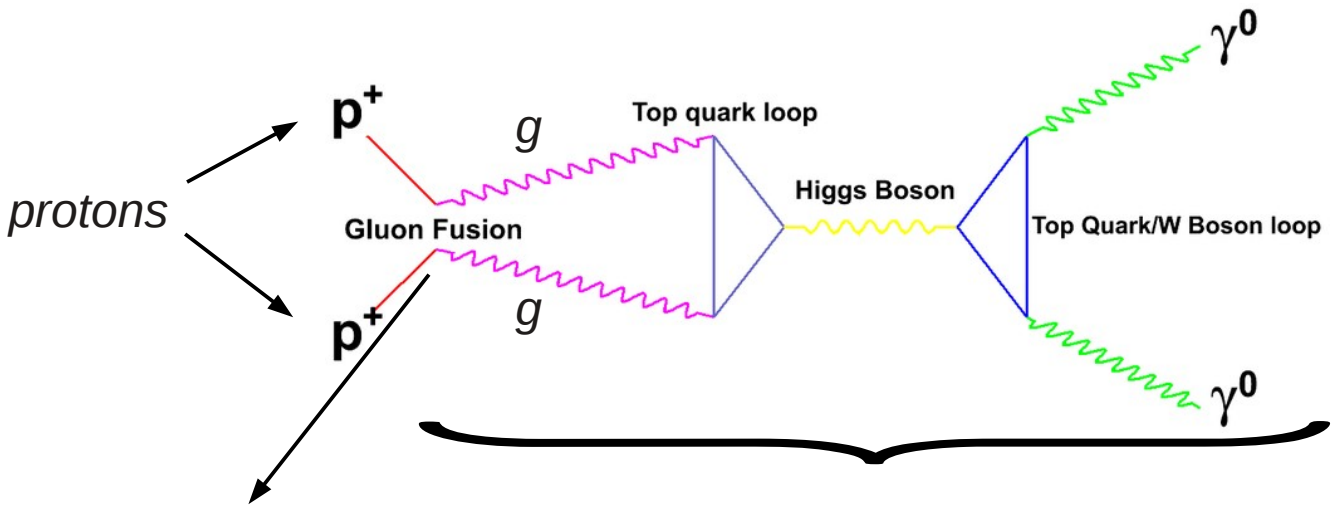
Electroweak + ***QCD***

Quantum Chromodynamics:
(color-dynamics) deals with the interactions of *quarks* and *gluons*

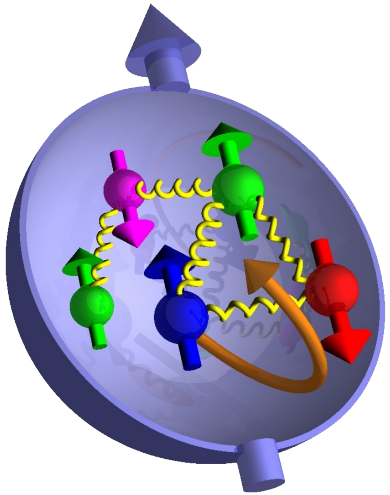


One interpretation of the candidate event

Diphoton production in gluon-gluon fusion: $gg \to H \to \gamma\gamma$



Nucleon structure



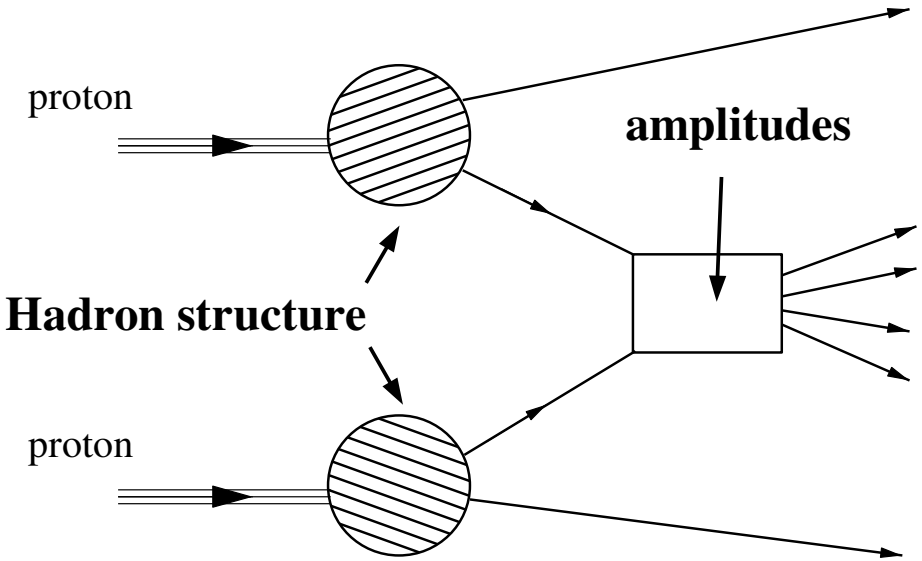
Using the Standard Model this can be "translated" into *quantitative* predictions:

Scattering amplitudes

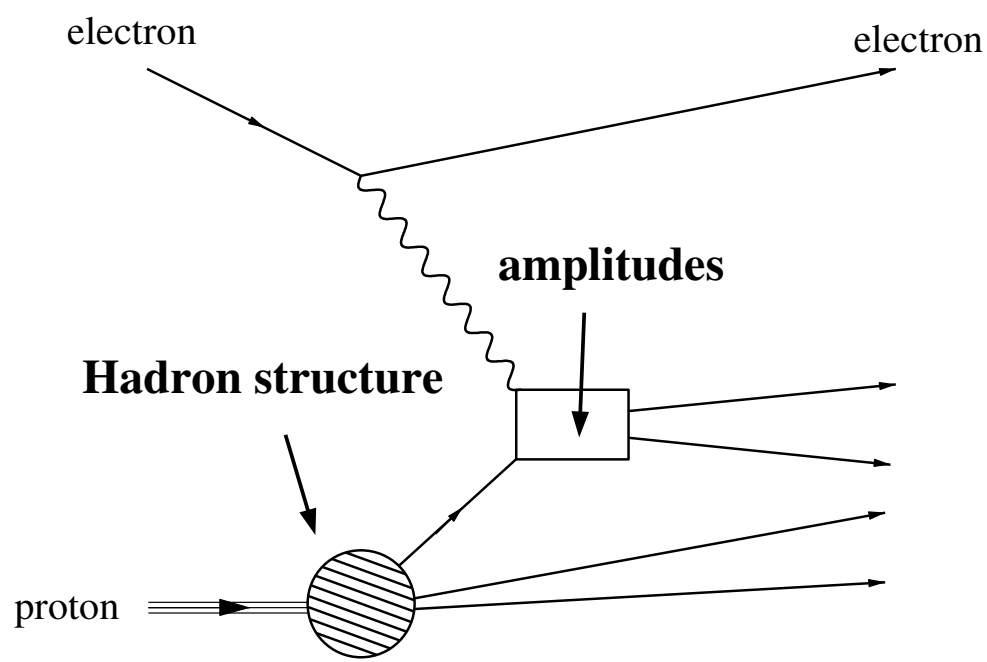
Hadrons are ***bound states*** of quarks and gluons

Hadron-hadron vs lepton-hadron collisions

At the LHC there are *two* protons



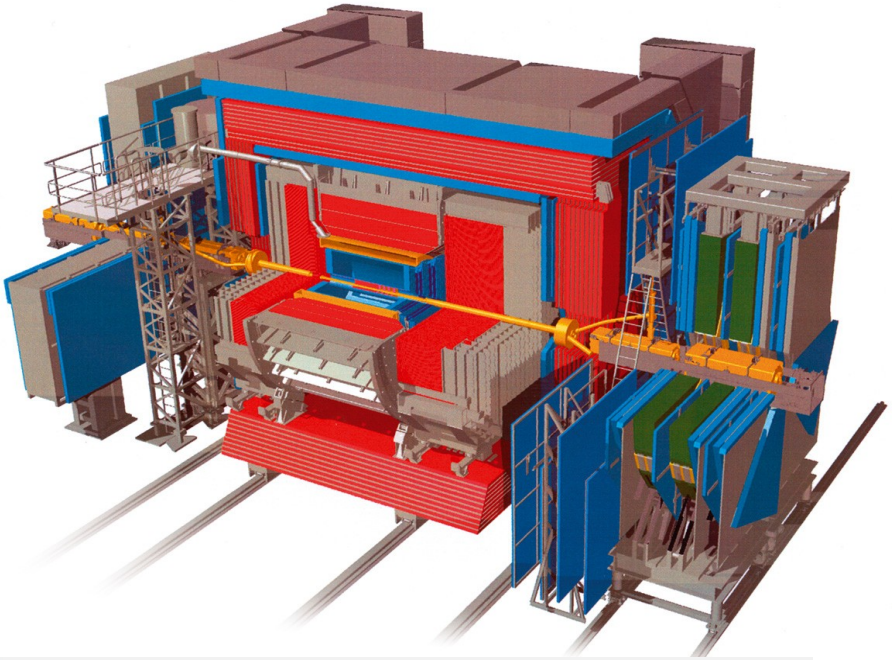
Nucleon structure can also be studied in electron-proton scattering

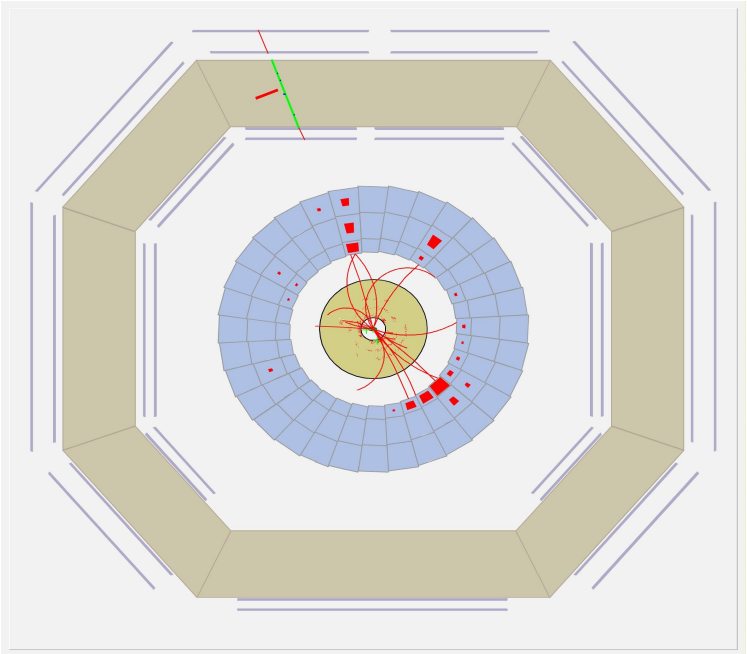


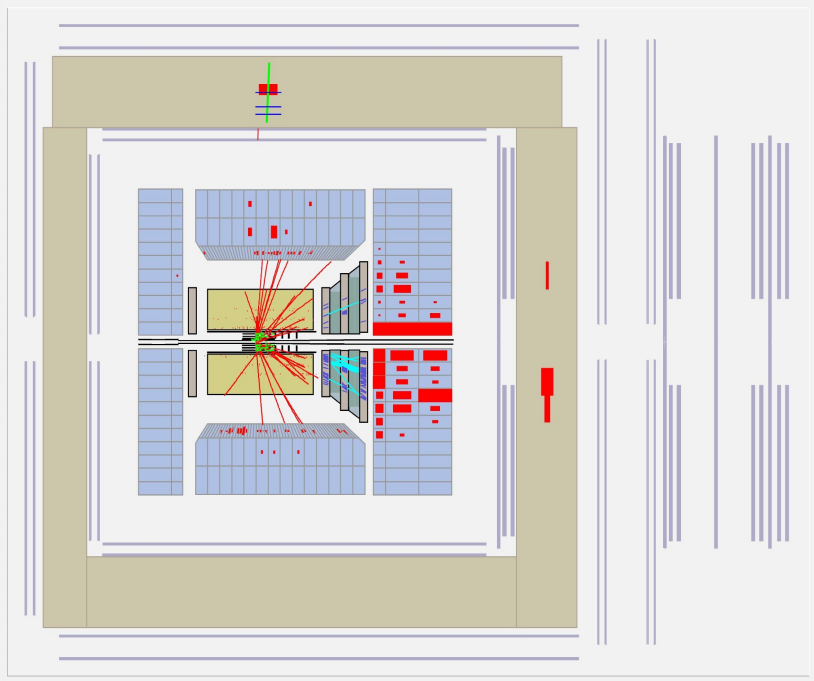
Deep Inelastic Scattering

use the electrons to "look" *deep* inside the nucleons (at the quark and gluons)

Example of DIS: ZEUS detector at HERA



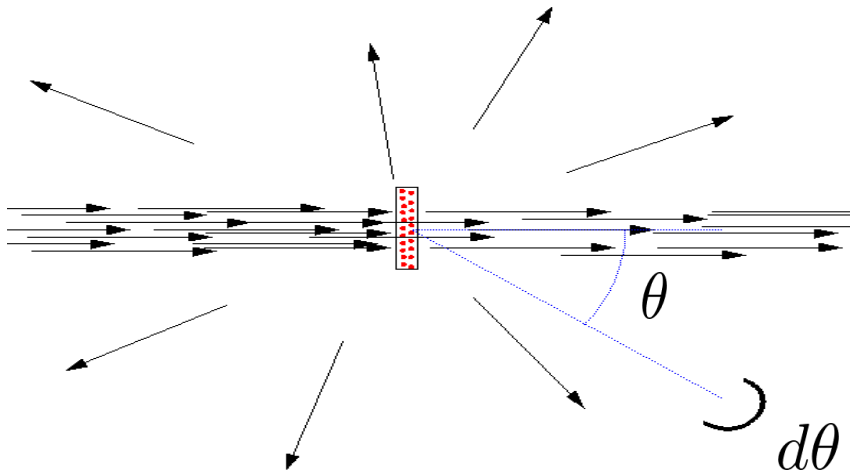




Observables in high-energy collisions

Scattering cross-section:

effective area giving the *probability* of the some scattering event



Differential (in θ) cross-section:

$$d\sigma = \frac{\text{outgoing particles in } d\theta}{\text{incoming particles per unit surface}}$$

(can be differential in [any number of] relevant variables)

A defining characteristic is the *exclusive/inclusive* character of the process

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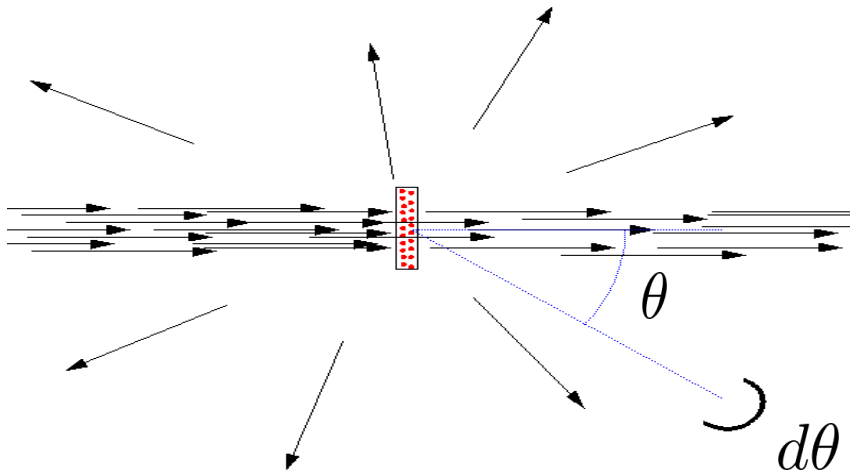

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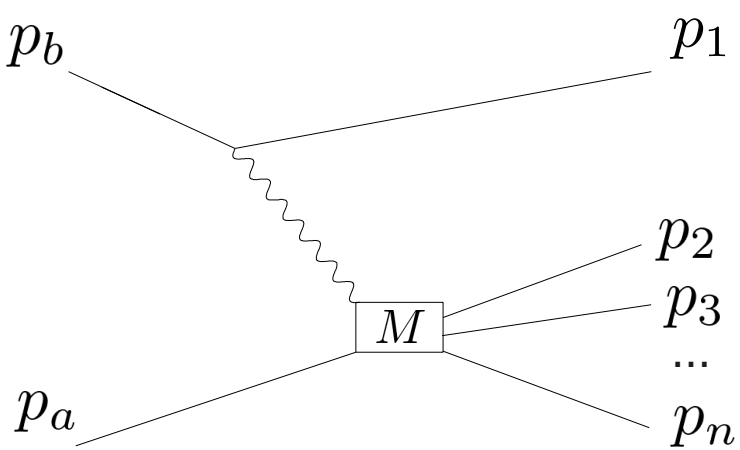
Total cross-section for scattering off a point-like particle:

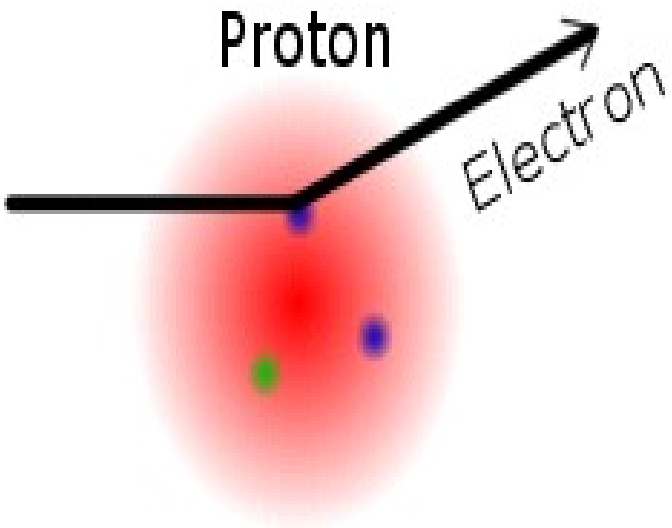


$$\sigma = \frac{(2\pi)^4}{4p_a \cdot p_b} \int |M|^2 \underbrace{\delta(p_a + p_b - \sum_i p_i)\ \Pi_i \frac{d^3 p_i}{(2\pi)^3 2E_i}}_{\text{phase space (lorentz invariant)}}$$

flux factor amplitude

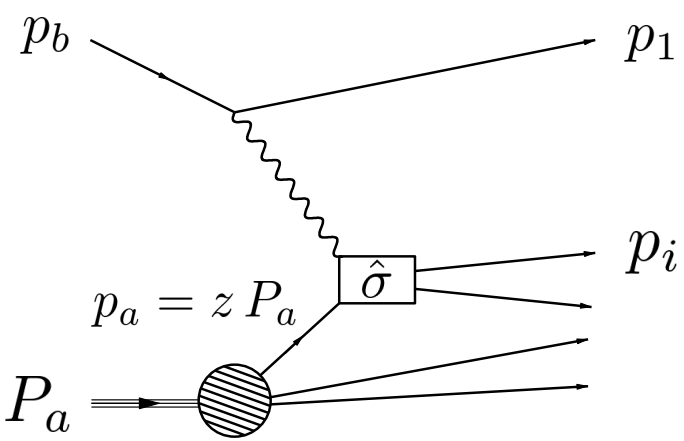
The parton model

Hadrons regarded as a compound of point-like constituents (partons)



Plausible if the hard interaction is much faster than the structural interactions (justified by time dilatation); i.e., at high energies

Thus the incoming particles scatter *incoherently off partons*:



Parton distribution functions

$$\sigma = \sum_{\text{partons}} \int_0^1 dz\, \hat{\sigma}\, f_{\text{parton}}(z)$$

$$= \sum_a \frac{(2\pi)^4}{4p_a \cdot p_b} \int |M|^2_{\text{parton}} \delta(p_a + p_b - \sum_i p_i)\, dz\, \Pi_i \frac{d^3 p_i}{(2\pi)^3 2E_i}\, f_{\text{parton}}(z)$$

The Monte Carlo approach

Simulate *many random* events and calculate their probabilities

Example: generate randomly partonic momentum fractions

$$z = x(\tfrac{1}{x})^r \Rightarrow \int_0^1 dz F(z) = \int_0^1 dr\, z \ln \tfrac{1}{x} F(z(r)) \simeq \tfrac{1}{N} \sum_{i=1}^{N} z \ln \tfrac{1}{x} F(z(r))$$

Random number $(0 \leq r \leq 1)$

The phase space integration over final momenta is well known

$$P_n(\hat{s}) = \int \delta(\sqrt{\hat{s}} - \sum_i p_i) \Pi_i \frac{d^3 p_i}{(2\pi)^3 2E_i} = \frac{1}{(2\pi)^{3n-4}} (\tfrac{\pi}{2})^{n-1} \frac{\hat{s}^{n-2}}{\Gamma(n)\Gamma(n-1)}$$

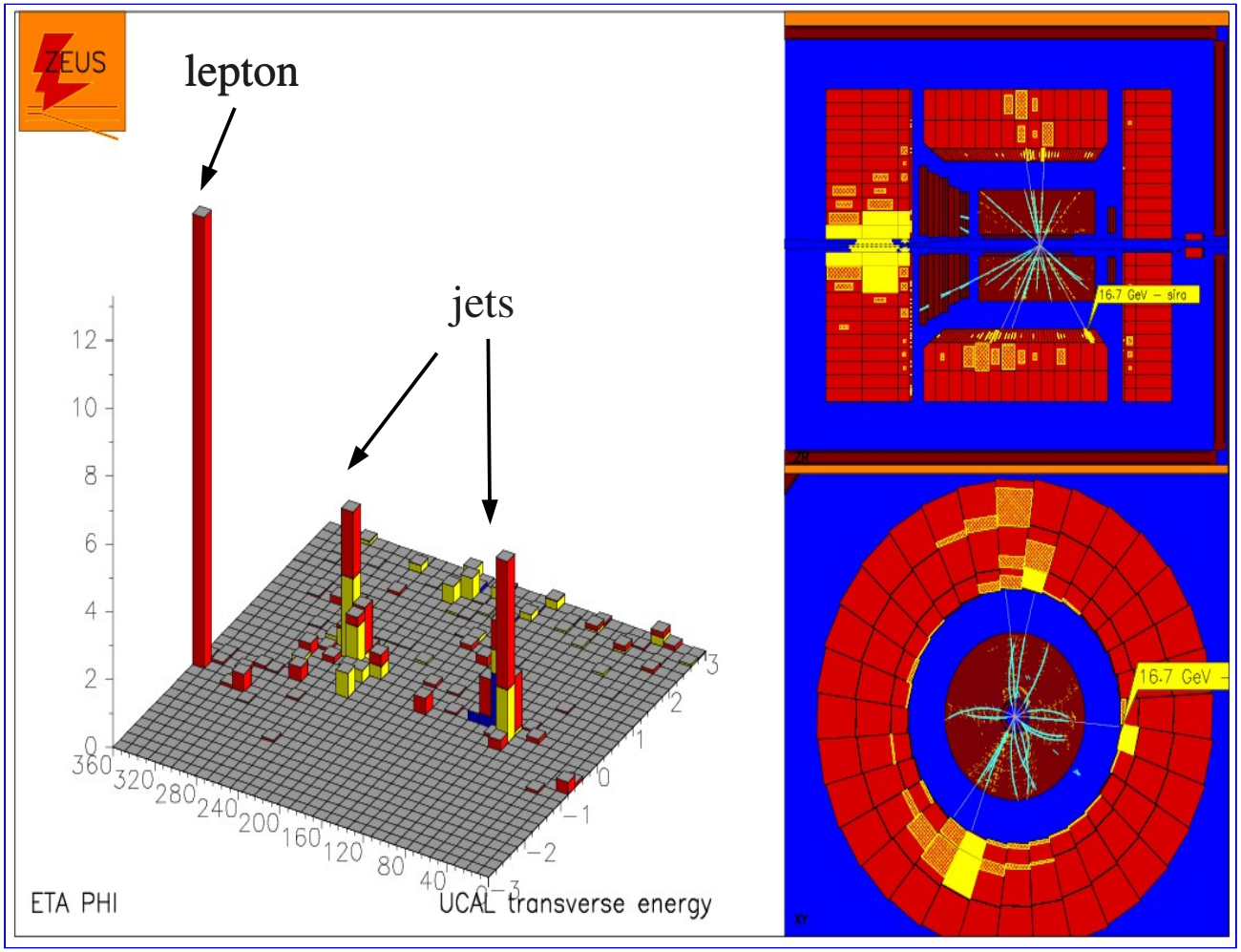
Thus the integrals can be calculated by assigning the following ***weights***:

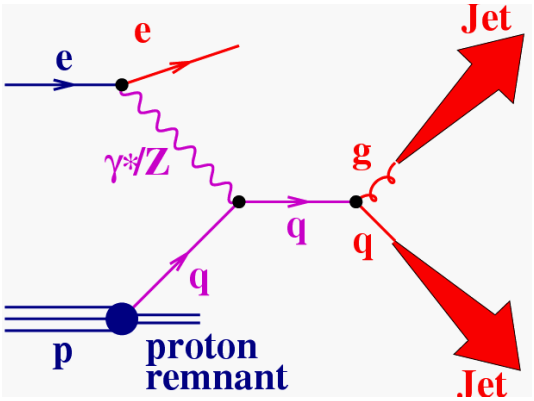
$$\sigma_i = \frac{|M|_i^2}{16 p_{-1} \cdot p_0} z \ln \tfrac{1}{x} P_n\, f(z)$$

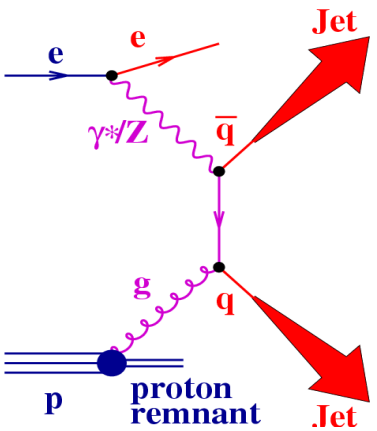
Calculations get more complicated at higher-orders (*loops*)
and with increasing number of particles in the final state (*legs*)

ANTJETS

One of my ongoing projects [with T . Gehrmann and G. Luisoni] is the development of a parton-level Monte Carlo for (2+1)-jet production in DIS up to NNLO of QCD



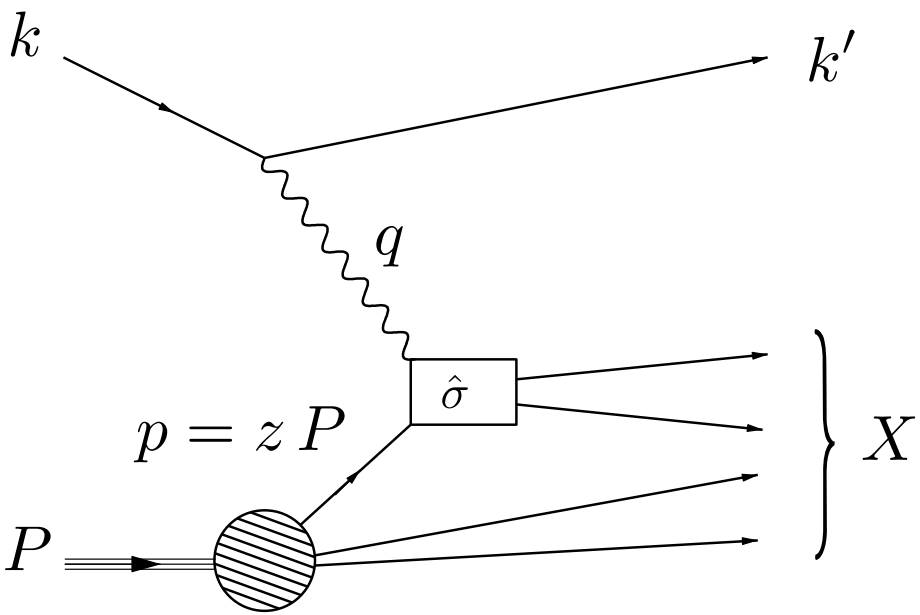




Requires the cancellation of QCD singularities: ***Subtractions Methods***

Kinematics for inclusive DIS

One can consider ***inclusive*** DIS, thus a *reduced* number of variables:



Virtuality: $Q^2 \equiv -q^2$

Bjorken-x: $x \equiv \dfrac{Q^2}{2P_0 \cdot q}$ $(0 \leq x \leq 1)$

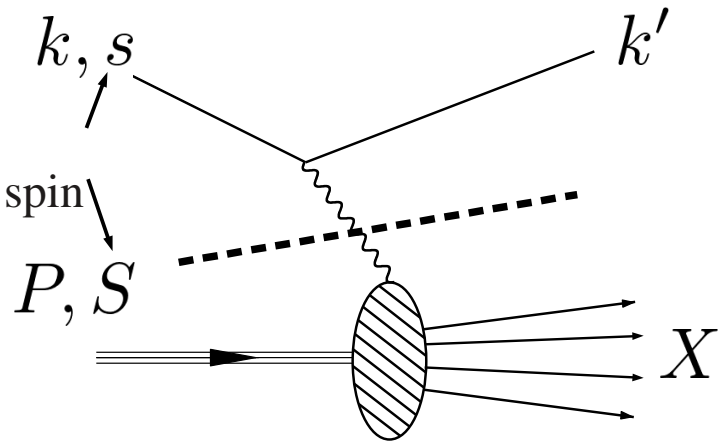
Inelasticity: $y \equiv \dfrac{P_0 \cdot q}{P_0 \cdot k}$ $(0 \leq y \leq 1)$

Q^2 sets the scale at which one is "looking" (larger Q^2, smaller distances, deeper)

In the *parton model* and LO QCD the $\hat{\sigma}$'s are delta functions: $z = x$

Structure Functions

One can consider *inclusive* DIS, thus a *reduced* number of variables:



$$\frac{d\sigma}{dx\,dy} \propto L_{\mu\nu} W^{\mu\nu}$$

Leptonic tensor (calculated)

Hadronic tensor (parametrized)

Nucleon structure in ***Structure Functions:***

$$W_{\mu\nu}(P,q,S) = (-g^{\mu\nu} + \tfrac{q^\mu q^\nu}{q^2})F_1(x,Q^2) + (P^\mu - \tfrac{P\cdot q}{q^2}q^\mu)(P^\nu - \tfrac{P\cdot q}{q^2}q^\nu)F_2(x,Q^2)$$
$$+iM\epsilon^{\mu\nu\rho\sigma}q_\rho[\tfrac{S_\sigma}{P\cdot q}g_1(x,Q^2) + \tfrac{S_\sigma(P\cdot q)-P_\sigma(S\cdot q)}{(P\cdot q)^2}g_2(x,Q^2)]$$

The spin-averaged double differential cross-section:

$$\frac{d^2\sigma}{dx\,dy} = \frac{2\pi\alpha^2}{xyQ^2}(1+(1-y)^2F_2 - y^2F_L)$$

We will ignore $F_L \simeq F_2 - 2xF_1$ and g_2, which are zero at first order

Spin-averaged and spin-dependent PDFs

To measure the polarized structure functions one makes asymmetries:

$$A_{\parallel} = \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} \qquad A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\uparrow\Leftarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\uparrow\Leftarrow}} \qquad \sigma^{\uparrow\Rightarrow}$$

nucleon spin orientation

electron spin orientation

Then $A_{\parallel} \propto \frac{g_1}{F_1}$. How to relate them to PDFs?

$f^{\pm}_{\pm}$

nucleon polarization

parton polarization

In principle four combinations:

$$\sigma^{+} = \sum_f \int_x^1 (f_+^+ \hat{\sigma}^+ + f_-^+ \hat{\sigma}^-)$$

$$\sigma^{-} = \sum_f \int_x^1 (f_+^- \hat{\sigma}^+ + f_-^- \hat{\sigma}^-)$$

But reduce to partons with same (f_+) or opposite (f_-) helicity as nucleon

$\sigma^+ + \sigma^- \propto f \equiv f_+ + f_-$ ⟵ Spin-averaged or ***unpolarized*** PDFs

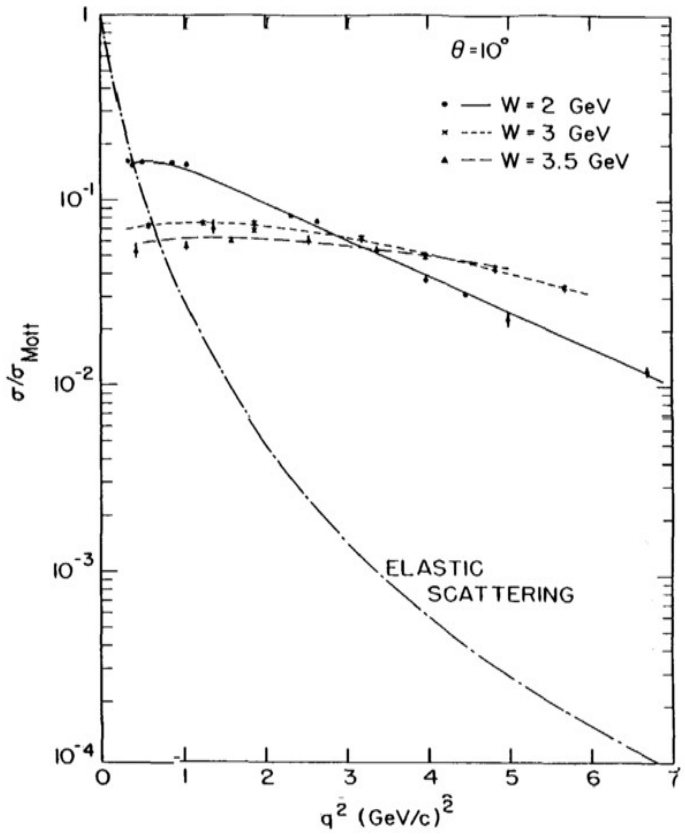
$\sigma^+ - \sigma^- \propto \Delta f \equiv f_+ - f_-$ ⟵ Spin-dependent or ***polarized*** (or helicity) PDFs

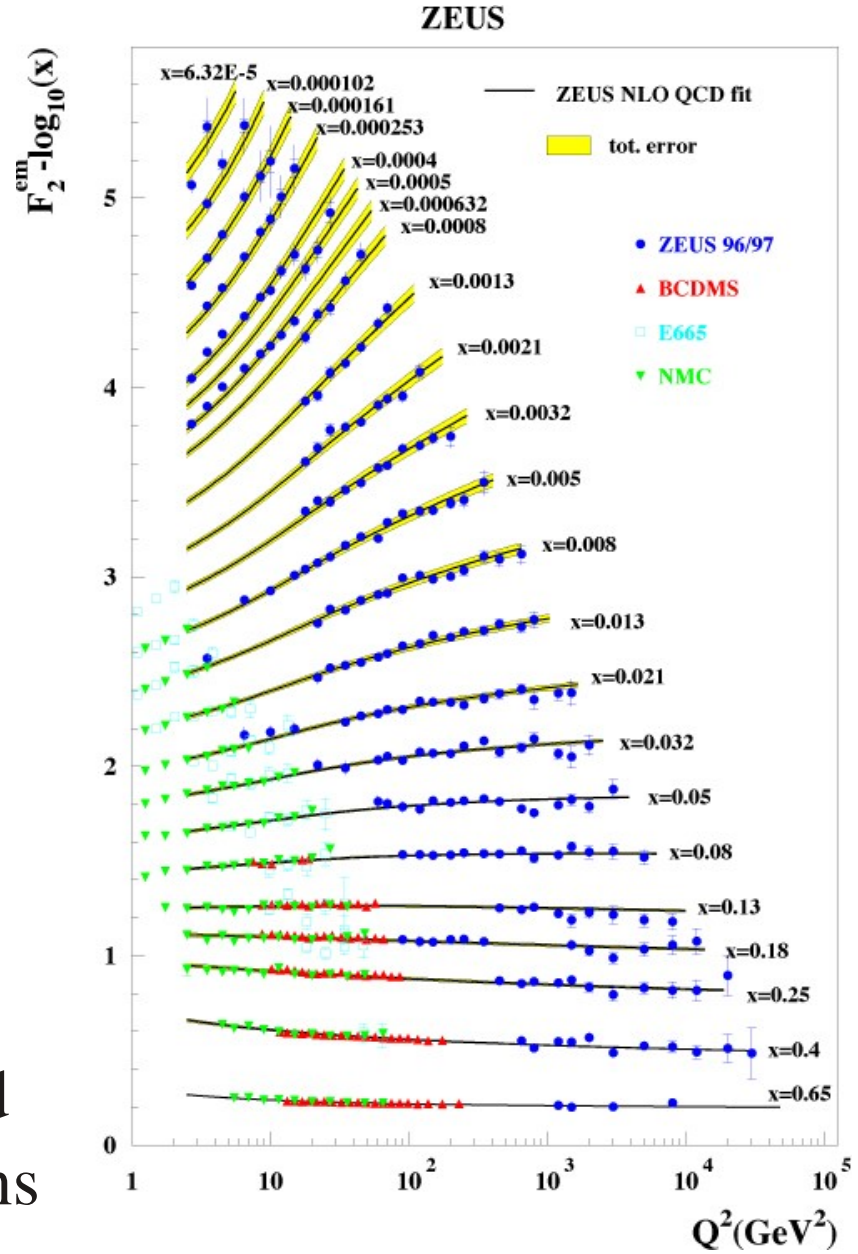
In the *parton model* the $\hat{\sigma}$'s are delta functions:

$$F_2 = x \sum_q e_q^2 (q(x) + \bar{q}(x)) \qquad g_1 = \frac{1}{2} \sum_q e_q^2 (\Delta q(x) + \Delta \bar{q}(x))$$

Scaling and QCD corrections

Bjorken scaling: DIS cross section (in the limit $Q^2 \to \infty$ for fixed x) predicted to depend only on x





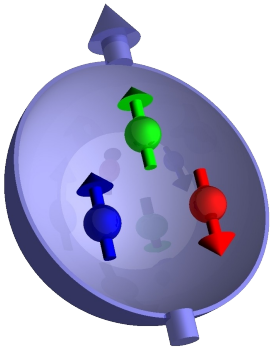
QCD-improved parton model: cloud of partons constantly emitted and absorbed

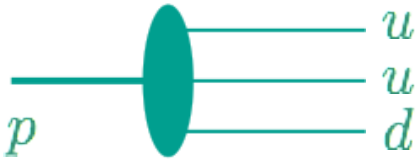
$\Longrightarrow$ calculable ***logarithmic*** corrections

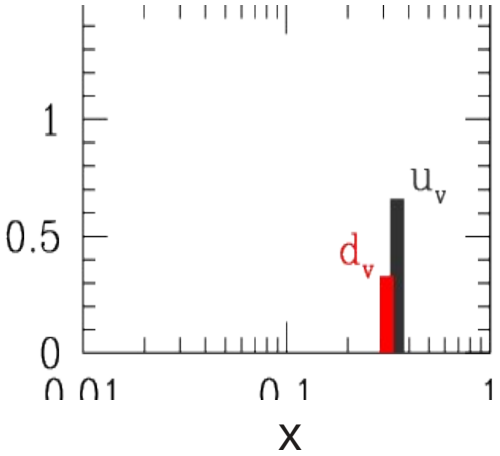
Momentum fraction dependence

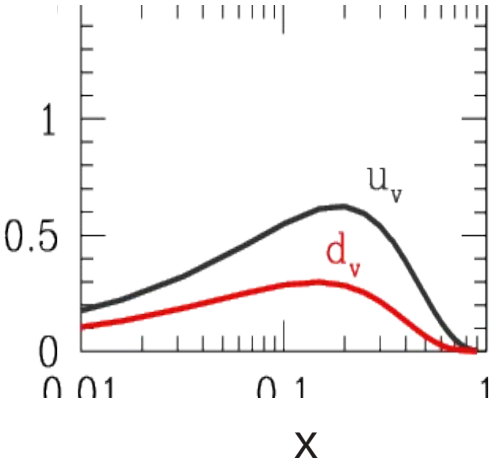
We do not know how to calculate x-dependence within pQCD

What to expect? For three ***valence*** (quantum numbers) quarks:

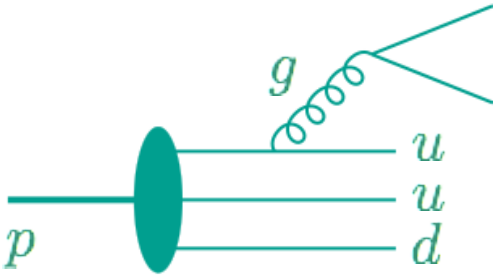


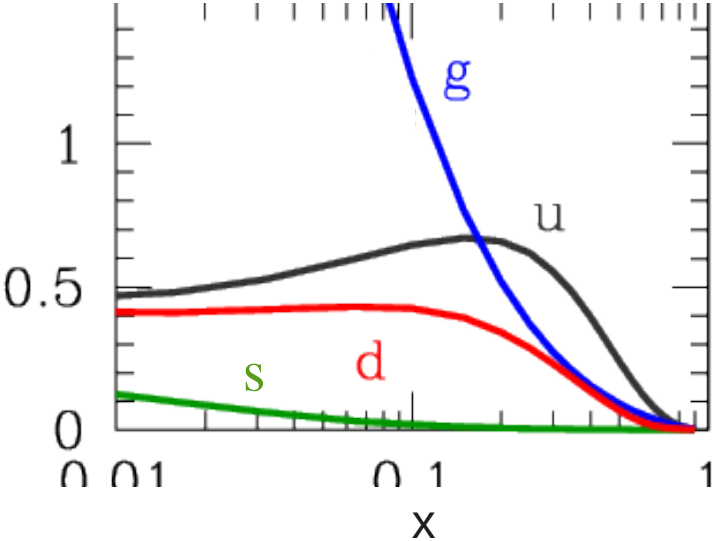






in a ***sea*** (vacuum) of gluons and quark pairs:





Global analysis of parton distributions

Goal: determination of the ***input distributions*** (for light quarks and gluons):

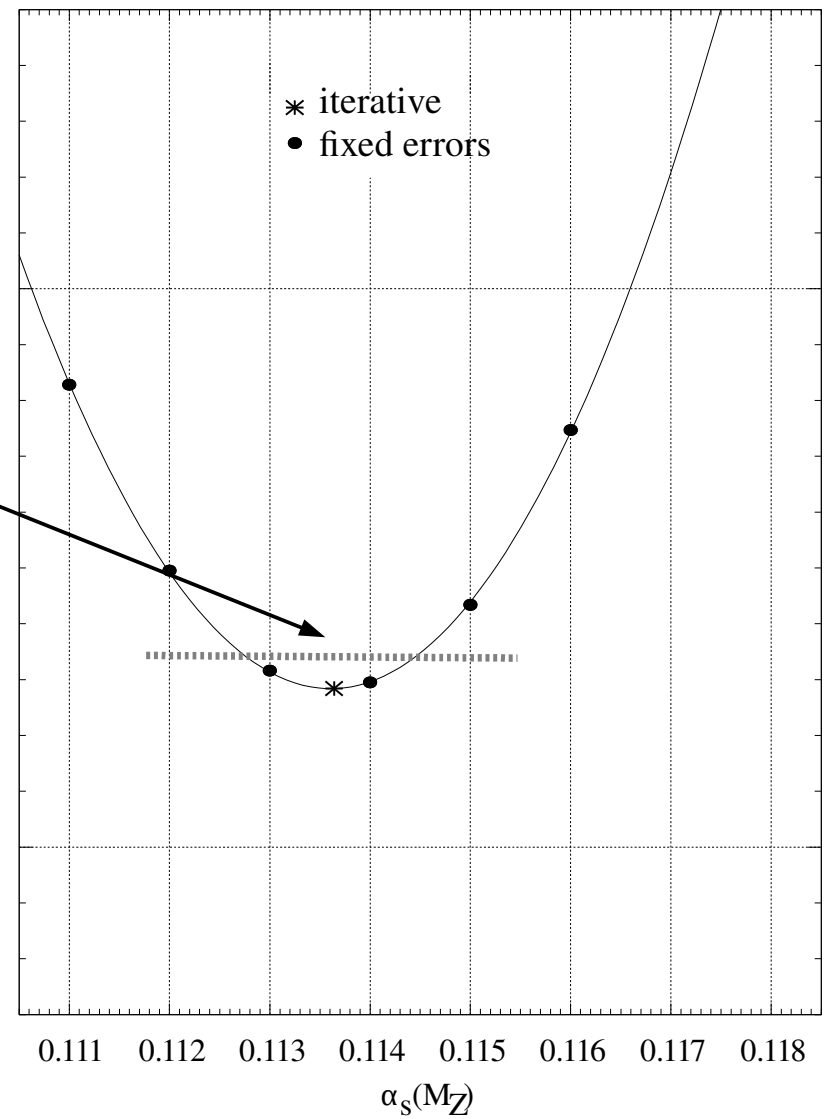
Method: Parametrizations $xf(x, Q_0^2) = Nx^a(1-x)^b \,\mathrm{function}(x)$
and usual *statistical estimation* (fits):

$$\chi^2(p) = \sum_{i=1}^{N} \left(\frac{\mathrm{data}(i) - \mathrm{theory}(i,p)}{\mathrm{error}(i)} \right)^2$$

Position of minimum gives the value and curvature gives the error (region within a certain "tolerance" $\Delta\chi^2 = 1$)

(Monte Carlo methods can also be used)

Usually the chi-square definition is more sophisticated and experimental correlations are also treated

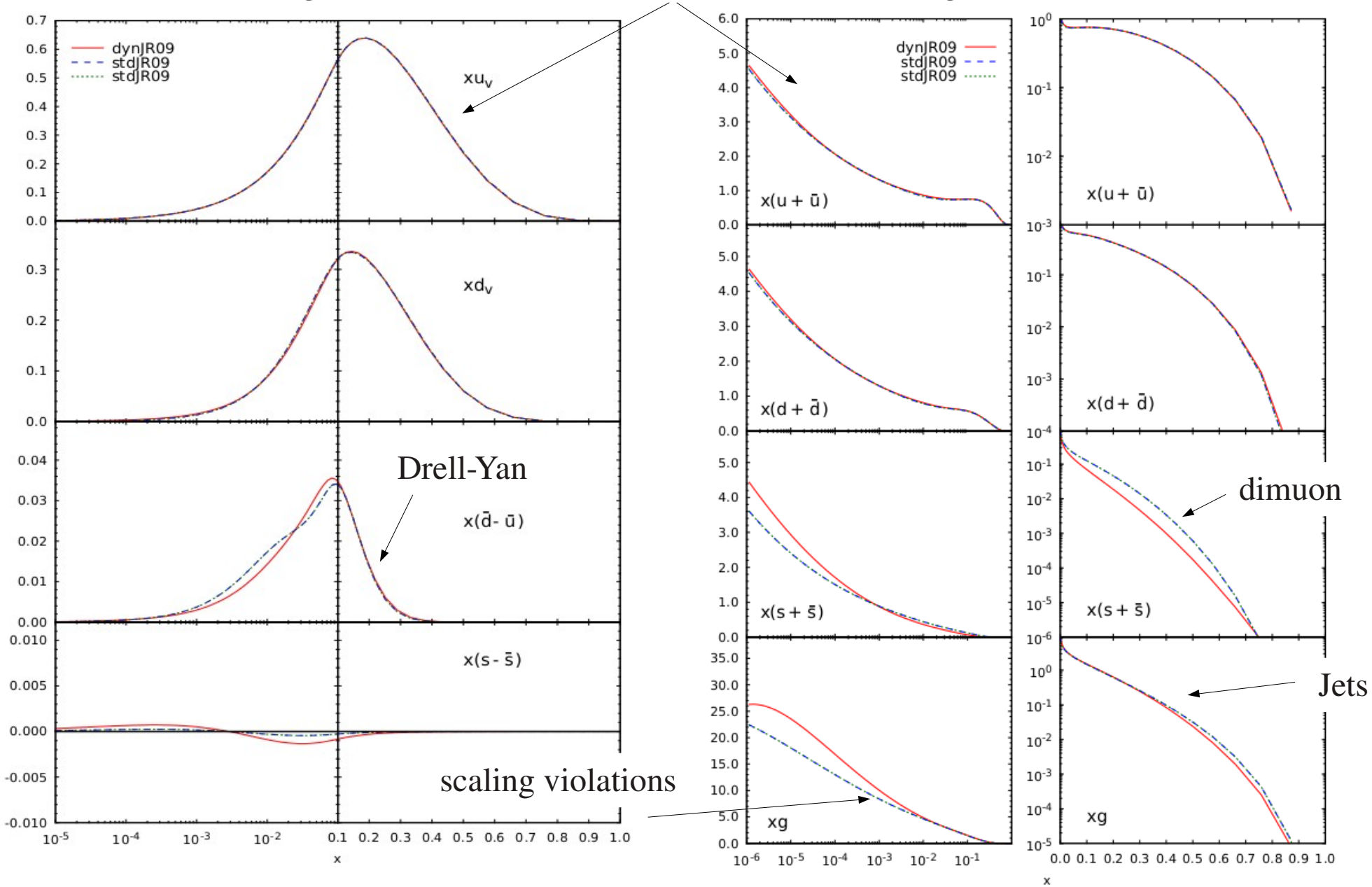


How do real unpolarized PDFs look like?

Non-singlet sector

structure functions

Singlet sector



Data for unpolarized distributions

Pre-LHC data:

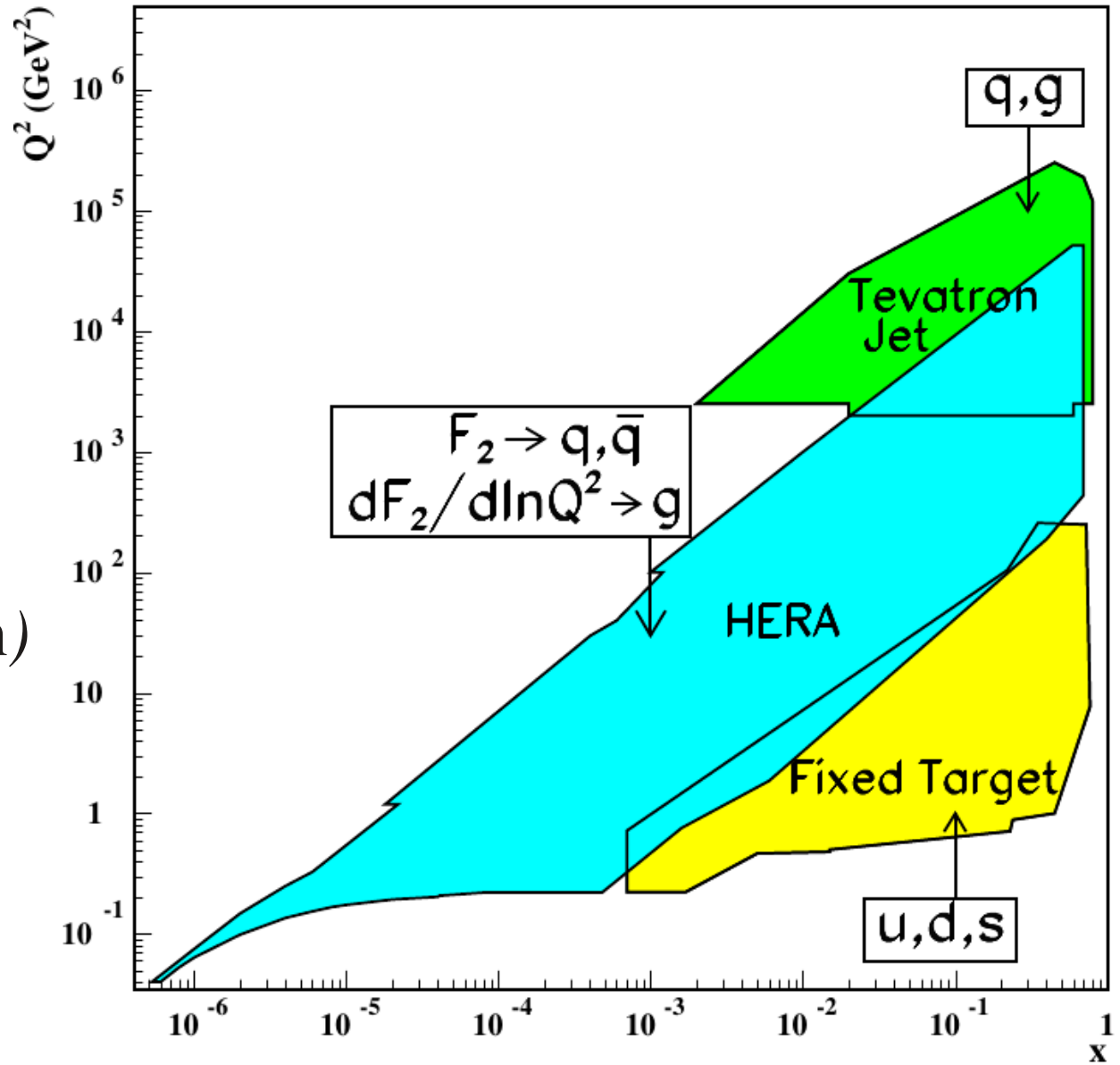
Inclusive DIS structure functions (FT and HERA)

Drell-Yan (or CC DIS) needed for $\bar{d} \neq \bar{u}$

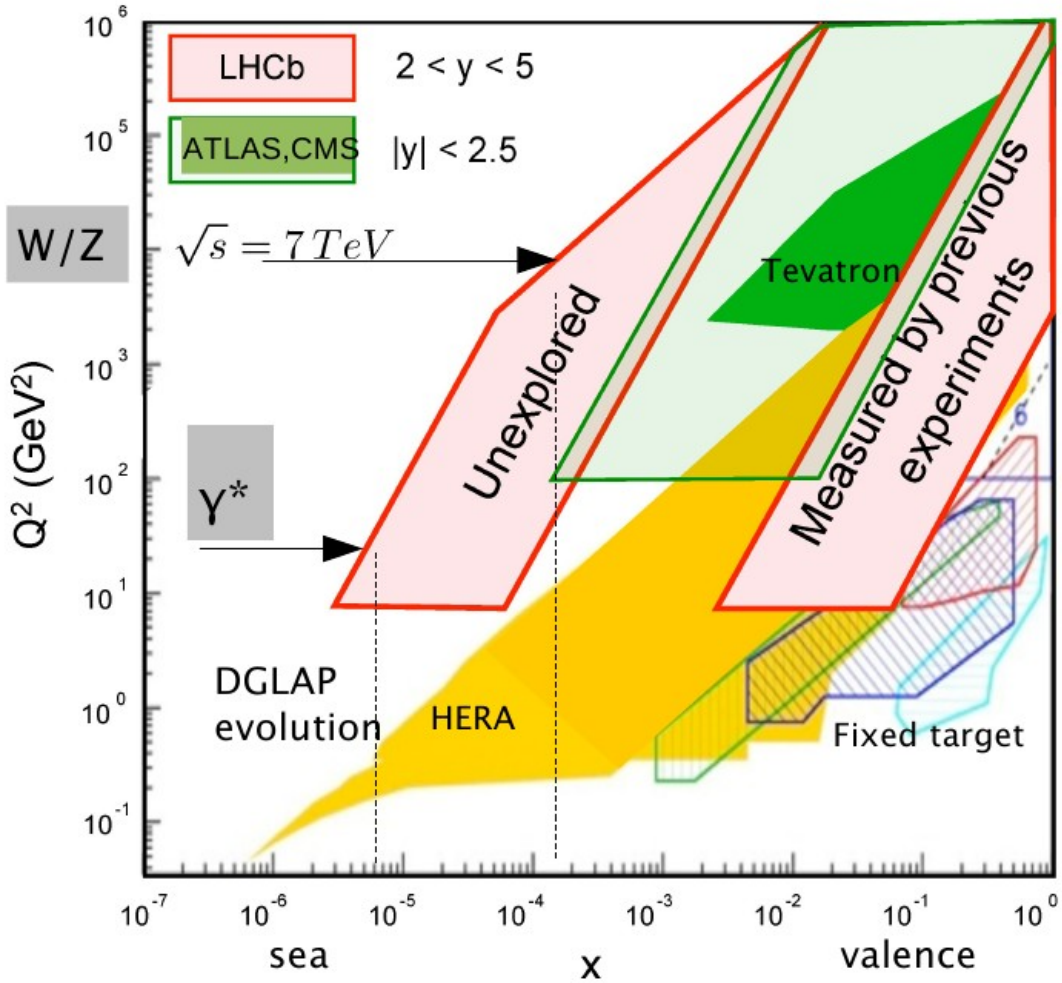
Neutrino dimuon data sensitive to strangeness

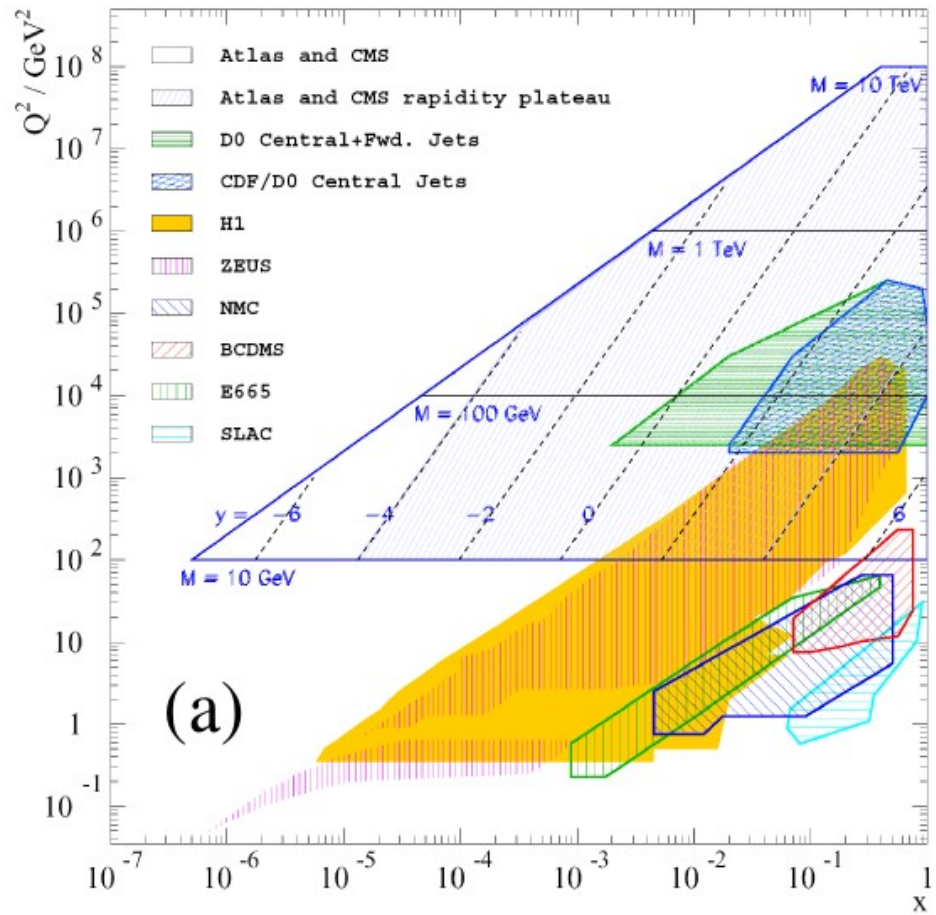
W/Z production (Tevatron) provides additional (redundant) information

Gluon only enters (at LO) in jet production (large-*x*) and semi-inclusive heavy-quark production in DIS (small-*x*)



Data for unpolarized distributions





We will go from predicting LHC measurements to using them for constraining the parton distributions (some groups have already started)

Current global PDF groups (unpolarized NNLO)

ABM: Careful treatment of experimental correlations, nuclear and power corrections in DIS, FFNS

MSTW: negative input gluons at small-*x*, rather "large" $\alpha_s(M_Z^2)$, GMVNS

HERAPDF: Only HERA data, less negative gluons, GMVFS

NNPDF: neural-network parametrization, Monte Carlo approach for error propagation, GMVFNS

CTEQ-TEA: parametrization with exponentials, substantially inflated uncertainties, GMVFNS

JR [with E. Reya]: dynamical (and "standard") approach, rather "small" $\alpha_s(M_Z^2)$, FFNS

(there are more groups focused on particular aspects, e.g. CTEQ-JLab)

Polarized data and groups

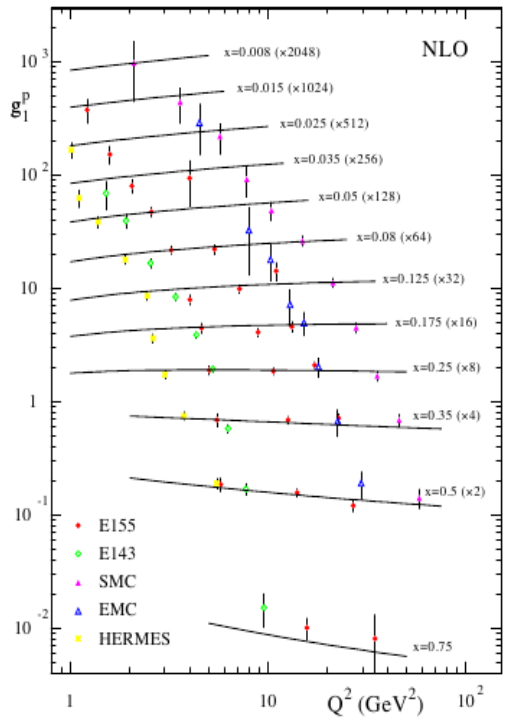
Mainly DIS structure functions

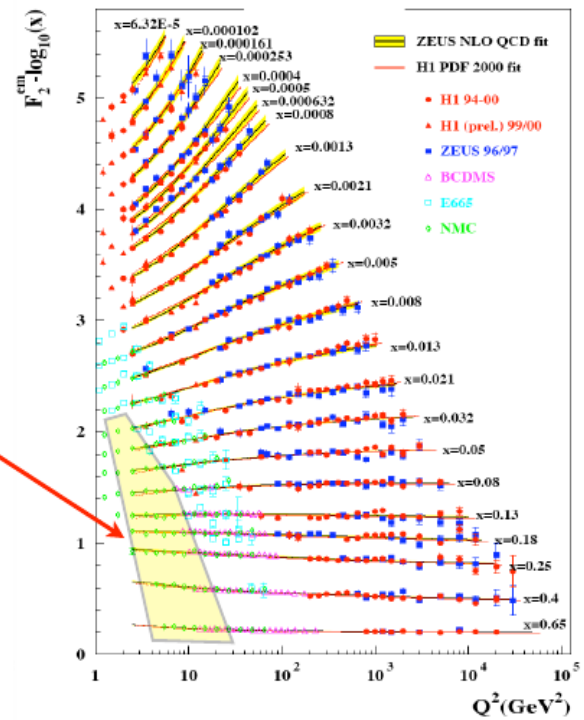
Kinematic coverage greatly reduced (compared to unpolarized)

One can use SIDIS (less "clean")

DSSV use pp data (RHIC) as well

State-of-the-art is NLO





[D. de Florian]

<u>Main current groups:</u>

DSSV: De Florian, Sassot, Stratmann, Vogelsang

LSS: Leader, Sidorov, Stavenov

BB: Bluemlein, Boetcher

AAC: Asymmetry Analysis Collaboration

NNPDF (early stage)

JAM (Jefferson Lab Angular Momentum Collaboration)

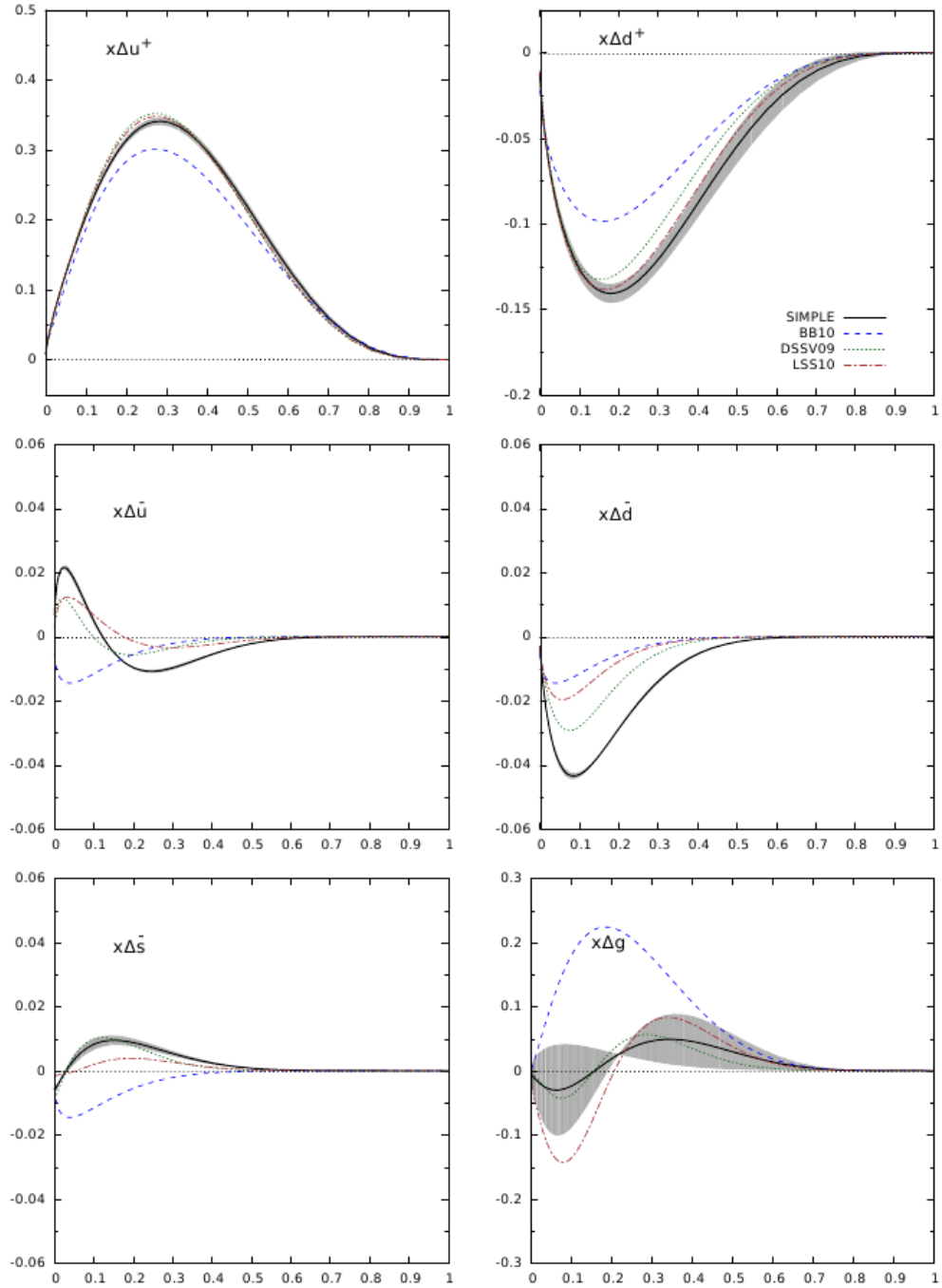
[with A. Accardi, W. Melnitchouk and representatives from JLab Hall A, B, C]

Example of polarized PDFs

Structure Functions

Semi-inclusive DIS

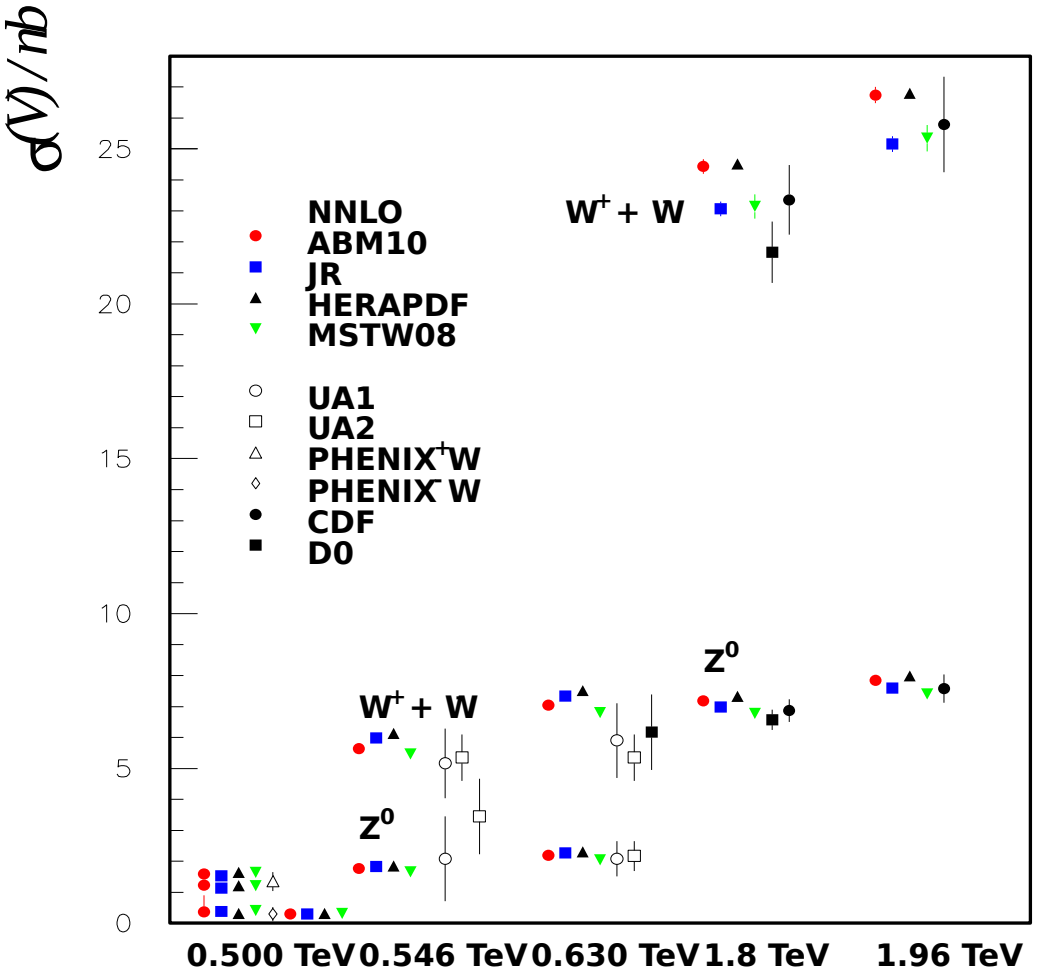
proton-proton

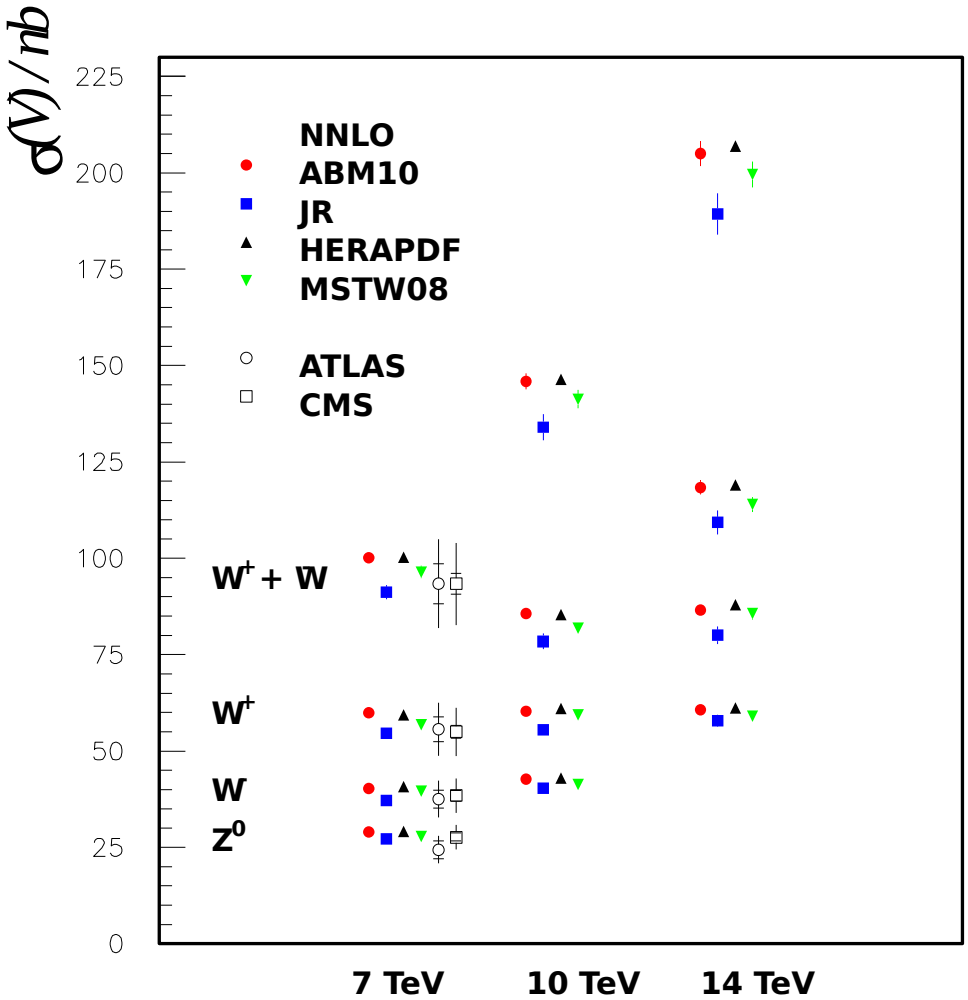


We will concentrate
on the unpolarized case

Benchmark predictions

Cross sections which are well under control serve as *benchmarks*

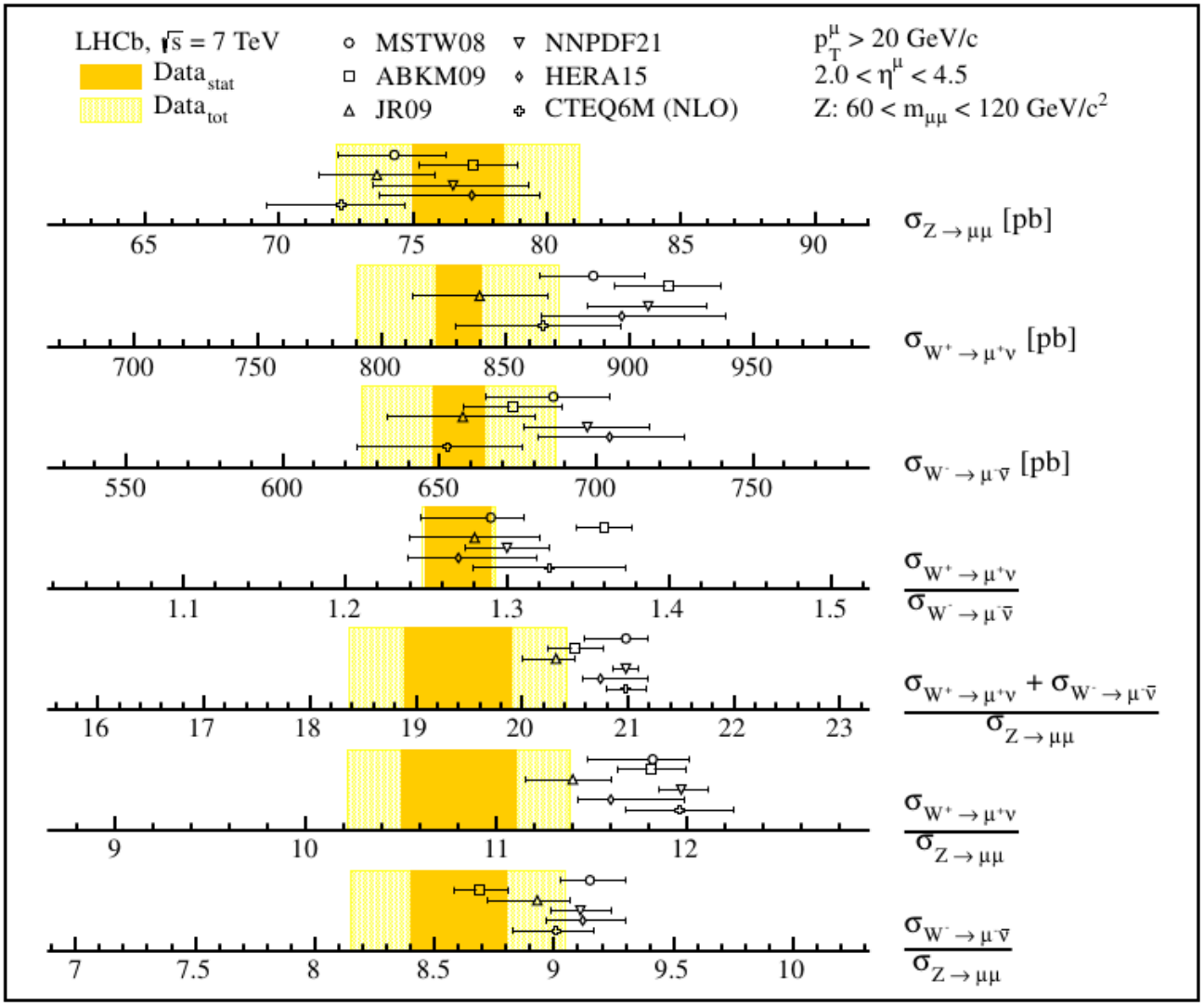




In general there is agreement between different predictions, although with some spread among the groups

Benchmark predictions

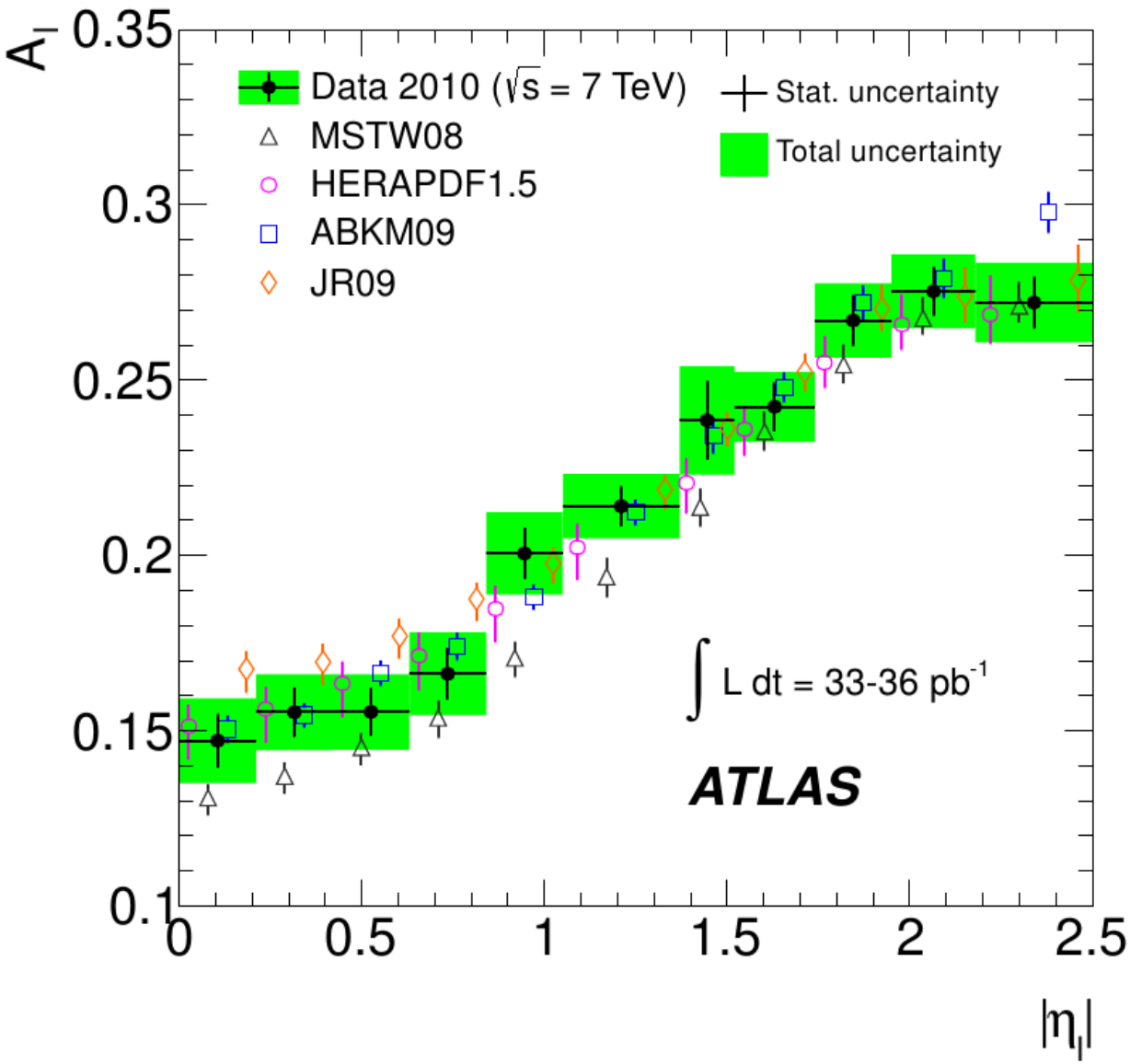
Cross sections which are well under control serve as *benchmarks*



They have been measured during the first phase of LHC

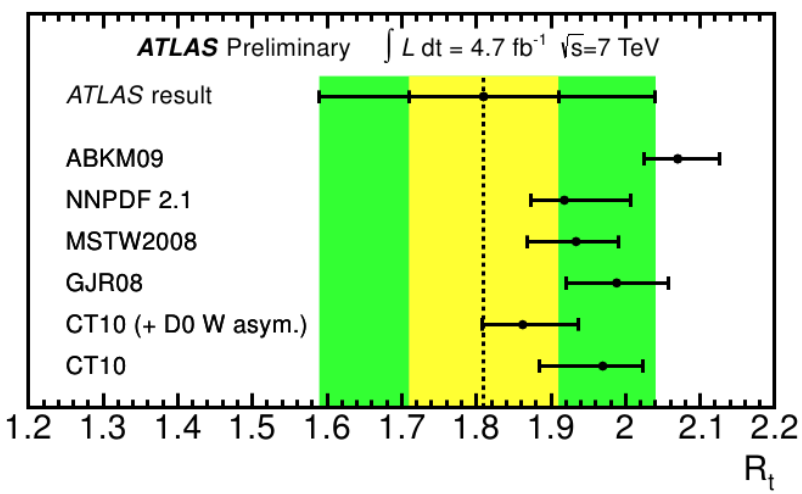
Benchmark predictions

Differential cross-sections (*distributions*) and ratios are more sensitive



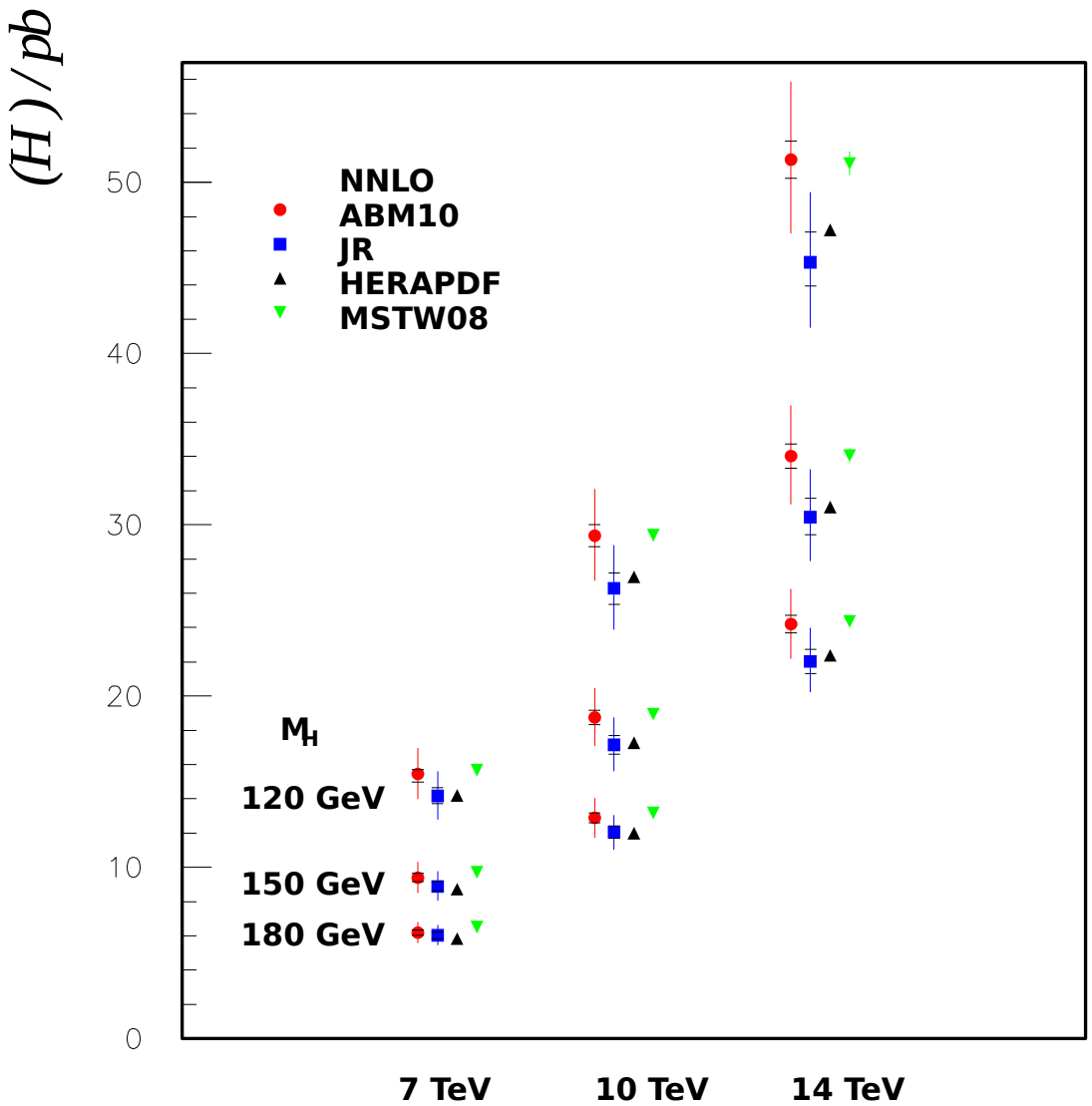
$$A_l = \frac{d\sigma_{W^+} - d\sigma_{W^-}}{d\sigma_{W^+} + d\sigma_{W^-}}$$

Single top $t/\bar{t}$ ratio



Higgs production at LHC

Predictions for Higgs production via *gluon-gluon fusion* (dominant at LHC)



Very briefly speaking:

NNLO mandatory (20% difference)

20% *Total* uncertainty

5% QCD theory

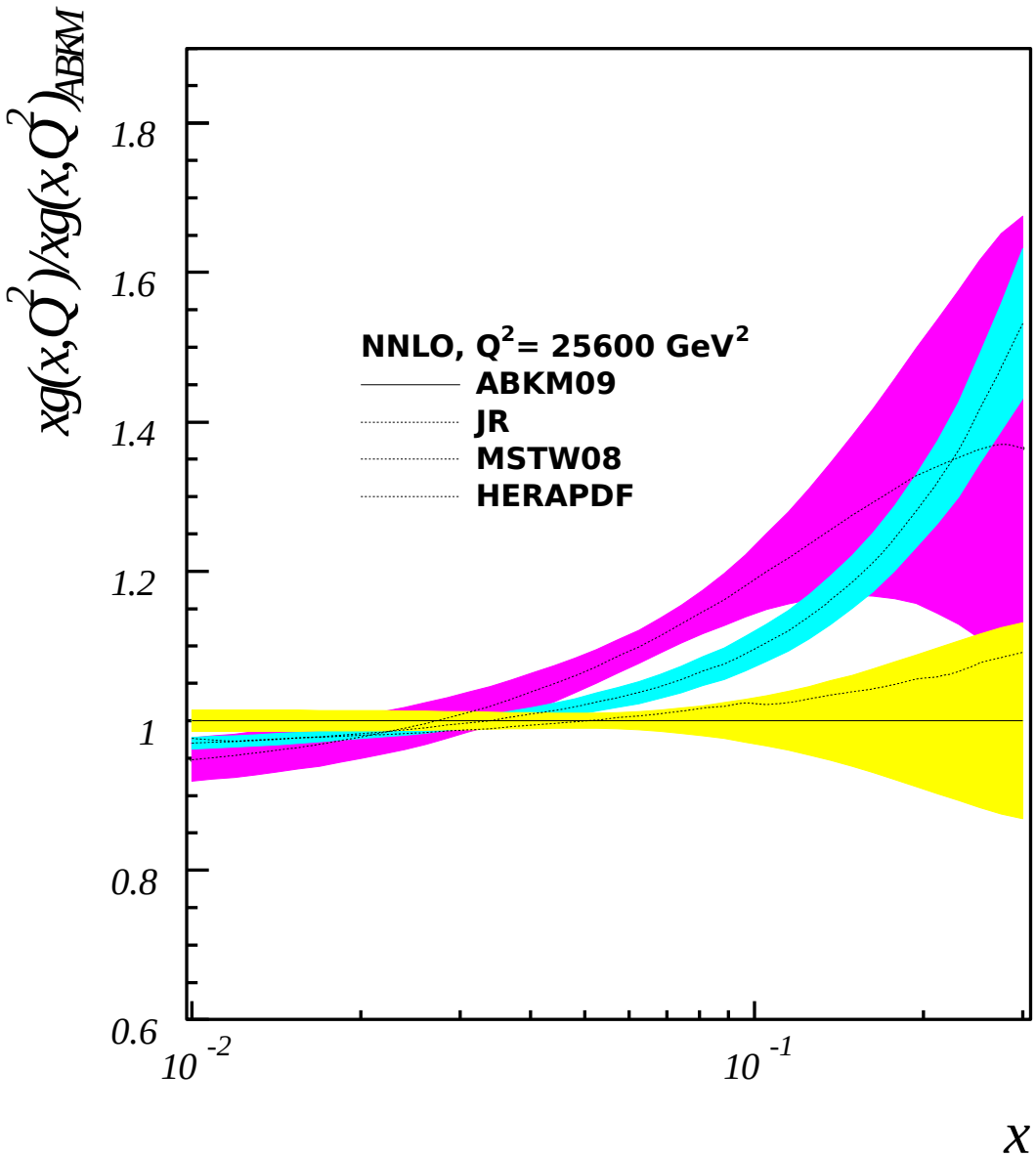
5% PDF individual

10% Different groups

A more *precise* PDF determination is *crucial*!

Higgs production at LHC

Differences *partly* understood: gluon distributions, $\alpha_s(M_Z)$ values, etc.



There are inter-collaborative efforts (PDF4LHC, Higgs WG) to compare, explain and reduce differences

Improvements in the individual analyses (theory, tools, and data) are *needed* to increase precision

Leading role in the development of several ideas in this direction

Conclusions and outlook

- We are (and will be) living exciting times in high-energy physics:
  - the Standard Model has recently been completed
  - we are (experimentally) looking for new physics beyond
  - QCD reaching ever greater precision

- A *precise* knowledge of the partonic structure of the nucleon (PDFs) is not only a goal in itself, but also *crucial* for the planning, analysis, and interpretation of high-energy experiments

- I will be contributing with:
  - the development of Monte Carlo event generators (**ANTJETS**)
  - the extraction of polarized (**JAM**) and unpolarized (**JR**) PDFs

Thank you for your attention!!