Modern hadron colliders era: proton dynamics, the quest for precision and new physics searches

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Outline

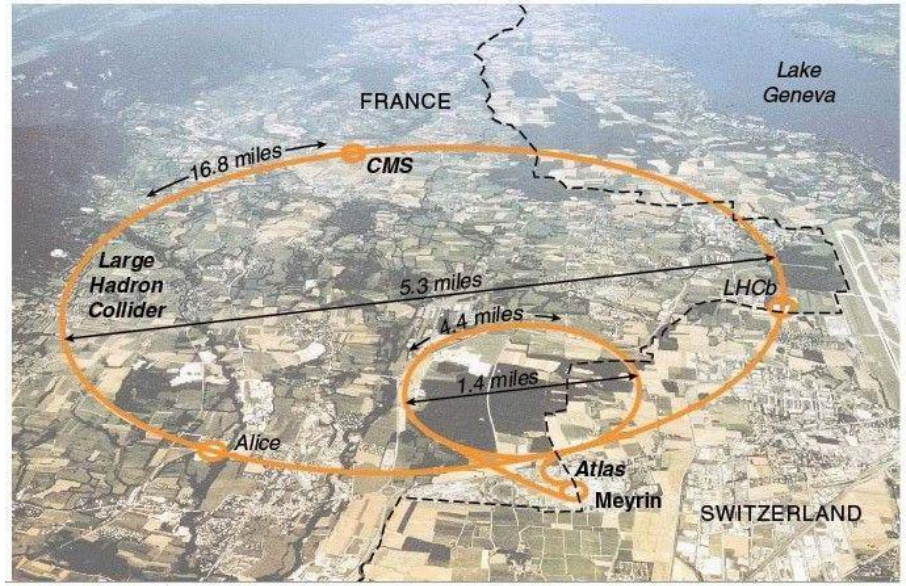
- Particle accelerators
- Particle Physics: exciting times ahead of us
- Quest for precision
- Inside a proton
- New Physics searches

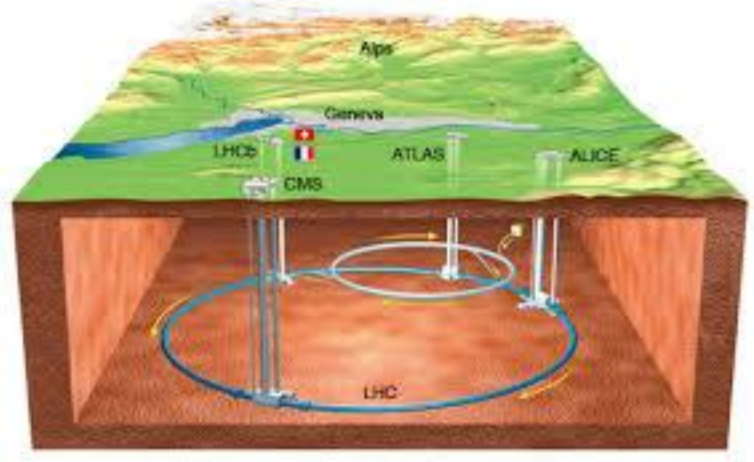
Particle Accelerators

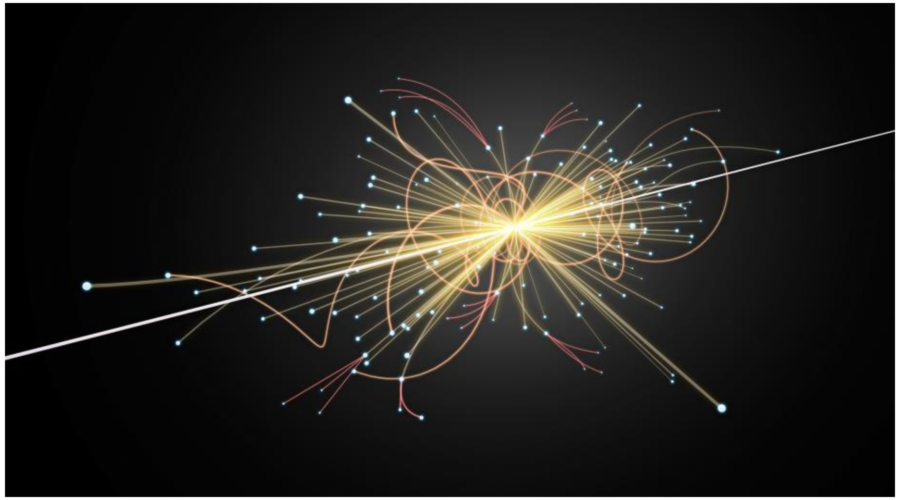
Several accelerators around the world (to name a few):

- RHIC, Brookhaven National Laboratory, NY
- SLAC Linac, SLAC National Accelerator Lab, CA
- JPARC, Tokay Ibaraki, Japan
- CEBAF, Thomas Jefferson Lab, Newport News, VA
- Dafne, Frascati, Italy
- UNILAC, GSI Helmholtz Centre, Germany
- **Electron Ion Collider (EIC) (to be built in Brookhaven)**
- **Large Hadron Collider, CERN,** (The European Organization for Nuclear Research), Swiss
- LHeC (CERN's Large Hadron electron Collider) awaiting approval
- FCC-eh (Future Circular lepton-hadron Collider) awaiting approval
- ……

The Large Hadron Collider (LHC)

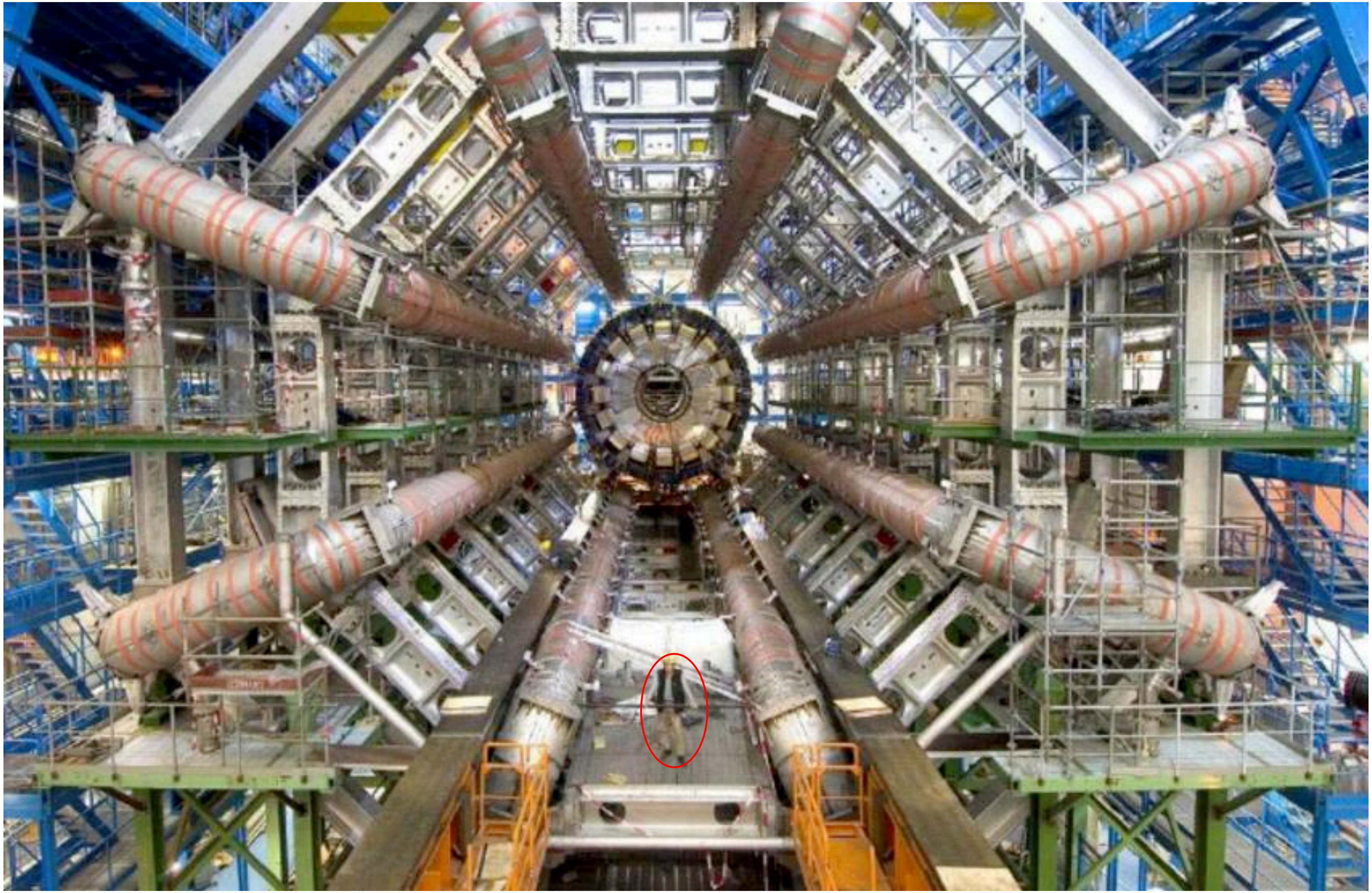




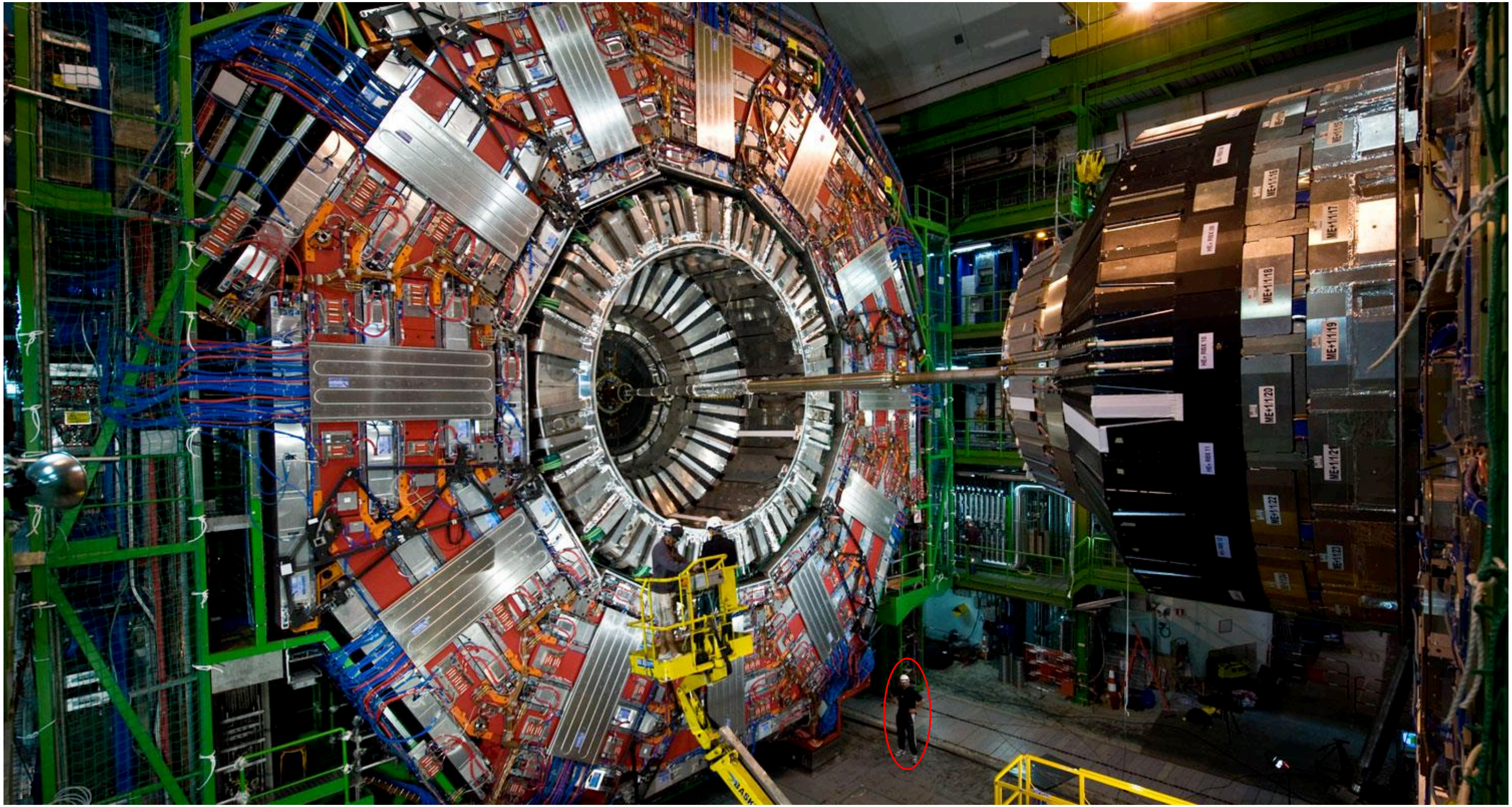


The CERN Large Hadron Collider is up and running (Run III) colliding protons at the largest center of mass energies ever: 13.6 TeV.

It really is large

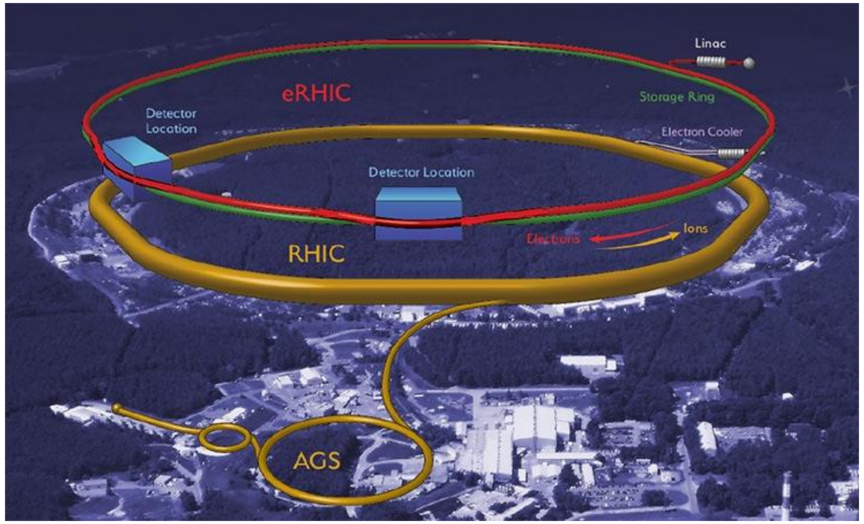


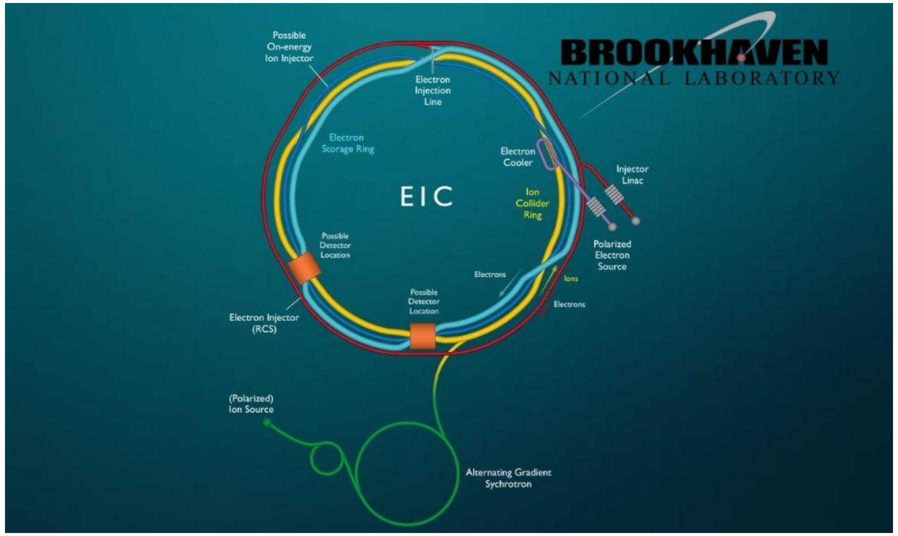
ATLAS DETECTOR

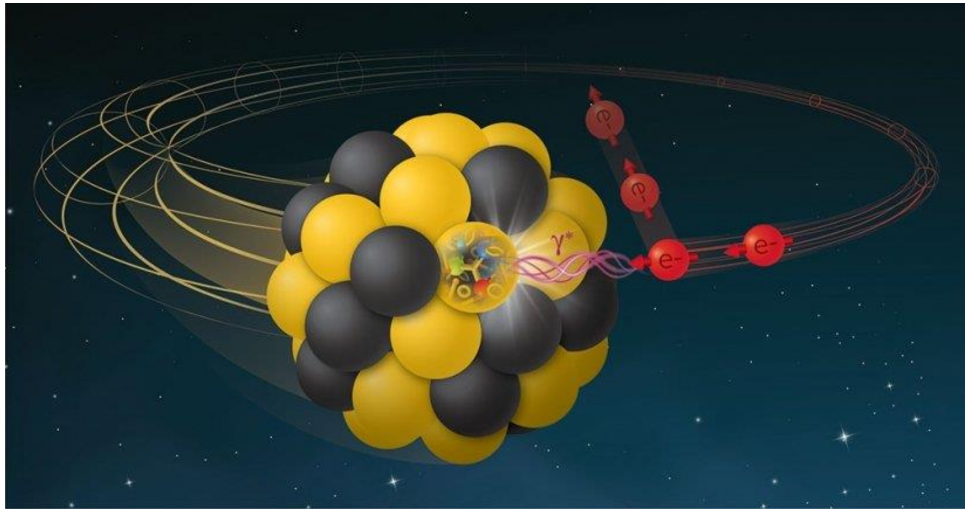


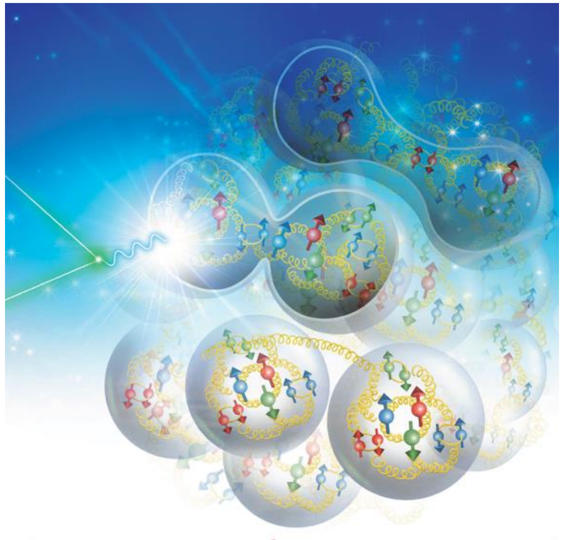
CMS DETECTOR

The Electron Ion Collider (EIC)



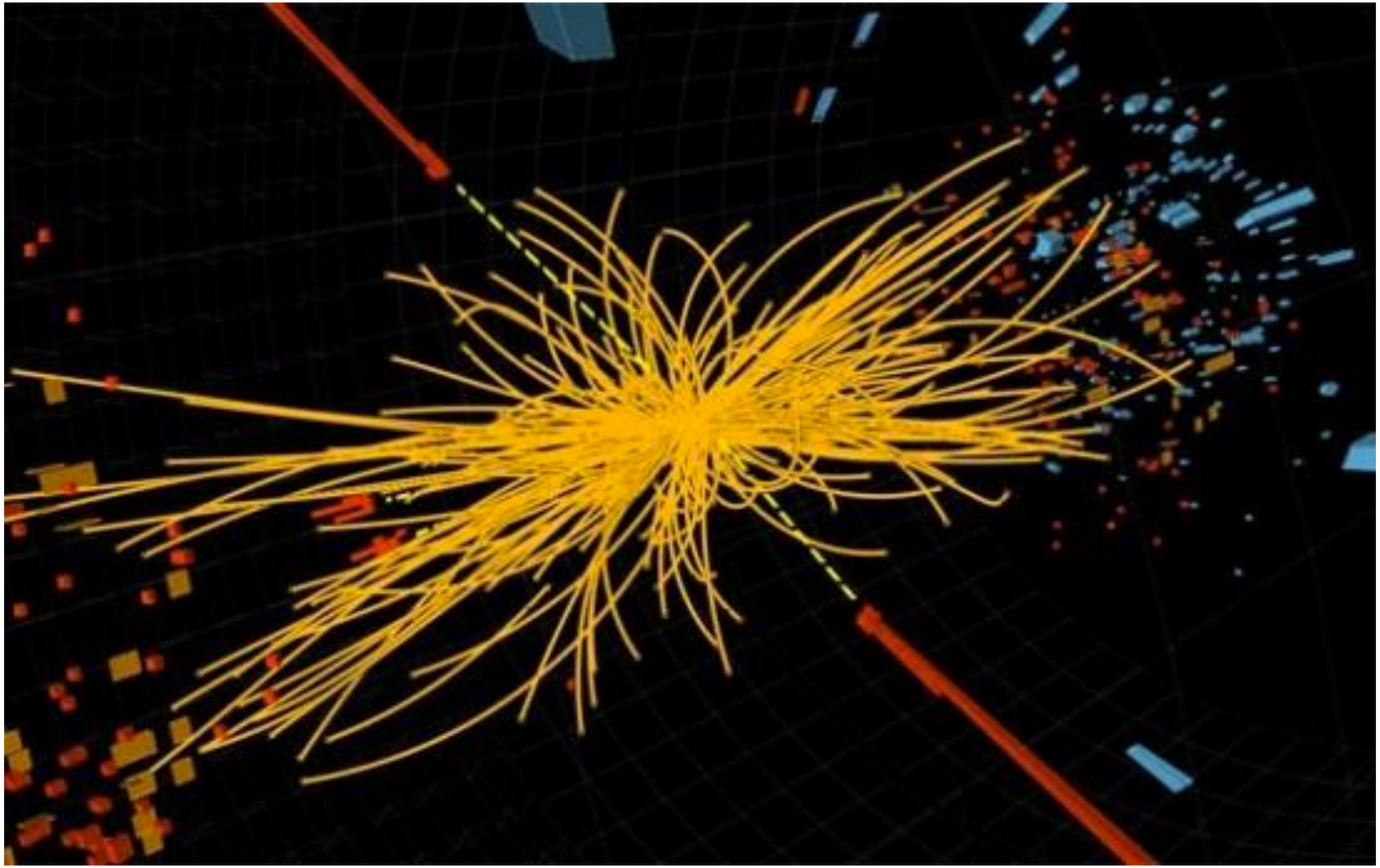






EIC: electron-nucleus collider with energies 20 - 140 GeV

At colliders, particles are smashed into each other at very high energy. A very complicated final state is produced, populated by thousands of particles



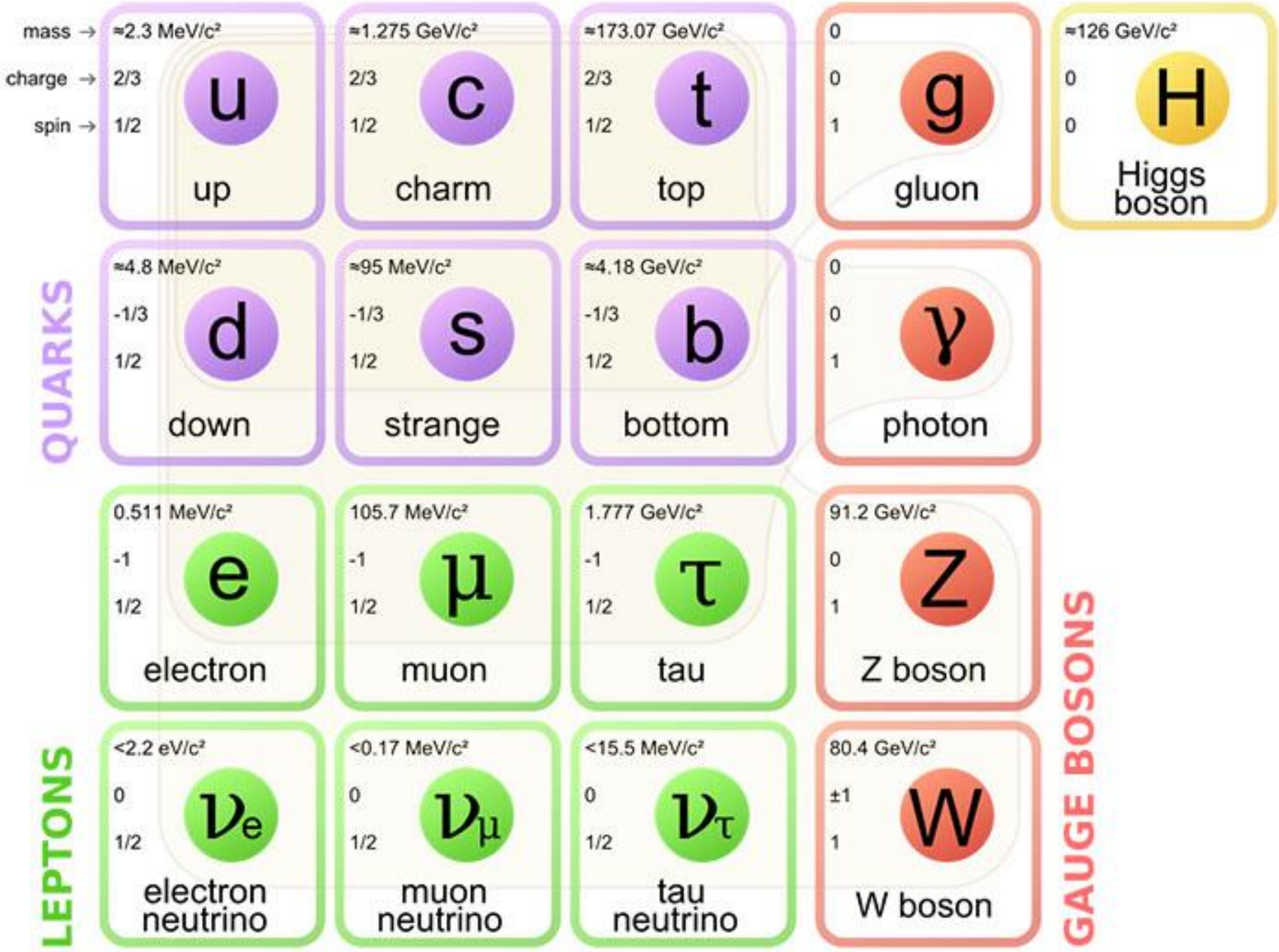
Detectors, plus sophisticated algorithmic procedures allow us to discriminate the ``signal'' from ``noise'' (background)

Modern particle accelerators provide us with a great opportunity to answer some of the most fundamental open questions in Physics

- Higgs boson's properties
- Electroweak Symmetry breaking
- SUSY?
- Origin of mass
- Origin of proton's spin
- New physics interactions
- Dark Matter, dark energy
- ….

A future synergy between the LHC and EIC will shed new light on them.

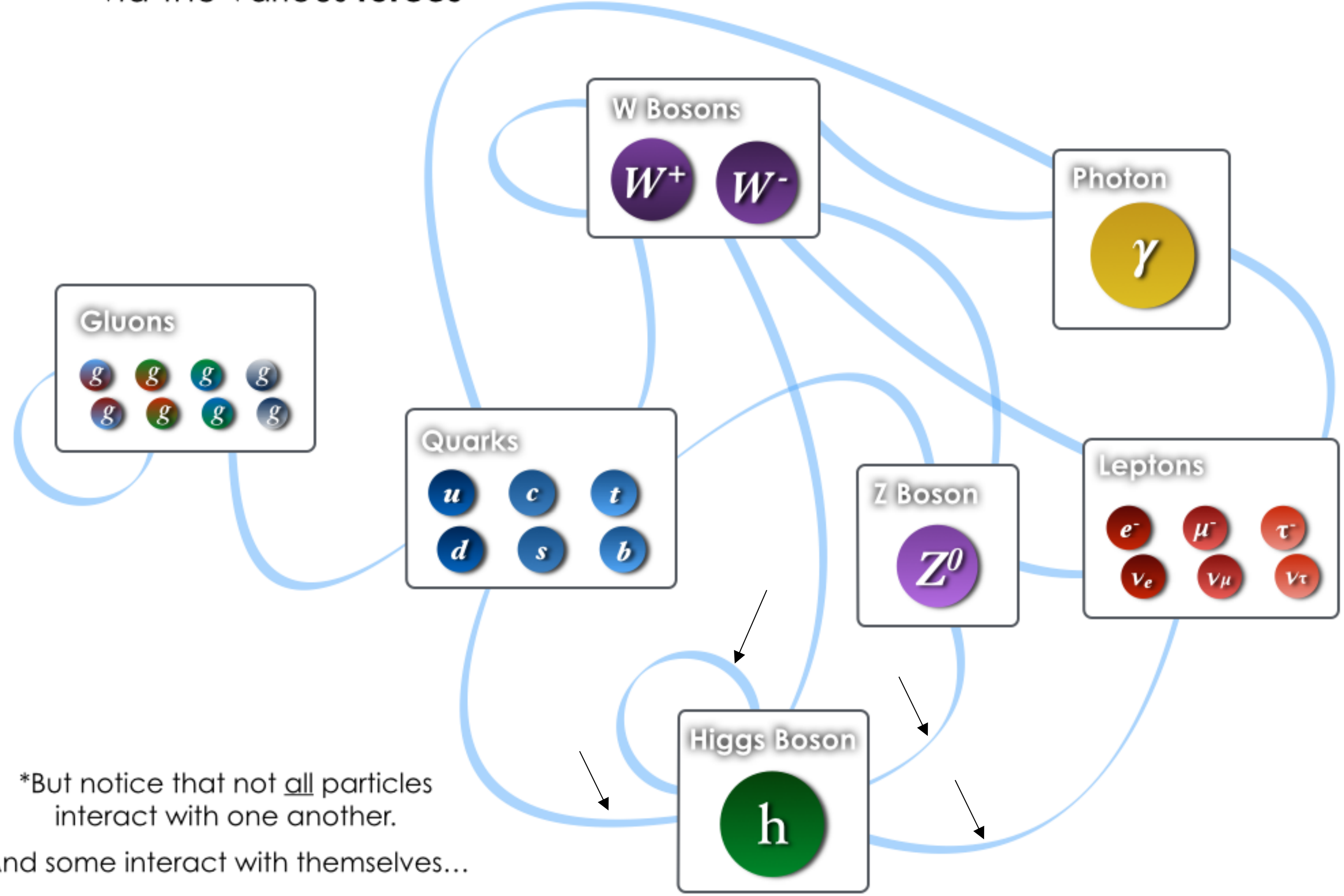
Standard Model: where we stand



Discovered at the LHC in 2012 after being theoretically predicted (at the same time) by theoretical physicists Brout, Englert, and Higgs in 1964.

Crucially the **fundamental particles** are all **connected to one another** *via* the various **forces***

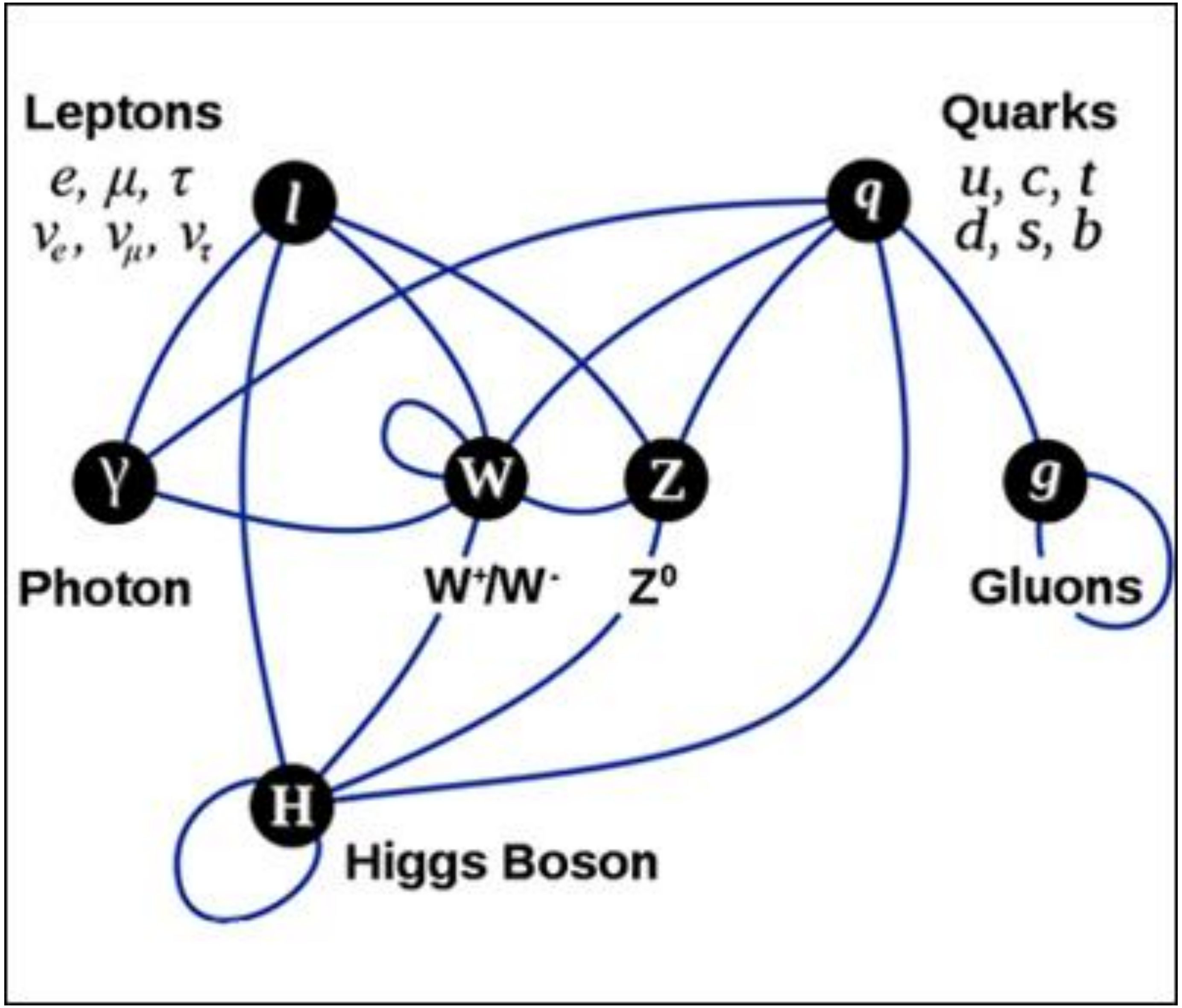
LHC is going to investigate Higgs boson couplings the with the other SM particles with higher precision in the next runs.



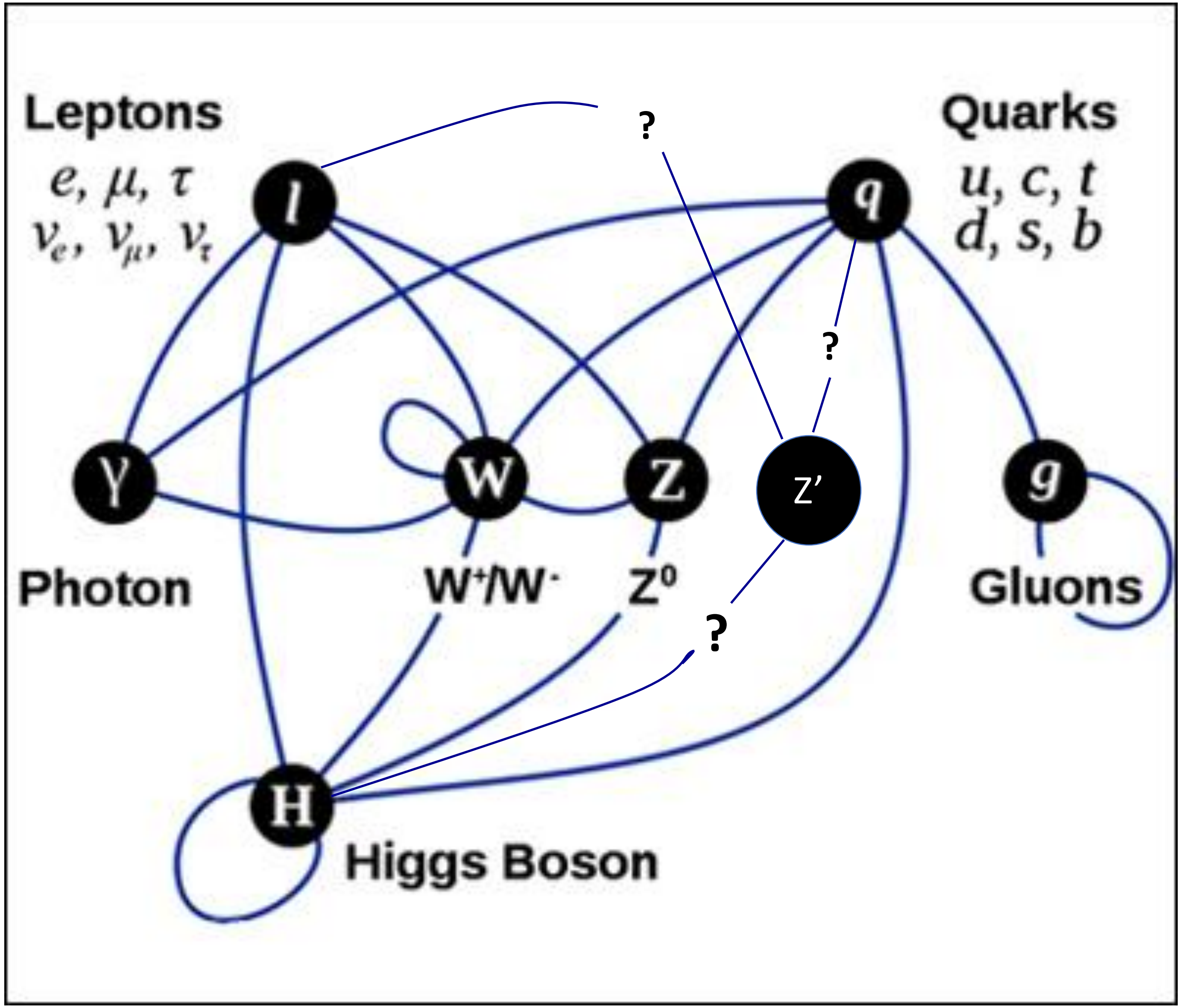
*But notice that not all particles interact with one another.

And some interact with themselves…

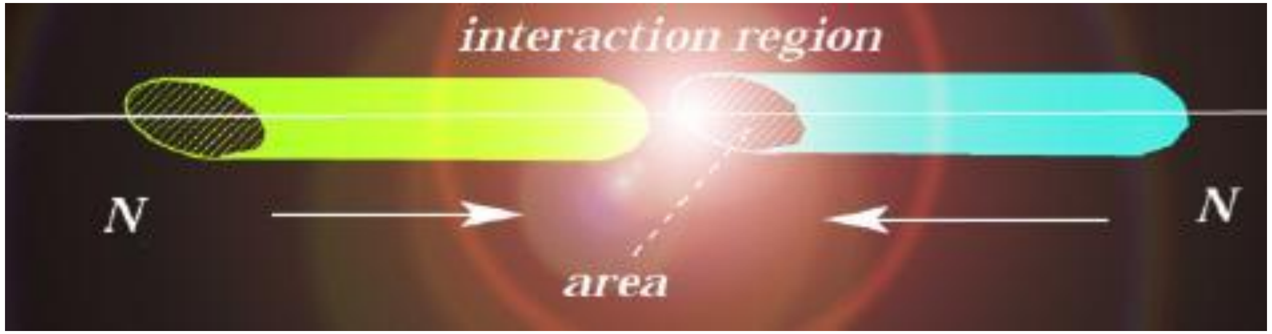
Are there other electroweak (EW) interaction carriers ?



Are there other electroweak (EW) interaction carriers ?



Discovery and precision machines



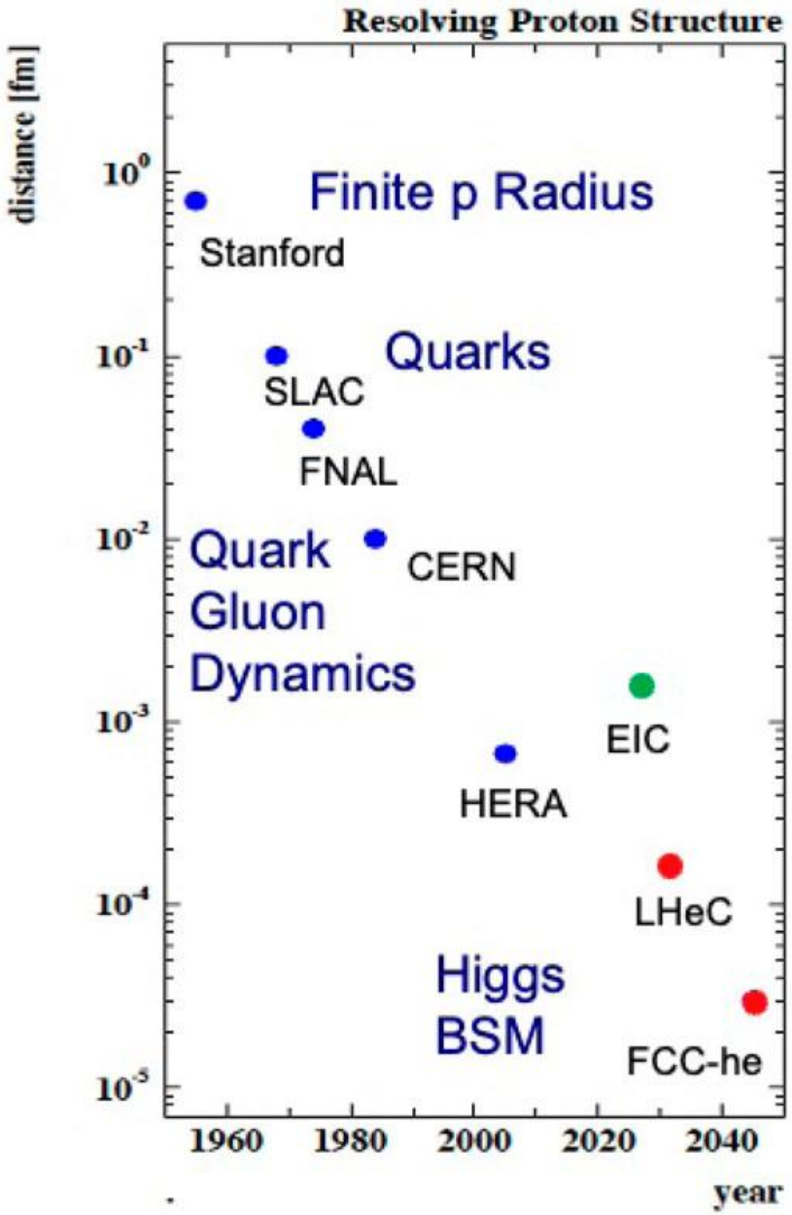
The CERN LHC: Collides protons at center of mass energy ($\sqrt{S}$) of 13.6 TeV.
With a luminosity* L = 10^{34} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ the LHC detectors can produce 10^{34} collisions per second and per cm^2.
It can look inside protons with high precision and has the potential to discover new particles.

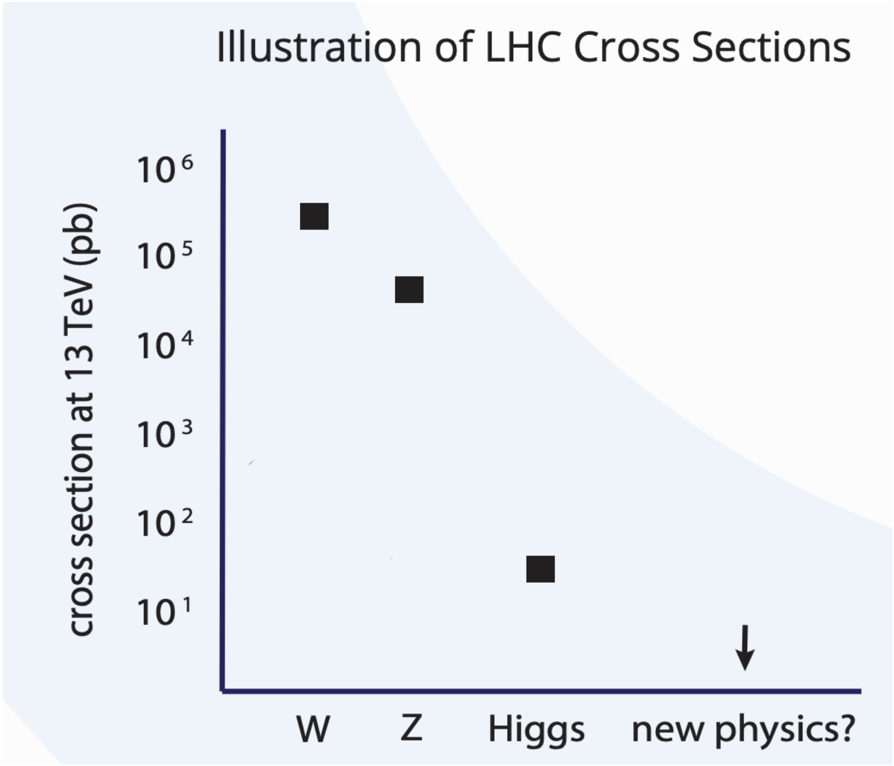
The EIC at RHIC: will collide electrons and ions. Can use spin-polarized protons with L =$10^{33} - 10^{34}$ $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$.
The hadron beam will use a wide range of particle species (p, Au, U, …) and energies (up to 255 GeV for protons).
Electrons are clean probes: EIC will be able to look inside protons with unmatched precision.

More particles are packed on the right

*Instantaneous luminosity: measures how tightly particles are packed into a given space, such as the LHC's proton beam.
A higher luminosity means a greater likelihood particles will collide and result in a desired interaction.

Structure of the proton resolution power

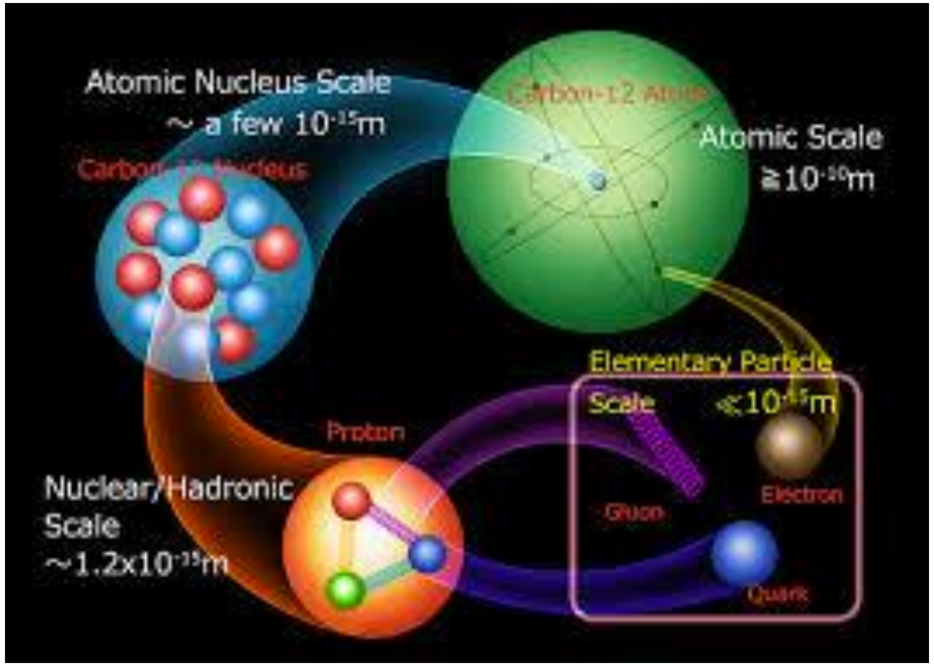




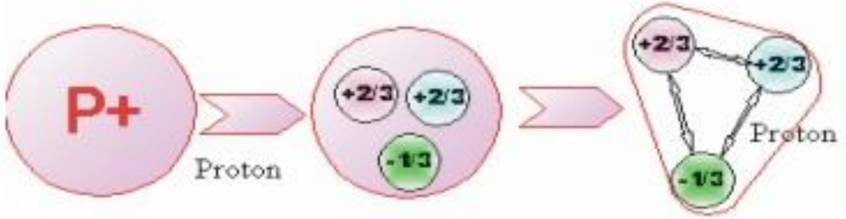
ATLAS cheat sheet

Brüning et al. Front. Phys. (2022)

Hadron colliders allow us to study in detail the strong nuclear force, that binds quarks into protons and other non-elementary particles, and to explore the other fundamental forces of nature.



The strong nuclear force is known as QCD:
Quantum ChromoDynamics.



$$\mathcal{L}_{QCD} = -\frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a + \sum_f q_f [i\gamma^\mu D_\mu - m_f] q_f$$

with the gluon field strength tensor

$$G_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu + g\, f^{bc}_{\ \ a} A_b^\mu A_c^\nu$$

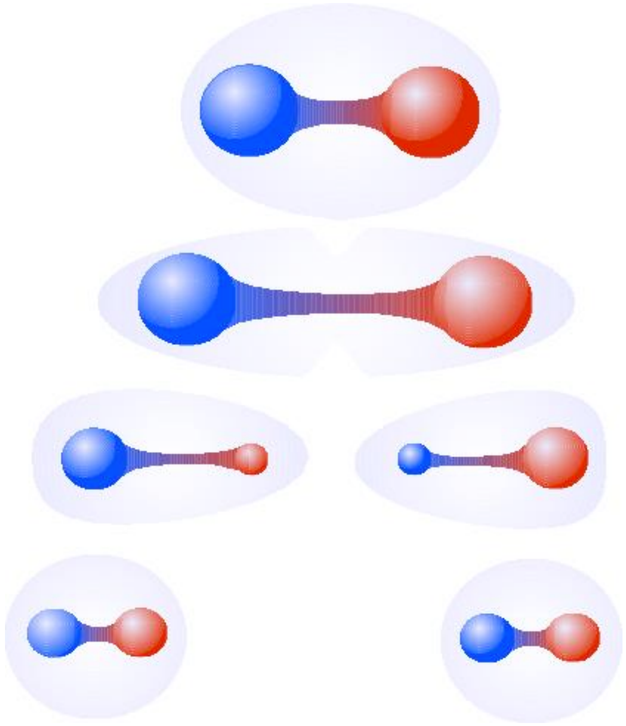
and the gauge covariant derivative

$$D^\mu = \partial^\mu - i\frac{g}{2} A_a^\mu \lambda^a$$

It is a generalization of the electromagnetic force, but there are differences that make QCD highly counterintuitive:

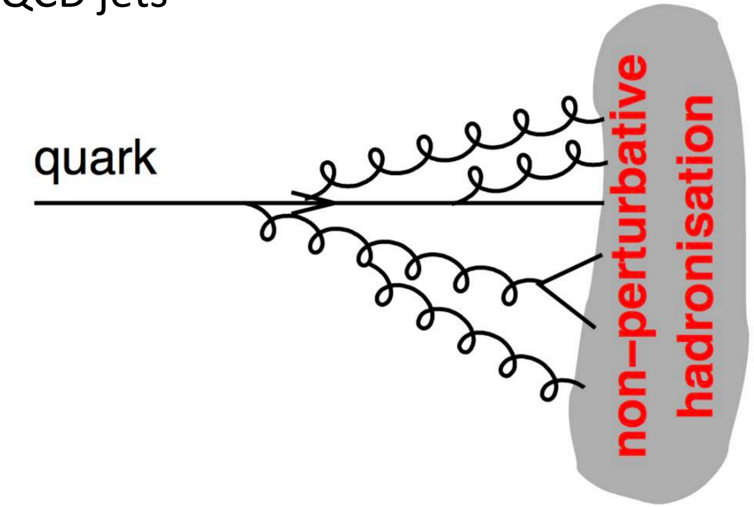
QCD has, among others, two remarkable properties:

Color Confinement: quarks and gluons are confined into hadrons (protons, neutrons, pions...). They have never been observed as isolated particles.



If energy is supplied to the quarks, the gluon tube elongates until it reaches a point where it "snaps" and forms a quark–antiquark pair. Thus, single quarks are never seen in isolation.

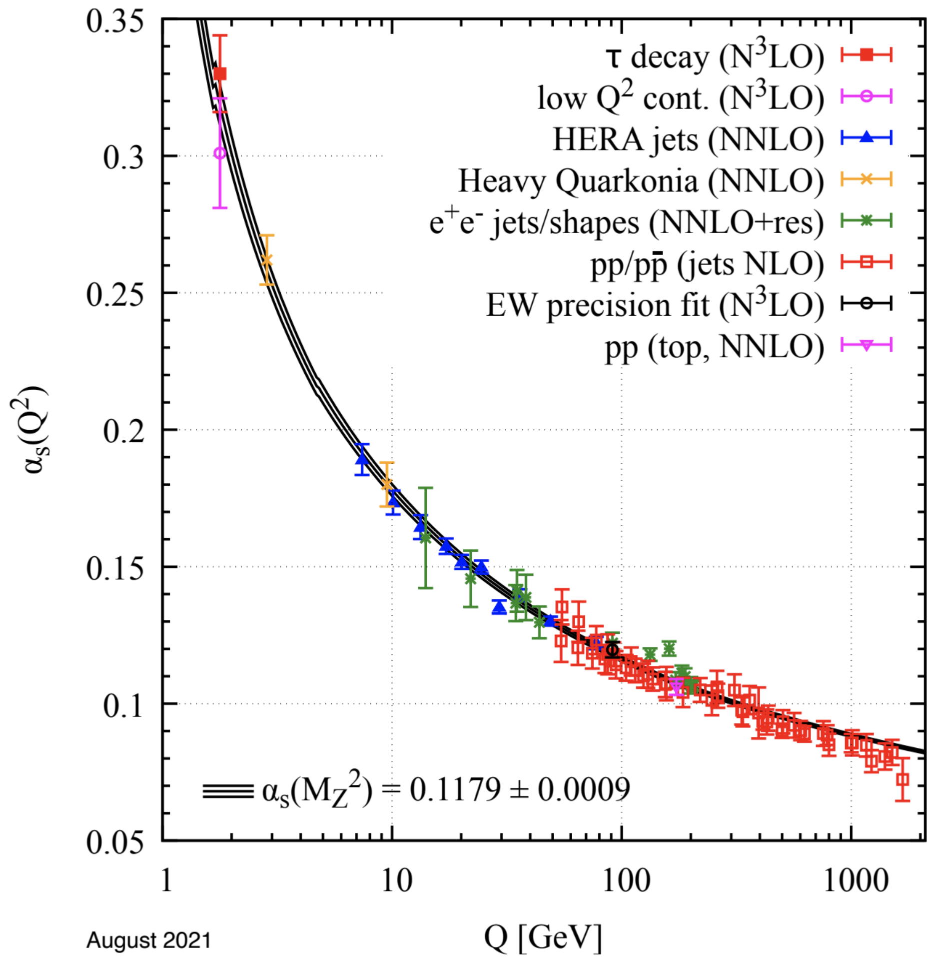
QCD jets



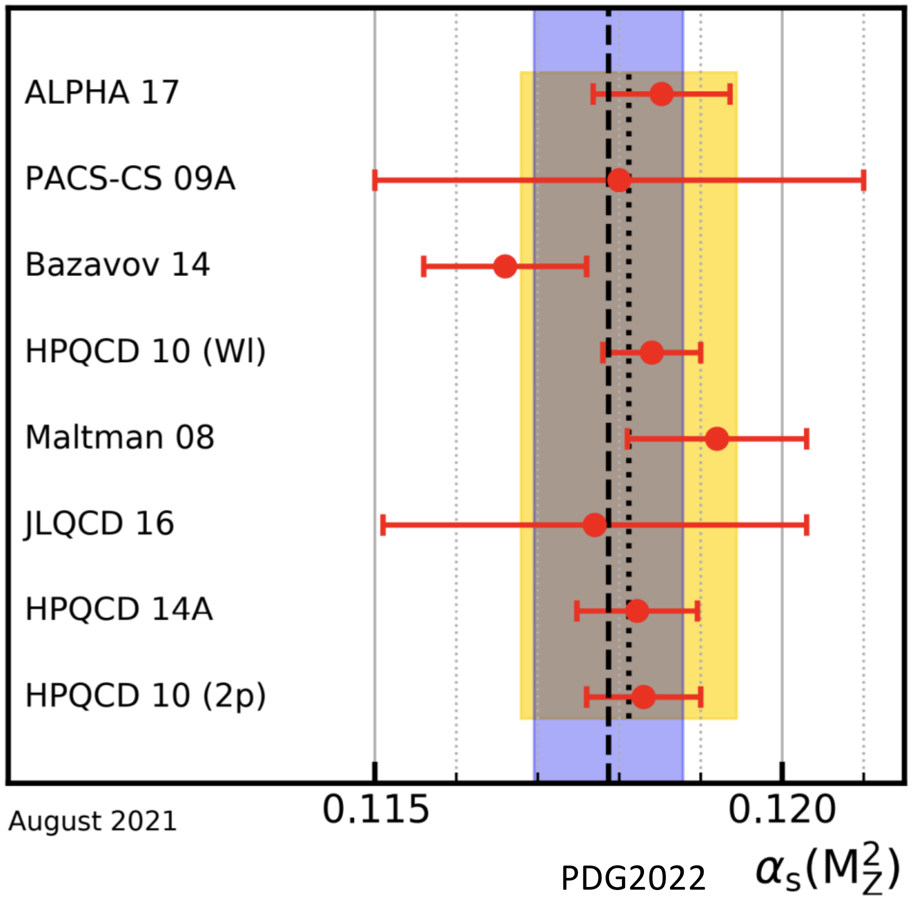
A jet is a narrow cone of hadrons and other particles produced by the hadronization of a quark or gluon

The confinement scale is that at which the perturbatively defined strong coupling constant $\alpha_s(\Lambda)$ diverges. This is known as the Landau pole ($\Lambda \cong 300$ MeV).

Asymptotic Freedom: the force between two strongly charged particle decreases when they are brought closer together



Lattice: non-perturbative approach to solving the QCD

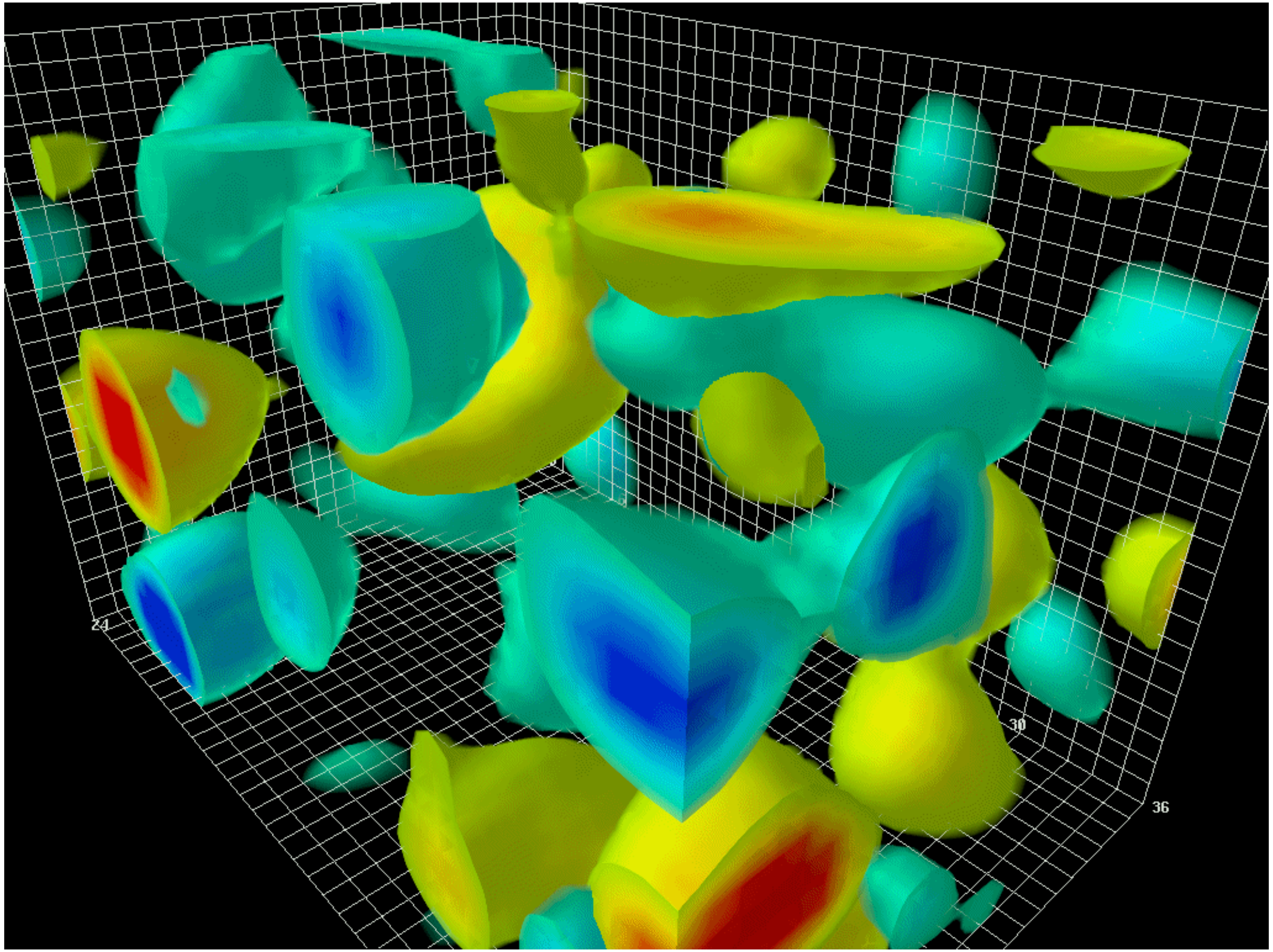


$$\frac{d\alpha_s(Q^2)}{d\ln(Q^2)} \equiv \beta(\alpha_s(Q^2)) = -\left(\beta_0\alpha_s^2 + \beta_1\alpha_s^3 + \beta_2\alpha_s^4 + \dots\right)$$

Gross ,Wilczek, Politzer: 2004 Nobel prize winners

A very rich and complicated dynamics!

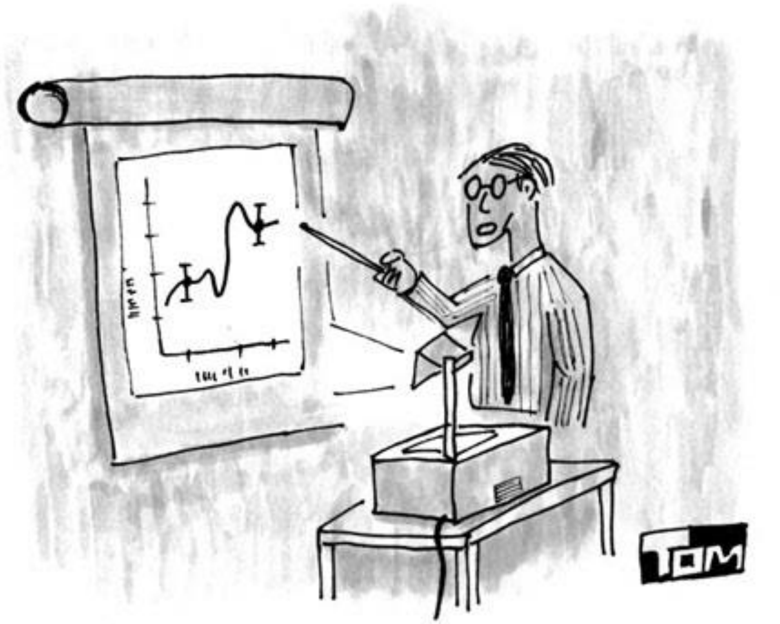
The QCD vacuum is not really empty!



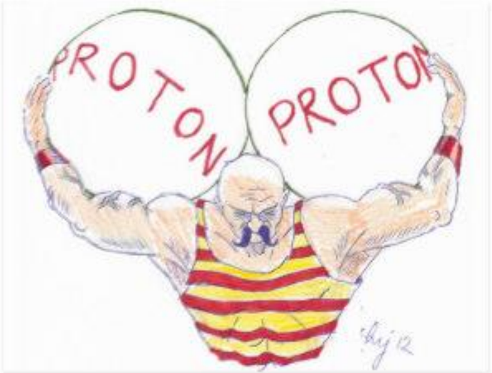
Vacuum properties of QCD in a box that can hold two protons

Image animation credits: [Derek Leinweber]

The quest for precision



" WE CAN SEE HERE THAT THE AGREEMENT WITH THEORY IS EXCELLENT "



The LHC already brought us in a new realm of precision

LHC collisions are produced at unprecedented energy. Physics observables are measured with unmatched precision.

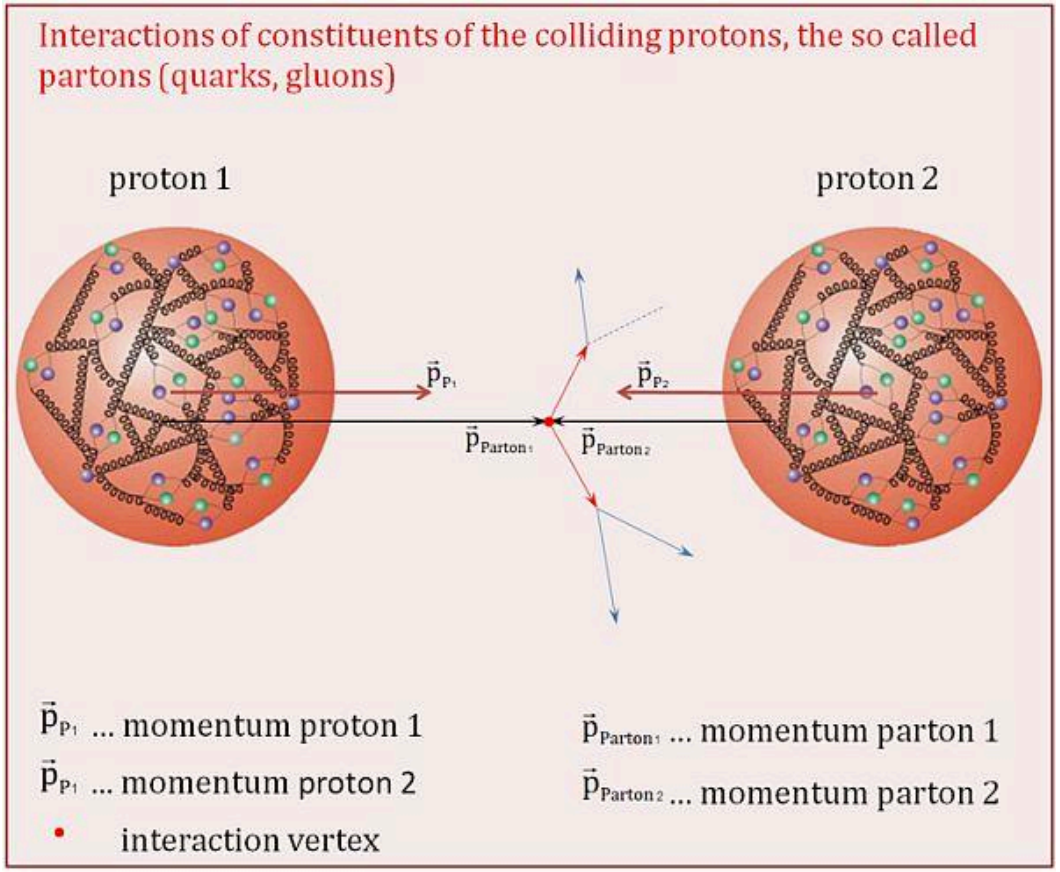
⬇

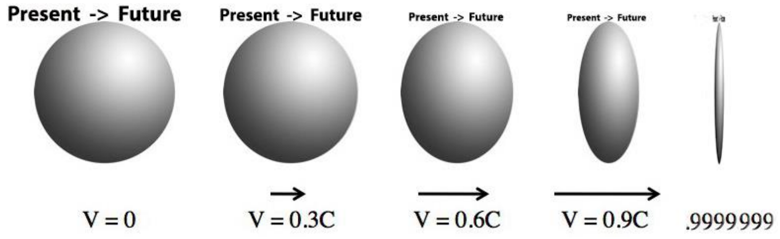
Theory predictions with comparable precision and accuracy are indispensable to:

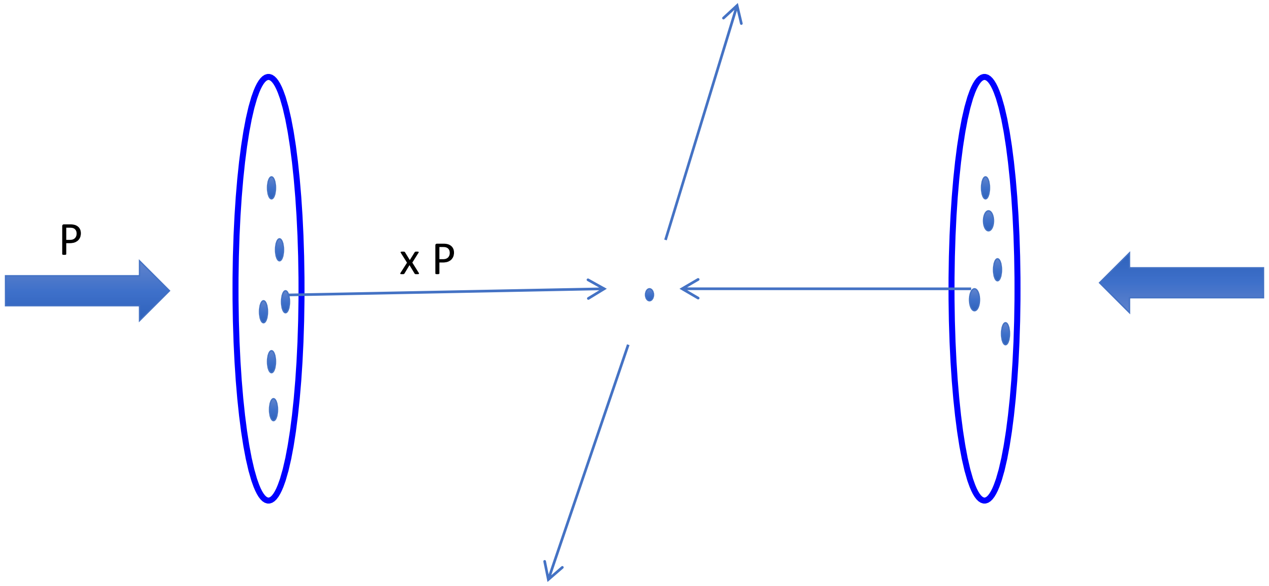
- set stringent tests on the Standard Model (SM),
- search for signatures of new physics Beyond the Standard Model (BSM)

When two protons collide

…it’s like smashing two pancakes with chocolate chips onto each other





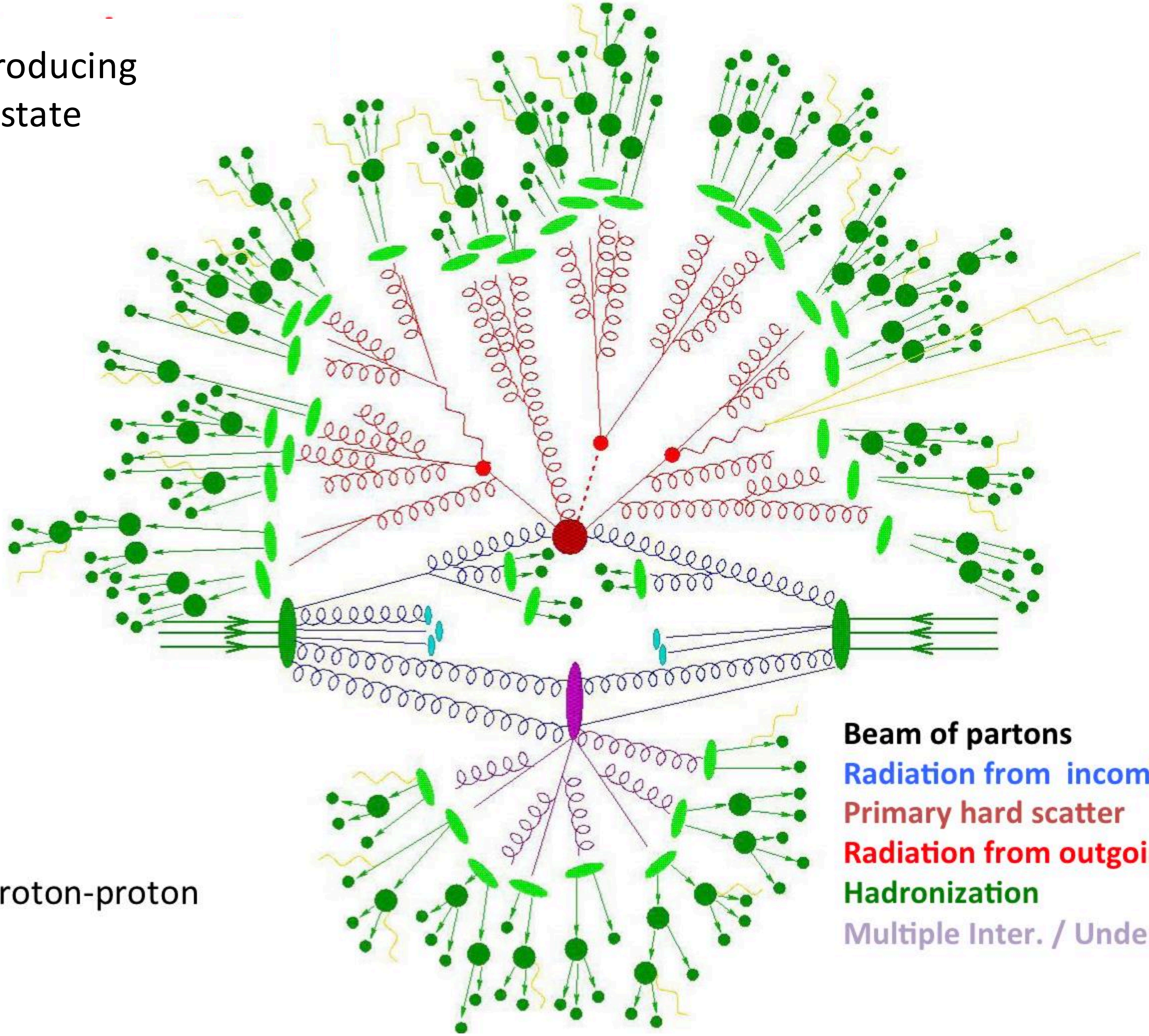


x = fraction of the initial proton’s longitudinal momentum

Protons appear like disks because of Lorentz contraction.
They travel at 99.9999991% the speed of light.
The constituent partons are spread on each disk.

… or a bit more realistically, in terms of elementary processes

Protons break up producing
a complicated final state
with thousands
of particles



Typical proton-proton
collision

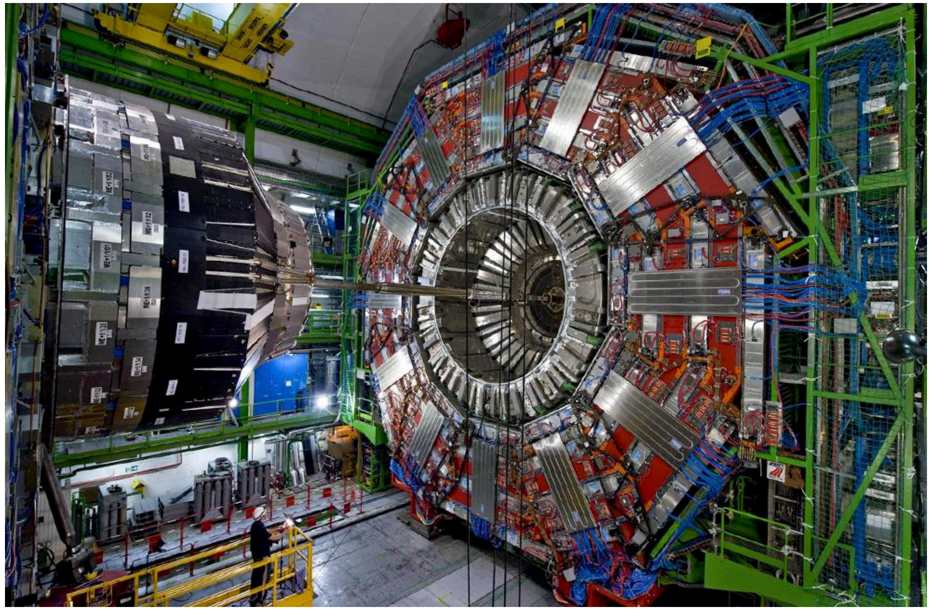
Image by F. Krauss

Quest for precision: what does it take to make a precise theoretical prediction at the LHC?

``Precisely'', what do we calculate? What do we observe?

- In particle collision experiments we count (observe) events relative to a specific collision (process) in our detector.

- The theory calculation predicts how many events are expected to be seen in the detector.



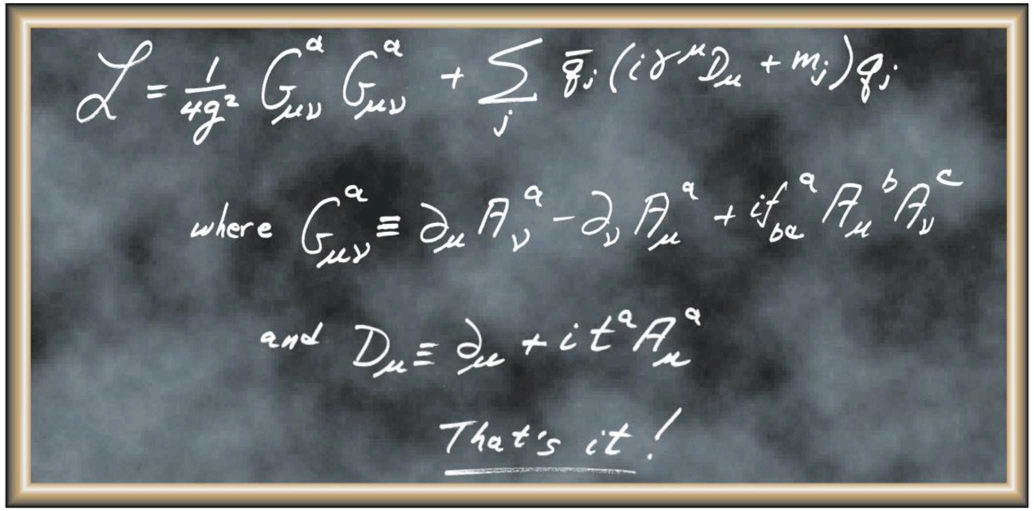


FIGURE 1. THE QCD LAGRANGIAN $\mathcal{L}$ displayed here is, in principle, a complete description of the strong interaction. But, in practice, it leads to equations that are notoriously hard to solve. Here m_j and q_j are the mass and quantum field of the quark of jth flavor, and A is the gluon field, with spacetime indices μ and ν and color indices a, b, c. The numerical coefficients f and t guarantee SU(3) color symmetry. Aside from the quark masses, the one coupling constant g is the only free parameter of the theory.

What does it take to make a precise theoretical prediction at the LHC?

How do we precisely estimate the theory rate at which events occur? This is given by a simple calculation

$$N_{\mathrm{ev}}/\mathrm{sec} = L \cdot \sigma$$

Can theoretically be calculated

N_{ev}/sec = number of events per second

L = luminosity: number of collisions that can be produced in a detector per cm^2 and per second.
At the LHC, L =10^(34) cm^(-2) s^(-1) .

σ = cross section: describes the probability that two particles collide.
(It´s measured in "barn": 1 barn = 10^(-24) cm^2)

The theory cross section is (approximately) the product of two quantities!

Then we can compare to the experimental measurements

cross section

collisions between protons constituents

$$\sigma = \sum_{\text{partons}=i,j} f_i \otimes f_j \otimes \hat{\sigma}_{ij}$$

+ tiny corrections if energy is high

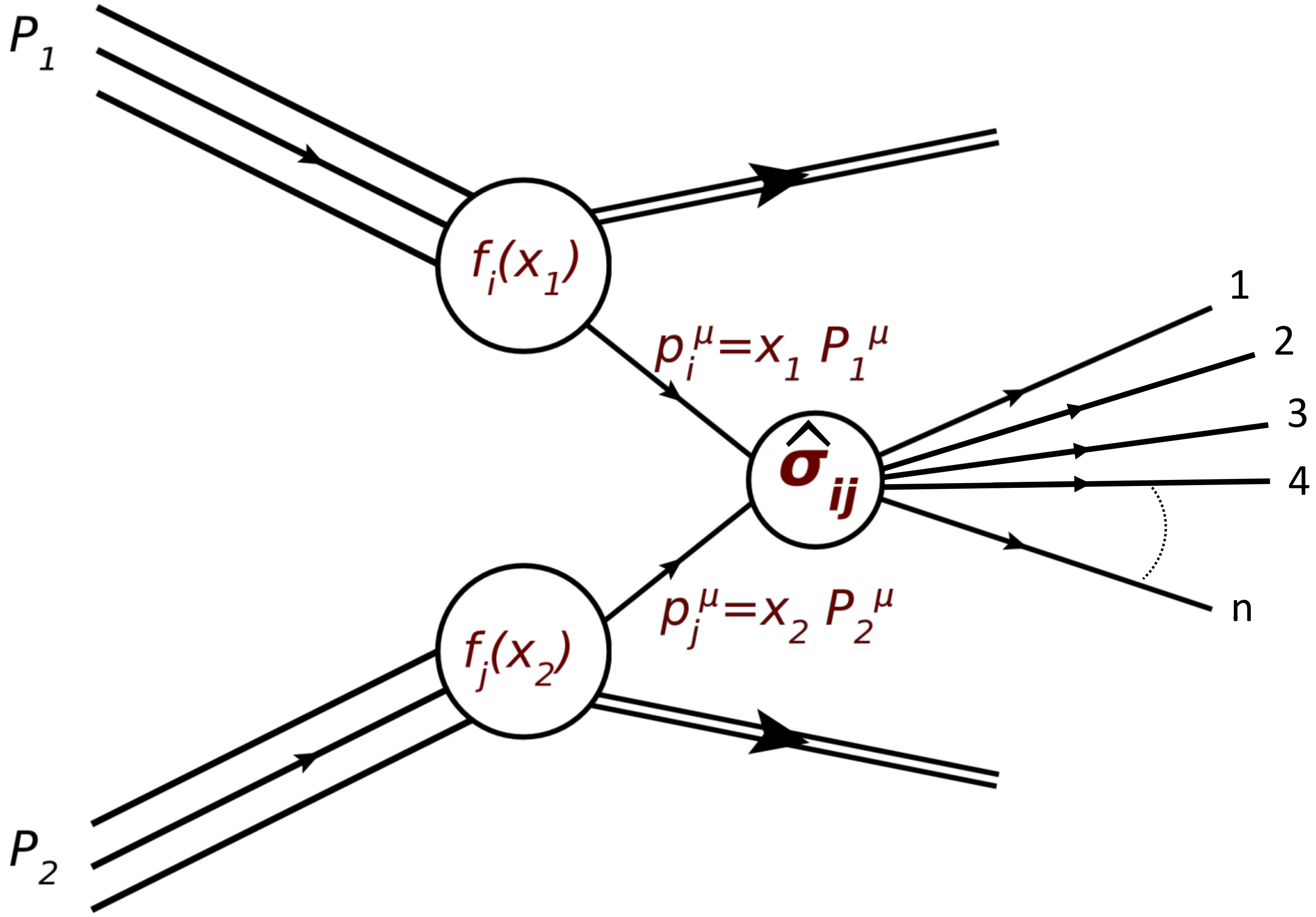
Inner structure of the proton

partons = proton's constituent quarks and gluons

f_i = parton distribution functions (PDFs) of the proton: universal probability that parton i is emitted by the proton at a certain energy scale: $f_i(x, Q^2)$

$\hat{\sigma}$ = hard scattering cross section: it depends on the elementary process we consider

Representation of a collision between protons at high energy

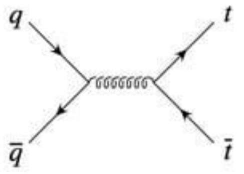


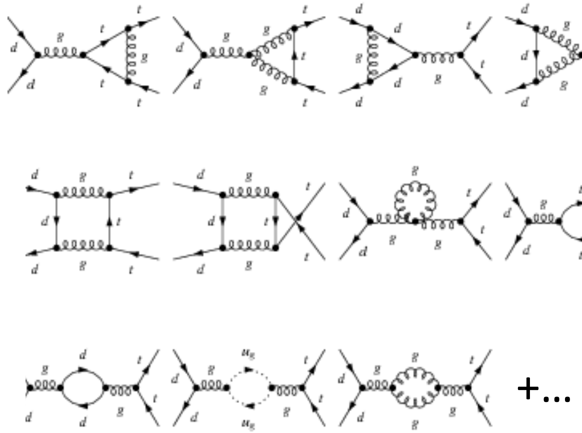
$f_i(x_1)$ = ? $\hat{\sigma}_{ij}$ = ?

A precise theory prediction at parton level

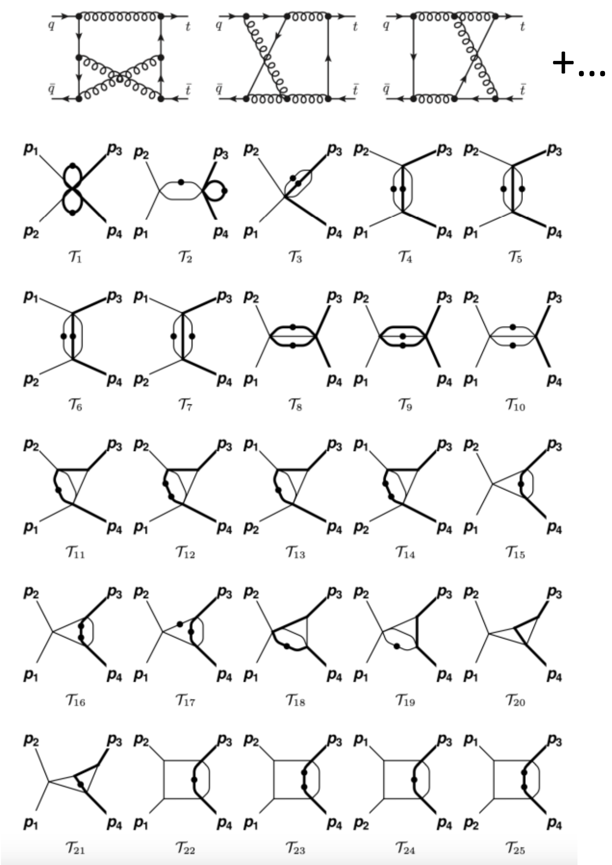
$\hat{\sigma}$: perturbatively calculable as a series expansion in a small parameter (coupling).
As the perturbative order increases, the number of Feynman diagrams and topologies get more involved

$q\bar{q} \rightarrow t\bar{t}$ @$NNLO$





Part of the NLO contributions



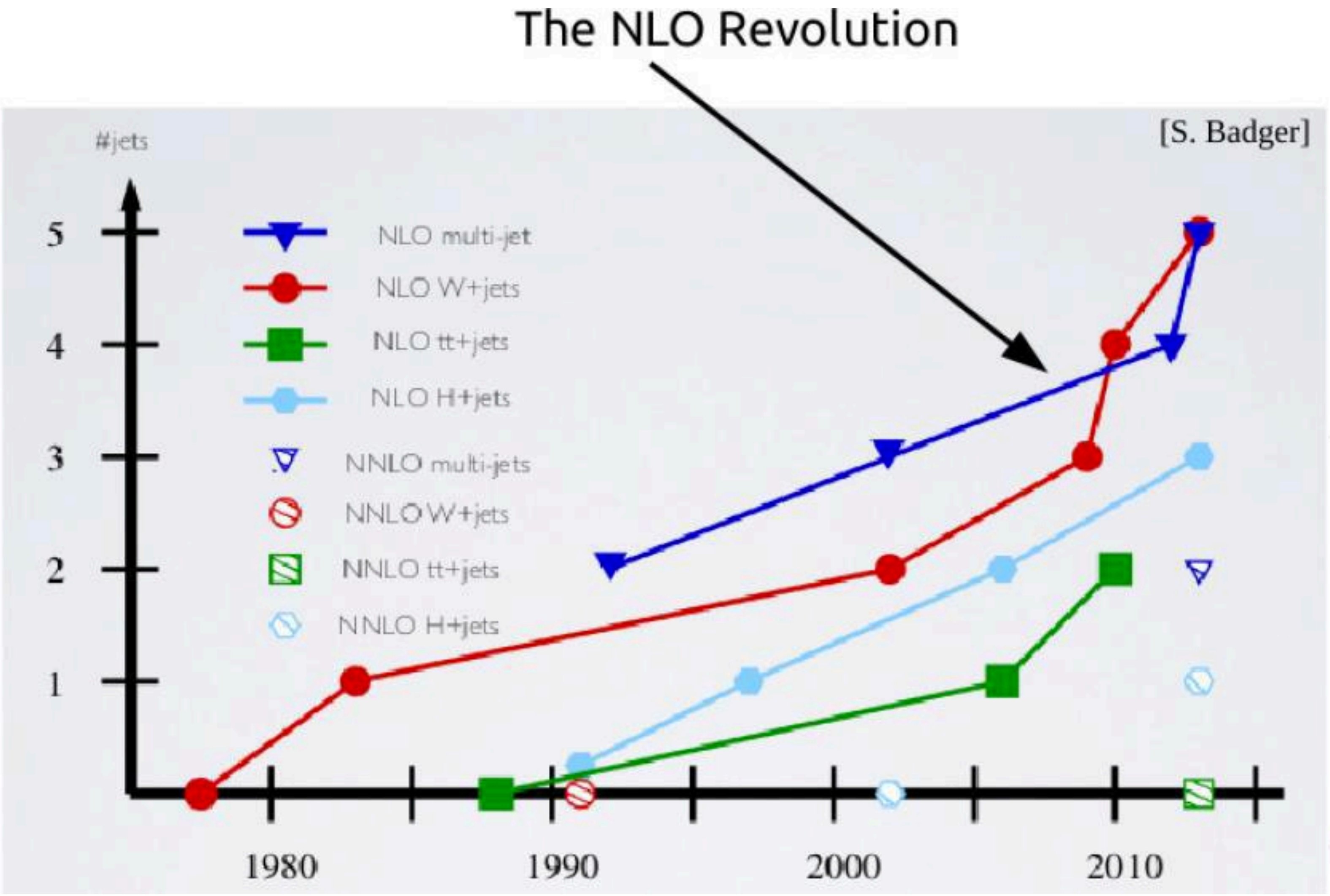
Di Vita, et al. JHEP 2019

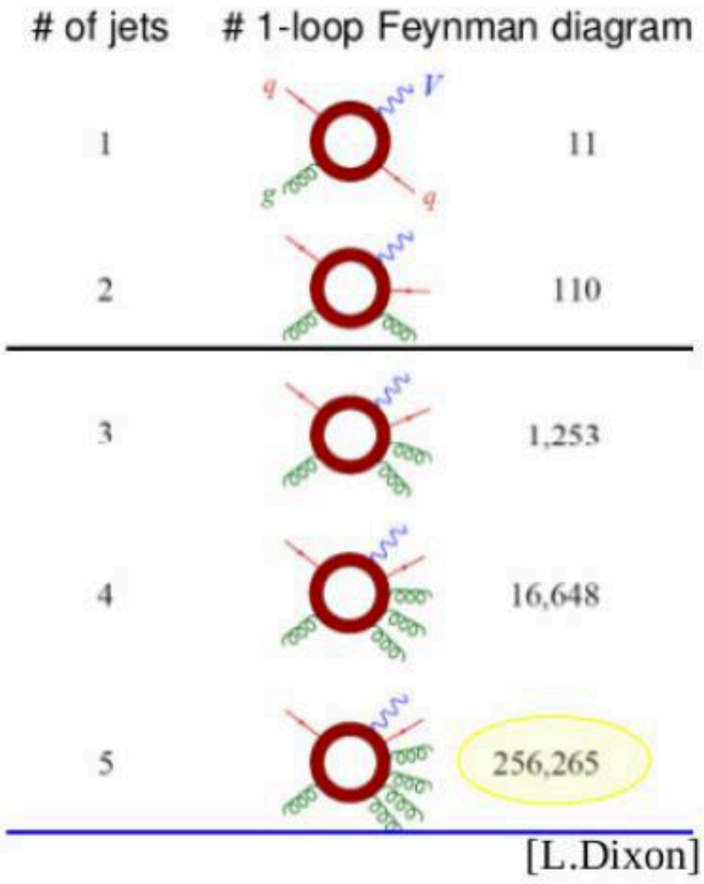
LO + NLO + NNLO + N^3LO + …

$$\hat{\sigma} = \hat{\sigma}_0 + \alpha\hat{\sigma}_1 + \alpha^2\hat{\sigma}_2 + \alpha^3\hat{\sigma}_3 + \ldots$$

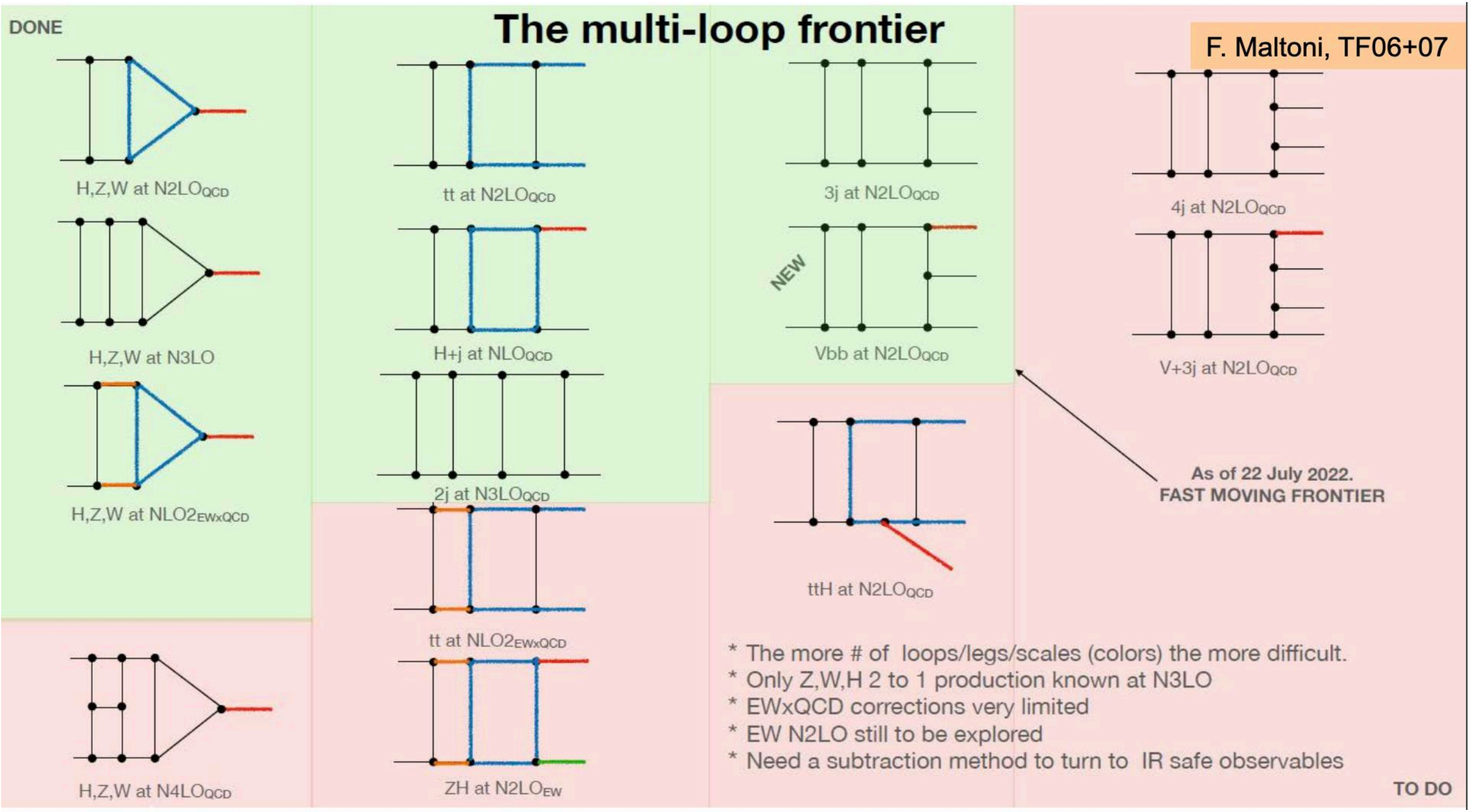
(leading order + next-to-leading order + next-to-next-to ...). More higher orders -> more precision

Remarkable progress in the past few years in Feynman diagrams calculations with many loops….and legs!





See related discussion in Gehrmann, Glover, et al. arXiv:2310.19757 for progress toward the next revolution at NNLO.



Dramatic advances in **perturbative** computations of NLO/NNLO/N3LO hard cross sections $\hat{\sigma}$.

The High Energy Theory group at MSU played an important role in this

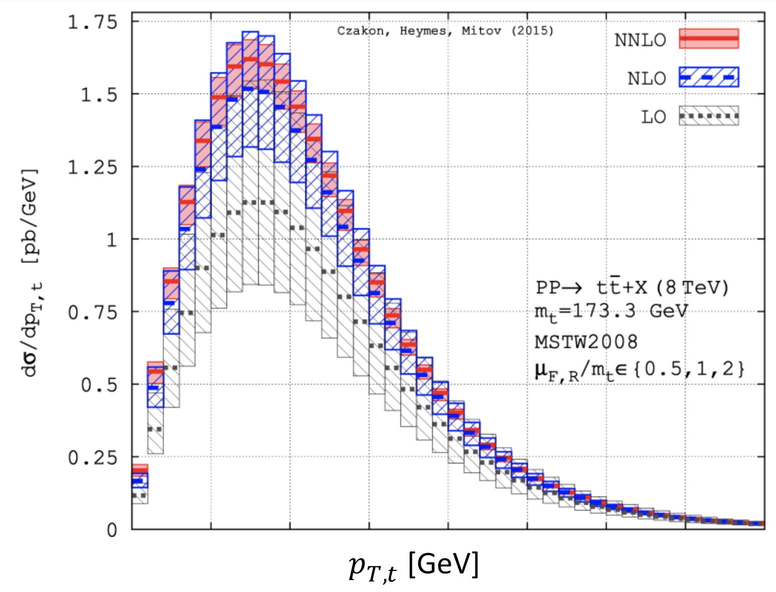
Many important processes have recently been obtained at high perturbative order, e.g., NNLO and N^3LO

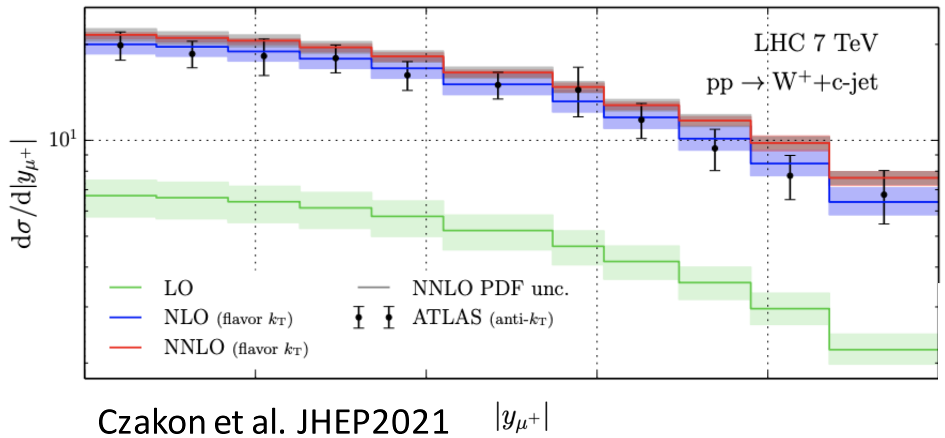
Theory uncertainty due to scale dependence is greatly reduced including higher orders!!

→ $\hat{\sigma}$ can be computed with very high precision!

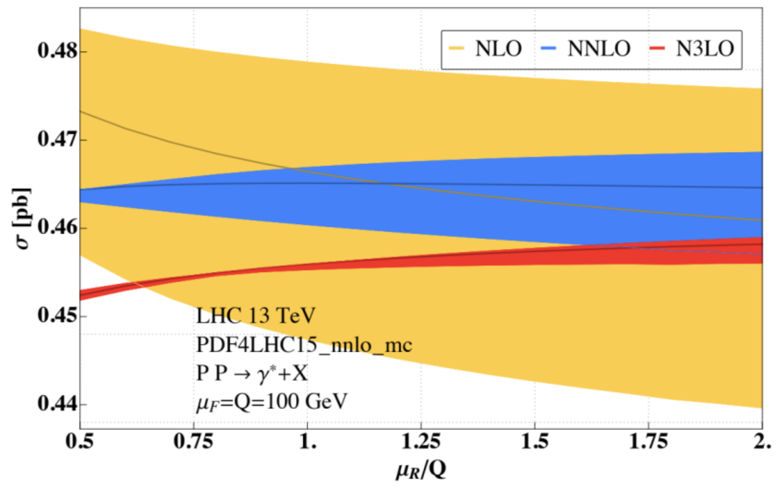
This list is of course not exhaustive.

Czakon et al. PRL2016

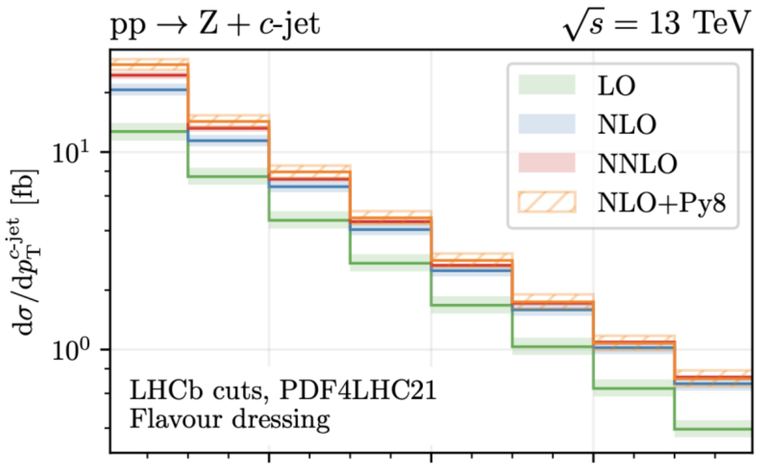




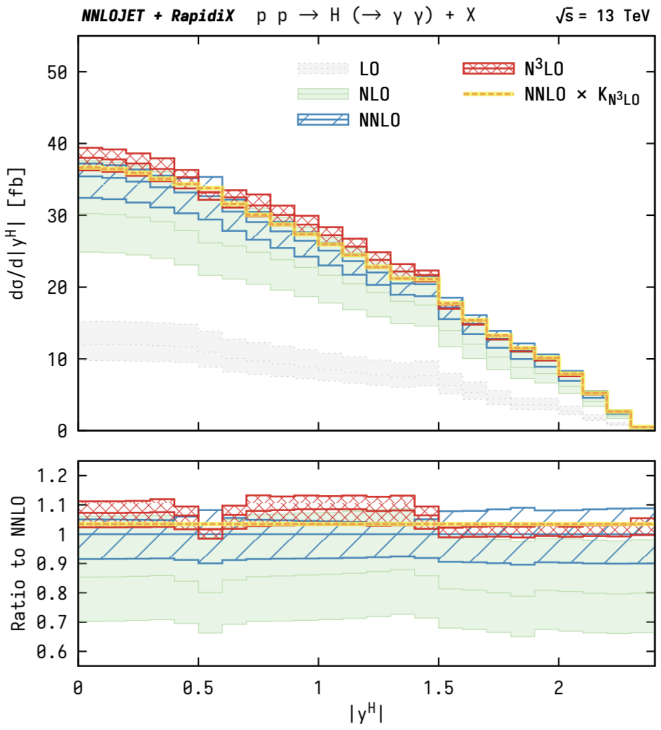
Czakon et al. JHEP2021



Baglio et al. JHEP2022, Duhr et al. JHEP2022



Gauld et al. EPJC2023



Chen et al. PRL2021

What about proton PDFs?

$$\sigma = \sum_{\text{partons}=i,j} f_i \otimes f_j \otimes \hat{\sigma}_{ij}$$

Inside a proton

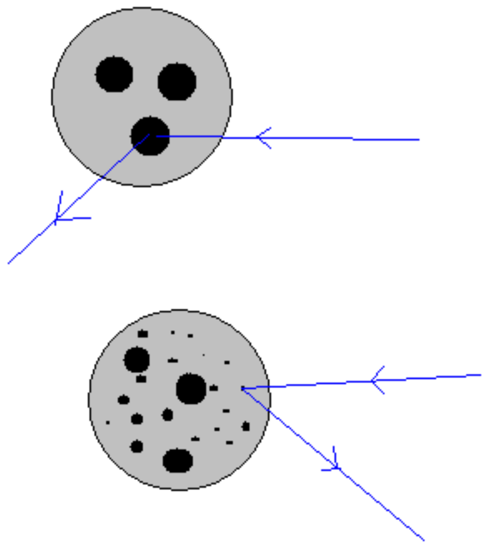
Parton Distribution Functions (PDFs) of the proton map out the longitudinal momentum distribution of proton's constituent quarks and gluons.

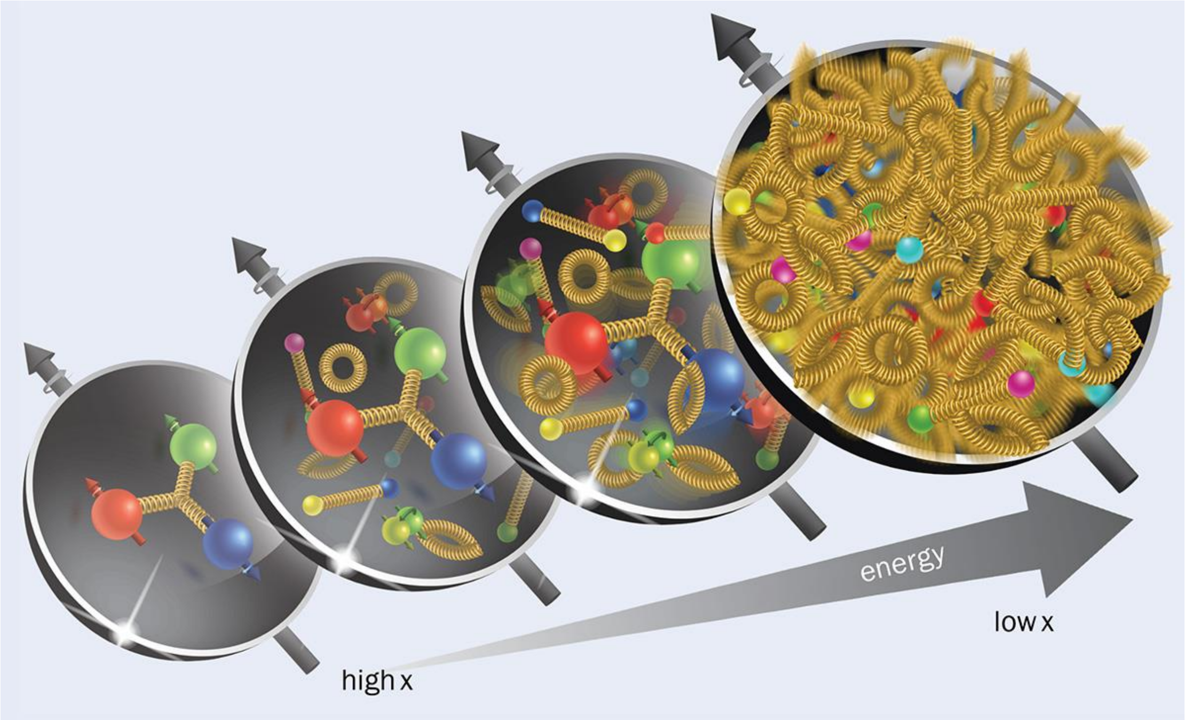
In collinear factorization, PDFs are defined as probability densities for finding a parton *i* with a certain longitudinal momentum fraction *x* at resolution scale *Q*.

$$f_i(x, Q^2)$$

PDFs are nonperturbative universal objects that cannot be fully predicted in pQCD.

We can only predict their energy behavior (Q-dependence).
The *x*-dependence must be extracted from experiments.

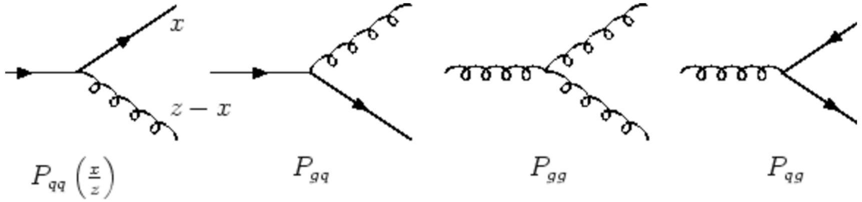




at scale Q_0 at scale $Q > Q_0$

$$\frac{d}{d\ln Q^2} f_a(x,Q^2) = \sum_{b=q,\bar{q},g} \int_x^1 \frac{dz}{z} P_{ab}\left(\frac{x}{z},Q^2\right) f_b(z,Q^2)$$

DGLAP RG Equations
Dokshitzer-Gribov-Lipatov-Altarelli-Parisi



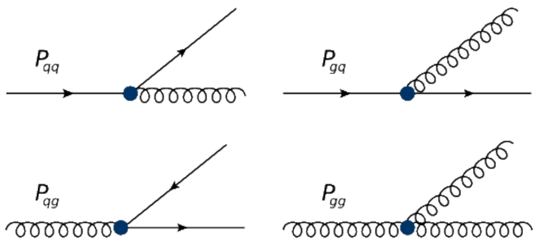
$P(x,Q^2)$ =splitting functions

Splitting functions at high perturbative order are very difficult to calculate!

$$P^{(0)}_{ns}(x) = C_F\left(2p_{qq}(x) + 3\delta(1-x)\right)$$
$$P^{(0)}_{ps}(x) = 0$$
$$P^{(0)}_{qg}(x) = 2n_f\, p_{qg}(x)$$
$$P^{(0)}_{gq}(x) = 2C_F\, p_{gq}(x)$$
$$P^{(0)}_{gg}(x) = C_A\left(4p_{gg}(x) + \frac{11}{3}\delta(1-x)\right) - \frac{2}{3}n_f\,\delta(1-x)$$

LO 1973

Here is the result for the quantum corrections to the splitting functions in QCD →



LO

$$\begin{aligned}
P^{(1)+}_{ns}(x) = {} & 4C_AC_F\Big(p_{qq}(x)\Big[\frac{67}{18} - \zeta_2 + \frac{11}{6}H_0 + H_{0,0}\Big] + p_{qq}(-x)\Big[\zeta_2 + 2H_{-1,0} - H_{0,0}\Big] \\
& + \frac{14}{3}(1-x) + \delta(1-x)\Big[\frac{17}{24} + \frac{11}{3}\zeta_2 - 3\zeta_3\Big]\Big) - 4C_Fn_f\Big(p_{qq}(x)\Big[\frac{5}{9} + \frac{1}{3}H_0\Big] + \frac{2}{3}(1-x) \\
& + \delta(1-x)\Big[\frac{1}{12} + \frac{2}{3}\zeta_2\Big]\Big) + 4C_F^2\Big(2p_{qq}(x)\Big[H_{1,0} - \frac{3}{4}H_0 + H_2\Big] - 2p_{qq}(-x)\Big[\zeta_2 + 2H_{-1,0} \\
& - H_{0,0}\Big] - (1-x)\Big[1 - \frac{3}{2}H_0\Big] - H_0 - (1+x)H_{0,0} + \delta(1-x)\Big[\frac{3}{8} - 3\zeta_2 + 6\zeta_3\Big]\Big)
\end{aligned}$$

$$\begin{aligned}
P^{(1)-}_{ns}(x) = {} & P^{(1)+}_{ns}(x) + 16C_F\Big(C_F - \frac{C_A}{2}\Big)\Big(p_{qq}(-x)\Big[\zeta_2 + 2H_{-1,0} - H_{0,0}\Big] - 2(1-x) \\
& - (1+x)H_0\Big)
\end{aligned}$$

$$P^{(1)}_{ps}(x) = 4C_Fn_f\Big(\frac{20}{9}\frac{1}{x} - 2 + 6x - 4H_0 + x^2\Big[\frac{8}{3}H_0 - \frac{56}{9}\Big] + (1+x)\Big[5H_0 - 2H_{0,0}\Big]\Big)$$

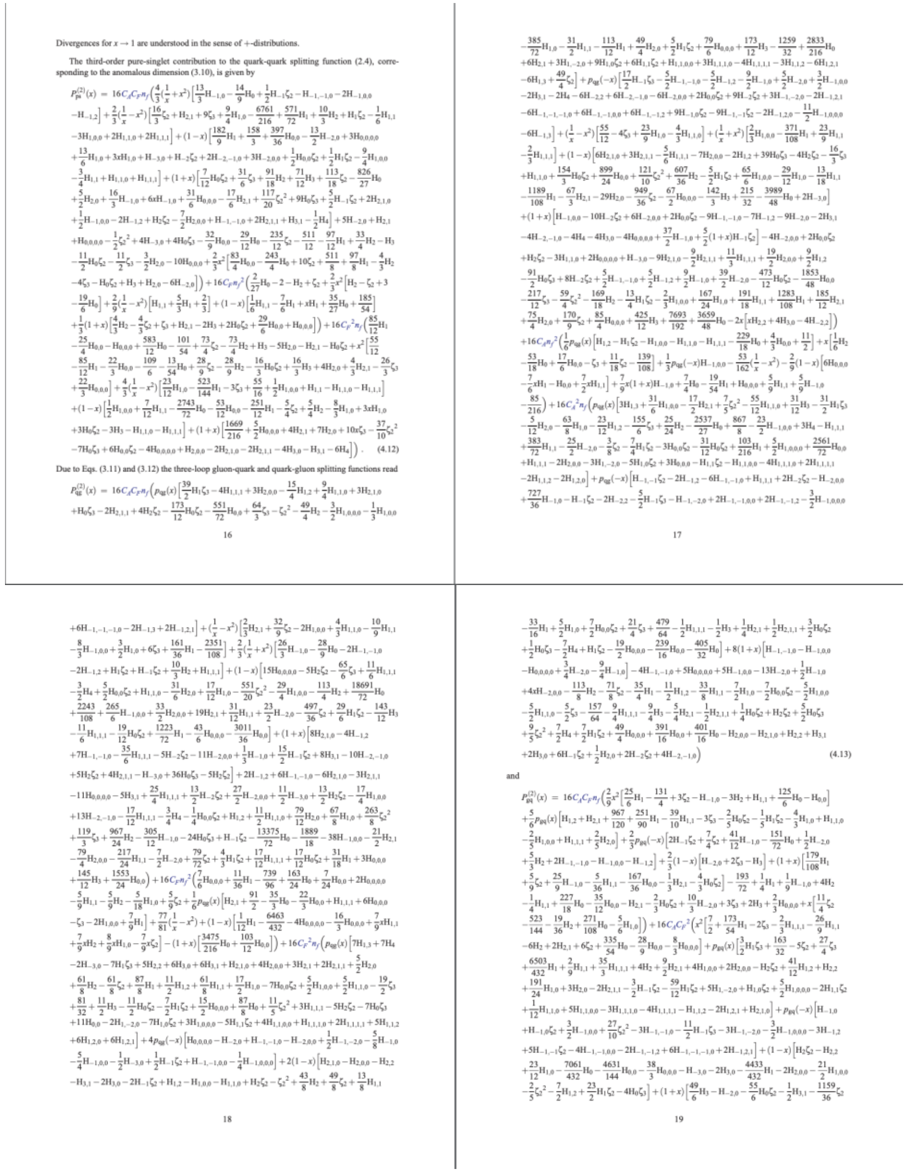
$$\begin{aligned}
P^{(1)}_{qg}(x) = {} & 4C_An_f\Big(\frac{20}{9}\frac{1}{x} - 2 + 25x - 2p_{qg}(-x)H_{-1,0} - 2p_{qg}(x)H_{1,1} + x^2\Big[\frac{44}{3}H_0 - \frac{218}{9}\Big] \\
& + 4(1-x)\Big[H_{0,0} - 2H_0 + xH_1\Big] - 4\zeta_2x - 6H_{0,0} + 9H_0\Big) + 4C_Fn_f\Big(2p_{qg}(x)\Big[H_{1,0} + H_{1,1} + H_2 \\
& - \zeta_2\Big] + 4x^2\Big[H_0 + H_{0,0} + \frac{5}{2}\Big] + 2(1-x)\Big[H_0 + H_{0,0} - 2xH_1 + \frac{29}{4}\Big] - \frac{15}{2} - H_{0,0} - \frac{1}{2}H_0\Big)
\end{aligned}$$

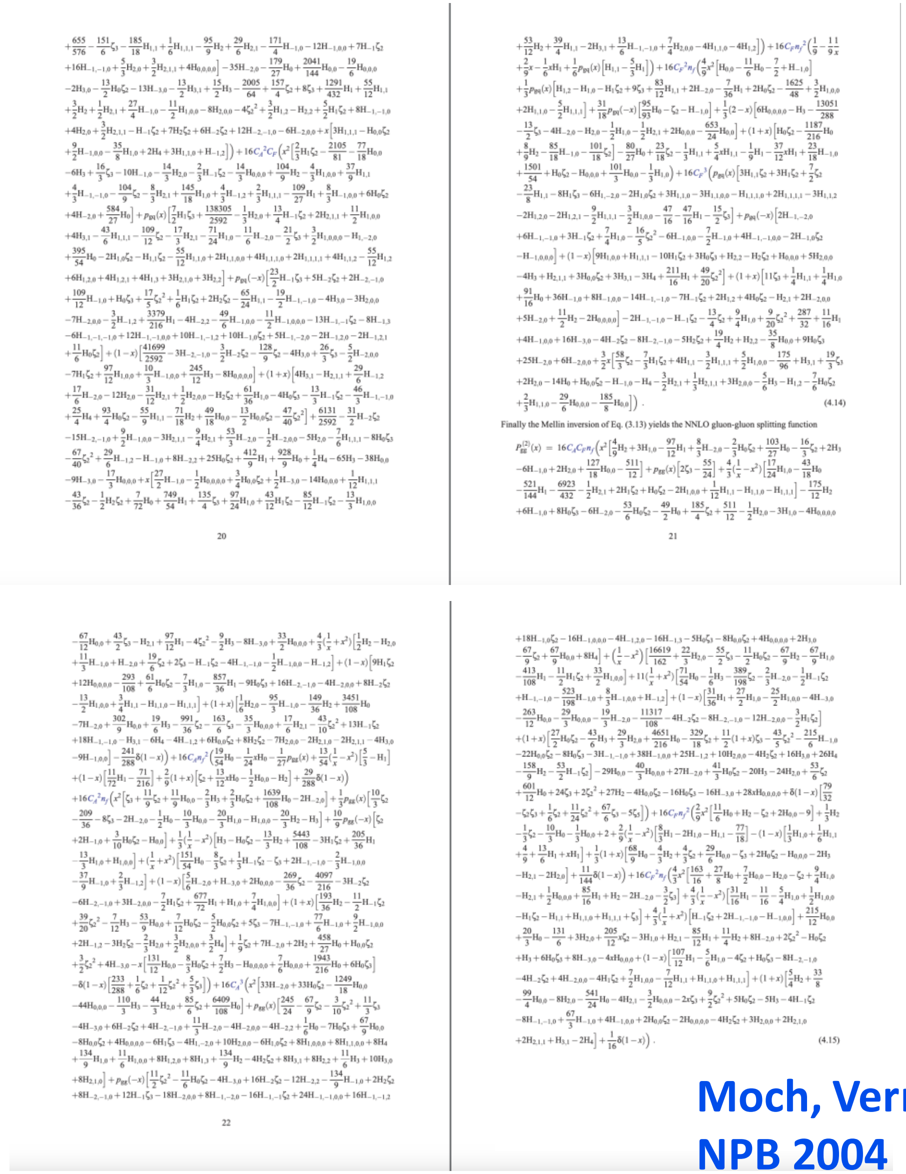
$$\begin{aligned}
P^{(1)}_{gq}(x) = {} & 4C_AC_F\Big(\frac{1}{x} + 2p_{gq}(x)\Big[H_{1,0} + H_{1,1} + H_2 - \frac{11}{6}H_1\Big] - x^2\Big[\frac{8}{3}H_0 - \frac{44}{9}\Big] + 4\zeta_2 - 2 \\
& - 7H_0 + 2H_{0,0} - 2H_1x + (1+x)\Big[2H_{0,0} - 5H_0 + \frac{37}{9}\Big] - 2p_{gq}(-x)H_{-1,0}\Big) - 4C_Fn_f\Big(\frac{2}{3}x \\
& - p_{gq}(x)\Big[\frac{2}{3}H_1 - \frac{10}{9}\Big]\Big) + 4C_F^2\Big(p_{gq}(x)\Big[3H_1 - 2H_{1,1}\Big] + (1+x)\Big[H_{0,0} - \frac{7}{2} + \frac{7}{2}H_0\Big] - 3H_{0,0} \\
& + 1 - \frac{3}{2}H_0 + 2H_1x\Big)
\end{aligned}$$

$$\begin{aligned}
P^{(1)}_{gg}(x) = {} & 4C_An_f\Big(1 - x - \frac{10}{9}p_{gg}(x) - \frac{13}{9}\Big(\frac{1}{x} - x^2\Big) - \frac{2}{3}(1+x)H_0 - \frac{2}{3}\delta(1-x)\Big) + 4C_A^2\Big(27 \\
& + (1+x)\Big[\frac{11}{3}H_0 + 8H_{0,0} - \frac{27}{2}\Big] + 2p_{gg}(-x)\Big[H_{0,0} - 2H_{-1,0} - \zeta_2\Big] - \frac{67}{9}\Big(\frac{1}{x} - x^2\Big) - 12H_0 \\
& - \frac{44}{3}x^2H_0 + 2p_{gg}(x)\Big[\frac{67}{18} - \zeta_2 + H_{0,0} + 2H_{1,0} + 2H_2\Big] + \delta(1-x)\Big[\frac{8}{3} + 3\zeta_3\Big]\Big) + 4C_Fn_f\Big(2H_0 \\
& + \frac{2}{3}\frac{1}{x} + \frac{10}{3}x^2 - 12 + (1+x)\Big[4 - 5H_0 - 2H_{0,0}\Big] - \frac{1}{2}\delta(1 -
\end{aligned}$$

NLO: 1980

It took several years to calculate higher orders in QCD perturbative expansions





Moch, Vermaseren, Vogt NPB 2004

NNLO: next-to-next-to leading order. N^3LO: is currently in progress. 2023/24 ?

QCD GLOBAL ANALYSIS OF DATA in a nutshell:

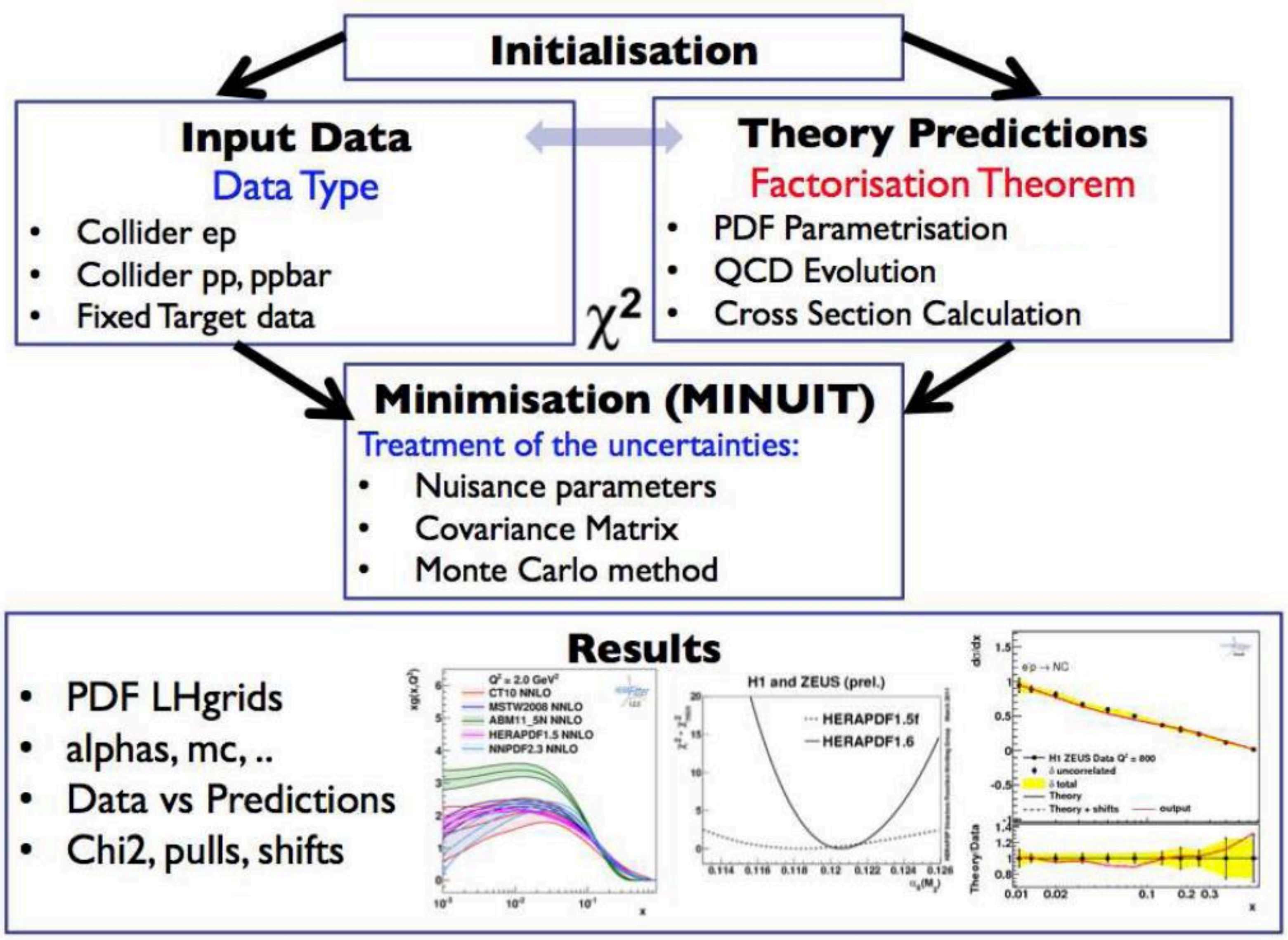
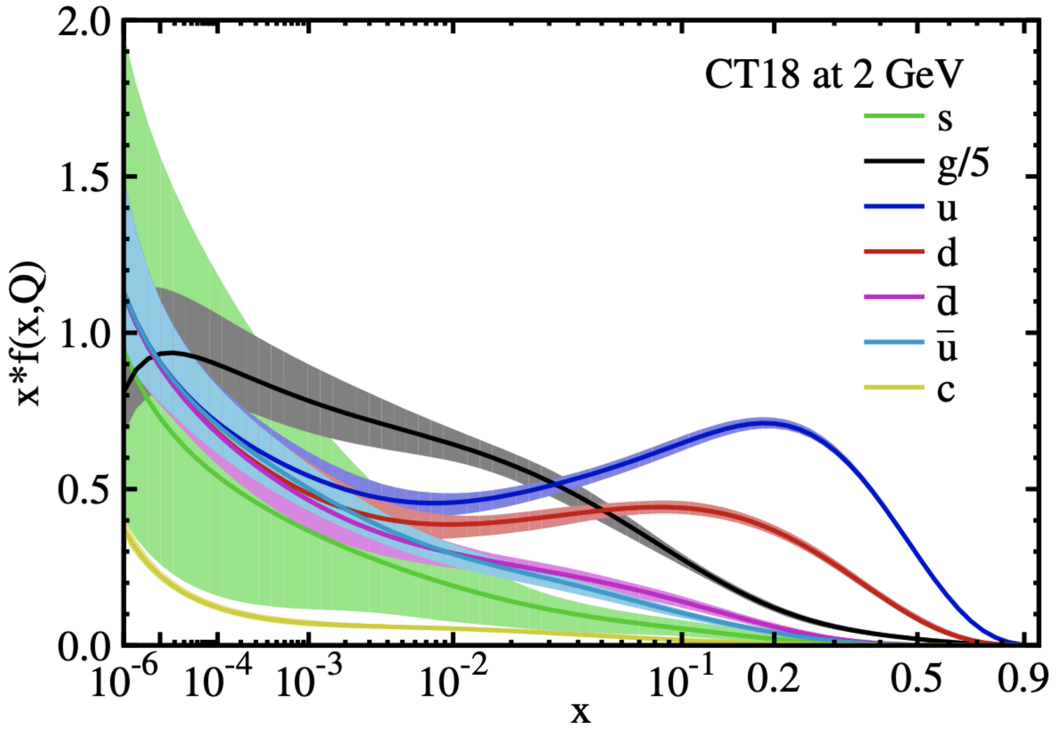
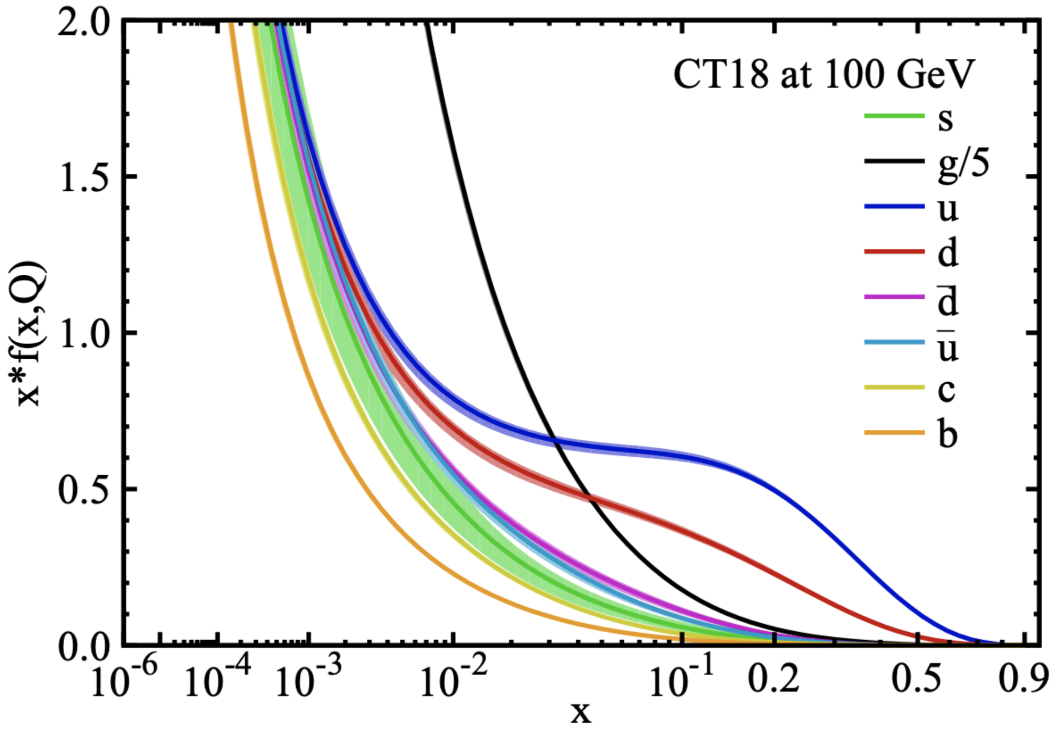


Image: The xFitter Coll.

CT18 NNLO PDFs (PRD 2021)





PDFs are determined by global analyses of world hadron data using a variety of analytical and statistical methods.

They still represent one of the major sources of uncertainties for theory predictions and simulations at hadron colliders: Bottleneck for precision!

The High Energy Theory group at MSU hosts the CTEQ group which is world leading in PDFs determinations

CTEQ

The Coordinated Theoretical-Experimental Project on QCD

CTEQ is a multi-institutional world leading collaboration devoted to a broad program of research projects and cooperative enterprises in high-energy physics centered on QCD and its implications in all areas of the SM and beyond.

- CTEQ – Tung Et Al. (TEA)

in memory of Prof. Wu-Ki Tung, who co-established CTEQ Collaboration in early 90's

- Current members:

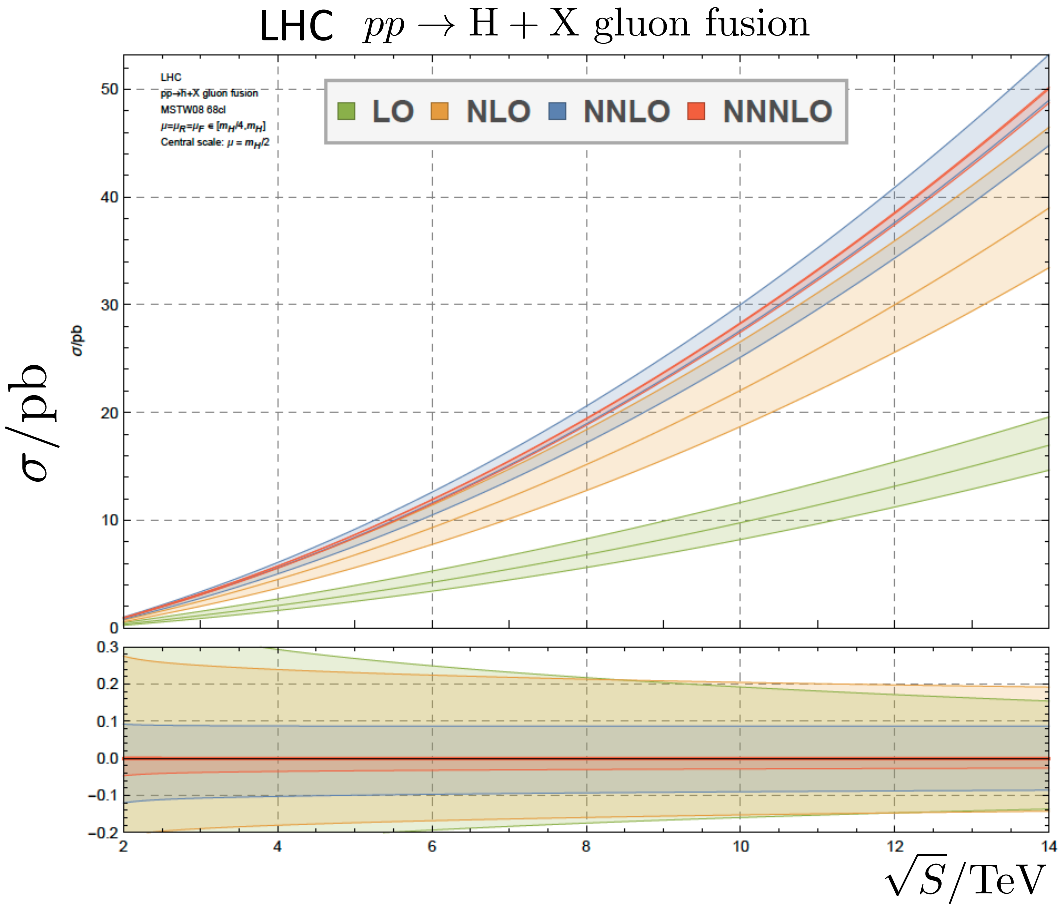
China: Sayipjamal Dulat, Ibrahim Sitiwaldi, Alim Albet (Xinjiang U.), Jun Gao (Shanghai Jiaotong U.), Mengshi Yan (Peking U.) , Tie-Jiun Hou (U. of South China), Yao Fu (USTC)

Mexico: Aurore Courtoy (Unam, Mexico)

USA: Marco Guzzi (Kennesaw State U.), Tim Hobbs (Argonne Lab), Pavel Nadolsky, Xiaoxian Jing (Southern Methodist U.), Keping Xie (Pittsburgh U.) Joey Huston, Huey-Wen Lin, Dan Stump, Carl Schmidt, C.-.P Yuan (Michigan State U.)

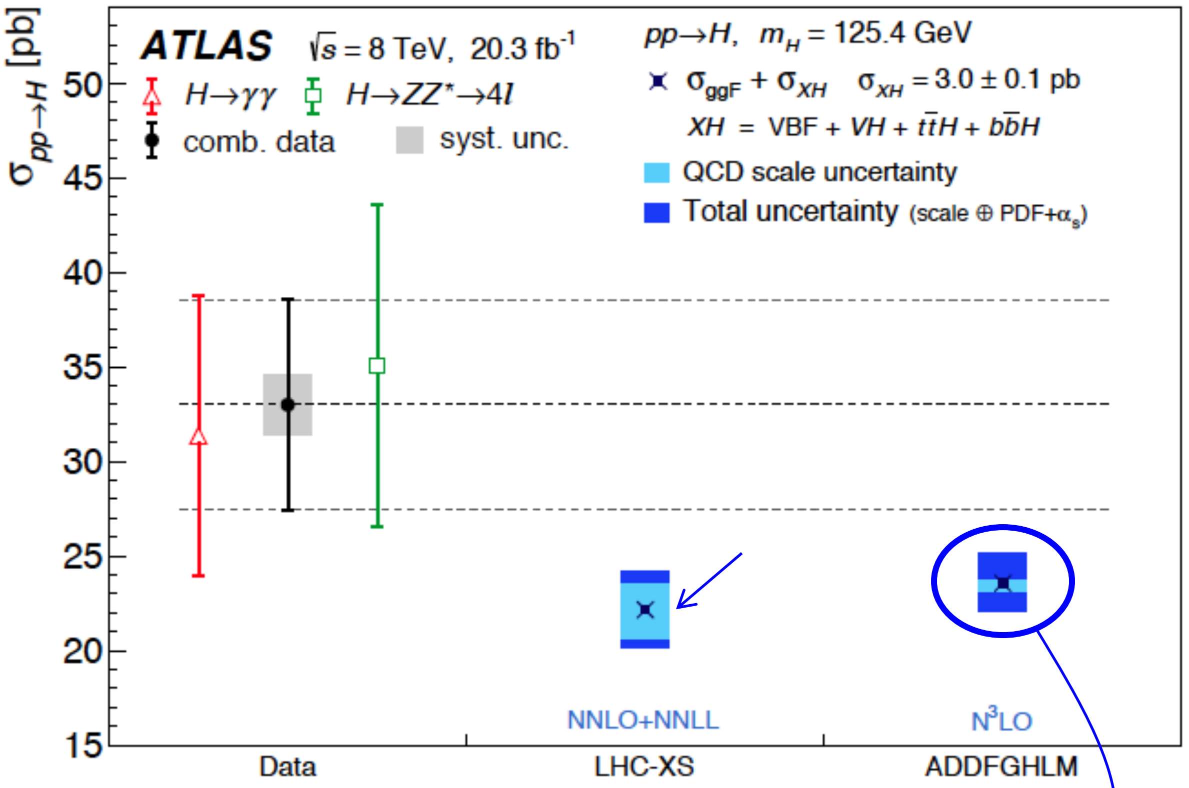
The High Energy Theory group at MSU hosts the CTEQ group which is world leading in PDFs determinations

Higgs production at the LHC



Higgs boson gluon-gluon fusion production at N^3LO QCD. Anastasiou, Duhr, et al., PRL2015

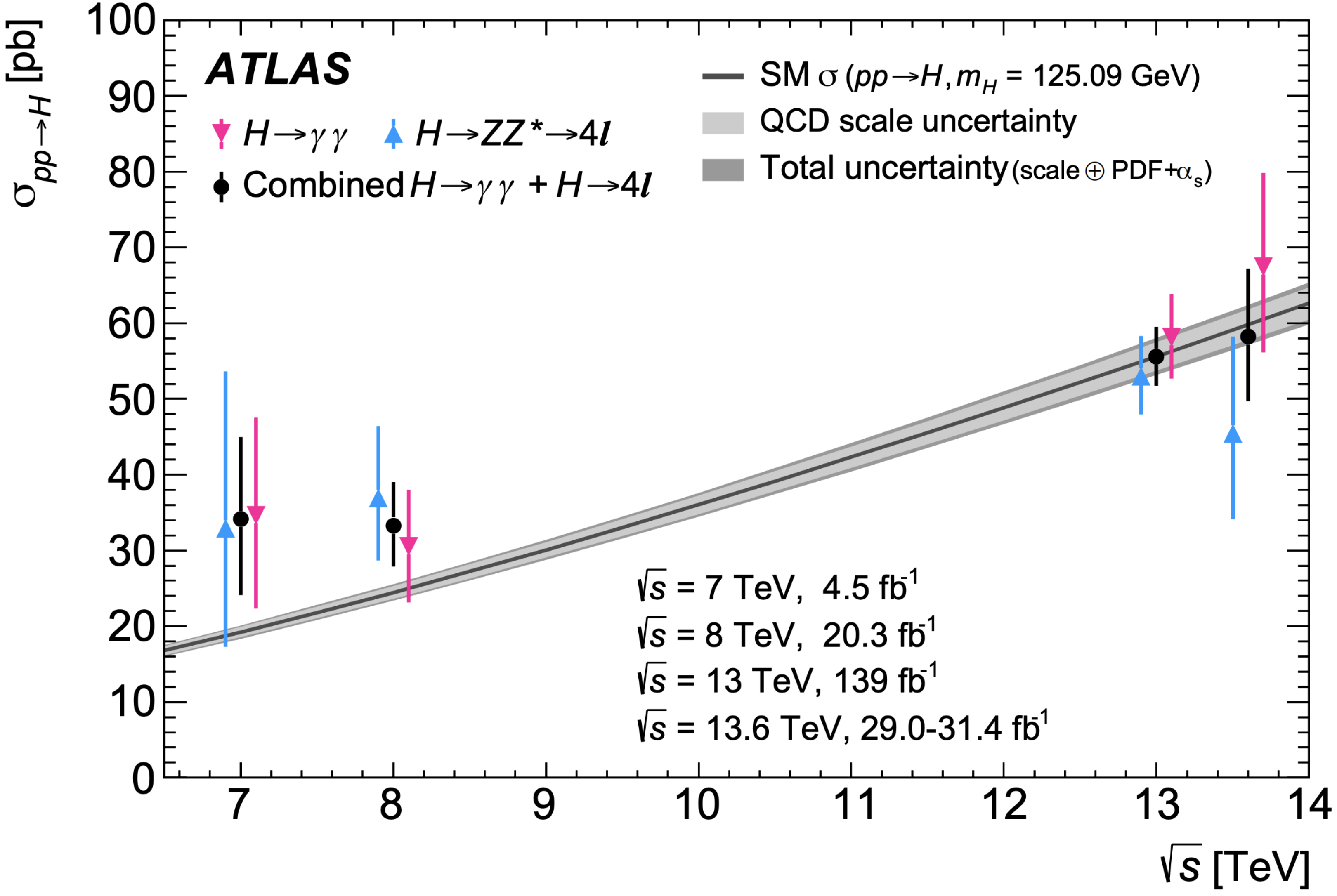
	NNLO	N3LO
Feynman diagrams	1000	100 000
Integrals computed	50 000	517 531 178



Higgs production at the LHC 8TeV.
ATLAS arxiv:1504.05833

PDFs are the main source of theory uncertainty

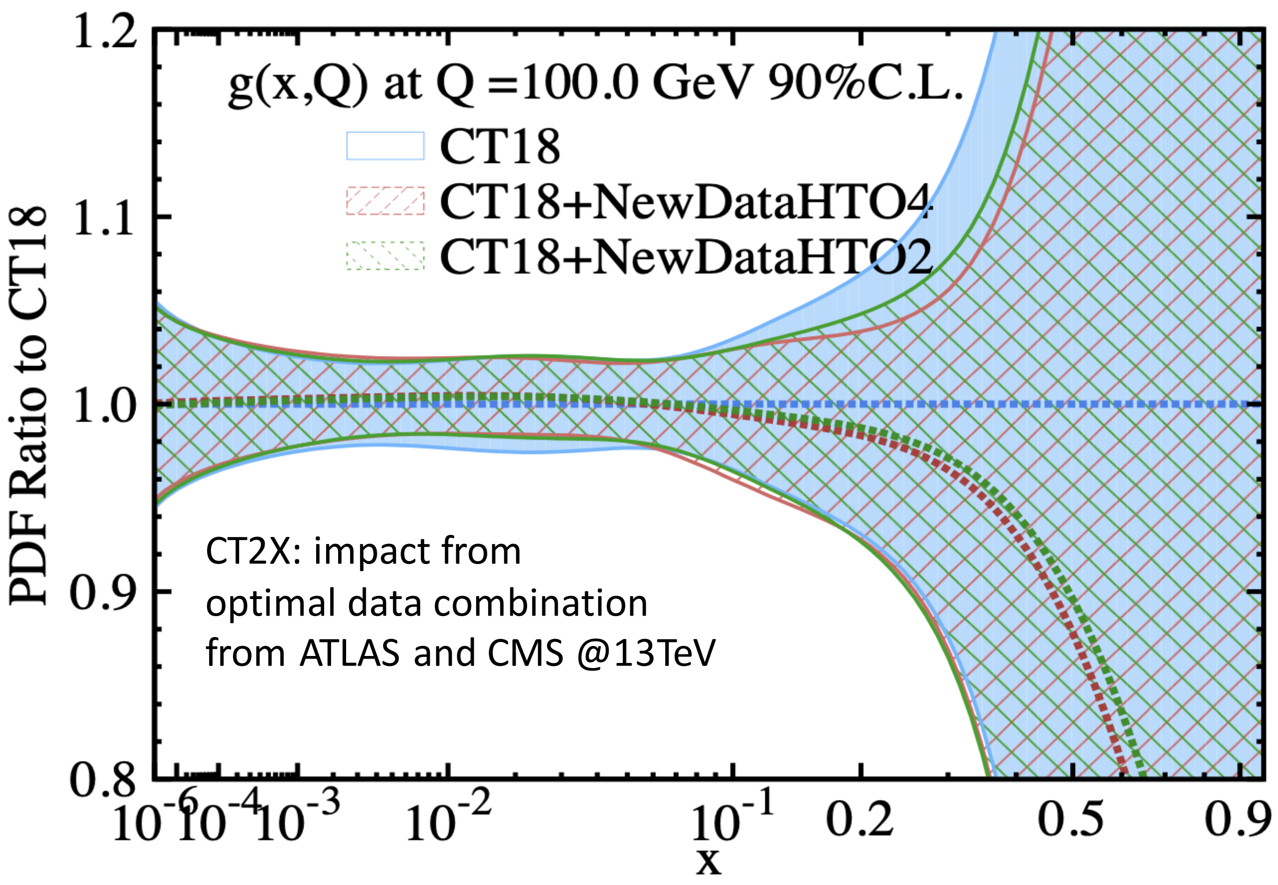
Higgs production at the LHC



ATLAS Coll. 2306.11379

High-precision data + precision calculations in QCD allow us to improve PDF determination:

Impact of LHC 13 TeV $t\bar{t}$ production on CT18 PDFs (Ablat, MG, Xie, Dulat, Hou, Sitiwaldi, Yuan, 2307.11153)



Theory predictions:

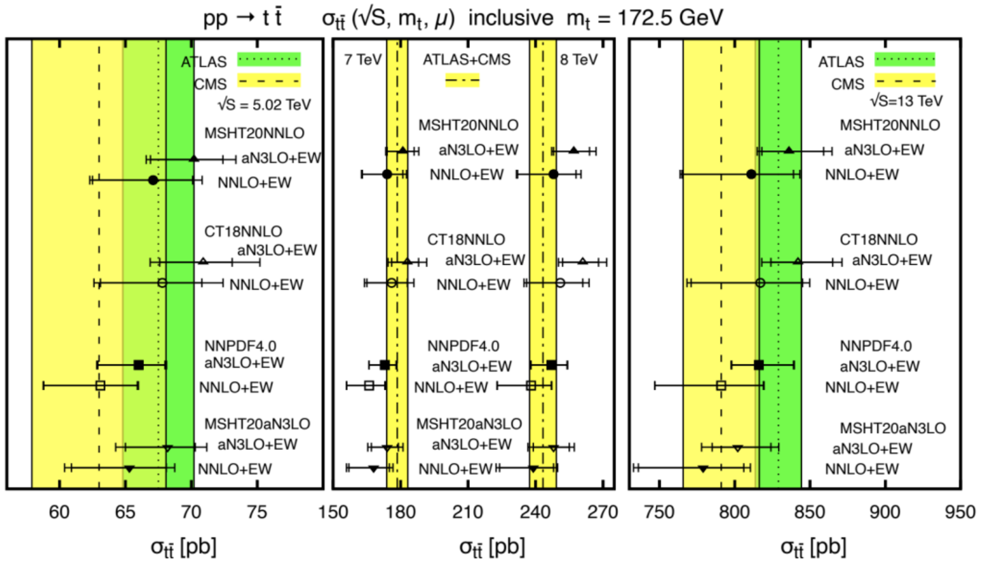
- MATRIX (Catani, Grazzini et al. PRD 2019)
- FastNNLO (Czakon, et al. 1704.08551)

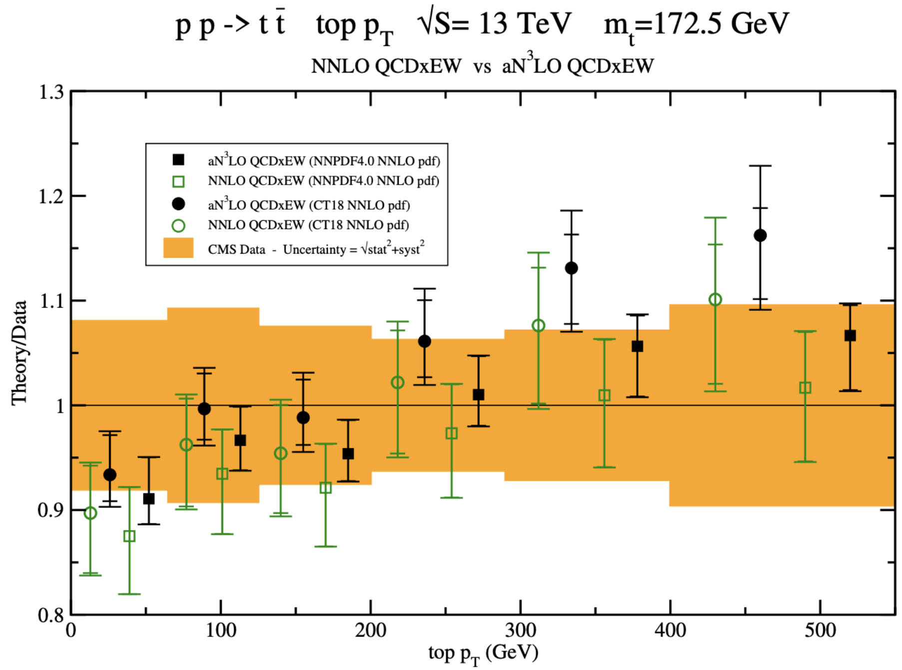
Blue band: CT18NNLO 90% C.L.
Hatched bands: CT18 + new top-quark data
Green: $\mu_R = \mu_F = H_T/2$
Red: $\mu_R = \mu_F = H_T/4$

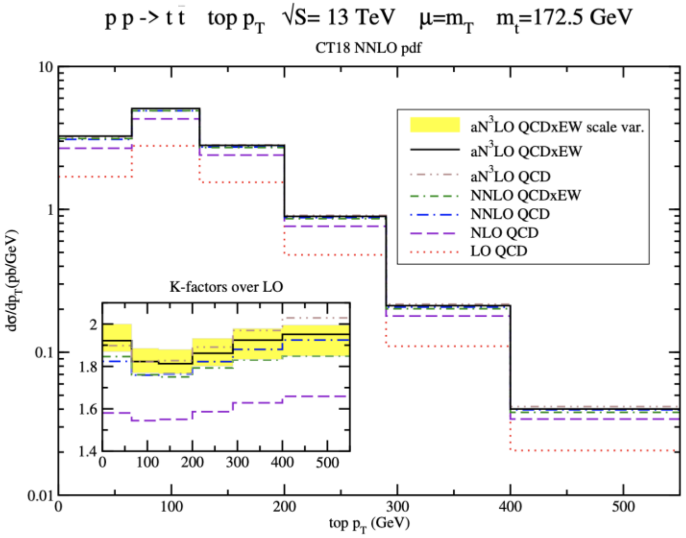
Differences related to different scale choices are well within the CT18 PDF error band.

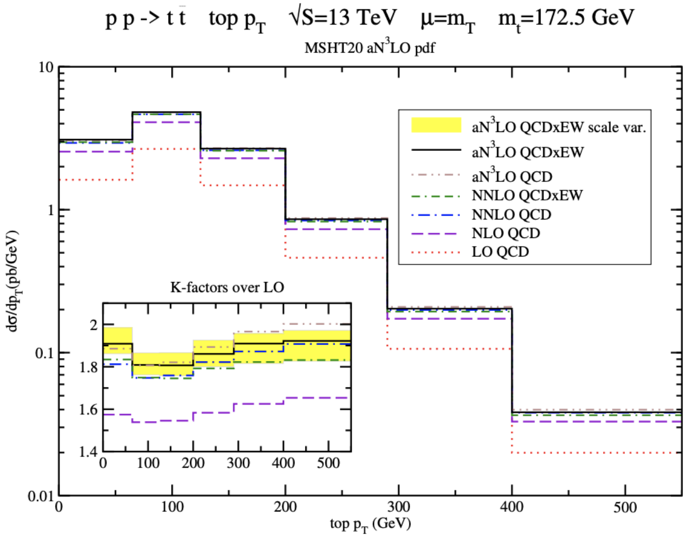
CTEQ

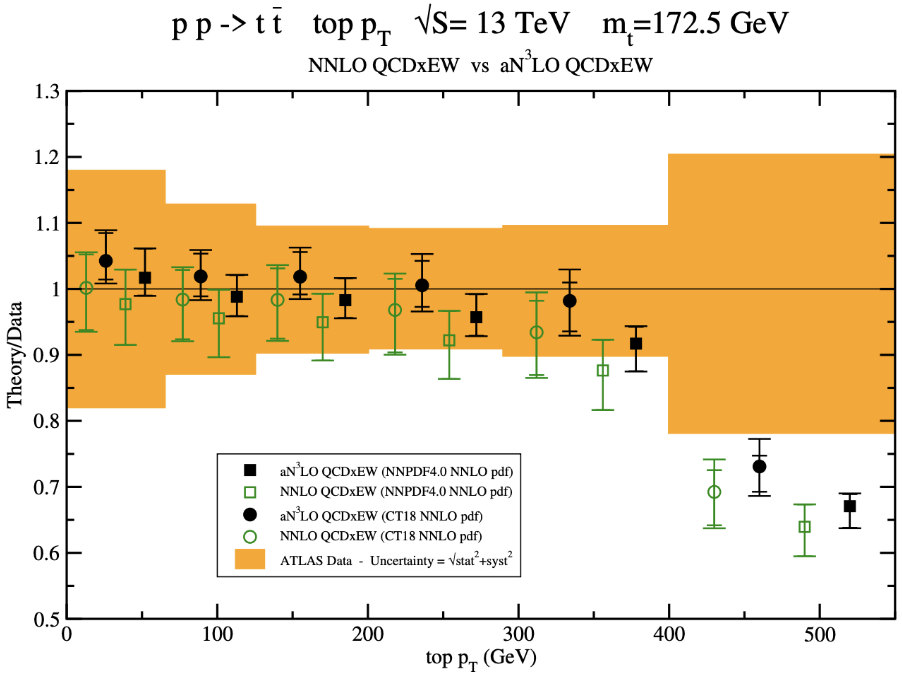
$t\bar{t}$ production at aN^3LO











Kidonakis, MG, Tonero, PRD 2023, arXiv:2306.06166

The need of precise predictions: ``Evil is in the details''

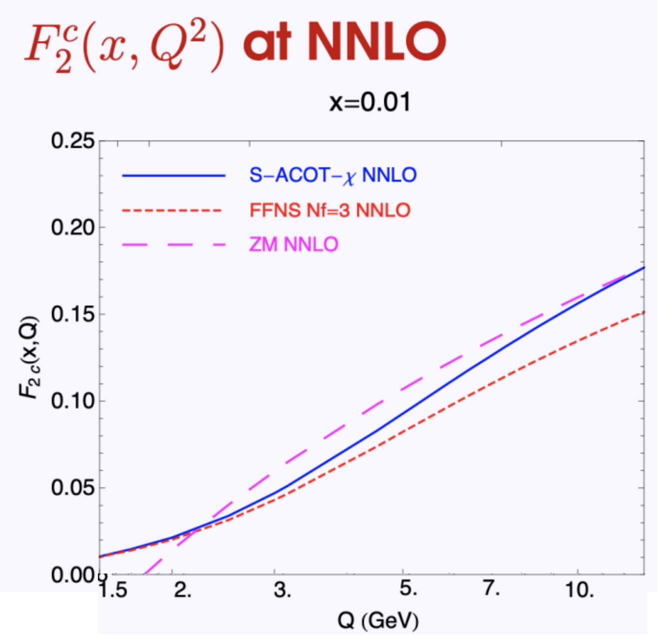
The quest for precision inevitably brings up a series of problems:

- Do higher-order (e.g., N^3LO, NNLO) computations provide better estimates than lower ones (NNLO, NLO) ?

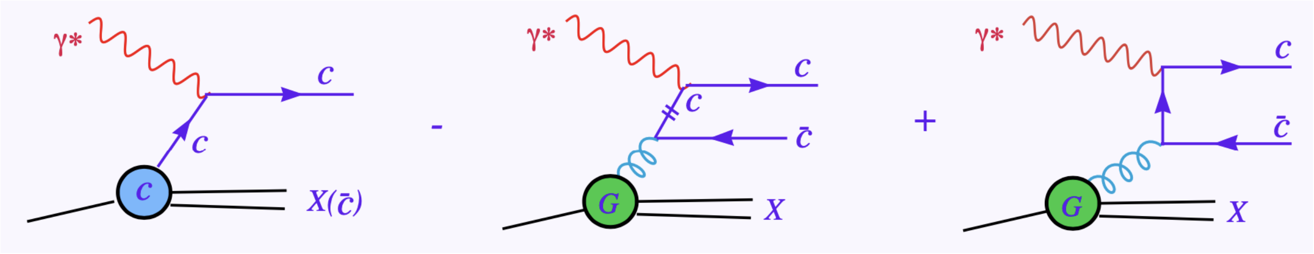
It is not automatically true!
Several quantities entering the computations have associated uncertainties that compete in magnitude with higher-order corrections.

An example of this is the treatment of heavy flavors in the factorization formulae for hadronic cross sections:

S-ACOT-χ @NNLO MG et al. PRD 2012



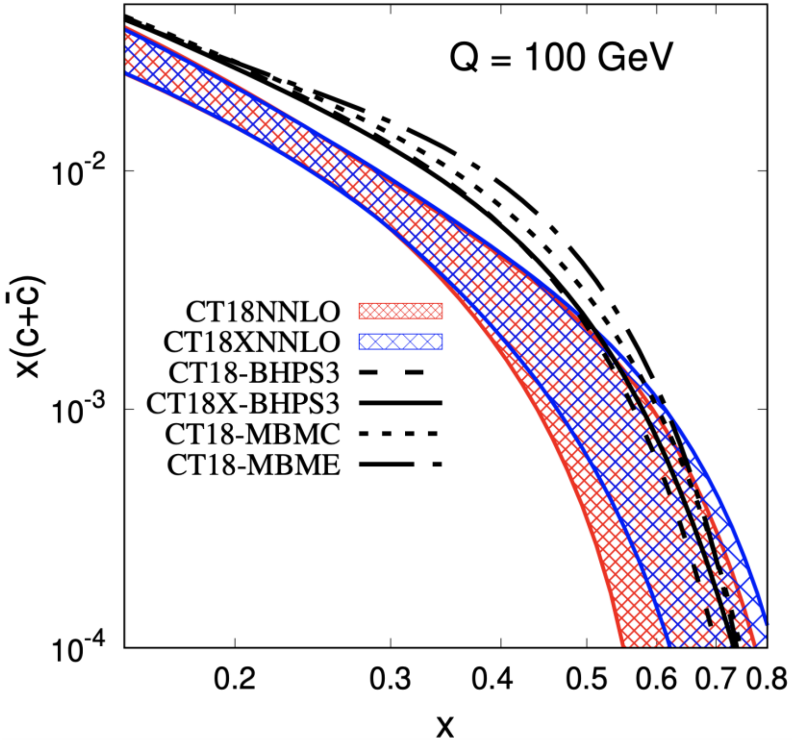
In neutral current Deep Inelastic Scattering (DIS) ACOT Aivazis, Collins, Olness, Tung PRD 1994

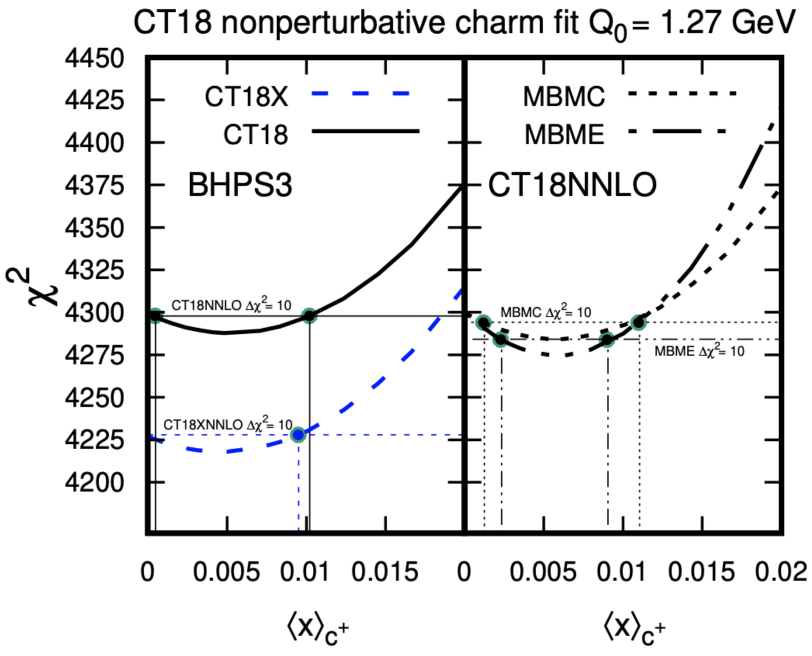


- S-ACOT-χ @NNLO in DIS with charge currents, Gao, Hobbs et al. PRD (2022)
- For pp collisions: MG, Nadolsky, Wackeroth, Reina, Xie, pp -> Z+c/b (in preparation)

Impact on nonperturbative charm in the proton

Proton's intrinsic charm, a non-vanishing charm PDF at $Q0$ (around 1 GeV) scale, remains indeterminate.
- Challenging to formulate a rigorous definition of intrinsic charm (IC) and its relation to fitted charm (FC).
- Need more NNLO and better showering calculations.
- Z+c theory predictions have sizable uncertainties, e.g., flavor-tag jet definition, multi-parton interaction (MPI), showering effect.
- Need more sensitive data





MG, Hobbs, Xie, et al. PLB2023

$\langle x\rangle_{\rm FC} \approx 0.5\%\ (\Delta\chi^2 \gtrsim -25)$ vs. $\langle x\rangle_{\rm FC} \approx 0.8\text{–}1\%\ (\Delta\chi^2 \gtrsim -40)$ in CT14 IC

- CT18FC study found no significant evidence for non-zero IC, as NNPDF4.0 IC, Nature 608 (2022) 7923, 483.
- FC in CT18FC study is currently consistent with zero, and with shallower $\Delta\chi^2$ than CT14IC.

CTEQ

The need of precise predictions: ``Evil is in the details''

The quest for precision inevitably brings up a series of problems:

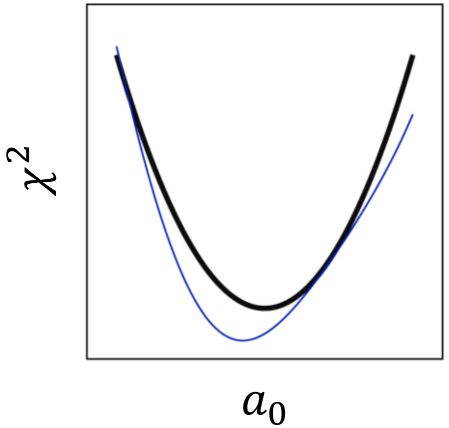
- Do higher-order (e.g., N^3LO, NNLO) computations provide better estimates than lower ones (NNLO, NLO) ?

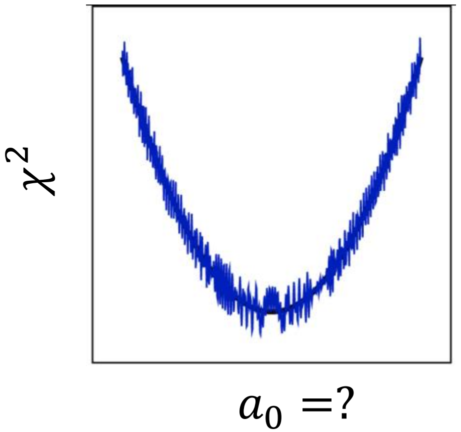
- Compatibility issues among experimental measurements when they are combined in global QCD analyses.

Tensions between data sets challenge our interpretation of experimental and theoretical uncertainties and how they enter the definition of the figure of merit (e.g., χ^2 definition)

$$\chi^2 = \sum_i \left(\frac{D_i - T_i - \sum_\alpha \beta_{i,\alpha}\lambda_\alpha}{\sigma_i} \right)^2 + \sum_\alpha \lambda_\alpha^2 \quad \text{vs} \quad \chi^2 = \sum_{i.j}^{N_{dat}} (D_i - T_i) \mathcal{C}_{ij}^{-1} (D_j - T_j)$$

What is the optimal way to represent experimental uncertainties in global fits?



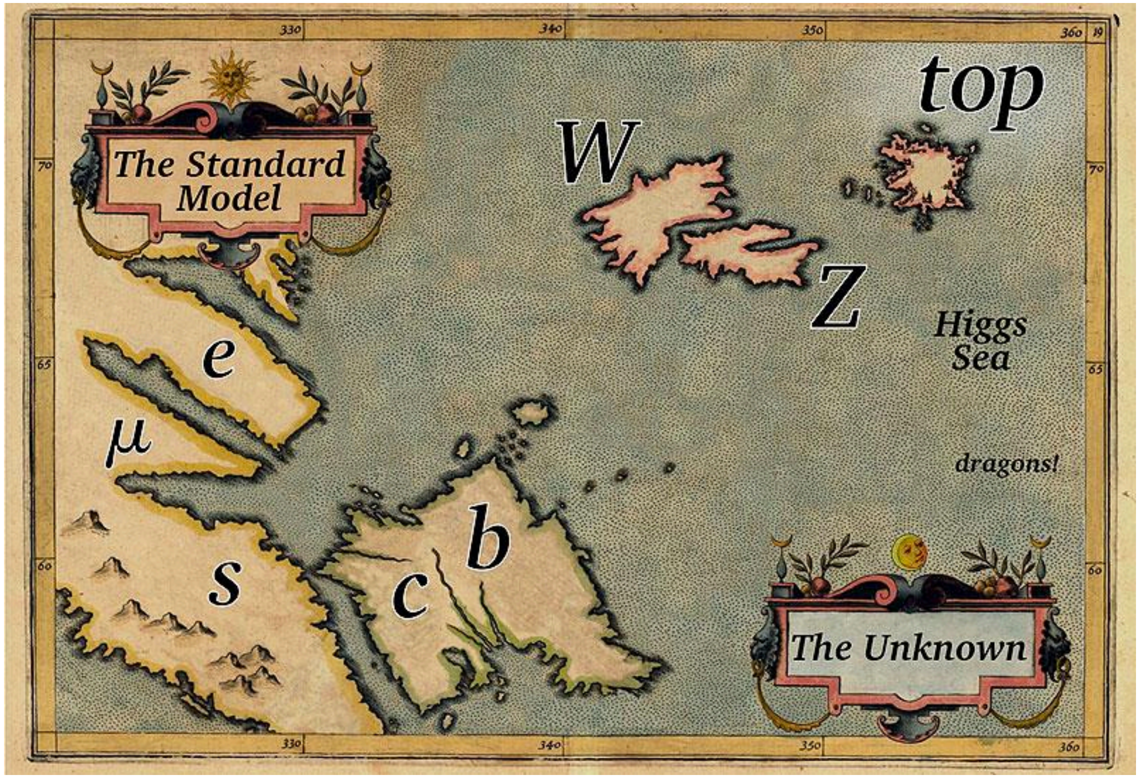


See related discussions in:

- Wang, Hobbs, et al. PRD (2018)
- Kovarik, Nadolsky, Soper Rev.Mod.Phys(2020)
- Courtoy et al. PRD (2023)

New Physics searches

What about new physics?
We all are eager to discover it.



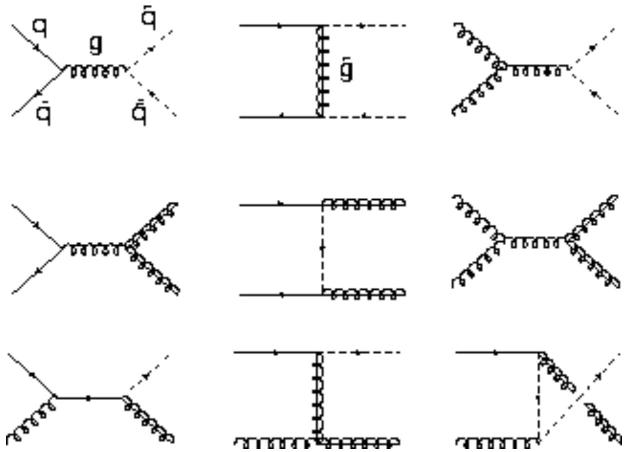
If new physics is there, our theory cross section is modified

$$\sigma = \sum_{\mathrm{partons=a,b}} f_{\mathrm{a}} \otimes f_{\mathrm{b}} \otimes \hat{\sigma}_{\mathrm{ab}}$$

$$\frac{d}{d\ln Q^2} f_a(x,Q^2) = \sum_{b=q,\bar{q},g} \int_x^1 \frac{dz}{z} P_{ab}\left(\frac{x}{z},Q^2\right) f_b(z,Q^2)$$

...and also have effects on PDFs
and their energy evolution (DGLAP).

We can have impact on the
hard scattering cross section...



Many Standard Model extensions predict the existence of new particles.

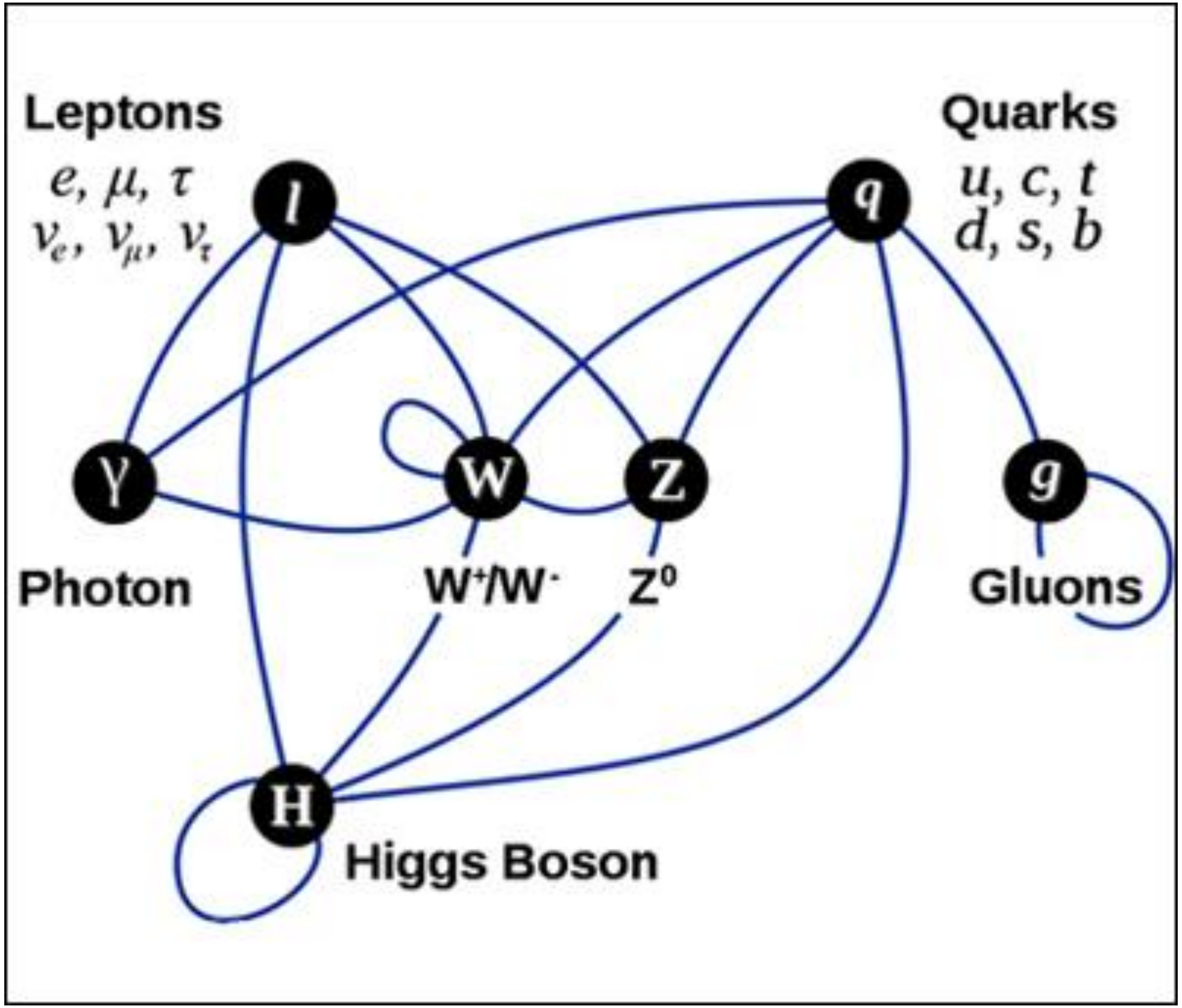
A larger symmetry structure of the SM?

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times \ldots ?$$

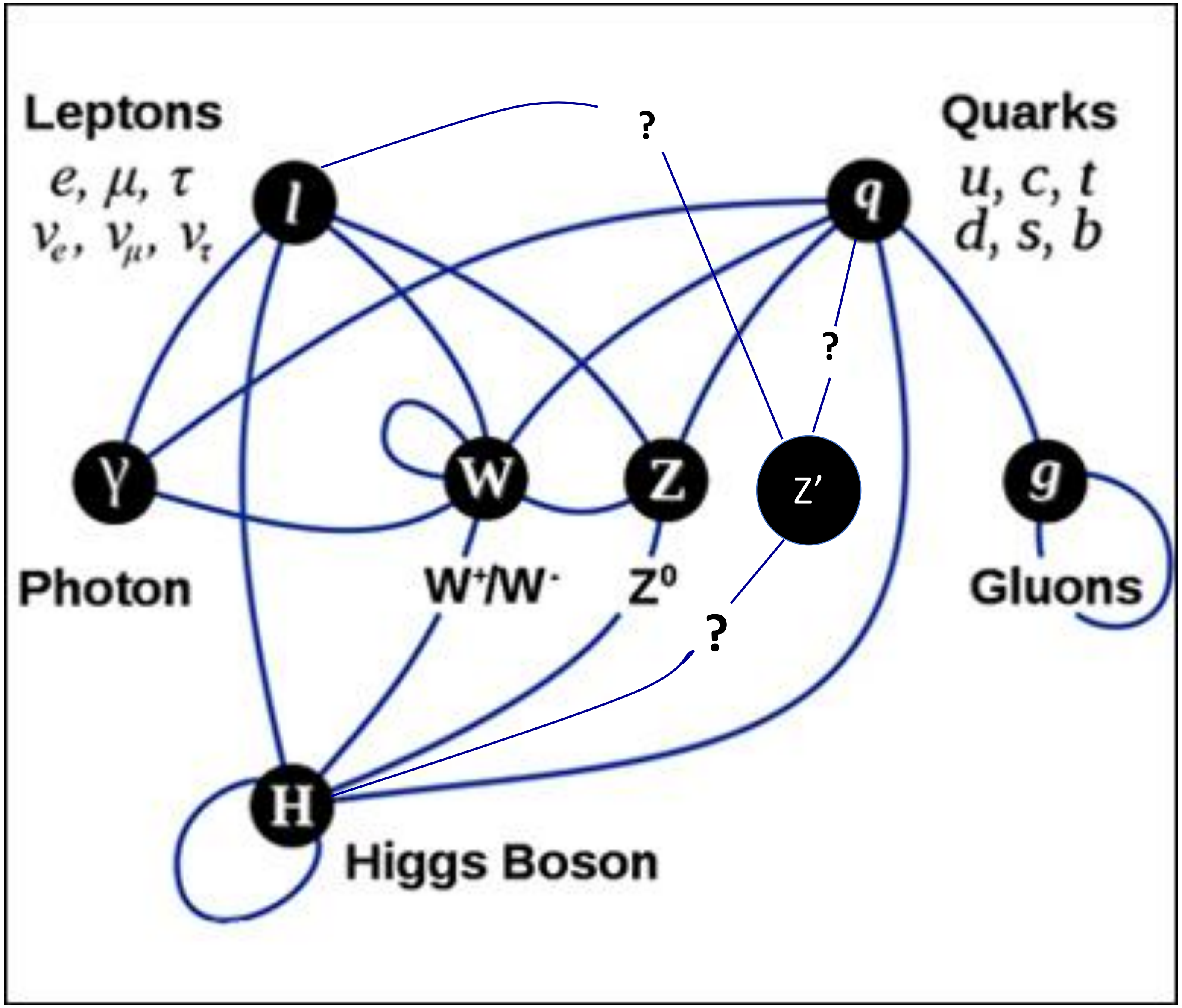
$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1) \ldots$$

Many questions still need an answer

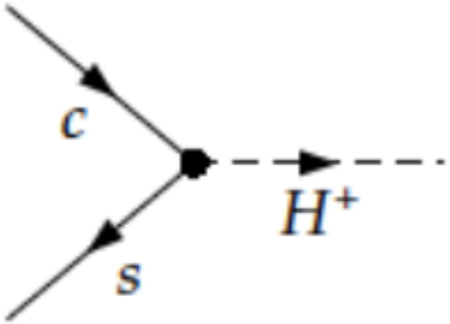
Are there other electroweak (EW) interaction carriers ?

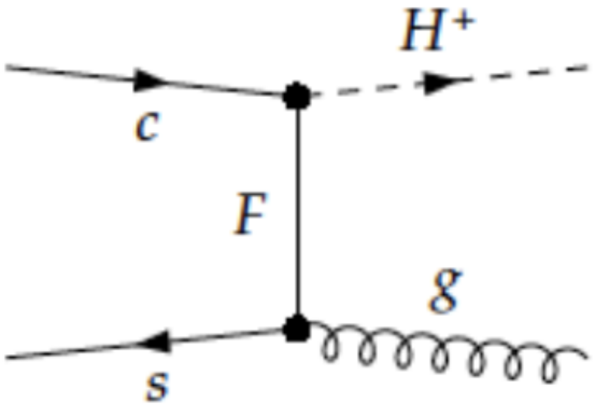


Are there other electroweak interaction carriers ?

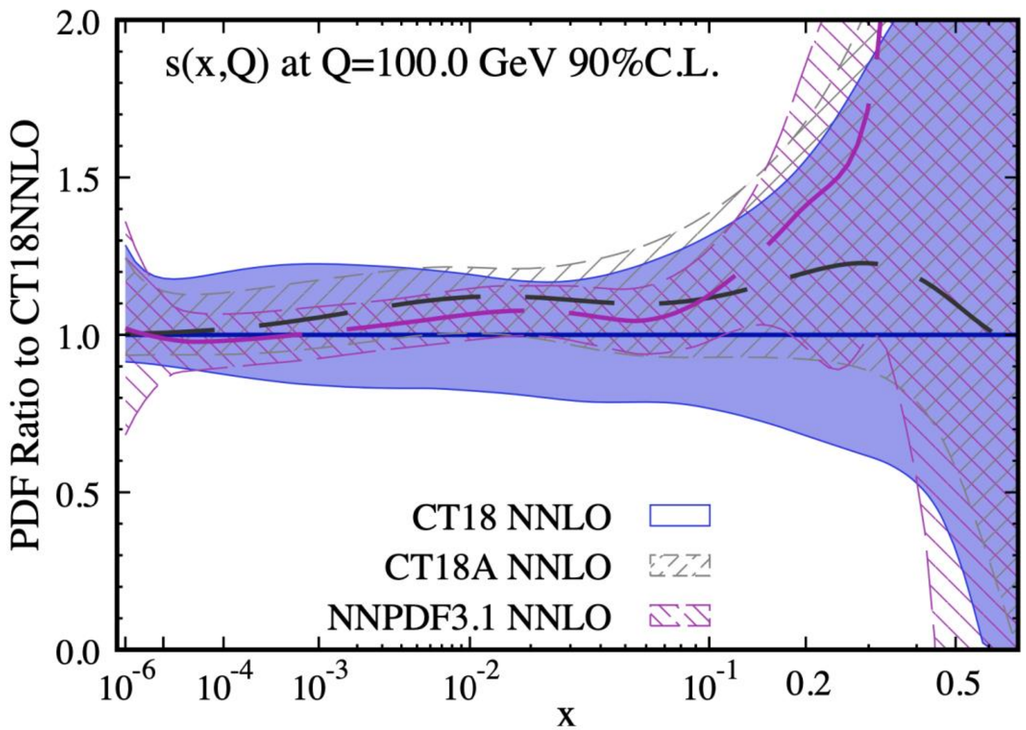


Does a charged sector for the Higgs boson exist?





Important to know the strange-quark PDF with high accuracy



CT18, PRD 2021

At the LHC new physics can occur through various kinds of signature (Discovery Machine)

- new final state particles
- new bumps or distortions in kinematic distributions
- ....

These must be discriminated from a complex SM background

⬇

Need to work hard on the main factors limiting the accuracy of theory predictions: missing higher orders in pQCD calculations, knowledge of proton's structure.

Let's take the example of an extended EW sector

A large class of new physics models predicts new interactions mediated by new gauge bosons generically referred to as Z' bosons that differ from the SM Z boson by having different mass and couplings.

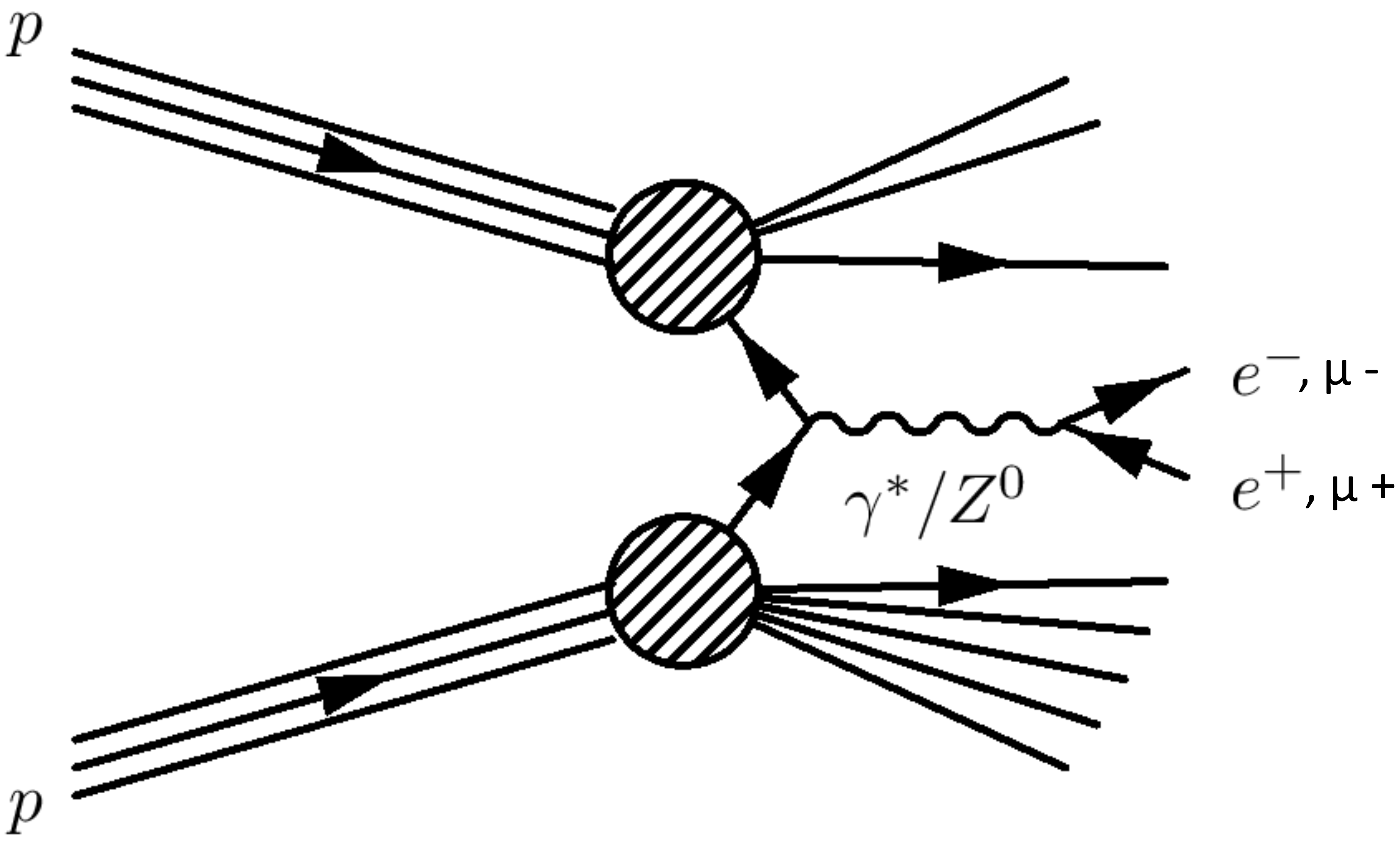
These new particles are supposed to be heavy, with masses of the order of a few TeV's , and can potentially be discovered in the future at the LHC or other future facilities.

In addition, if multiple Z's will be discovered, it will be crucial to validate the presence or not of their self-interactions.

The presence of Z's can directly be detected using the invariant mass distribution of Drell-Yan (DY) events.

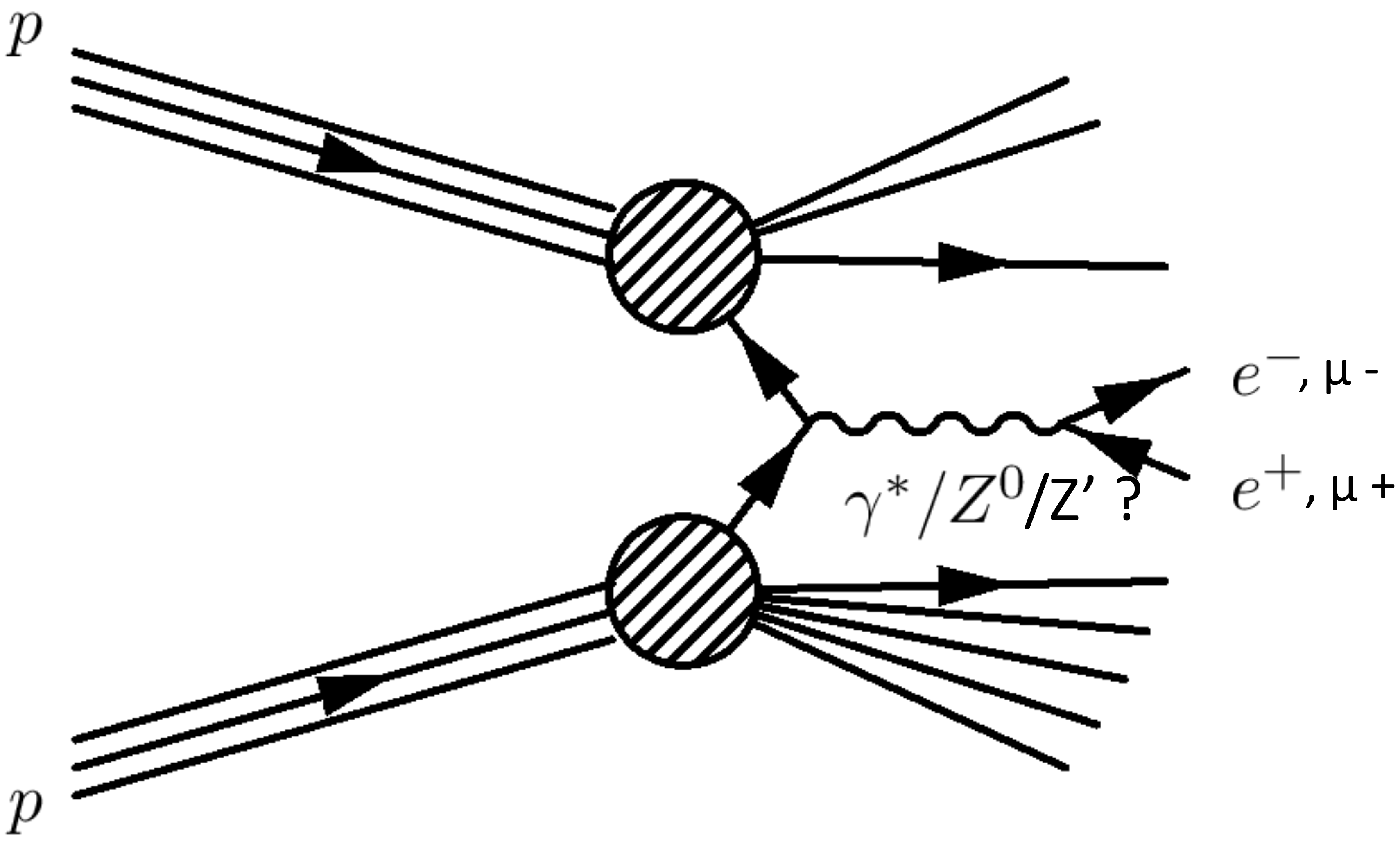
Drell-Yan

It takes place when a quark of one hadron and an antiquark of another hadron annihilate, creating a virtual photon or Z boson which then decays into a pair of oppositely-charged leptons.

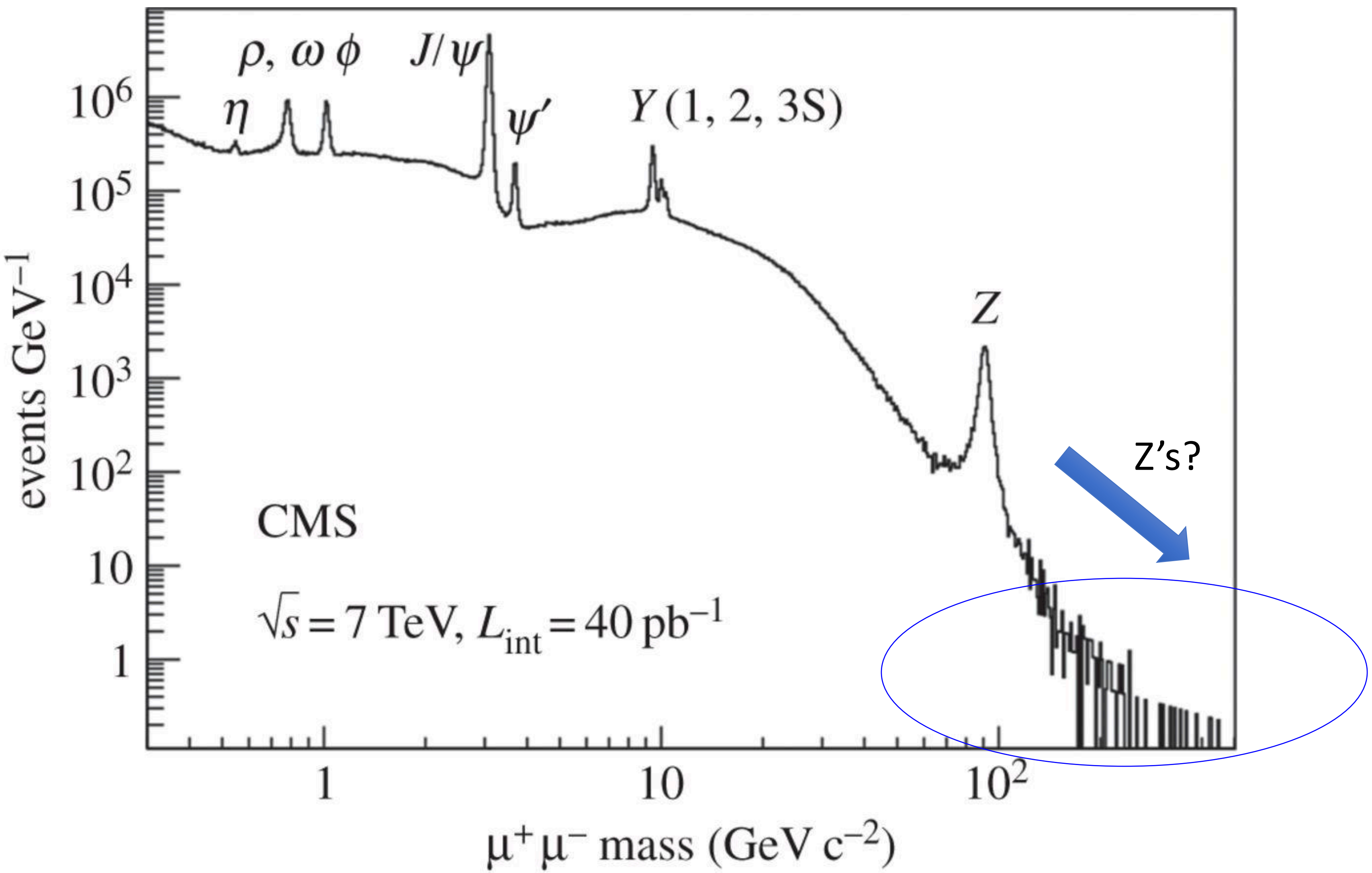


Drell-Yan

It takes place when a quark of one hadron and an antiquark of another hadron annihilate, creating a virtual photon or Z boson which then decays into a pair of oppositely-charged leptons.

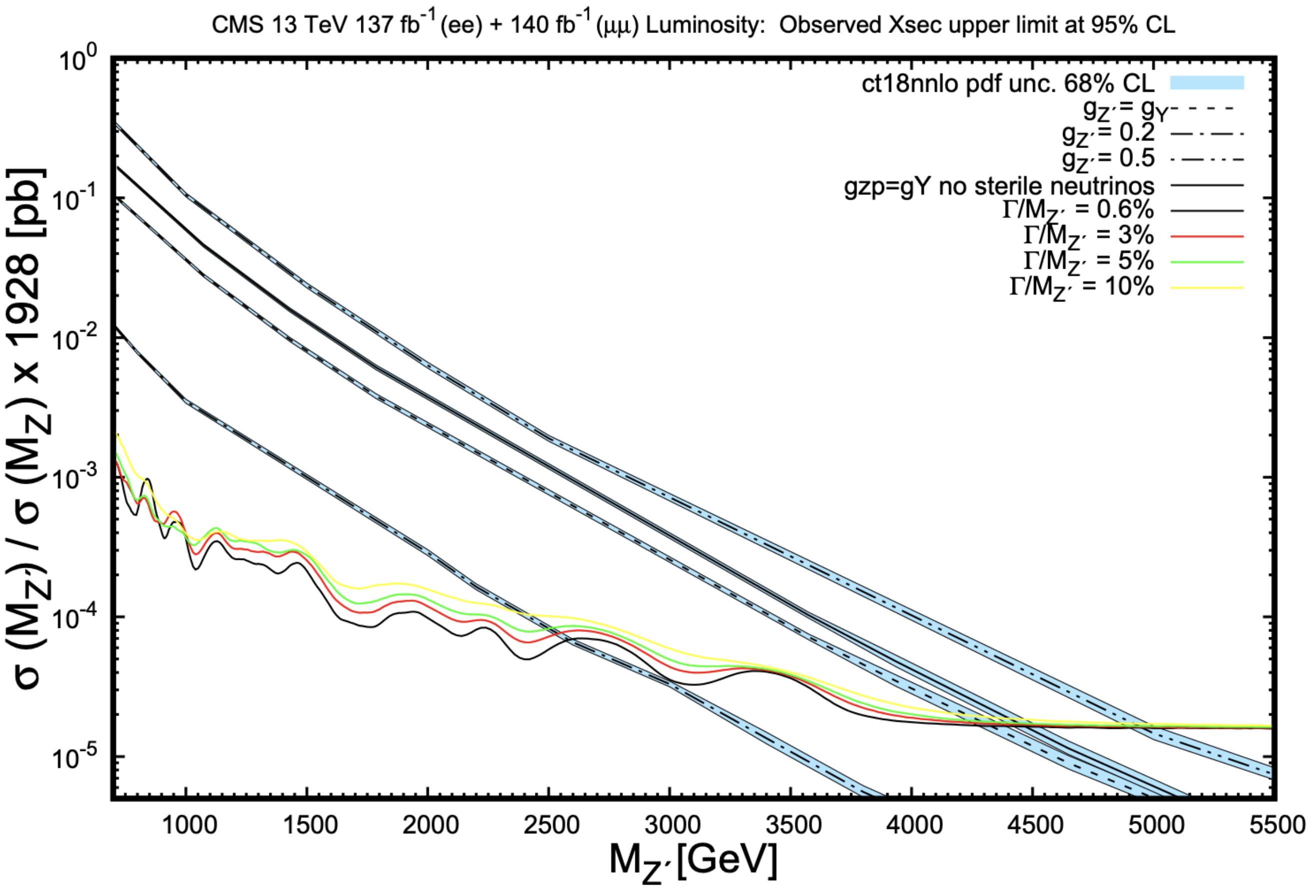


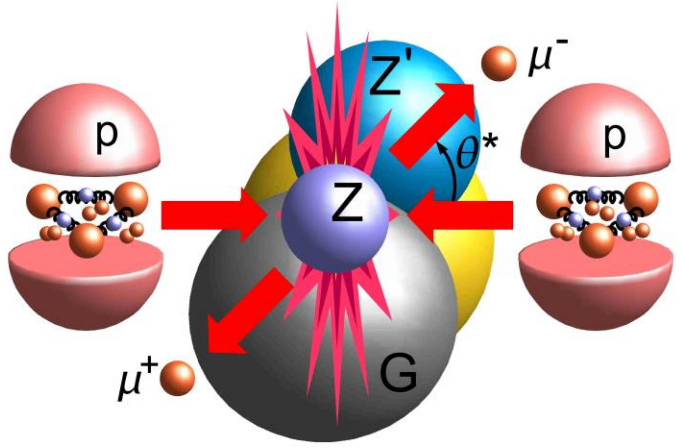
Invariant mass distribution for di-muon pair production in PP collisions at the LHC



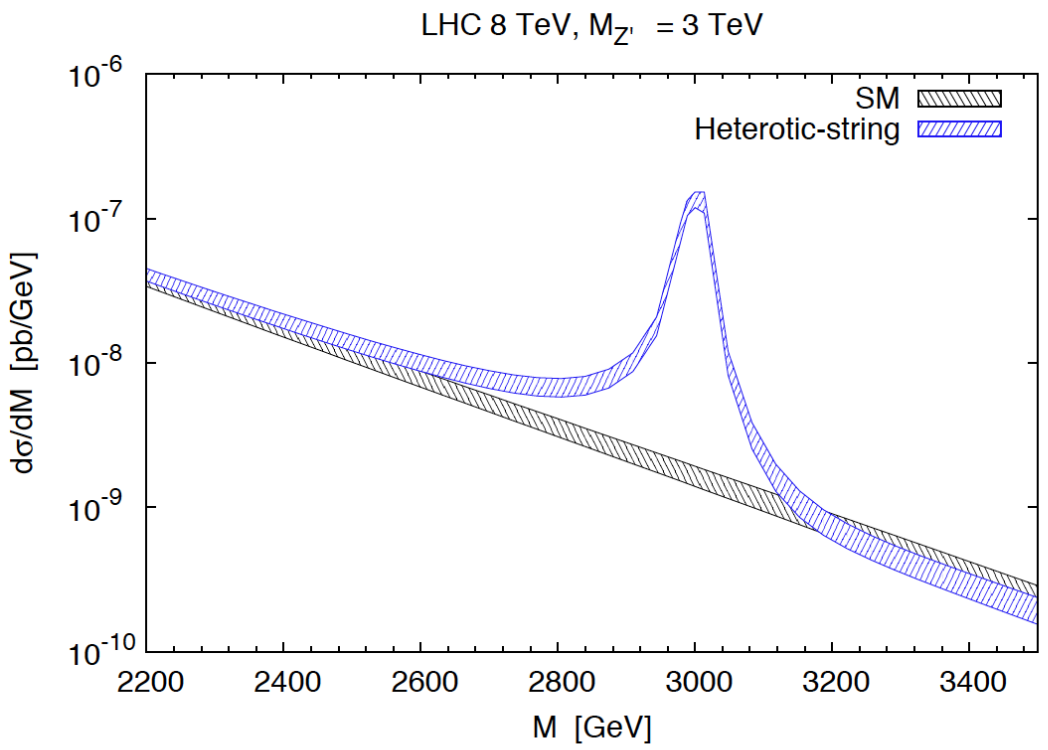
What happens at higher invariant mass?

Searches for new resonances are going on at both CMS and ATLAS





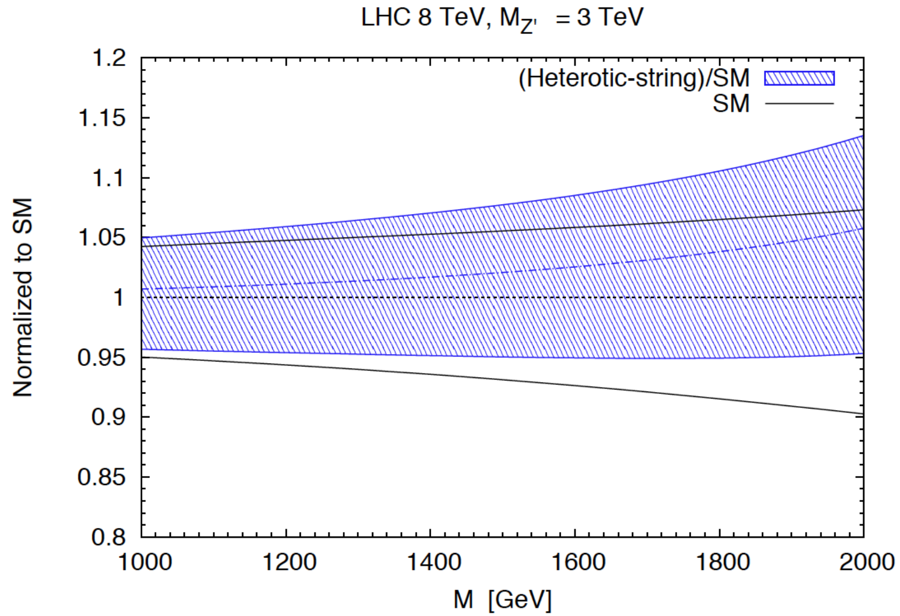
M.G., Faraggi EPJC2022



Bump searches in Drell-Yan

Some recent Z' proposal from heterotic string inspired models for which predictions are testable at the LHC.

M.G., Faraggi EPJC 2015



But PDF uncertainties are large…

Conclusions

- ❖ The LHC had wonderful I and II runs, culminating in the Nobel-Prize-winning discovery of the Higgs boson.

  It was a great achievement!

- ❖ The Standard Model of particle physics has been verified to an unexpected, even amazing degree of accuracy.

  A lot of efforts are put into testing the SM with further unprecedented precision

- ❖ The current absence of new physics signals is quietly shifting the focus of the theory community away from the `Standard BSM’ scenario of `Naturalness + Supersymmetry’.

- ❖ LHC next run may effectively kill many cherished models. The probability of striking, macroscopic new physics signatures with a moderate increase in energy appears low. We will probably have to disentangle small distortions from large SM backgrounds.

- ❖ In the forthcoming years, we will need precise and accurate predictions of increasingly complex SM processes.

- ❖ A great time for the QCD community