Introduction to QCD factorization for hadron colliders

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Southern Methodist University (Dallas, TX)

Lecture 1
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About myself and these lectures

I am a professor of theoretical physics involved in

- **perturbative** computations for rare short-distance particle interactions, with the goal to develop reliable theory to search for new physics
- analysis of **universal nonperturbative** hadronic functions describing complicated long-distance particle interactions (**CTEQ PDFs**)
- studies of the **interplay** of perturbative and nonperturbative effects in hadronic dynamics

Factorization in quantum chromodynamics (QCD) is the main guiding principle for these calculations. In these lectures, I will review applications of QCD factorization in precision computations for hadronic interactions at TeV energies.

Structure of the lectures

General thrust: discussion of QCD factorization methods for TeV colliders

Lecture1. Parton model and collinear factorization for one-momentum-scale observables

Lectures 2 and 3: Introduction to the global analysis of parton distributions (CTEQ)

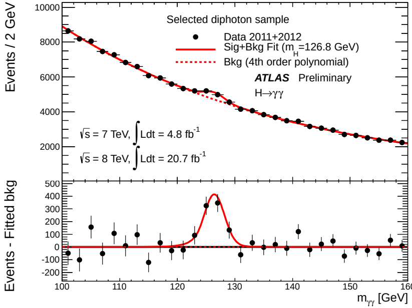
Lecture 4: Drell-Yan-like processes and transverse momentum resummation

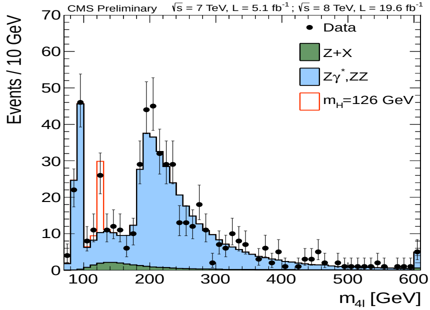
The difficulty is at the intermediate level. **Please ask questions if you need explanations!**

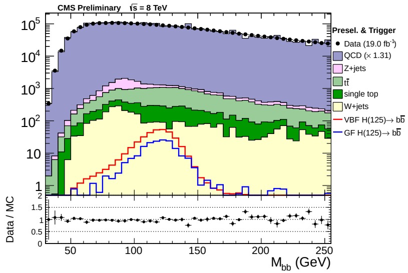
Large Hadron Collider in the top news of 2012

The quick discovery of Higgs bosons and a variety of other measurements at the LHC rely on precise understanding of hadronic interactions provided by quantum chromodynamics

Higgs searches involve a variety of precision QCD methods







My university, SMU, contributed to the discovery of the Higgs boson in the $\gamma\gamma$ decay channel

Now I have questions for you

From time to time, I will ask questions to check if you are following me. Just answer what you can.

Please raise your hand if you are

- an undergraduate student
- a graduate student
- you have studied quantum mechanics
- you have studied particle physics and/or quantum field theory

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Show "1", "2", "3" on your fingers

- Do you understand my English?
  1-don't understand, 2-a little, 3-understand well
- How much do you know about the Large Hadron Collider and Higgs boson?
  1-nothing, 2-a little, 3-a lot
- How much do you know about perturbative QCD?
  1-nothing, 2-a little, 3-a lot
- Have you done perturbative QCD calculations?
  1-never, 2-simple ones, 3-complicated ones

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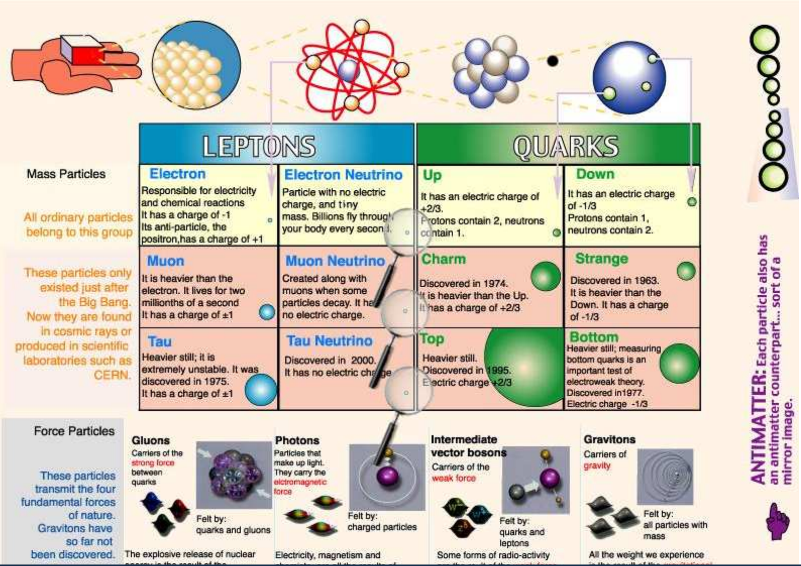
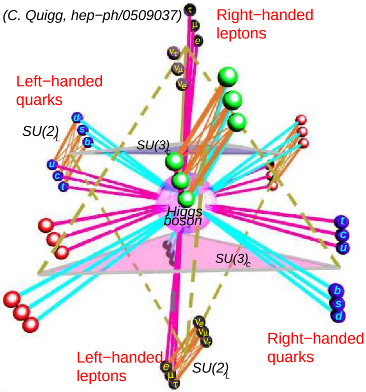
Standard Model: a successful effective theory of elementary particles

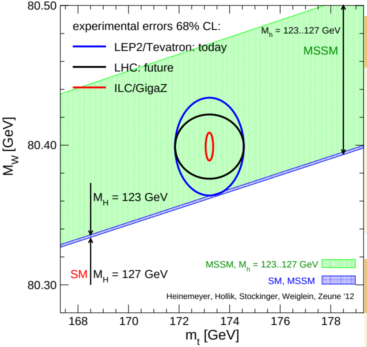


Symmetries of standard model



- Forces between SM particles emerge from the local $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ symmetry of SM Lagrangian
- Mass terms relate left- and right-handed fermions; arise as a result of the $SU(2)_L \otimes U(1)_Y \to U(1)_{EM}$ symmetry breaking, induced by the existence of Higgs scalar field doublet(s)
  - Nature of the electroweak breaking mechanism is still uncertain

Higgs sector in SM and minimal supersymmetry



Green band: $114 \le M_H \le 1000$ GeV

SM: 1 Higgs doublet, one boson H

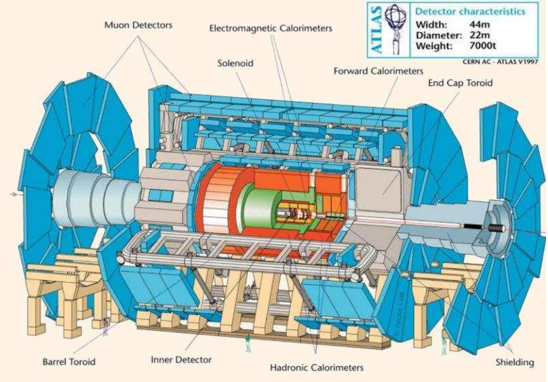
- Direct observation at the LHC
  $m_H \approx 125$ GeV at 95% c.l.
- indirect: $m_H = 80^{+39}_{-28}$ GeV at 68% c.l.

MSSM: 2 Higgs doublets; $h^0, H^0, A^0, H^\pm$

$m_h \le m_Z|\cos 2\beta| +$ rad. corr. $\lesssim 135$ GeV

- In these models, expect one or more Higgs bosons with mass below 140 GeV
- Many other possibilities for EW symmetry breaking exist!

High energy DENSITY physics

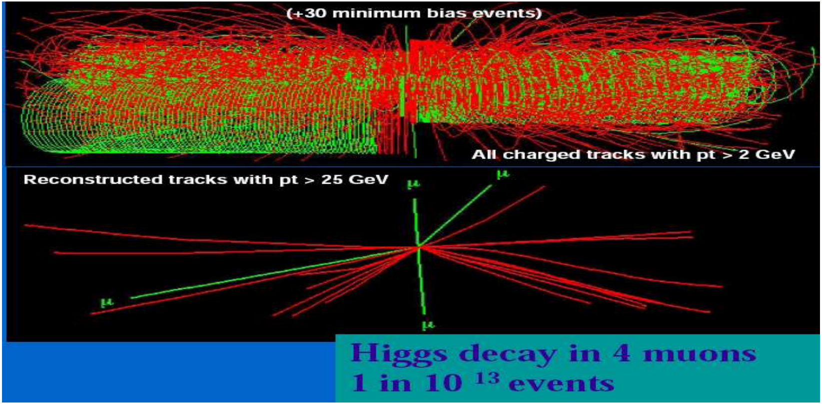


ATLAS detector at CERN

- Collision of two highly focused proton beams sometimes creates extreme energy density in a pointlike region

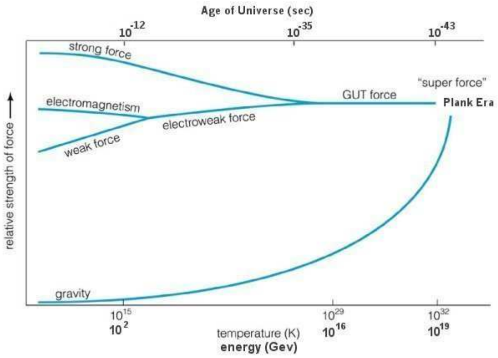
- Rarely, new energetic particles X are produced from this region

Finding a needle in a haystack:
A typical Higgs production event at the LHC



Production of high-energy particles can be systematically described in perturbation theory, in contrast to messy production of low-energy particles

Energy dependence of fundamental interactions



- Electroweak forces and gravity become stronger at high energies
- The strong force weakens at high energies
  - asymptotic freedom

    Gross, Politzer, Wilczek, 1973;

    Nobel prize, 2004

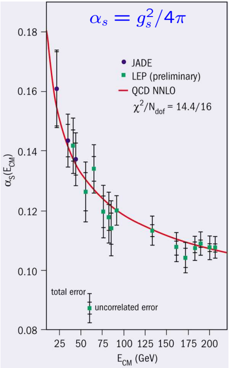
- Two types of forces may unify when their strengths become comparable

Three essential concepts of QCD

1. Asymptotic freedom of quarks and gluons at **large energy (short distance)**
2. Confinement of quarks and gluons at **small energy (large distance)**
3. Factorization of high-energy and low-energy contributions

1. Asymptotic freedom of strong interactions

- **Strong interactions are extremely intensive at small energies; weaken at large energies**



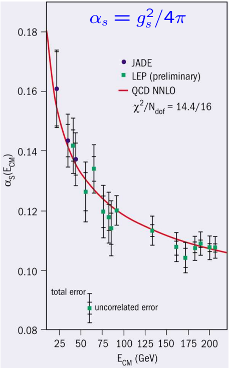
- At $E > 1$ GeV, the proton or another **hadron** (bound state) is a loosely bound system of **partons** (quarks and gluons)

- hard scatterings of partons are independent from one another

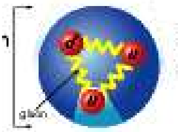
- probability of emissions quickly reduces with the number of emitted particles $\Rightarrow$ is described by **perturbation theory**

2. Confinement

- Strong interactions are extremely intensive at small energies; weaken at large energies

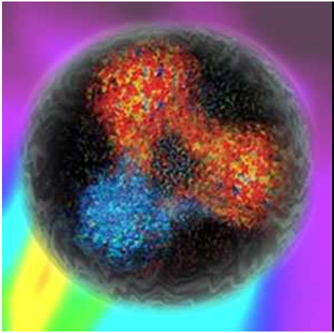
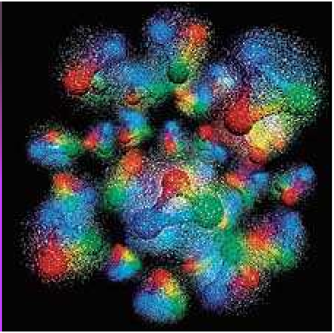
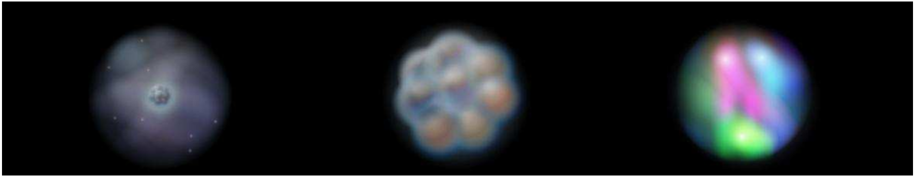


- At $E < 1$ GeV, **partons** clump together because of increasing strength of interaction and phase transitions



- Probability of partonic emissions grows with the number of emitted particles $\Rightarrow$ requires **non-perturbative computations**

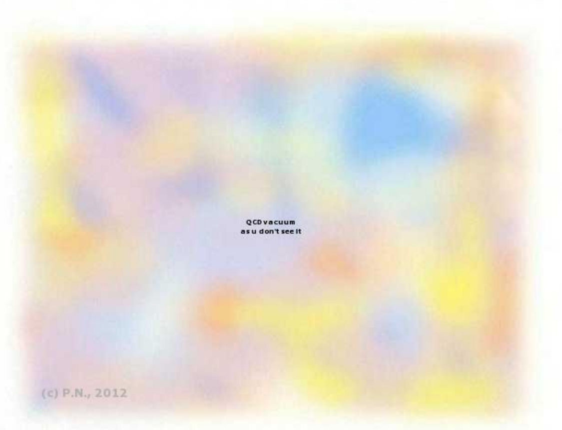
Simple visualization: colored quarks and gluons

The distribution of color depends on the resolution of your microscope (energy of the probing field)

A little trick showing dependence of color on resolution

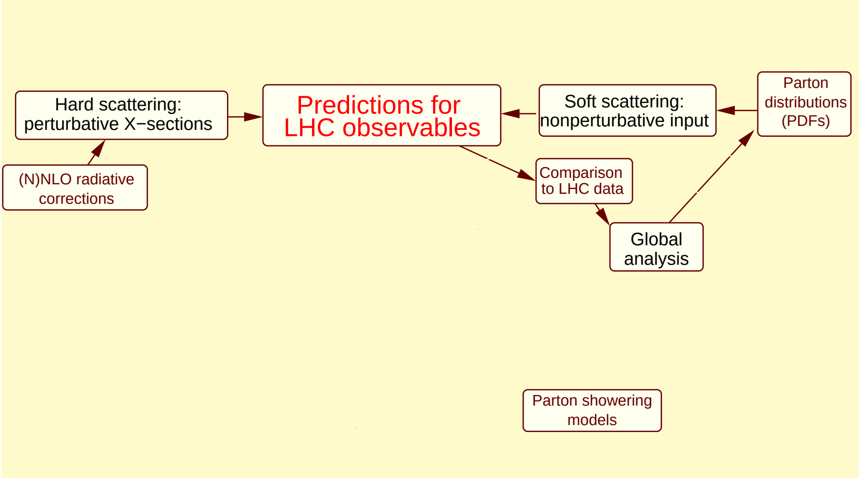
The angular resolution in the the human's eye is lower at the periphery of the eye than at its center. If you focus on the sentence at the center for 30 seconds, the colors away from the center may disappear.



By loose analogy, the QCD color force disappears at low resolution.

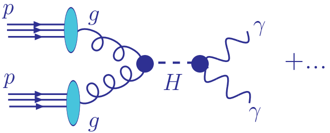
3. Factorization of QCD cross sections

On the example of an LHC cross section



Example 1: QCD factorization for $H \to \gamma\gamma$ process

A. Cross section $\sigma_{pp\to H\to\gamma\gamma}$ for production and decay of H, e.g. via $g+g \to H$; at lowest order in g_s

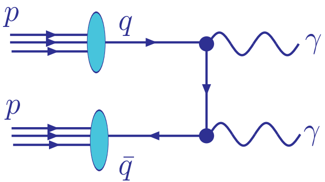


$$\sigma_{pp\to H\to\gamma\gamma} = \sigma_{gg\to H\to\gamma\gamma} f_{g/p}(x_1, M_H) f_{g/p}(x_2, M_H) + \ldots$$

- $\sigma_{gg\to H\to\gamma\gamma}$ is the cross section for scattering of two gluons; can be computed as a perturbation series in g_s, **at least formally**
- $f_{g/p}(x,\mu)$ is the probability to a find a gluon g with momentum $x\vec{P}$ in a proton with momentum $\vec{P}$ ($\left|\vec{P}\right| \approx E \approx \mu > 1$ GeV); $f_{g/p}(x,\mu)$ is nonperturbative (no full calculation yet)

Example 2: Factorization for the $\gamma\gamma$ background

B. Cross section (probability) $\sigma_{pp\to\gamma\gamma}$ for $pp \to \gamma\gamma$ via conventional channels, at the lowest order in g_s

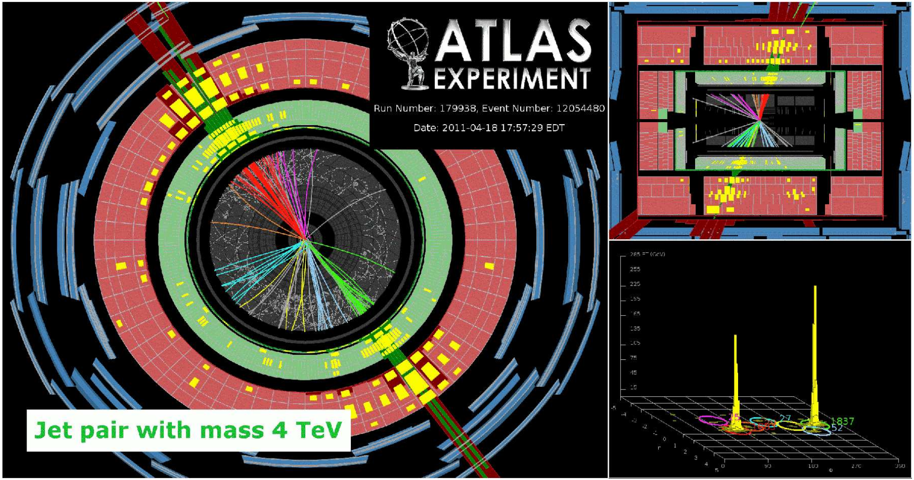


$+\ldots$

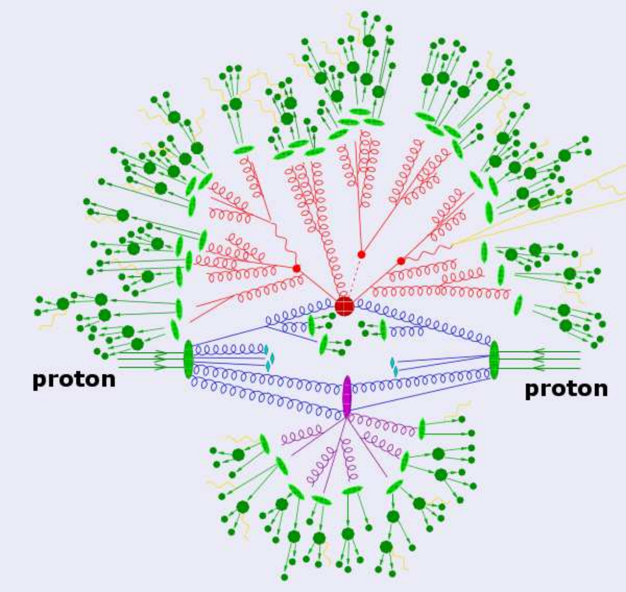
$$\sigma_{pp\to\gamma\gamma} = \sum_{q=u,d,s\ldots} \left[\sigma_{q\bar{q}\to\gamma\gamma} f_{q/p}(x_1) f_{\bar{q}/p}(x_2) + (q \leftrightarrow \bar{q})\right] \ldots$$

- $\sigma_{q\bar{q}\to\gamma\gamma}$ ($\sigma_{gg\to H\to\gamma\gamma}$) is the cross section for $q\bar{q}$ scattering; perturbative!
- $f_{q/p}(x,\mu)$ is the probability to a find a quark q in the proton; nonperturbative!
- Other scattering channels ("...") are **formally** suppressed by g_s

Example 3: Hadronic jet production at ATLAS



Structure of the collision event



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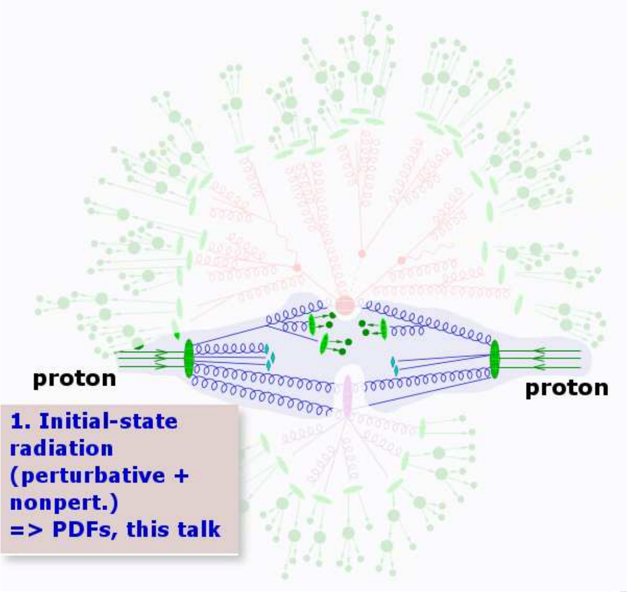

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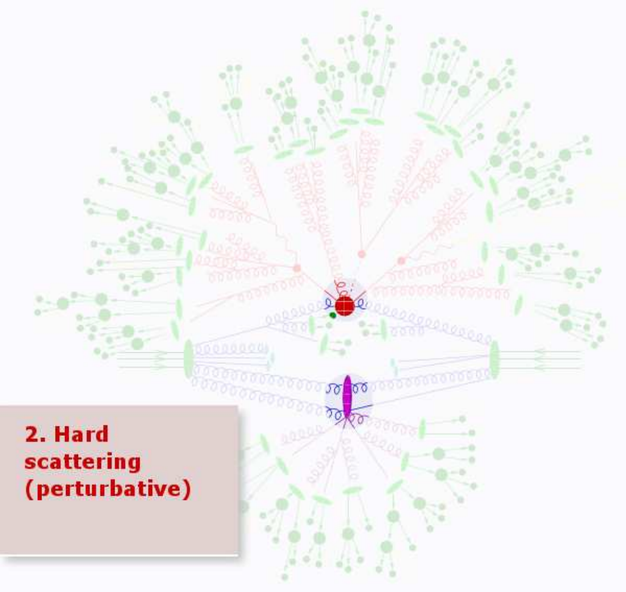

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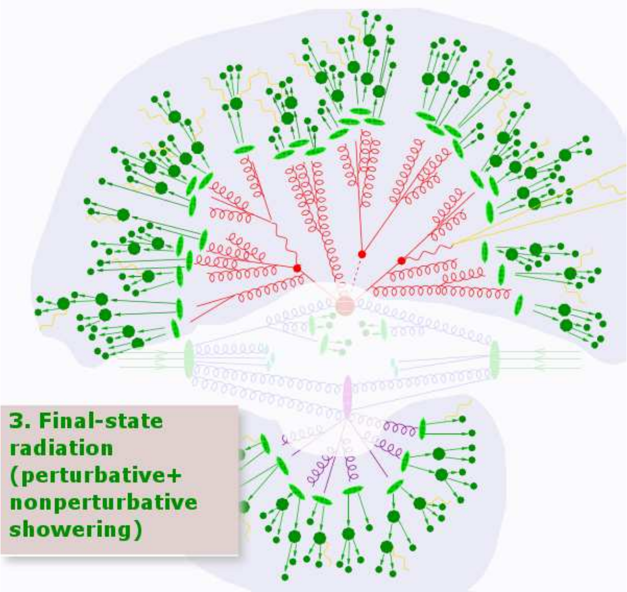

The actual calculation is very involved!

- The validity of this factorized picture must be proved to any order in g_s
- Short-distance contributions are evaluated by applying **perturbation** theory
- The **nonperturbative** functions (PDF's, etc.) must be reliably determined **(the speciality of the SMU group!)**
- The factorization proof is complicated by large logarithms of energy scale ratios in hard-scattering cross sections
- The large logs must be summed to all orders in g_s using **renormalization group**; **only after this summation**, the remaining higher-order corrections are indeed suppressed by powers of g_s and produce **scaling violations**

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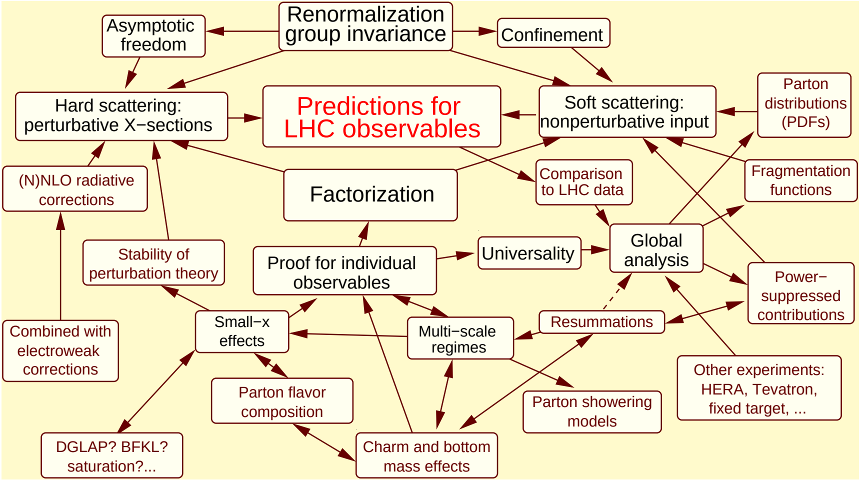

The full underlying theory

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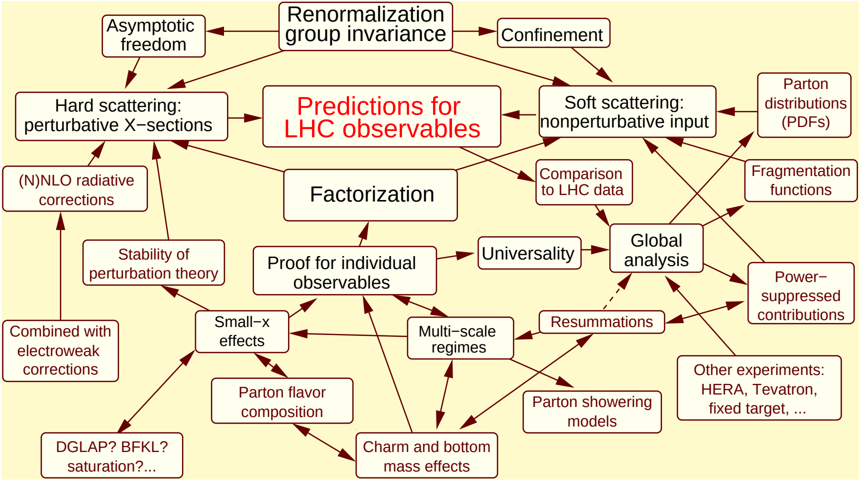

QCD is an extremely rich theory that is now explored in the new energy domain!