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Color Physics & Hadron Colliders

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Students Seminar
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OUTLINE

- Motivation
- Standard Model
- Quantum Chromodynamics
 - pQCD & non-pQCD calculations
 - QCD Phenomenology
- Conclusions

- Why study the Color Physics or Quantum Chromodynamics (QCD) ?

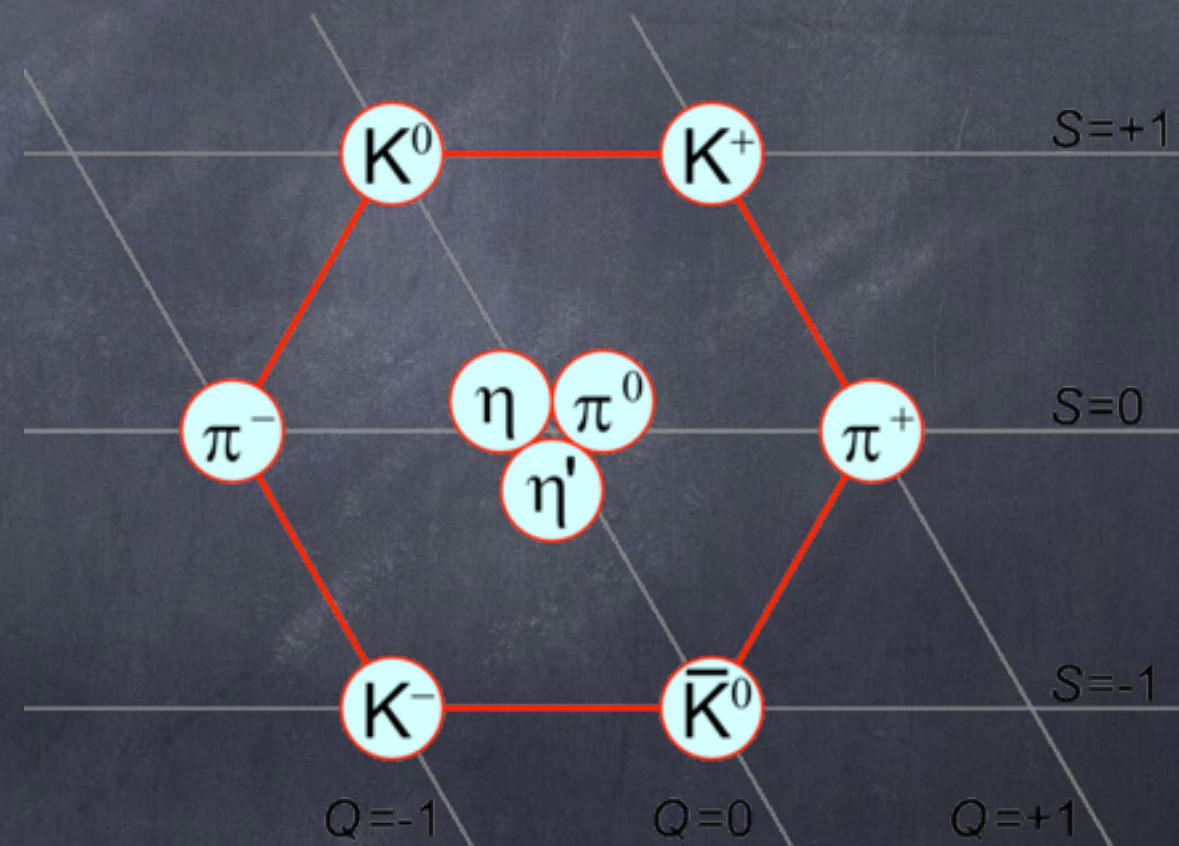
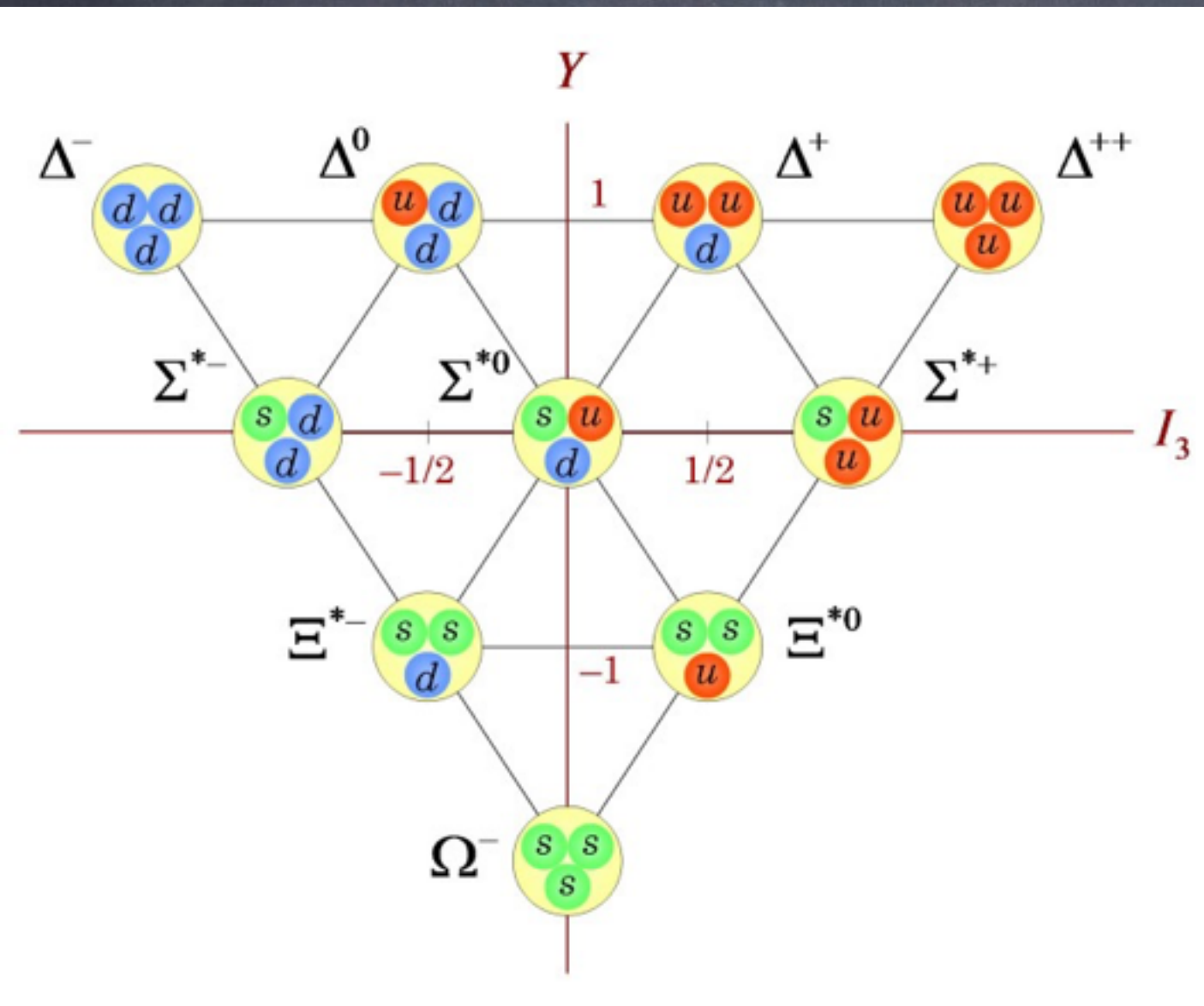
- New physics is studied in hadron colliders and the precise understanding of QCD is essential for disentangle the physics of the smallest

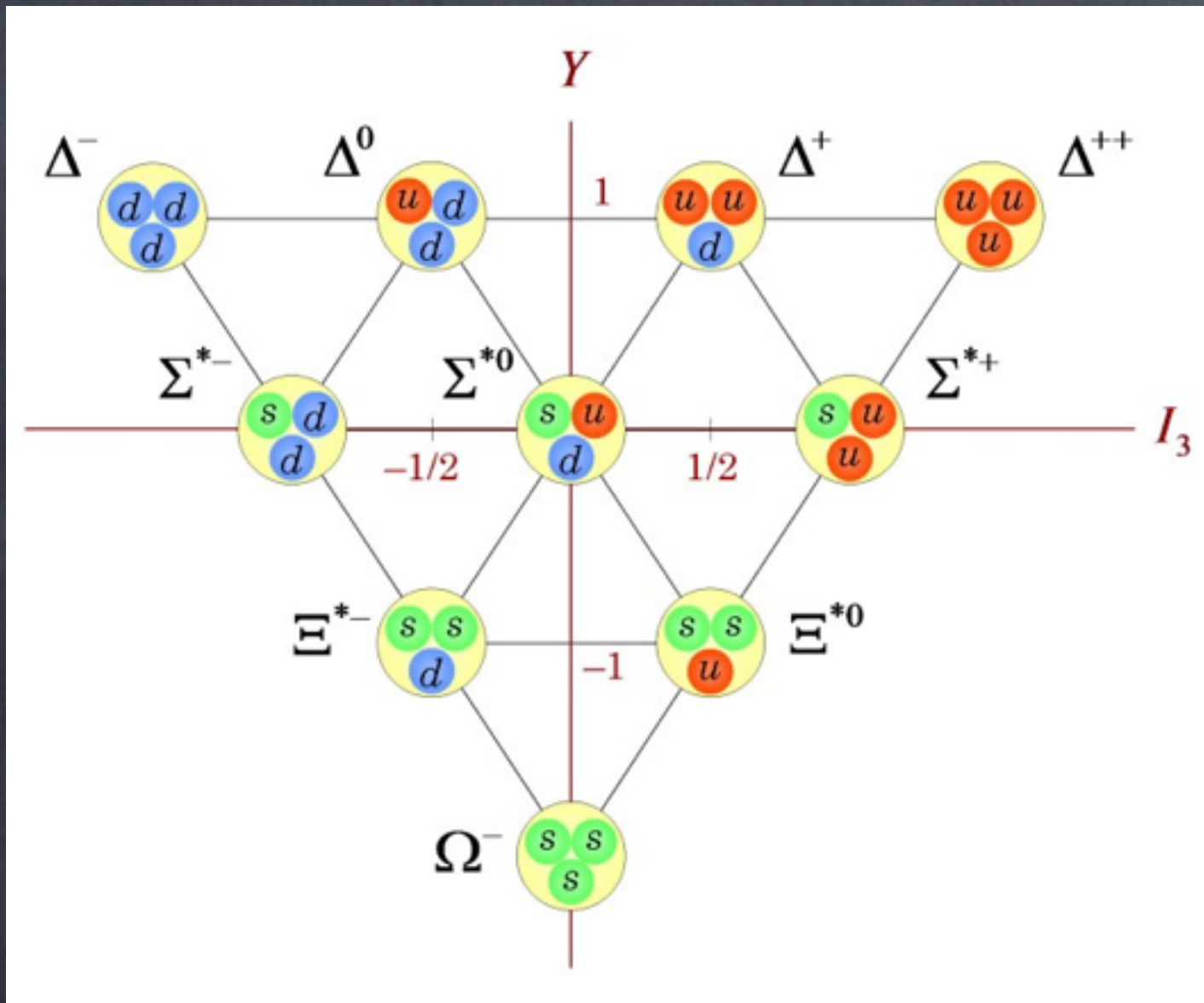
- QCD dominates the production mechanisms

- QCD is the main background in all the analysis at the LHC

Eightfold way

Gell-Mann & Zweig (1964) proposed the quarks





Bound states

Barions

qqq

Mesons

$q\bar{q}$



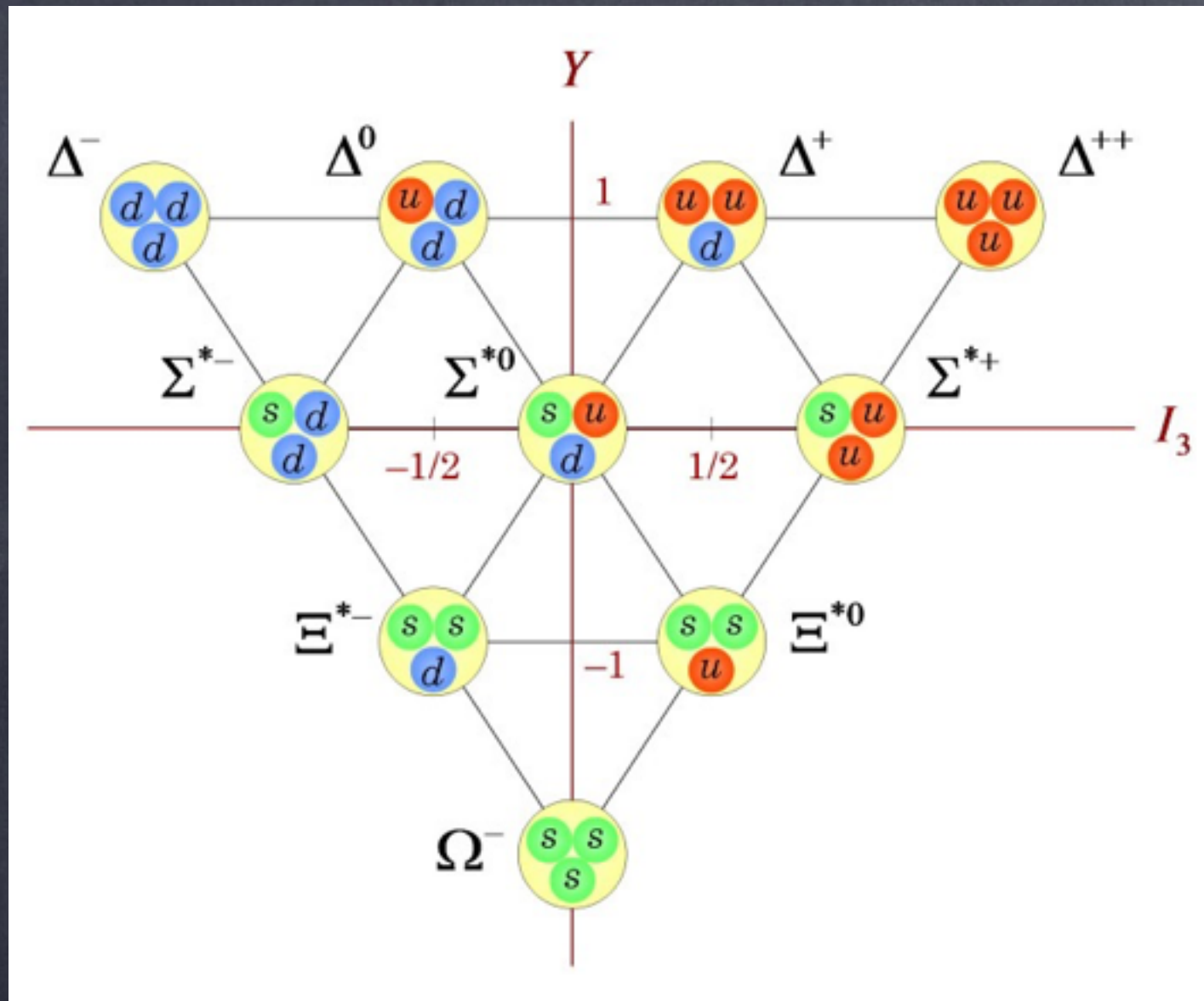
Ω^- in 1964



$J/\psi = (c\bar{c})$ in 1971 (BNL & SLAC)

$\Upsilon = (b\bar{b})$ in 1977 (Fermilab)

in 1995 (Tevatron)



quark	carga	mass (aprox)
u	$2/3$	$\sim 4 \text{ MeV}$
d	$-1/3$	$\sim 7 \text{ MeV}$
c	$2/3$	$\sim 1.3 \text{ GeV}$
s	$-1/3$	$\sim 150 \text{ MeV}$
t	$2/3$	$\sim 171 \text{ GeV}$
b	$-1/3$	$\sim 4.4 \text{ GeV}$

u

d

s

Ω^- in 1964

c

b

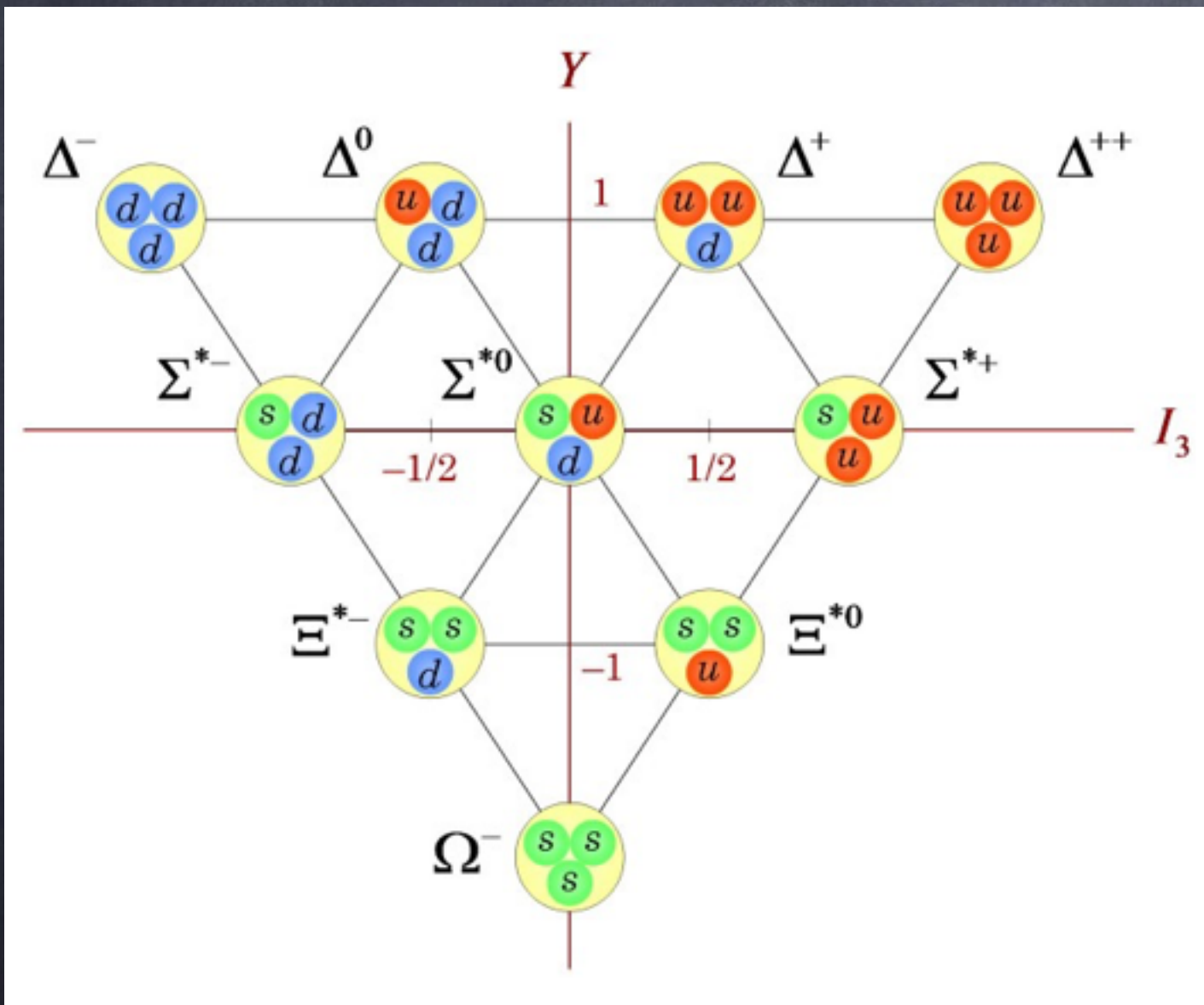
t

$J/\psi = (c\bar{c})$ in 1971 (BNL & SLAC)

$\Upsilon = (b\bar{b})$ in 1977 (Fermilab)

in 1995 (Tevatron)

Spin-Statistics Problem



$$\Delta^{++} = u \uparrow u \uparrow u \uparrow$$

The wave function is completely symmetric

Forbidden by Pauli exclusion principle

New quantum number:
COLOR

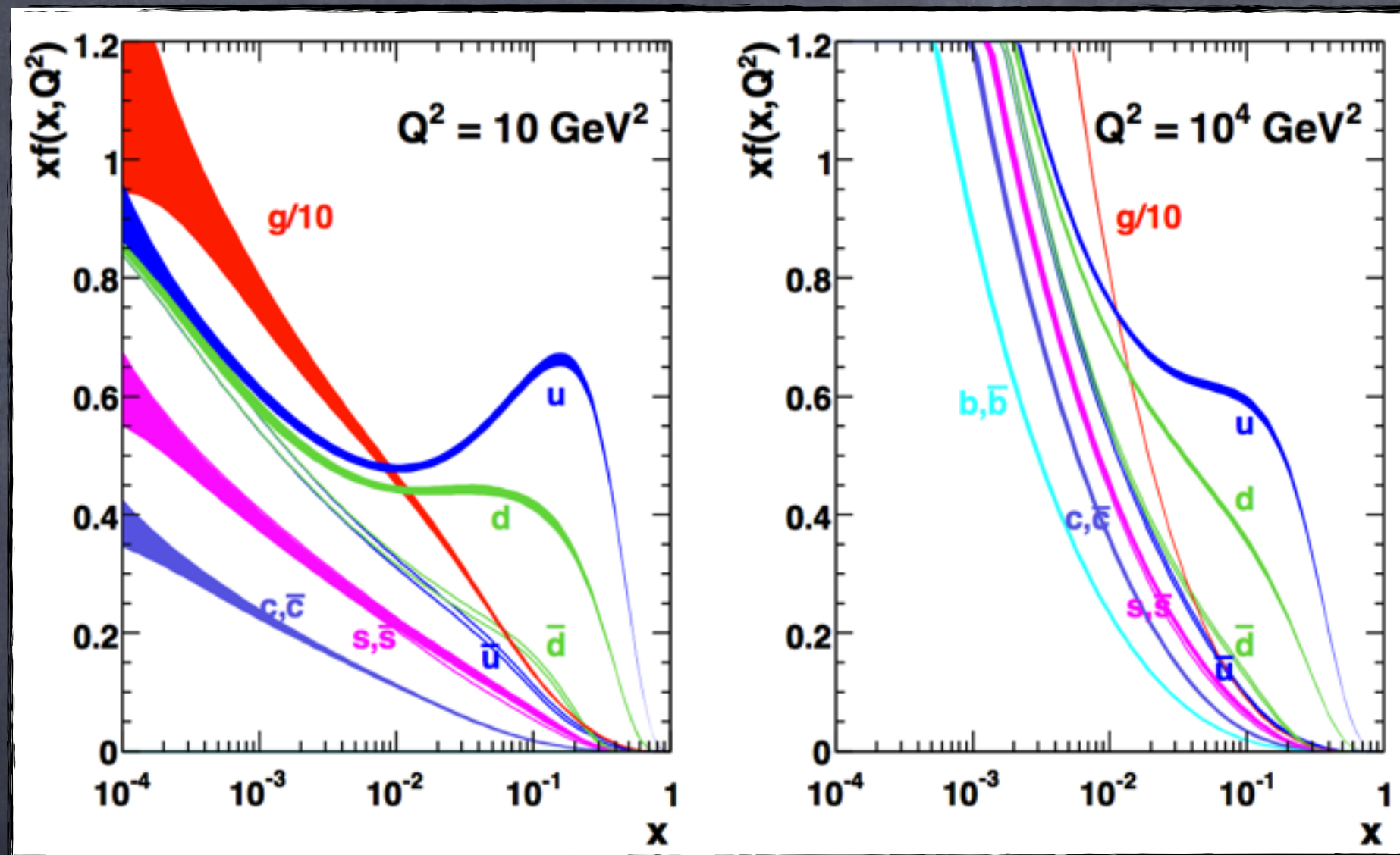


$$\Delta^{++} = \epsilon_{ijk} u_i \uparrow u_j \uparrow u_k \uparrow$$

Hadron

- A hadron is a particle made of quarks and bounded by the strong interaction (color)
- They are divided in two groups: barions and mesons
- Barions: protons, neutrons, etc.
- Mesons: Pions, Kaons, etc.
- In a naive way, everybody (?) knows that a proton is made of 3 quarks (uud), therefore is a barion. However, the probability to find other quarks is not zero

PDF



A proton is made of partons: quarks & gluons
 Valence quarks (uud)

Standard Model

The model which can explain all observables so far can be written as follows,

$$\mathcal{L}_{SM} = \mathcal{L}_{YM} + \mathcal{L}_{WD} + \mathcal{L}_{Yu} + \mathcal{L}_H$$

$$\mathcal{L}_{YM} = -\frac{1}{4} \sum_{A=1}^8 G_{\mu\nu}^A G^{\mu\nu A} - \frac{1}{4} \sum_{a=1}^3 F_{\mu\nu}^a F^{\mu\nu a} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

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

$$\mathcal{L}_{WD} = \sum_i^3 \left(L_i^\dagger \sigma^\mu \mathcal{D}_\mu L_i + \bar{e}_i^\dagger \sigma^\mu \mathcal{D}_\mu \bar{e}_i + Q_i^\dagger \sigma^\mu \mathcal{D}_\mu Q_i + \bar{u}_i^\dagger \sigma^\mu \mathcal{D}_\mu \bar{u}_i + \bar{d}_i^\dagger \sigma^\mu \mathcal{D}_\mu \bar{d}_i \right)$$

$$\mathcal{L}_{Yu} = i \hat{L}_i \bar{e}_j H^* Y_{ij}^{[e]} + i \hat{Q}_i \bar{d}_j H^* Y_{ij}^{[d]} + i \hat{Q}_i \bar{u}_j \tau_2 H Y_{ij}^{[u]} + h.c.$$

$$\mathcal{L}_H = (\mathcal{D}_\mu H)^\dagger (\mathcal{D}^\mu H) - V(H)$$

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Matter fields transform as

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}_L \sim (\mathbf{1}^c, \mathbf{2}, y_1);$$

$$e_{iR} \sim (\mathbf{1}^c, \mathbf{1}, y_2);$$

$$Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L \sim (\mathbf{3}^c, \mathbf{2}, y_3);$$

$$u_{iL} \sim (\mathbf{3}^c, \mathbf{1}, y_4);$$

$$d_{iL} \sim (\mathbf{3}^c, \mathbf{1}, y_5);$$

$$H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \sim (\mathbf{1}^c, \mathbf{2}, y_h)$$



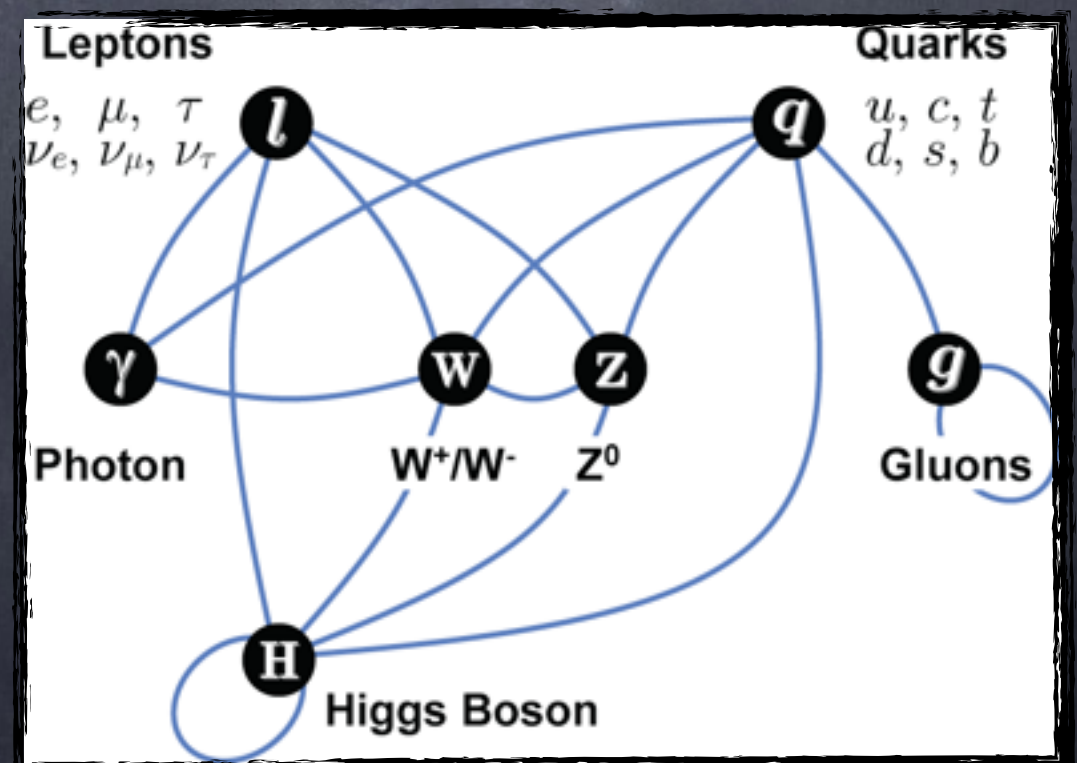
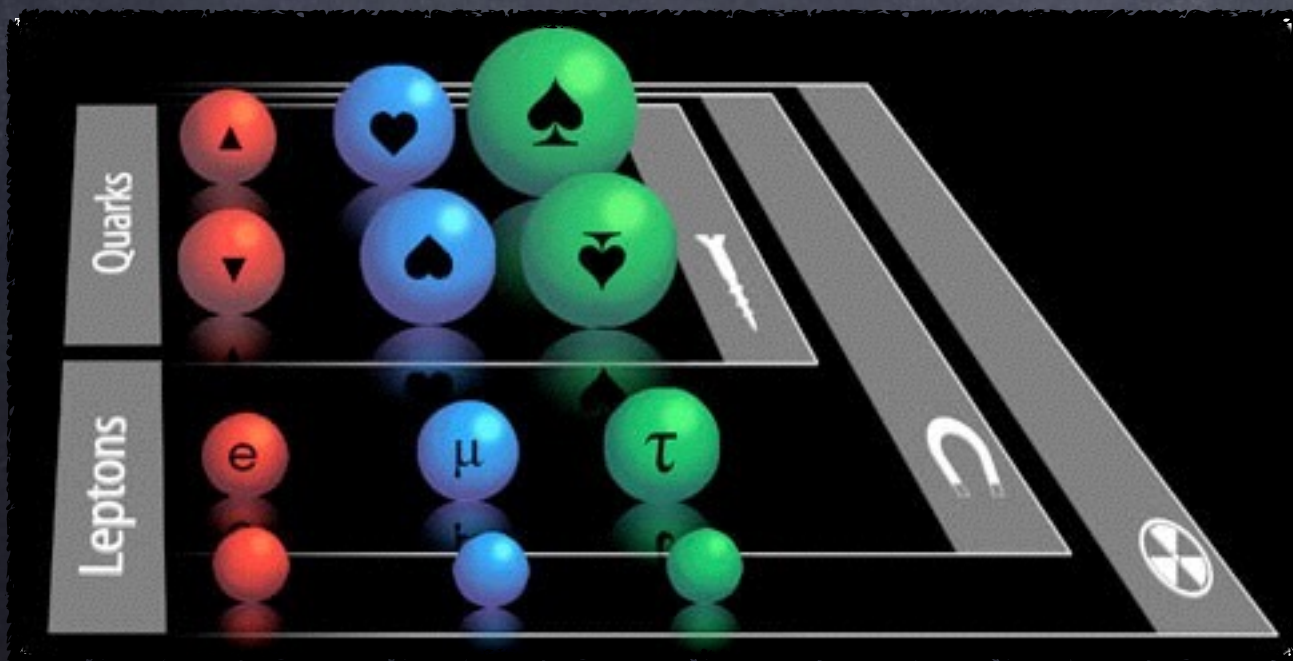
Gauge invariance

&

anomaly cancellation:

$$y_1 = -1, \quad y_2 = +2, \quad y_3 = +\frac{1}{3},$$

$$y_4 = -\frac{4}{3}, \quad y_5 = +\frac{2}{3}.$$



Quantum Chromodynamics (QCD)

- The fundamental principle in the SM is the gauge invariance which is manifested in the Lagrangian

- In QCD, these are local rotations in the SU(3) color space


$$\psi = \begin{pmatrix} \text{red} \\ \text{blue} \\ \text{green} \end{pmatrix} \xrightarrow{\text{rotation}} \psi' = \begin{pmatrix} \text{green} \\ \text{red} \\ \text{blue} \end{pmatrix}$$

- Quarks, fields of spin 1/2, are arranged in the SM, as color triplets

- Due to the unbroken local gauge invariance, there are 8 massless bosonic particles, the gluons, they interact between quarks and gluons

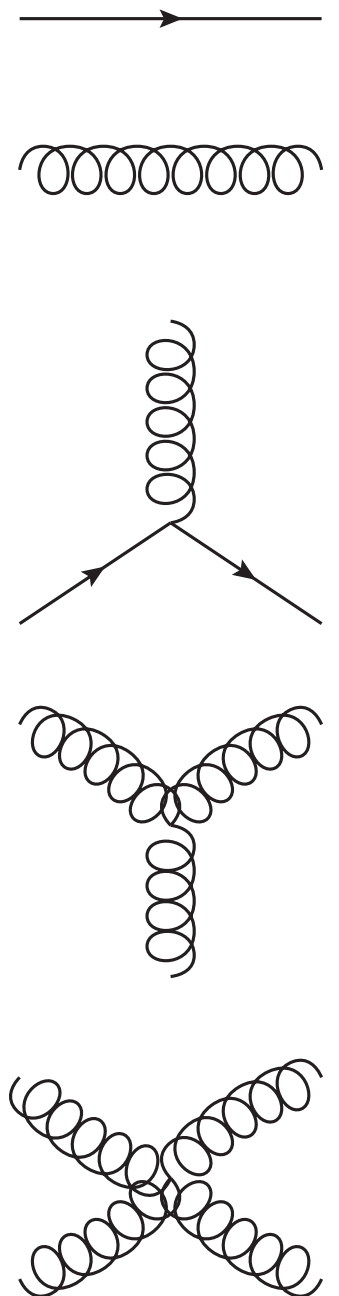
- The non-abelian structure is such as

$$[T^a, T^b] = if^{ab}_c T^c$$
$$C_A = 3; C_F = \frac{4}{3}; T_F = \frac{1}{2}$$

- Physics related with strong interactions can be described with the **QCD** Lagrangian.
- For the perturbative calculations, Feynman rules can be read directly,

$$\begin{aligned}
 \mathcal{L}_{QCD} = & \bar{\Psi}(i\partial_{\mu}\gamma^{\mu} - m)\Psi \\
 & - (\partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu})^2 \\
 & - g\bar{\Psi}A_{\mu}^a T_a \gamma^{\mu} \Psi \\
 & - \frac{1}{2}g(\partial_{\mu}A_{\nu}^a - \partial_{\nu}A_{\mu}^a)f^a_{bc}A^{\mu b}A^{\nu c} \\
 & - \frac{1}{4}g^2 f_{abc}f_{ade}A_{\mu}^b A_{\nu}^c A^{\mu d} A^{\nu e}
 \end{aligned}$$

- Without gauge fixing



- The gauge principle is elegant and powerful but, any theory in Physics will stand (or fall) when the comparison with experimental results is made
- Can we use QCD perturbatively in any energy range ??

Confinement

hadronic structure
non perturbative

e.g. Lattice QCD

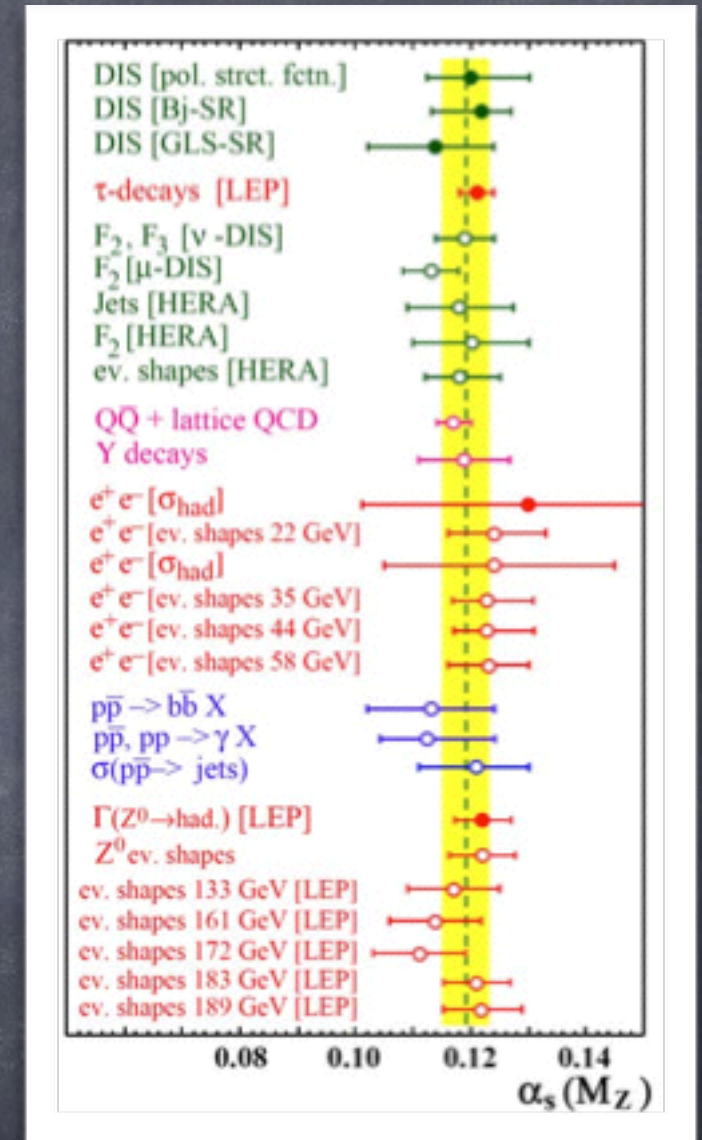
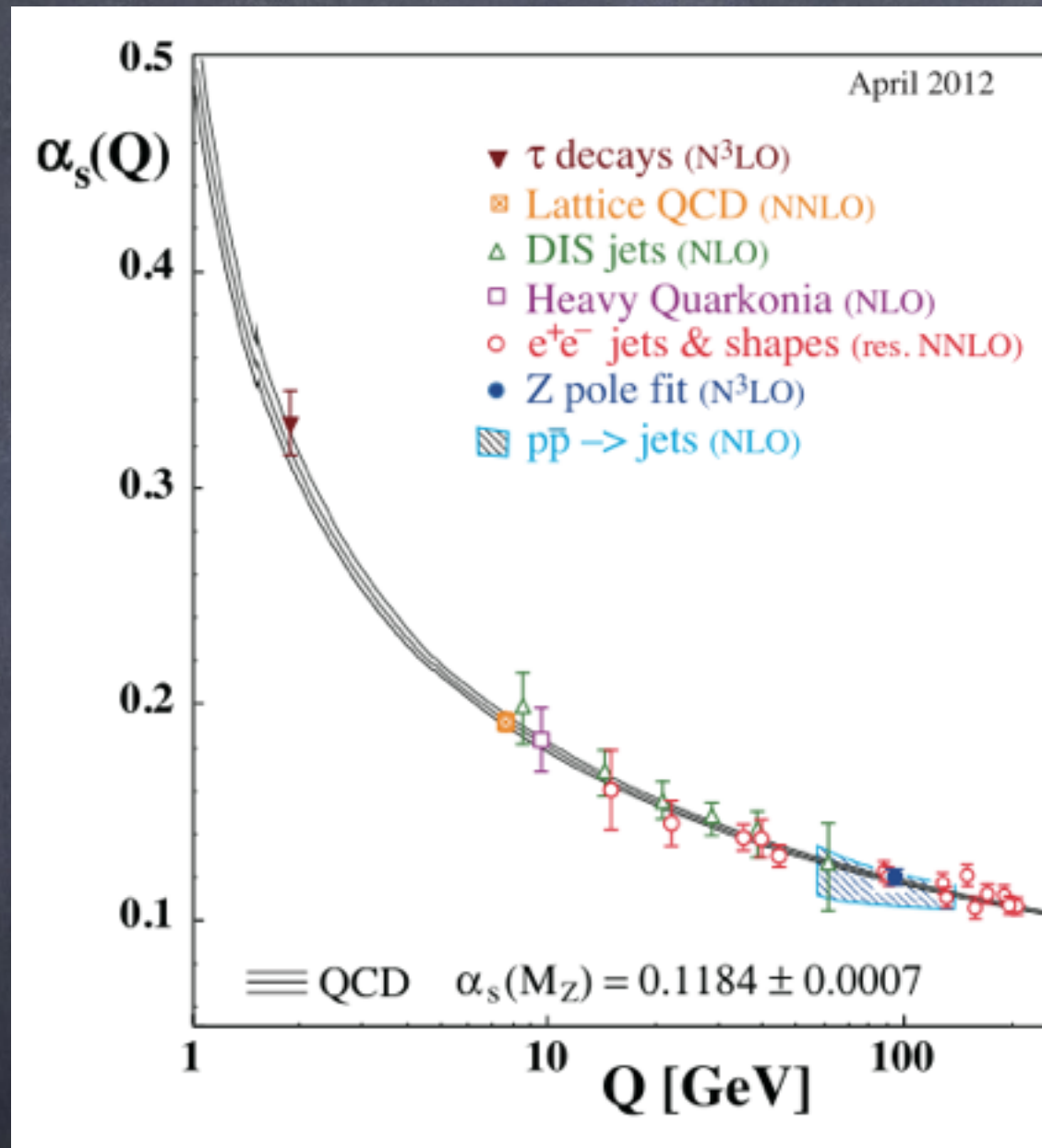


Asymptotic freedom

Cross sections in "hard"
processes

Perturbative methods

- **QCD** check: Experimental proof of the asymptotic freedom



Confinement



Asymptotic
freedom

A strongly interacting theory at large distances could become a weakly interacting at short distances.

A strongly interacting theory at large distances could become a weakly interacting at short distances.

Is this enough for explaining the success of the parton model and the perturbative **QCD** (pQCD)?

A strongly interacting theory at large distances could become a weakly interacting at short distances.

Is this enough for explaining the success of the parton model and the perturbative **QCD** (pQCD)?

No !!!



Asymptotic freedom only allows us to compute interactions at short distances

Detectors are located at long distances !!!

Experiments only detect hadrons and not free partons.

LHC

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Large Hadron Collider

From Wikipedia, the free encyclopedia

Coordinates: 46°14′N 06°03′E﻿ / ﻿46.233°N 6.050°E﻿ / 46.233; 6.050

"LHC" redirects here. For other uses, see [LHC \(disambiguation\)](#).

The **Large Hadron Collider** (**LHC**) is the world's largest and highest-energy particle accelerator, and considered "one of the great engineering milestones of mankind".^[1] It was built by the [European Organization for Nuclear Research](#) (CERN) from 1998 to 2008, with the aim of allowing physicists to test the predictions of different theories of [particle physics](#) and [high-energy physics](#), and particularly prove or disprove the existence of the theorized [Higgs boson](#)^[2] and of the large family of new particles predicted by [supersymmetric theories](#).^[3] The LHC is expected to address some of the [still unsolved questions of physics](#), advancing human understanding of [physical laws](#). It contains [six detectors](#) each designed for specific kinds of exploration.

The LHC was built in collaboration with over 10,000 scientists and engineers from over 100 countries, as well as hundreds of universities and laboratories.^[4] It lies in a tunnel 27 kilometres (17 mi) in circumference, as deep as 175 metres (574 ft) beneath the [Franco-Swiss border](#) near [Geneva, Switzerland](#).

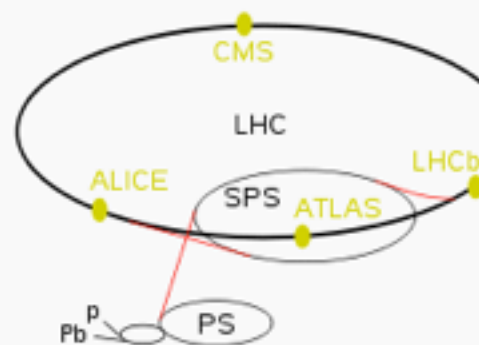
As of 2012, the LHC remains one of [the largest and most complex experimental facilities](#) ever built. Its [synchrotron](#) is designed to initially [collide](#) two opposing [particle beams](#) of either [protons](#) at up to 7 [teraelectronvolts](#) (7 TeV or 1.12 [microjoules](#)) per [nucleon](#), or [lead nuclei](#) at an energy of 574 TeV (92.0 μ J) per nucleus (2.76 TeV per nucleon-pair),^{[5][6]} with energies to be doubled to around 14 TeV collision energy - more than seven times any predecessor collider - by around 2015. Collision [data](#) was also anticipated to be produced at an unprecedented rate of tens of [petabytes](#) per year, to be analysed by a grid-based [computer network](#) infrastructure connecting 140 computing centers in 35 countries^{[7][8]} (by 2012 the [LHC Computing Grid](#) was the world's largest [computing grid](#), comprising over 170 computing facilities in a [worldwide network](#) across 36 countries^{[9][10][11]}).

The LHC went live on 10 September 2008, with proton beams successfully circulated in the main ring of the LHC for the first time,^[12] but 9 days later a [faulty electrical connection](#) led to the rupture of a [liquid helium](#) enclosure, causing both a [magnet quench](#) and several tons of [helium gas](#) escaping with [explosive force](#). The incident resulted in damage to over 50 [superconducting magnets](#) and their mountings, and contamination of the [vacuum pipe](#), and delayed further operations by 14 months.^{[13][14]} On November 20th 2009 proton beams were successfully circulated again,^{[15][16]} with the first recorded proton–proton [collisions](#) occurring 3 days later at the injection energy of 450 GeV per beam.^[17] On March 30th 2010, the first collisions took place between two 3.5 TeV beams, setting the current world record for the highest-energy man-made particle collisions,^[18] and the LHC began its planned research program.

By November 2012, the LHC had discovered two previously unobserved particles (the χ_b (3P) [bottomonium](#) state and a massive boson awaiting identification but suspected to be a [Higgs boson](#)), created a [quark–gluon plasma](#), and recorded the first observations of the very rare decay of the B_s [meson](#) into two [muons](#) ($B_s^0 \rightarrow \mu^+ \mu^-$) (a major test of [supersymmetry](#)).

The LHC operated at 4 TeV per beam until the end of 2012, 0.5 TeV higher than in 2010 and 2011.^[19] It will operate for two months in 2013 colliding protons with lead nuclei, and go into shutdown for upgrades to increase beam energy to 6.5 TeV per beam, with reopening planned for early 2015.^[20]

Large Hadron Collider (LHC)



LHC experiments

ATLAS	A Toroidal LHC Apparatus
CMS	Compact Muon Solenoid
LHCb	LHC-beauty
ALICE	A Large Ion Collider Experiment
TOTEM	Total Cross Section, Elastic Scattering and Diffraction Dissociation

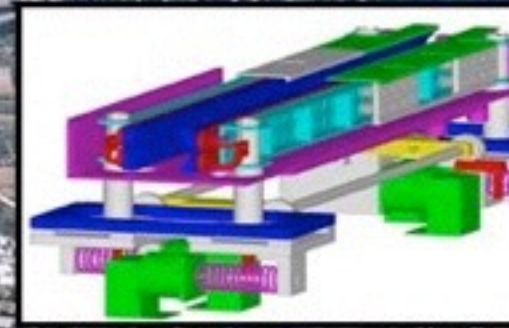
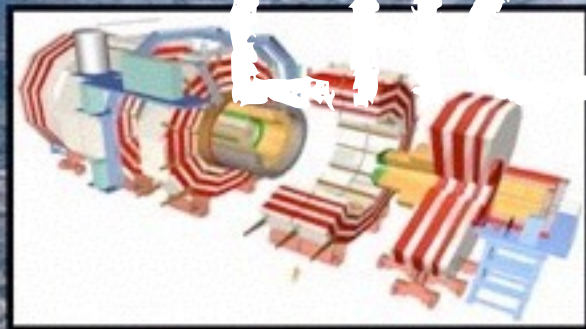
LHCf	LHC-forward
MoEDAL	Monopole and Exotics Detector at the LHC

LHC preaccelerators

p and Pb	Linear accelerators for protons (Linac 2) and Lead (Linac 3)
(not marked)	Proton Synchrotron Booster
PS	Proton Synchrotron
SPS	Super Proton Synchrotron

Contents [hide]

- [Etymology](#)
- [Purpose](#)



In order to establish a connection between theory and experiment, two ingredients are needed:

Control of infrared divergences

Factorisation theorem

Infrared divergences

There are quantities which are independent of the physics at large distances, then, computable within pQCD.

Factorization

There are a wide number of processes which can be factorised in universal pieces (it depends strongly on the processes)

QCD cannot be solved exactly
Perturbation theory

The coupling constant is "large" at the LHC
energies
Higher orders are needed for high precision
measurements

Other problems appear when a full QCD
calculation is performed

QCD cannot be solved exactly
Perturbation theory

The coupling
energies
Higher order
measurements



the LHC
precision

Other problems appear when a full QCD
calculation is performed

Perturbative calculations

perturbative QCD

- Dimensional Regularization

$$4 \Rightarrow D$$

- Divergences appear like poles in D ,

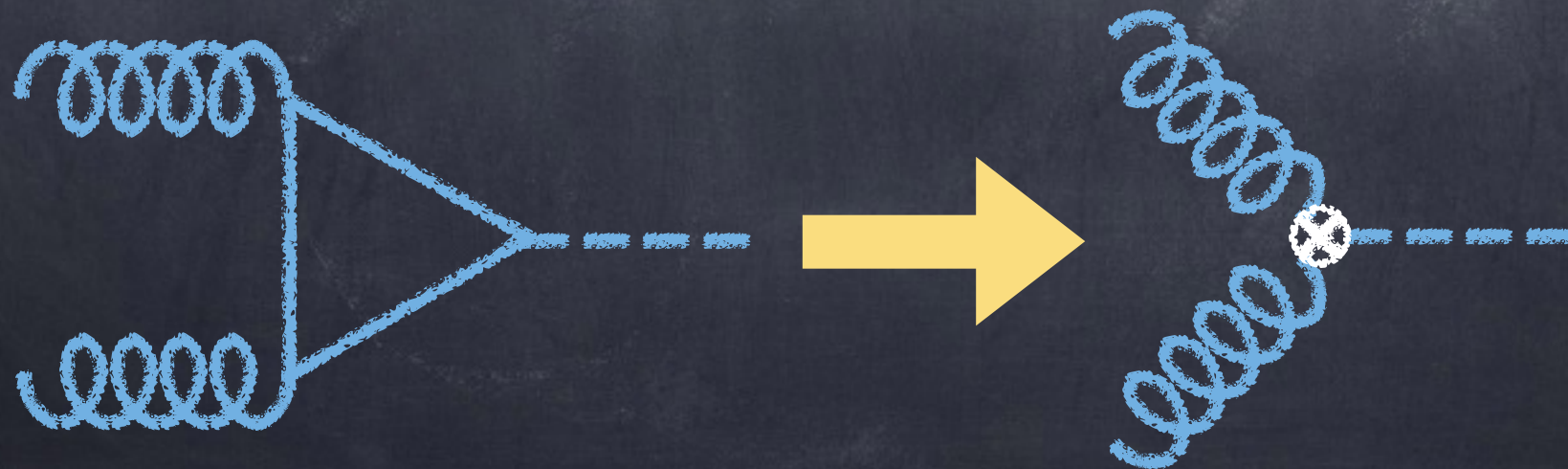
$$\frac{1}{D-4}$$

- JOB: Extract the finite parts at all orders, i.e. LO, NLO, NNLO, etc.

- But, what does it mean phenomenologically NLO or NNLO?
- The cross section in pQCD can be expressed at certain accuracy as,

$$\sigma = \sigma^{(0)} + \alpha_S(\mu)\sigma^{(1)} + \alpha_S^2(\mu)\sigma^{(2)} + \dots$$

- Where the sum is finite after the complete sum
- As an example, let's work in the EFT framework for the ggH process, i.e.



@ amplitude level

LO



$$\mathcal{O}(g_S^2)$$

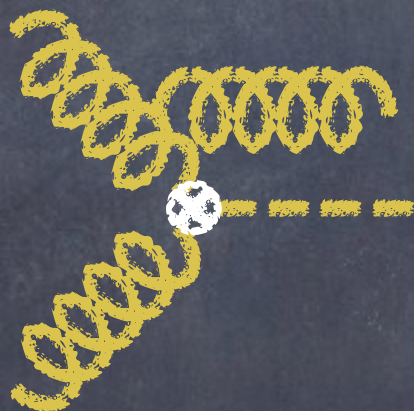
Phase space

$$2 \rightarrow 1$$

$$2 \rightarrow 2$$

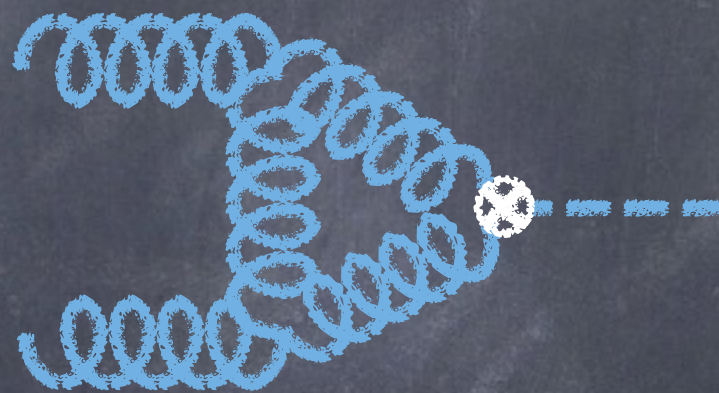
$$2 \rightarrow 3$$

NLO



$$\mathcal{O}(g_S^3)$$

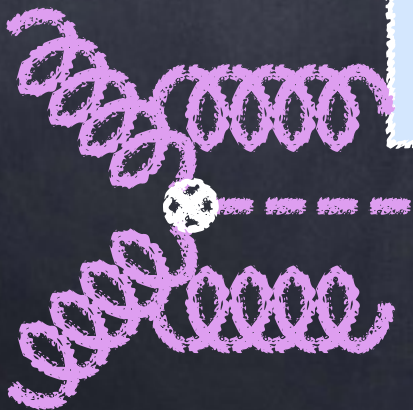
real correction



$$\mathcal{O}(g_S^4)$$

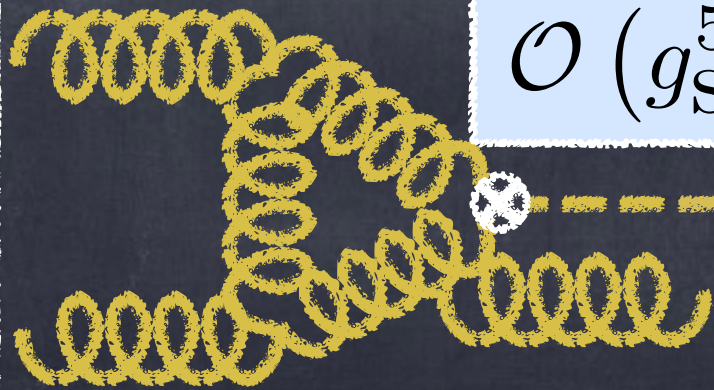
virtual correction

NNLO



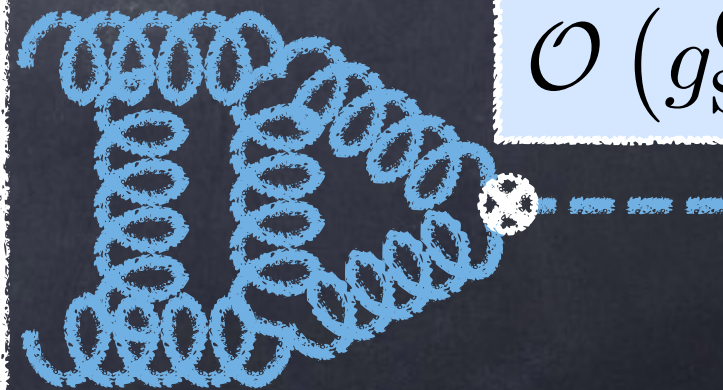
$$\mathcal{O}(g_S^4)$$

RR-correction



$$\mathcal{O}(g_S^5)$$

VR-correction



$$\mathcal{O}(g_S^6)$$

VV-correction

- The total cross section will be then,

$$\sigma = \sigma^{(LO)} + \alpha_S(\mu)\sigma^{(NLO)} + \alpha_S^2(\mu)\sigma^{(NNLO)} + \dots$$

- where,

$$\sigma^{(NLO)} = \int_{\Omega} d\sigma^V + \int_{\Omega+1} d\sigma^R$$

$$\sigma^{(NNLO)} = \int_{\Omega} d\sigma^{VV} + \int_{\Omega+1} d\sigma^{RV} + \int_{\Omega+2} d\sigma^{RR}$$

- But, divergences appears everywhere, and they cancel after the complete sum of individual pieces

KLN Theorem

(Kinoshita-Lee-Nauenberg)

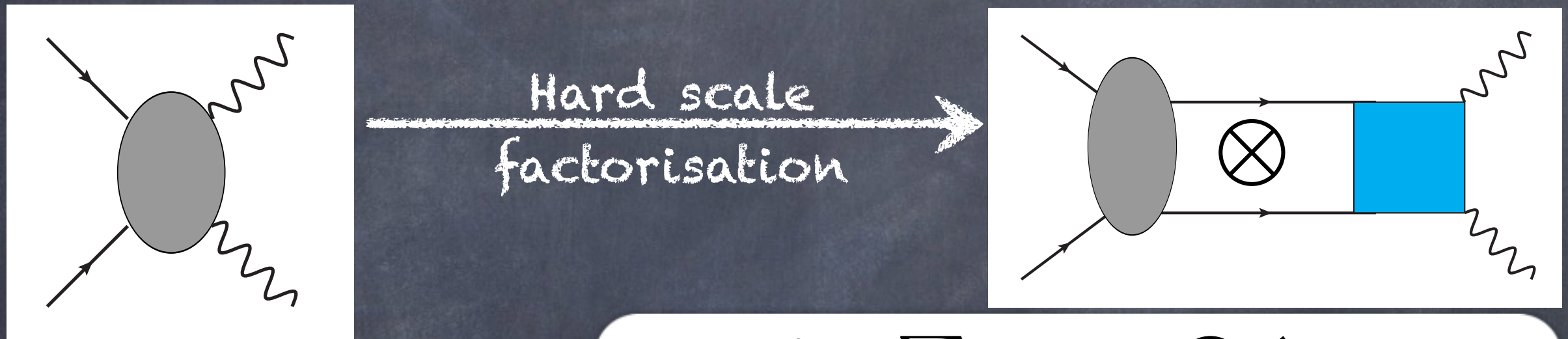
Infrared singularities, in a massless theory, cancel when all degenerate states are added (in the initial and final states)

Experimentally, a parton with large transverse momentum (jet) CANNOT be distinguished between: a parton plus a gluon with small momentum (soft particle) and two colinear partons

Non-perturbative
calculations

Factorisation

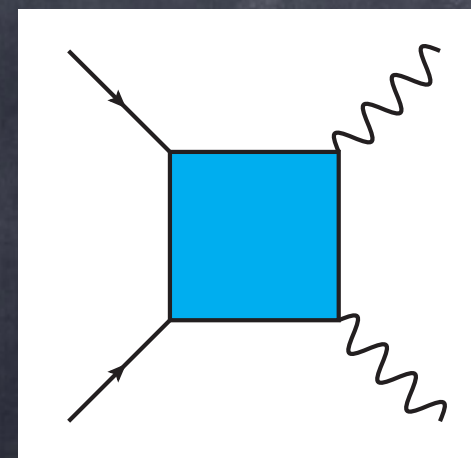
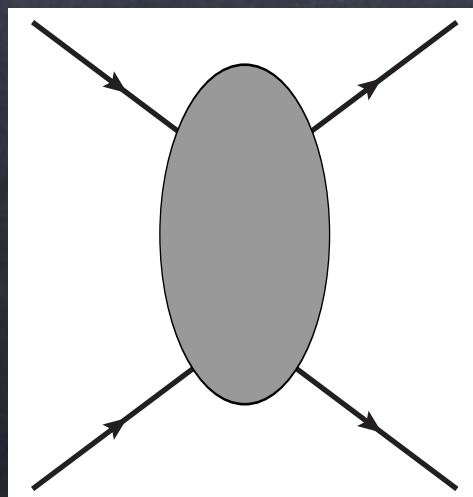
A representation of the factorisation is



$$F_2(x, Q^2) \sim \sum_a f_a(x, \mu_f) \otimes \hat{F}_2^a(x, Q/\mu_f)$$

Not a unique way to separate long and short distances

Parton
Distributions
(long dist.)



Structure
functions
(short dist.)

The factorisation scale (μ_f) determines the limit between long and short distances

The factorisation schemes allow to absorb all singularities which appear at long distances within the bare PDFs

Parton densities are defined as the probability to find a particle with certain fraction of longitudinal momentum "x", at some transferred energy " Q^2 ", i.e.

$$f_a(x, \mu_f) = \frac{1}{2} \int \frac{dy^-}{2\pi} e^{ixp^+ y^-} \langle p | \bar{\Psi}_a(0, y^-, 0) \gamma^+ \mathcal{F} \Psi_a(0) | p \rangle_{\bar{MS}}$$

Parton densities are extracted by implementing global **QCD** fits

QCD

Phenomenology

Is everything set ?

- Experiments do not cover the complete solid angle
- The resolution that they have is not infinite
- Simulations of the detectors which are not perfect and they have different thresholds
- Numerical simulations are needed in order to recreate the collisions at the LHC
- These simulations are performed by using the Monte Carlo method

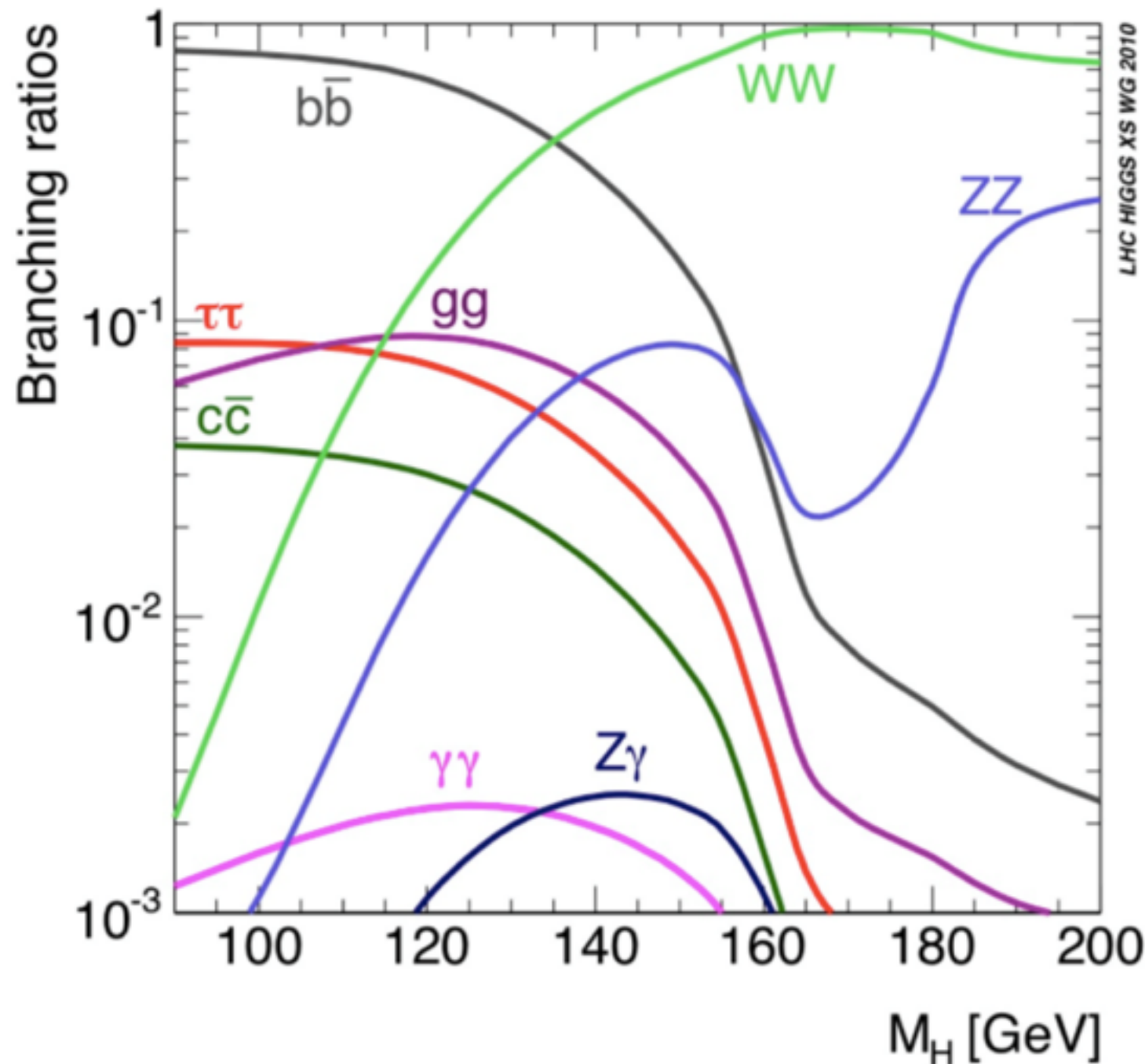
Higgs production @LHC

- Higgs discovery has been achieved with a high precision due to theoretical and experimental advantages
- Both groups have done such a hard work that in July 4th 2012, the 5σ discovery was announced at CERN
- How was the path of the Higgs discovery?

Higgs discovery

- Higgs has so many different channels to decay, once it is produced
- One has to be able to separate all contributions from each individual channel, i.e. distinguish all signatures in the most accurate way
- Monte Carlo simulations were computed in order to provide the distributions which are the smoking gun of the Higgs particle

Decay modes of Higgs

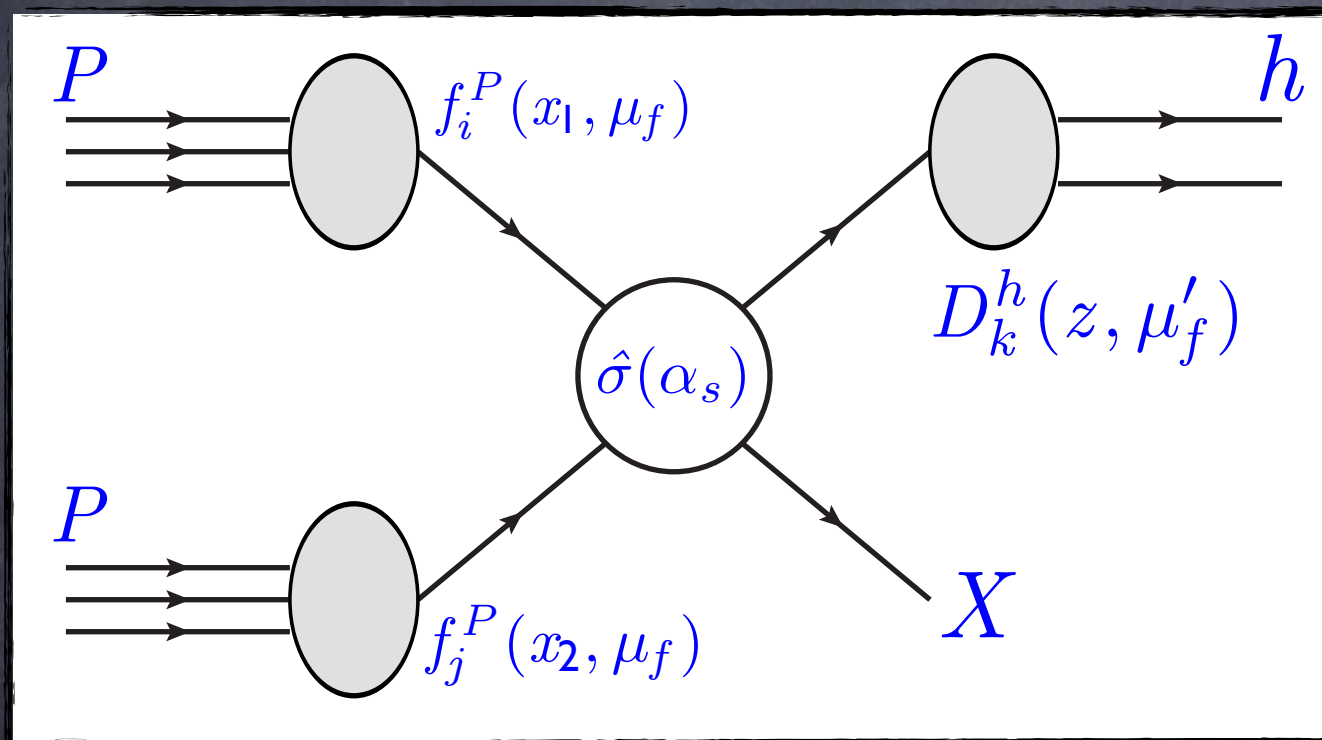


One needs to analyse all channels in order to confirm that the particle is the one predicted by the SM or to claim new physics

Everything have to be extremely precise in the measurement (experimentally) and in the prediction (theoretically)

Theo & Exp

- How to translate the theoretical results to experimental measurements?

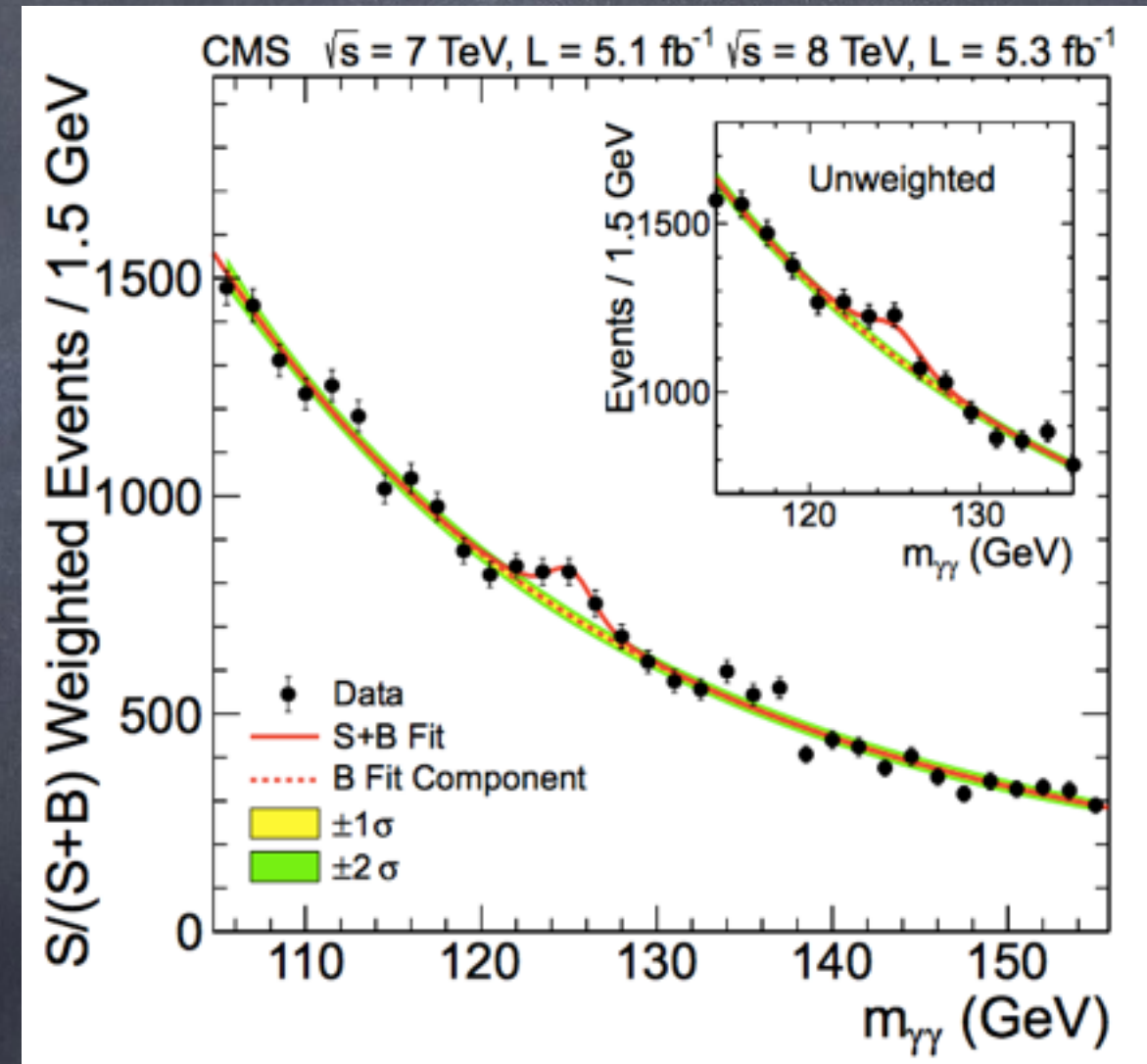
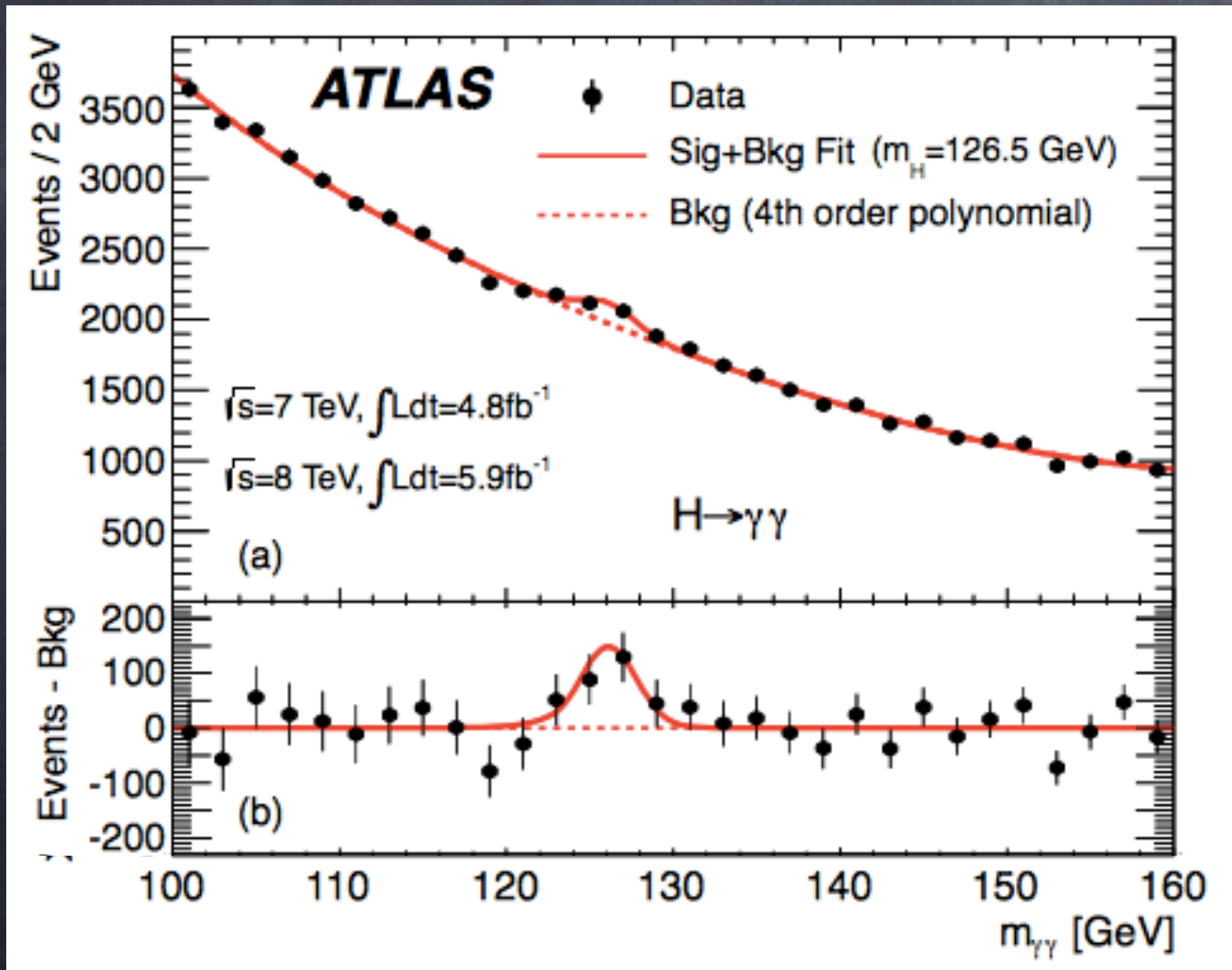


Perturbative

Non perturbative

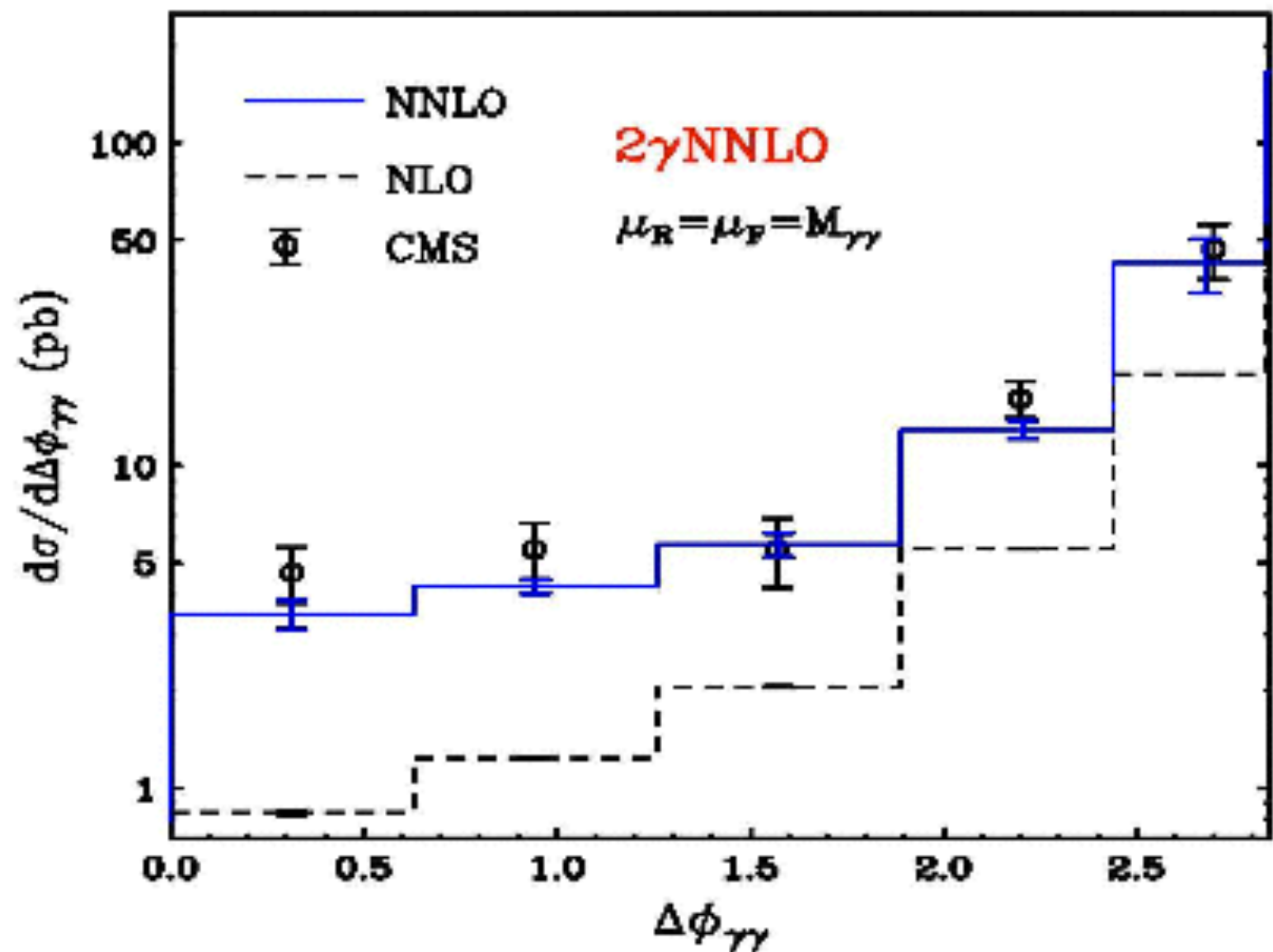
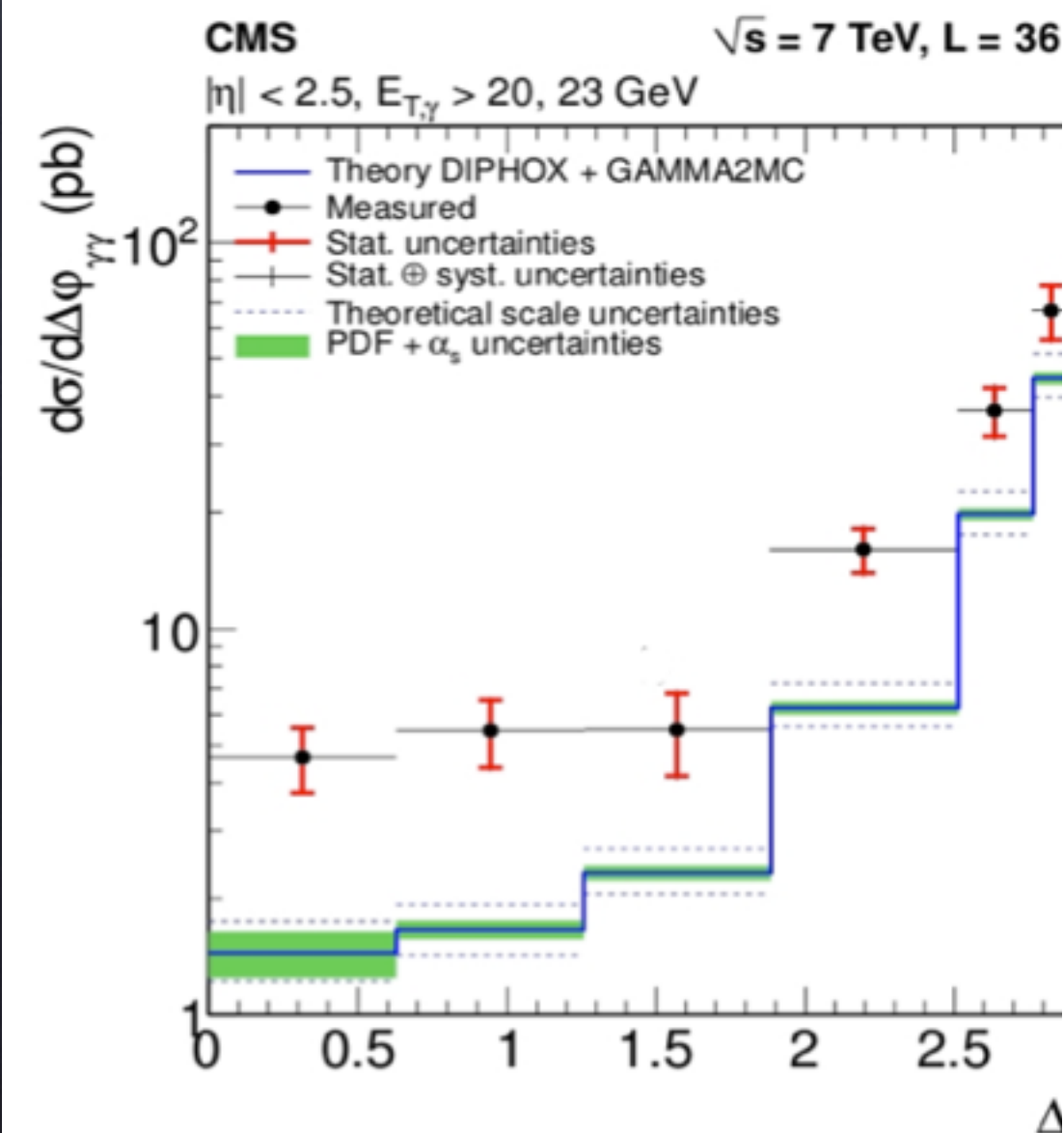
$$\frac{d\sigma(pp \rightarrow hX)}{dp_T d\eta} = \sum_{i,j,k} \int dx_1 dx_2 dz \left(f_i^P \otimes f_j^P \otimes D_k^h \otimes \frac{d\hat{\sigma}(ij \rightarrow kX')}{dp_T d\eta} \right)$$

ATLAS & CMS

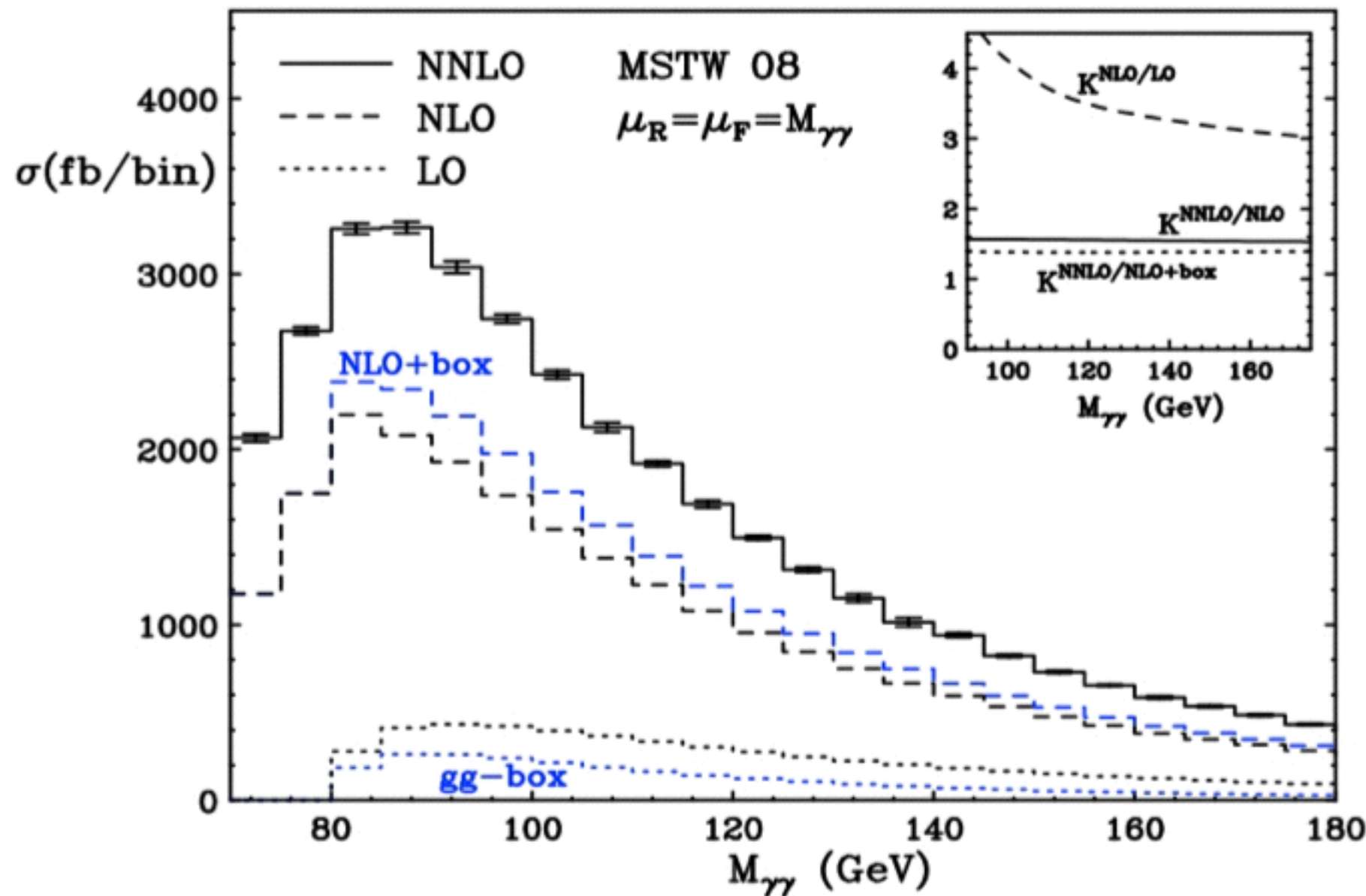


Both experiments showed excess in the two photon decay channel

- The complete understanding of physics has to be achieved in all senses
- LO, NLO and NNLO could sometimes explain the misunderstanding of some distributions



- NNLO calculations are important for the LHC now and for the next run



virtual corrections could have an enormous impact on the physics@LHC

High precision implies new Feynman diagrams to be considered

CONCLUSIONS

- The physics at hadron colliders is well understood within the theory of QCD
- Nevertheless, interplay between large and small distances is a phenomenological challenge for theorist and experimentalists
- pQCD is useful in order to understand the processes at parton level, and also to take care of the singularities which appears in the calculation
- The undeniable comparison between theory and experiment requires the inclusion of non perturbative distributions in the hadronic cross section

- The LHC has a huge amount of data and the precision of them is extremely high which is a challenge for the theoretical community in particle physics
- Monte Carlo simulations and theoretical distributions are centrals for any discovery
- In our times, it is extremely hard to discover a particle due to resonances; discoveries of new physics, or confirmation of SM predictions, will be achieved by looking to small deviations
- Finally, the correct understanding of QCD will give us a clue of the fundamental interactions of the building blocks of nature

Thanks ...

