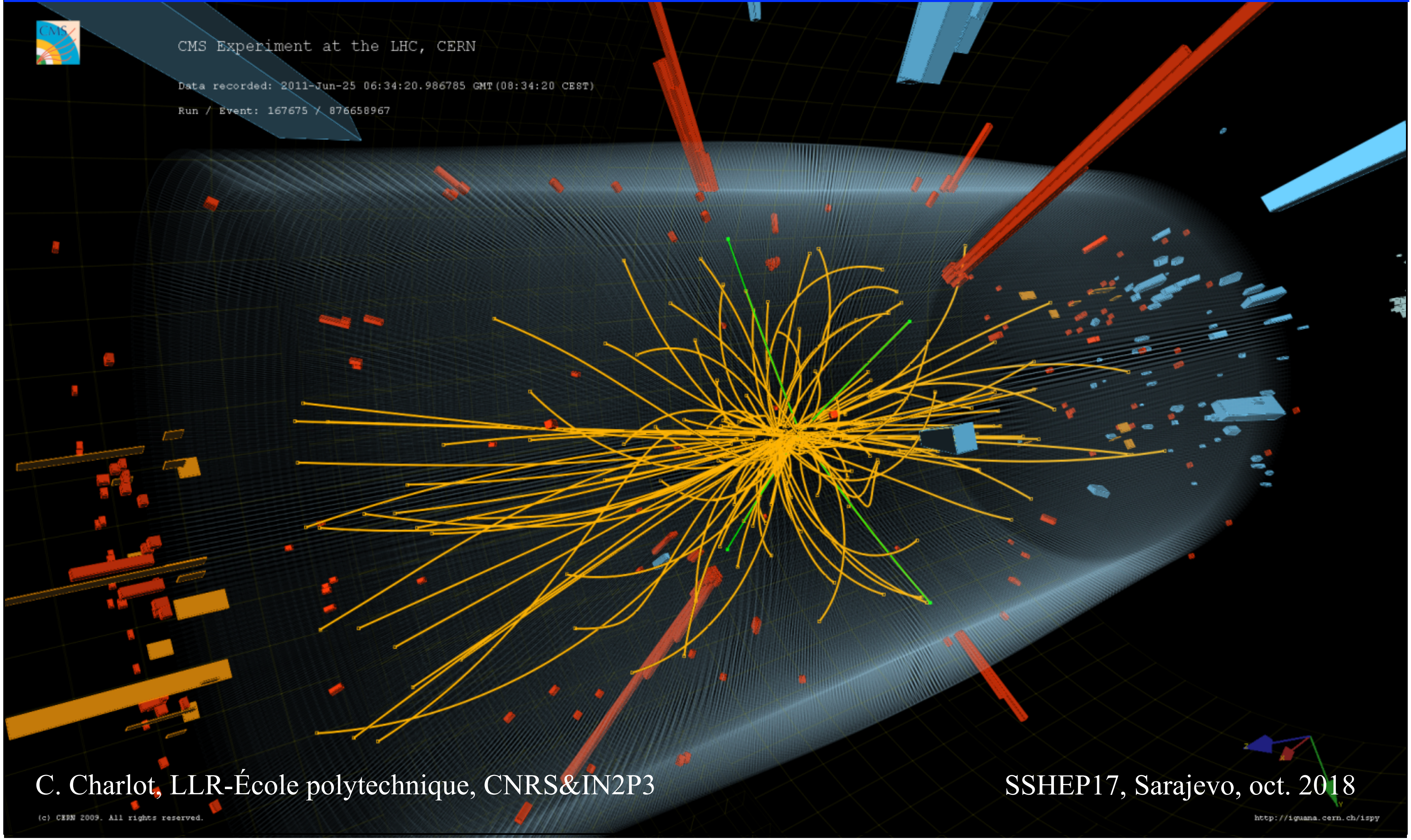
LHC Physics



C. Charlot, LLR-École polytechnique, CNRS&IN2P3

http://iguana.cern.ch/ispy

Content

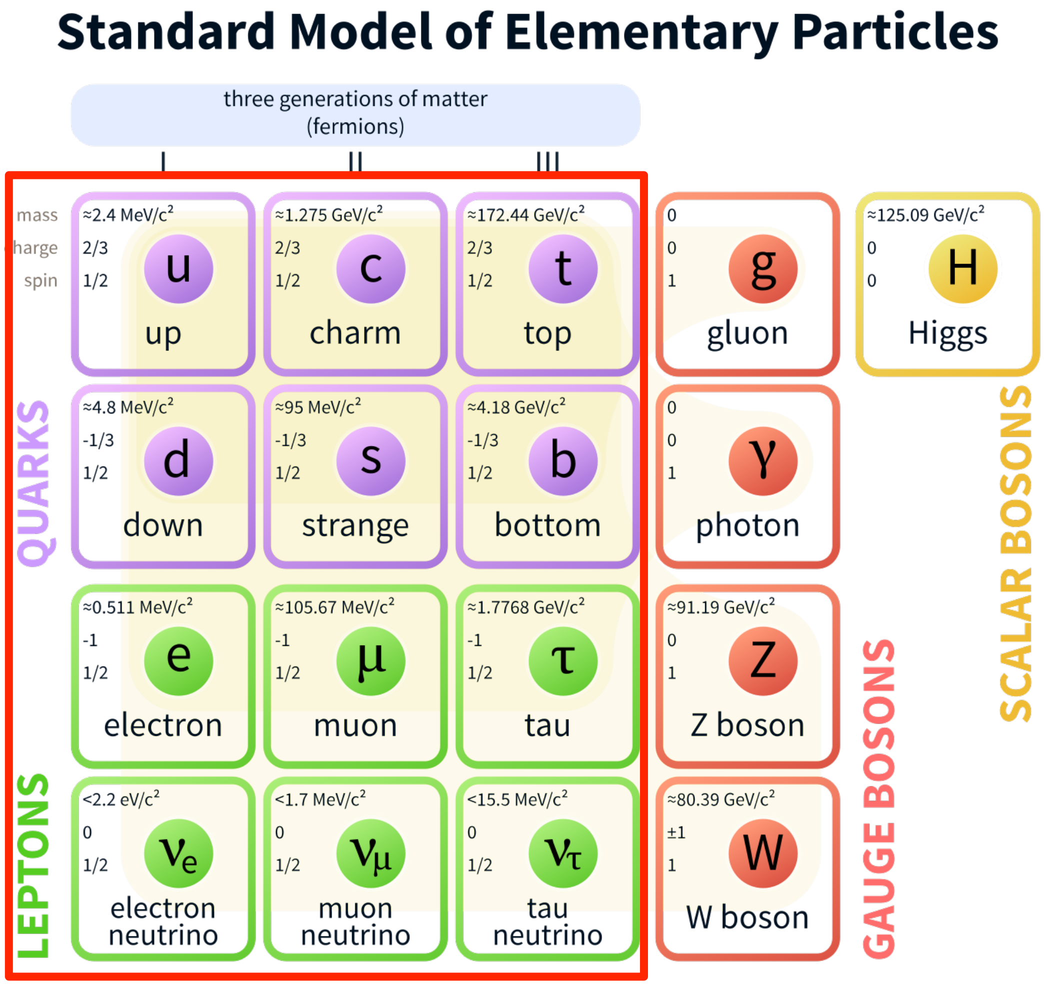
- Part 1: Introduction
- Part 2: QCD Physics
- Part 3: Electroweak Physics
- Part 4: B Physics
- Part 5: Beyond Standard Model Physics

- Not covered here:
  - Higgs Physics (dedicated lecture from prof. Puljak)
  - Heavy ion Physics
  - Many other topics

Part 1: Introduction

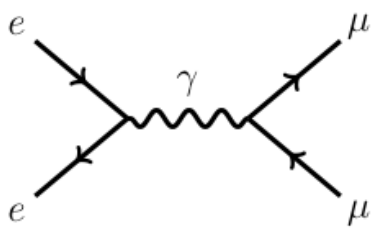
Fundamental particles & interactions

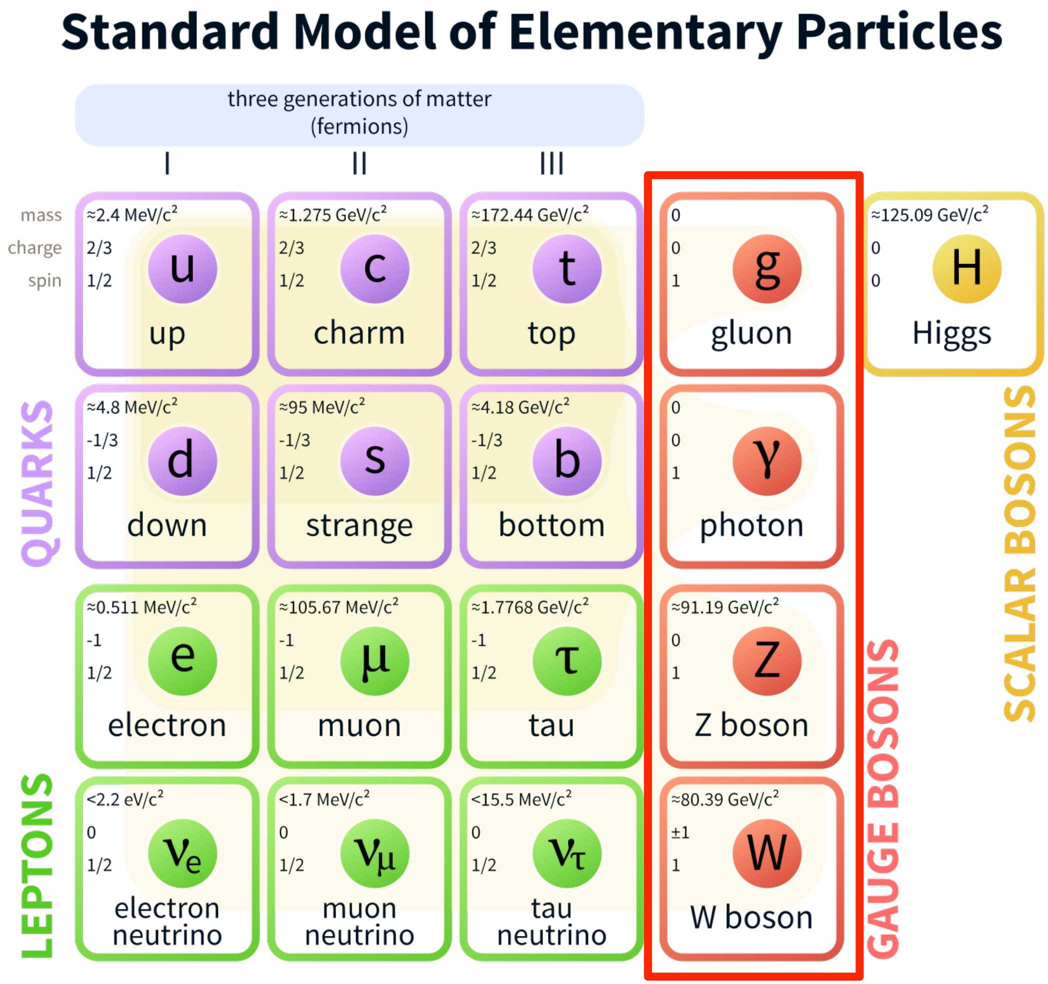
- Matter particles:
- Fermions, spin 1/2
- Quarks and leptons, SU(2) symmetry
- 3 families, we don't know why …



Fundamental particles & interactions

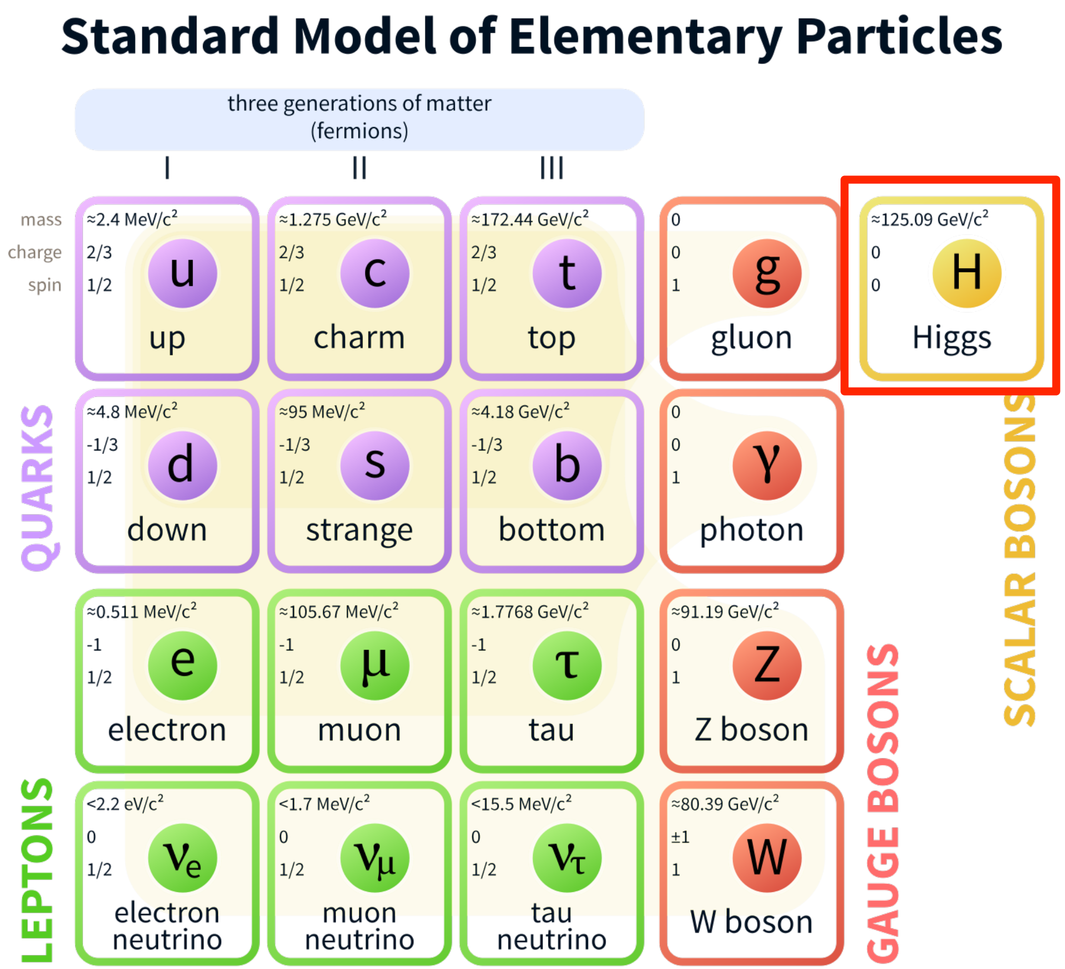
- Interactions: bosons, spin 1
- Electroweak, strong
- Gravitation is too weak at LHC energies
- Interaction = particle exchange





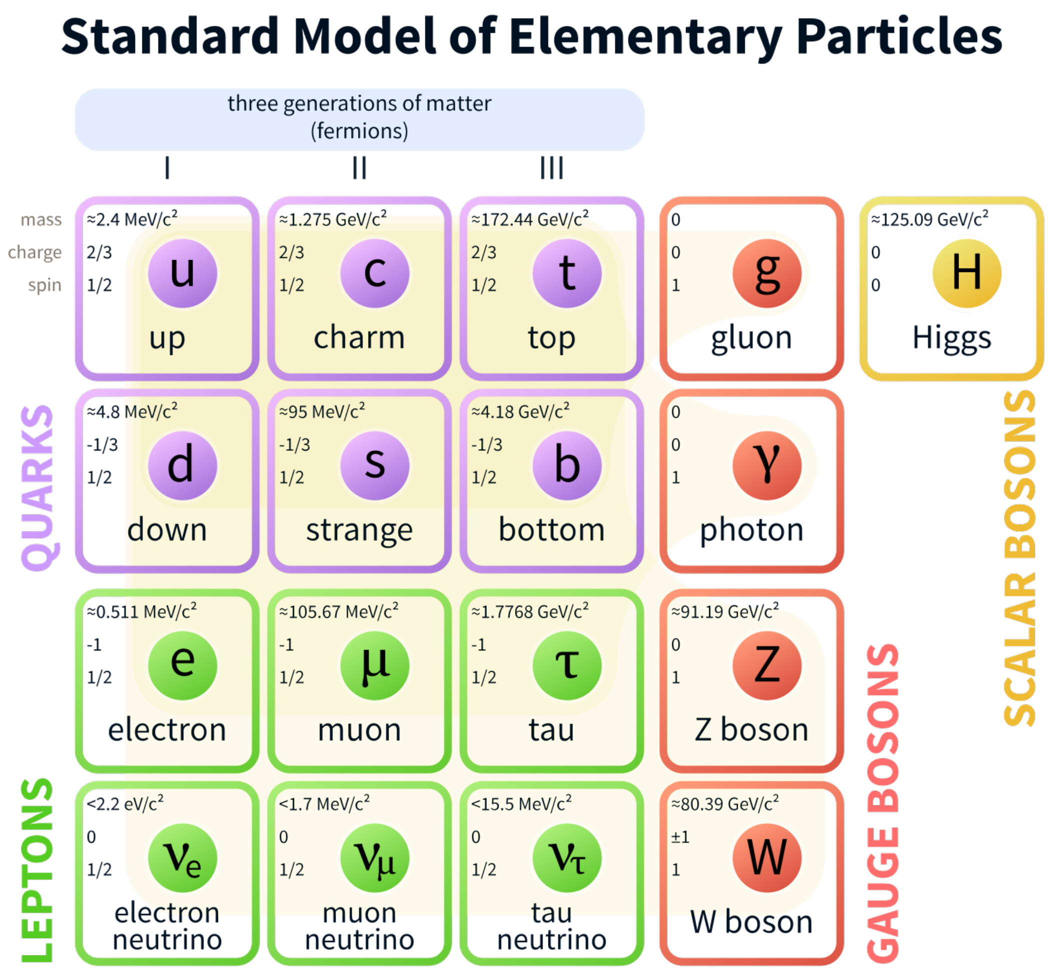
Fundamental particles & interactions

- Higgs boson:
- Spin 0 (unique)
- Discovered in 2012 by ATLAS and CMS
- Resolve conflict between gauge interactions and masses
- New interaction
- More on this in dedicated lecture

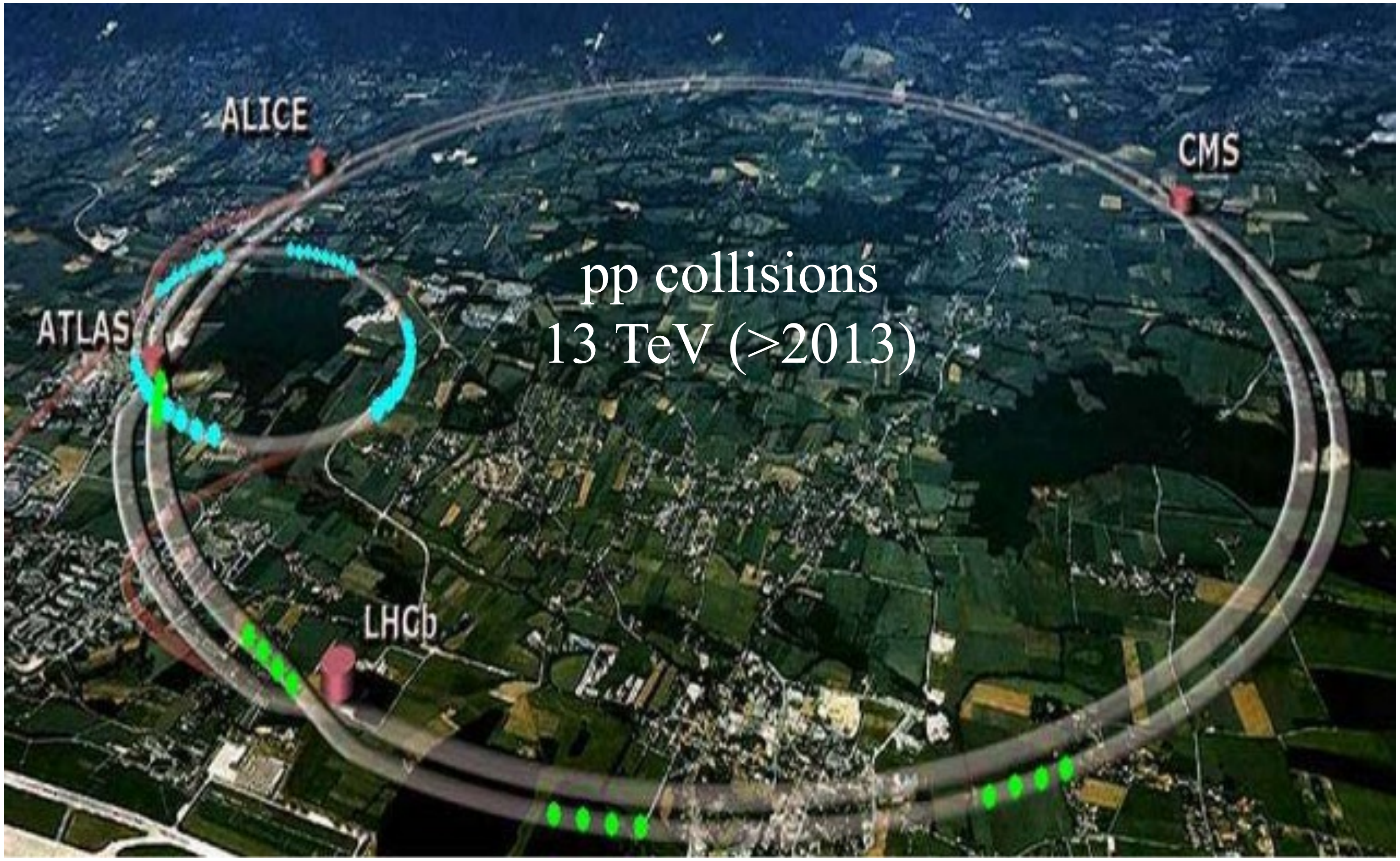


Fundamental particles & interactions

- *Caveats*:
- Particles are point like objects
- Particles have anti-particles associated
- Particles in these drawings correspond to quanta of relativistic quantum fields (QFs)
- QFs can create or annihilate particles (relativity)
- QFs have well defined quantum numbers

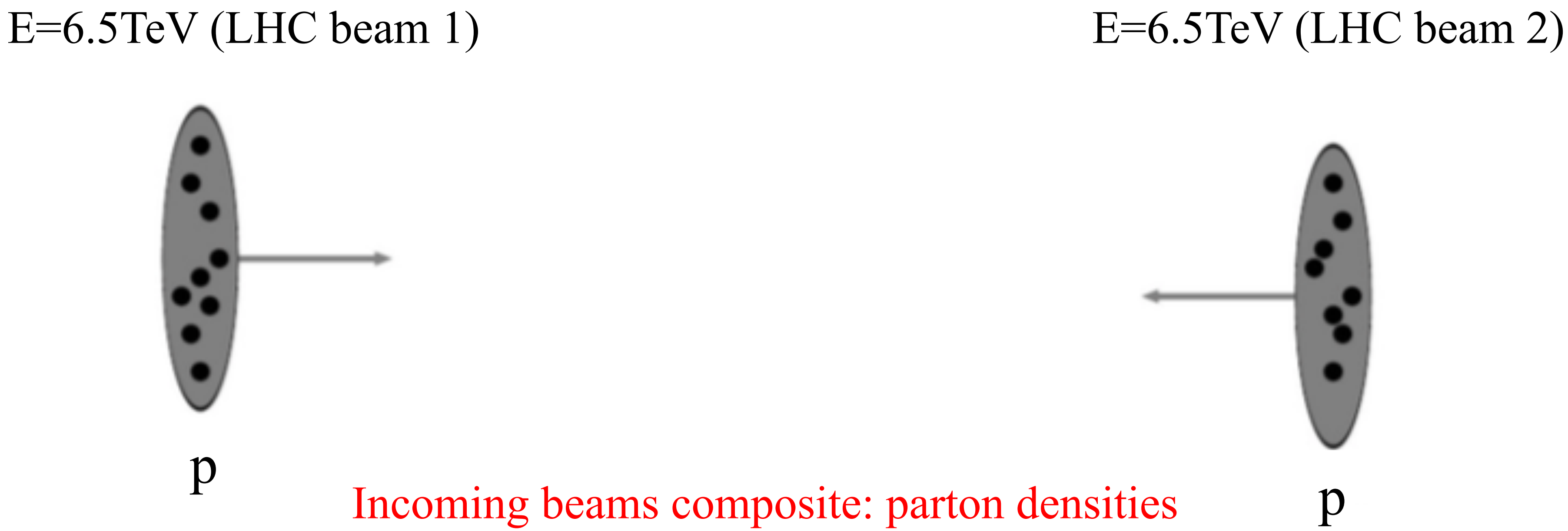


The Large Hadron Collider



- A 27 km circumference accelerator located at the Franco-Swiss border, 100m underground
- Accelerates protons to *nearly* the speed of light, in two counter rotating beams
- B=8.3T dipoles (1232, operating at 1.9K, 14m long)

Proton-proton collisions

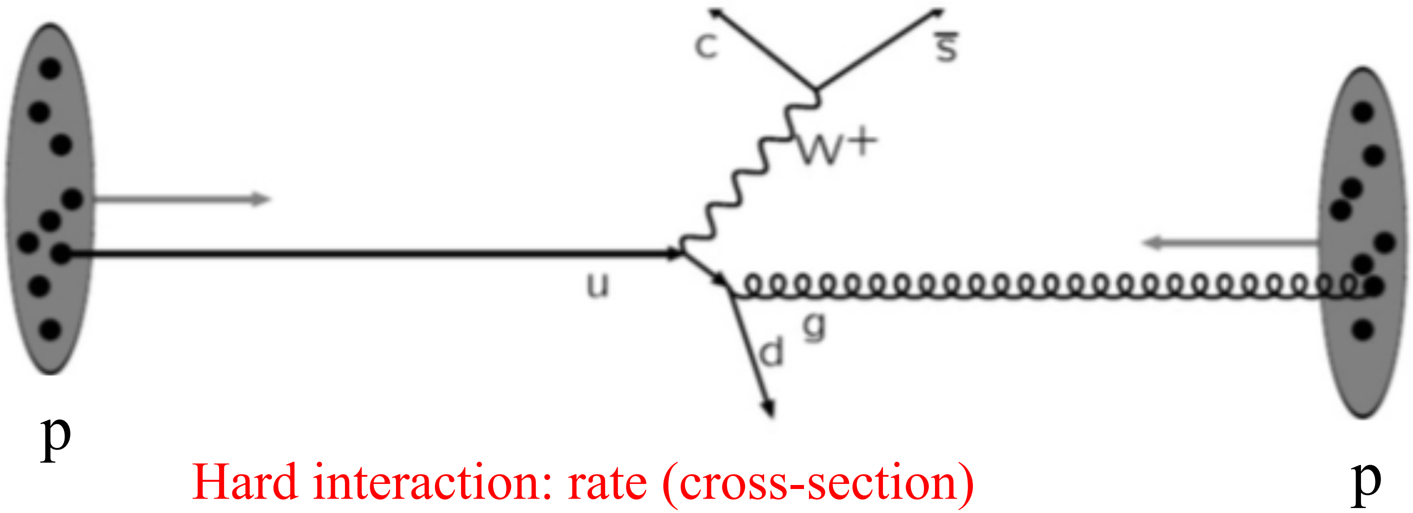


Incoming beams composite: parton densities

- Protons are **composite**, actual collisions occur between **quarks** and **gluons** (partons)
- Parton densities describe the probability density to find within the proton a parton of given type with a given momentum

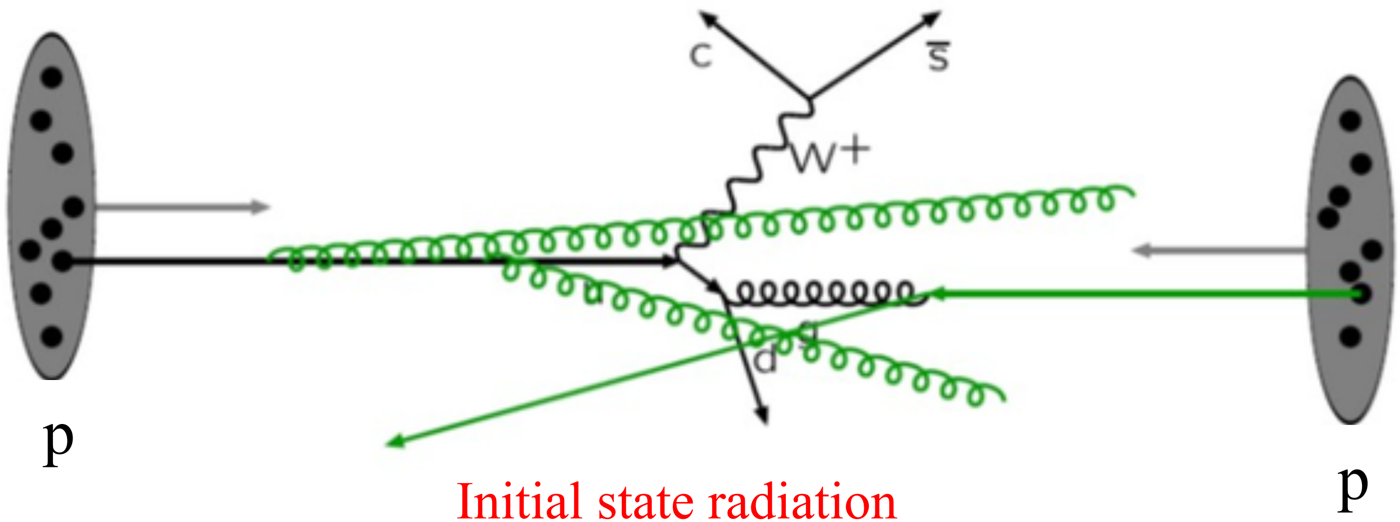
Proton-proton collisions

Ex. $\boxed{u\bar{d} \rightarrow W^+ \rightarrow c\bar{s}}$



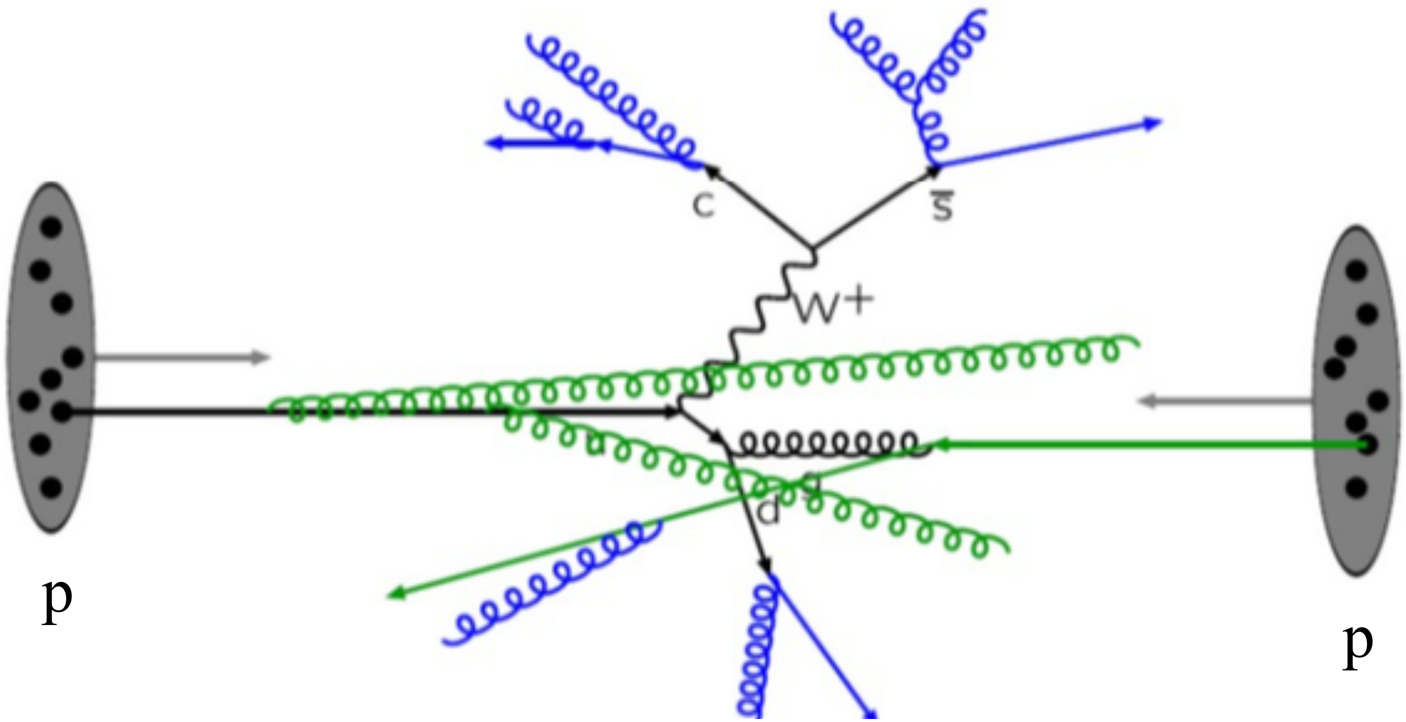
Hard interaction: rate (cross-section) computable from theory, including resonance decay

Proton-proton collisions



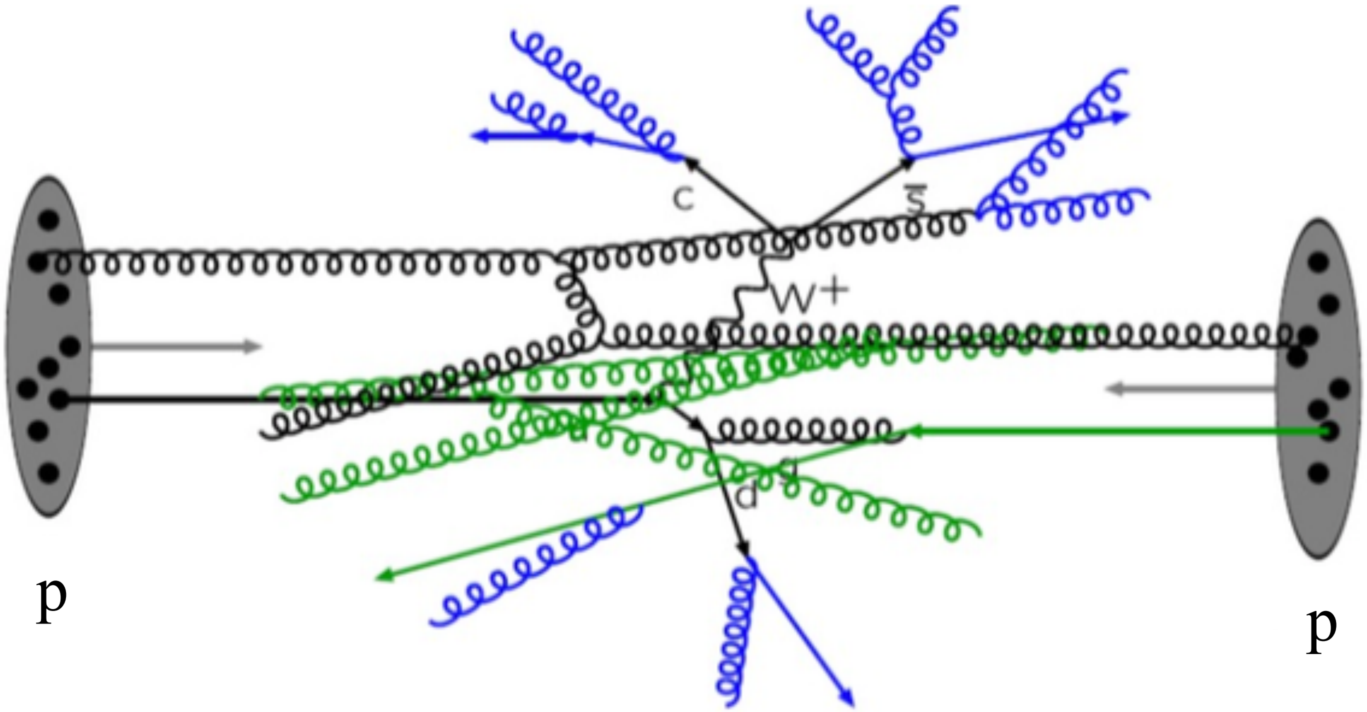
Initial state radiation (ISR)

Proton-proton collisions



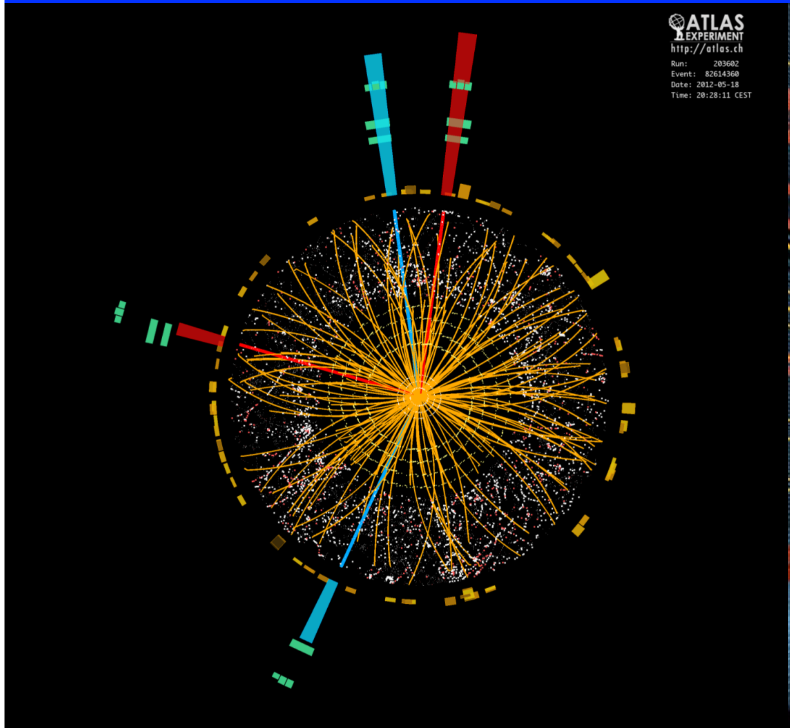
Final state radiation
(FSR)

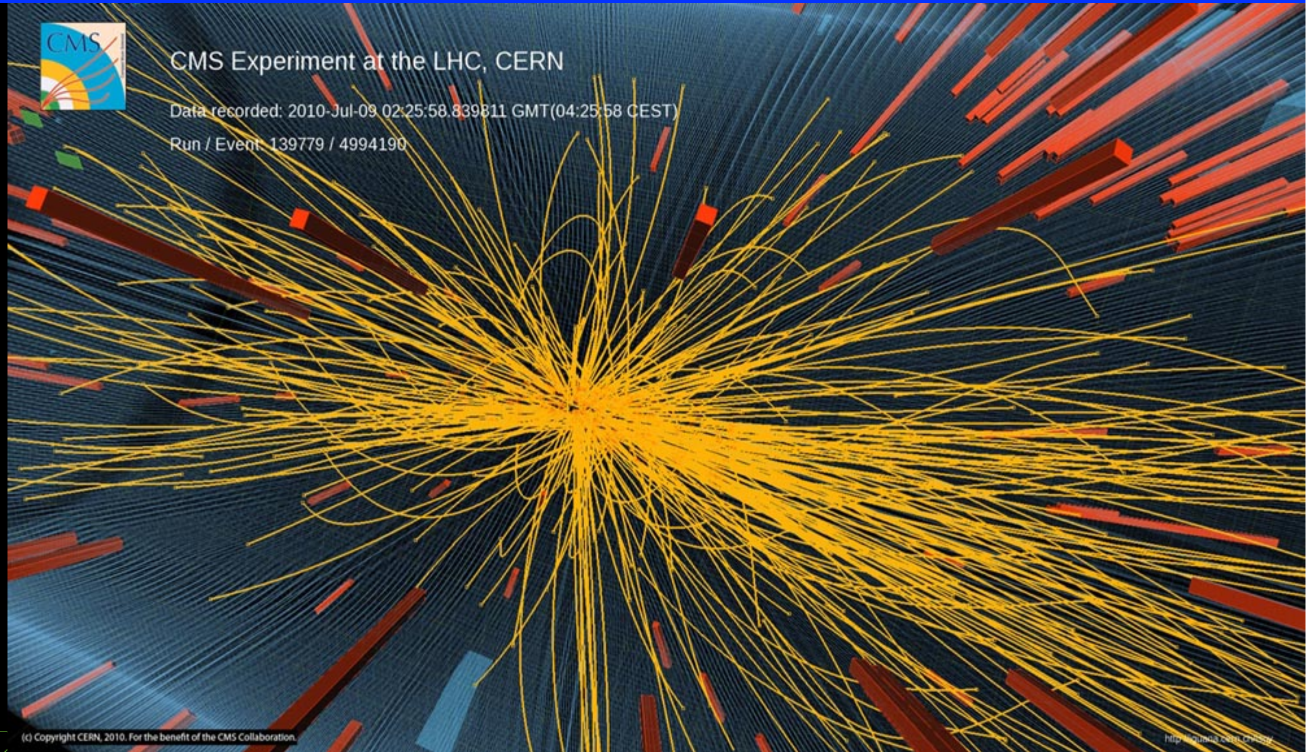
Proton-proton collisions



Multiple parton/parton interactions ...
… each with their ISR and FSR

Events at LHC

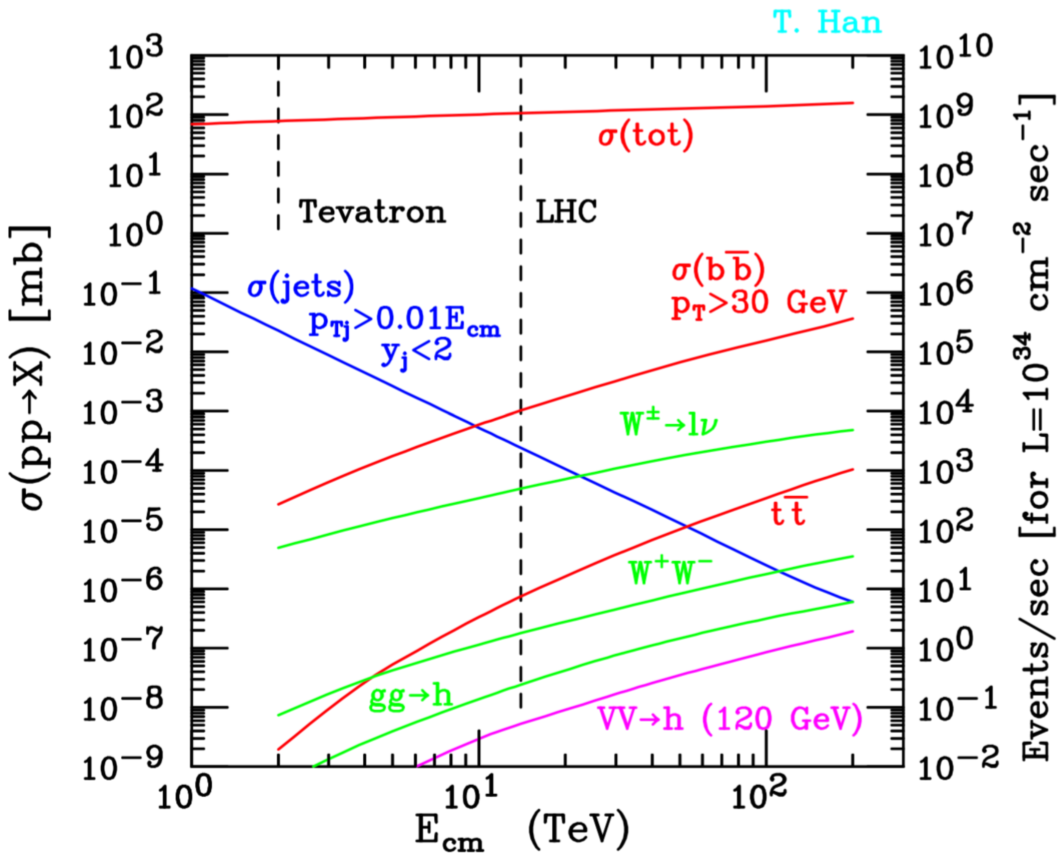




and pileup …

LHC cross-sections & rates

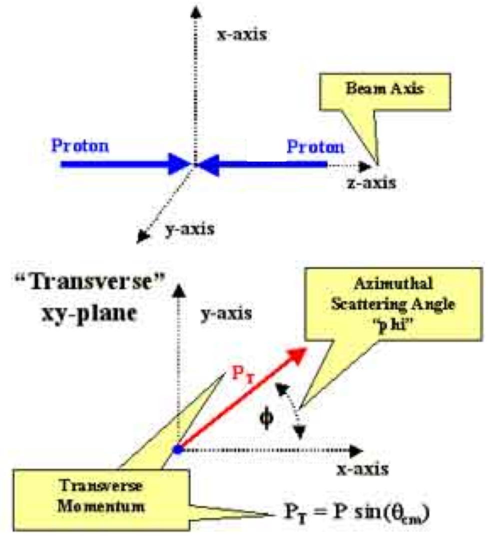
- Rates **increase with energy** (jets here do not because of threshold)
- Total: ~$\mathbf{10^9}$ **interactions /sec**
- Corresponds to σ_{tot}~100mb
- b-quark (B factory)
- $W^\pm \rightarrow l^\pm \nu$, $Z^0 \rightarrow ll$, $t\bar{t}$, dibosons, Higgs in gluon fusion, in VBF
- Higgs rather copiously produced: ~0.1/sec
- The **problem is to identify it** from the many other processes



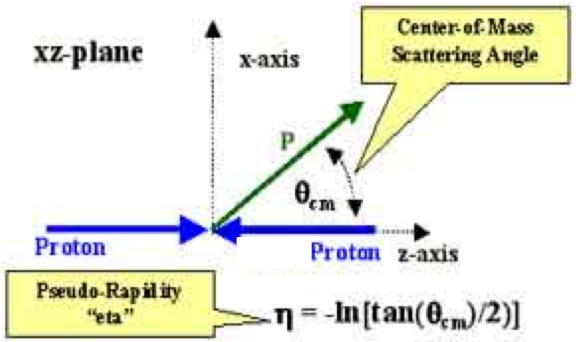
→ need to look for rare decays that have less background (e.g. $H \rightarrow ZZ \rightarrow llll$ with $H \rightarrow ZZ$ and $Z \rightarrow ll$ ~ 3% at m_H=125 GeV)

Kinematics at hadrons colliders

- Particle in the final state $p^{\mu}=(E,\mathbf{p})$ in the lab frame
- **Longitudinal momentum is not known** (collisions between partons), use variables that are invariant under longitudinal boosts
- Choose z-axis along the beam axis
- <u>Transverse momentum and azimutal angle</u>:
- $p_T=\mathrm{sqrt}(p_x^2+p_y^2) = p\sin(\theta)$, $\phi = \mathrm{atan}(p_y/p_x)$
- The polar angle alone is not invariant



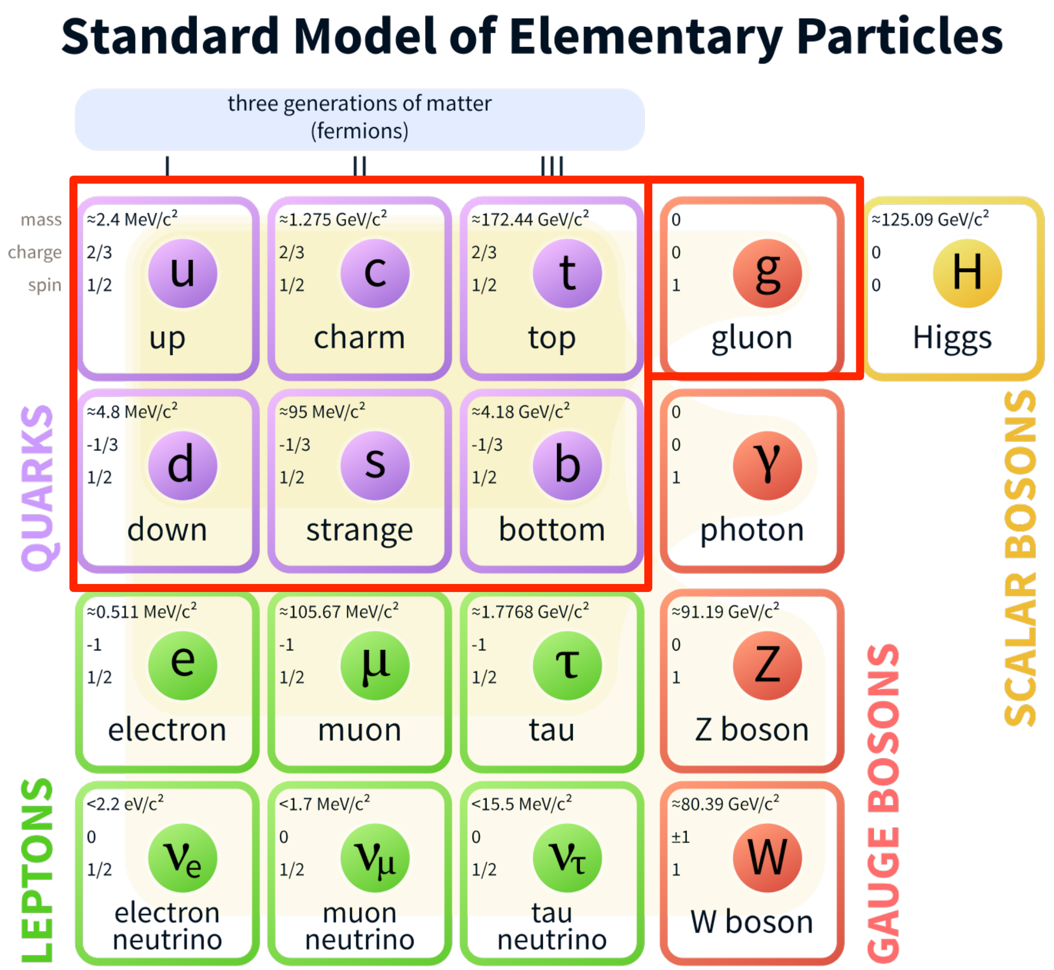
- <u>Rapidity and pseudorapidity</u>:
- $y=1/2\ \ln[(E+p_z)/(E-p_z)]$
- $y'=y-y_0$ the rapidity in a boosted frame is shifted, and rapidity differences are invariant
- In the massless limit; $y \sim \eta = -\ln\tan(\theta/2)$



Part 2: QCD Physics

Fundamental particles & interactions

- In this lecture:
  - Basics of QCD
  - Fragmentation and hadronization: jets
  - PDFs and factorization
  - QCD corrections to EW processes
  - Measurement of α_s



Quantum chromodynamics

- **Quantum chromodynamics describes interaction between quarks and gluons**
- Interactions are mediated by massless spin-1 particles called gluons
- They are the gauge bosons for the strong interaction, similar to the photon that is the gauge boson for the electromagnetic interaction
  - But here there are 8 gluons (SU(3) symmetry)
- Gauge bosons couple to conserved charges:
  - QED: photons couples to electric charge (Q)
  - QCD: gluons couple to color charges (Y^C, the color hypercharge and I_3^C, the colour isospin charge)
- The strong interaction acts in the same way on u,d,s,c,b and t quarks, where each quark corresponds to a colour triplet

Quantum chromodynamics

- The colour hypercharge (Y^C) and the isospin charge (I_3^C) can be used to define **3 colours** for the quarks (and 3 anti-colours for the anti-quarks)

	Y^c	I_3^c		Y^c	I_3^c
r	1/3	1/2	$\bar{r}$	-1/3	-1/2
g	1/3	-1/2	$\bar{g}$	-1/3	1/2
b	-2/3	0	$\bar{b}$	2/3	0

- All observed states (hadrons = mesons and baryons) have a total colour charge of zero. This is due to the **colour confinement**.
- Zero colour charge implies that the hadrons can have the following quark content and colour wave-functions:

$$q\bar{q} = \frac{1}{\sqrt{3}}(r\bar{r}+g\bar{g}+b\bar{b}) \quad q_1q_2q_3 = \frac{1}{\sqrt{6}}(r_1g_2b_3-g_1r_2b_3+b_1r_2g_3-b_1g_2r_3+g_1b_2r_3-r_1b_2g_3)$$

Quantum chromodynamics

$$\boxed{\mathcal{L} = \bar{\psi}_q^i (i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}}$$

A_μ often called G_μ

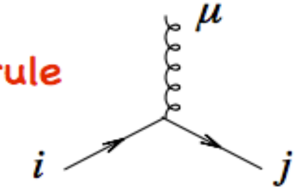
quark fields

$$\psi_q^j = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$$

covariant derivative

$$D_{\mu ij} = \delta_{ij}\partial_\mu - \underline{i g_s T^a_{ij} A^a_\mu}$$

⇒ Feynman rule



Gell-Mann matrices

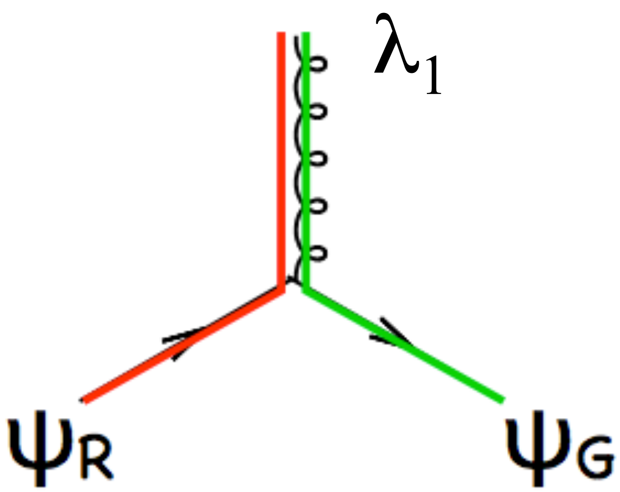
$$(T^a = \lambda^a/2)$$

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & \frac{-2}{\sqrt{3}} \end{pmatrix}$$

Interactions in color space

Quark-gluon interactions



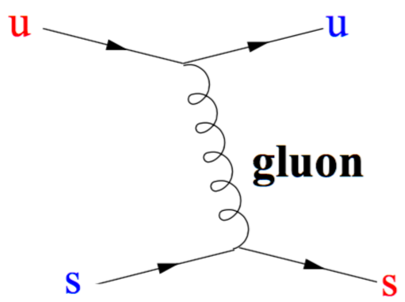
$$\underset{\lambda_1}{\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}} \underset{\psi_R}{\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}} = \underset{\psi_G}{\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}}$$

- ❑ Take a red quark that under interaction with a gluon becomes a green quark
- ❑ The gluon that transforms red → green is the one that corresponds to the λ_1 matrix

Interactions in color space

- The colour hypercharge and colour isospin are additive quantum numbers. The gluon quantum numbers can therefore be easily determined.
- Example:

$I_3^C = 1/2 \quad Y^C = 1/3$ $\qquad$ $I_3^C = 0 \quad Y^C = -2/3$



$I_3^C = 0 \quad Y^C = -2/3$ $\qquad$ $I_3^C = 1/2 \quad Y^C = 1/3$

Gluon:

$$\begin{array}{c} \ \text{u} \qquad \text{u} \end{array}$$

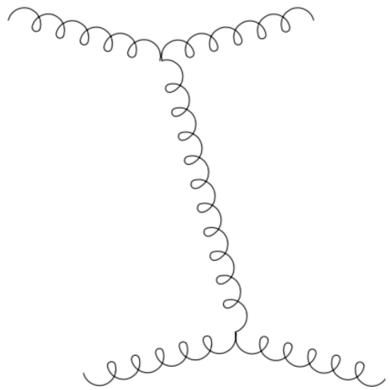
$$I_3^C = I_3^C(r) - I_3^C(b) = \frac{1}{2}$$

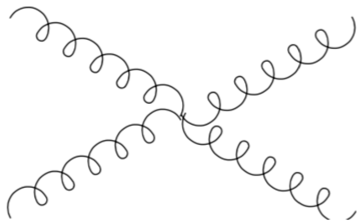
$$Y^C = Y^C(r) - Y^C(b) = 1$$

$$\chi_{g3}^c = r\,\bar{b}$$

Interactions in color space

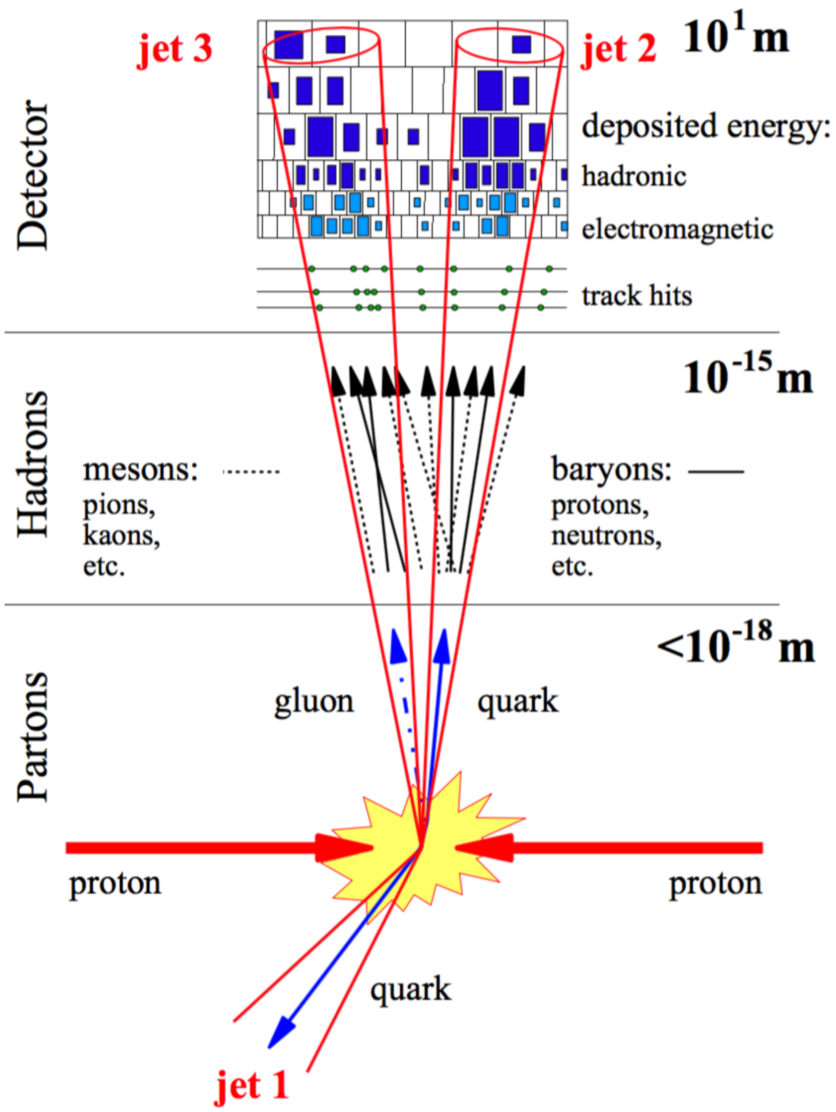
- Contrary to QED, gluon can couple to other gluons since they carry colour charge





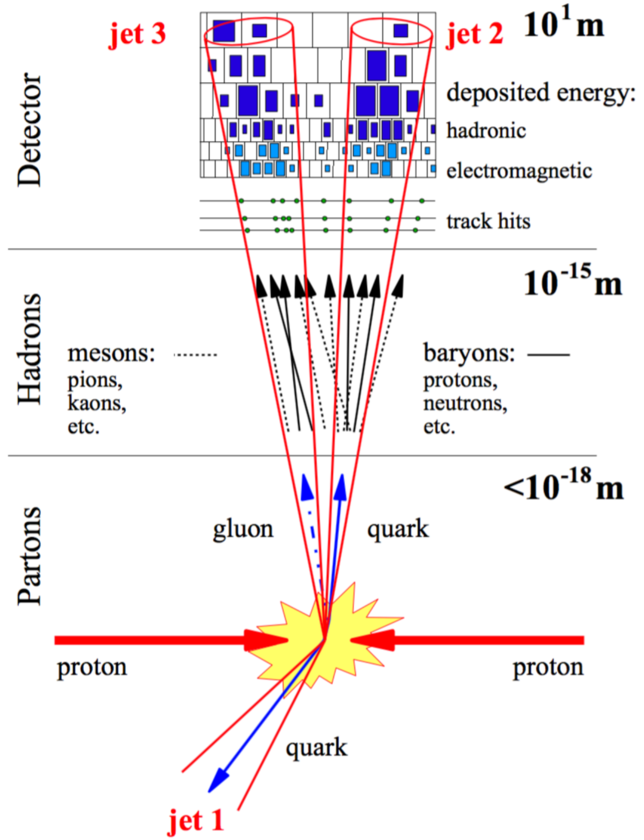
- This has important consequences, in particular it is at the heart of the confinement property → **only colorless states can be observed: quarks produce jets** constituted of colorless hadrons (pions, kaons, ..)

Hadronization and jets



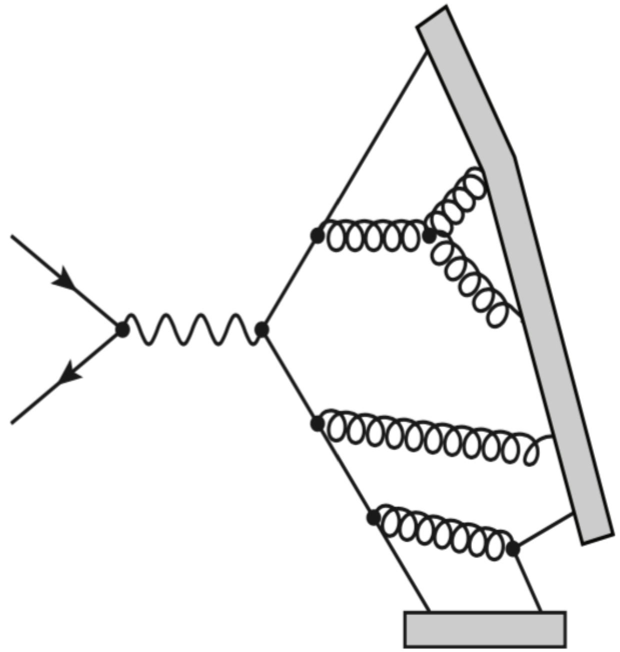
Hadronization models

- ❑ Transition from partons to hadrons is in the non-perturbative regime
  => Rely on phenomenological models
- ❑ Models based on Monte Carlo simulations very successful
  - ❑ Generation of complete final sates: used by experimentalist in event simulations
  - ❑ Caveat: tunable ad-hoc parameters, use LHC data to tune these
- ❑ Most popular models
  - ❑ Pythia: Lund string model (nothing to do with string theory!)
  - ❑ Herwig cluster model

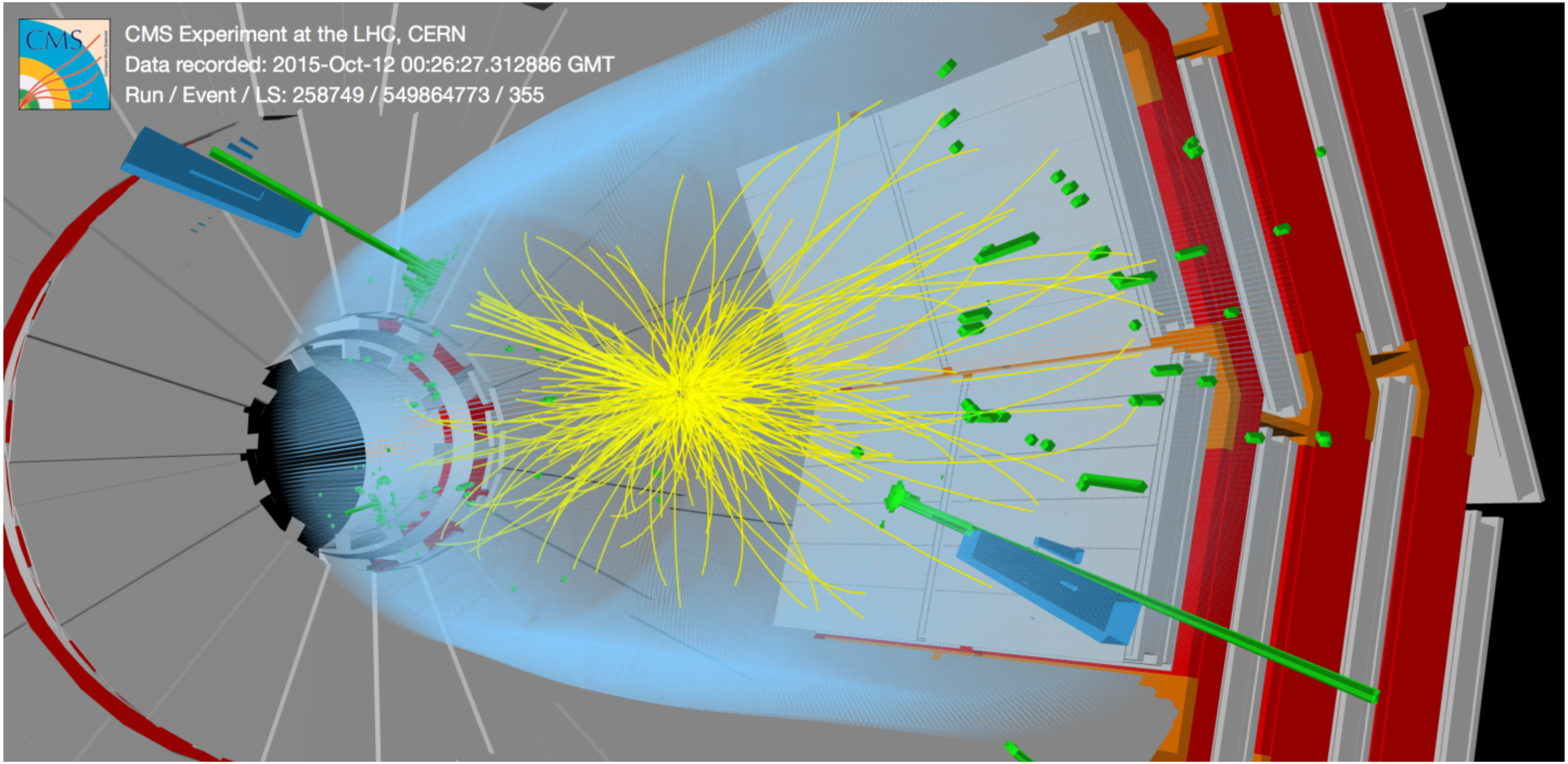


String model

- Lund string model (Andersson et al. 1983)
- QCD potential: $V(r) = -\frac{4}{3}\frac{\alpha_S(1/r^2)}{r} + kr$
  - large tension of « color string »
- String formation between initial quark-anti-quark pair
- String breaks up when potential energy large enough
  - new quark-antiquark pair(s)
- When energy is low enough: hadron formation
- Very widely used, example is Pythia



A di-jet event at CMS

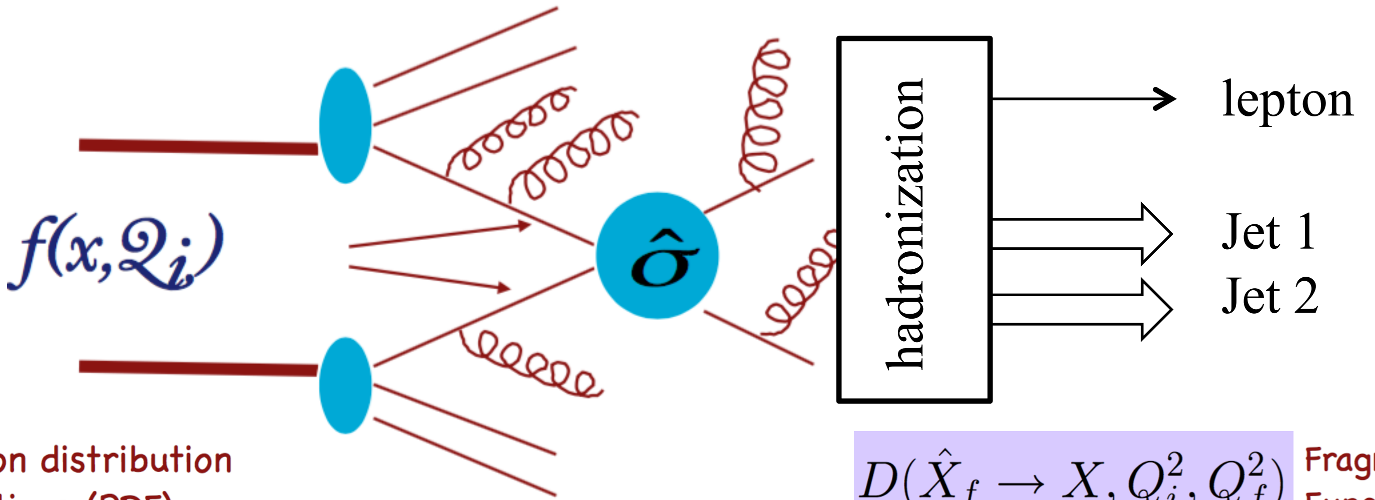


Largest di-jet mass in 2015 13 TeV CMS data: 6.14 TeV

Factorization theorem

- Factorization expresses the independence of the soft (long-distance) processes on the nature of the hard (short-distance) process

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \sum_{a,b}\sum_{f}\int_{\hat{X}_f} f_a(x_a, Q_i^2) f_b(x_b, Q_i^2) \frac{\mathrm{d}\hat{\sigma}_{ab\to f}(x_a, x_b, f, Q_i^2, Q_f^2)}{\mathrm{d}\hat{X}_f} D(\hat{X}_f \to X, Q_i^2, Q_f^2)$$



$f_a(x_a, Q_i^2)$ Parton distribution functions (PDF)

$D(\hat{X}_f \to X, Q_i^2, Q_f^2)$ Fragmentation Function (FF)

Probability ditribution to find an inital parton with momentum fraction x_a from the incident proton

Probability distribution to get hadron X from final state f (FSR + hadronization)

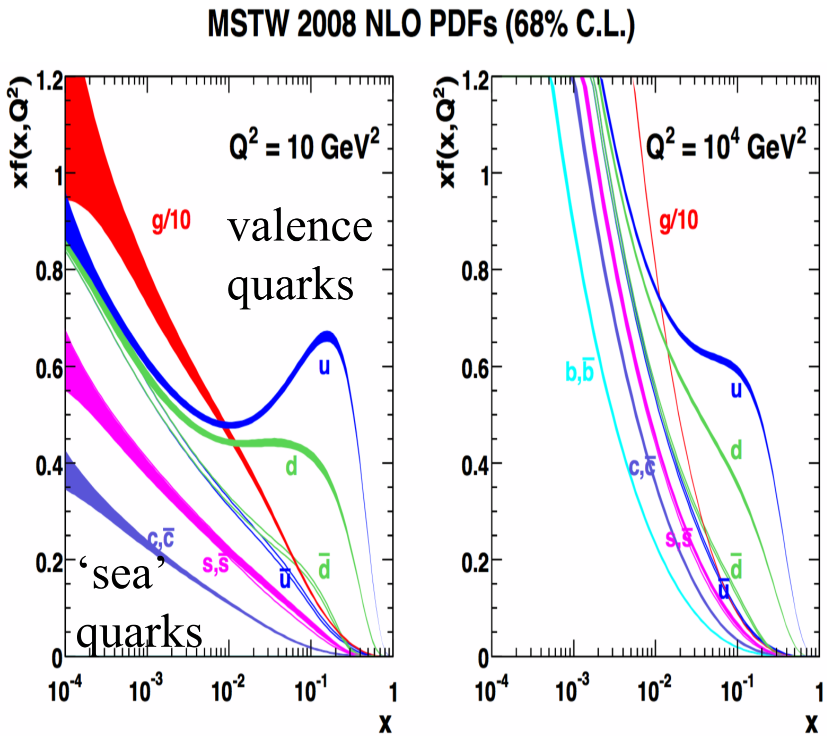
Parton distribution functions

- Proton is composite: contains valence quarks, sea quarks and gluons

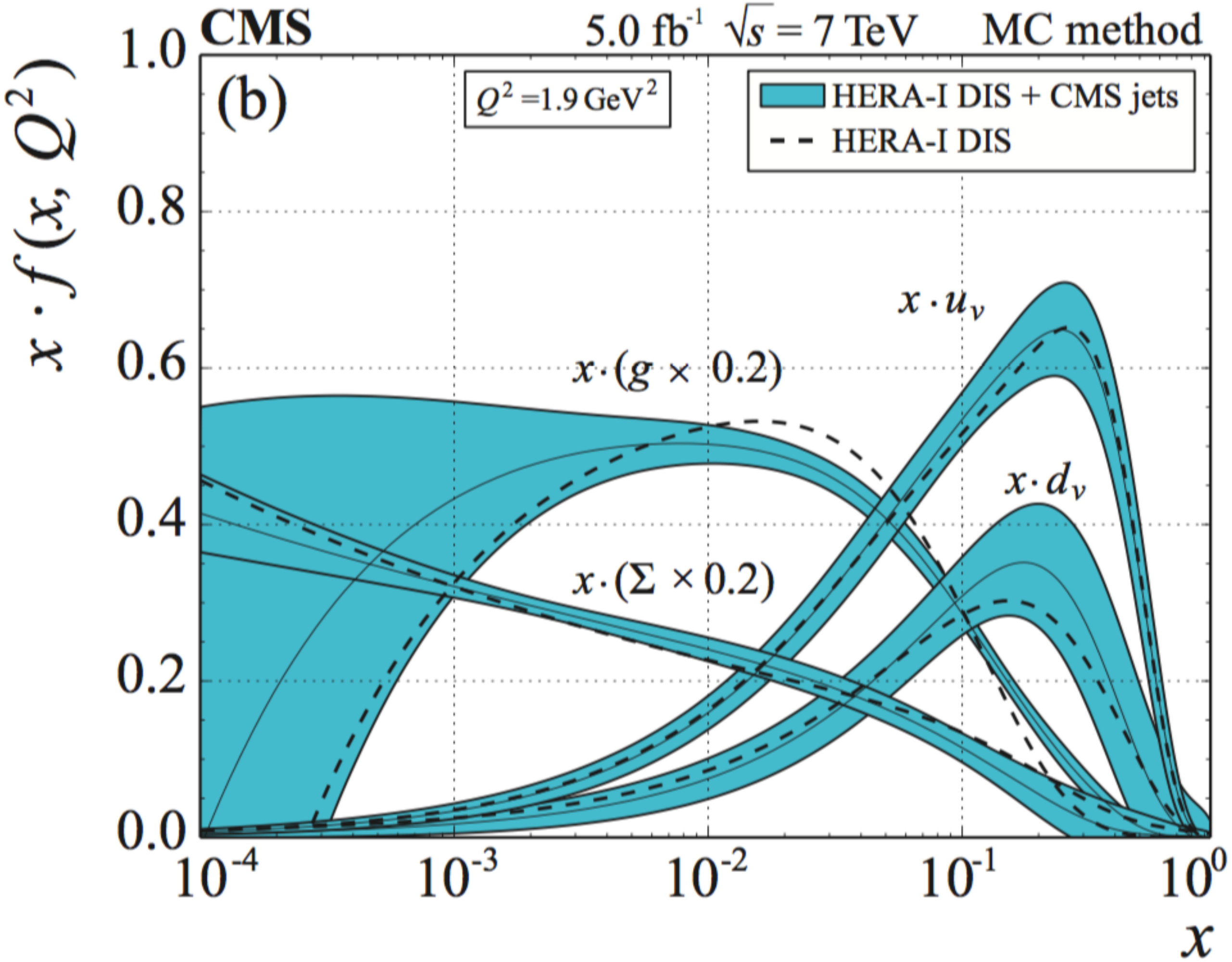
- PDFs $f_a(x_a,Q_i^2)$ gives the probability density to find the parton a with **momentum fraction $x_a=p_a/p_{proton}$**
- c.m energy of the parton (hard) collision: $s_{hard} = m_X^2 = x_1 x_2 s_{pp}$ ($\sqrt{s_{pp}}$=13 TeV at the LHC)
- Typical x values (assume $x_1=x_2$):
  - m_X=100 GeV ⇔ <x> = 0.08
- PDFs strongly rise at small x

→ Larger cross sections at LHC energies

- Gluons dominate at LHC



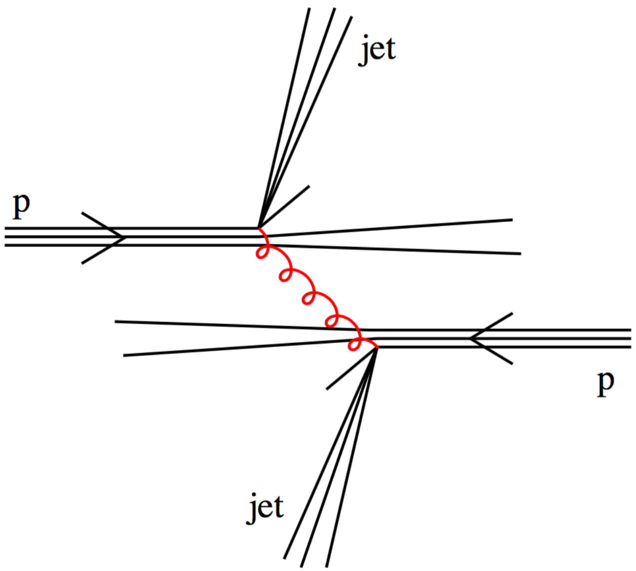
Jets and the gluon PDF

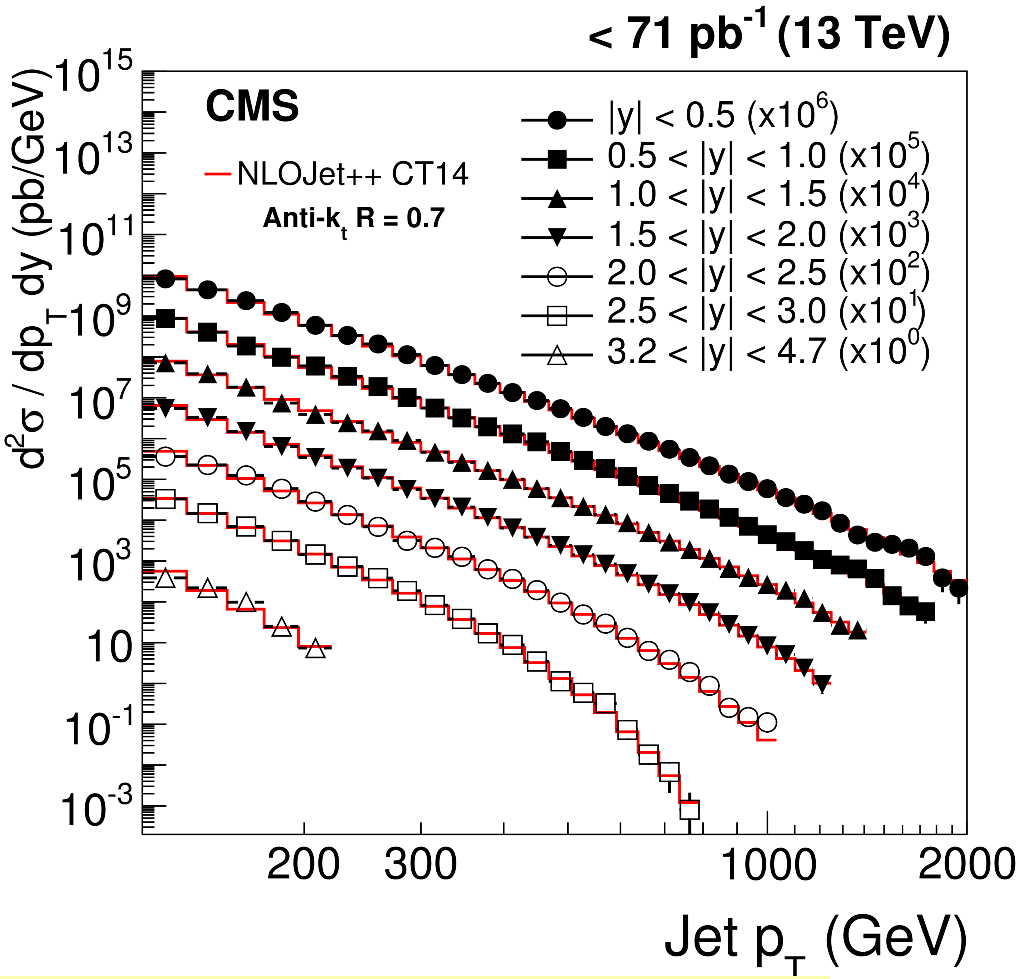


→ LHC data improve gluon PDF in particular for x>0.01

Jet production

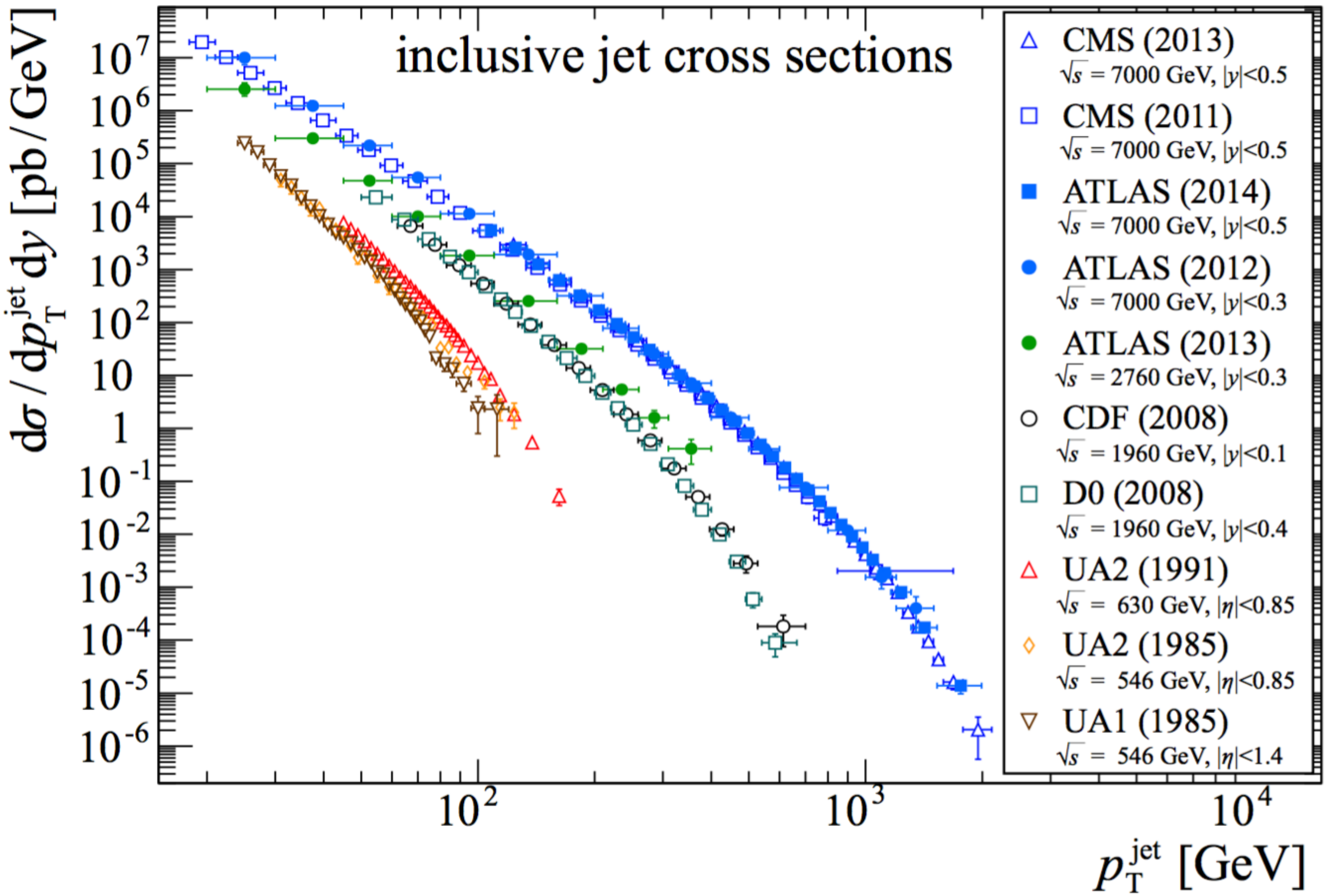
- Most fundamental quantity: jet double differential cross section $d^2\sigma/dp_T dy$
- Measured from multijet events





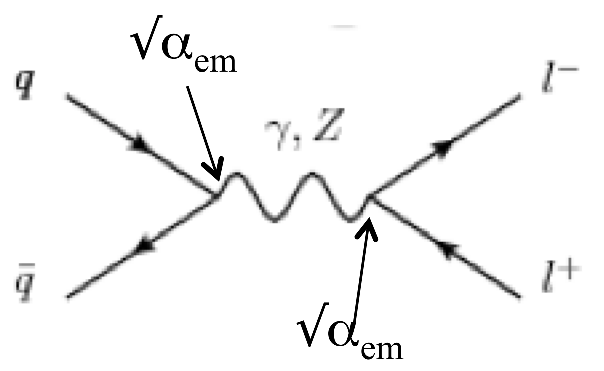
→ Data and theory agree over many orders of magnitude, when taking into account quantum corrections from QCD

Jet production: 7 TeV CMS and ATLAS results

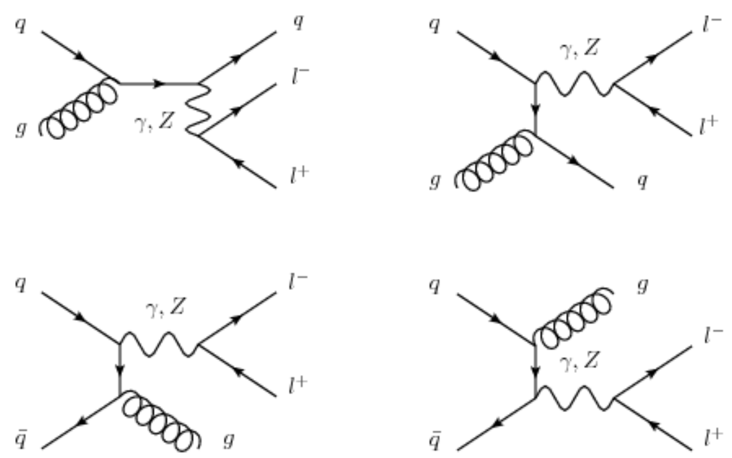


QCD corrections: Drell-Yan

- The **Drell-Yan process** is the process in which a quark and an anti-quark annihilate into a γ or a Z^0 boson which then decays into a fermion pair
- It is **purely electroweak** at leading order (LO) in perturbation theory



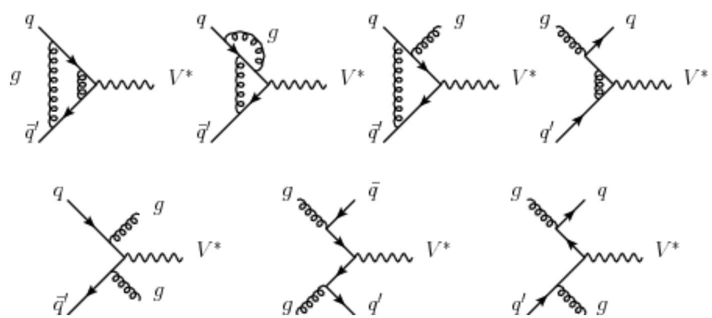
- As many processes at LHC, the Drell-Yan receives large **higher order corrections from QCD** (factor ~2)
- These corrections arise from additional contributions where a QCD vertex is added

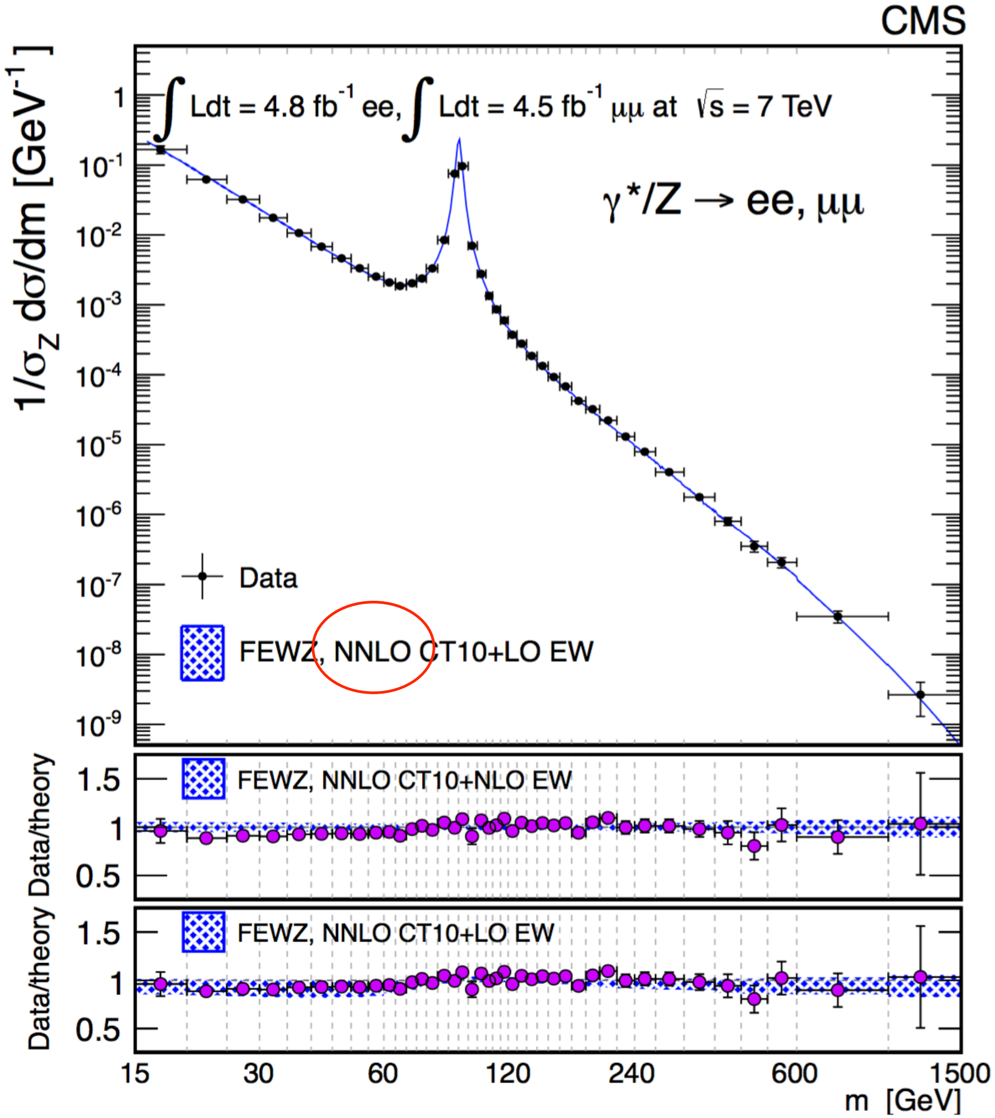


QCD corrections: Drell-Yan

- Drell-Yan process very precisely measured at LHC

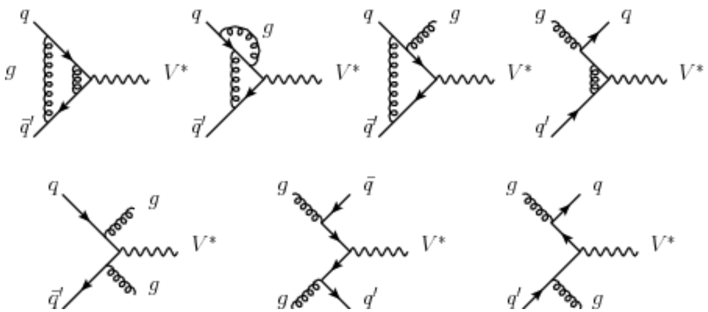
→ measured distributions agree with theory if next-to-next-to-leading order (NNLO) corrections from QCD are included

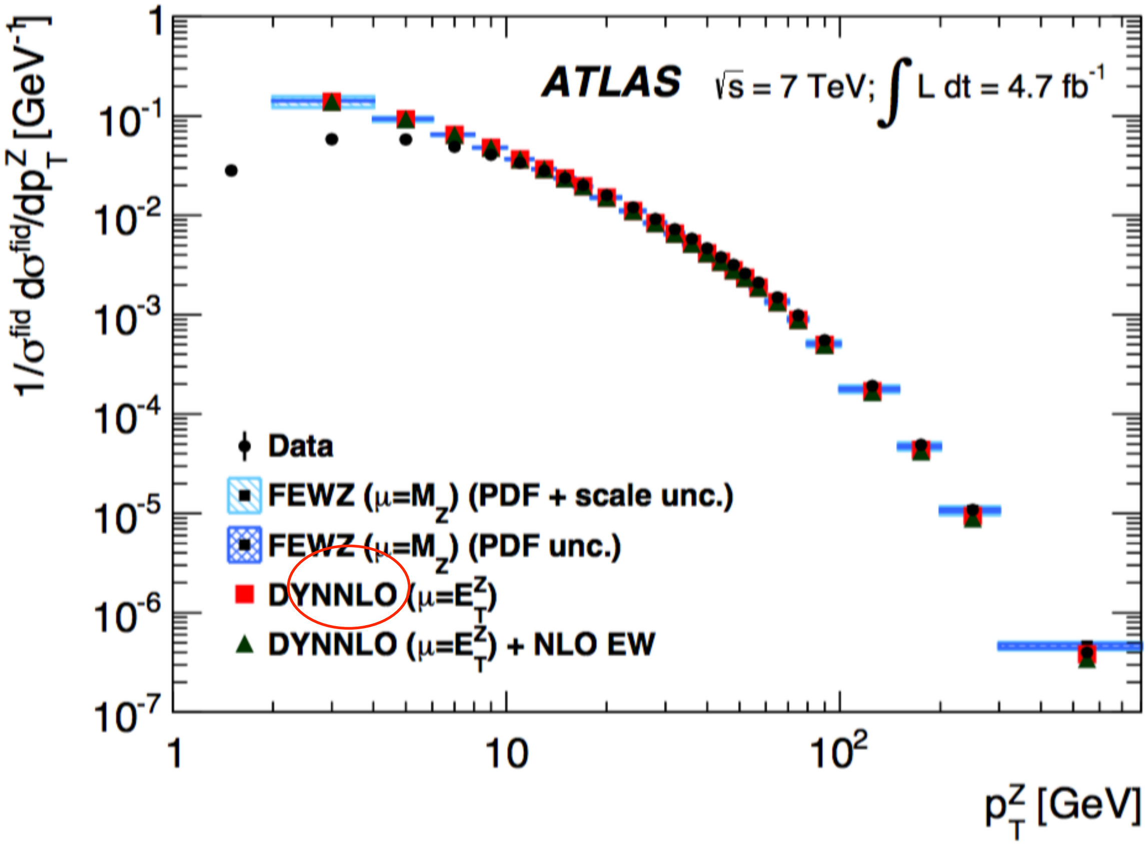




QCD corrections: Drell-Yan

- p_T distribution also agrees with prediction when next-to-next-to-leading order (NNLO) corrections from QCD included

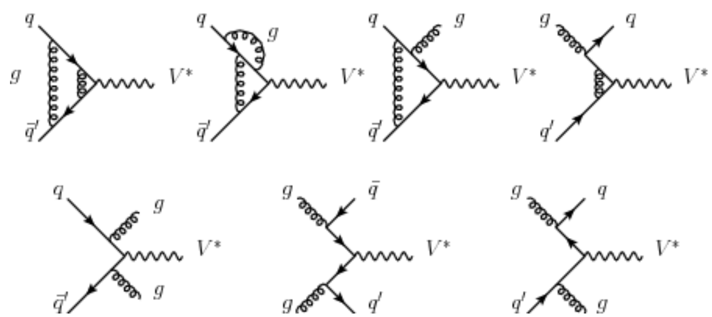


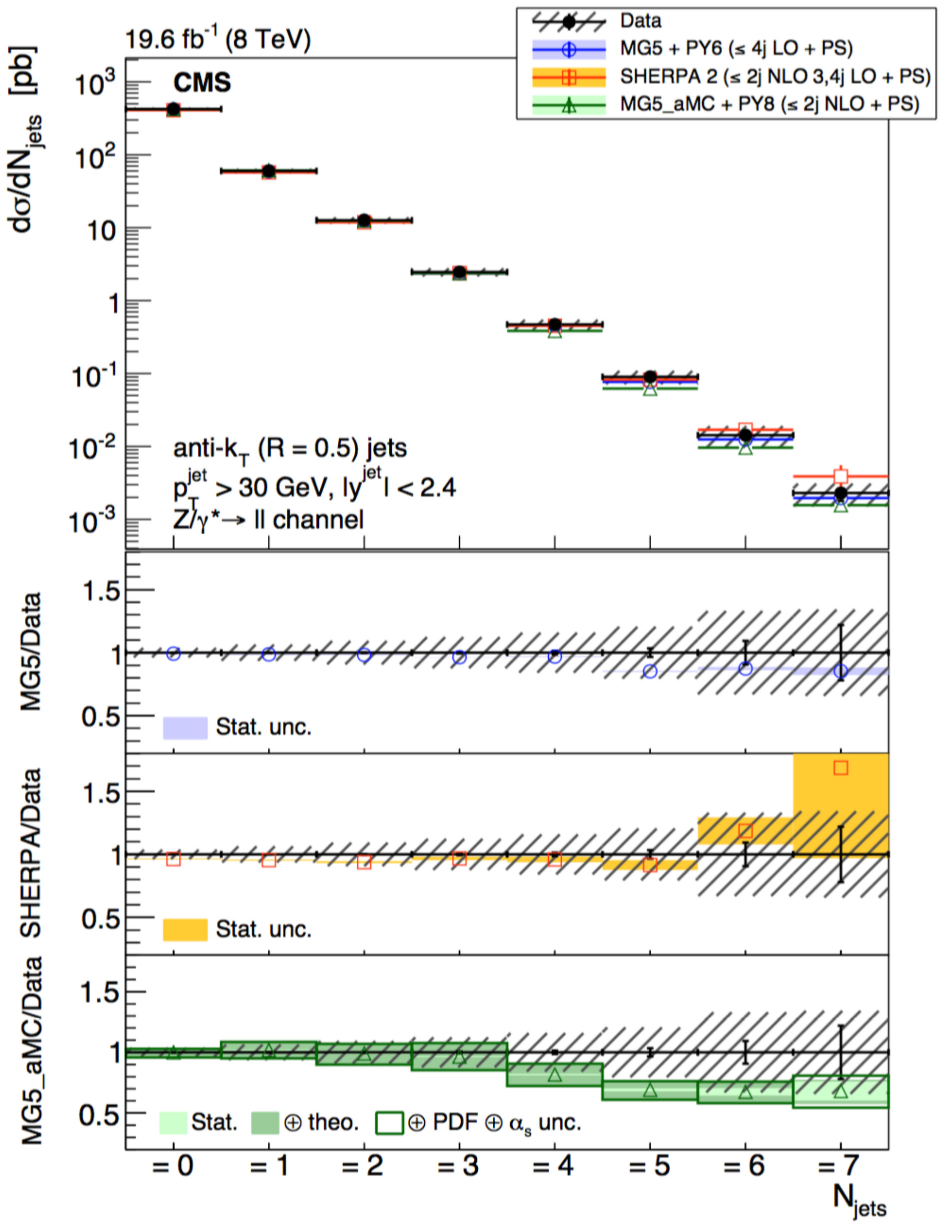


QCD corrections: Drell-Yan + jets

- Going further: cross section for Z+Njets, Njets=0,1,2,..

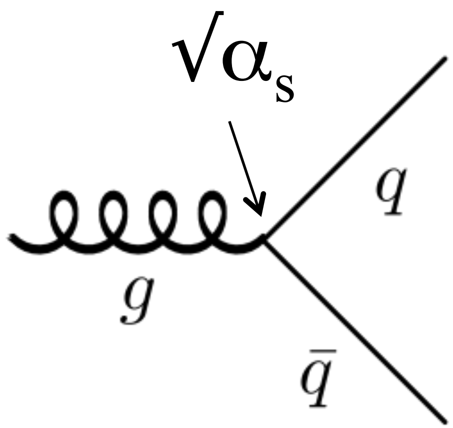
- Predictions with next-to-next-to-leading order (NNLO) corrections from QCD are accurate up to 4-5 jets





The strong coupling α_s

- α_s determines and parametrizes the strength of the strong interaction between coloured-objects, quarks and gluons
- It is <u>one of nature's fundamental parameters</u>, like the elementary electric charge e, the electron mass m_e, the gravitational constant G, ..
- Its numerical value is not predicted by the SM, has to <u>be measured experimentally</u>
- It's energy dependence however is <u>predicted by QCD</u>



Running of the strong coupling

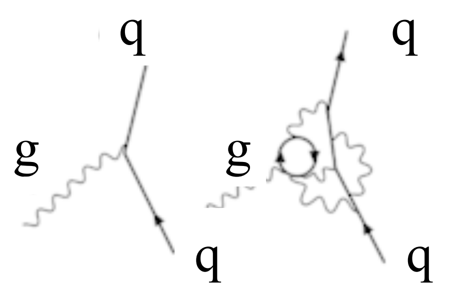
- The strong coupling 'constant', in leading order QCD, is given by

$$\boxed{\alpha_s = \frac{12\pi}{(33-2N_f)\ln(Q^2/\Lambda^2)}}$$

N_f: number of quark flavours

Λ: QCD scale parameter to be determined experimentaly (Λ=217±24MeV)

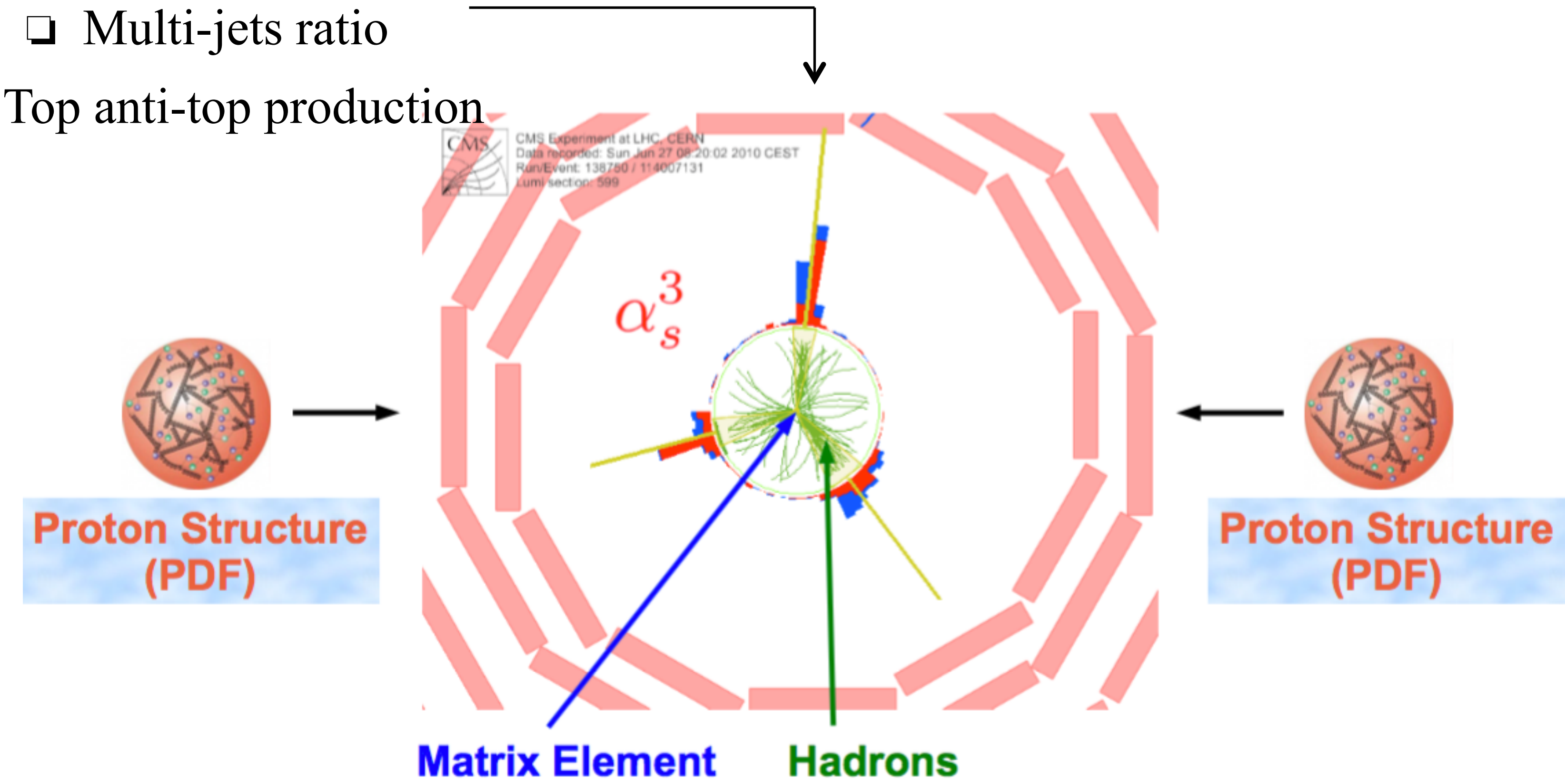
- The dependency on the energy (Q) corresponds to **virtual corrections** that depend on the energy or distance being probed



- This leads to 2 remarkable asymptotic behaviours for QCD:
  - α_s <<1 at high energy: **asymptotic freedom** (Gross, Politzer, Wilczek)
  - α_s >>1 at low energy: **confinement**

α_s measurement at LHC

- Many ways to measure α_s at hadron colliders
- Jet measurements
  - Inclusive jets
  - Multi-jets mass
  - Multi-jets ratio
- Top anti-top production

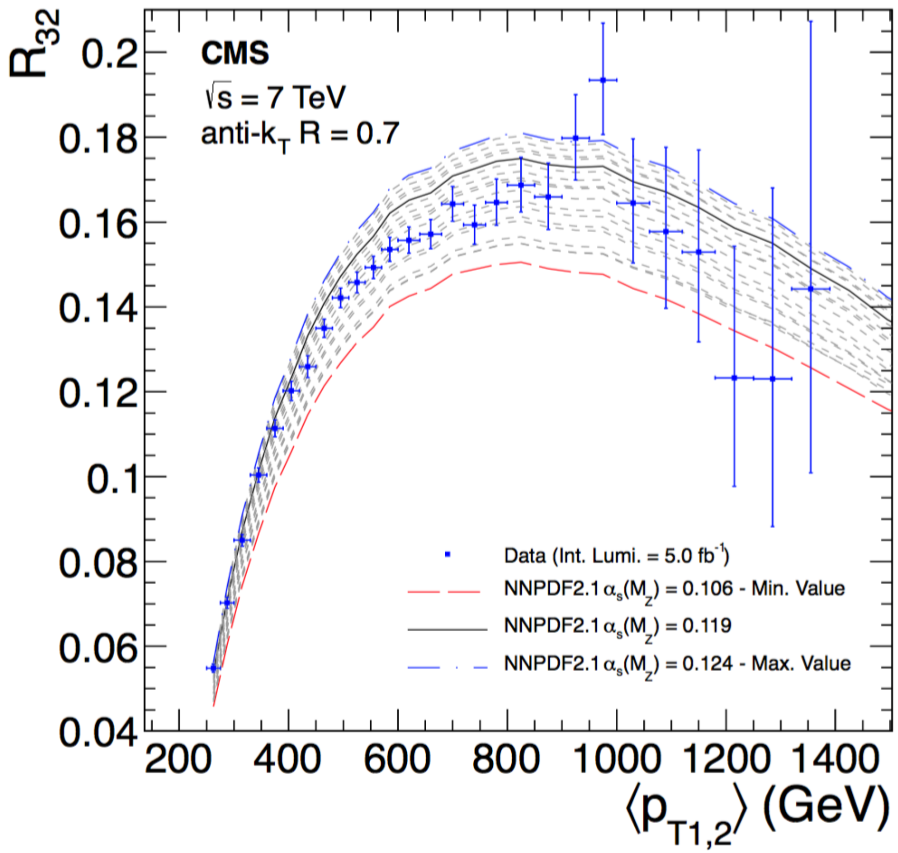


α_s measurement at LHC

- Measure the ratio R_{32} of 3-jet over 2-jet production
- $R_{32} = \sigma_{3jets} / \sigma_{2jets} \approx \alpha_s$

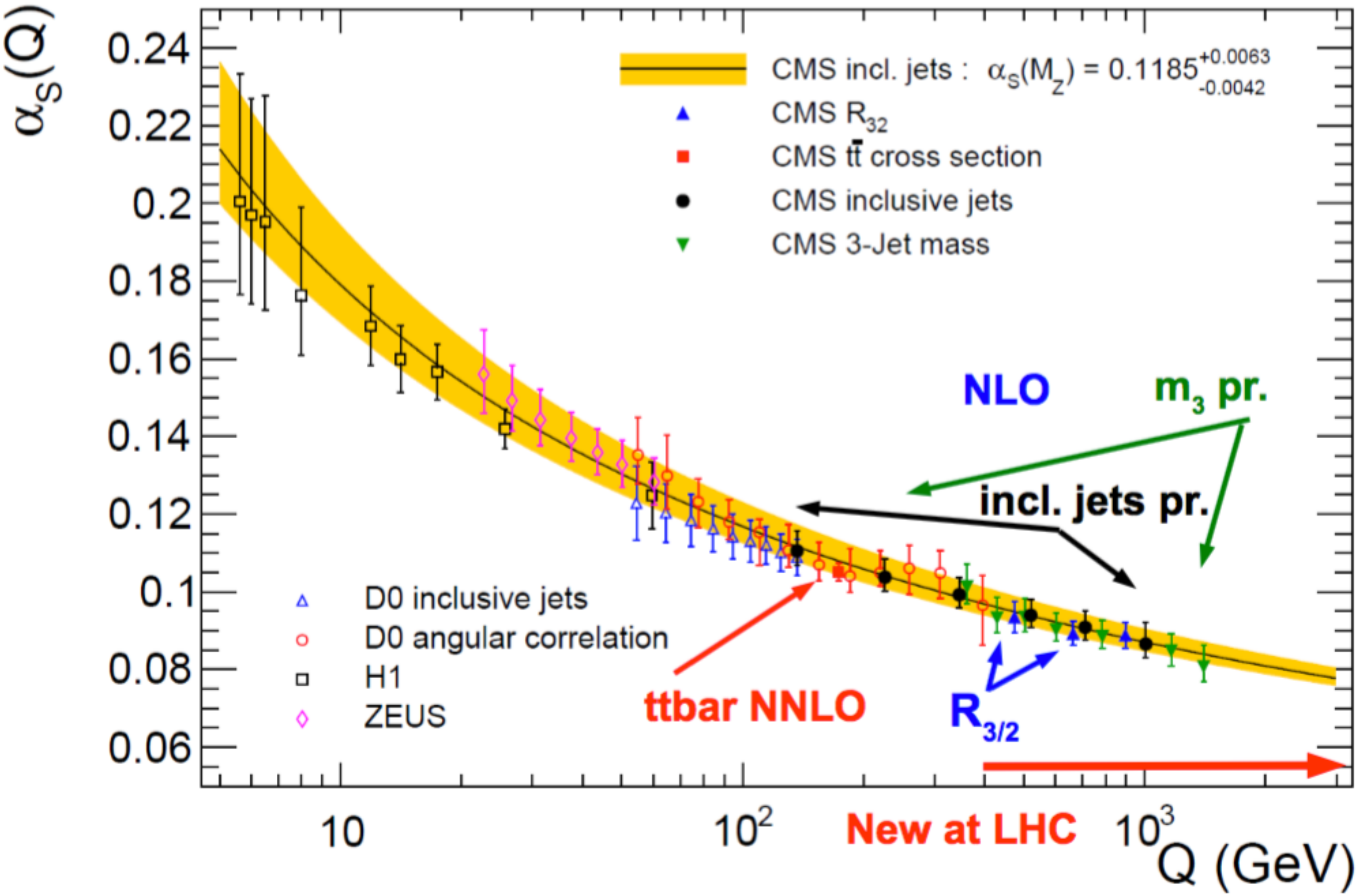
- Compare the measured ratio to prediction for different values of α_s as function of $<p_{T1,2}>=(p_{T1}+p_{T2})/2$
- Best fit value → measured α_s

$\alpha_s(m_Z) = 0.1148 \pm 0.0014$ (exp) ± 0.0018 (PDF) ± 0.0050 (theory)



→ precision dominated by NLO theory uncertainty

α_s measurement



→ New world average (2016): $\alpha_s(m_Z) = 0.1181 \pm 0.0013$

QCD summary

- QCD is the theory for the interactions between **quarks and gluons**
- **gluons carry** (color) **charge**, contrary to photons for the e.m. interaction
- This leads to **confinement** and **asymptotic freedom** properties
  - One cannot observe a colored state, quarks hadronize to produce bound states of either 2 ($q\bar{q}$) or 3 (qqq) quarks called **hadrons**
  - Experimentally observed as **hadrons' jets**
- QCD is unavoidable at hadron collider to compute processes' rates accurately
- The study of rates of production of events with 1, 2, or more jets allows to determine the **strong coupling constant** and its behaviour with the energy involved in the hard interaction
- LHC measurements for now *confirm* asymptotic freedom and QCD predictions at the **highest available energy**