Measurements of the Strong Coupling α_s

- particles and forces
- history of the Strong Interaction
- Quantum-Chromodynamics (QCD) vs. QED
- from quarks to hadrons
- experimental determinations of α_s
- world summary of α_s
- asymptotic freedom at its best…

Dimensions and Structure of Matter

Universe	10^{26} m	dominating force: gravity
Galaxy	10^{21} m	
Solar System	10^{13} m	
Earth	10^{7} m	
Human	10^{0} m	el.-magn.
Atom	10^{-10} m	
Atomic Nucleus	10^{-14} m	strong
Nucleon	10^{-15} m	
Quark; Lepton	$< 10^{-18}$ m	
?????	???	

The „Standard Model" of Particle Physics

... is rather simple and clearly arranged („übersichtlich"):

Elementary Particles

	Generation 1	Generation 2	Generation 3
Quarks	**u** **d**	**c** **s**	**t** **b**
Leptons	ν_e **e**	ν_μ μ	ν_τ τ

... as well as anti-particles

Elementary Forces

	exchange boson	relative strength
Strong	g	1
el.-magn.	γ	1/137
Weak	$W^{\pm}, Z^0$	10^{-14}
Gravitation	*G*	10^{-40}

... describes the unified electro-weak interaction and the Strong force with gauge invariant quantum field theories;

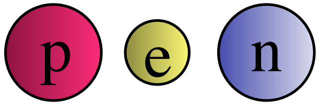
... precisely describes all particle reactions observed to date

... provides a consistent (yet incomplete) picture of the evolution of the very early universe –> cosmology

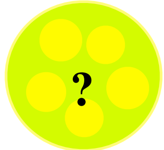
... explains particle masses through: the Higgs Boson

History of Strong Interactions (1)

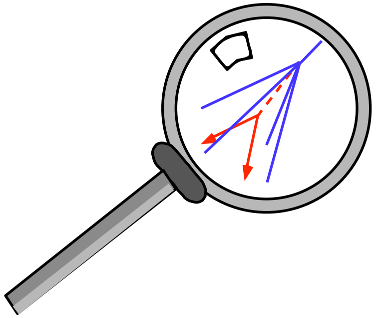
1932: discovery of neutrons



1933: $\vec{\mu} \cong 2.5 \, \frac{e}{2\, m_p} \, \vec{\sigma} \Rightarrow$ substructure of the protons

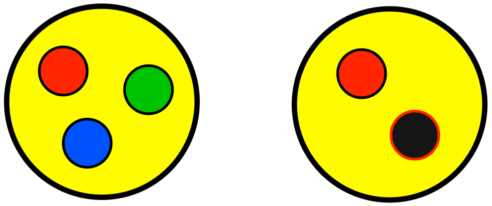


1947: discovery of π-mesons and long-living V-particles (K^0, Λ) in cosmic rays



1953: V-particles produced at accelerators
new inner quantum number ("strangeness").

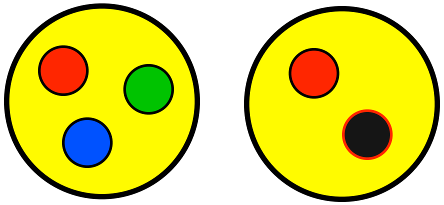
1964: static quark-model;
new inner quantum number: colour



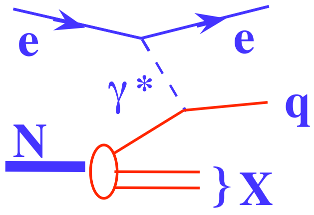
Baryon (p,n, Λ,...) Meson (π,K,...)

History of Strong Interactions (2)

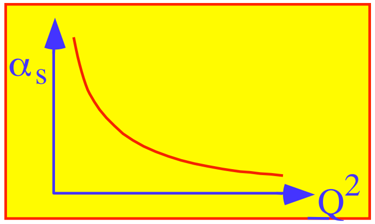
1964: static quark model ; new inner quantum number: colour.



1969: dynamic parton model :

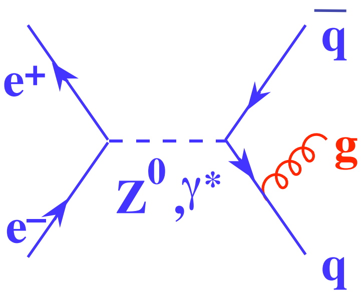


1973: concept of asymptotic freedom ; Quantum Chromo Dynamics.



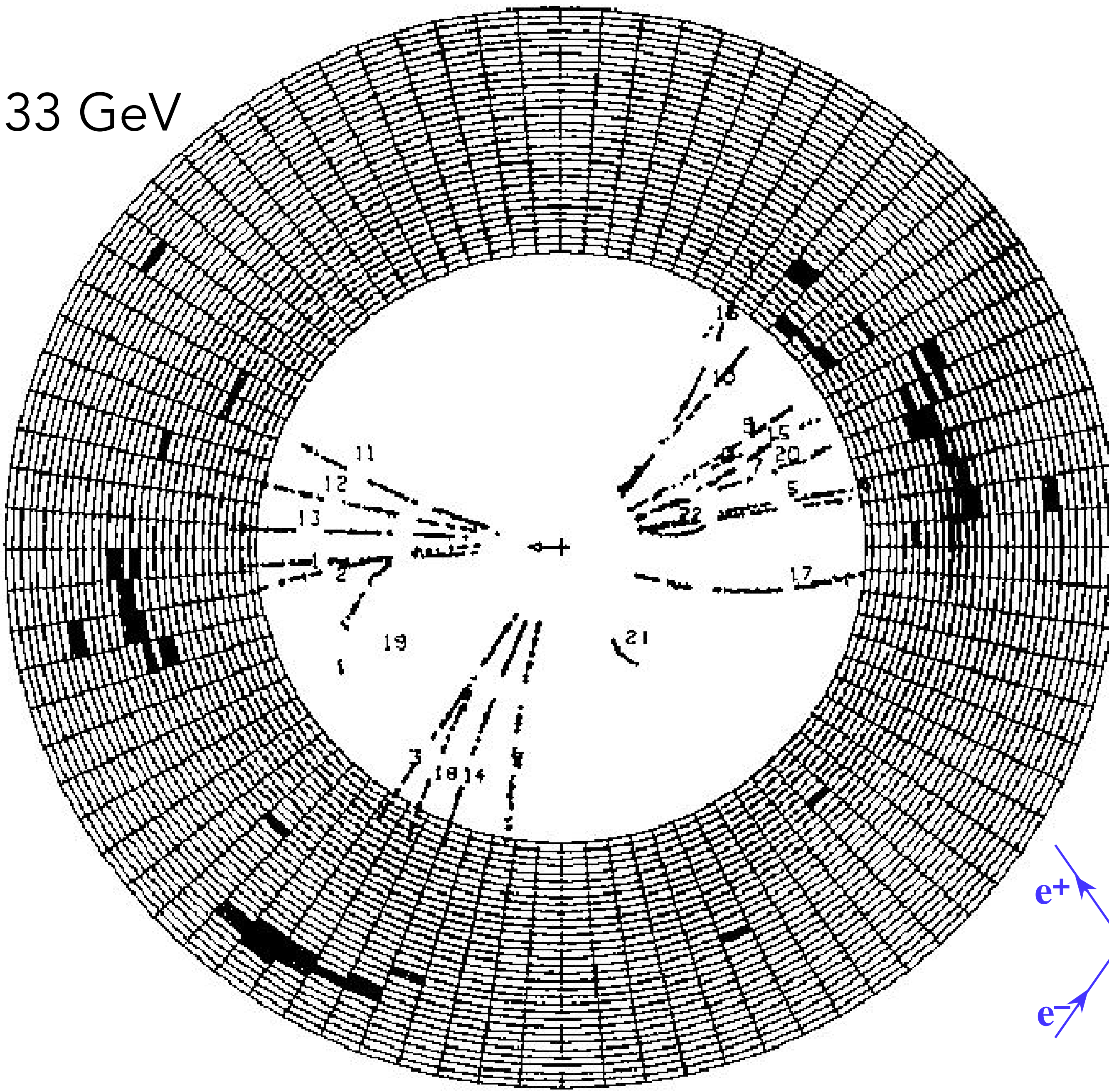
1975: 2-Jet structure in $e^+ e^-$ - annihilation: confirmation of quark-parton-model.

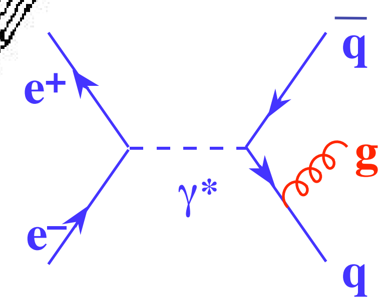
1979: discovery of gluons in 3-Jet-events of $e^+ e^-$ -annihilations.



3-Jet event recorded with the JADE Detector (1979-1986)

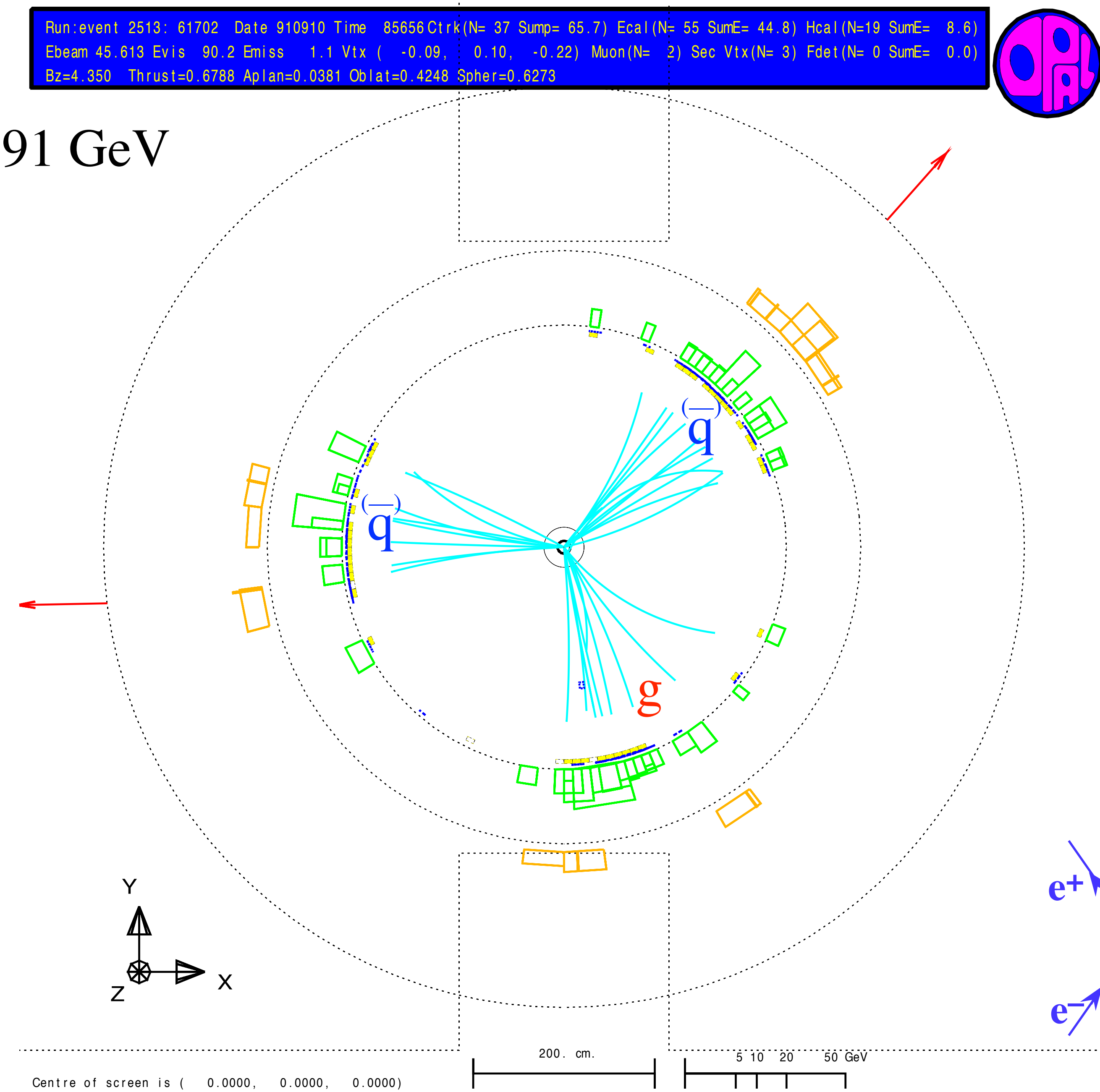
E_{cm} ~33 GeV

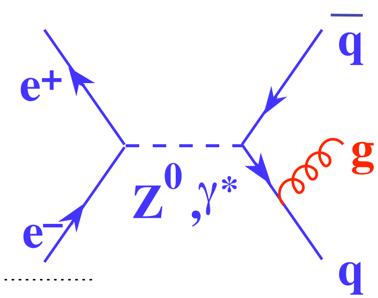




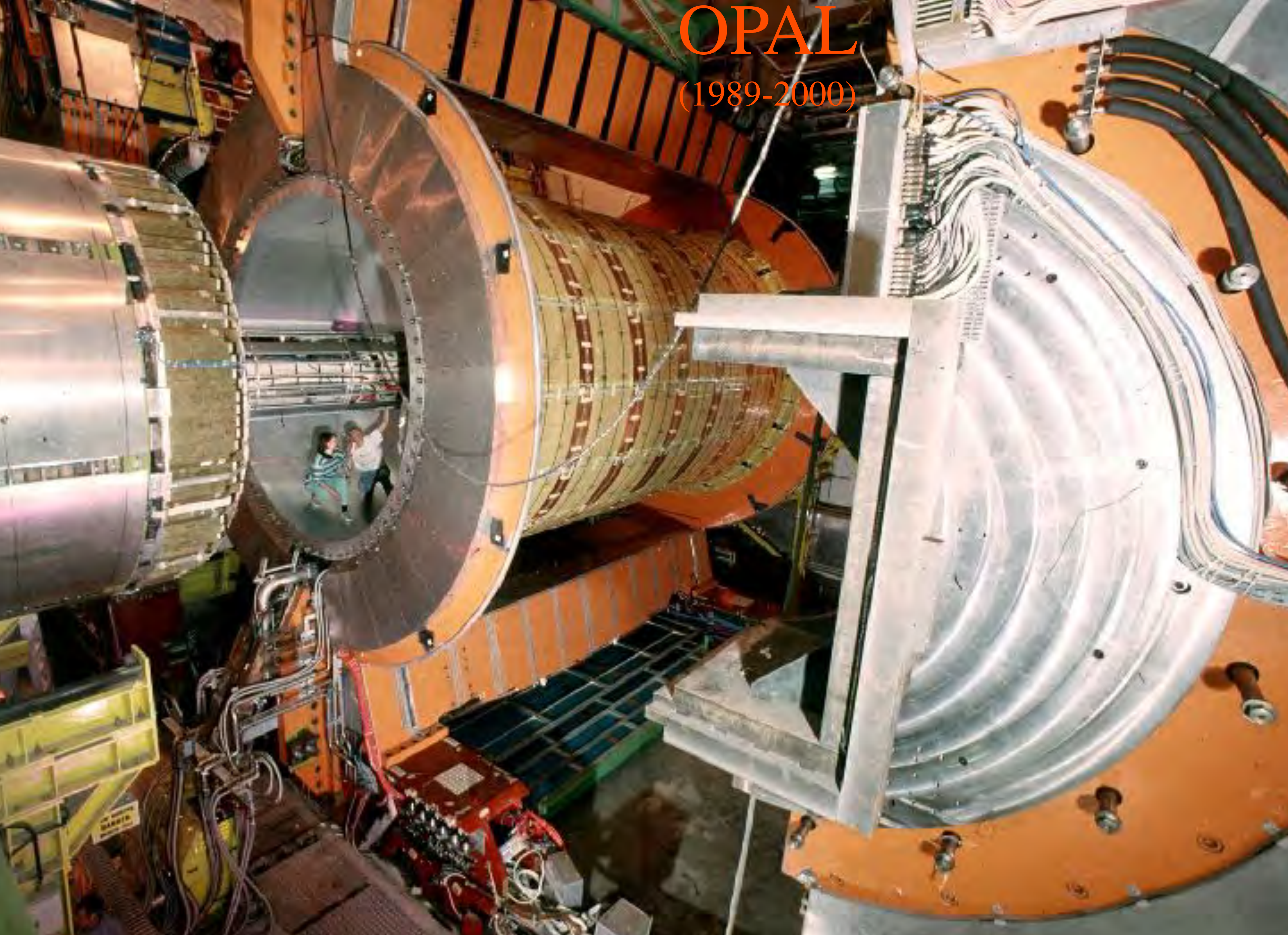
3-Jet event recorded with the OPAL Detector (1989-2000)

$E_{cm} = 91$ GeV

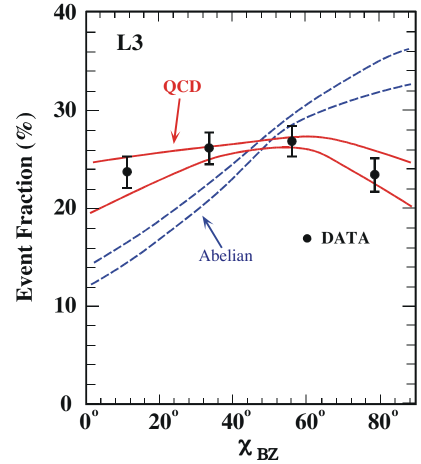


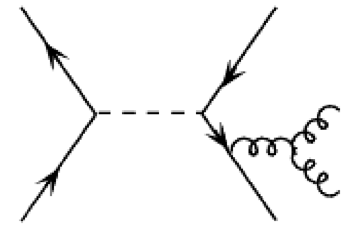


OPAL
(1989-2000)

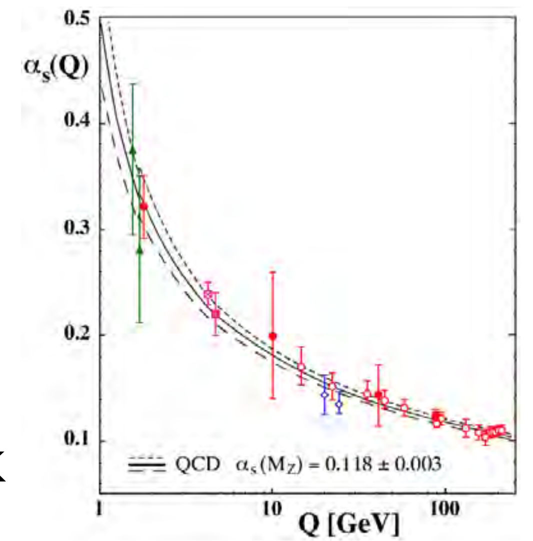


History of Strong Interactions (3)



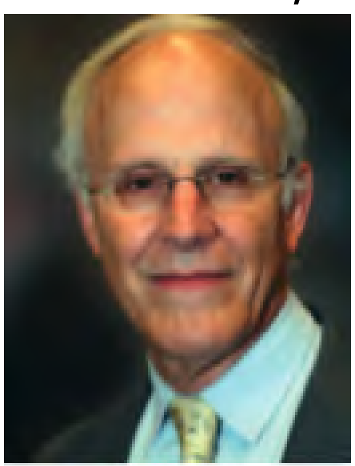


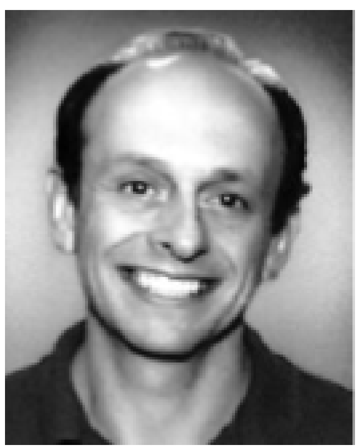
1991: exp. signature of the
gluon self coupling



1990-2000: confirmation of
asymptotic freedom

2004: Nobel Prize (concept of A.F.) to
D. Gross, H.D. Politzer und F. Wilczek

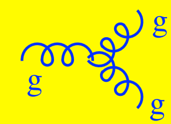
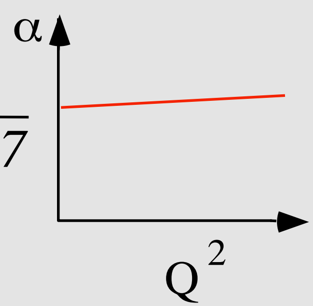
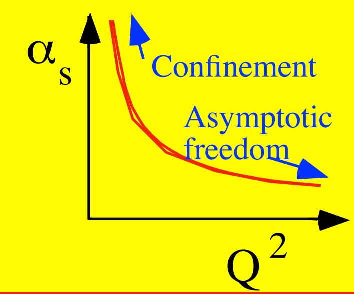




QCD:

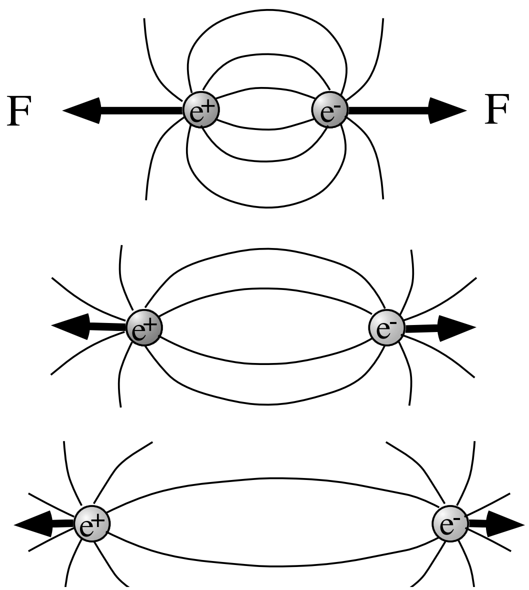
- gauge-field theory of Strong Interactions
- underlying gauge group: SU(3) ; non-abelian
- force mediating particles/quanta: gluons
- self-coupling of gluons
- renormalised coupling constant α_s is energy dependent:
- α_s large at small energies (large distances): confinement of quarks
- α_s small at large energies (small distancies): asymptotic freedom of quarks

properties of QED and QCD:

	QED	QCD
fermions	*leptons* (e, μ, τ)	*quarks* (u, d, s, c, b, t)
force couples to	*electric charge*	*3 color-charges*
exchange quantum	*photon* (γ) (carries no charge)	*gluons* (g) (carry 2 color charges) $\Rightarrow$  is possible
coupling "constant"	$\alpha(Q^2=0) = \frac{1}{137}$ 	$\alpha_s(Q^2 = M_Z^2) \approx 0.12$ 
free particles	*leptons* (e, μ, τ)	color neutral bound states of q and $\bar{q}$ — *Hadrons*
theory	*perturbation theory up to* $O(\alpha^5)$	*perturbation theory up to* $O(\alpha_s^4)$
precision achieved	10^{-6} .... 10^{-7}	0.1% ... 20%

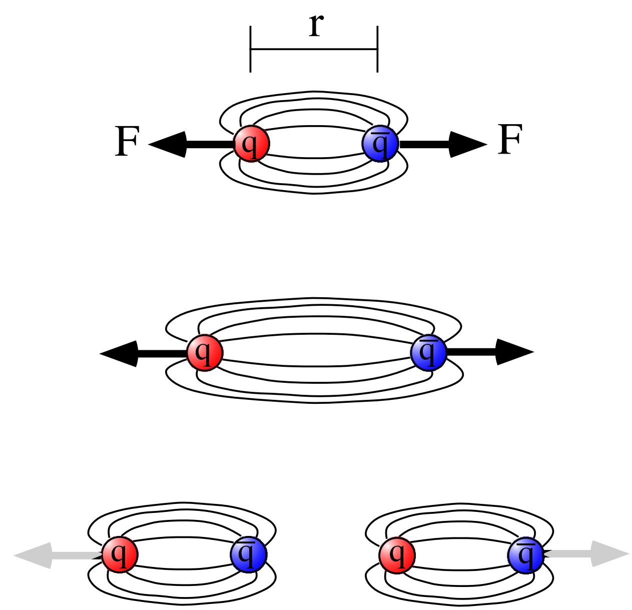
why are there no free quarks?

QED	QCD
electric charges: force $F \sim 1/r^2$; energy density $\sim 1/r$	color charges: force $F \sim$ const.; energy density $\sim r$



energy density between carriers of electric charges decreases with increasing distance

carriers of electric charges are free particles

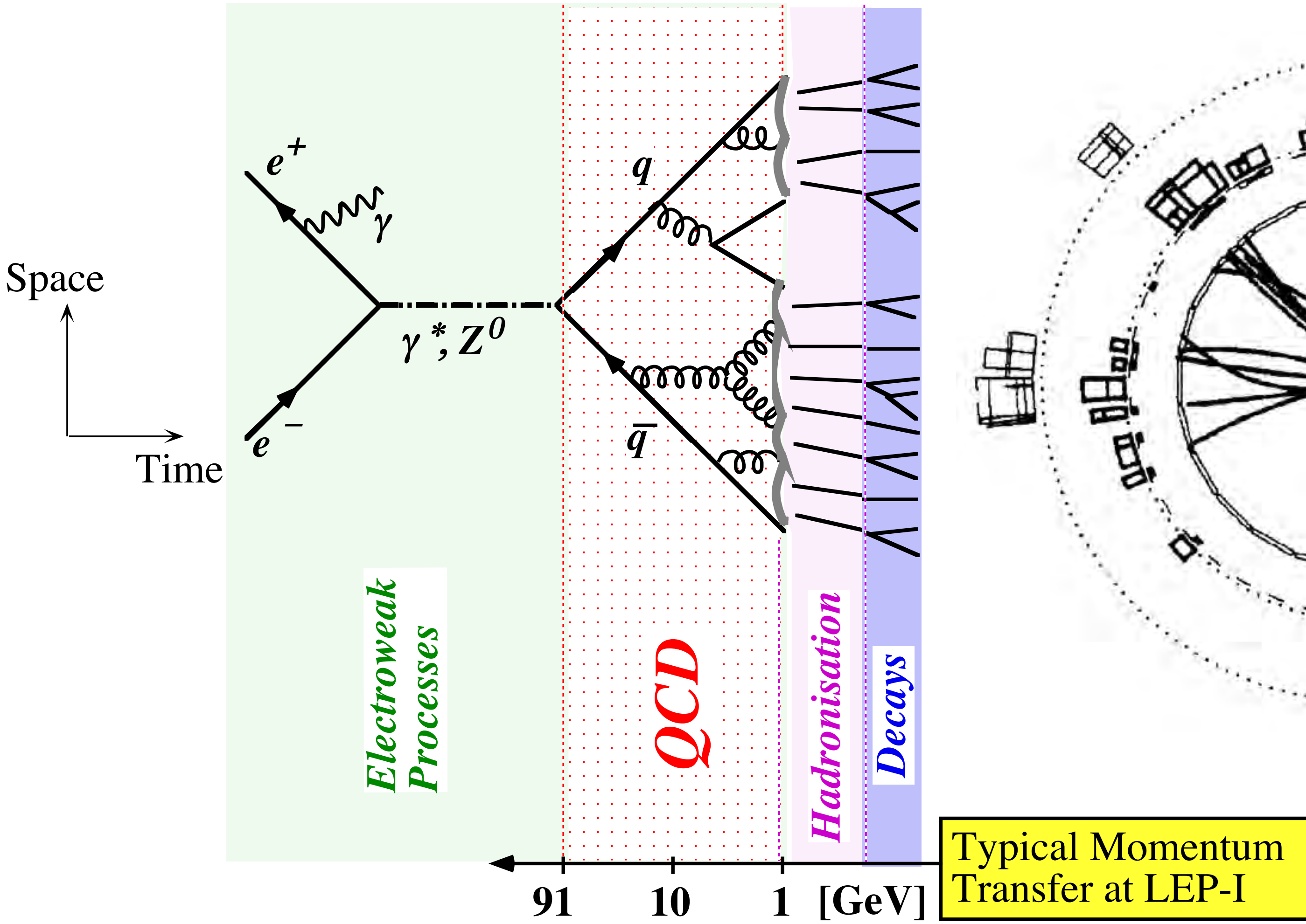


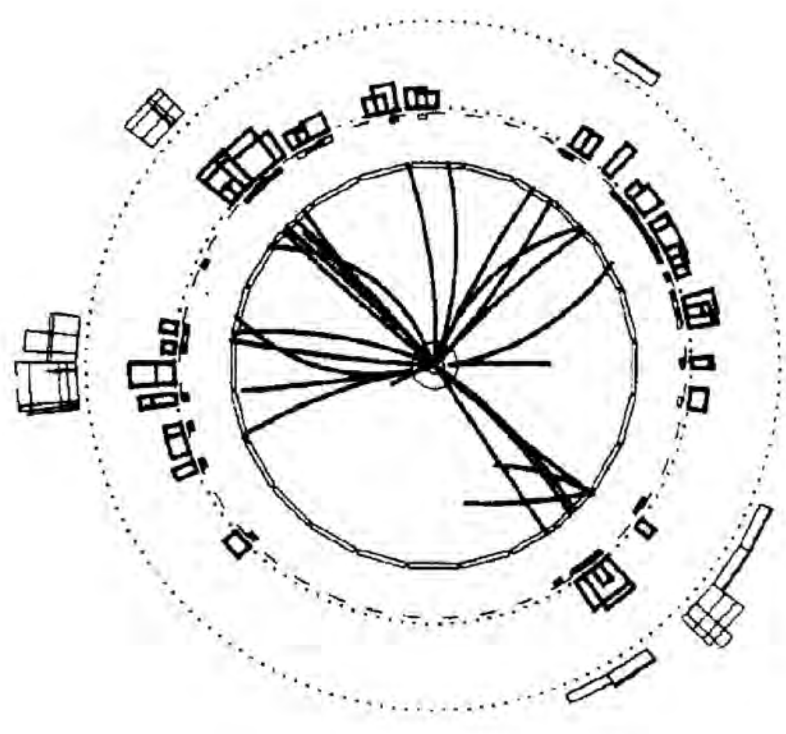
energy density increases, until a new quark-antiquark pair is created out of the vacuum

carriers of color charges only exist as color-neutral bound states of hadrons.

"Confinement"

Anatomy of hadronic events in e^+e^- annihilation





- QCD: shower development described by perturbation theory
- Hadronisation: phenomenological models of string-, cluster- or dipole fragmentation
- Decays of unstable hadrons: randomized according to experimental decay tables

energy dependence of coupling "constants":

renormalisation group equation ("β-function") (μ : renormalisation [energy] scale)

- in leading order perturbation theory:

$$\mu \frac{d}{d\mu} \alpha_i(\mu) = -\beta_0\, \alpha_i^2$$

with $$\beta_0 = \frac{1}{2\pi}\left[\frac{11}{3}\begin{pmatrix} N_c \equiv 0 \\ N_c \equiv 2 \\ N_c \equiv 3 \end{pmatrix} - \frac{4}{3}\begin{pmatrix} N_{fam} \\ N_{fam} \\ N_f/2 \end{pmatrix} - N_{Higgs}\begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}\right] \begin{matrix} \leftarrow \text{QED} \\ \leftarrow \text{weak} \\ \leftarrow \text{QCD} \end{matrix}$$

- integration ⇒

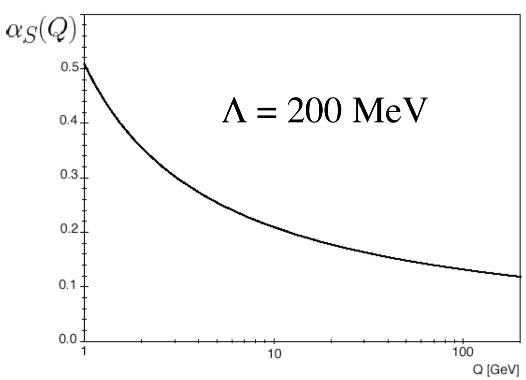
$$\alpha_i\left(q^2\right) = \frac{\alpha_i\left(\mu^2\right)}{1 + \frac{\beta_0}{2}\alpha_i\left(\mu^2\right) \ln\frac{q^2}{\mu^2}}$$

or

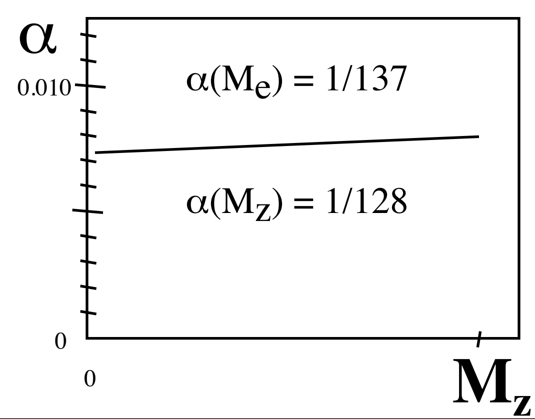
$$\alpha_i\left(q^2\right) = \frac{2}{\beta_0 \ln\frac{q^2}{\Lambda^2}}$$

with $$\Lambda^2 = \frac{\mu^2}{e^{2/\beta_0 \alpha_s\left(\mu^2\right)}}$$

QCD: $N_c = 3$; $N_f = 5$ $\quad \beta_0 = \frac{23}{6\pi}$

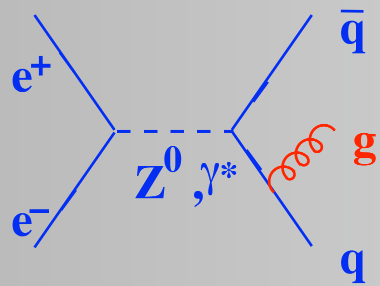


QED: $N_c = 0$; $N_{fam} = 3$ $\quad \beta_0 = -\frac{12}{6\pi}$

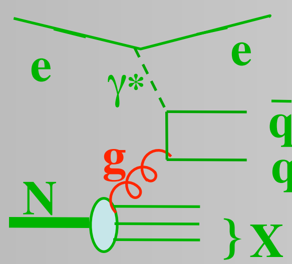


Determination of α_s

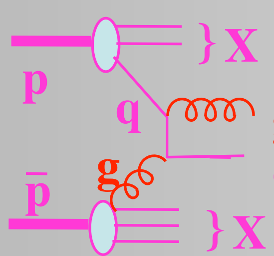
possible from all processes where gluons occur:



- e^+e^- annihilations
  - total hadronic production cross section
  - hadronic decay widths of the Z^0 and of the τ
  - jet rates and shape variables



- deep inelastic lepton-nucleon-scattering
  - scaling violations of structure functions
  - jet rates and shape variables



- proton-(anti-)proton collisions
  - jet rates and shape variables
  - production cross sections

- lattice gauge theory
  - observables calculated on discrete space-time lattice
  - normalised to measured hadron masses and spectra

perturbative predictions of physical quantities

$$\mathcal{R}(Q^2) = P_l \sum_n R_n \alpha_s^n$$
$$= P_l \left(R_0 + R_1 \alpha_s(\mu^2) + R_2(Q^2/\mu^2)\alpha_s^2(\mu^2) + \ldots \right)$$

in n^{th} order perturbation theory

R_1 : "leading order coefficient" (lo)
R_2 : "next to leading coefficient" (nlo)
R_3 : "next-next-to leading" (nnlo)

how to determine α_s:

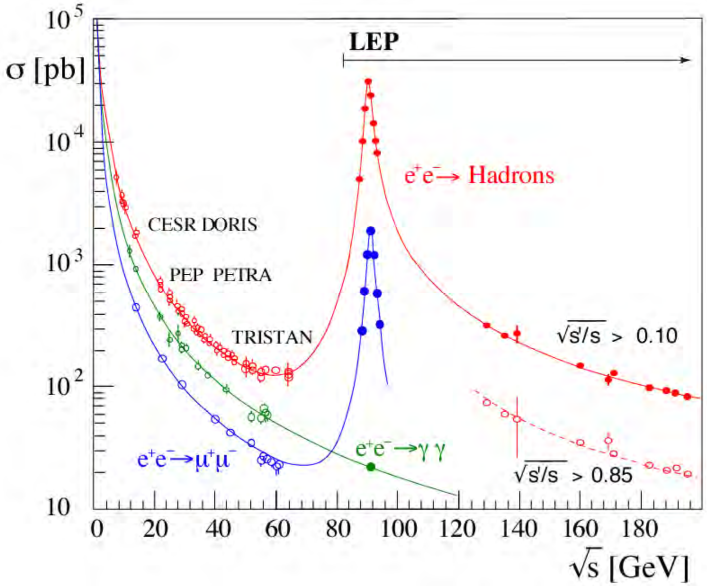
- accurate prediction of observable (perturbative QCD in nlo, nnlo,..)
- precise measurement of observable in (high energy) particle reactions
- matching measurements (hadrons!) to calculations (quarks&gluons)
- determination (fit) of free parameter(s): α_s, (+possible further nuisance params.)

assessment of systematic uncertainties:

- experimental (statistics; detector effects; method biases; …)
- theoretical (missing perturbative higher orders; non-perturbative effects and parametrisation of hadronisation (quarks -> hadrons); procedural;…)

theoretical uncertainties mostly dominate!

example 1: hadronic width of Z^0 boson



$$R_Z = \frac{\Gamma(Z^0 \to \text{hadrons})}{\Gamma(Z^0 \to \text{leptons})} = 20.768 \pm 0.0024$$

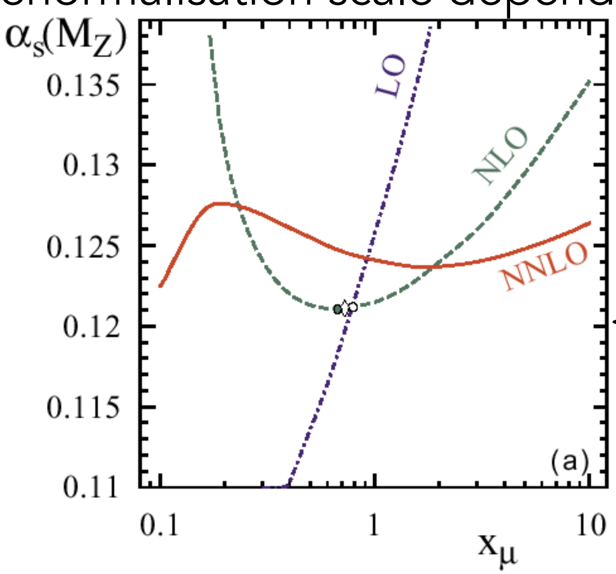
$$R_Z = 19.934\left[1 + 1.045\frac{\alpha_s(\mu)}{\pi} + 0.94\left[\frac{\alpha_s(\mu)}{\pi}\right]^2 - 15\left[\frac{\alpha_s(\mu)}{\pi}\right]^3\right]$$

$$\Rightarrow \quad \alpha_s(M_Z) = 0.124 \pm 0.004 \quad (\text{exp.})$$

~~$\pm\ 0.002$ (M_H, M_{top})~~

$^{+\,0.003}_{-\,0.001}$ (QCD)

renormalisation scale dependence:

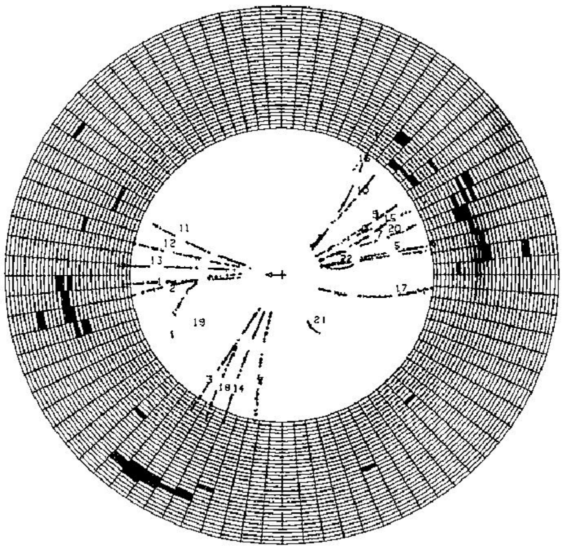


$x_\mu = \mu / E_{cm}$

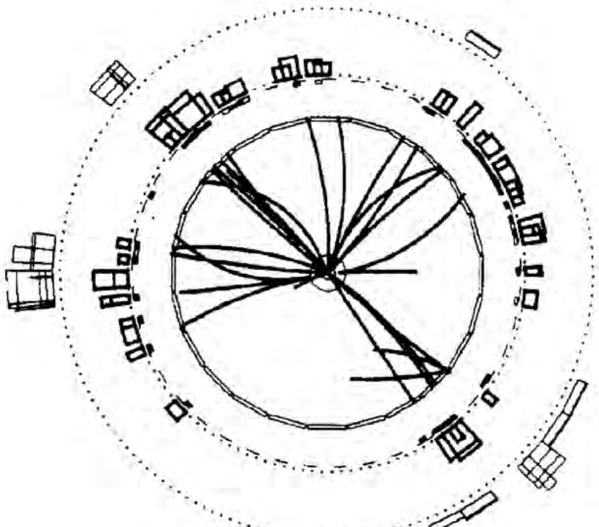
error source	$\Delta\alpha_s(M_{Z^0})$	now (2019) known to:
$\Delta M_{Z^0} = \pm 0.0021$ GeV	± 0.00003	
~~$\Delta M_t = \pm 5$ GeV~~	~~± 0.0002~~	173.0 ± 0.4
~~$M_H = 100 \ldots 1000$ GeV~~	~~± 0.0017~~	125.18 ± 0.16 (GeV)
$\mu = (\frac{1}{4} \ldots 4)\ M_{Z^0}$	$^{+\,0.0028}_{-\,0.0004}$	
renormalization schemes	± 0.0002	
total	$^{+\,0.003}_{-\,0.002}$	

dominating uncertainty: experimental (statistical)

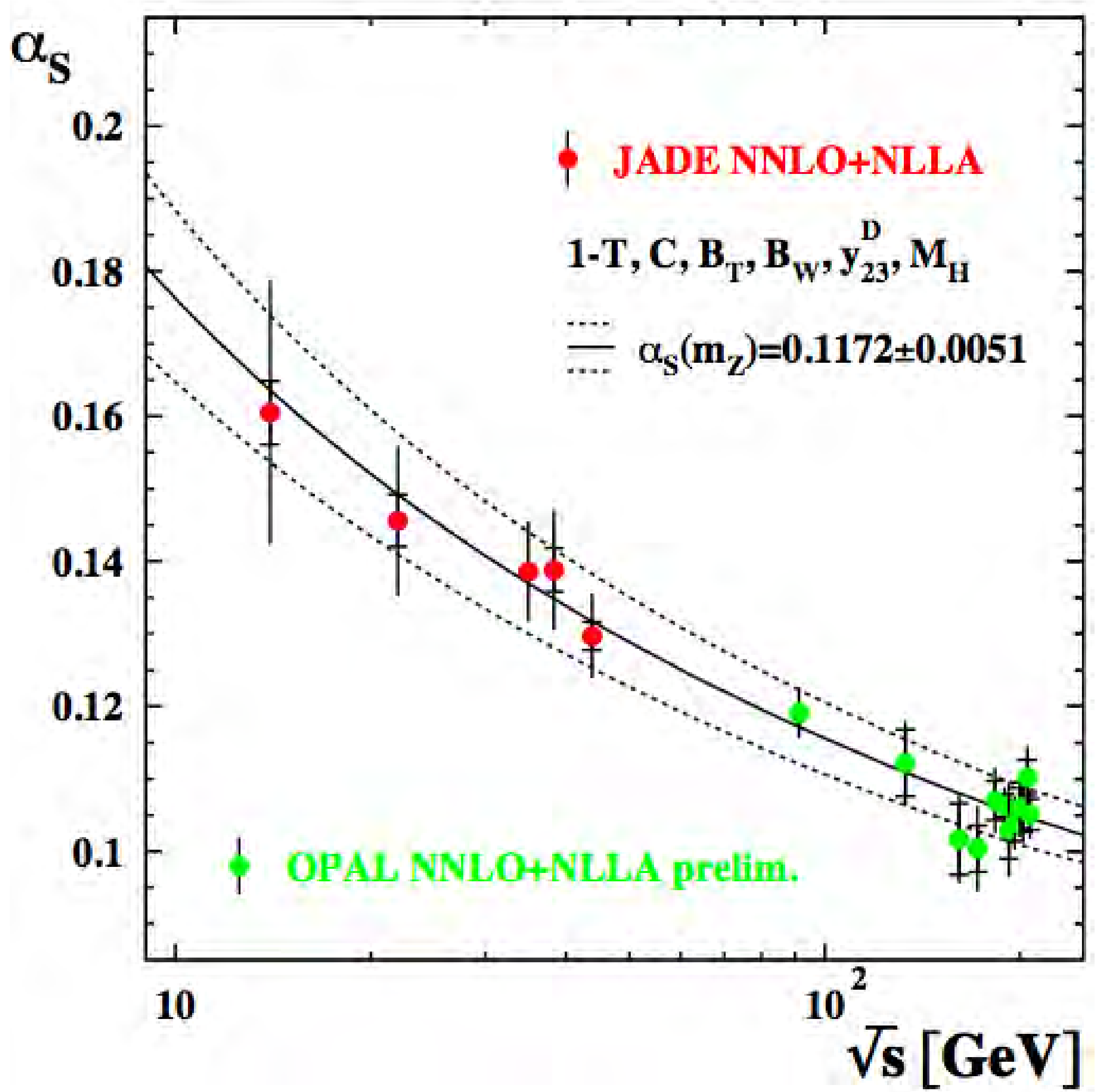
example 2: α_s from jet rates und event shapes:



$\sigma_{3\text{-jet}} \sim \alpha_s$

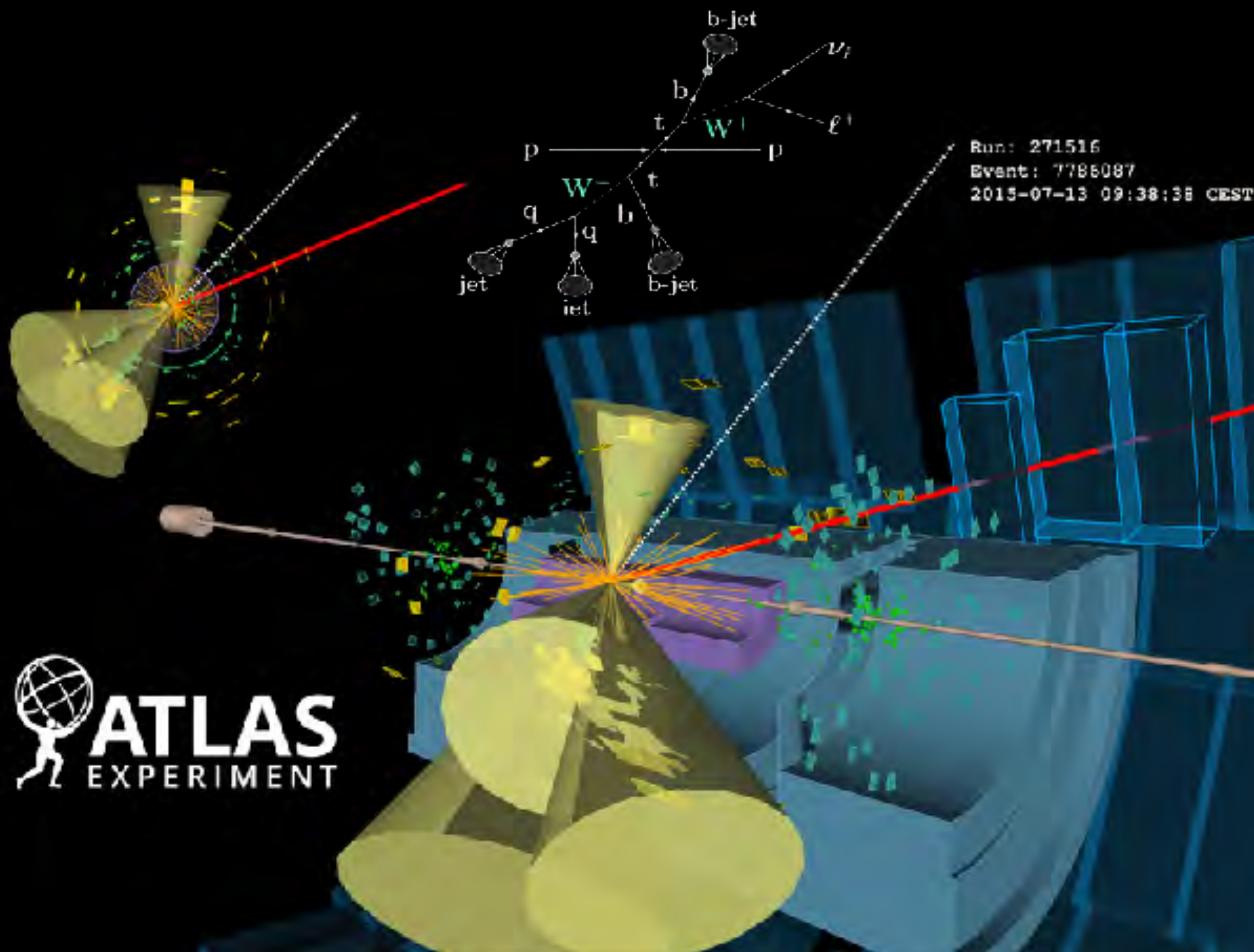


$\sigma_{4\text{-jet}} \sim \alpha_s^2$



dominating uncertainty: theoretical (perturb., hadr..)

example 3: α_s from top-quark pair production cross section in hadron-hadron collisions

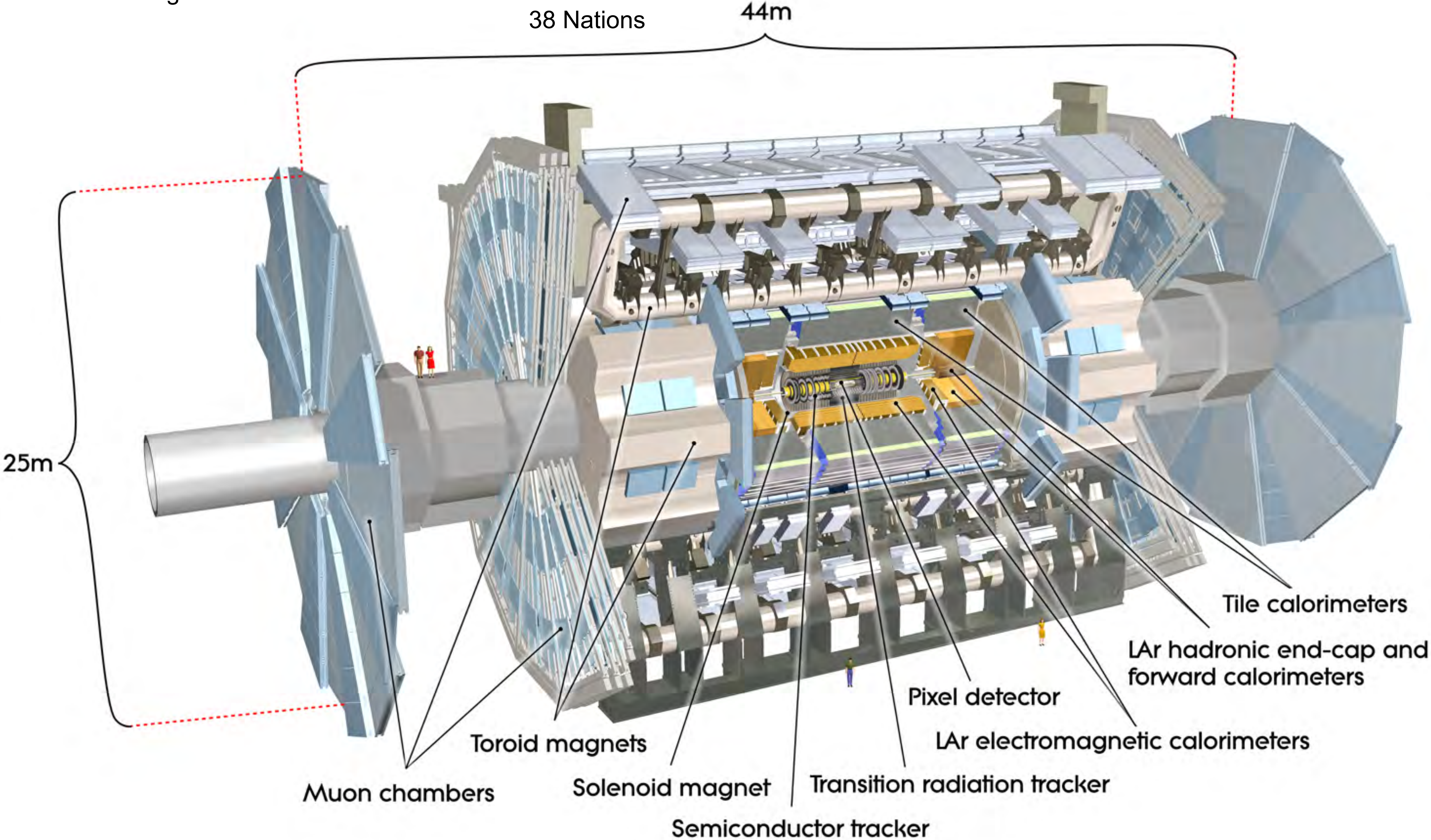


The ATLAS Detector at the LHC

Length: 44 m
Height: 22 m
Weight: 7000 t

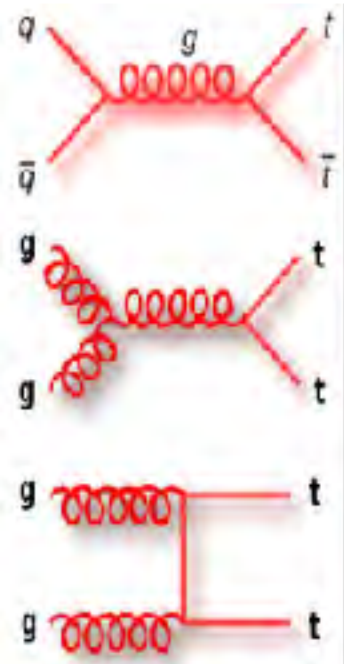
3000 Physicists & Engineers (incl. 1000 Students)
178 Institutes
38 Nations

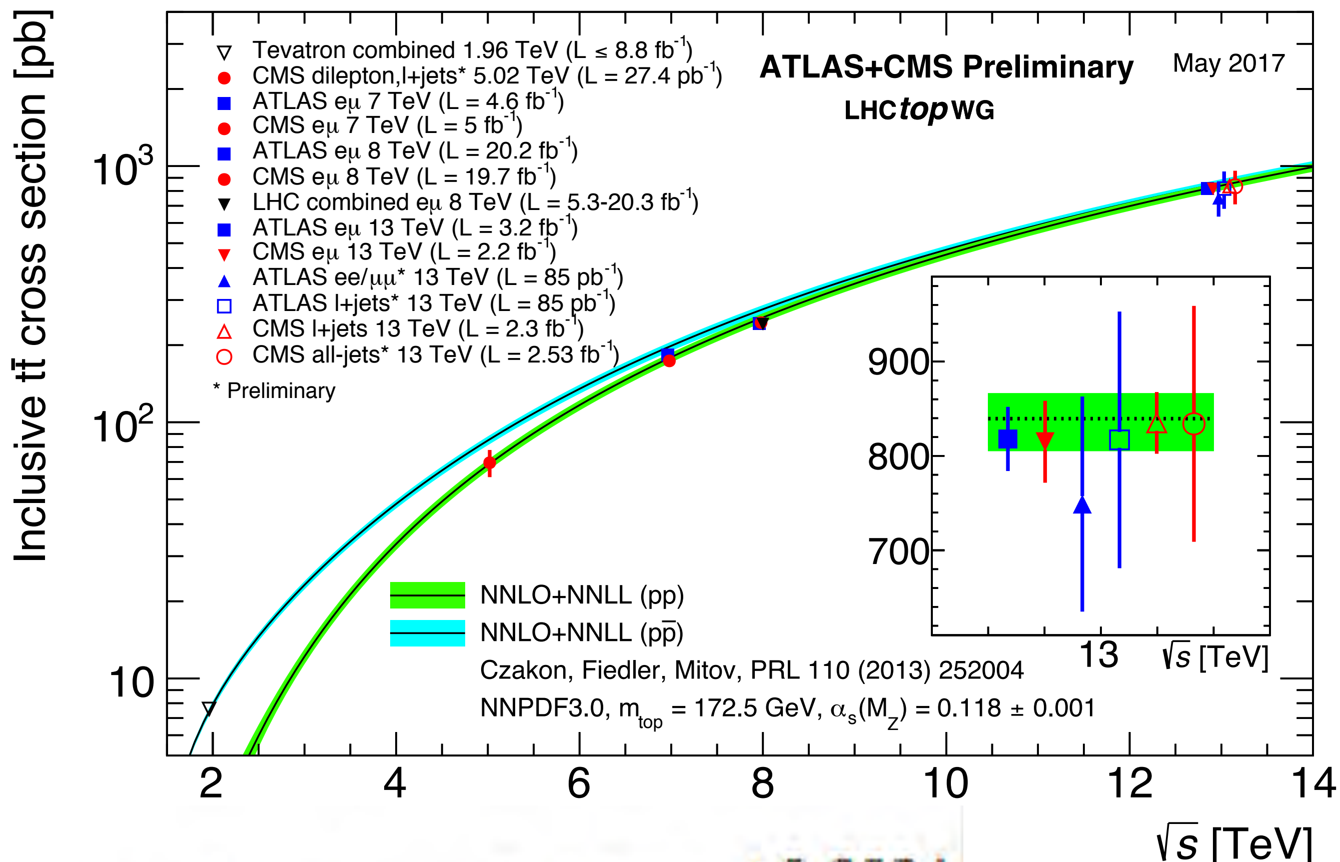
$150 \cdot 10^6$ electronic readout channels
40 MHz collision rate
10^{14} B/s raw data flux



Planning & construction 1990 to 2007, operation from 2009, for ~ 25 years

example 3: α_s from top-quark pair production cross section in hadron-hadron collisions



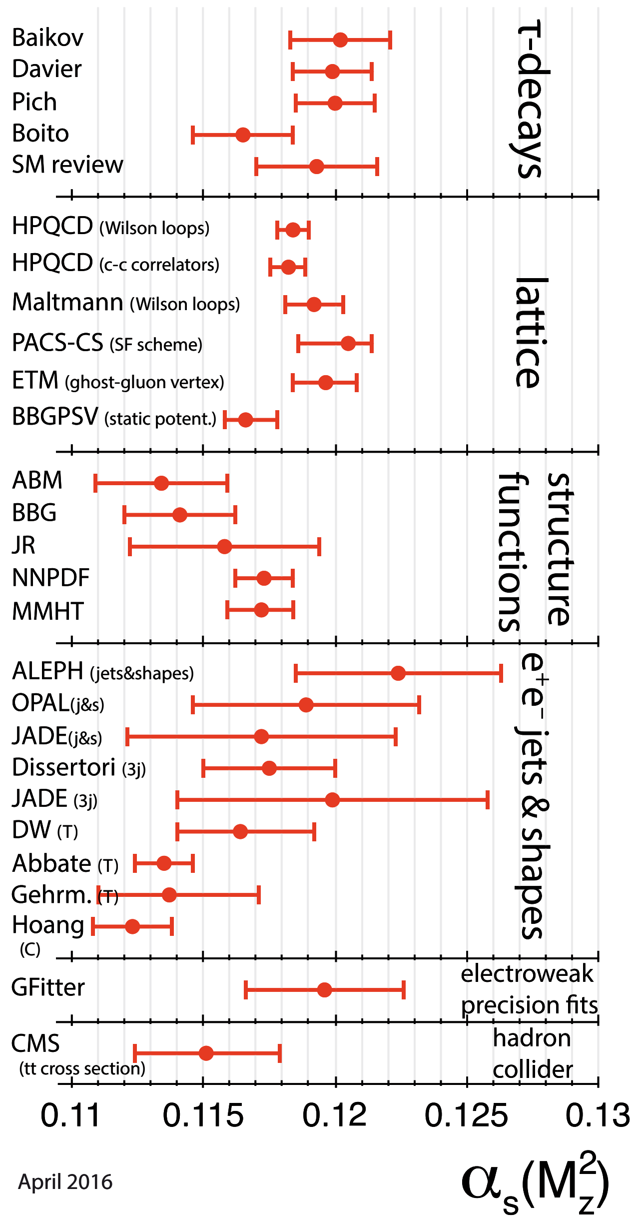


$$\alpha_s(m_Z) = 0.1177 \begin{array}{l} +0.0034 \\ -0.0036 \end{array}$$

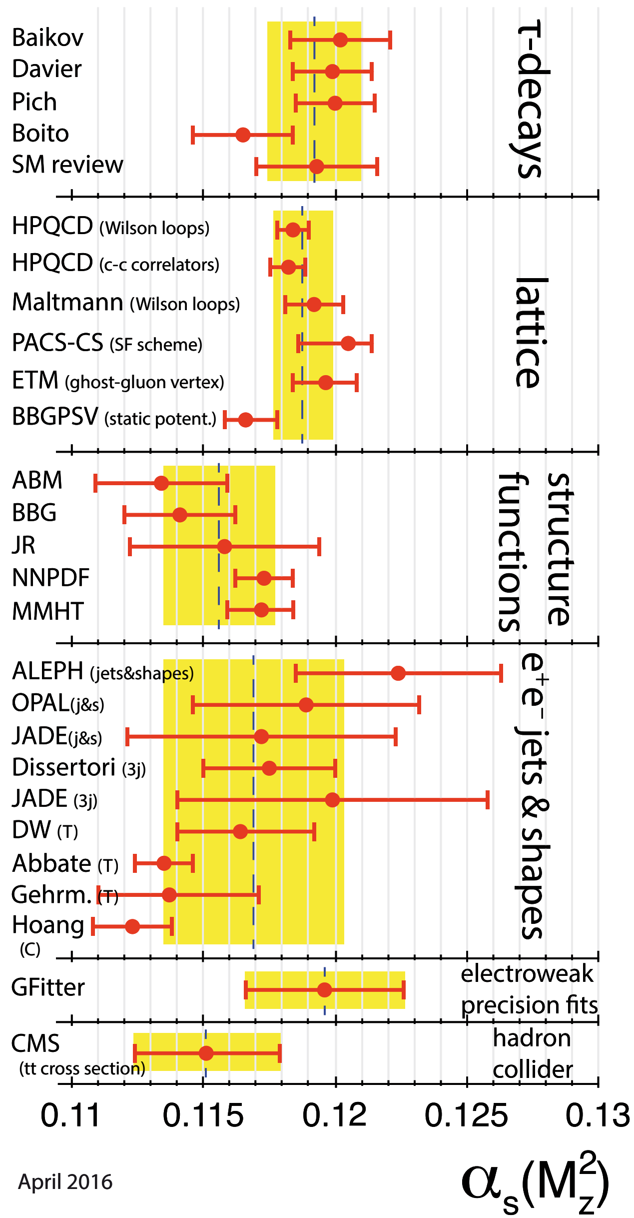
S.B., G. Dissertori, T. Klijnsma, G. Salam, arXiv:1708.07495

dominating uncertainty: theoretical (pert.; pdf)

summary of α_s



summary of α_s



class averages:

$\alpha_s(Mz)= 0.1192 \pm 0.0018$

$\alpha_s(Mz)= 0.1188 \pm 0.0011$

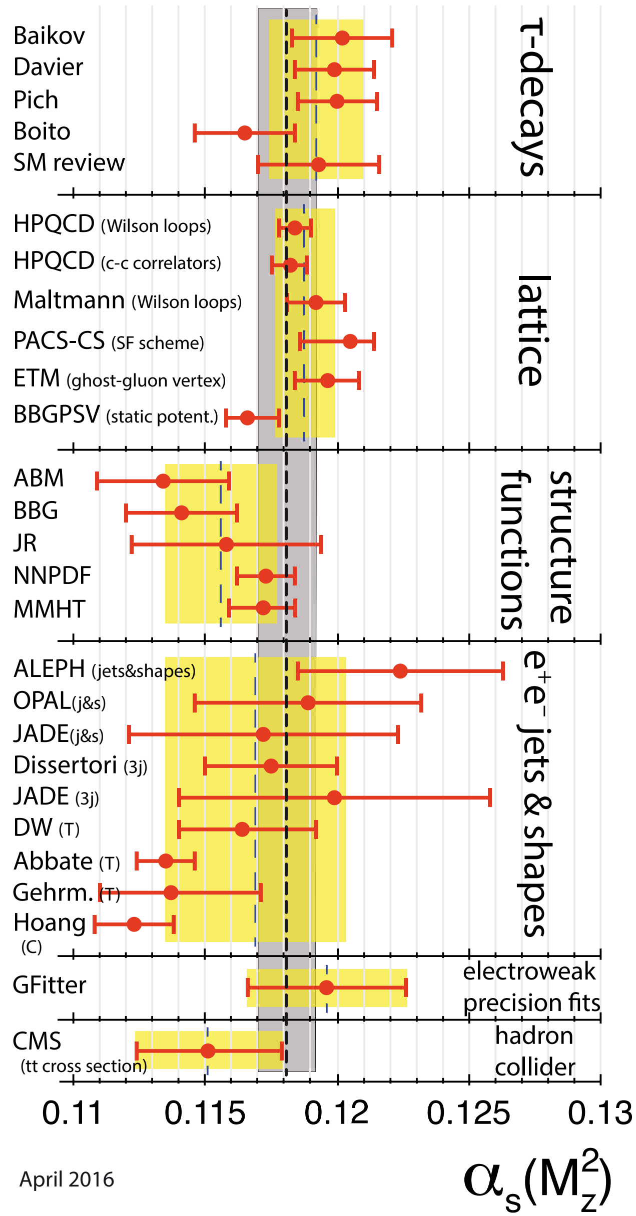
$\alpha_s(Mz)= 0.1156 \pm 0.0021$

$\alpha_s(Mz)= 0.1169 \pm 0.0034$

$\alpha_s(Mz)= 0.1196 \pm 0.0030$

$\alpha_s(Mz)= 0.1151 \pm 0.0028$

summary of α_s



class averages:

$\alpha_s(M_Z) = 0.1192 \pm 0.0018$

$\alpha_s(M_Z) = 0.1188 \pm 0.0011$

$\alpha_s(M_Z) = 0.1156 \pm 0.0021$

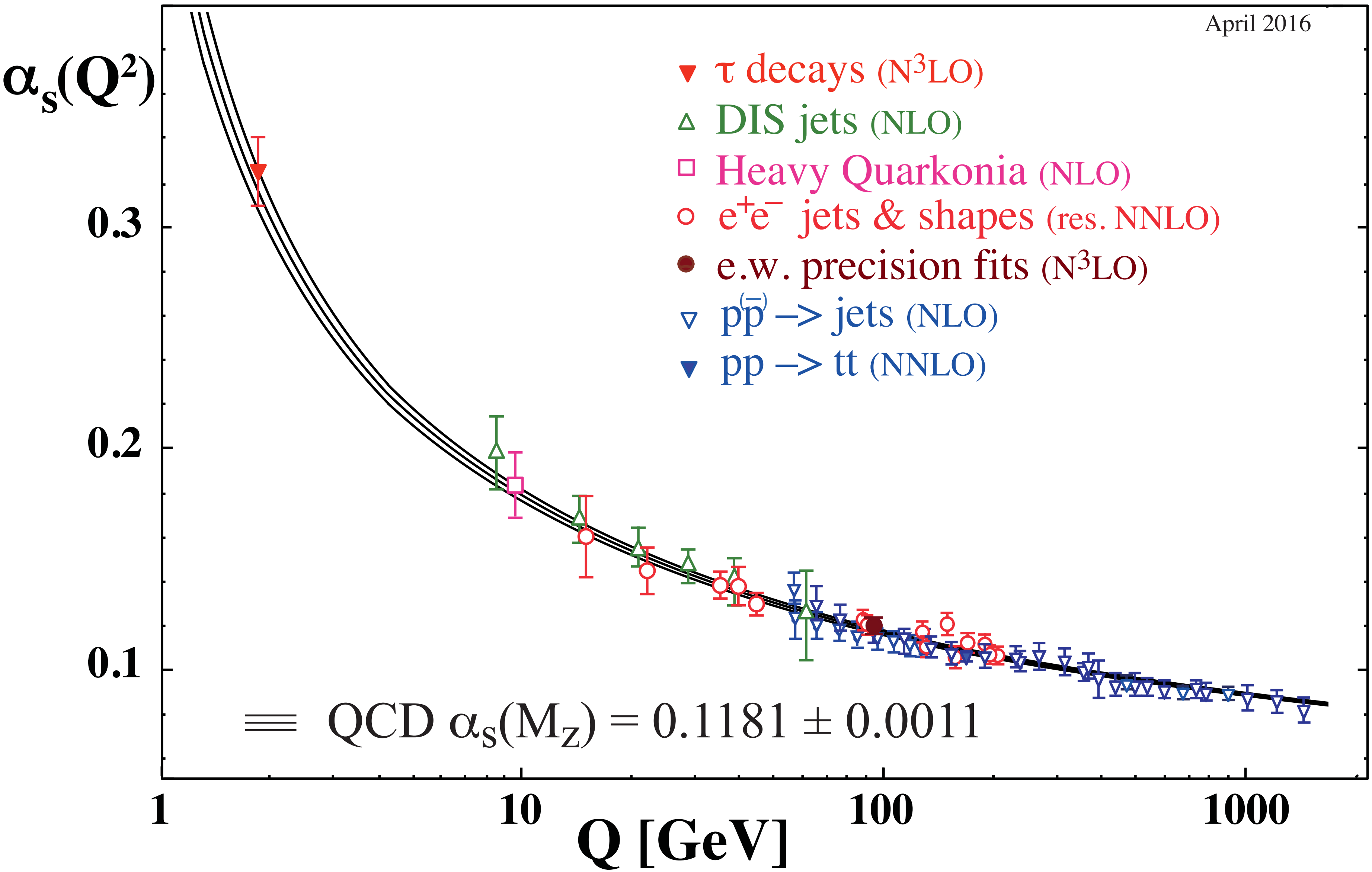
$\alpha_s(M_Z) = 0.1169 \pm 0.0034$

$\alpha_s(M_Z) = 0.1196 \pm 0.0030$

$\alpha_s(M_Z) = 0.1151 \pm 0.0028$

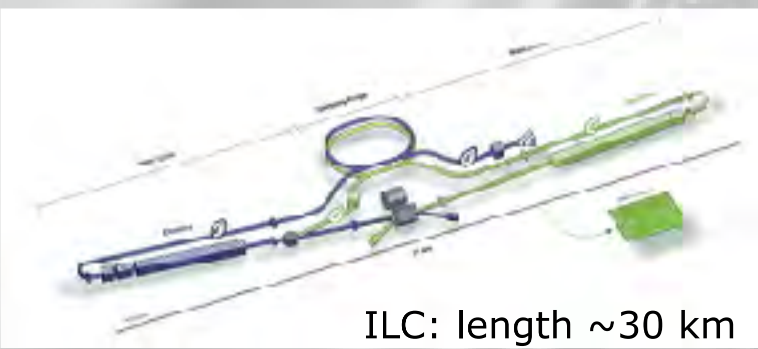
overall world average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$

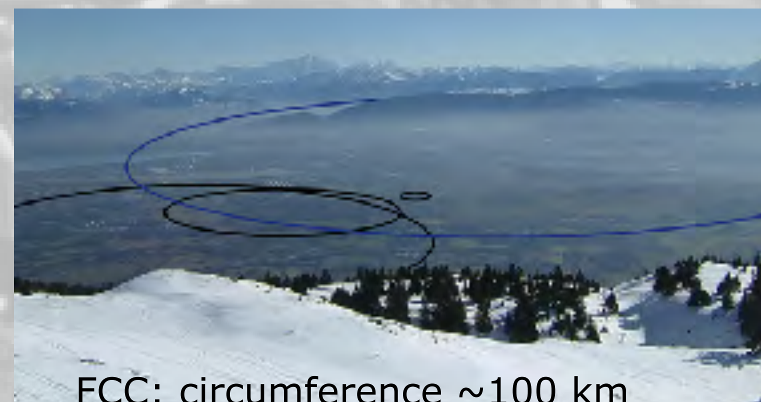
summary of running α_s



outlook:

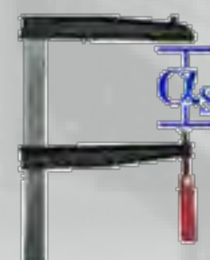
- (only?) realistic chances for sub-% total uncertainty of $\alpha_s(M_z)$:
  - improved lattice calculations
  - Giga/Tera-Z running at future e^+e^- colliders like ILC / CLIC / CEPC / FCC-ee


ILC: length ~30 km


FCC: circumference ~100 km

time evolution of world average $\Delta\alpha_s(M_Z)/\alpha_s$:

- 1989: 10 % (G. Altarelli)
- 2016: 1 % (see above)
- future: 0.1% (your guess...)



Summary:

- QCD is the established gauge field theory of Strong Interaction
- the strong coupling strength, α_s , is one of the fundamental "constants" of nature. It is not given by theory, but must be determined by experiment
- basic constituents of QCD are quarks and gluons, while in experiment, (jets of) hadrons reveal their underlying kinematics
- α_s is determined from a large number of particle reactions spanning energy scales from ~1 GeV to more than 1 TeV, averaging at $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (total uncertainty of ~1%)
- systematic uncertainties are predominantly theoretical (limited perturbative order; hadronisation; nonperturbative effects)
- measurements unambiguously prove the specific energy dependence of α_s predicted by QCD: Asymptotic Freedom

α_s is the least precisely known fundamental coupling, but its energy dependence is the most (only) accurately tested one!