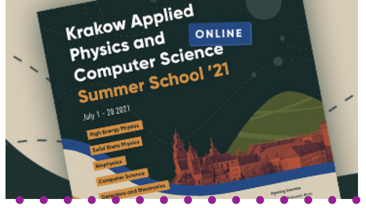
Lecture: Particles and Interactions

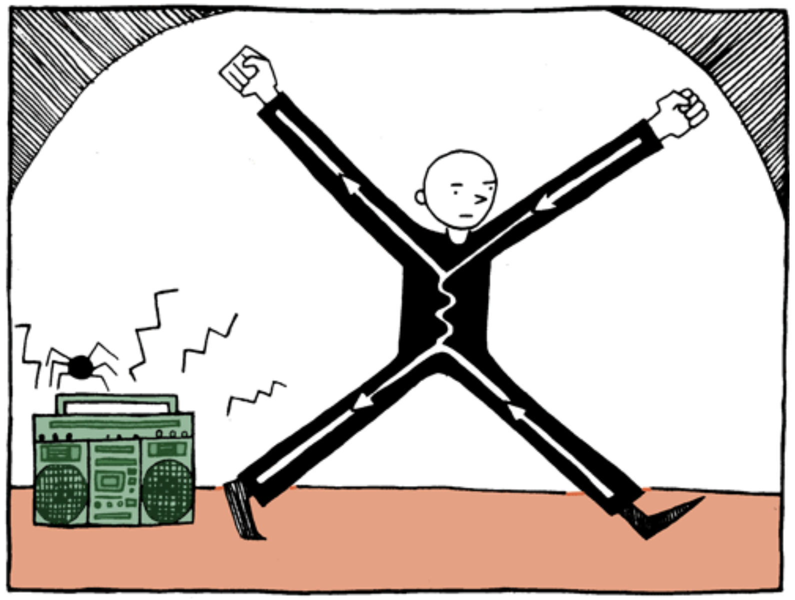
[Some slides courtesy of Prof. Anna Kaczmarska (IFJ PAN)]

Iwona Grabowska-Bołd
Department of Interactions and Particle Detection AGH UST
email: Iwona.Grabowska-Bold@fis.agh.edu.pl
https://sites.google.com/view/iwonagrabowska-bold

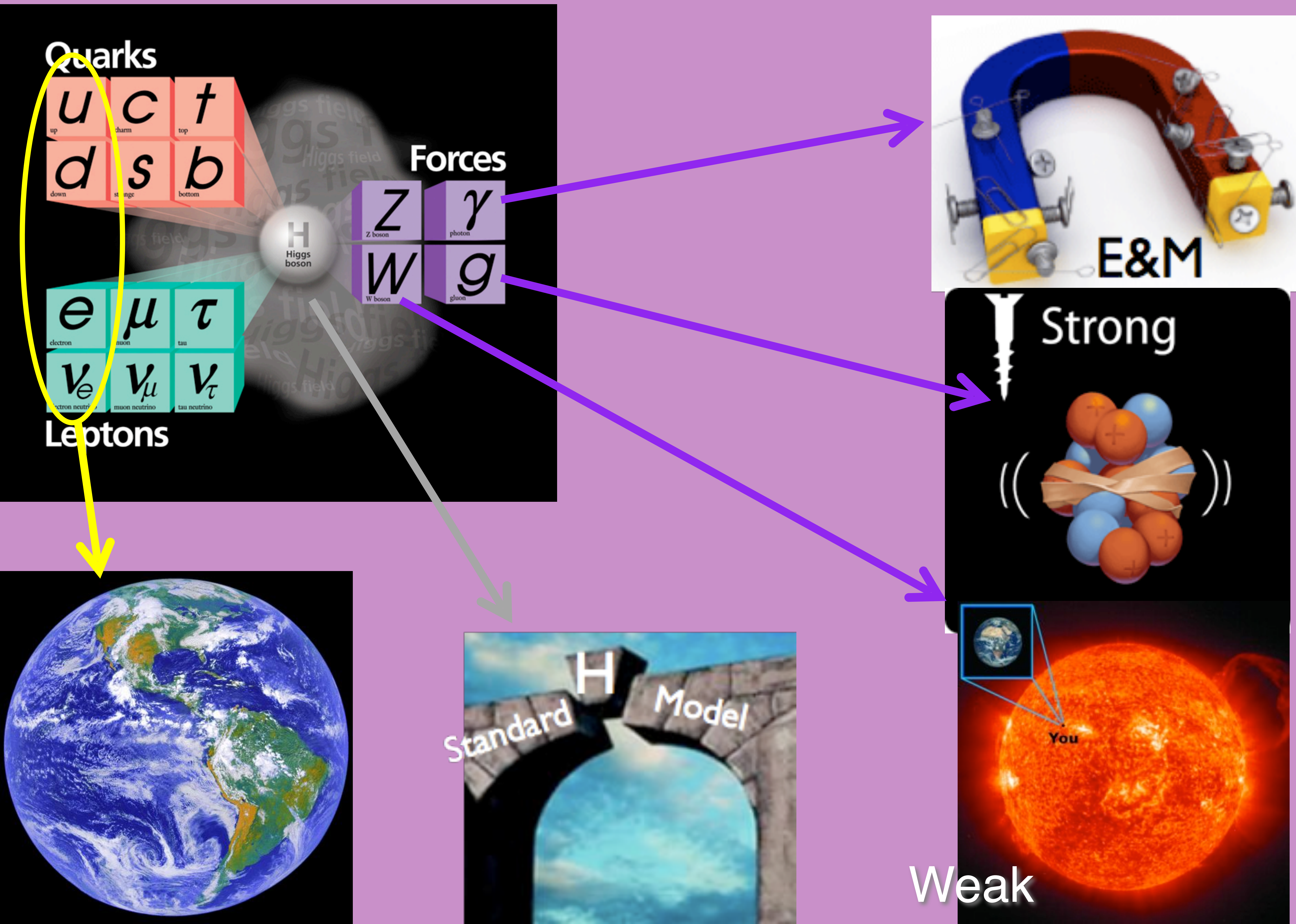
CONTENT



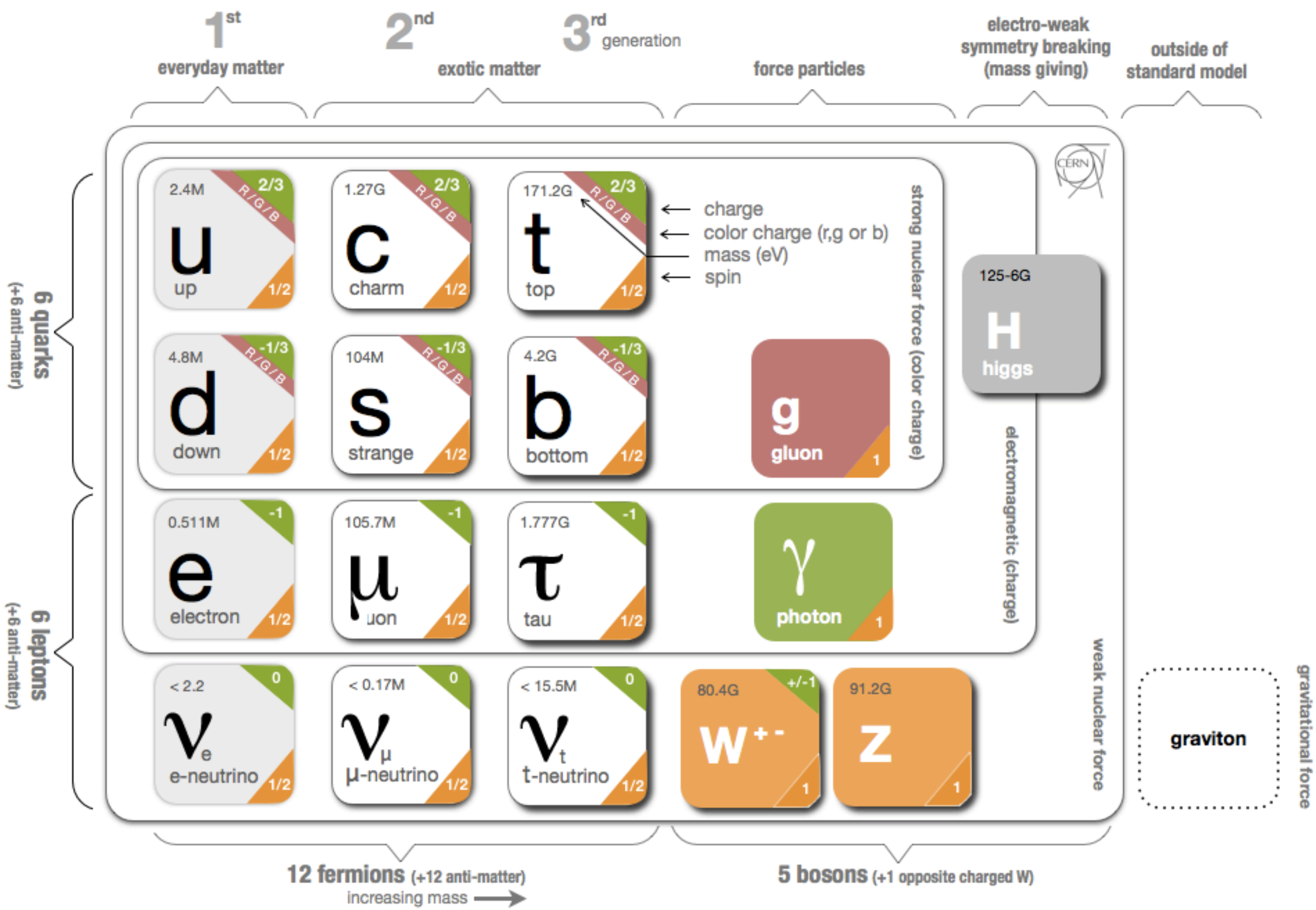
1. Standard Model: particles and interactions
2. Useful tool for HEP theory calculations
   - Feynman diagrams
3. Theory of electromagnetic interactions
4. Theory of strong interactions
   - A few features and examples



PARTICLES and INTERACTIONS

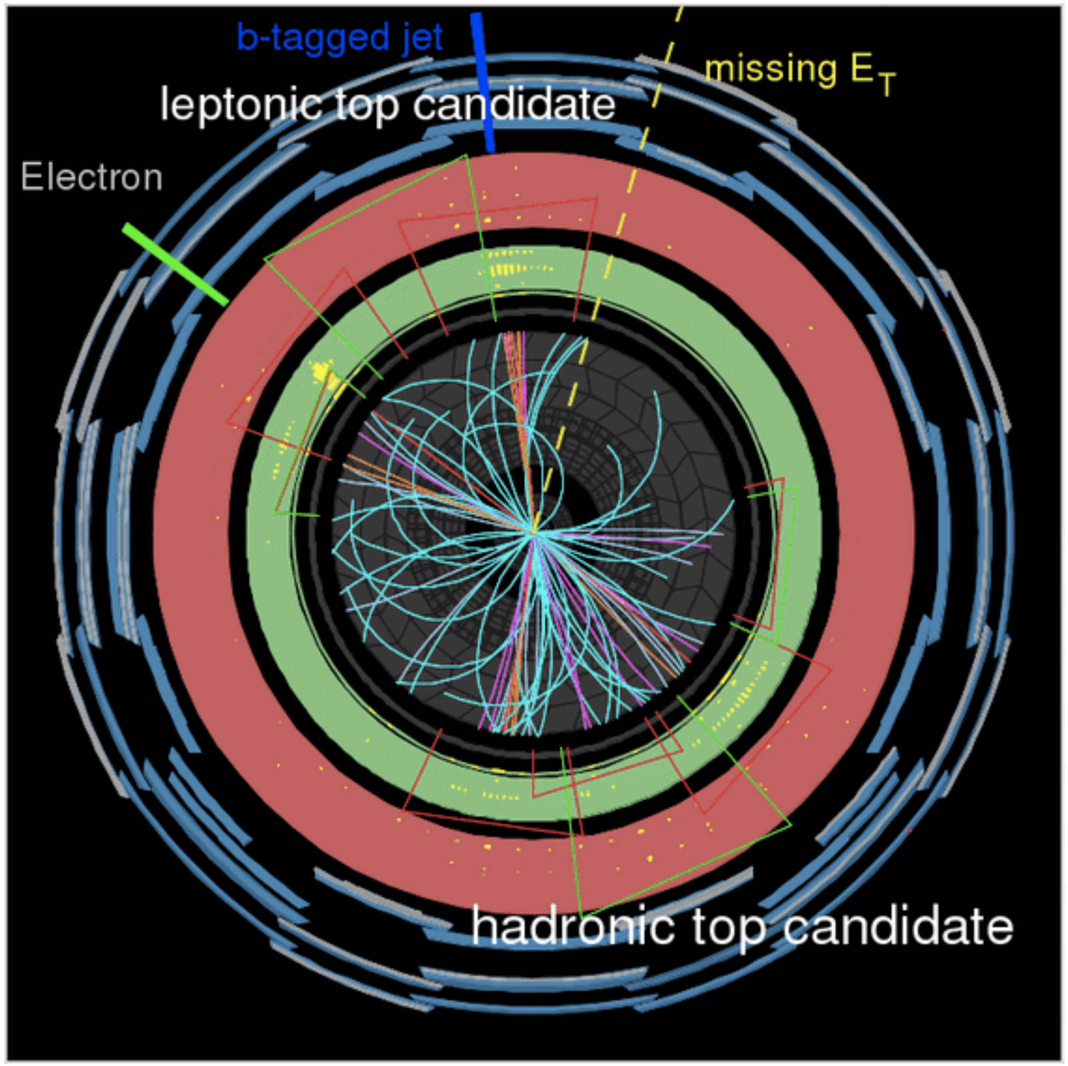


STANDARD MODEL



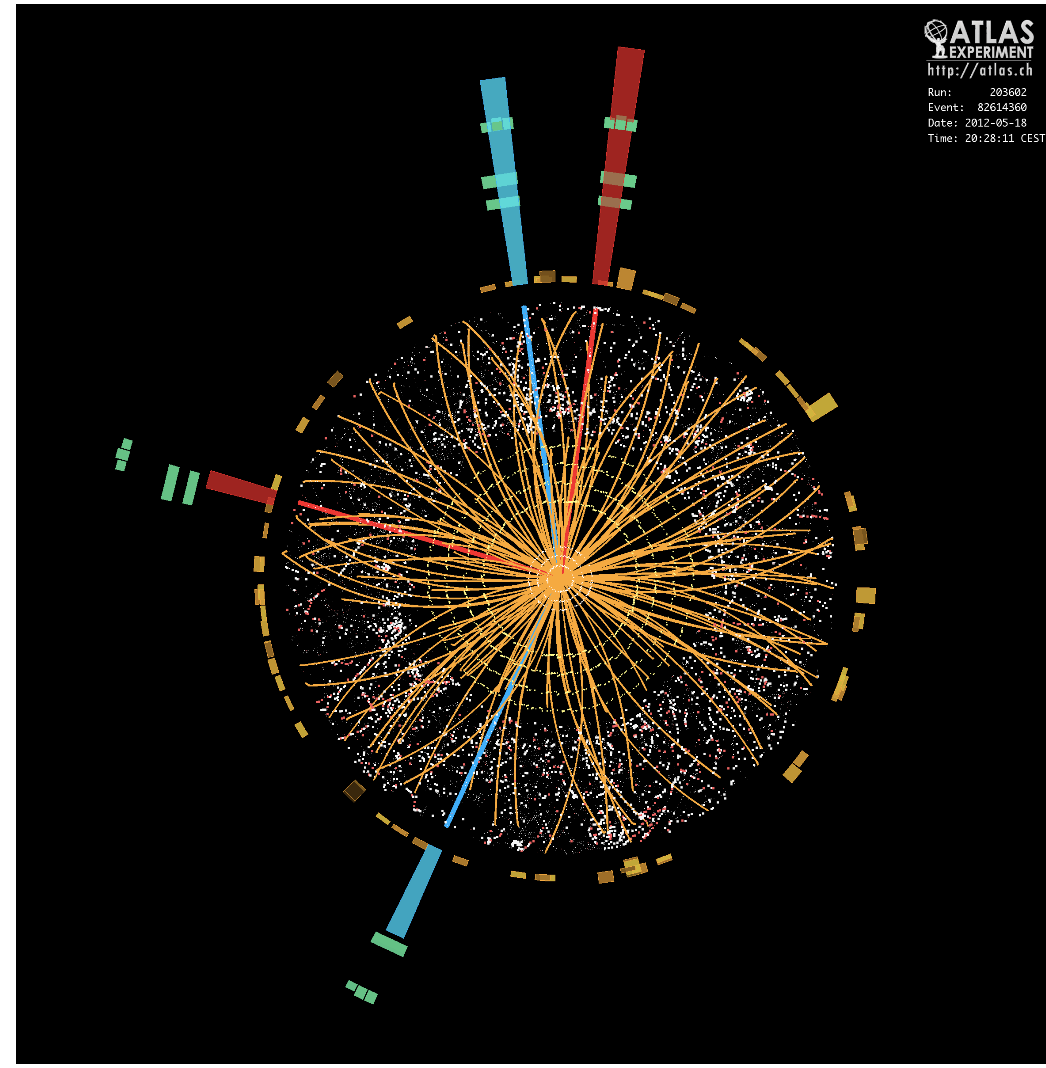
- Note: no gravity!
- Focus of this lecture: electromagnetic and strong interactions

EACH COLLISION IS DIFFERENT



$$p + p \rightarrow t\bar{t} + X$$

initial state final state



$$p + p \rightarrow H + X$$

initial state final state

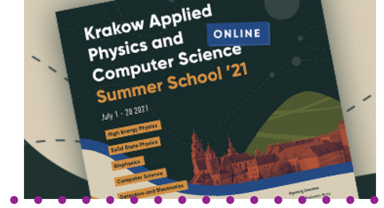
- Each collision is different at the LHC
- How do we understand what happened in the collision?

TRANSITION PROBABILITY AND FEYNMAN DIAGRAMS

- Reactions (e.g $ab \rightarrow cd$) have transition probability
  - how likely a particular initial state will transform to a specified final state
- If we want to calculate the transition rate between initial state and final state, we use **Fermi's Golden Rule**

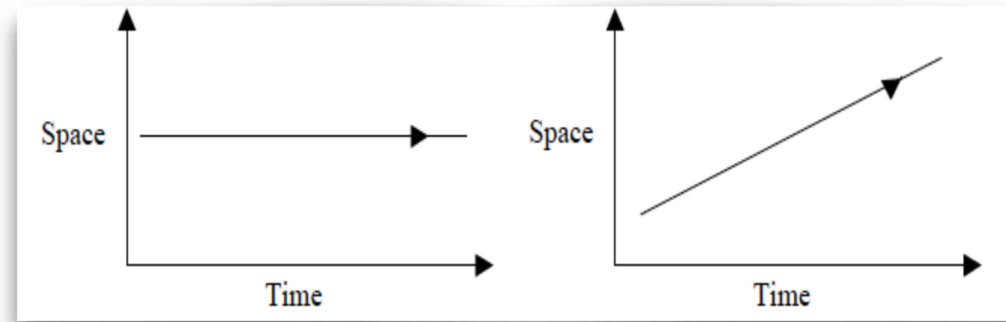
$$\text{transition rate} = \frac{2\pi}{\hbar} |M|^2 \times (\text{phase space})$$

- **The amplitude M** (or matrix element) for the process contains all the dynamical information. It is essentially the probability for the process to occur
- **The phase-space factor** is purely kinematic and it depends on the masses, energies and momenta of the participants
- The Golden Rule is the prescription for calculating decay and scattering rates
- In most cases $|M|^2$ cannot be calculated exactly
- Often M is expanded in a power series
- Feynman diagrams are pictorial representations of terms in the series expansion of M
- Every line in the diagram has a strict mathematical interpretation

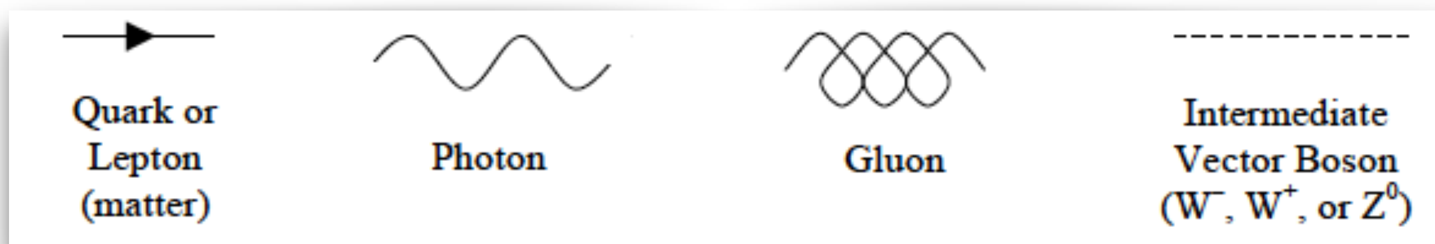


FEYNMAN DIAGRAMS – KEY CONCEPTS

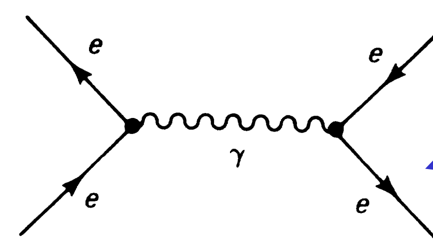
- To make a Feynman diagram, you plot time on the horizontal axis and position on the vertical axis
- This is called a space-time diagram



- We use the following symbols in Feynman diagrams:

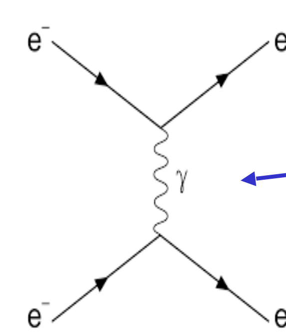


- **Annihilation diagram**: note that the arrow on the bottom is supposed to be backwards. We do that any time we have an antiparticle
- **Scattering diagram**: two electrons coming towards each other then repelling each other through the EM force via exchange of a virtual photon. Virtual photon exists for an instant of time - there is no movement in time (horizontal) axis



Real particles
"on the mass shell"

$E^2 = m^2 + p^2$



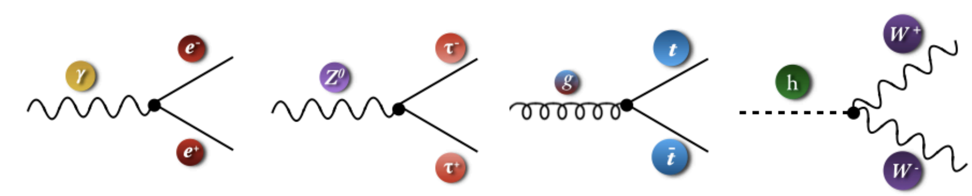
Virtual particles
"off the mass shell"

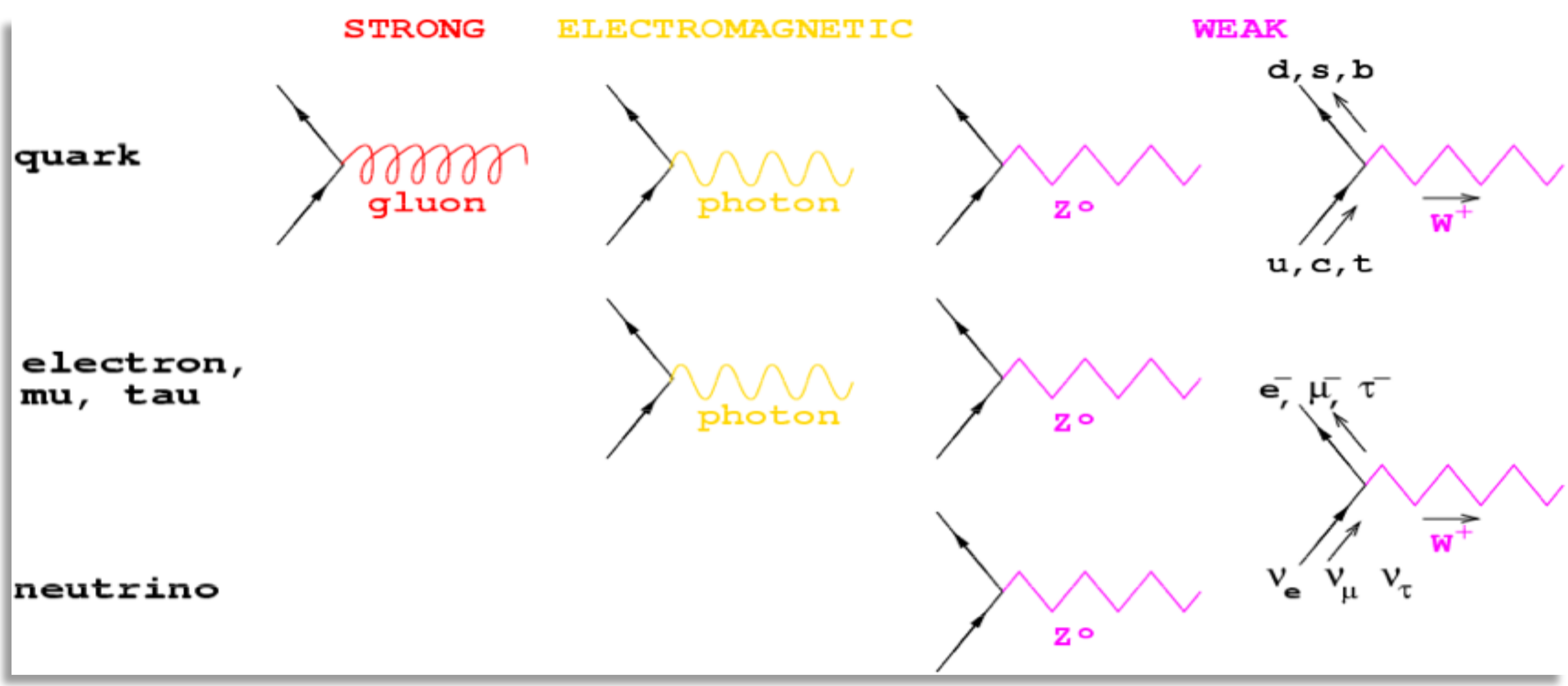
$E^2 \neq m^2 + p^2$

FEYNMAN DIAGRAMS – VERTICES

- Diagrams consist of **lines** representing particles and **vertices** where particles interact
- Quantum numbers are conserved at a vertex e.g. electric charge, lepton number, also E and p are conserved
- "Virtual" particles do not conserve E, p
  - virtual particles are internal to diagram(s) (propagators)
  - in all calculations we integrate over the virtual particles 4-momentum (4d integral)
- To calculate the contribution to **M**, for each vertex we associate a vertex factor → coupling constant $\sqrt{\alpha}$, e.g. for EM interaction α= 1/137=fine structure constant

A Few Allowed Vertices

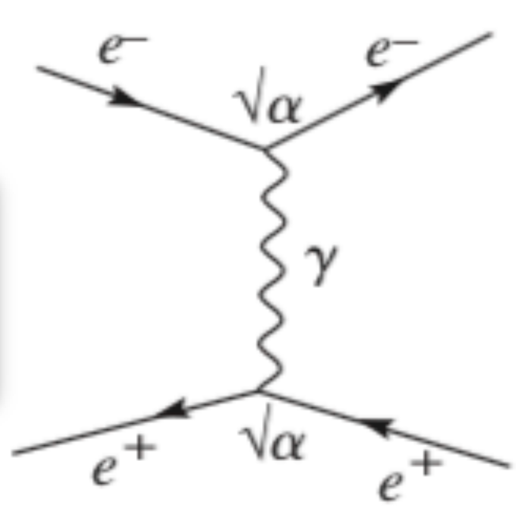


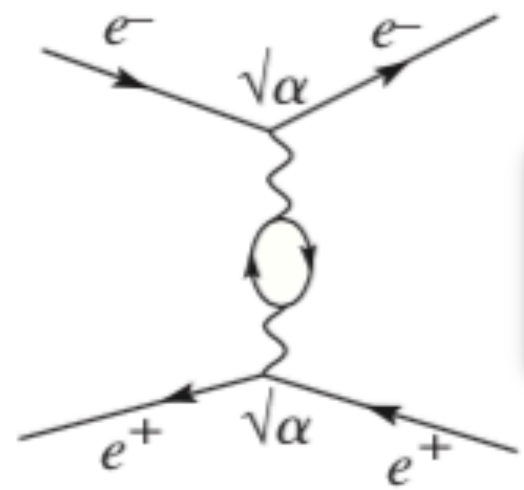


ORDERING OF ALPHA

- We classify diagrams by the order of **the coupling constant**
- Example: Bhabha scattering $e^+e^- \rightarrow e^+e^-$

Amplitude is of order α (1/137)
LO – leading order





Amplitude is of order α^2 ($[1/137]^2 \sim 5*10^{-5}$)
NLO – next-to- leading order

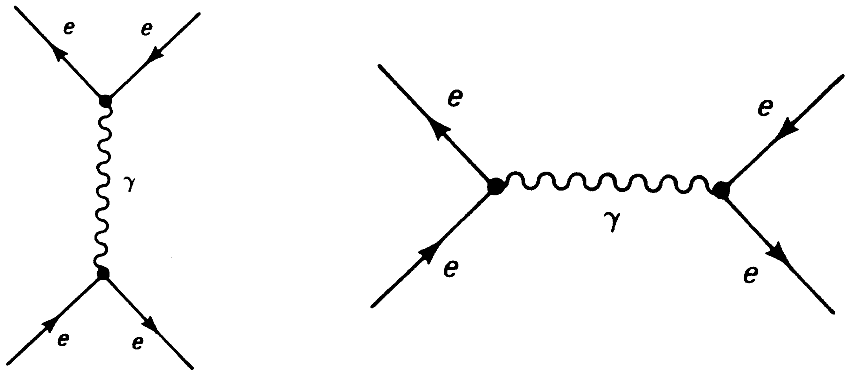
- Since $\alpha_{QED} = 1/137$ higher order diagrams should be corrections to lower order diagrams
- **This is just a Perturbation Theory!!!**
- Higher precision needed? More (higher order) diagrams have to be considered
  - This expansion in the coupling constant works for QED since $\alpha_{QED} = 1/137$
  - Does not work well for QCD where $\alpha_{QCD} \approx 1$

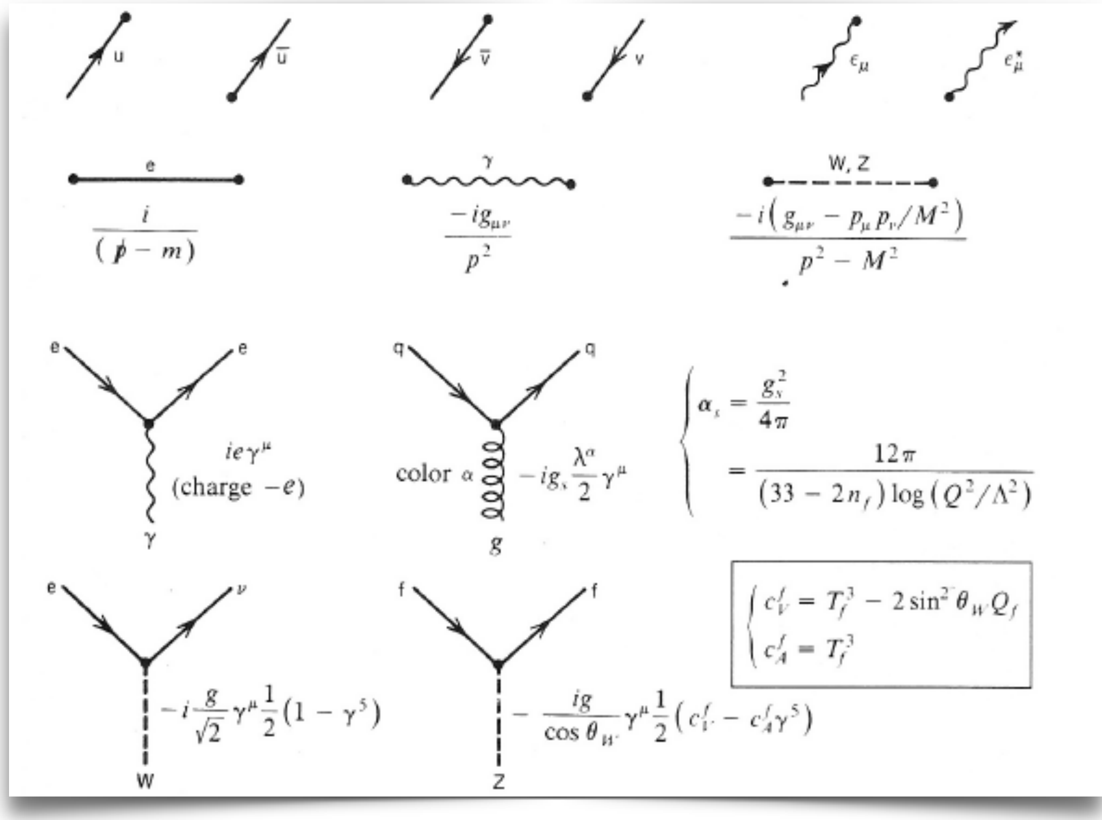
FEYNMAN DIAGRAMS – CALCULATIONS

Recipe for calculations:

- **Draw all possible diagrams for initial- and final-state particles configuration**
  - For a given order of the coupling constant there can be many diagrams
- **Calculate amplitude M_i for each diagram and add them**
  - Transition amplitudes (matrix elements) must be summed over indistinguishable initial and final states
  - Amplitudes can interfere constructively or destructively
- **Take modulo from that sum and square it**
- **Use Fermi's Golden Rule to calculate cross section of the process**

Bhabha scattering: $e^+e^- \rightarrow e^+e^-$

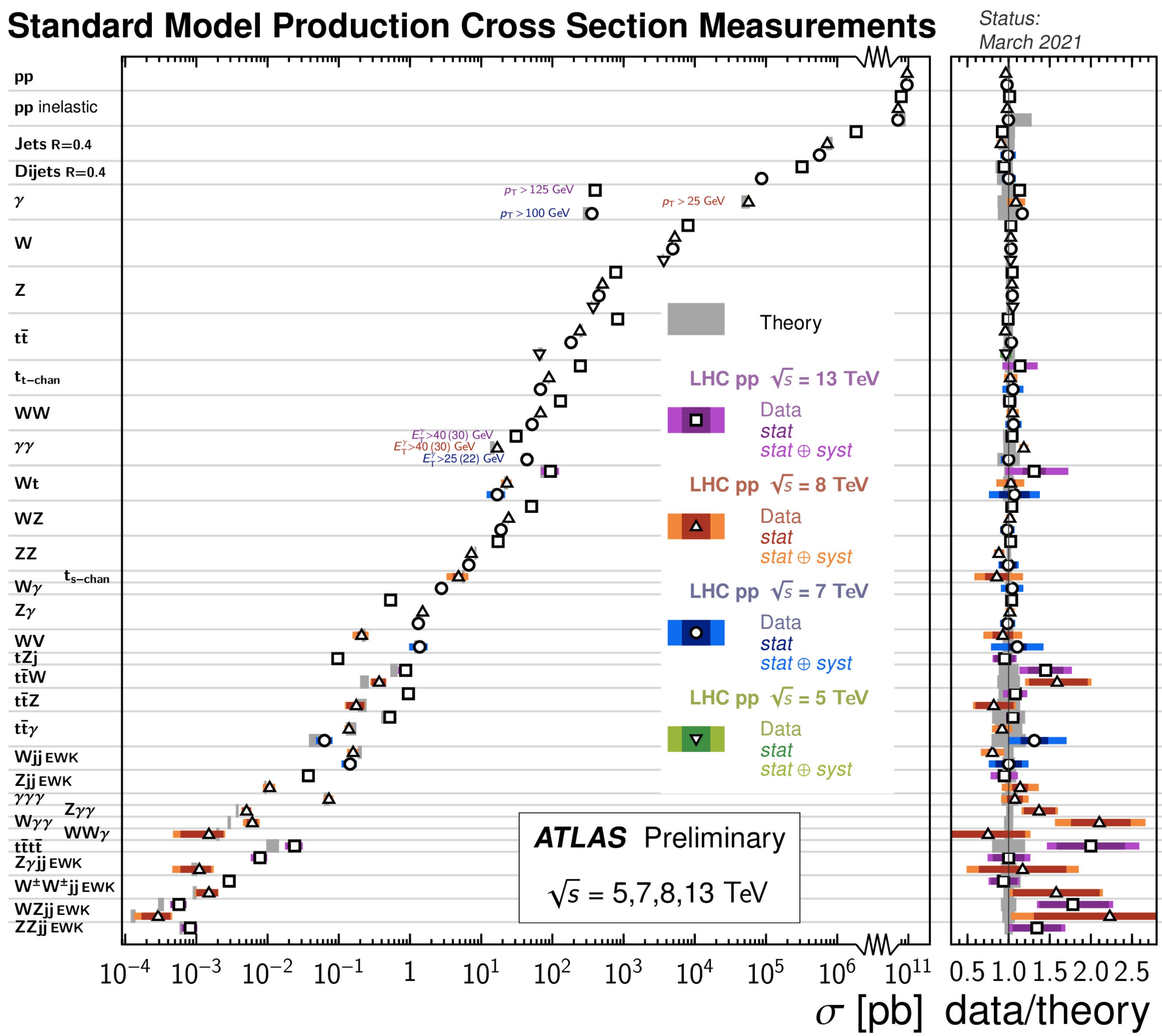




- Normally, a full matrix element contains an **infinite** number of Feynman diagrams
- In practice, we will only consider the lowest order contributions to processes

THEORY VERSUS MEASUREMENT

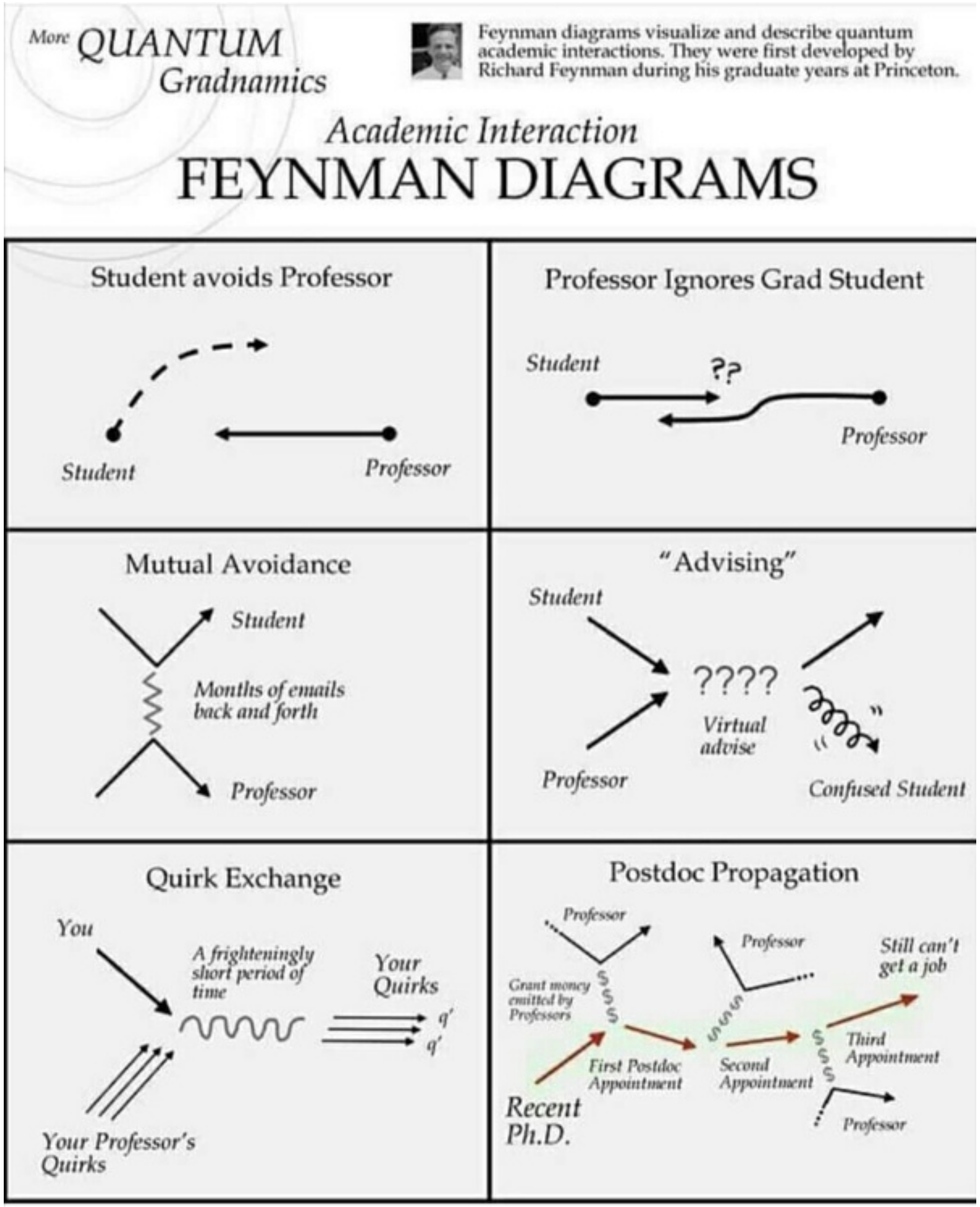
very abundant processes



very rare processes

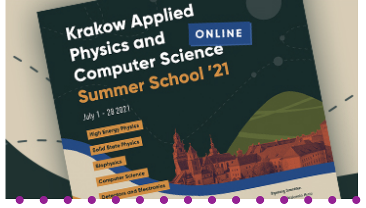
- Transition rate is represented by a cross section σ in the measurement
- X axis spans over 15 orders of magnitude
- Excellent agreement between data and theory predictions

EXAMPLE: STUDENT AND SUPERVISOR

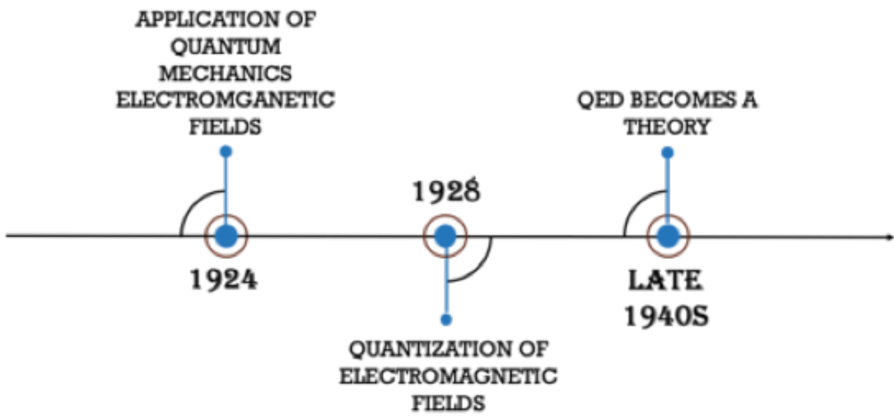


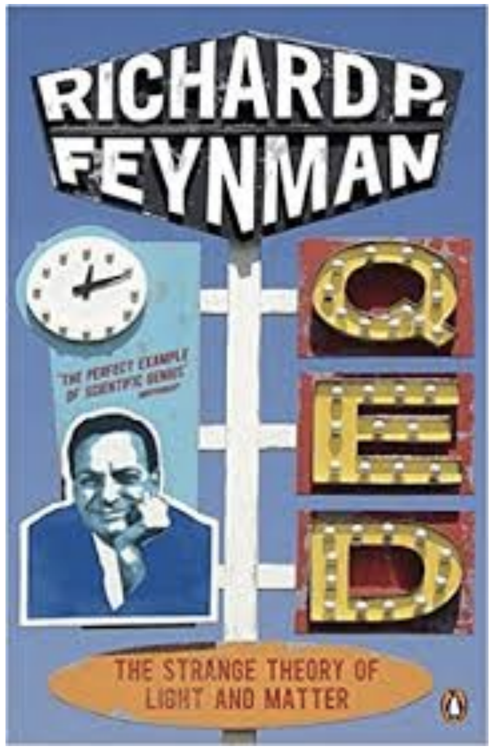
- I wish none of those gets realised in this school

QUANTUM ELECTRODYNAMICS (QED)

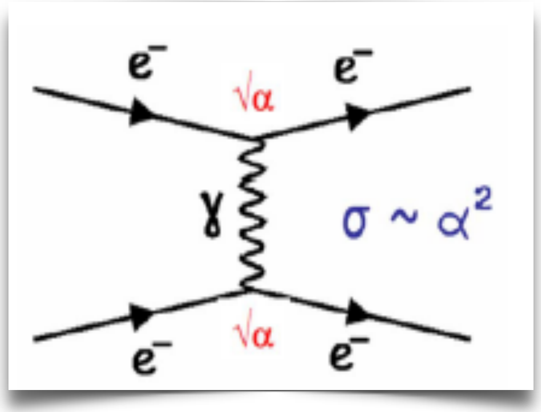


- First quantum field theory was **Quantum Electrodynamics (QED)**, the theory of interacting **electrons** (charged particles) and **photons**, developed in 1930s
- QED is a perturbation theory ($\alpha = 1/137$) - the basic calculation method uses Feynman diagrams
- Each vertex of Feynman diagram represents emission or absorption of a photon
- Examples of important QED processes:





Rutherford scattering – Coulomb scattering by one photon exchange: $e^-e^- \rightarrow e^-e^-$

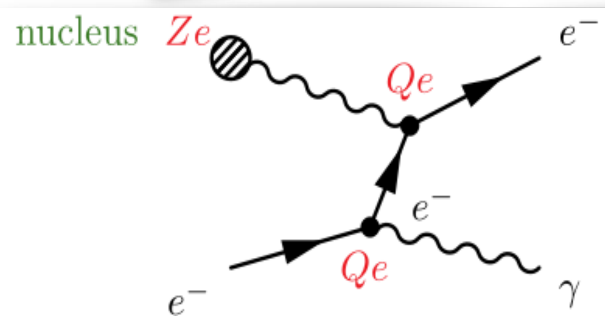


Contribution to M:

- Vertices ~ $\sqrt{\alpha}\,\sqrt{\alpha} = \alpha$
- Photon propagator ~ $1/q^2$
- M ~ α/q^2
- Differential cross section $d\sigma/dq$ ~ M^2 ~ α^2/q^4

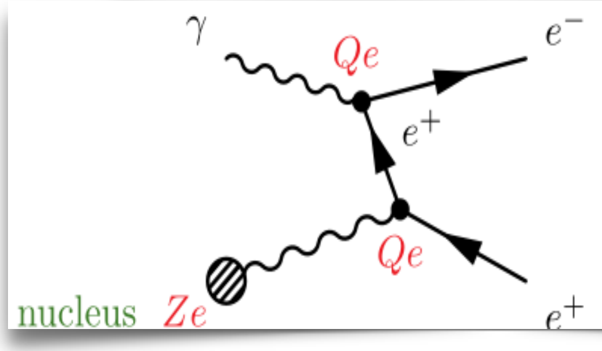
$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} = \frac{1}{137}$$

Bremsstrahlung: $e^- \rightarrow e^-\gamma$



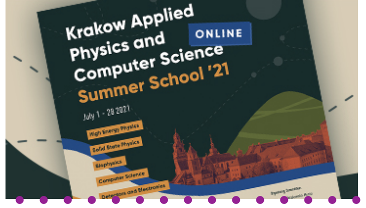
$$M \propto Ze^3$$
$$\sigma \propto |M|^2 \propto Z^2e^6 \propto (4\pi)^3 Z^2\alpha^3$$

Pair Production: $\gamma \rightarrow e^+e^-$

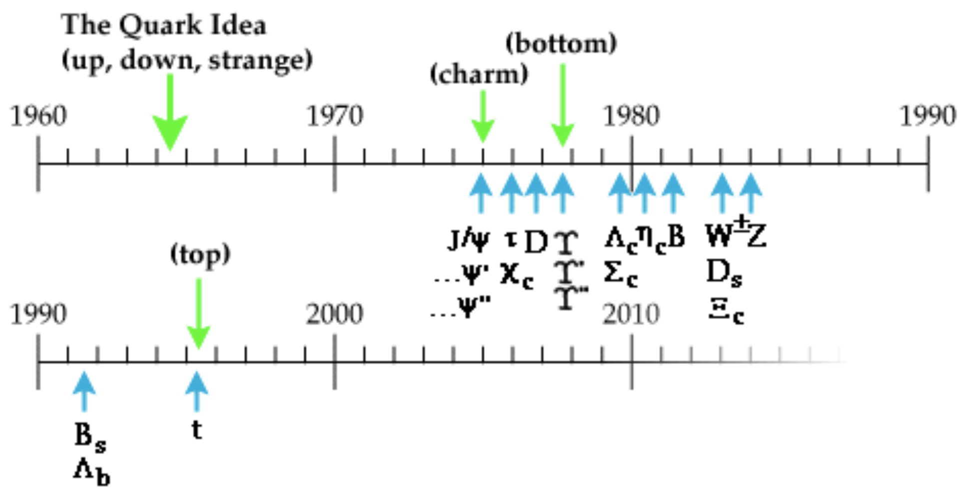


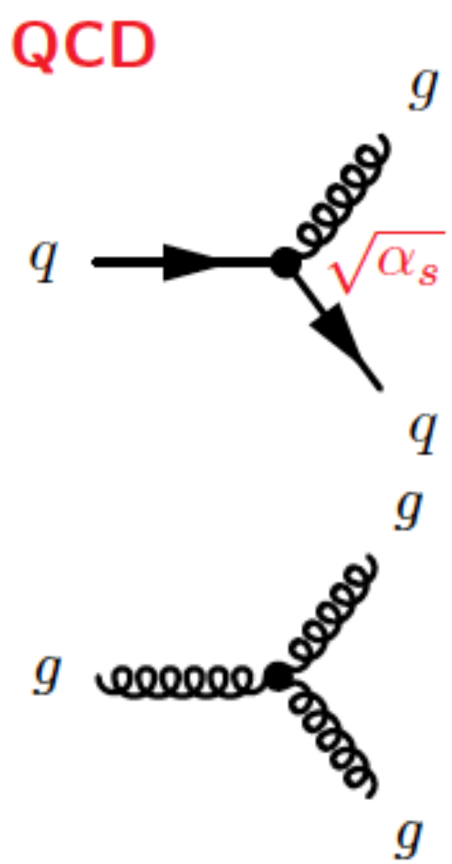
$$M \propto Ze^3$$
$$\sigma \propto |M|^2 \propto Z^2e^6 \propto (4\pi)^3 Z^2\alpha^3$$

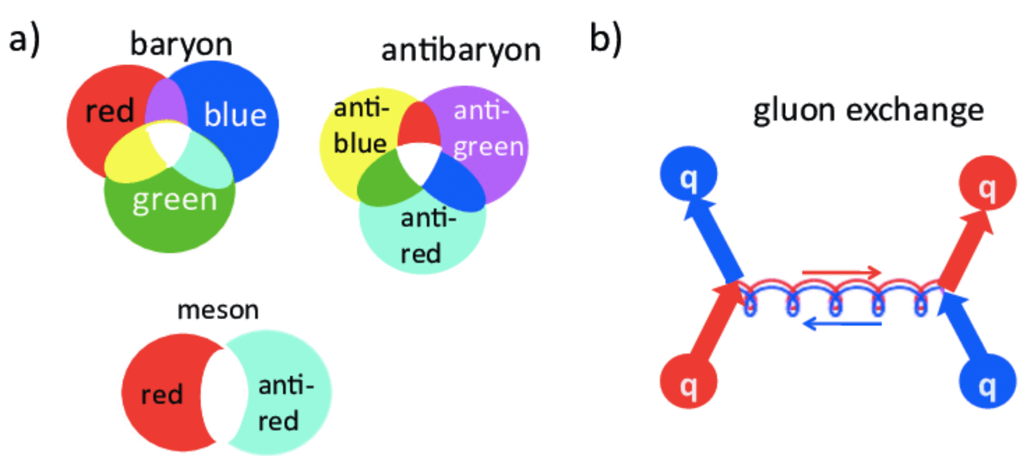
QUANTUM CHROMODYNAMICS (QCD)



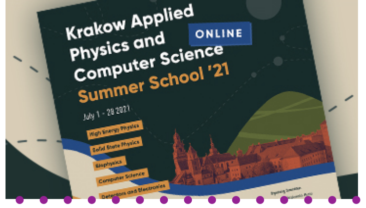
- In **the 70s**, physicists (Gross, Politzel, Wilczek) developed a theory of the strong interaction - **Quantum Chromodynamics (QCD)**
- Properties of QCD:
  - Describes the interaction of quarks with the particle responsible for the strong interaction: massless spin-1 gluons
  - Charge responsible for this interaction is called colour
  - Gluons couple only to objects that have "colour": quarks and gluons
  - There are three different charges ("colours"): red, green, blue
    - Note: in QED there is only one charge (electric)
  - Gluon can change the colour of a quark but not its flavour
    - Example: red u-quark can become a blue u-quark via gluon exchange
  - Gluons can interact with other gluons
  - Both gluons and photons are massless thus a range of strong/EM force should be ∞
    - But it is ~ 1 fm!







EXAMPLE: BARYONS



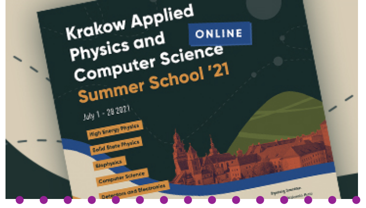
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{p}$	antiproton	**$\bar{u}\bar{u}\bar{d}$**	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Baryons consist of three quarks which add up to a colour-neutral state

Quarks carry fractional charge: u: +2/3, d: -1/3

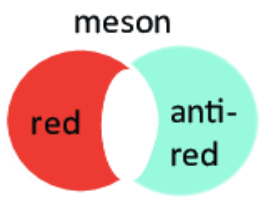
EXAMPLE: MESONS

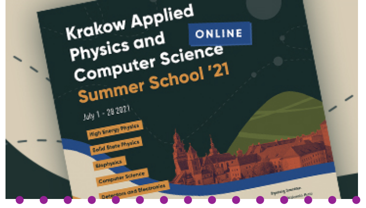


Mesons $q\bar{q}$ Mesons are bosonic hadrons These are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Mesons consist of quark and anti-quark pairs which add up to a colour-neutral state

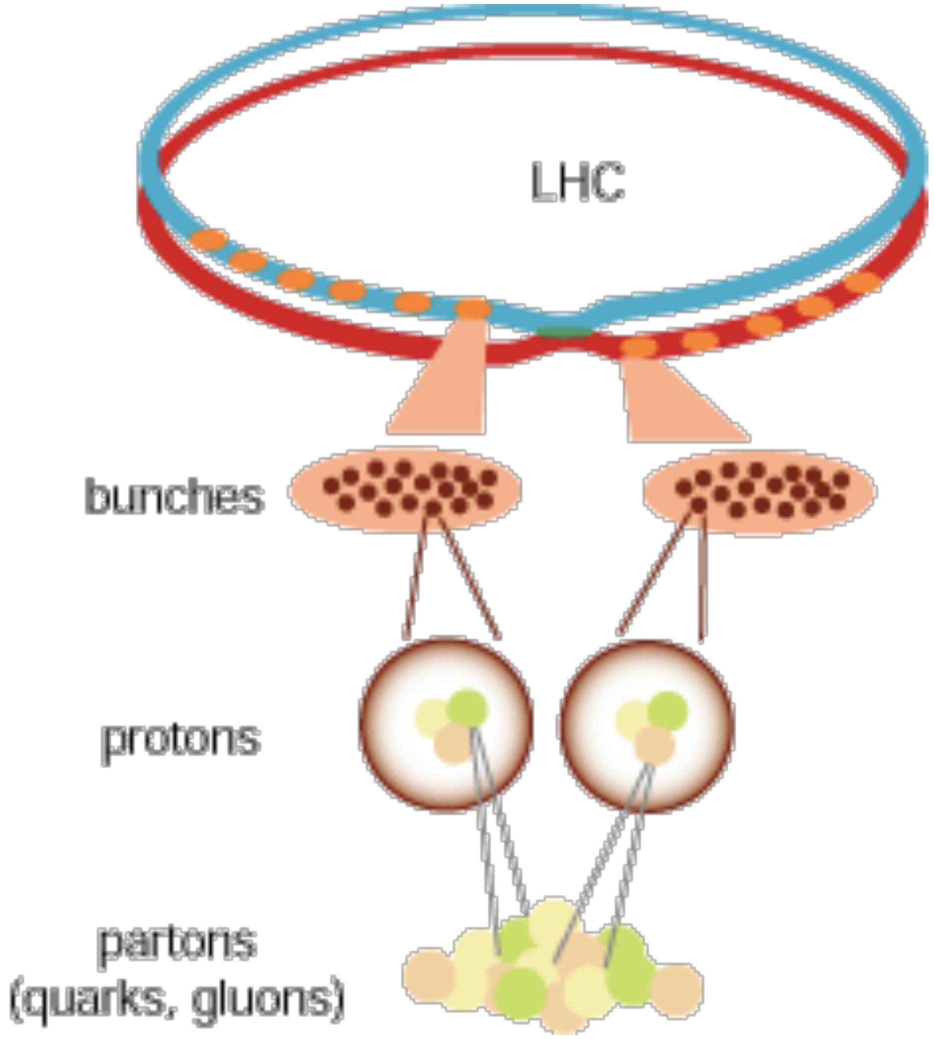
Quarks carry fractional charge: u: +2/3, d: -1/3

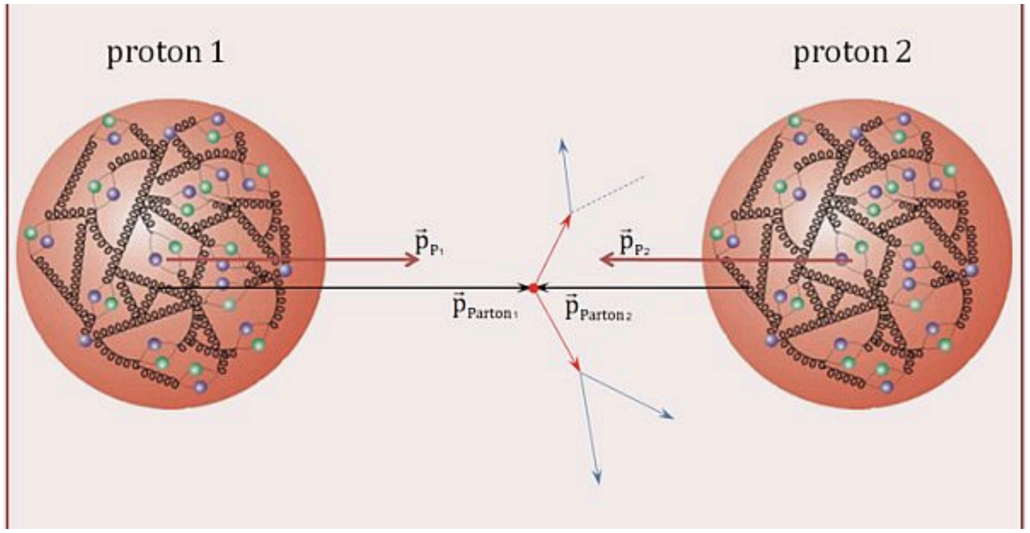




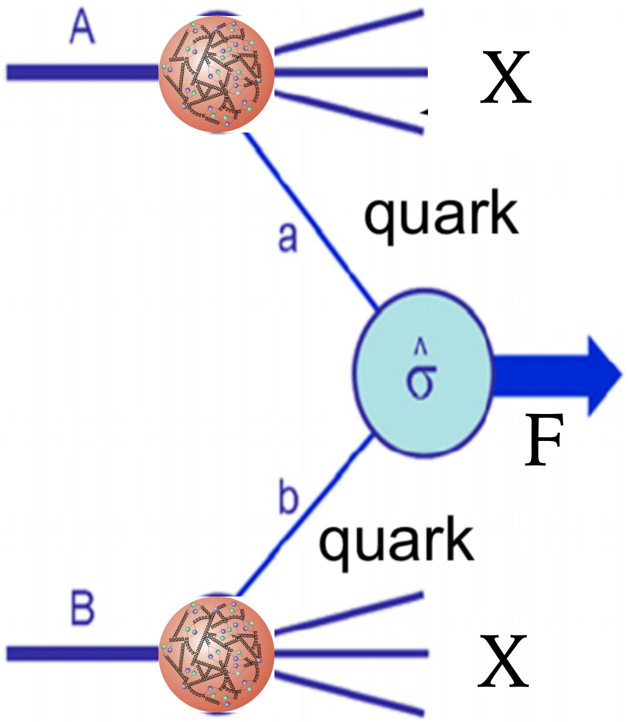
HOW CAN WE TEST QCD?

- At the LHC protons are grouped in bunches: 2808 in each beam
- Number of turns per second: 11 245
- Number of protons per bunch: 1.1×10^{11}
- Protons are baryons, complex particles: three quarks each





DEEPER INTO THE COLLISION

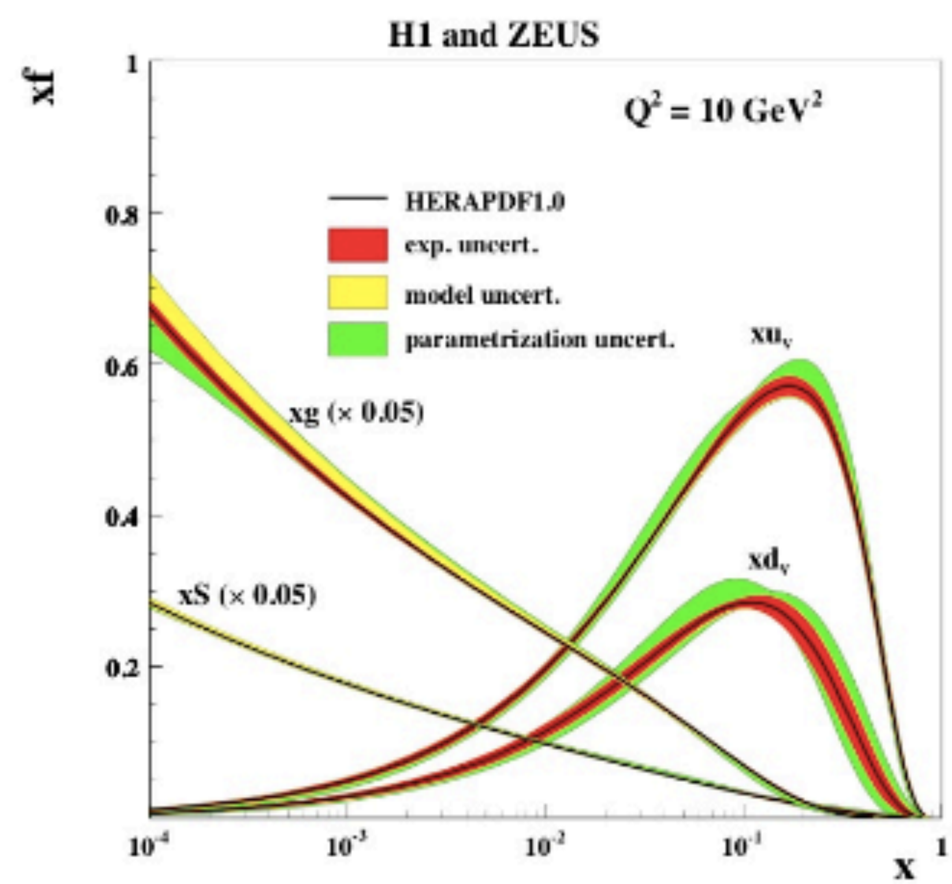


- X - the inclusive remnant
- F - the relevant final state
- a,b - partons (quarks/gluons) inside A, B (protons at the LHC)

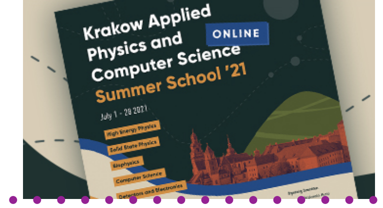
- Cross section

$$\sigma(AB \to FX) = \sum_{a,b} \int dx_1 dx_2 P_a(x_1, Q) P_b(x_2, Q) \hat{\sigma}(ab \to F)$$

- $dxP_{a/b}(x, Q)$ - probability of finding the parton a/b inside A/B with fractional momentum between *x* and *x+dx* at a scale Q
- $P_{a/b}(x, Q)$ - fitted/measurable: Parton Distribution Function (PDF)
- $\hat{\sigma}(ab \to F)$ - calculable as if a/b were free quarks (gluons) if no small momenta in the process $ab \to F$

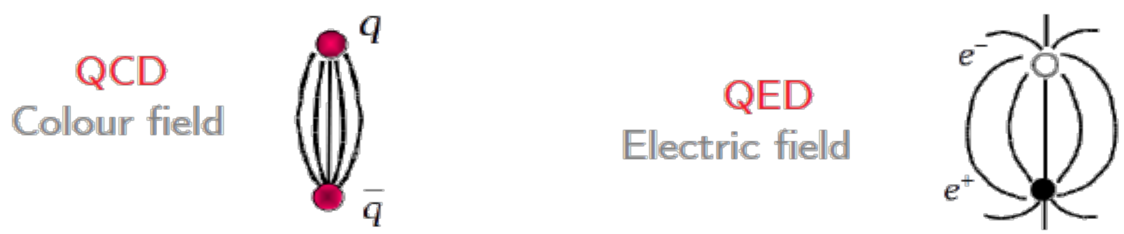


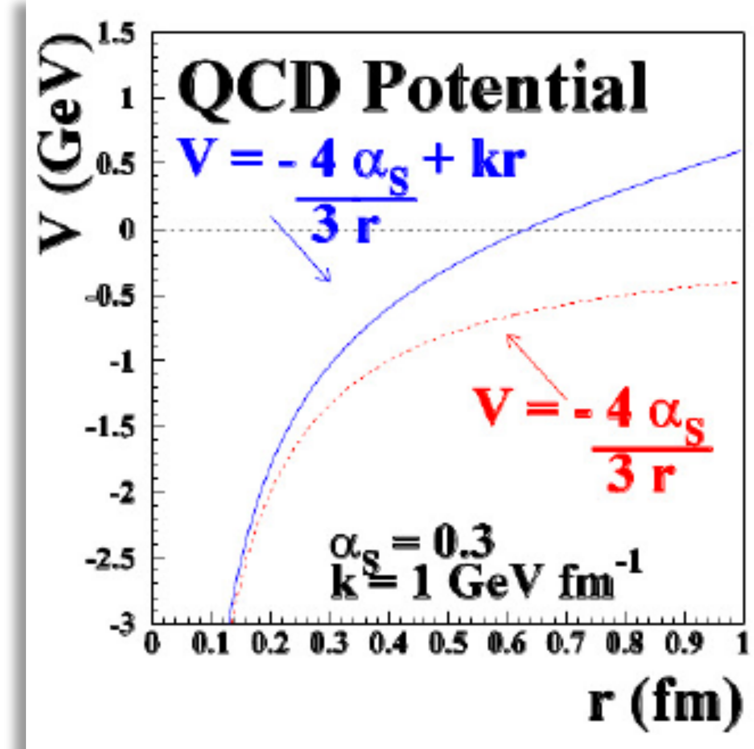
Measured PDF



HOW STRONG IS STRONG?

- QCD potential between quark and anti-quark has two components:
  - Short range, Coulomb-like term: $-4/3\ \alpha_S/r$
  - Long range, linear term: $+kr$, with k ~ 1 GeV/fm





- Self interactions of the gluons squeeze the lines of force into a narrow tube/string of approximately constant energy density (~ 1 GeV/ fm)
- The string has a "tension" and as the quarks separate the string stores potential energy
- Energy required to separate two quarks is infinite
  - Quarks always come in combinations with zero net colour charge => **Confinement**

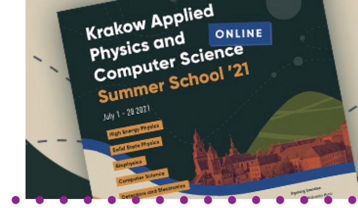
$$F = -\frac{dV}{dr} = \frac{4\alpha_s}{3\,r^2} + k$$

at large r

$$F = k \sim \frac{1.6 \times 10^{-10}}{10^{-15}}\,\mathrm{N} = 160{,}000\,\mathrm{N}$$

Equivalent to weight of ~150 people

HADRONISATION AND JETS



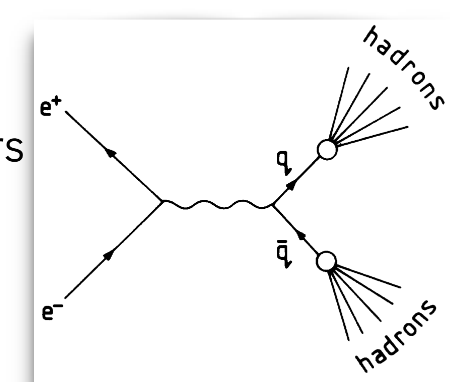
- What happens when we try to pull apart two quarks?
- Imagine q - anti-q produced at same point in space with very large momentum. They fly apart:

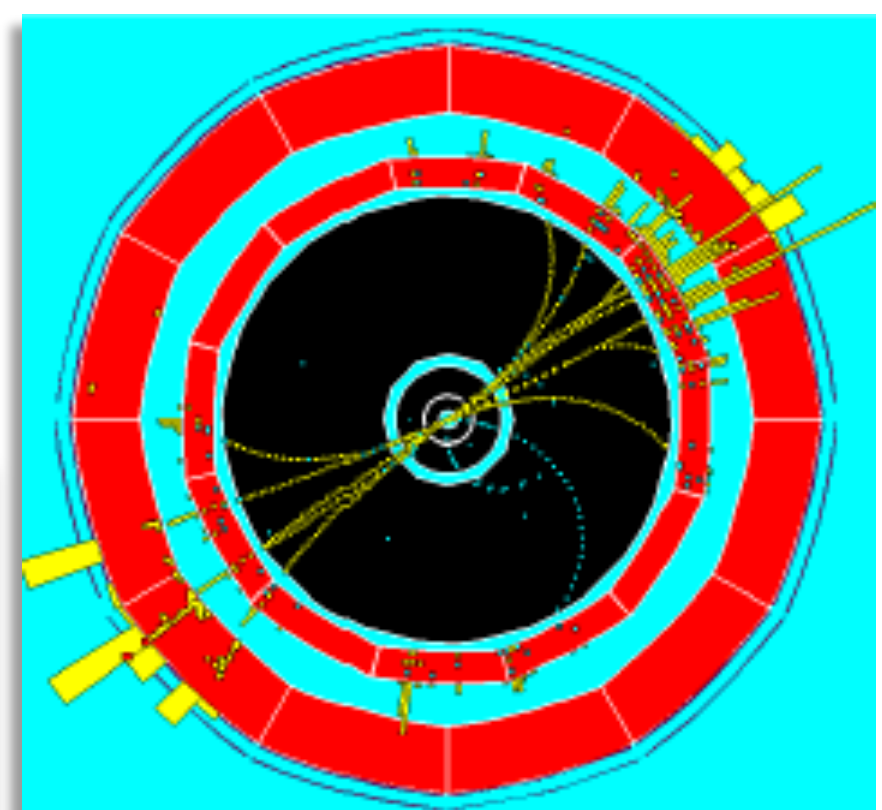
- The energy between the q- anti-q increases as they move apart E~V(r)~kr

- When E > 2 $m_q c^2$... (breaking of a “string”)

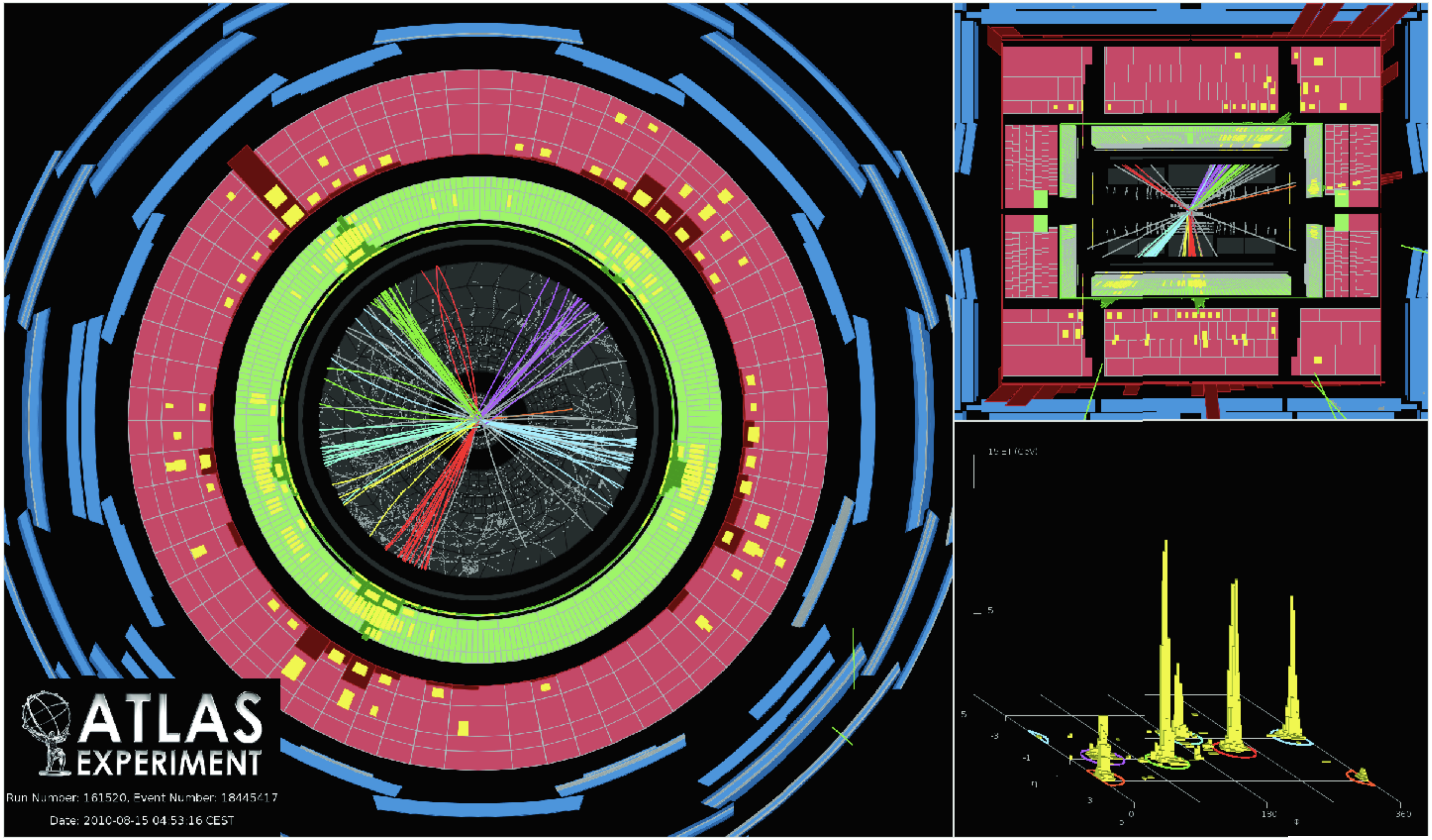
- As the kinetic energy decreases ... the hadrons freeze out

- This process is known as **hadronisation**
  - For quarks created with high energy start out with quarks and end up with narrowly collimated jets of hadrons
  - This is how we see quarks and gluons in our detectors

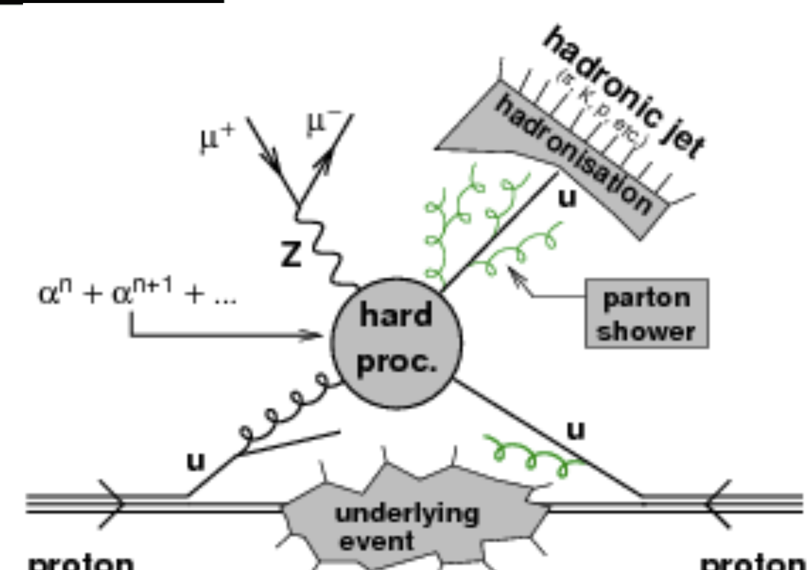




JETS AT THE LHC

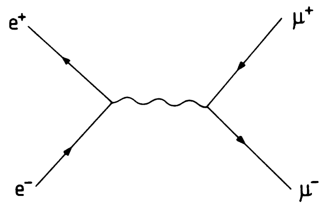


- Many jets detected in the detector in a single proton-proton collision



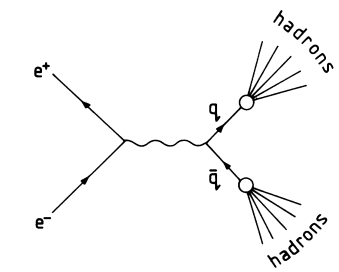
WHAT IS THE EVIDENCE FOR COLOUR?

- One of the most convincing arguments for colour comes from a comparison of the cross sections for two processes:



$$e^+e^- \to \mu^+\mu^-$$

$$e^+e^- \to q\bar{q}$$



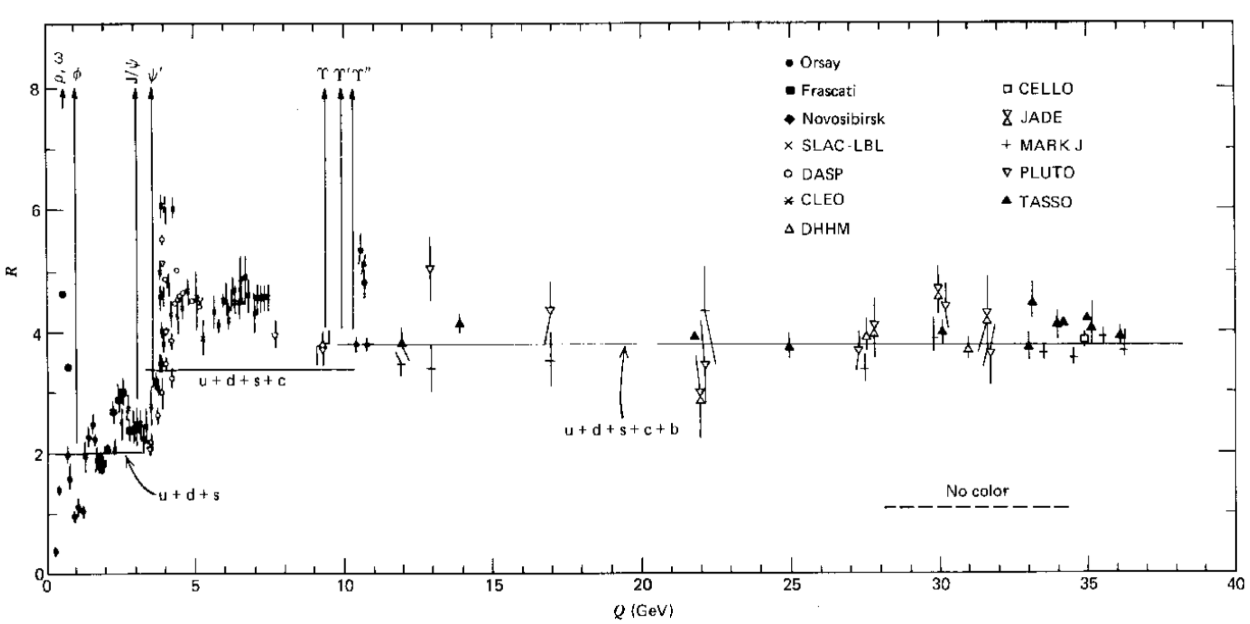
- If colour plays no role in quark production then the ratio of events should only depend on the charge (Q_i) of the quarks that are produced

$$R = \frac{N(e^+e^- \to q\bar{q})}{N(e^+e^- \to \mu^+\mu^-)} = \sum_{i=1}^{n} Q_i^2$$

- However, **if colour is important for** quark production then the above ratio should be multiplied by the number of colours (3)

$$R = \frac{N(e^+e^- \to q\bar{q})}{N(e^+e^- \to \mu^+\mu^-)} = 3\sum_{i=1}^{n} Q_i^2$$

- Agreement with e^+e^- colliders data under assumption of quark fractional-charge and 3 colours

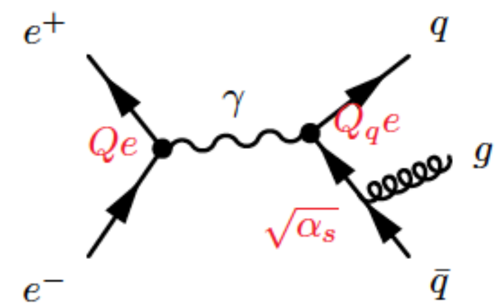


Energy	Ratio R	
$\sqrt{s} > 2m_s$ ~1 GeV	$3(\frac{4}{9}+\frac{1}{9}+\frac{1}{9})$ u,d,s	= 2
$\sqrt{s} > 2m_c$ ~4 GeV	$3(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}+\frac{4}{9})$ u,d,s,c	$= 3\frac{1}{3}$
$\sqrt{s} > 2m_b$ ~10 GeV	$3(..+\frac{1}{9})$ u,d,s,c,b	$= 3\frac{2}{3}$
$\sqrt{s} > 2m_t$ ~350 GeV	$3(..+\frac{4}{9})$ u,d,s,c,b,t	= 5

WHAT IS THE EVIDENCE FOR GLUONS?

- In QED, electrons can radiate photons. In QCD, quarks can radiate gluons

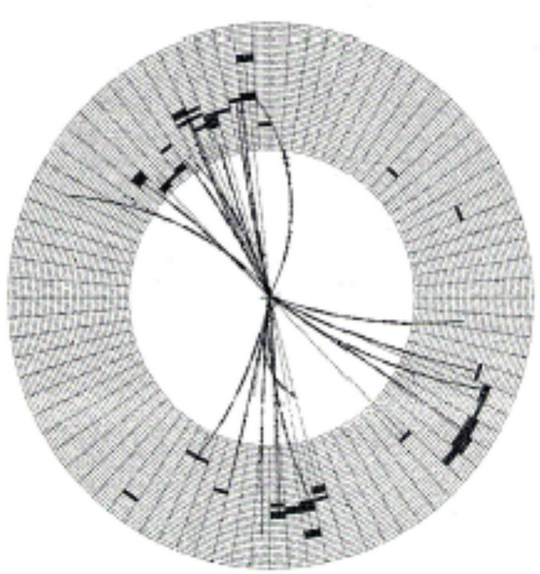
Example: $e^- e^+ \to q\bar{q}g$

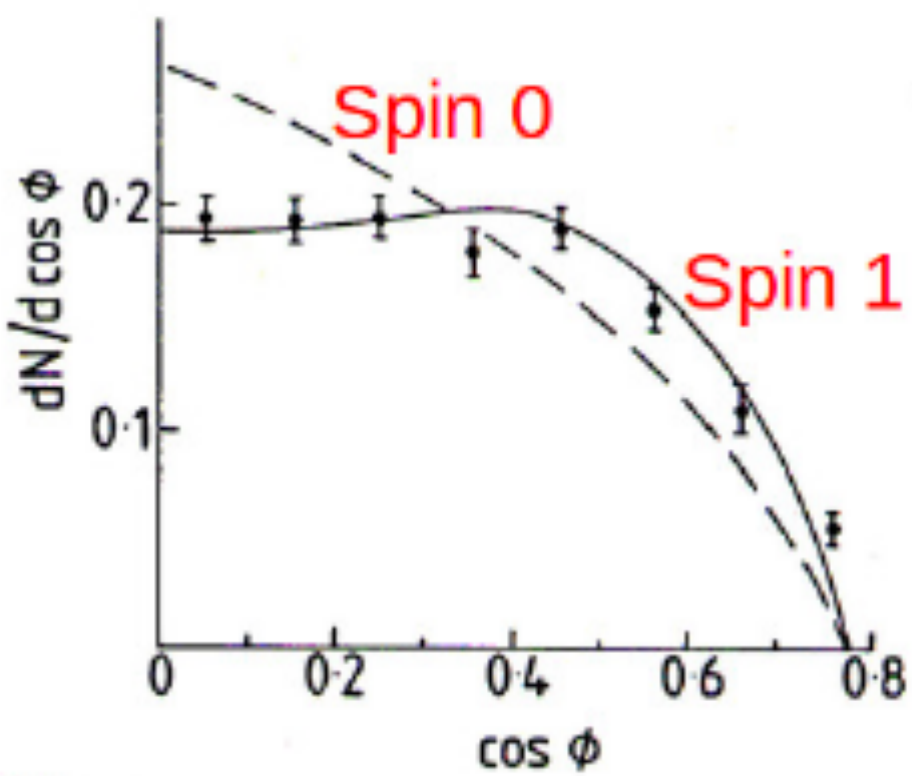


$$M \sim \frac{Q_q}{q^2}\sqrt{\alpha}\sqrt{\alpha}\sqrt{\alpha_s}$$

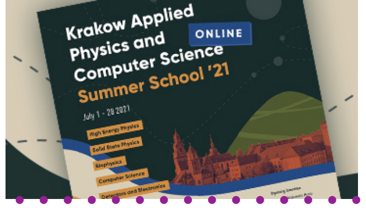
- In QED we can detect photons. In QCD, we never see free gluons due to **confinement**
- Experimentally, detect gluons as an additional jet: **3-jet events**
  - Angular distribution of gluon jet depends on gluon spin
  - Distribution of the angle, ϕ, between the highest energy jet (assumed to be one of the quarks) relative to the flight direction of the other two (in their cm frame). Distribution depends on the spin of the gluon => **Gluon is spin 1**

JADE event $\sqrt{s} = 31$ GeV
First direct evidence of gluons (1978)

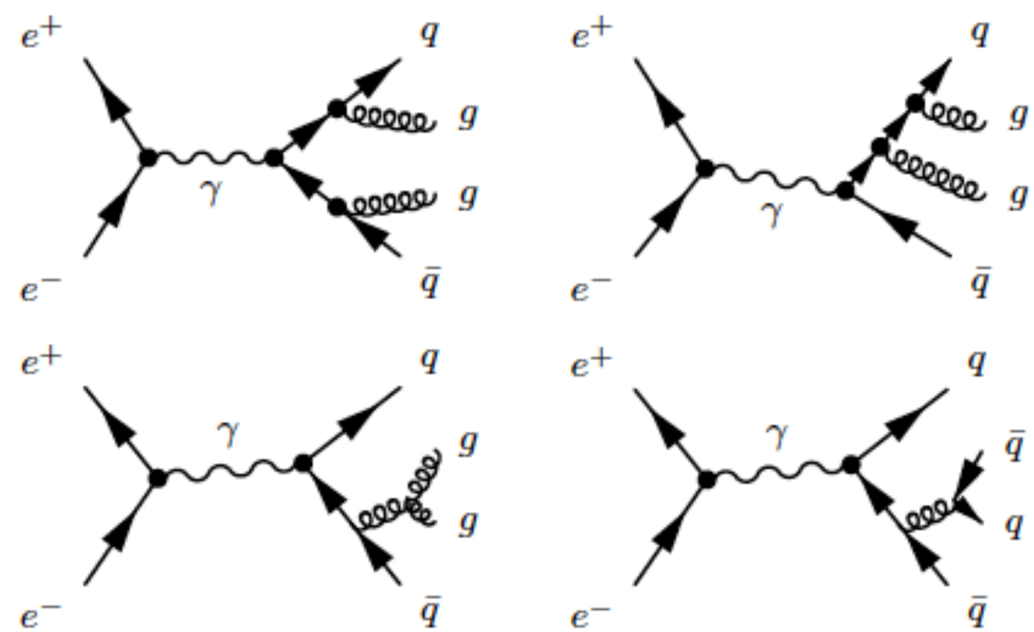


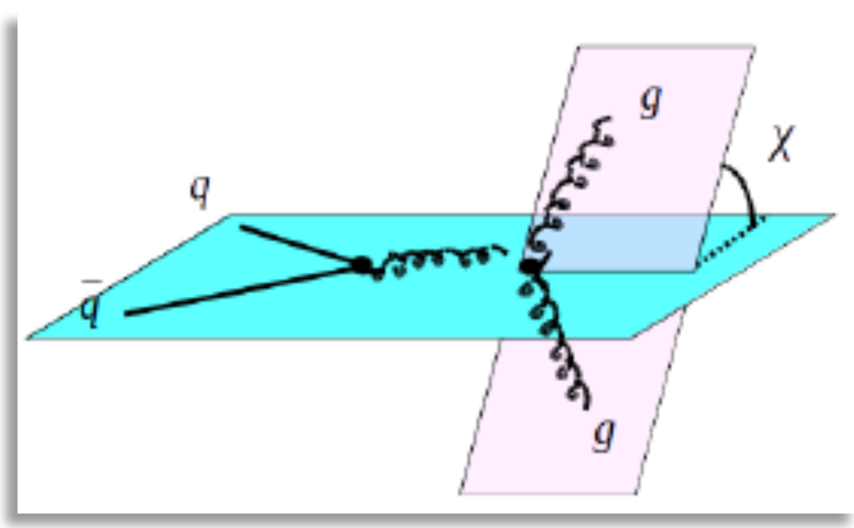


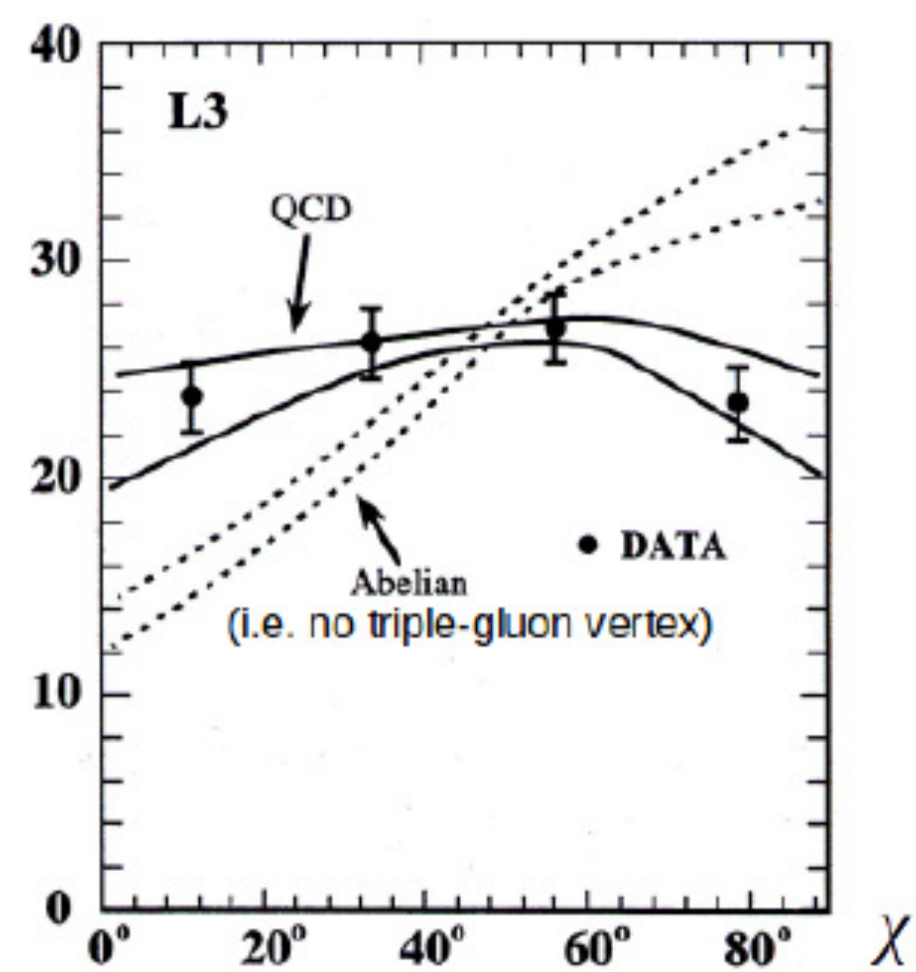
EVIDENCE FOR GLUON SELF-INTERACTIONS



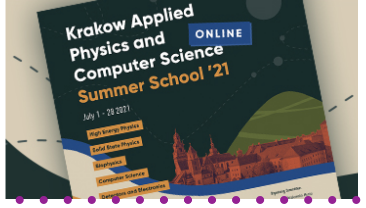
- Direct evidence for the existence of the **gluon self-interactions** comes from 4-jet events
- The angular distribution of jets is sensitive to existence of triple-gluon vertex
  - qqg vertex consists of two spin 1/2 quarks and one spin 1 gluon
  - ggg vertex consists of three spin-1 gluons => different angular distribution
    - Define the two lowest energy jets as the gluons (they are more likely to be lower energy than quark jets)
    - Measure angle between the plane containing the “quark" jets and the plane containing the “gluon" jets.



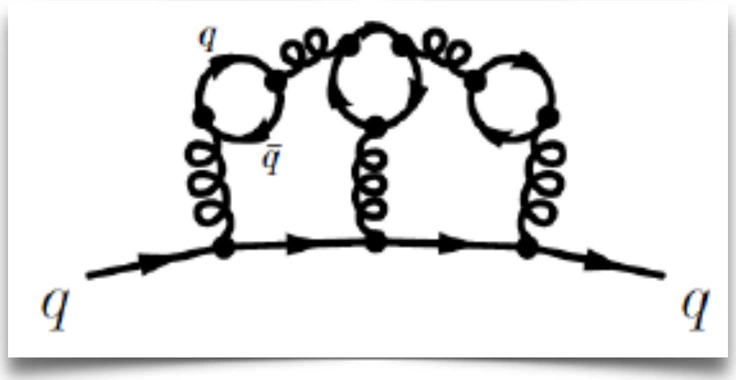


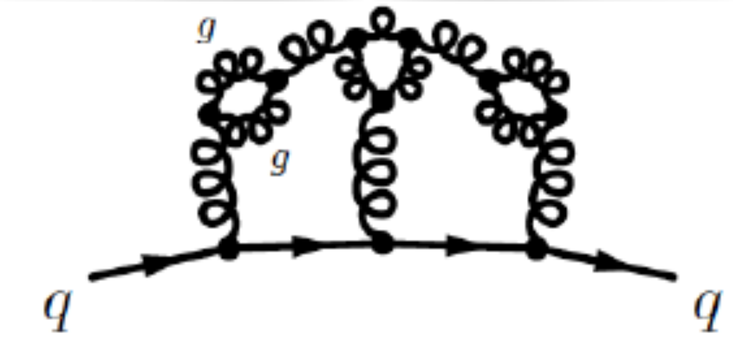


RUNNING OF α_s

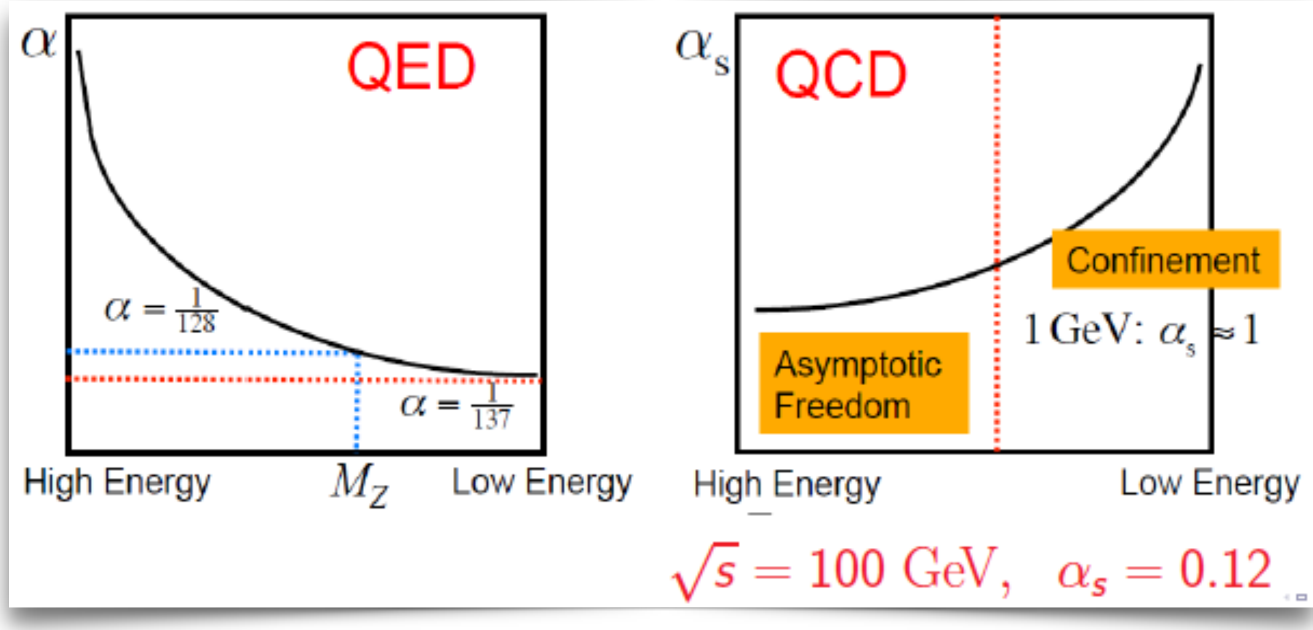


- α_s specifies the strength of the strong interaction
- But, just as in QED, α_s **is not a constant**. It "runs" (i.e. depends on energy/distance)
- In QCD, quantum fluctuations lead to a cloud of virtual $q\bar{q}$ pairs => one of many (an infinite set) of such diagrams analogous to those for QED
- In QCD, the gluon self-interactions also lead to a cloud of virtual gluons => one of many (an infinite set) of such diagrams. No analogy in QED, photons do not carry the charge of the interaction. **This effect dominates!** –> **Colour Anti-Screening**
- The cloud of virtual gluons carries colour charge and the effective colour charge decreases at smaller distances (high energy)!
  - Hence, at low energies (<200 MeV, >1 fm) α_s is large! Cannot use perturbation theory! **Confinement**
  - But at high energies α_s is small. In this regime, can treat quarks as free particles and use perturbation theory! **Asymptotic Freedom**



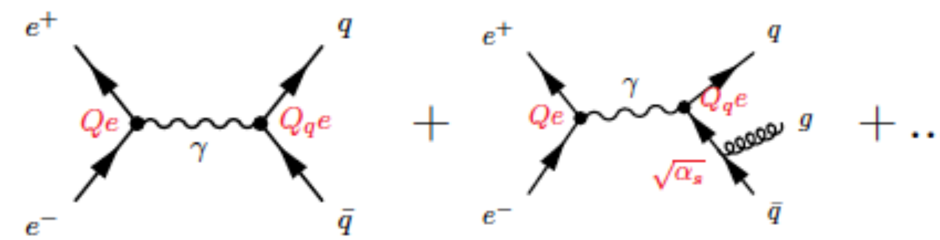


dominant



HOW TO MEASURE α_s

- α_S can be measured in many ways and at different energies
- Example 1: From the ratio $R = \dfrac{N(e^+e^- \to \text{hadrons})}{N(e^+e^- \to \mu^+\mu^-)}$

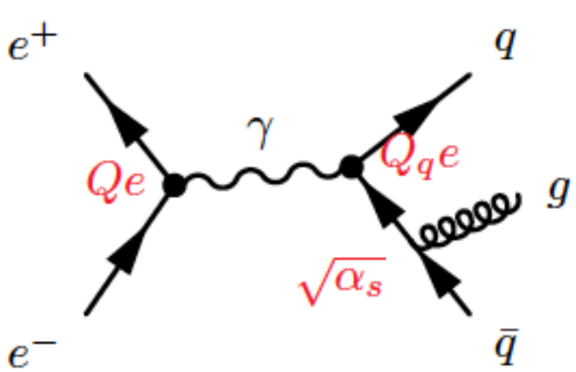


  - In practice, measure
  - i.e. don't distinguish between 2 and 3 jets

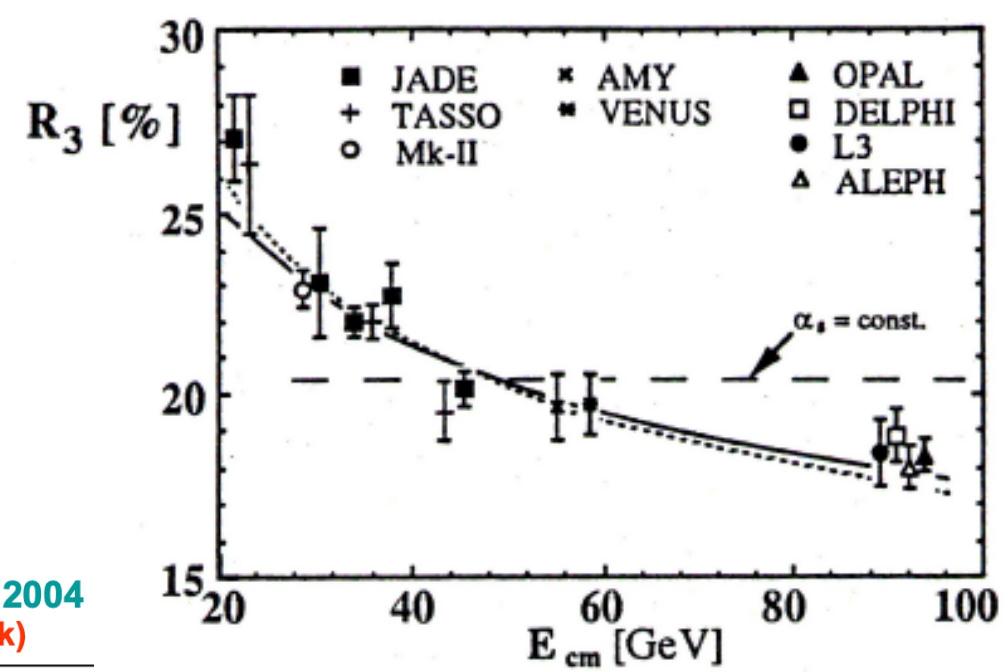
When gluon radiation is included:

$$R = 3\sum Q_q^2\left(1 + \frac{\alpha_s}{\pi}\right)$$

- Example 2: Rate of 3-jet events in $e^+e^- \to q\bar{q}g$



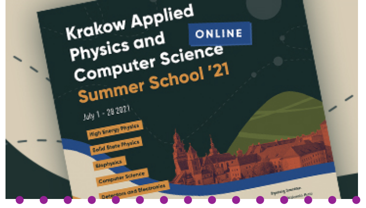
$$R_3 = \frac{N(e^+e^- \to 3\text{ jets})}{N(e^+e^- \to 2\text{ jets})} \sim \alpha_s$$

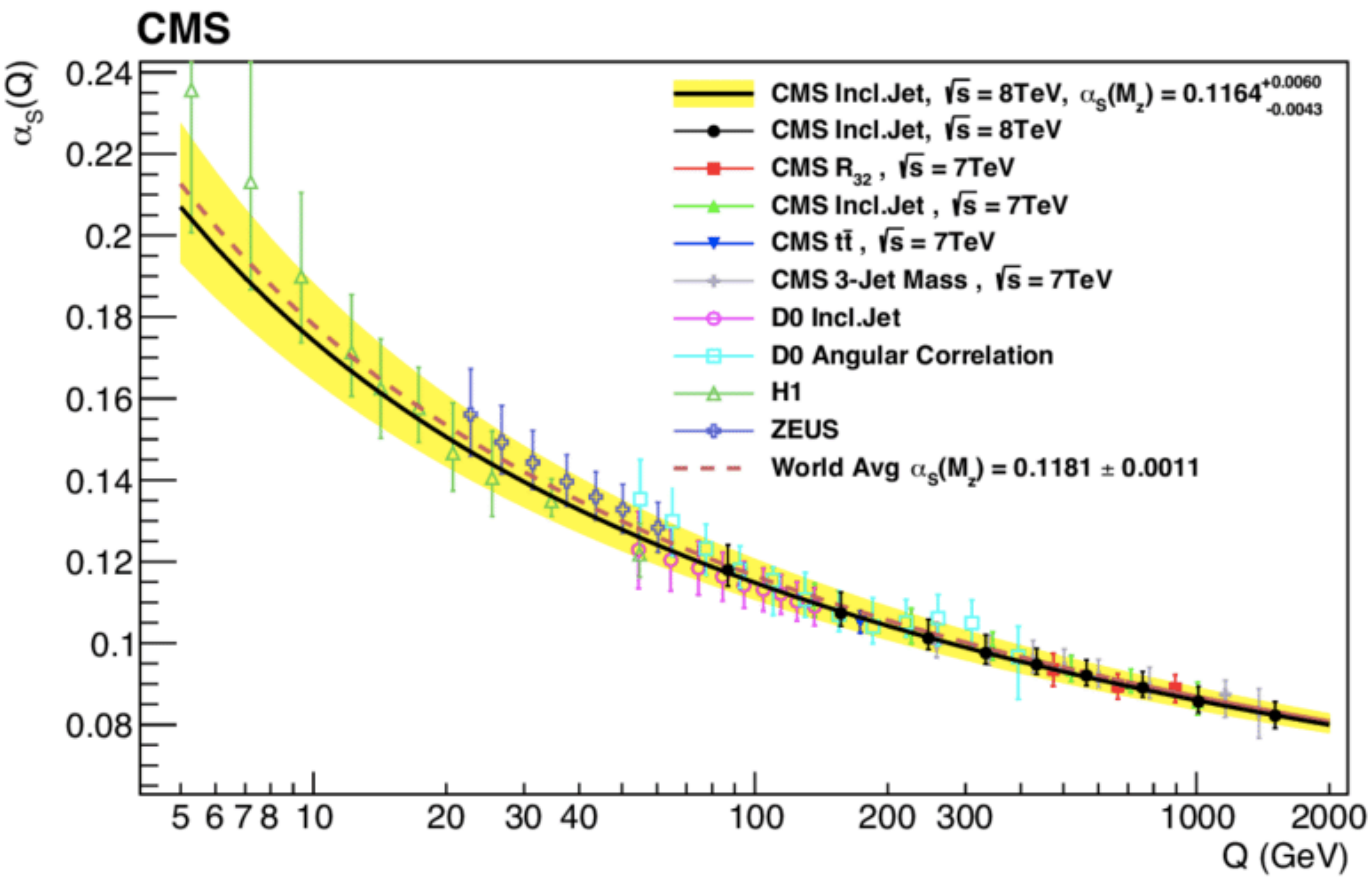


α_s **decreases with Q^2**

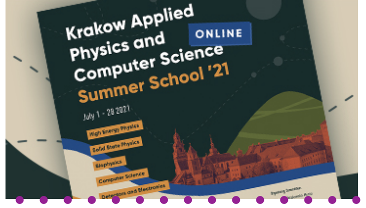
Nobel Prize for Physics, 2004
(Gross, Politzer, Wilczek)

α_s AT THE LHC





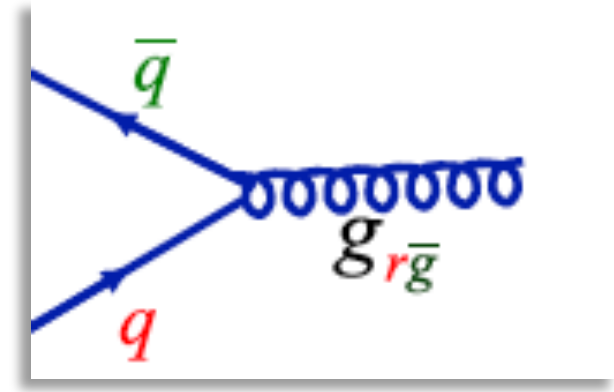
- Probing α_S in a very broad energy range at the LHC: 5-2000 GeV
  - Measurements from many independent experiments are shown
- α_S decreases with energy
- Very good agreement with QCD predictions



BACK-UP SLIDES

GLUONS

- Gluons are massless spin-1 bosons, which carry the colour quantum number
  - Colour is exchanged via gluons, but always conserved (overall and at each vertex)
  - Expect 9 gluons $r\bar{b}\ \ r\bar{g}\ \ g\bar{r}\ \ g\bar{b}\ \ b\bar{g}\ \ b\bar{r}\ \ r\bar{r}\ \ b\bar{b}\ \ g\bar{g}$
  - However: Real gluons are orthogonal linear combinations of the above states. The combination $\frac{1}{\sqrt{3}}(r\bar{r} + b\bar{b} + g\bar{g})$ is colourless and does not participate in the strong interaction
    - => **8 coloured gluons**
  - QCD looks like a stronger version of QED. However, there is one big difference => **gluons carry colour charge**
    - Gluons can interact with other gluons
    - Note: In QED photon self-couplings are absent since the photon does not have an electric charge (technically – gluons self-interact because SU(3) is non-abelian group)
  - All particles (mesons and baryons) are colour singlets
    - This "saves" the Pauli Principle
    - In the quark model the Ω^- consists of 3 s quarks in a totally



$r\bar{g}\ \ r\bar{b}\ \ g\bar{b}\ \ g\bar{r}\ \ b\bar{r}\ \ b\bar{g}$

$\sqrt{1/2}\,(r\bar{r} - g\bar{g})$

$\sqrt{1/6}\,(r\bar{r} + g\bar{g} - 2b\bar{b})$