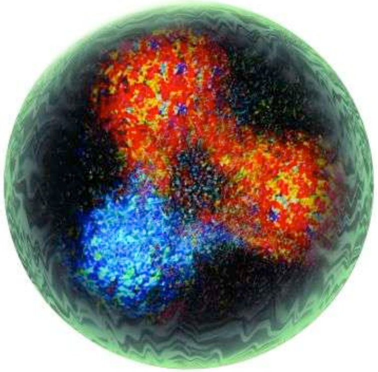
Flavour Physics and Lattice QCD



C.-J. David Lin

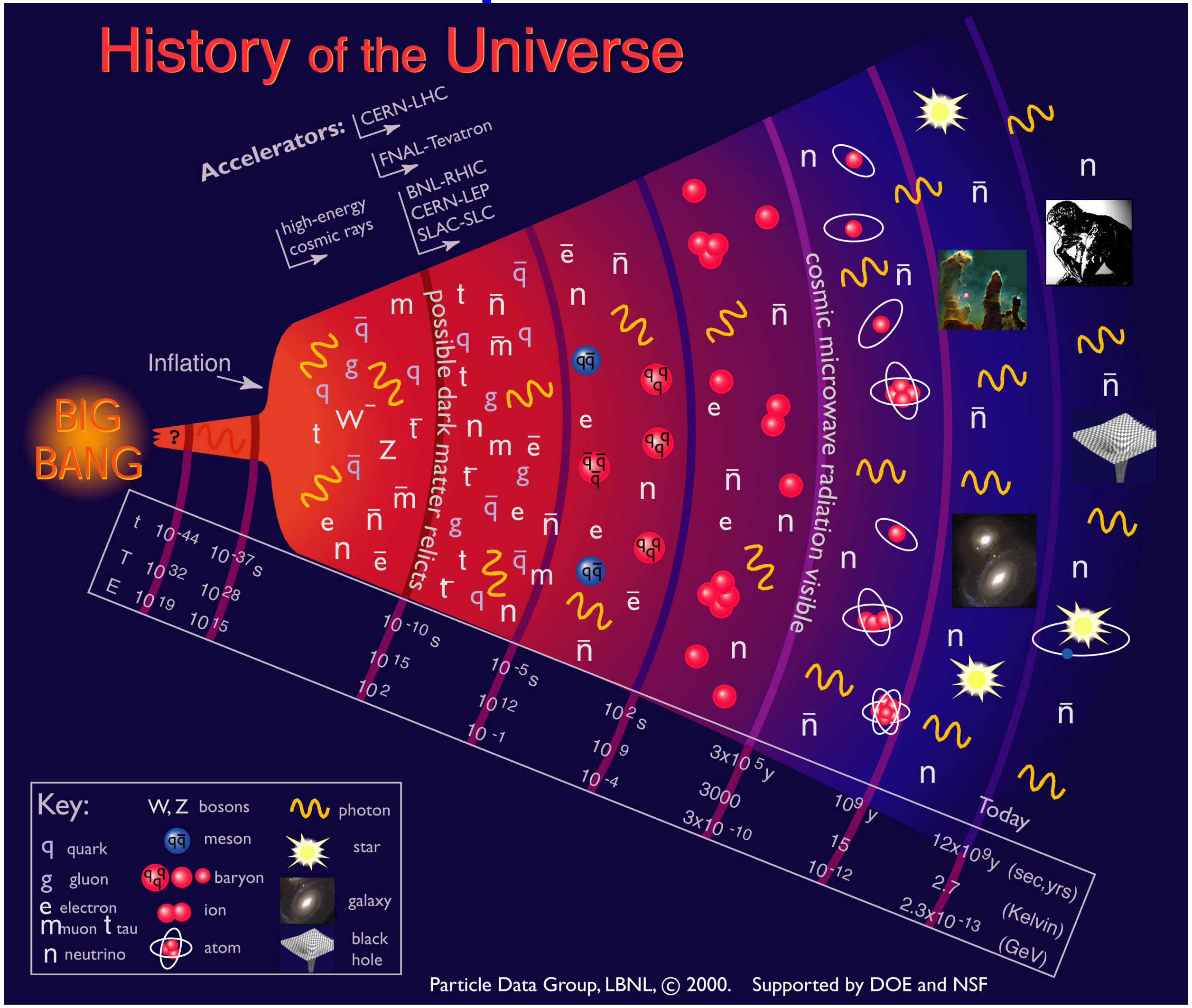
Department of Physics, NTHU
25/05/07

Outline

- Charge conjugation and parity: Why should we care?
- The Standard Model of particle interactions.
- The strong interaction and Lattice QCD.

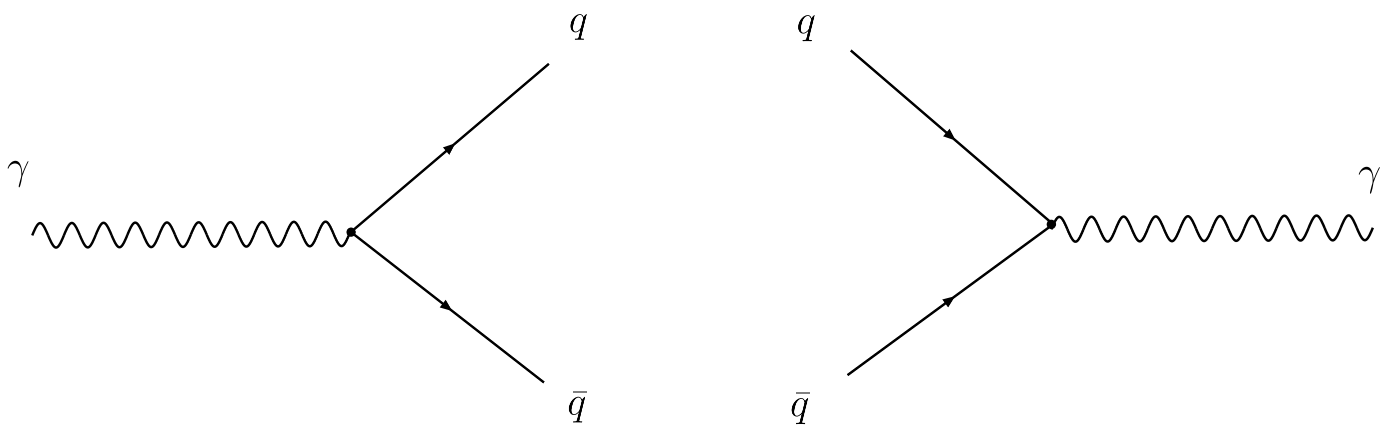
Part I. Charge conjugation and parity

Once upon a time.....



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Charge conjugation: Does it worry you?



- Relativity → particle/anti-particle.
- Matter and anti-matter annihilate into radiation.
- Why do we exist?
- More matters than anti-matters at this corner of the Universe...

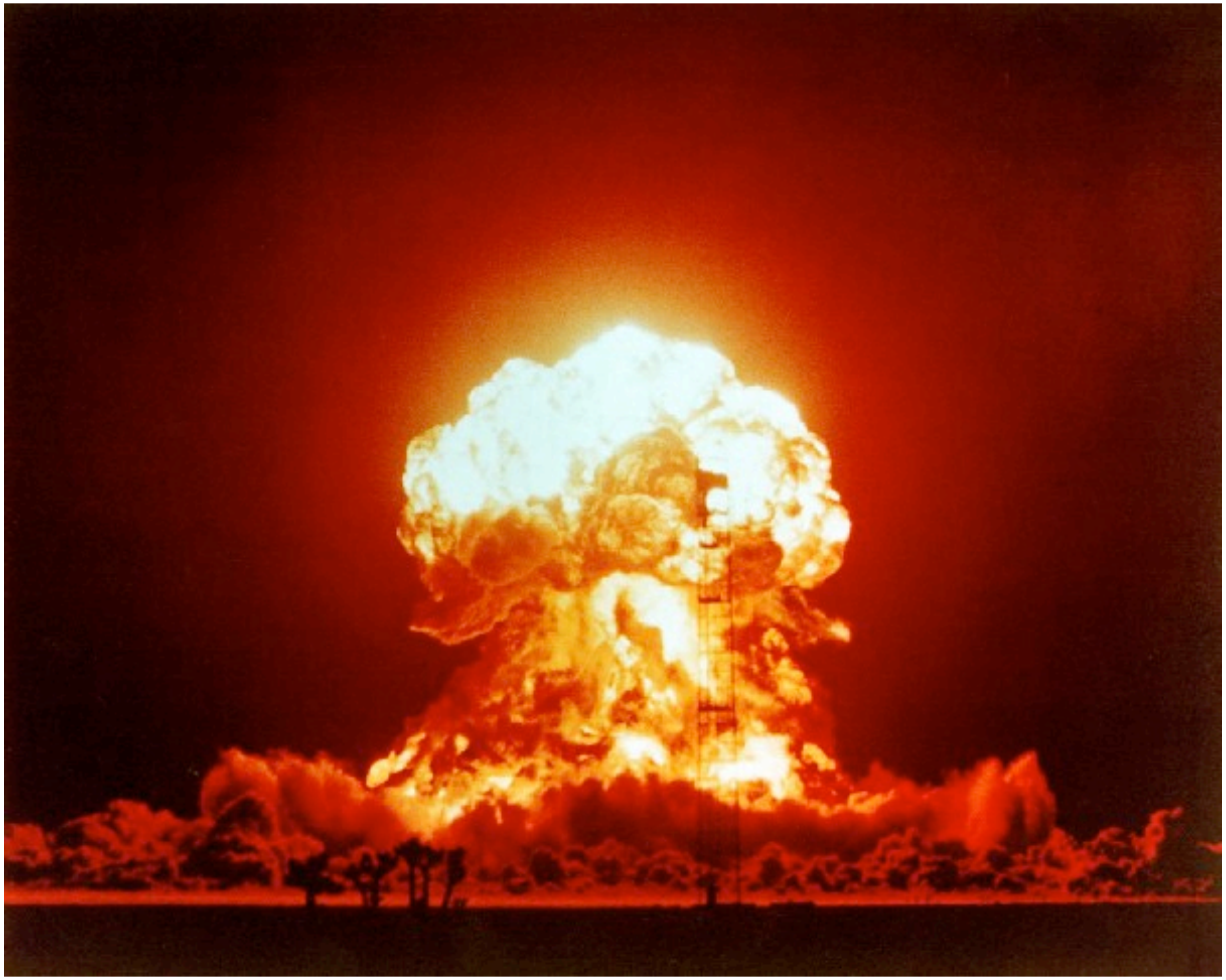
Suppose in a science fiction.....

- Our civilisation is in touch with an alien civilisation.
- We have been "talking" via radiation.
- We finally decide to physically meet our friends.

Well, there is a problem.

Our dear friends might be made of anti-matters....

So, this might happen...



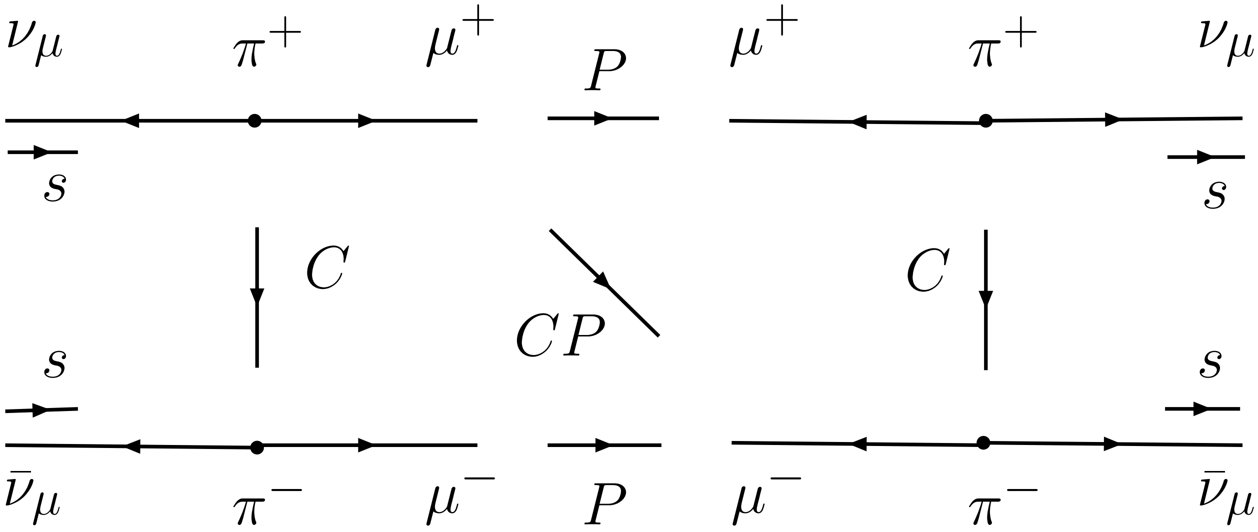
Violation of charge-conjugation

- C is violated by “weak interactions”.
- So is parity (mirror reflection) though.....

- CP, however, is conserved for most weak-interaction processes.
- C and P are purely defined by convention.

Difficulties in communications......

ν is always left-handed while $\bar{\nu}$ is always right-handed.



- Earth: The π that decays into left-handed ν_μ carries positive charge.
- Planet X: But what do you mean by “left”?

Thanks to CP violation!

- K_L is its own anti-particle.
- It decays into both $\pi^+e^-\bar{\nu}_e$ and $\pi^-e^+\nu_e$
- But it decays slightly less often into $\pi^+e^-\bar{\nu}_e$ (CP violation).

So now, we can proceed.

- Earth: The π resulted by the less often K_L decay mode carries the same charge as the proton.
- Planet X: Thanks, mate!

Sakharov 1967

Matter/anti-matter asymmetry can occur only if

- Baryon number is violated
- Thermal equilibrium is not respected by interactions.
- CP is violated

Enough CP violation in the theory of particle interactions?

Part II. the Standard Model

Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

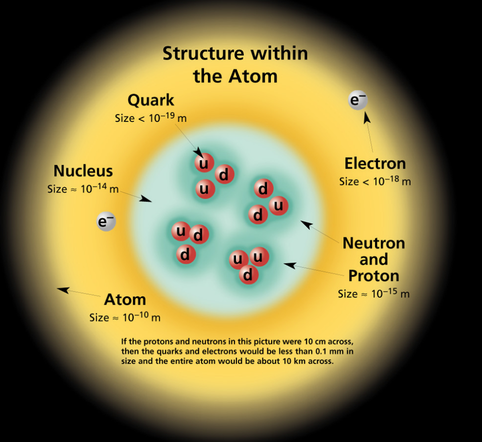
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W⁻	80.4	–1
W⁺	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W⁺ W⁻ Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–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

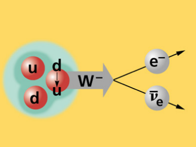
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

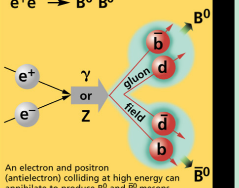
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



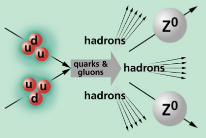
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 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	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

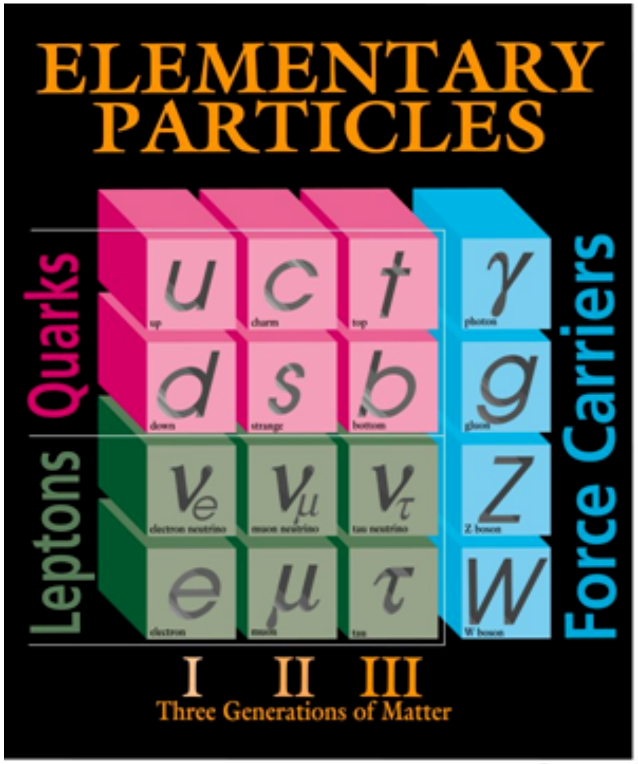
The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

Contemporary Physics Education Project. CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 50-308, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see:

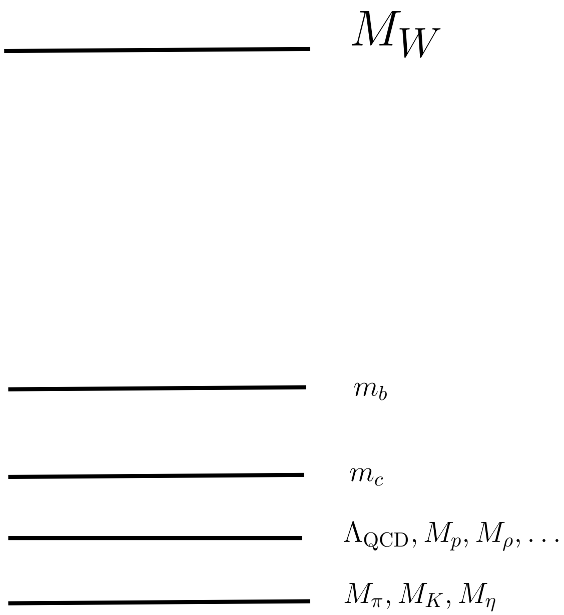
http://CPEPweb.org



Fermilab 95-759

And the (yet) unobserved Higgs particles.

The mass scales



M_W

m_b

m_c

$\Lambda_{\text{QCD}}, M_p, M_\rho, \ldots$

M_π, M_K, M_η

- Leptons are not shown explicitly.
- From almost zero to around 100 GeV.

It is a quantum field theory

Or, rather,three quantum field theories

- Quantum mechanics: signature of a particle in space-time

  $\longrightarrow [x, p] = i.$

- How to describe particle creation and annihilation?

- QFT: signature of a particle in field configurations

  $\longrightarrow [\phi, \pi_\phi] = i.$

  $\longrightarrow$ The second quantisation.

- C → complex conjugate.

- The Feynman path integral formulation can be derived.

Weak interactions amongst quarks
The study of quark-flavour mixing

- The six flavours of quarks:

$$\begin{pmatrix} u^{2/3} \\ d^{-1/3} \end{pmatrix} \begin{pmatrix} c^{2/3} \\ s^{-1/3} \end{pmatrix} \begin{pmatrix} t^{2/3} \\ b^{-1/3} \end{pmatrix}.$$

- The up-type and down-type quarks:

$$\mathcal{U}^{2/3} = \begin{pmatrix} u^{2/3} \\ c^{2/3} \\ t^{2/3} \end{pmatrix}, \ \mathcal{D}^{-1/3} = \begin{pmatrix} d^{-1/3} \\ s^{-1/3} \\ b^{-1/3} \end{pmatrix}.$$

- Flavour-changing neutral processes are observed to be very small.

The unitary Cabibbo-Kobayashi-Maskawa matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv \widehat{V}_{\mathrm{CKM}} \mathcal{D}^{-1/3} = \left(\mathcal{D}'\right)^{-1/3} .$$

- Quark-flavour mixing in the Standard Model:

$$\overline{\mathcal{U}}^{2/3} \gamma_\mu (1 - \gamma_5) \left(\mathcal{D}'\right)^{-1/3} .$$

- Notice

$$\left(\overline{\mathcal{D}'}\right)^{-1/3} \Gamma \left(\mathcal{D}'\right)^{-1/3} = \left(\overline{\mathcal{D}}\right)^{-1/3} \Gamma \left(\mathcal{D}\right)^{-1/3} .$$

The Wolfenstein parameterisation

Three “angles” and one complex phase in the CKM matrix

$$\widehat{V}_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4).$$

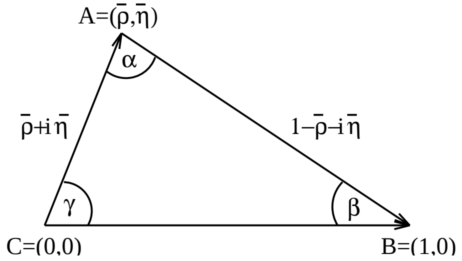
Unitarity implies $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0.$

$$\Rightarrow (\rho + i\eta) + (1 - \rho - i\eta) = 1.$$

CKM matrix elements are input parameters to be determined.

The $b\!-\!d$ unitarity triangle

$$(\rho + i\eta) + (1 - \rho - i\eta) = 1.$$



$$\mathrm{BC} = 1.$$

$$\mathrm{AB} \sim |V_{td}/V_{cb}|,\ \mathrm{AC} \sim |V_{ub}/V_{cb}|.$$

$$\beta = -\mathrm{arg}(V_{td}),\ \gamma = \mathrm{arg}(V_{ub}^*).$$

The goal of CKM physics:

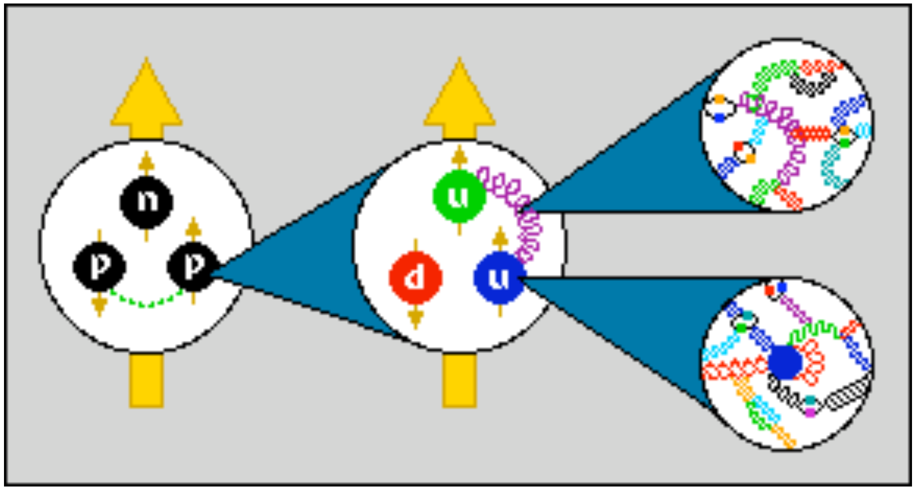
Accurately (over-)determine the CKM matrix elements to test the Standard Model and physics beyond it.

Difficulties in CKM physics

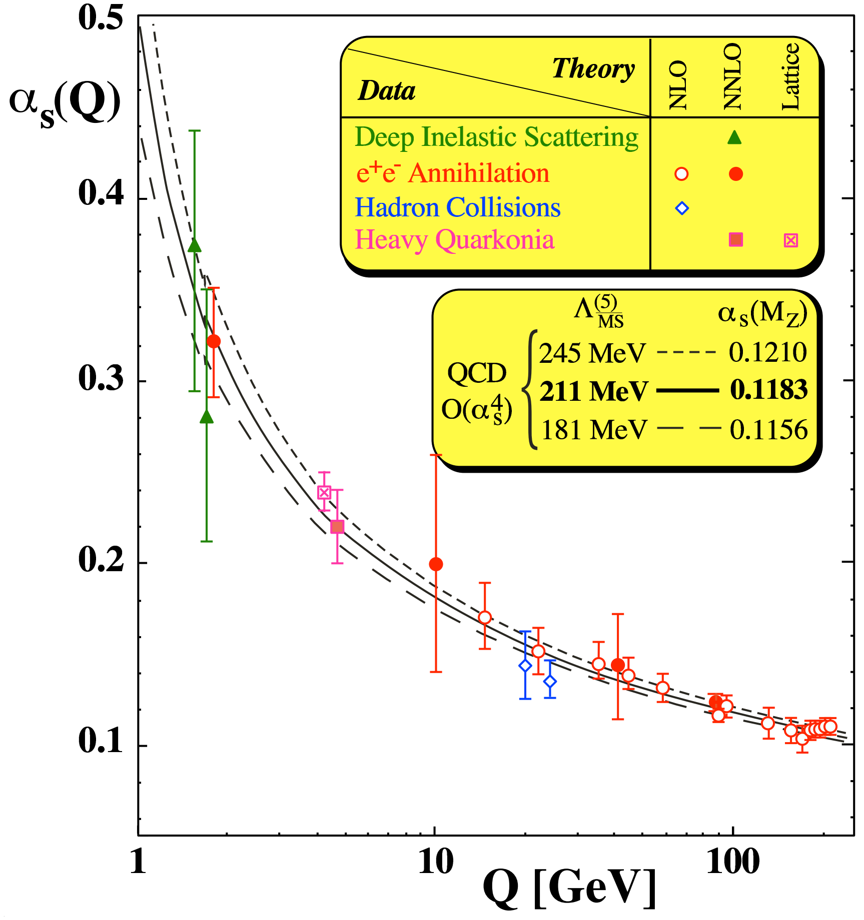
- Probing physics at scale $\gg M_W \sim 80$ GeV via experiments at a few GeV

  $\longrightarrow$ High-precision is required in both experiments and theory.

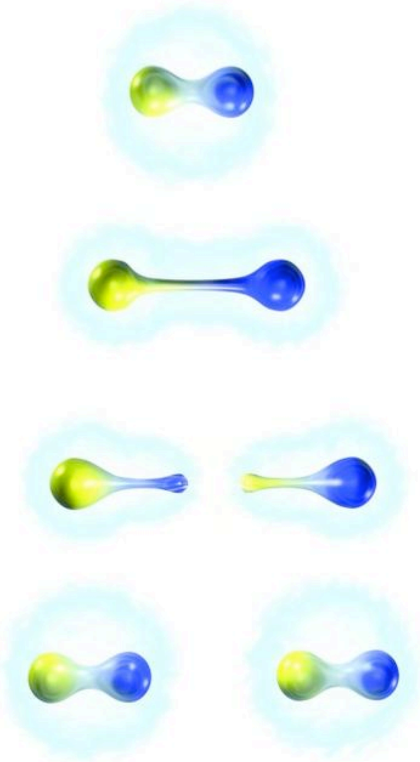
- Quarks are bound with gluons into hadrons via the strong interaction.



Quantum Chromodynamics coupling constant

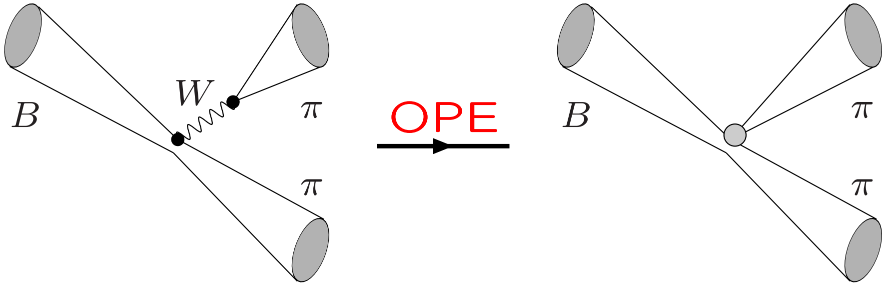


Quark confinement



Strategy in CKM physics

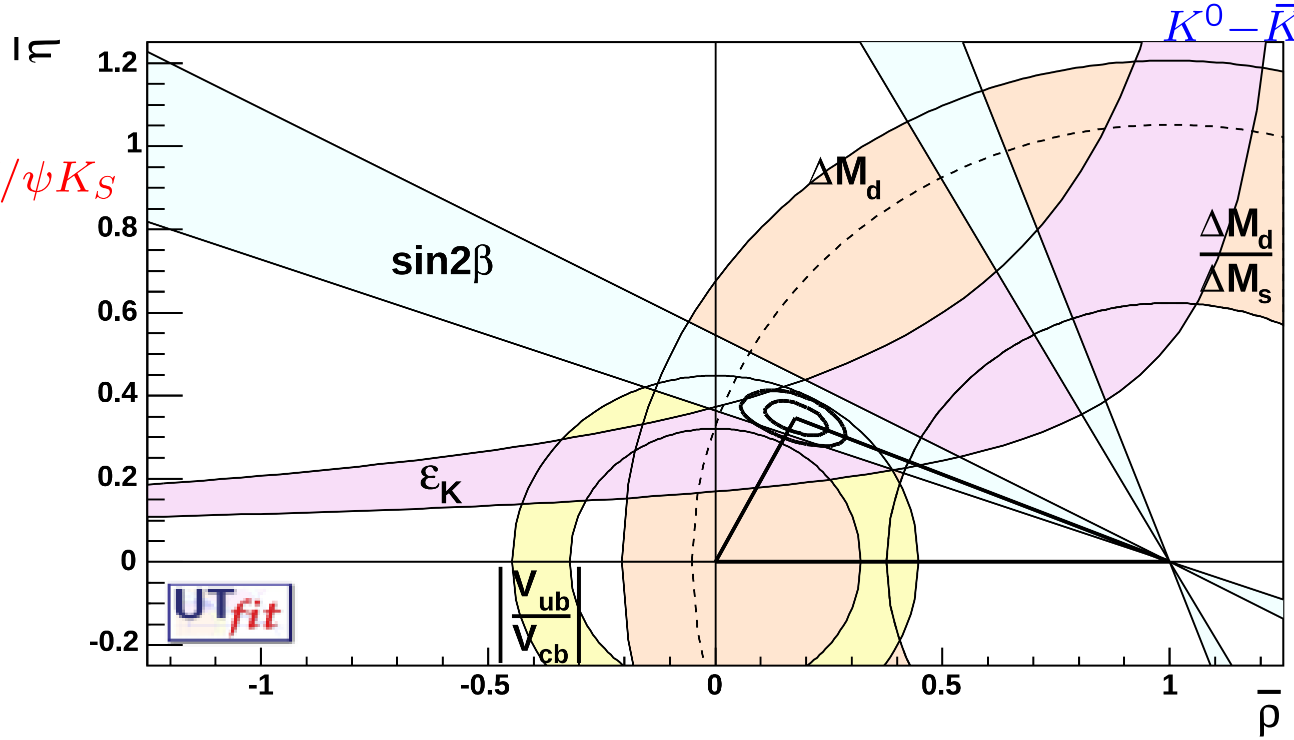
- $A(B \to H) = \underbrace{C_{ij}(V_{\mathrm{CKM}}, M_W, \mu)}_{\text{includes short–distance QCD}} \quad \overbrace{\langle H|\mathcal{O}(\mu)|B\rangle}^{\text{long–distance QCD}}$



- Factorise short- and long-distance physics.
- Short-distance physics in QCD is calculated perturbatively.
- Use non-perturbative techniques reliable to scale μ.

The global CKM fit

Exp $= V_{ij}$ (short-distance)$\otimes$(long-distance QCD matrix element)



$K^0 - \bar{K}^0$

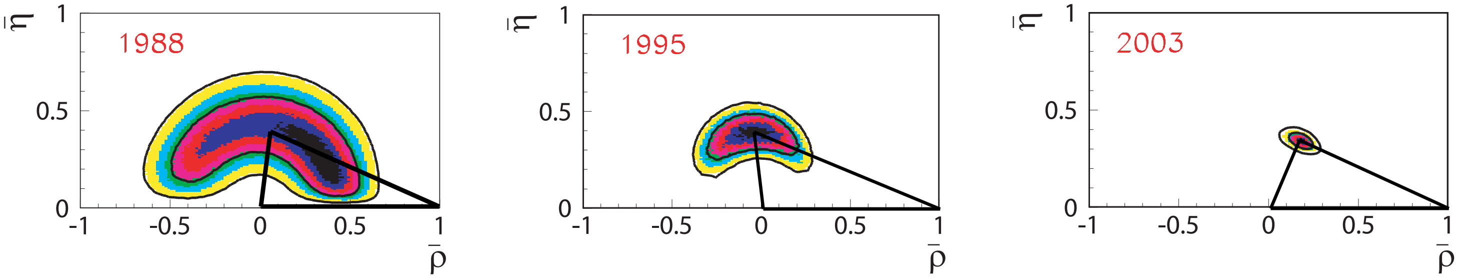
$B \to J/\psi K_S$

$B^0_{(s)} - \bar{B}^0_{(s)}$

$B \to \pi l \bar{\nu}$

α & γ : $B \to M_1 M_2$. Need ϕ_{B,M_1,M_2}.

Lattice QCD working with experiments



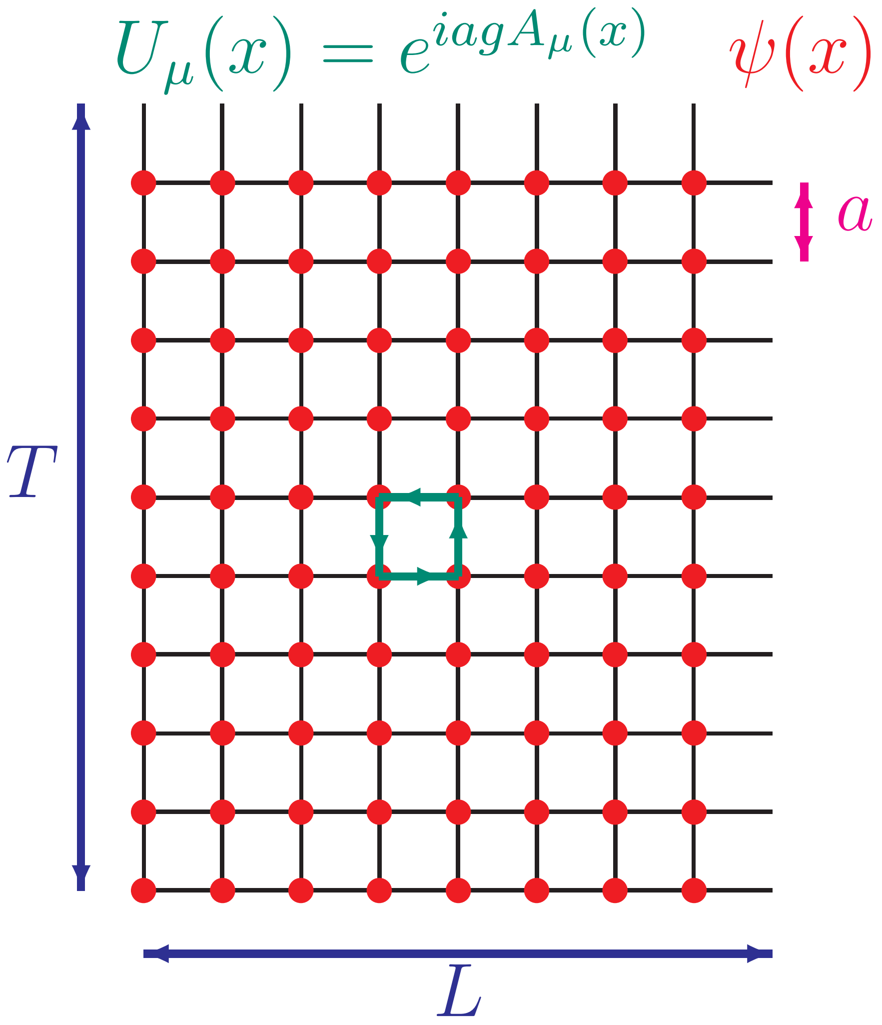
- Lattice QCD → From first principles.

- Impressive progress.

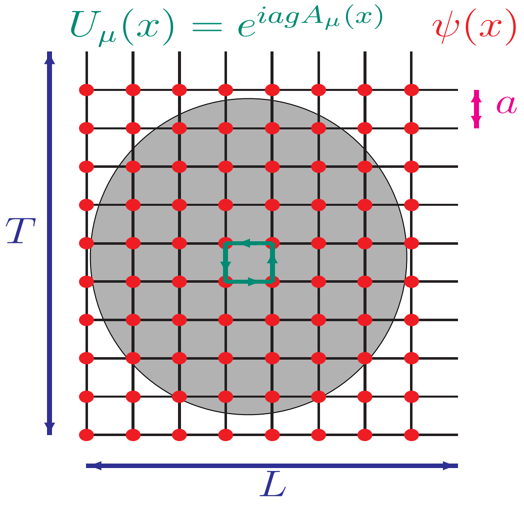
- On-going efforts to pursue high precision in “’sides’.

- Need new ideas for “angles”.

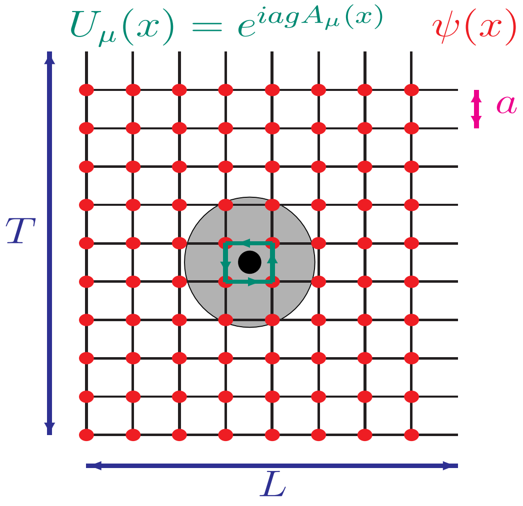
Part III. Lattice QCD


$U_\mu(x) = e^{iagA_\mu(x)}$
$\psi(x)$
a
T
L

Mesons on a lattice

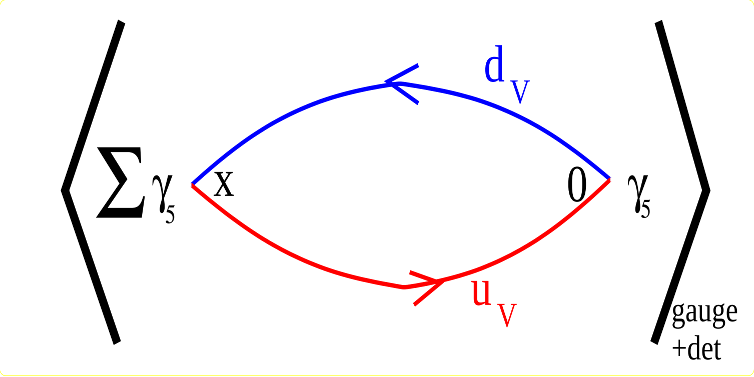


Light-light meson



Heavy-light meson

The pion correlator



$$\begin{aligned} C_\pi(\tau) &= -\left\langle \sum_{\vec{x}} \bar{u}\gamma_5 d(\vec{x},\tau)\ \bar{d}\gamma_5 u(0) \right\rangle \\ &\equiv -\frac{1}{Z}\int DU \prod_q Dq D\bar{q}\, e^{-S_{\text{gauge}} - \int_x \sum_q \bar{q}(\not{D}+m_q)q} \sum_{\vec{x}} \bar{u}\gamma_5 d(\vec{x},\tau)\ \bar{d}\gamma_5 u(0) \\ &= \frac{1}{Z}\int DU \prod_q \det(\not{D}+m_q)\, e^{-S_{\text{gauge}}} \sum_{\vec{x}} \text{Tr}\left[\gamma_5 \left(\frac{1}{\not{D}+m_d}\right)_{x0} \gamma_5 \left(\frac{1}{\not{D}+m_u}\right)_{0x}\right] \end{aligned}$$

Numerical calculations – Steps

- Monte Carlo methods for generating gauge-field distributions.

- Quarks will “propagate on these distributions”.

  → Need to invert a matrix of the order $30^3 \times 60 \times 12$.

- Put things together to get quark-gluon bound states.

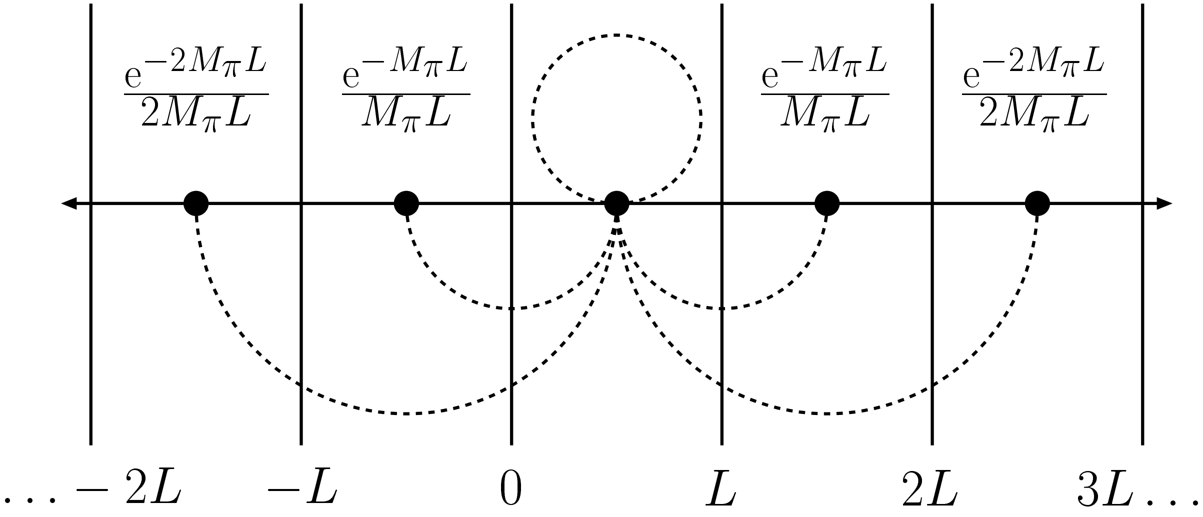
- Data analysis → Statistics.

Effective Field Theory for Lattice QCD

- Relies on symmetries of QCD.
- QCD exhibits very interesting/complicated symmetry patterns
  - when $m_{\text{quark}} \to 0$.
  - when $m_{\text{quark}} \to \infty$.
  - and don't forget Λ_{QCD}.
- EFT predicts how quantities vary w.r.t. quark masses in these limits.

HL mesons in finite L ($T \to \infty$)
Pions wrapping the world

D.Arndt and C.-J.D.L., 2004.



Future research interests

Physics beyond the SM at the LHC @ CERN, Geneva.

Specific topics

- Polarised Λ_b baryons

  →Different types of couplings for new particles.

- Composite Higgs particles
  - Mechanism of generating masses for observed particles.
  - Strongly coupled fermions at TeV scale.
  - Spectrum of QCD-like theories at the LHC energy level.