QCD and particle physics

Emi Kou (LAL-IN2P3)

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
LPT Orsay
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

"Matinée des Théoriciens de la vallée d'Orsay"
at Orsay, 12 June 2017

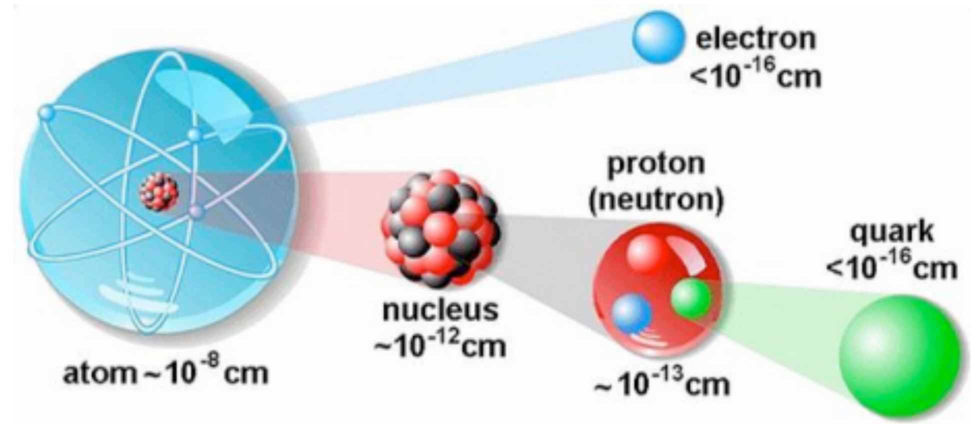
To begin with...

- This presentation is to give rough idea of our field, QCD and particle physics
- Many thanks to people who gave me some slides
- And apologies that I can't cover fully the interesting topics people are working on...

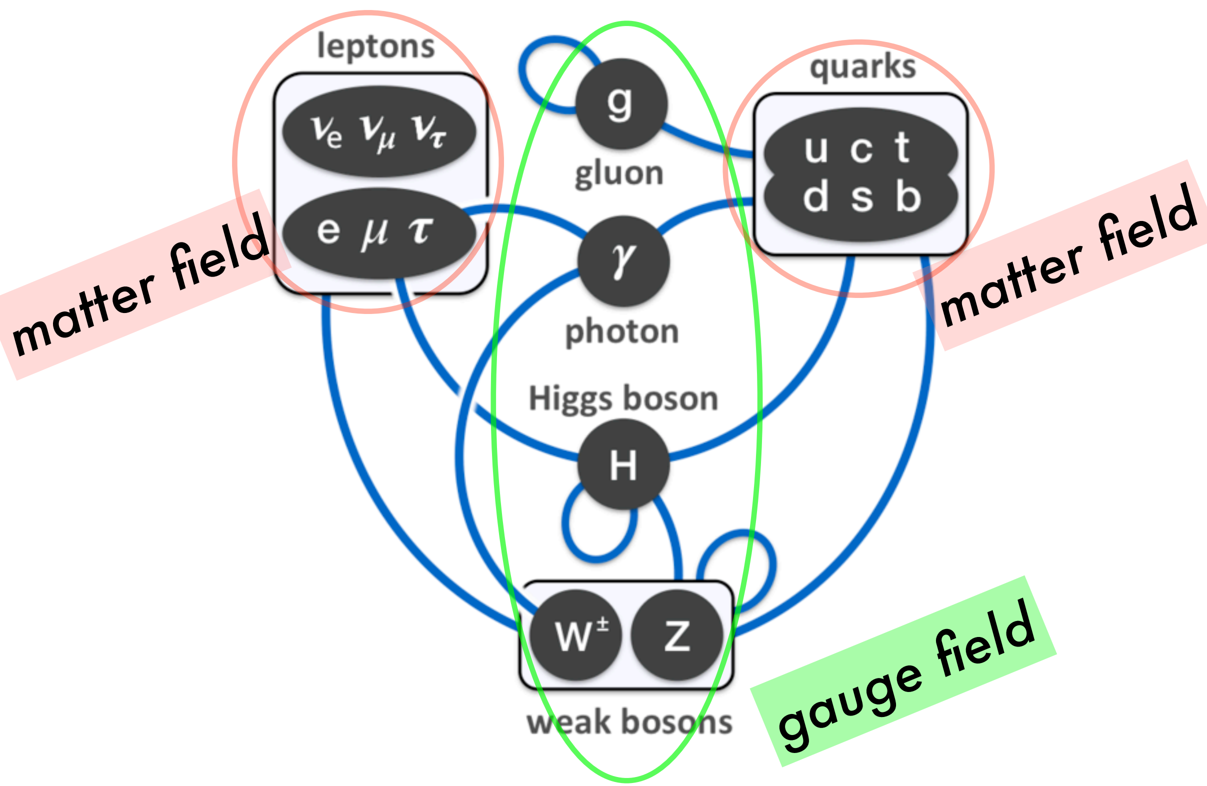
- LPT: D. Becirevic, B. Blossier, P. Boucaud, S. Descotes-Genon, M. Fontannaz, S. Wallon, A. Le Yaouanc
- IPNO: V. Bernard, J.-P. Lansberg, B. Moussallam, H. Sazdjian
- LAL: E.K.

There are many collaborations among 3 labs including co-supervision of PhD.

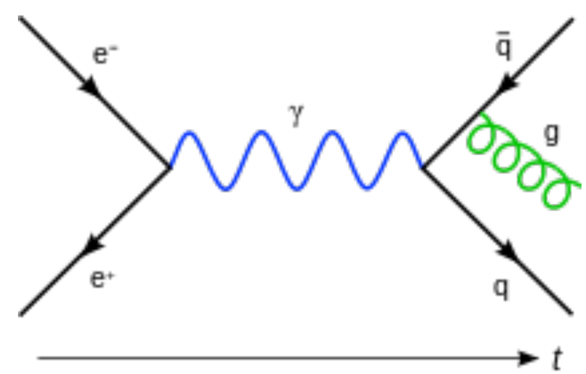
Particle physics



- *We use quantum field theory*
- *We investigate fundamental particles and their interactions*



Feynman diagram of e+e- →q q̄ g process



The Standard Model

$SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

interaction **Strong** QCD **Weak Electromagnetic** *Electro-weak theory*

coupling g_s (g, g', θ_W)

1968 SLAC:
deep inelastic scattering

1973 Gross/Wilczek/Politzer:
asymptotic freedom

1974 Wilson:
Lattice gauge theory

1931 Pauli: neutrino prediction
1933 Fermi: theory of β decay
1956 Lee/Yang: parity violation prediction

1956 Reines/Cowan: neutrino discovery
1957 Wu: parity violation discovery

1928 Dirac: positron prediction

1932 Anderson: positron discovery

1964 Higgs: symmetry breaking
1967 Weinberg/Salam: electroweak unification

1973 Gargamelle: Z boson discovery

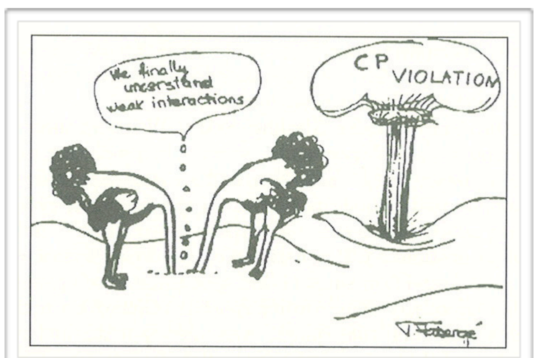
2012 LHC: Higgs boson discovery

1989-2000 LEP experiment:
precision measurement of
(g, g', θ_W)

The Standard Model

3 generation of quarks and leptons

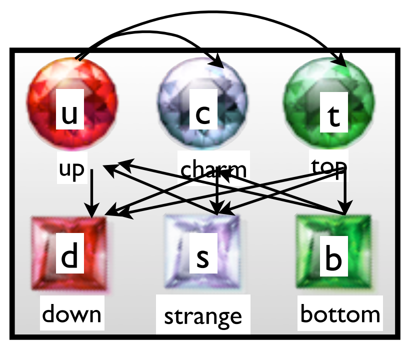
interaction	Strong (QCD)	Weak	Electromagnetic
coupling	g_s	(g, g', θ_W), V_{CKM}(quarks only), 12 masses	

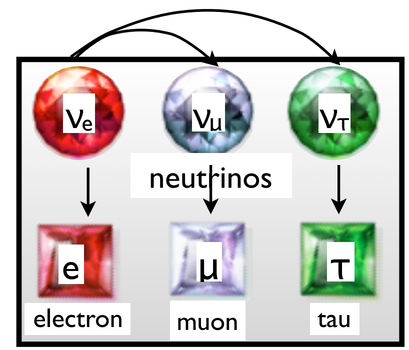


1964 Cronin/Fitch: CP violation in K meson

1973 Kobayashi/Maskawa: theory of CP violation

1974 Ting/Richter: charm quark discovery





Flavour physics!

2000-2010 B factories experiment
1997-2001 NA48 (kaon) experiment
2010-present LHCb experiment
2015-present NA62 (kaon) experiment
2018-2025 Belle II experiment

Searching physics beyond the SM

- New physics searches: the most important task for low energy, high energy particle physics experiments

$$\Delta_{NP} = \text{Deviation from SM} = (\text{exp.} - \text{SM}) \pm \sqrt{(\sigma_{exp})^2 + (\sigma_{SM})^2}$$

We see several hints but not significant enough so far...

- L.H.S. = Propose models beyond the SM and how to observe them (talk by Y. Mambrini)
- R.H.S. = Provide a more precise SM theoretical prediction by improving our QCD computation techniques (this talk)

Searching physics beyond the SM

- *New physics searches: the most important task for low energy, high energy particle physics experiments*

$$\Delta_{NP} = \text{Deviation from SM}$$
$$= (\text{exp. - SM}) \pm \sqrt{(\sigma_{exp})^2+(\sigma_{SM})^2}$$

QCD is essential for SM prediction!

e.g. *LHC* ,
CP violation...

$$\Gamma = Q \times T$$

mesure expérimentale

contribution de QCD

paramètres SM ou BSM

Searching physics beyond the SM

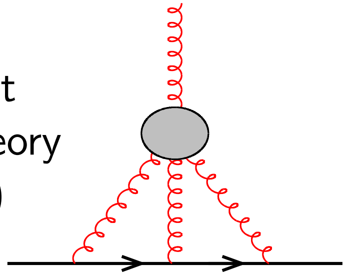
- *New physics searches: the most important task for low energy, high energy particle physics experiments*

$$\Delta_{NP} = \text{Deviation from SM} = (\text{exp.} - \text{SM}) \pm \sqrt{(\sigma_{exp})^2 + (\sigma_{SM})^2}$$

→ Example: hadronic contributions to muon g-2 (5-σ discrepancy)

$$a_\mu^{exp} = 116592089(63) \cdot 10^{-11}$$
$$a_\mu^{th} = 116591778(45) \cdot 10^{-11}$$

→ Most difficult piece: light-by-light hadronic amplitude (combine theory and experimental measurements)



Quantum Chromo Dynamics (QCD)

QCD Lagrangian

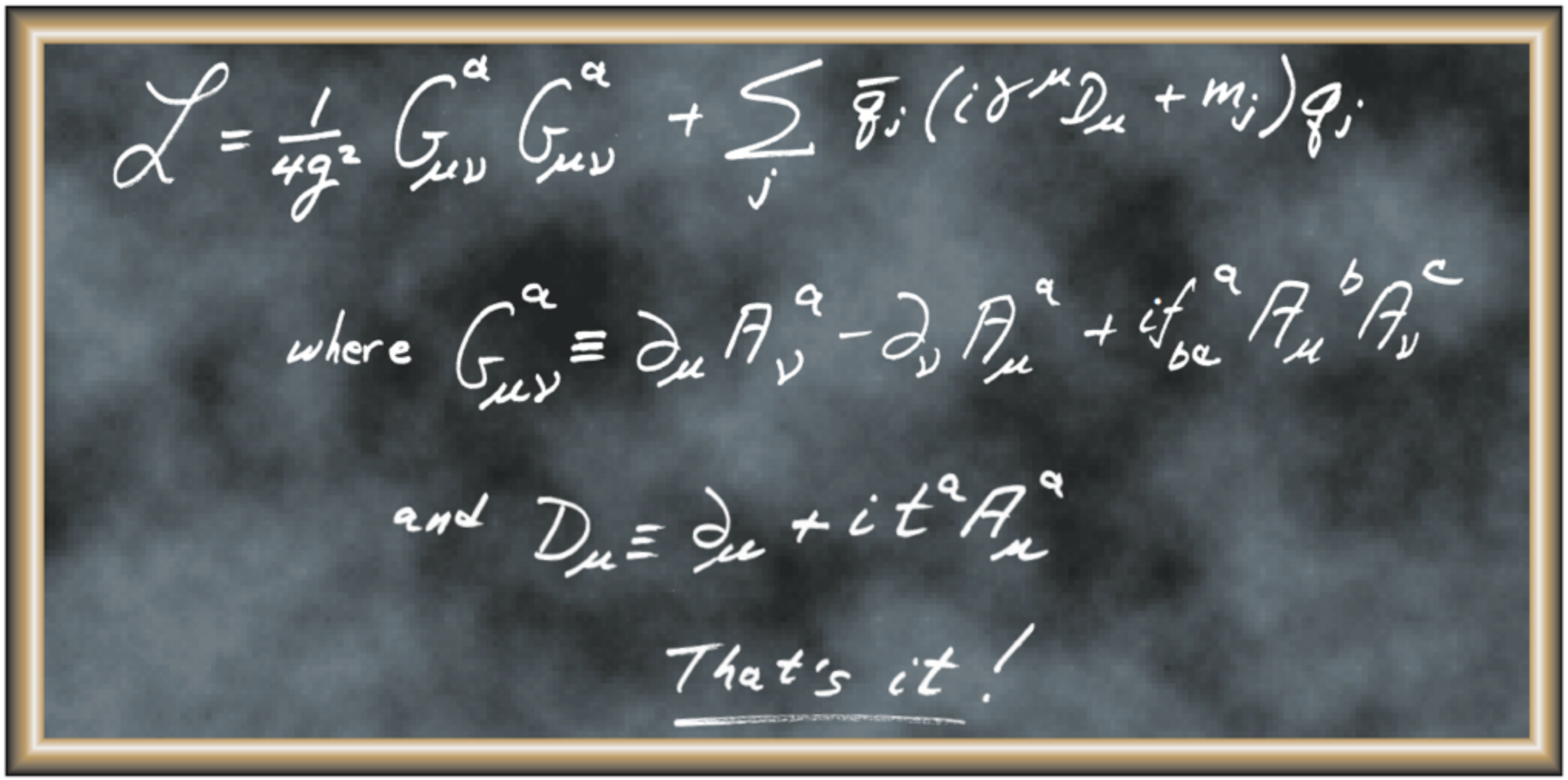
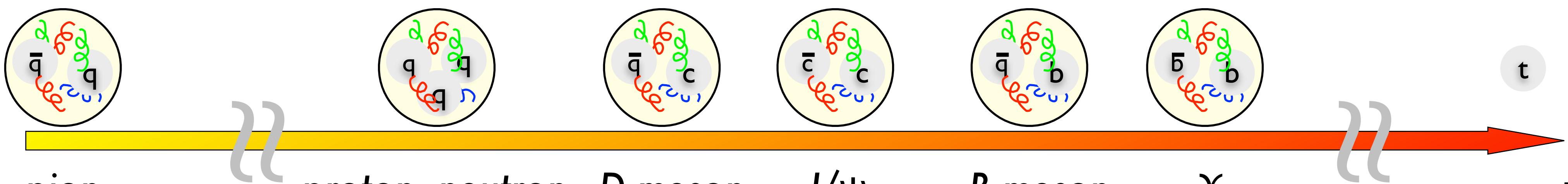


FIGURE 1. THE QCD LAGRANGIAN $\mathcal{L}$ displayed here is, in principle, a complete description of the strong interaction. But, in practice, it leads to equations that are notoriously hard to solve. Here m_j and q_j are the mass and quantum field of the quark of jth flavor, and A is the gluon field, with spacetime indices μ and ν and color indices a, b, c. The numerical coefficients f and t guarantee SU(3) color symmetry. Aside from the quark masses, the one coupling constant g is the only free parameter of the theory.

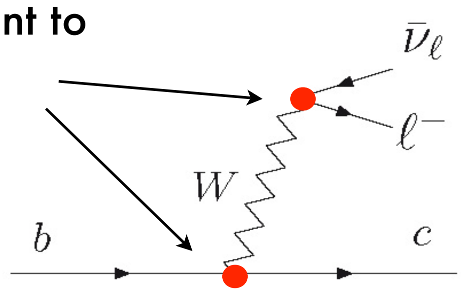
Quantum Chromo Dynamics (QCD)

Quarks are glued into hadrons

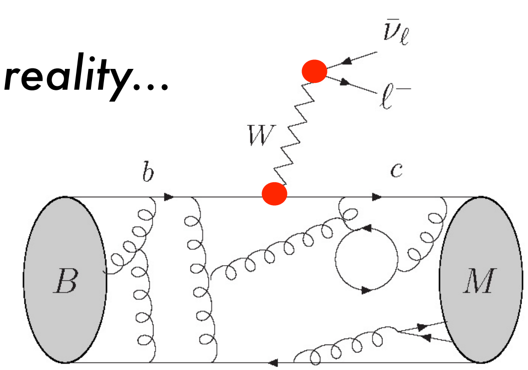


pion	proton, neutron	D meson	J/ψ...	B meson	ϒ...	top quark
0.1GeV	~1GeV	~1.5GeV	~3GeV	~5GeV	~10GeV	~175GeV

couplings we want to measure



but in reality...



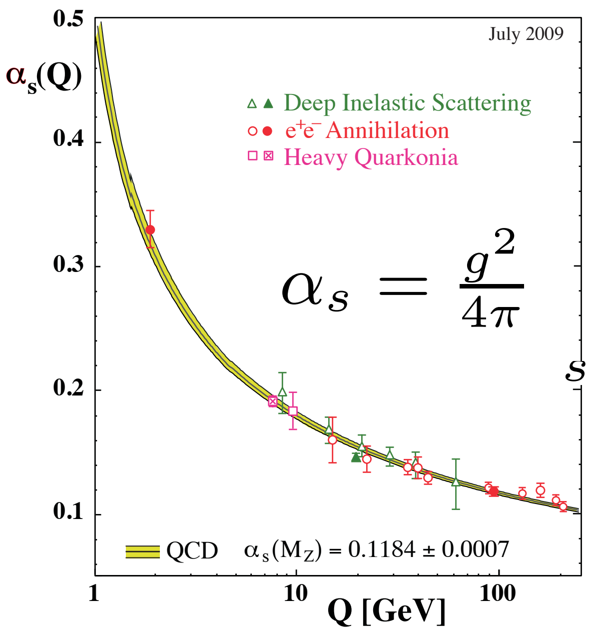
gluons don't allow us to see only quark interactions...

What shall we do?!

Quantum Chromo Dynamics (QCD)

Quarks are glued into hadrons

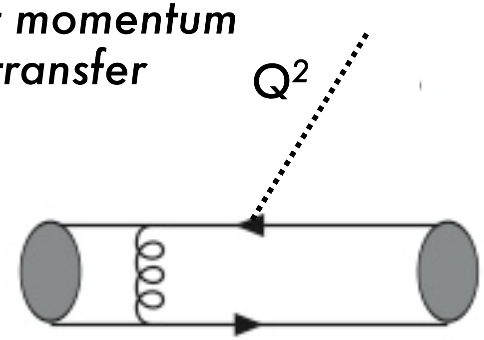
Asymptotic freedom!



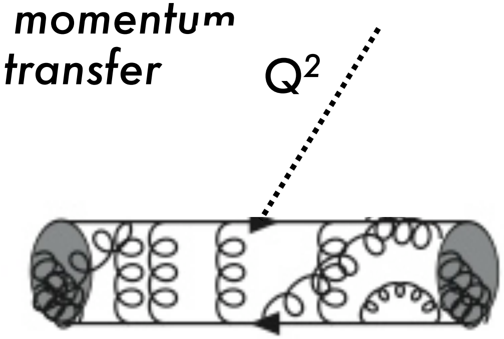
coupling $\alpha_s(Q) \ll 1$ (Q = typical energy)

for $Q \gg \Lambda_{QCD} \simeq 200\ MeV$ *i.e.* distance $\sim 1/Q \ll 1$ fm

hight momentum transfer Q^2

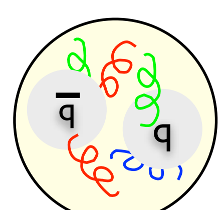


low momentum transfer Q^2



gluons couple weakly: *perturbative expansion in* α_s *is possible!*

gluons couple strongly: *non-perturbation computation necessary*



Confinement is non-perturbative QCD

Perturbative QCD

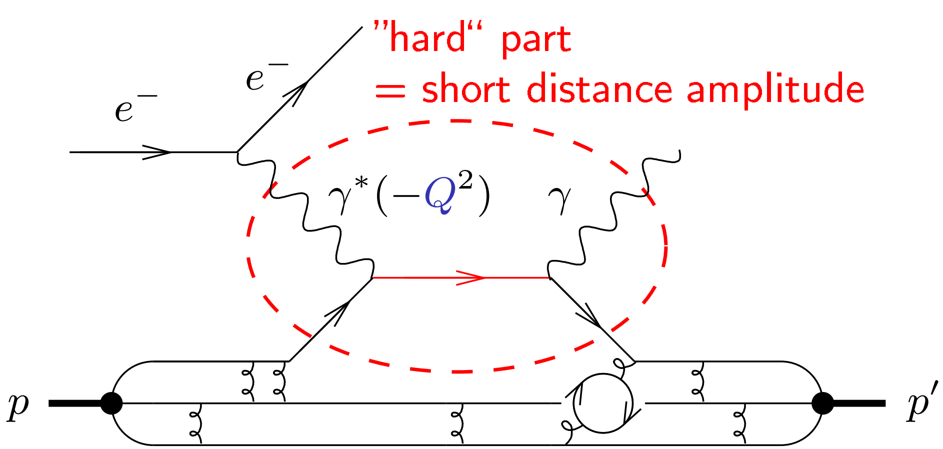
Michel Fontannaz, Jean-Philippe Lansberg, Samuel Wallon

Description of a wide class of processes relying on perturbative methods

- "factorization" of the short distance dynamics from the large distance dynamics of quantum chromodynamics (QCD)

$$M = \text{short distance amplitude} \otimes \text{non-perturbative content of the hadron}$$

convolution



Generalized Parton Distribution (GPD)

virtual photon $\gamma^* =$ probe

$1/Q =$ spatial resolution

(Heisenberg inequality)

$M_{\gamma^* p \to \gamma\, p'}$

***perturbative* corrections**

resummation ?

$$= \quad (\# + \#\,\alpha_s + \cdots)$$

$$+ \; \frac{1}{Q}(\# + \#\,\alpha_s + \cdots)$$

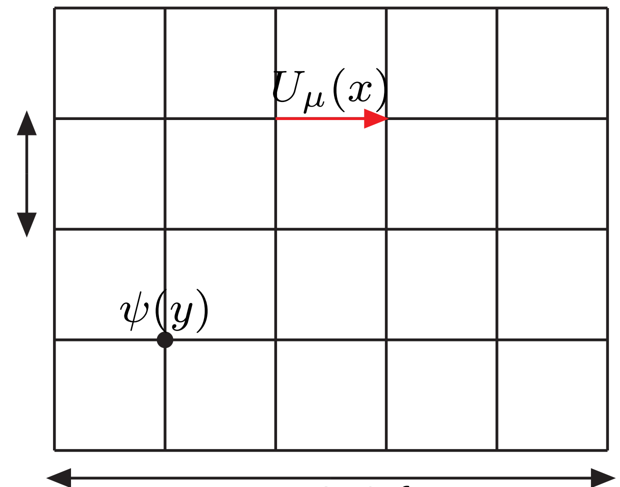
$\nwarrow$ ***power* corrections**

Lattice QCD *(non-perturbative QCD)*

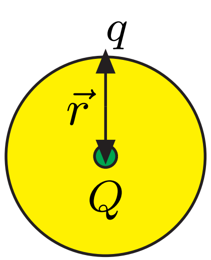
D. Becirevic, V. Bernard, B. Blossier, P. Boucaud, A. Le Yaouanc

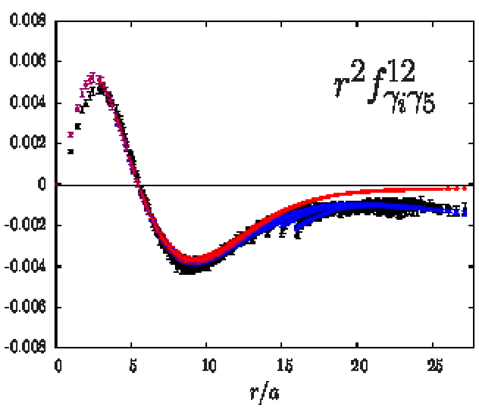
Discretization of space-time!

Statistical sample of spin configurations following Boltzmann distribution.
Spin placed on a grid: lattice QCD
Compute average of correlation functions



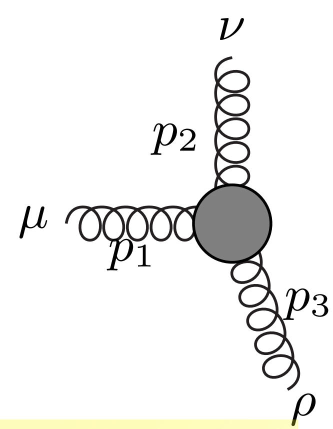
Radial excitation!





observation of node of wave function!

Fundamental coupling of QCD

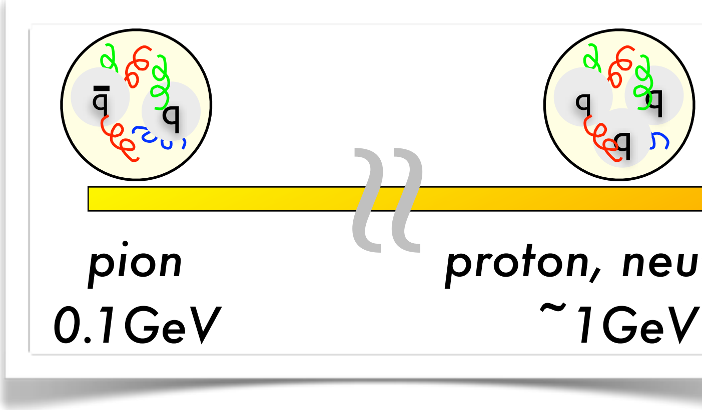


change of sign of 3-gluon vertex observed!

Study of unstable particle

Chiral perturbation theory

B. Moussallam, V. Bernard, H. Sazdjian, S. Descotes-Genon



- EFT of QCD (low energy)
  - → Physics of QCD affected by pattern of quark masses:
    Imaginary world: $1 GeV < m_u,\ m_d,\ m_s,\ m_c,\ m_b,\ m_t$
    lightest hadron is glueball

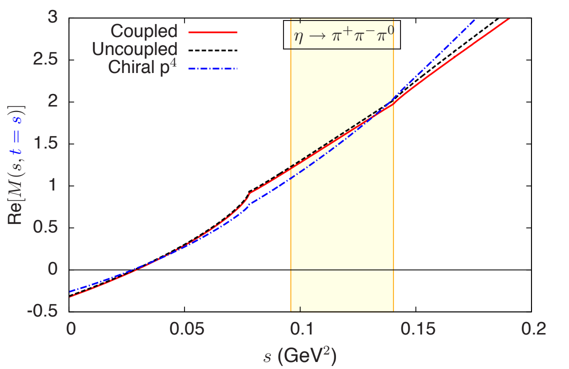
    Our world : $m_u,\ m_d,\ m_s < 1 GeV < m_c,\ m_b,\ m_t$
    lightest hadron is pion
  - → ChPT: Light quark mass expansion.

    Lagrangian formalism (classification of independent terms, classification of counterterms) to 2-loops

    but: slow convergence

Combine ChPT+Analyticity+Unitarity ⇒ improved convergence

Example: $\eta \to 3\pi$, good conv. in unphysical region, use analyticity extrapolation to physical region



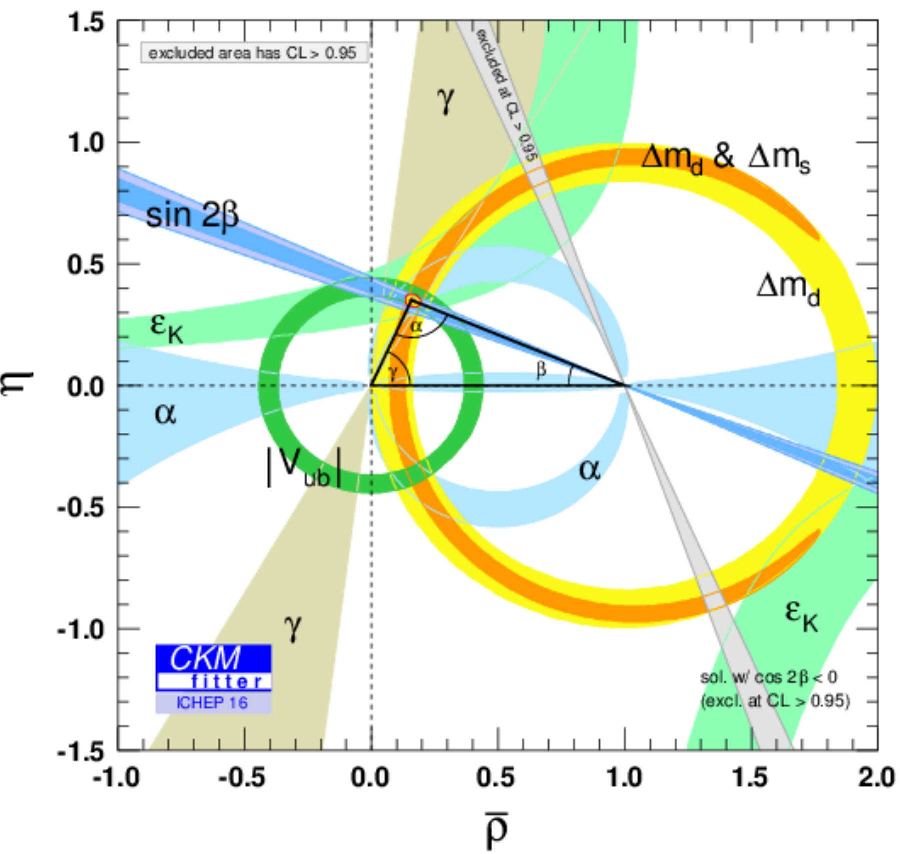
Dispersive representation

ππ, πK scattering, charmed mesons

Applying QCD methods to Phenomenology

D. Becirevic, B. Blossier, P. Boucaud, S. Descotes-Genon, M. Fontannaz, S. Wallon, A. Le Yaouanc, V. Bernard, J.-P. Lansberg, B. Moussallam, H. Sazdjian, E. Kou

Statistical method to incorporate theory uncertainties, very tricky!



To estimate theoretical uncertainties accurately, tests of validity of the QCD methods are very important!

Perturbation QCD: how well it is converging?
Lattice QCD: is the spacing small enough?
ChPT: pion mass small enough?
How about kaon, eta eta'?
etc................

Collaborations with experimentalists are crucial !

Conclusions

- *IPN-LAL-LPT have many common projects and collaborations.*
- *IPN-LAL-LPT have expertise of basic techniques in QCD.*
- *QCD is unavoidable for particle physics programs. Collaborations with experimentalists crucial.*

✻ *I gave only a few examples of the on-going works but these are only a tiny portion!*