Quantum Chromodynamics and B Physics

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Titles of lectures

- Strong Interaction
- Factorization Theorem and LHC Physics
- Quantum Mechanics in B Physics

Strong Interaction

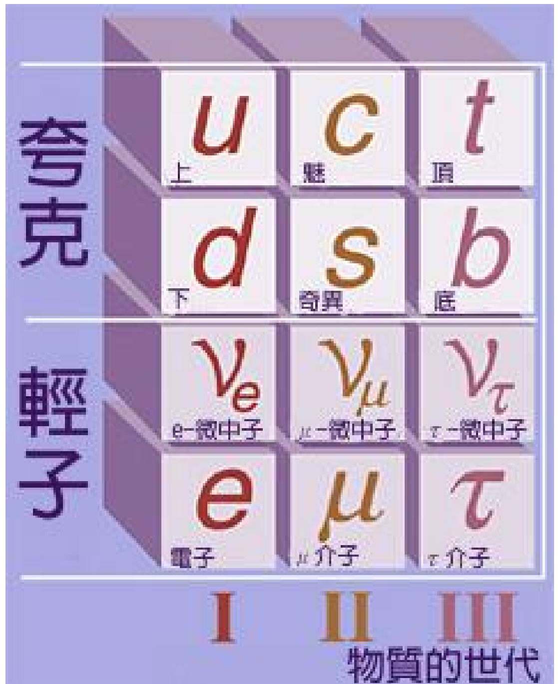
Outlines

- Introduction
- History
- Asymptotic Freedom
- Confinement
- Summary

Introduction

Understood composition of our universe

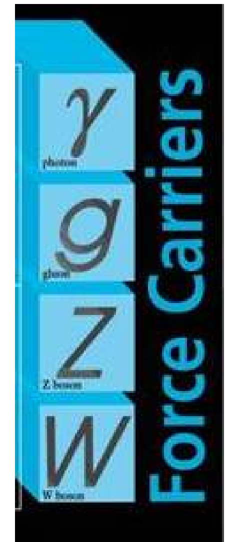
Elementary particles

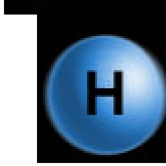


+反物質

+

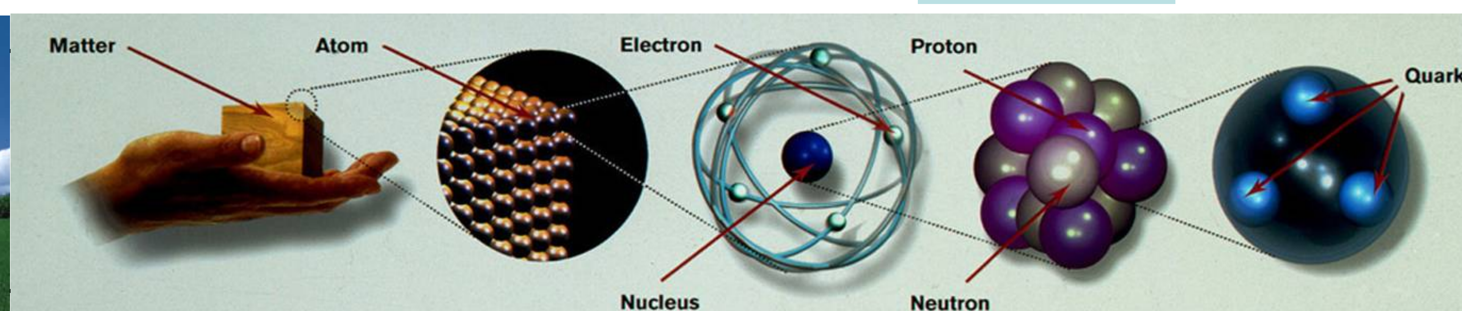
EM





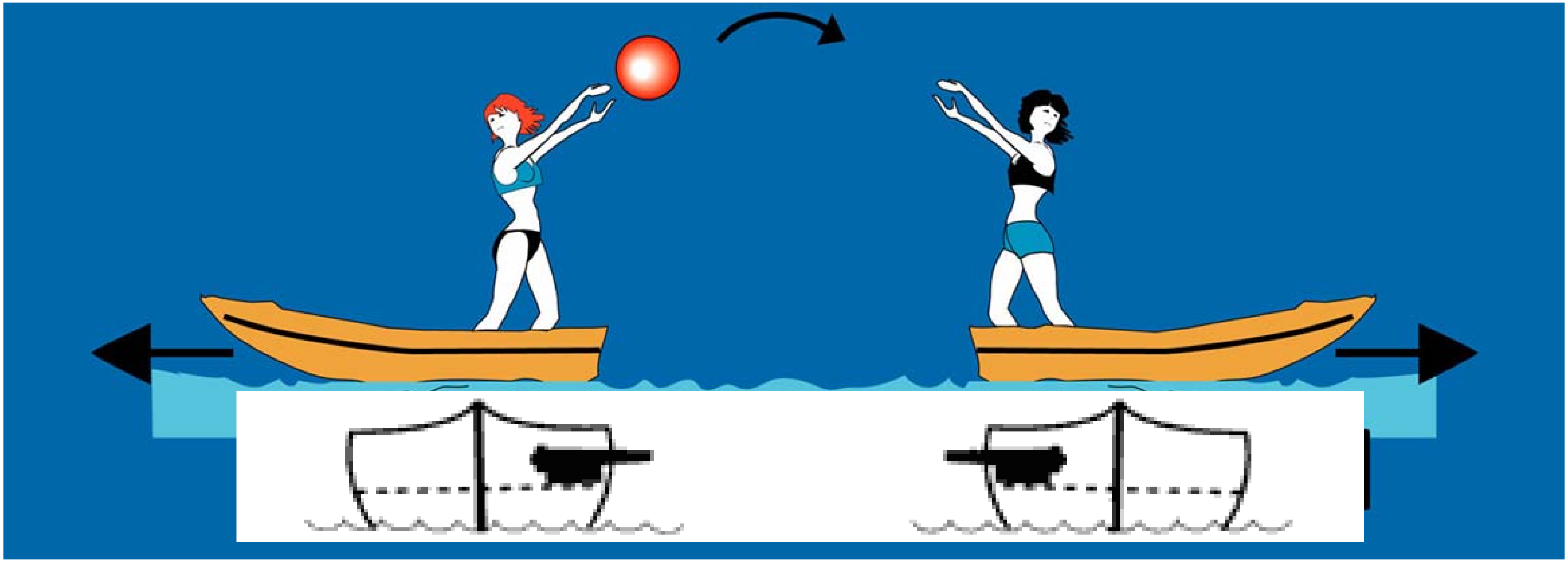
Higgs
（未被發現）

Strong

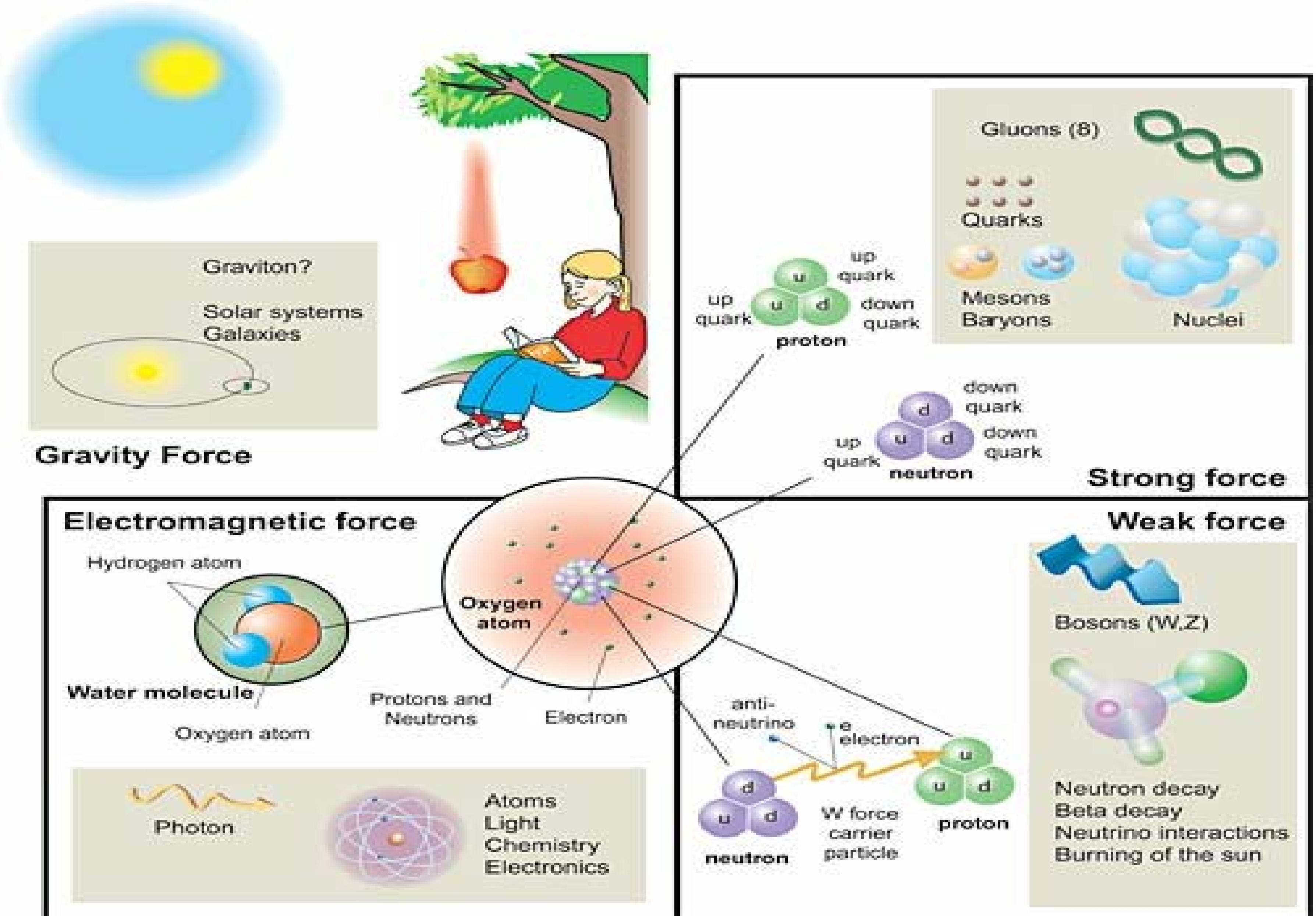


Force carriers

- Graviton propagates gravity
- Photon propagates EM force
- Gluon propagates strong interaction



4 fundamental interactions



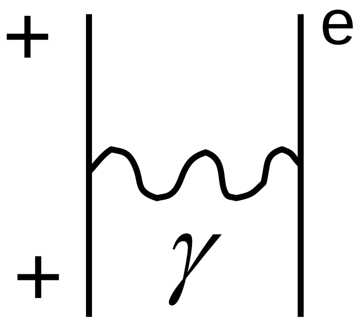
簡短描述

- 重力:決定星系,棒球的運動,無所不在
- 電磁力:控制電器,化學反應,摩擦力的來源,
  無所不在
- 弱作用力:宇宙存在的要素,感受不到,僅可
  感受其效應---陽光
- 強作用力:產生物體90%的質量,
  只存在於原子核內,感受不到

History

Electric Charges & Photons

- Our understanding of EM interaction at beginning of 20th century···
- EM interaction between electric charges through exchanging photons.
- Electron carries an electric charge, but a photon does not.
- Described by U(1): electron charge does not change as emitting a photon.
- No EM interaction between photons.
- All electric charges add into electric neutrality.



Why nucleus exists?

- Nucleus full of protons, which repel each other.
- New interaction must exist, which differs from gravity and EM force.
- New interaction ⇨ new force carrier, like EM force ⇨ photon
- Yukawa called this new carrier as meson.
- Nucleus size 10E(-13) cm, where meson propagates.
- Uncertainty principle ⇨ meson mass 100 MeV
- Strong interaction appeared. Yukawa was awarded in 1949.

Gauge Field Theories

- Describe interactions in the viewpoint of group theory (Yang, Mills 1954)
- Symmetry dictates interaction!
- EM (QED)   weak   strong (QCD)
- U(1)   SU(2)   SU(3), color charge
- It was a math model at that time.
- Effect of gluon emission

$$\begin{pmatrix} \text{3X3} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \text{red} \\ \text{blue} \\ \text{green} \end{pmatrix}$$

- Pauli: long-range forces, but not observed

Difficulties of gauge theory

- It is difficult to make sense out of gauge theory⋯
- Gauge theory is local, ultraviolet divergence (infinite energy) associated with point particle
- Systematic way to remove this divergence in order to extract physical prediction

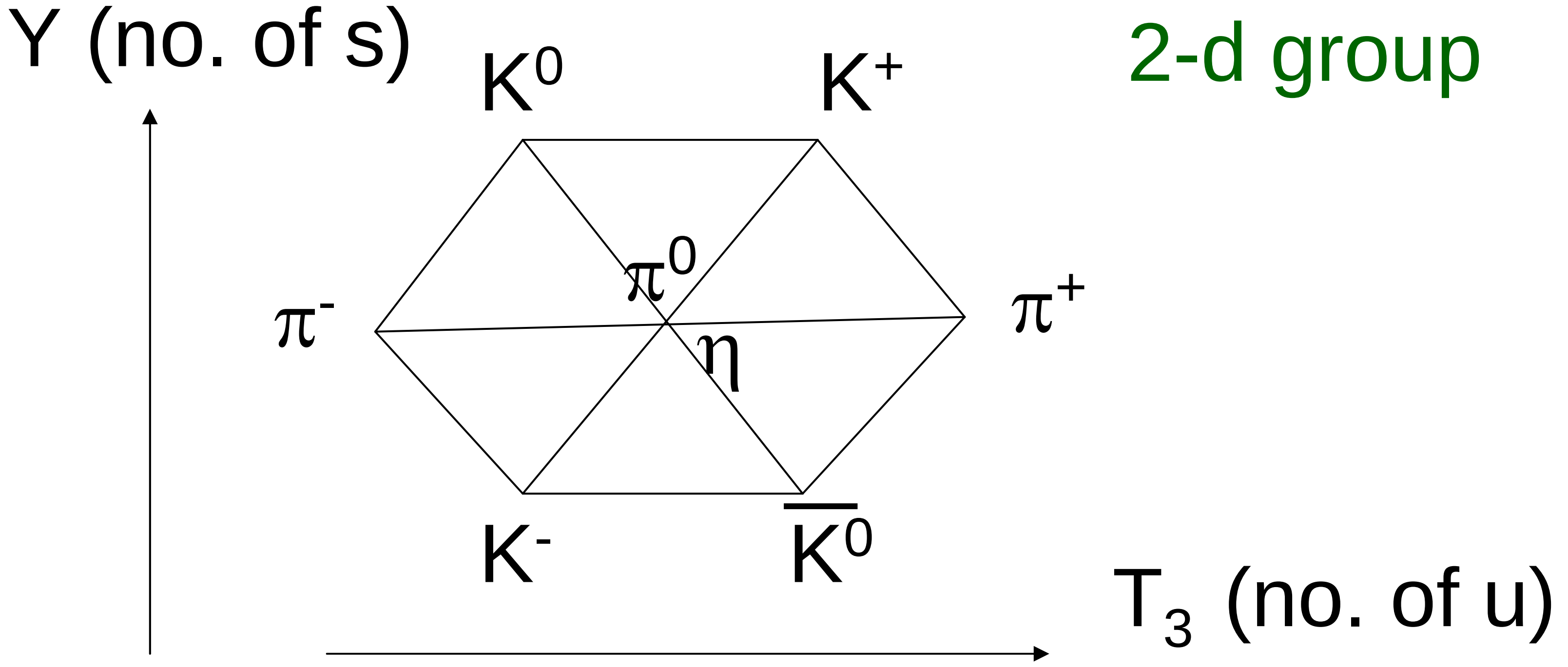
  $\Rightarrow$ Renormalization!
- A physical quantum field theory must be renormalizable

Quark Model

- Chemical "elements" are classified according to proton numbers, leading to the periodic table.
- Many "elementary" particles were found in 60's. There should exist more elementary particles.
- Gell-Mann proposed that "elementary" particles are composed of quarks (1964).
- "Elementary" particles were classified, and new particles were predicted.

Eightfold Ways

- Quark was only a math identity, not real.
- DIS at SLAC indicated existence of "quarks" inside a proton at the end of 60's.



Deep inelastic scattering

- DIS at SLAC showed something like quarks inside a proton at end of 60’s.
- Gell-Mann was awarded in 1969.
- No interaction among quarks, like free particles.
- Incredible, because interaction should get stronger, when particles are closer.
- If free particles, why can’t get quarks out of a proton
- DIS was awarded in 1990.

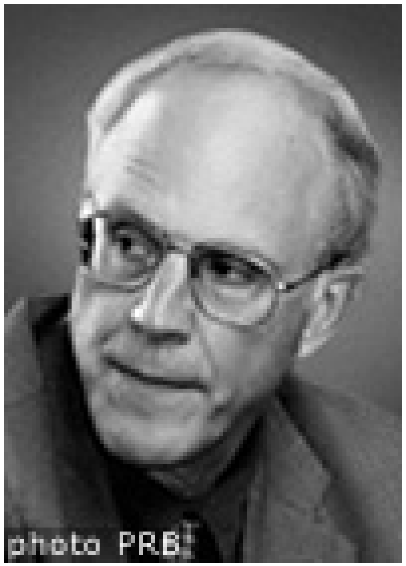
People were puzzled, when pieces of knowledge could not be connected together

Asymptotic Freedom

Gross, Politzer, Wilczek

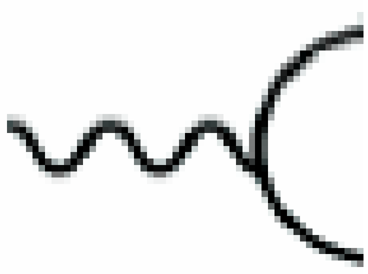
Nobel prize 2004

2004 Nobel Prize awarded to



David J. Gross
Kavli Institute for Theoretical Physics, University of California, Santa Barbara, USA,
H. David Politzer
California Institute of Technology (Caltech), Pasadena, USA, and
Frank Wilczek
Massachusetts Institute of Technology (MIT), Cambridge, USA

Vaccum $\neq$ empty



$$\Delta t \Delta E \sim h$$

Violate energy conservation $\Delta E \neq 0$

Impossible in classical mechanics $h = 0$

Allowed in quantum mechanics

As long as electrons exist in

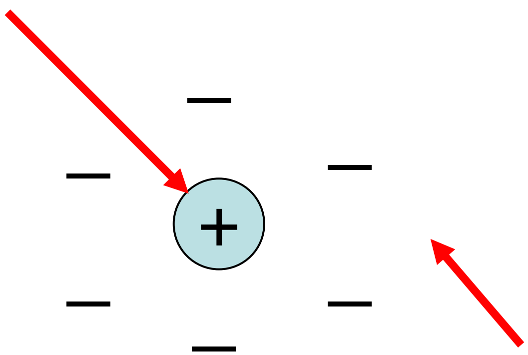
A sufficiently short time. $\Delta t \to 0$

Vacuum Polarization

Electron and positron pop out from the vacuum

Short distance
(high energy)

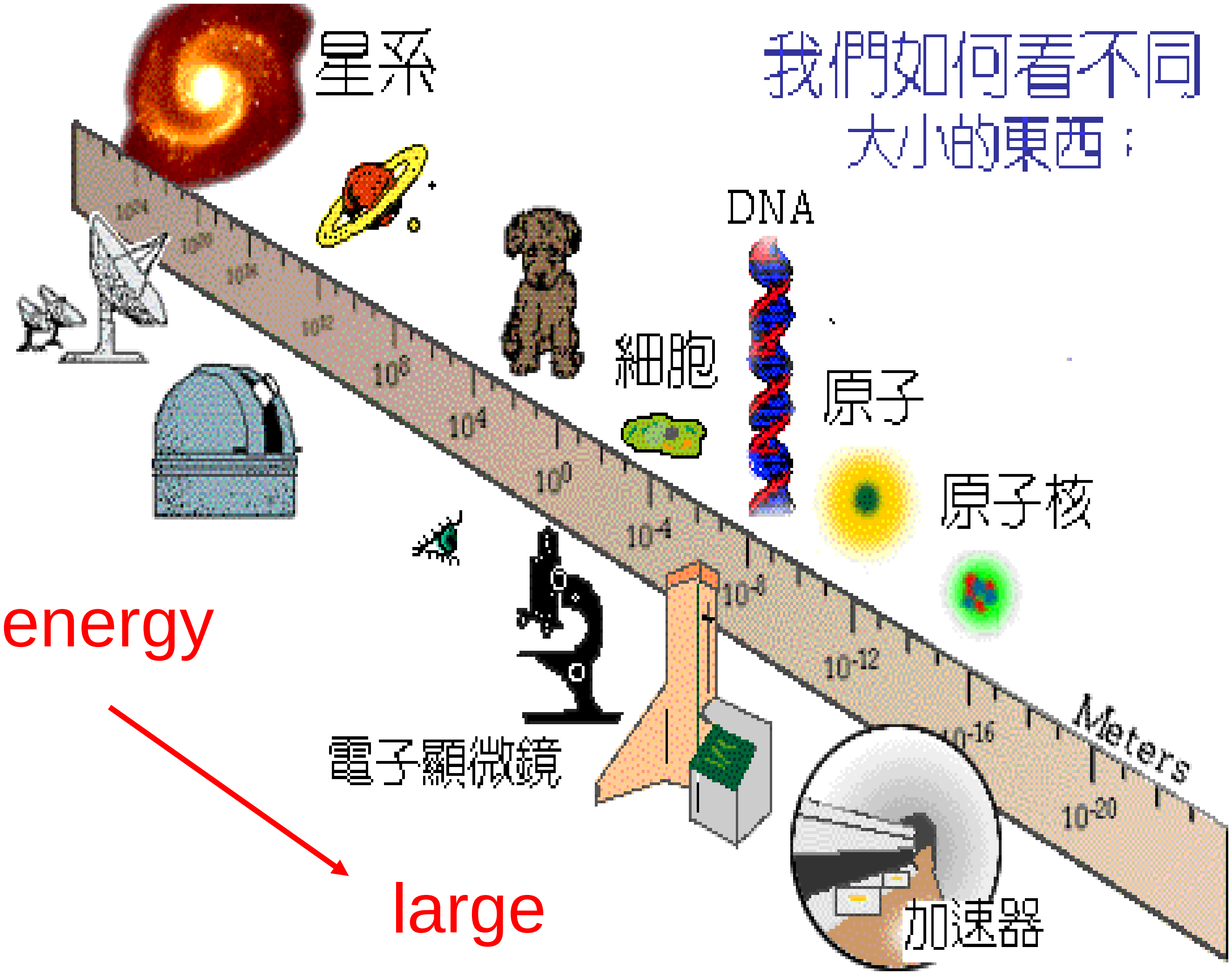
More positive
charge



Measured e varies
with energies

Long distnace
(low energy)
less positive
charge

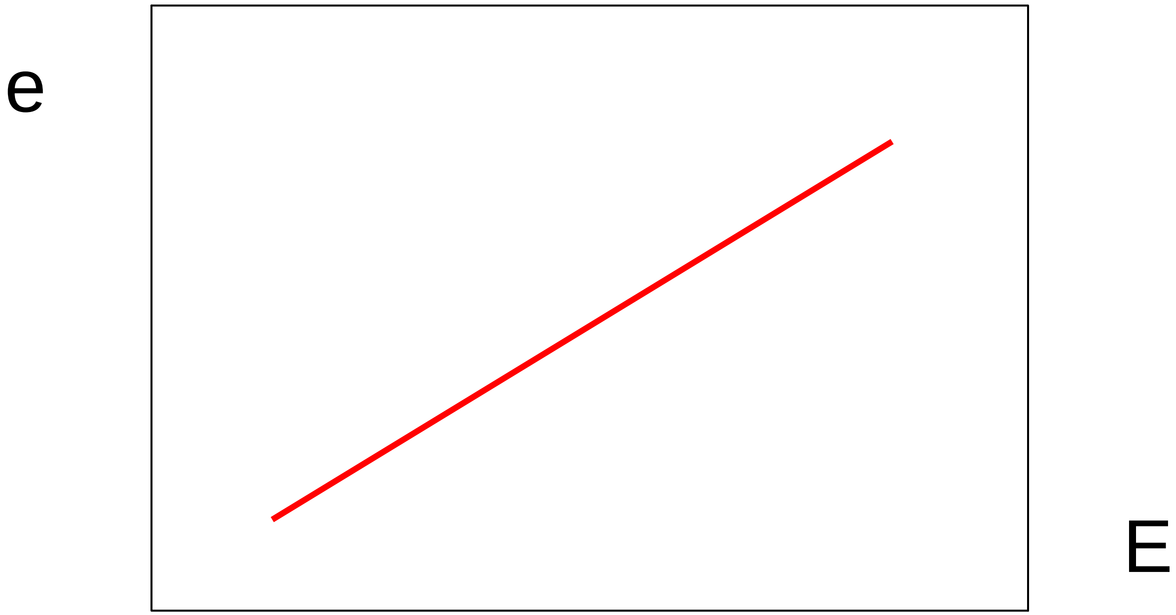
Distance vs. energy



energy

large

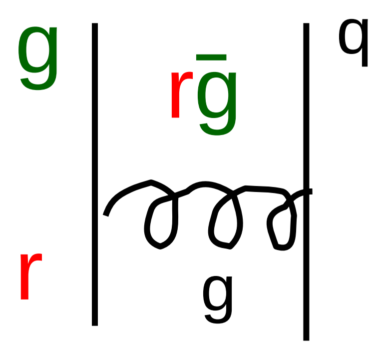
EM interaction → screening effect

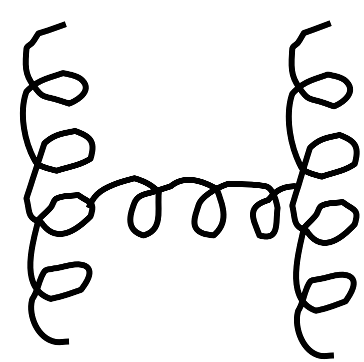


Precision measurement of hydrogen atom’s energy levels has confirmed this effect, Lamb shift (Nobel prize,1955)

Color Charges & Gluons

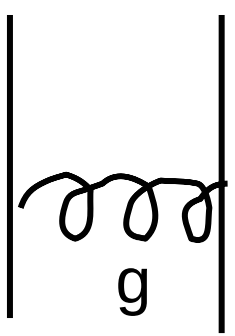
- Strong interaction between color charges through exchanging gluons.
- Both quark and gluon carry color charges.
- Strong interaction between gluons.
- Electric charges: positive and negative; color charges: red, blue, green
- All color charges add into color neutrality.



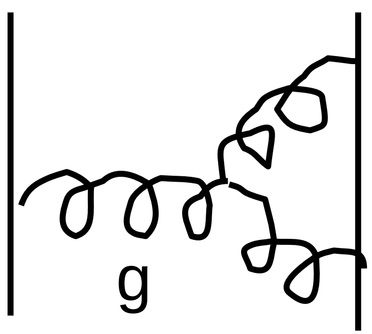


Nonlinearity of QCD

- Gluon-gluon interaction corresponds to nonlinearity of QCD.
- Field strength between two quarks:



linear



nonlinear

Anti-screening of QCD

Vacuum ≠ empty,
full of gluons

Screening

Gluon carries color

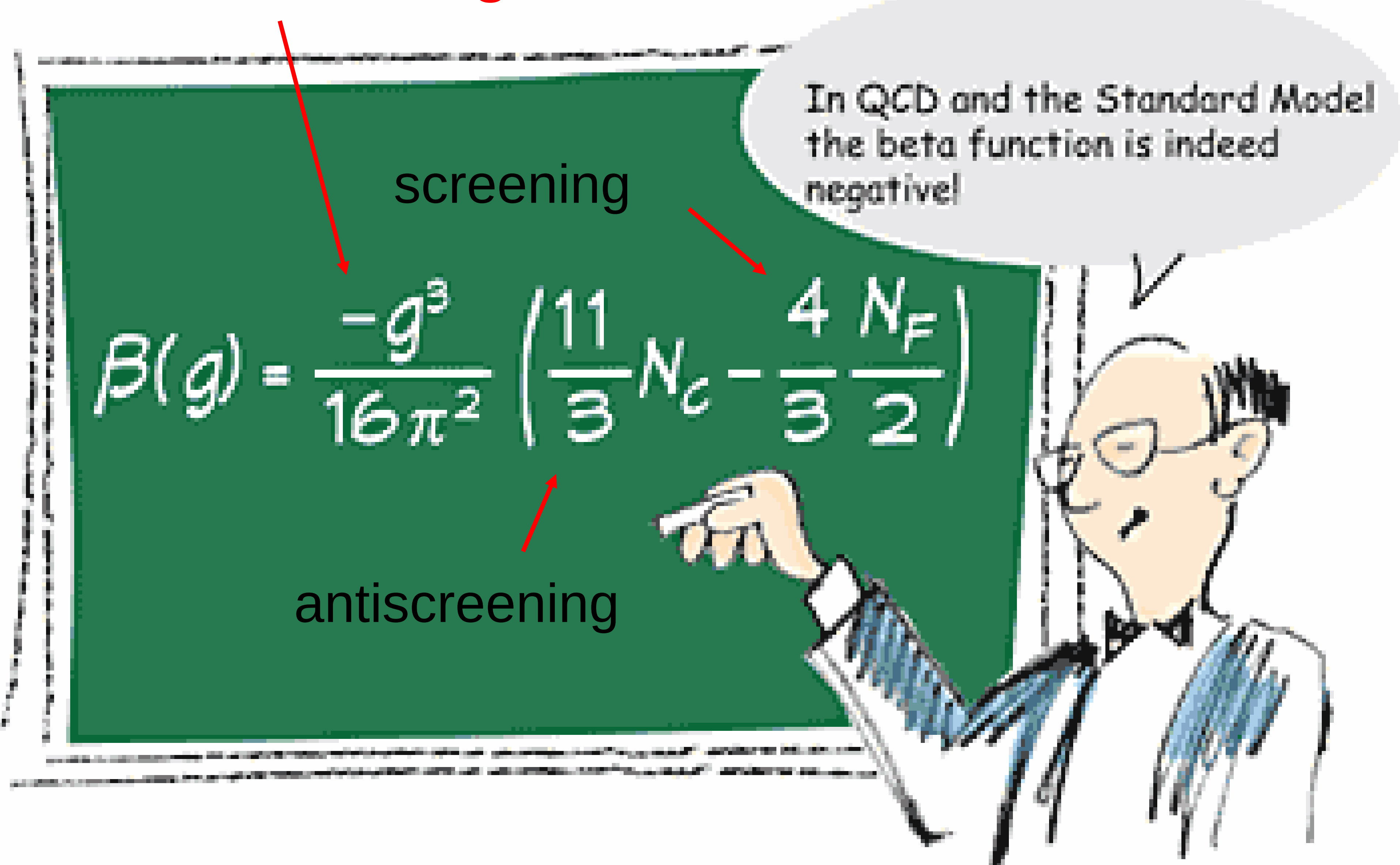
Anti-screening

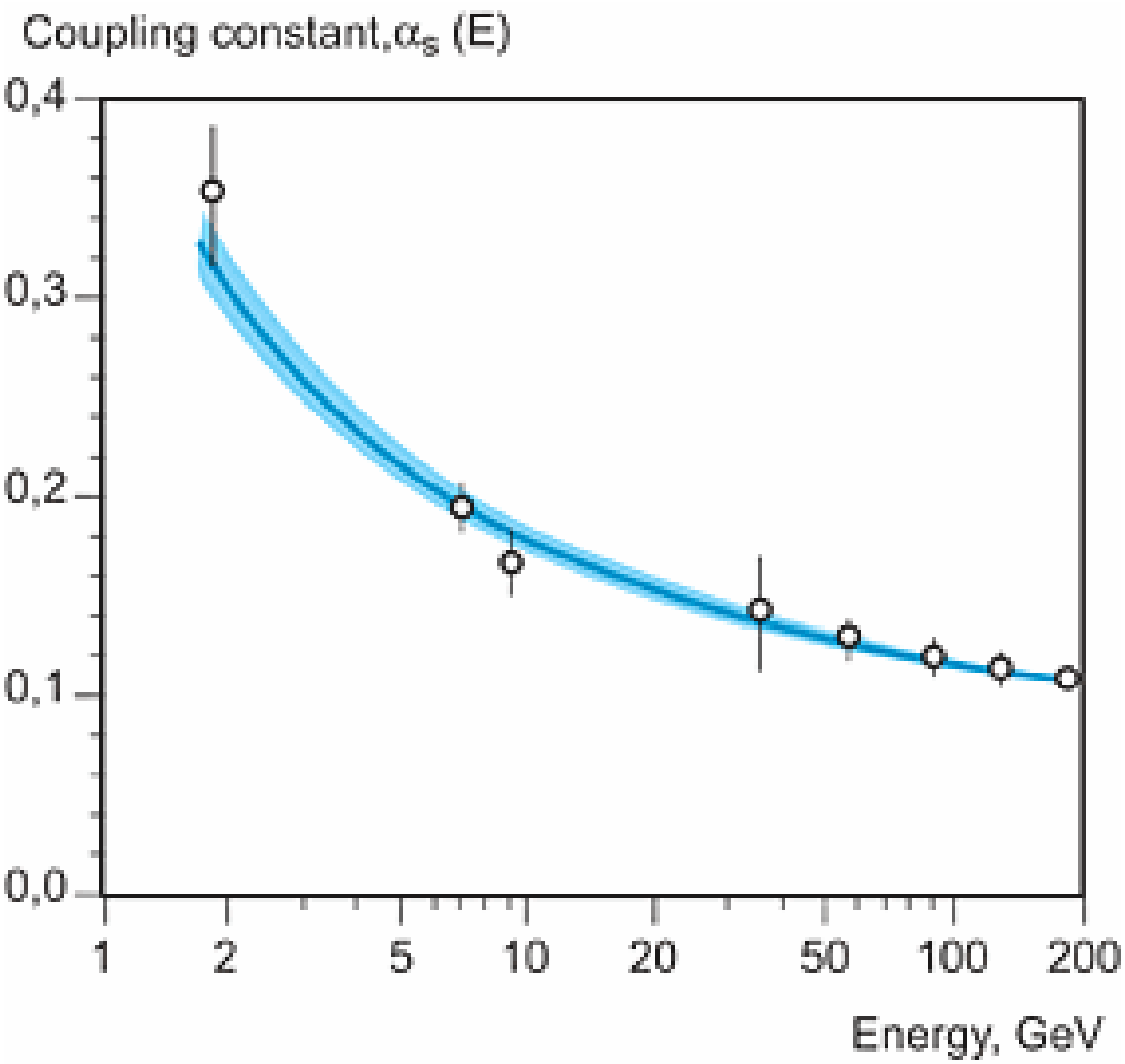
Anti-screening > screening

Beta function

- T'Hooft, Veltman renormalized gauge theory in 1971.
  - Gauge theory was then applicable to meaningful calculation.
- T'Hooft, Veltman were awarded in 1999.
- Sign of beta function determines relation of interaction to energy.
- Beta function of EM (strong) force has a plus (minus) sign.
  - Gross, Wilczek (Apl. 27, 1973), Politzer (May 3, 1973) published beta function of SU(3) gauge theory.

This minus sign worth of million dollars





Coupling decreases (freedom)

Opposite to EM

High energy (asymototic)

Suddenly…

- Gell-Mann’s quarks are not math identity.
- Interaction among quarks is described by gauge theory.
- Quarks behave like free particles at high energy (long distance).
  - Gauge theory is no math model, but real physics.
  - 3 in SU(3) means 3 colors $\Longrightarrow$ QCD.
- Quarks can not be separated. They form bound states at long distance.
- Yukawa’s meson model describes interaction among bound states.

Confinement

Next Nobel prize in QCD

Ionization of an Atom

- Atom is a bound state of a nucleus and electrons.
- They are bounded by Coulomb's potential energy, electromagnetic (EM) interaction,

$$V(r) = ((+Z)\, e)\, (-e)\, /r$$

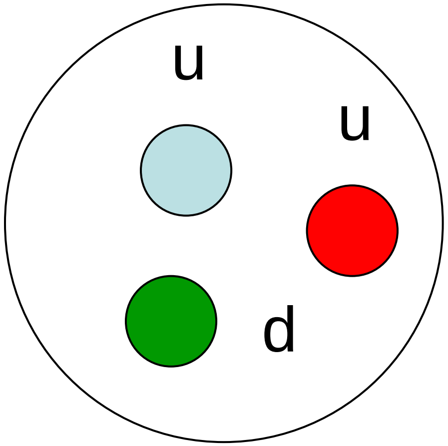
- Can see a free electron via ionization

$$A(\mathrm{g}) \rightarrow A^{+}(\mathrm{g}) + e^{-}(\mathrm{g})$$

- Ionization energy is finite.

Confinement of Quarks

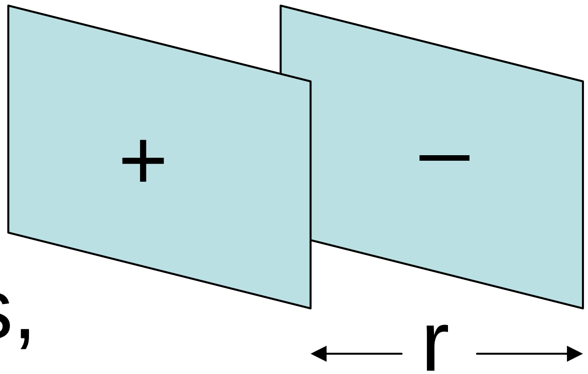
- Hadron is a bound state of quarks, such as pion, proton, neutron,…
- They are bounded by strong interaction, color potential energy.
- Never see free quarks,
  no matter how much energy
  is supplied.
- Why is the confinement?



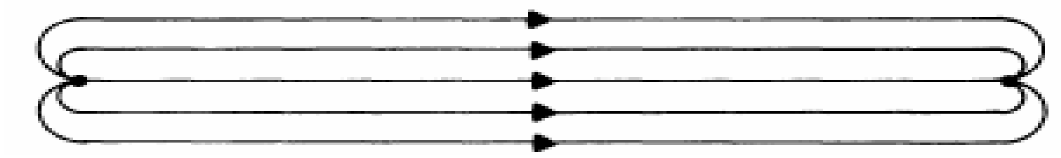
Flux Tube

- To produce a strong potential, consider 1-dim QED
- E=constant, $V \propto r$
- Field lines are parallel
- To separate the two plates, infinite energy is needed

  $\Rightarrow$ confinement



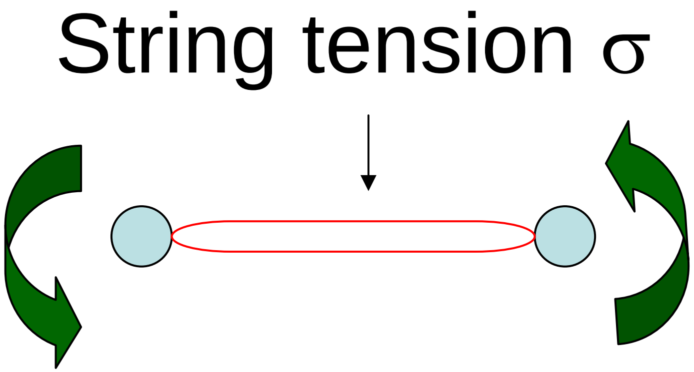
- Conjecture: field lines between a pair of quarks are deformed into a tube.



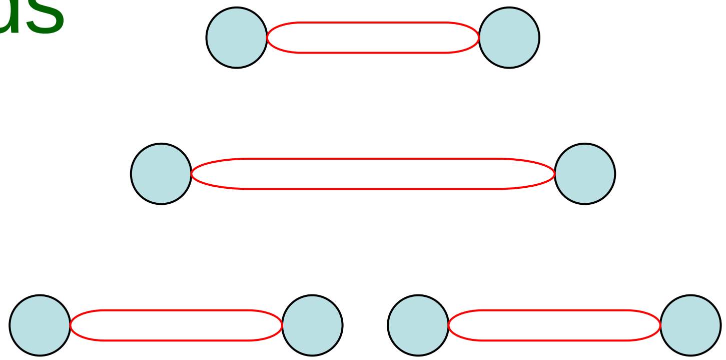
String Model

- Regge trajectory
- $J=E^2/2\pi\sigma$

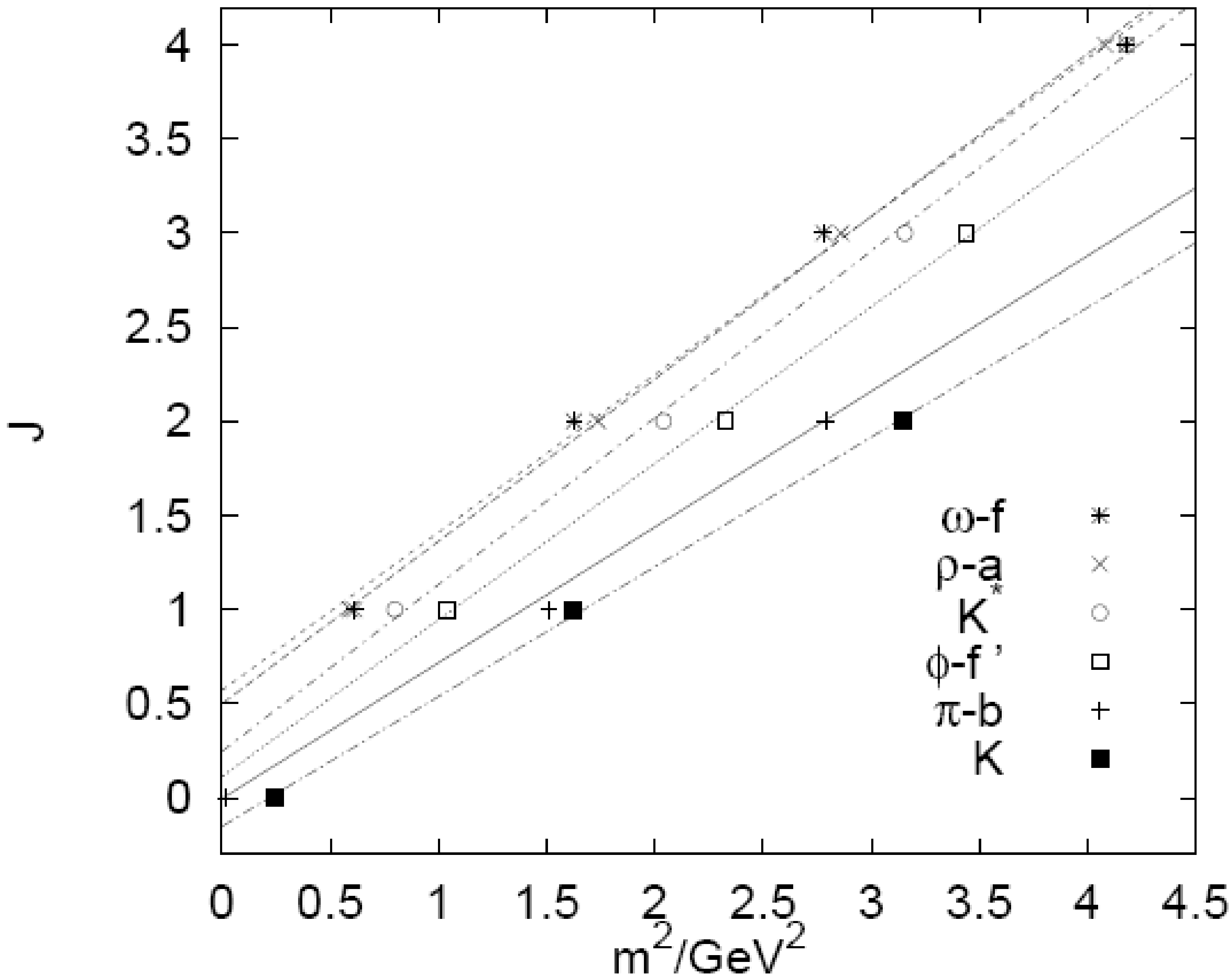
spin, mass



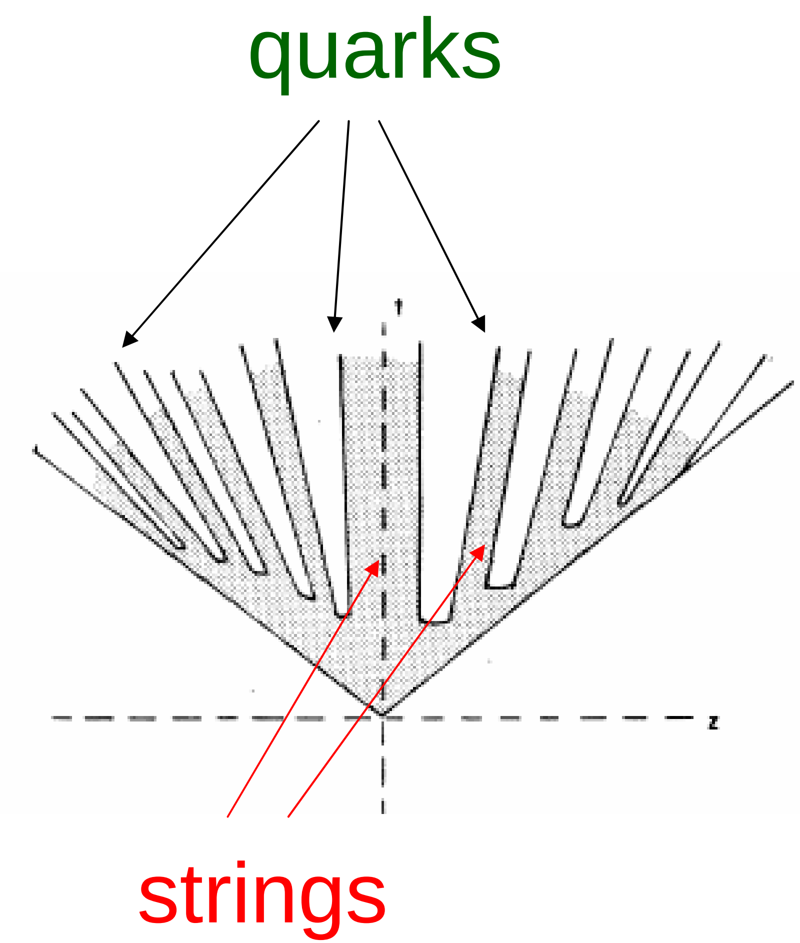
- Multiplicity
- As dosed energy exceeds the mass of quark pair, string breaks, and new pair appears

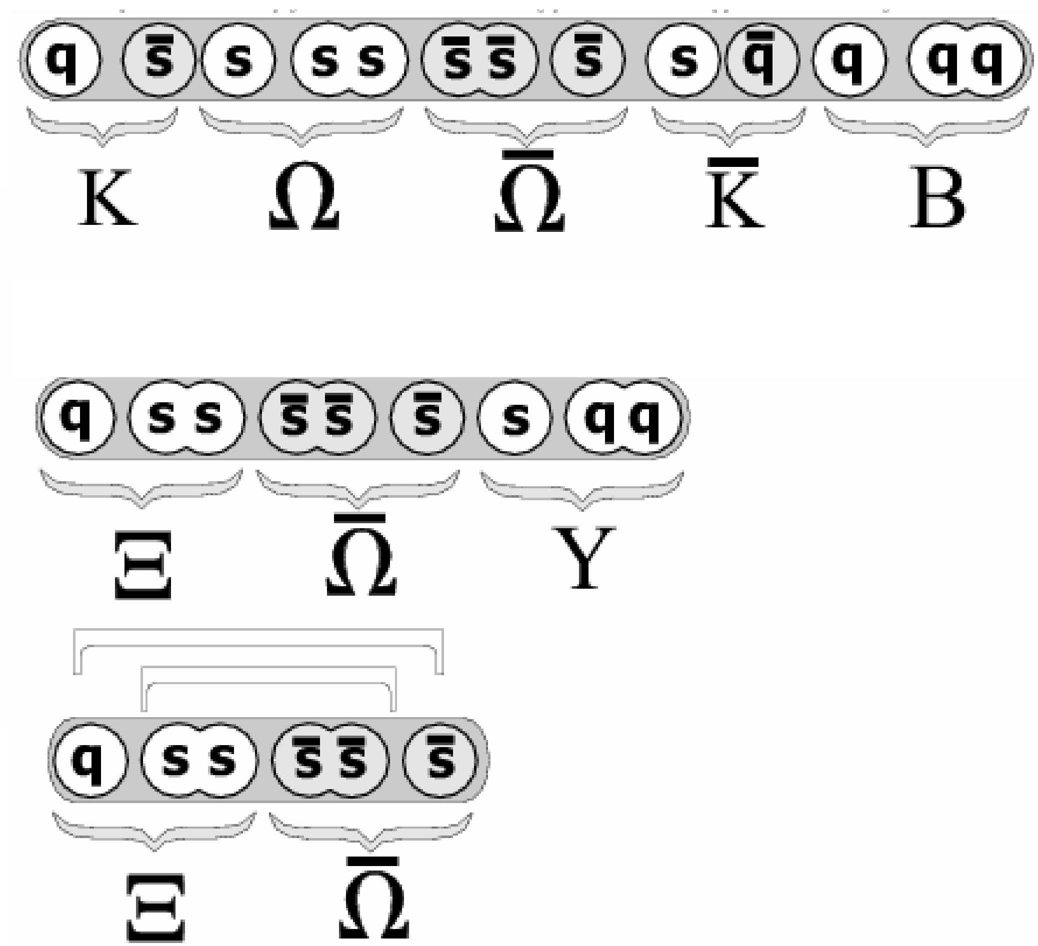


Regge Trajectory



Multiplicity dn (No. particles)/dy (rapidity)

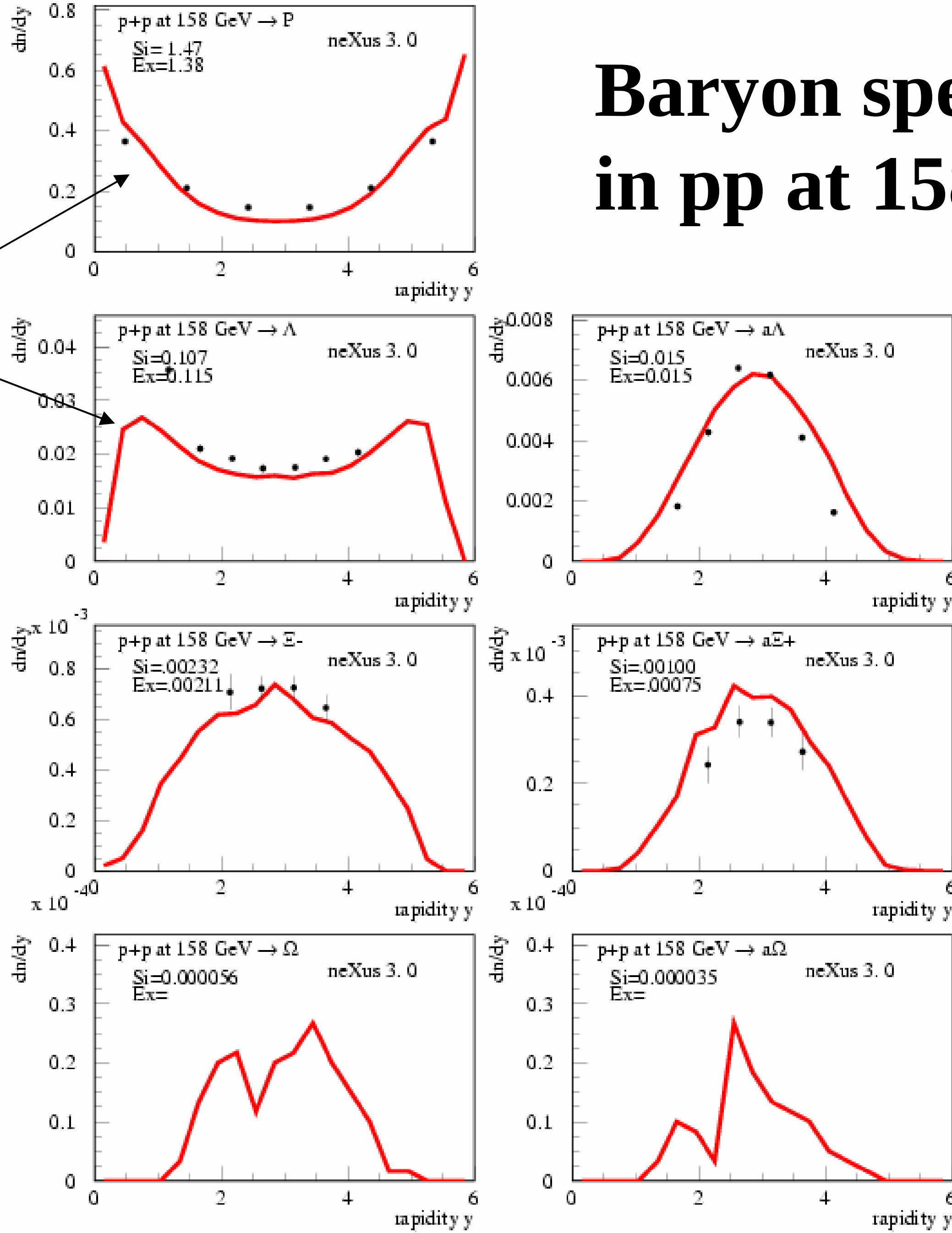




Baryon spectra in pp at 158 GeV

Leading particles

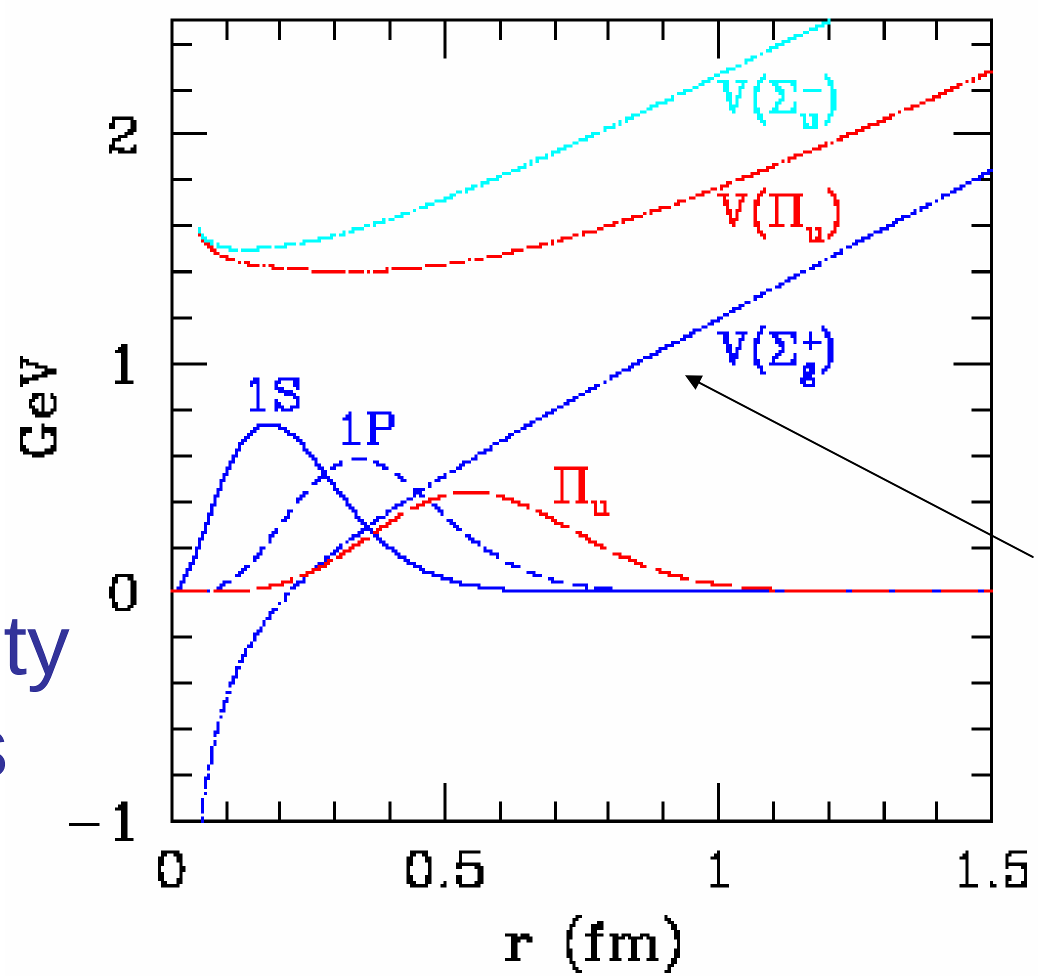
(mainly from remnants)



Gribov-Regge Theory: (FM Liu et al)

Data: NA49

Lattice QCD (Juge et al.)



different gluonic excited states

Radial Probability densities

Fit to $V_0+e/r+\kappa\ r$

Static quark potentials

Our understanding of confinement mainly comes from numerics.

No one solves QCD after decades

Factorization theorem and LHC physics

Outlines

- Introduction
- Factorization theorem
- Application
- LHC physics
- Summary

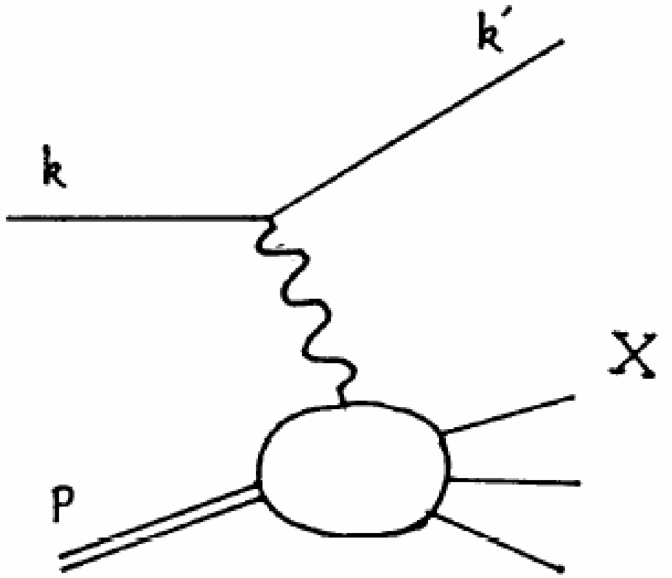
Introduction

- QCD Lagrangian $\mathcal{L} = \bar{\psi}(iD^{\mu}\gamma_{\mu} - m)\psi - F^{\mu\nu}F_{\mu\nu}/4$
- ψ: quark field, F: gluon field strength
- Confinement at low energy, hadronic bound states: pion, proton, B meson,…
- Asymptotic freedom at high energy: a small coupling constant $\Rightarrow$ perturbation
- Test QCD at hgih-energy scattering!
- Nontrivial due to initial hadrons
- A sophisticated prescription is necessary ---factorization theorem

Factorization theorem

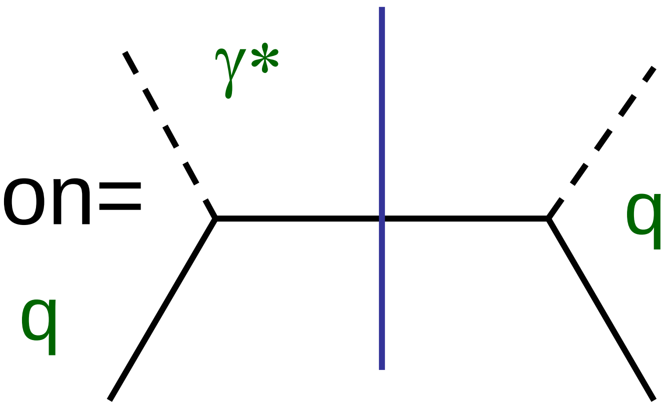
Deep inelastic scattering

- Electron-proton DIS $l(k)+N(p)\rightarrow l(k')+X$
- Large momentum transfer $-q^2=(k-k')^2=Q^2$
- Calculation of cross section σ requires the nonperturbative quark distribution in the proton
- Is it possible to factor the perturbative part, and the nonpert part is left for other methods?



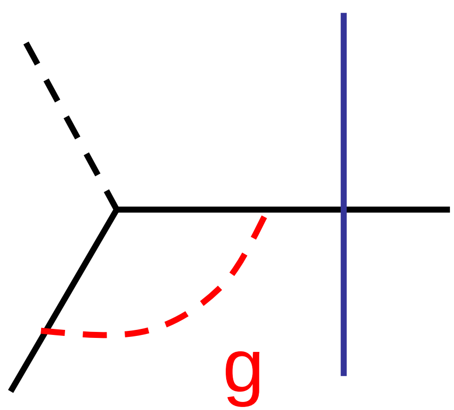
Feynman diagrams

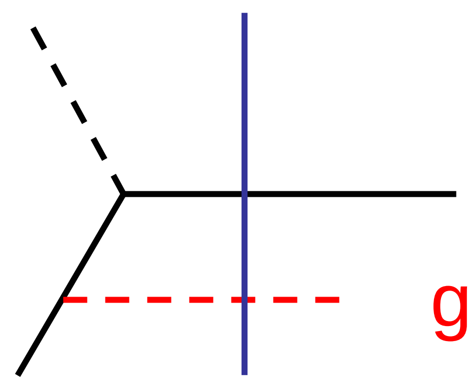
- Lowest order
- Cross section=



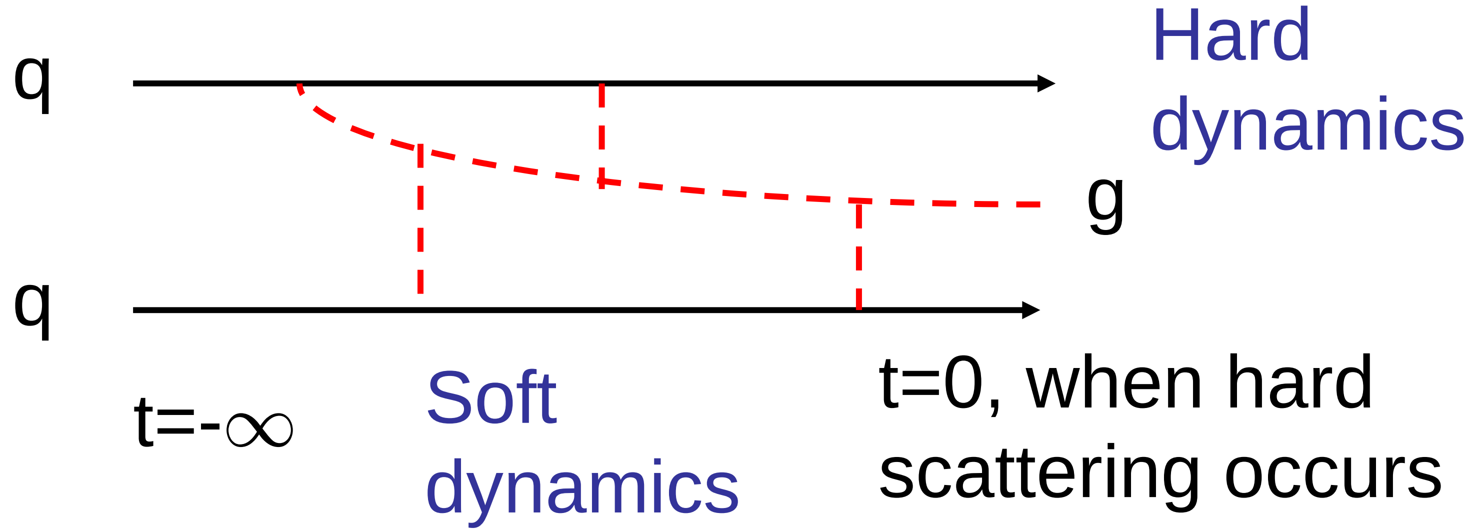
|amplitude|^2

- Next-to-leading order, infrared div, except for UV div





IR divergence is physical!



- It’s a long-distance phenomenon, related to confinement.
- All physical hadronic high-energy processes involve both soft and hard dynamics. How to test QCD?

Parton model

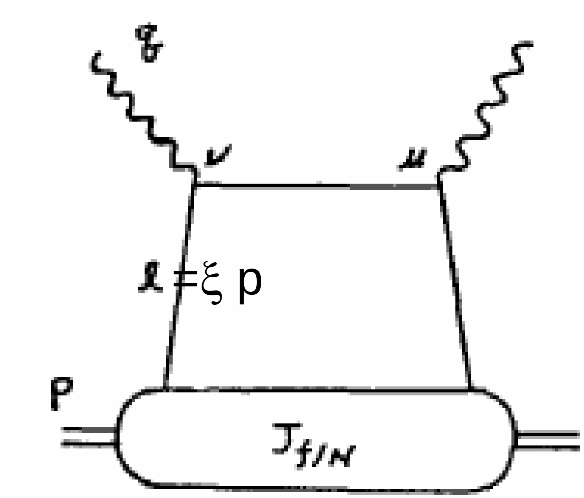
- The proton travels huge space-time, before hit by the virtual photon
- As $Q^2 \rightarrow \infty$, hard scattering occurs at point space-time
- The quark hit by the virtual photon behaves like a free particle
- It decouples from the rest of the proton
- Cross section is the incoherent sum of the scattered quark of different momentum
- Just need to know the probability of the quark carrying a momentum fraction ξ

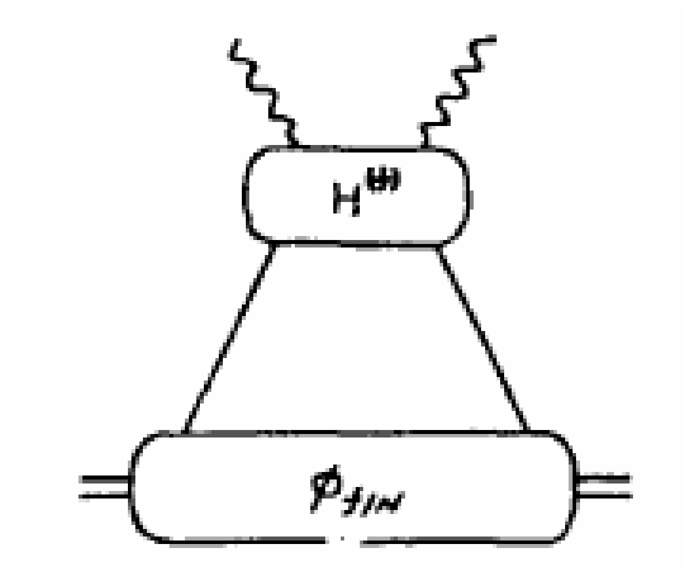
Factorization formula

- Define Bjorken variable $x=Q^2/(2p\cdot q)$
- Following the parton model, the factorization formula for DIS
- $F(x)=\sum_f \int_x^1 (d\xi/\xi) H_f(x/\xi)\phi_{f/N}(\xi)$
- F: structure function for cross section
- H_f: hard kernel, cross section of the quark f, calculable in perturbation theory
- $\phi_{f/N}$: parton distribution function (PDF) for quark f in N, $\int_0^1 \phi_{f/N}(\xi)d\xi=1$

Factorization picture

- Lowest-order $H_f^{(0)}$, all-order H_f





$Q^2/(\xi\ p\cdot\ q)=x/\xi$

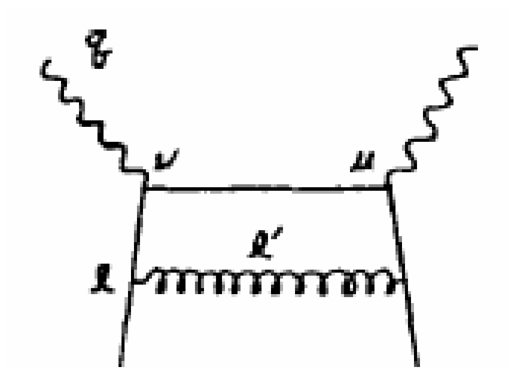
Parton distribution function

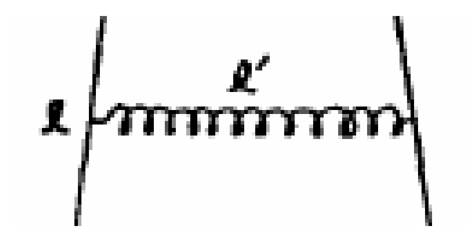
- PDF is defined by a matrix element of a nonlocal operator
- $\phi_{f/N}(\xi)=\int dy^-/(2\pi)\exp(i\xi\, p^+y^-)$
  $\langle N(p)|\bar{f}(y^-)\gamma^+W(y^-,0)f(0)|N(p)\rangle$
- $W(y^-,0)$: Wilson link for gauge invariance
- PDF can be computed by nonperturbative methods, like lattice QCD, or extracted from experiment data
- PDF is universal (process-independent)

Application

Hard kernel

- PDF is infrared divergent, if evaluated in perturbation ⇔ confinement
- Quark diagram is also IR divergent.
- Difference between the quark diagram and PDF gives the hard kernel H^{DIS}

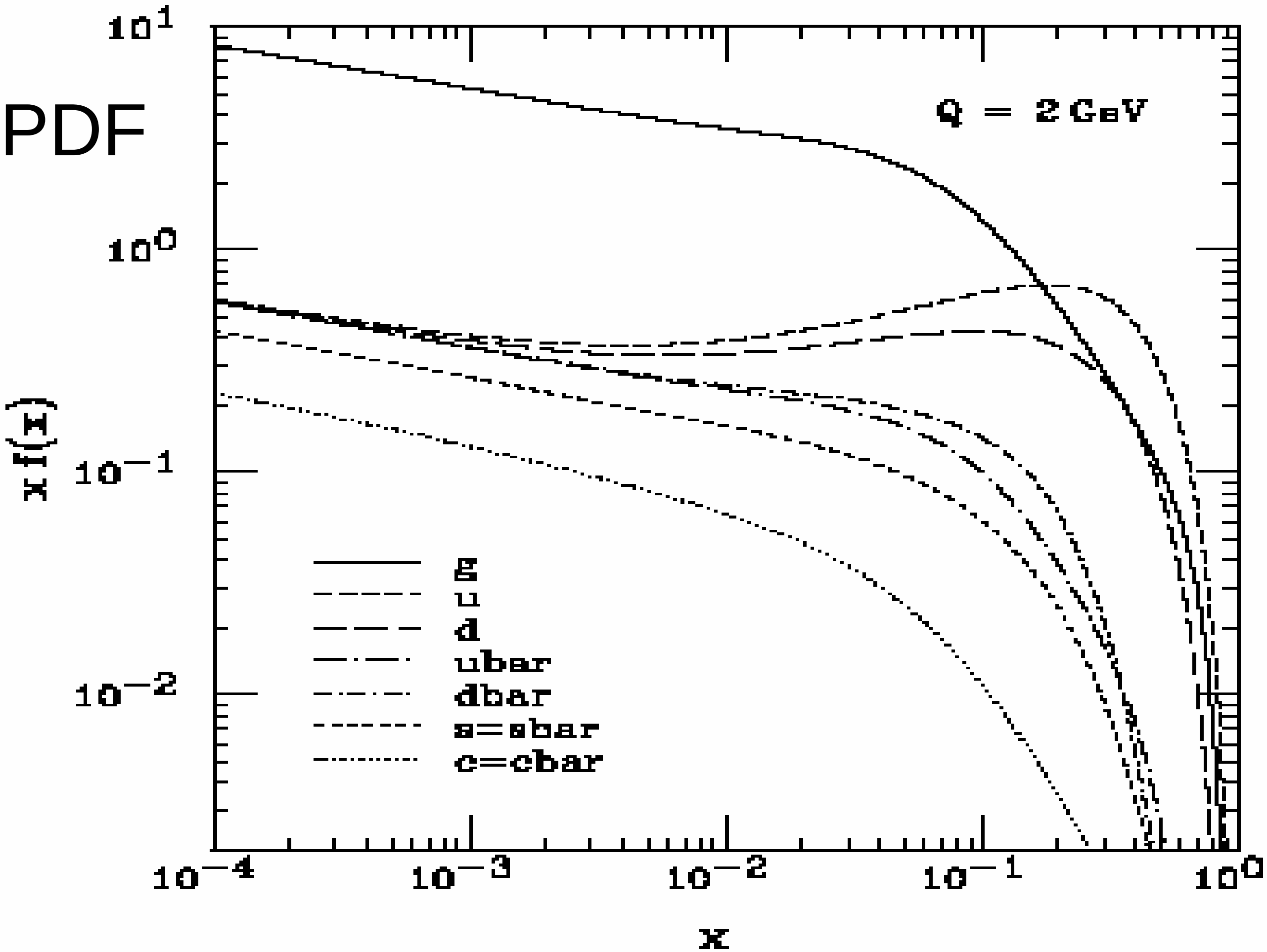
$H^{DIS}=$ 

$-$ 

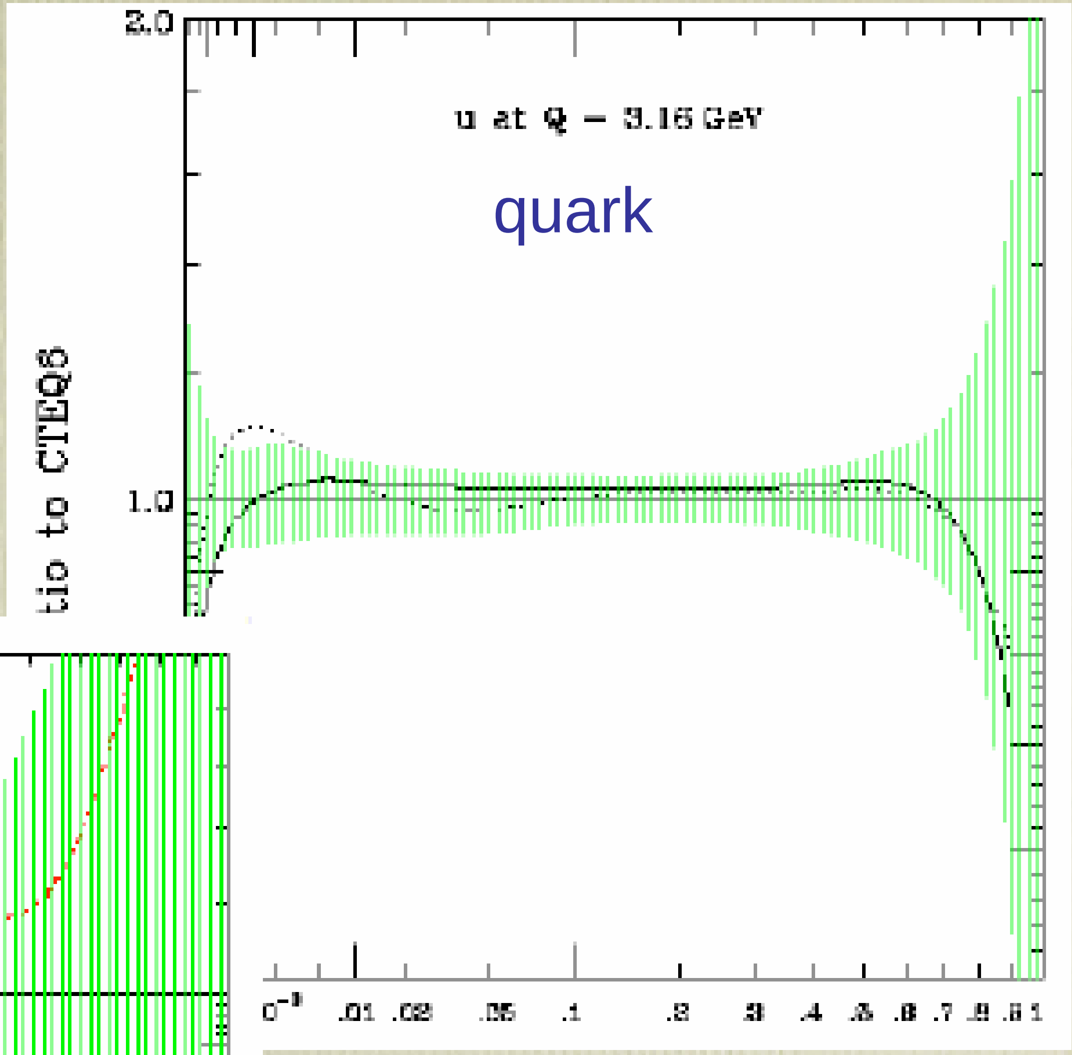
Extraction of PDF

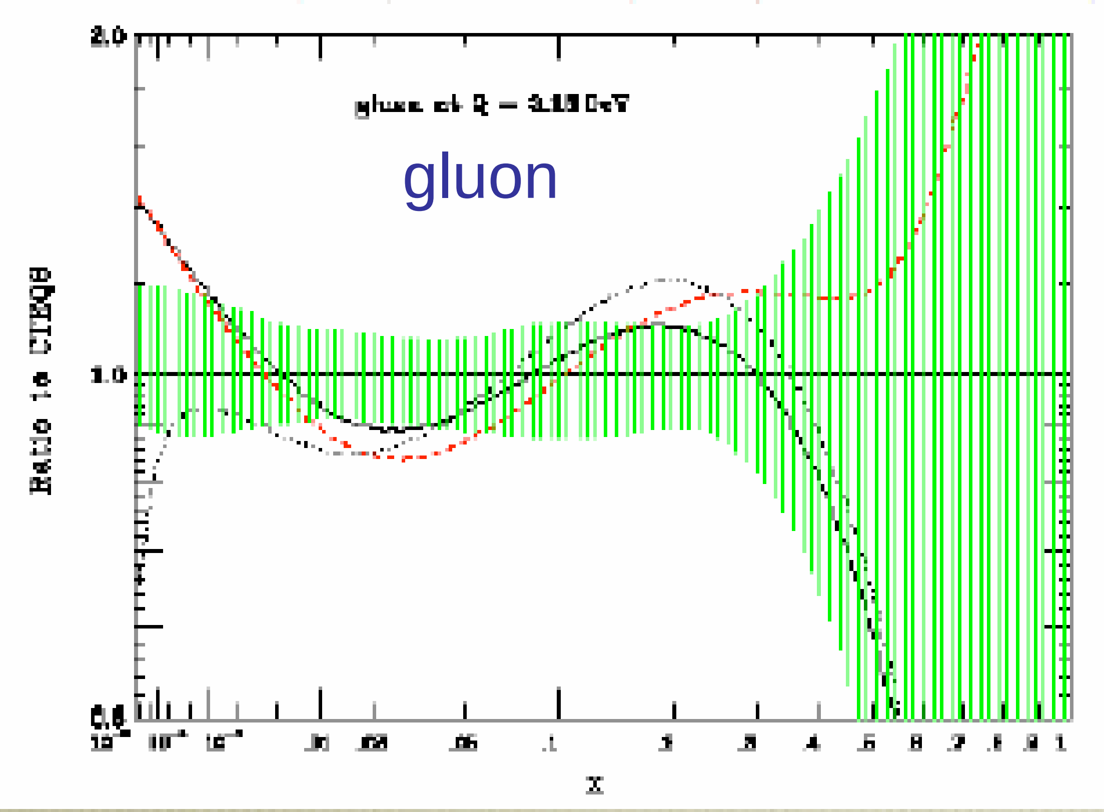
- Fit the factorization formula $F=H^{DIS}\otimes \phi_{f/N}$ to DIS data. Extract $\phi_{f/N}$ for f=u, d, s,…,g(luon)

CTEQ PDF



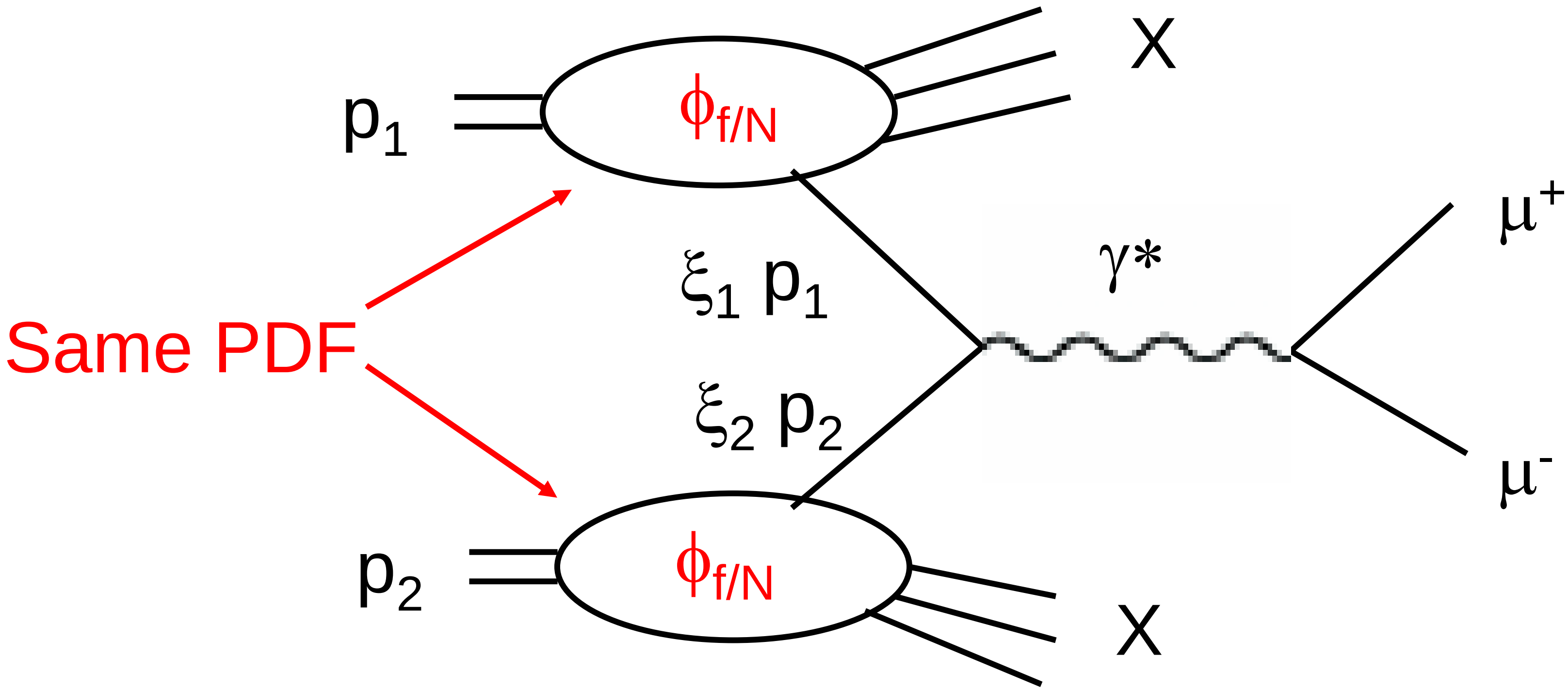
PDF uncertainties





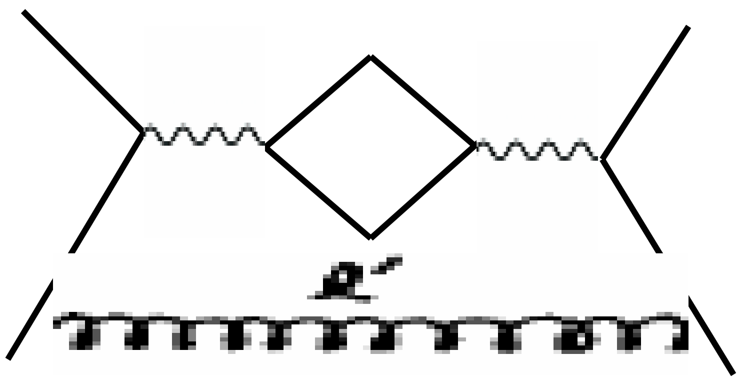
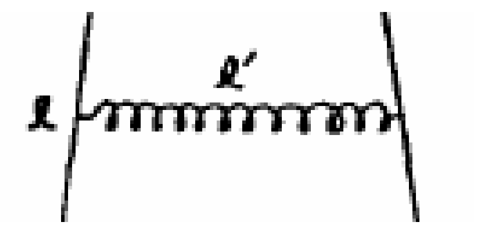
Drell-Yan process

- Derive factorization theorem for Drell-Yan process $N(p_1)+N(p_2) \to \mu^+\mu^-(q)+X$



Hard kernel for DY

- Compute the hard kernel H^{DY}
- IR divergences in quark diagram and in PDF must cancel. Otherwise, factorization theorem fails

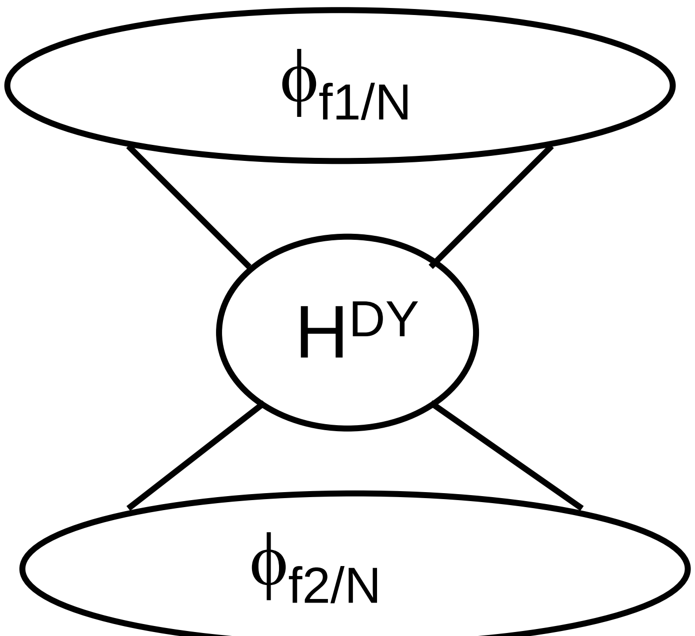
$H^{DY} =$  $-$ 

Same as in DIS

Prediction for DY

- Use $\sigma^{DY} = \phi_{f1/N} \otimes H^{DY} \otimes \phi_{f2/N}$ to make predictions for DY process

$\sigma^{DY} =$



Factorization scheme

- Definition of an IR regulator is arbitrary, like an UV regulator:
  $\phi^{(1)} \propto 1/\varepsilon_{IR}$+finite part
- Different finite parts correspond to different factorization schemes.
- Hard kernel depends on schemes
- Extraction of a PDF depends not only on powers and orders, but on schemes.
- Must stick to the same scheme. The dependence of predictions on factorization schemes would be minimized.

LHC physics

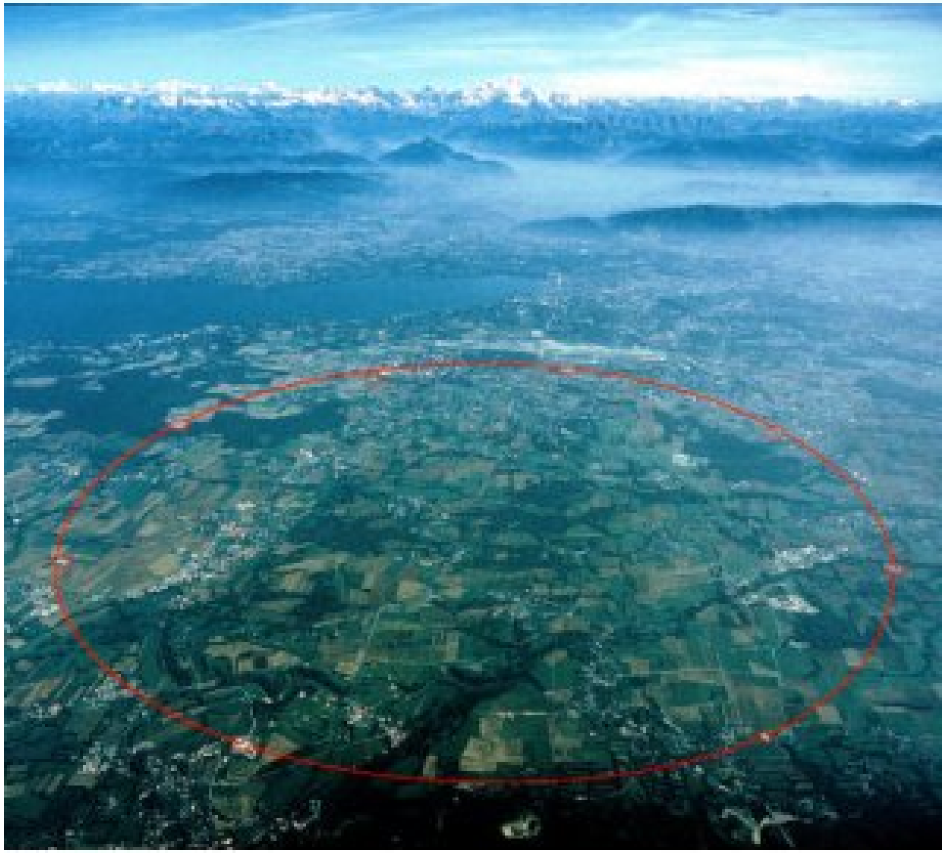
LHC will answer

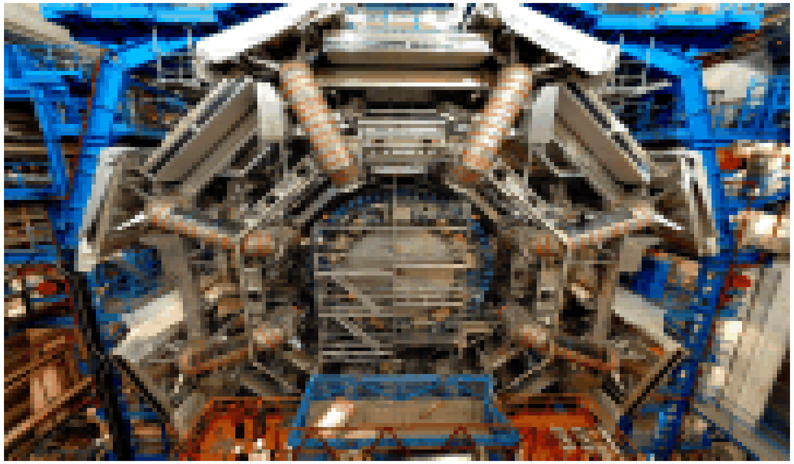
- why masses are what they are?
- why neutrino masses?
- why symmetry breaking?
- why Universe dominated by matter? CP violation?
- why gauge interactions?
- why $SU(3)xSU(2)xU(1)$?
- why 3 generations?
- what about gravity?
- why 4 dimensions?

Hope to find Higgs, and new physics signals.

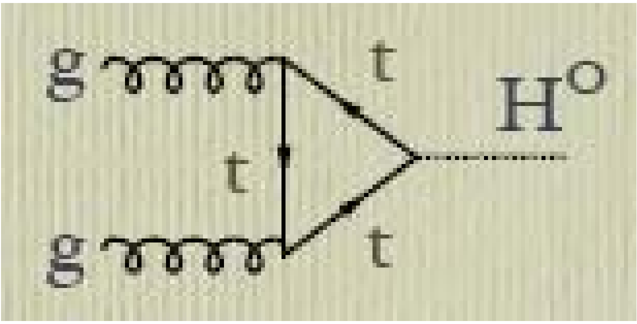
CERN

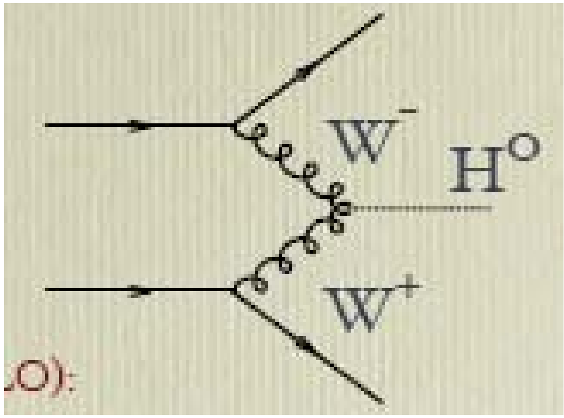
- world's largest particle physics laboratory
- Proton-proton collision at E=14 TeV

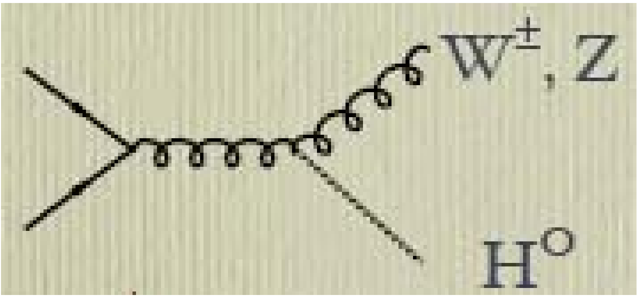


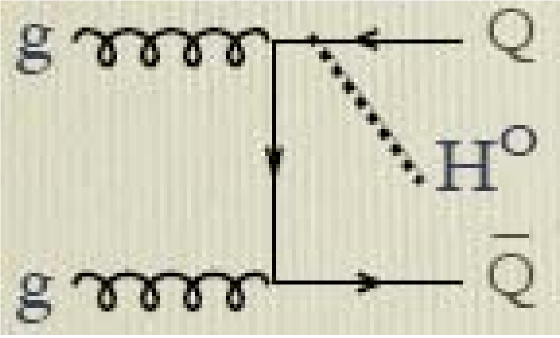


Higgs production channels

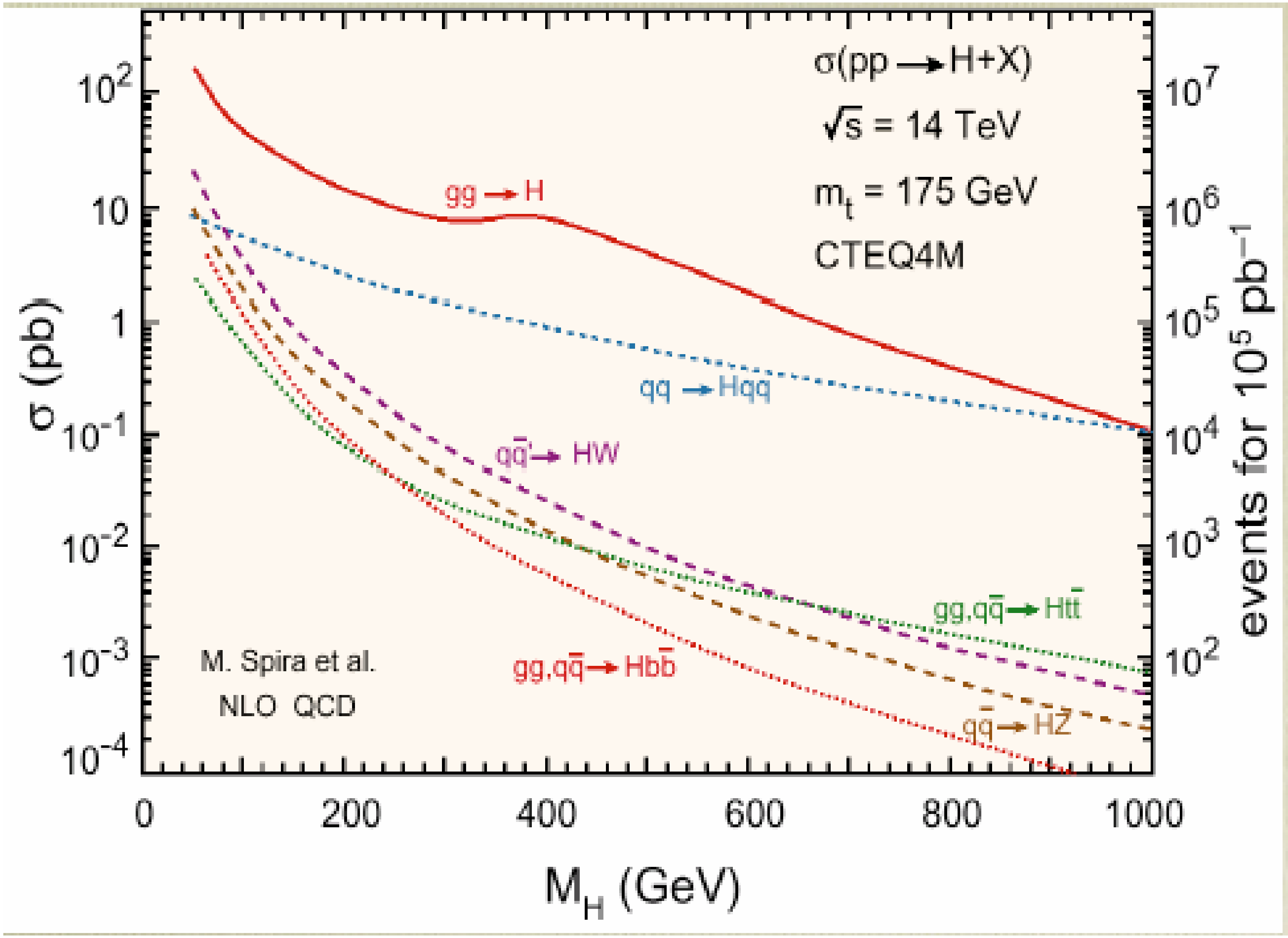




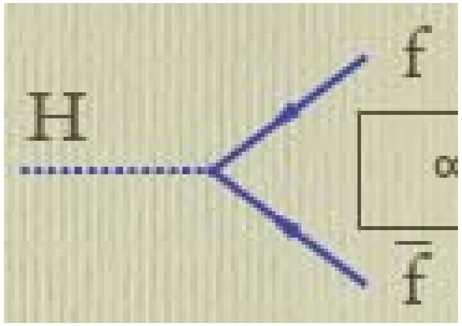


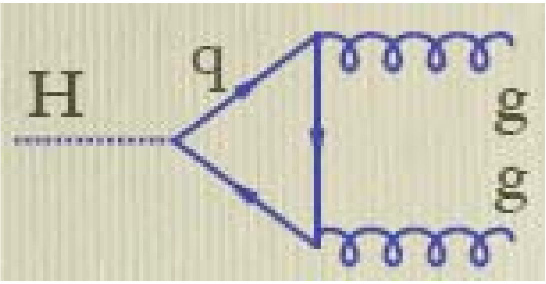


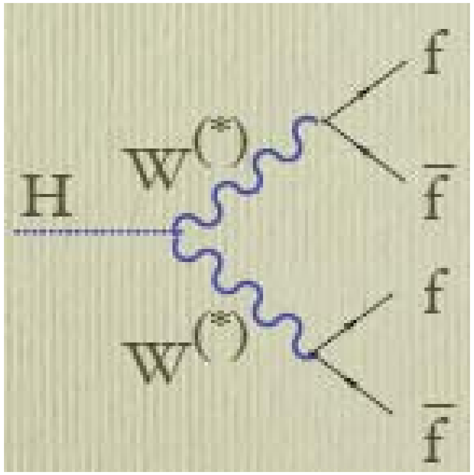
Higgs production rates

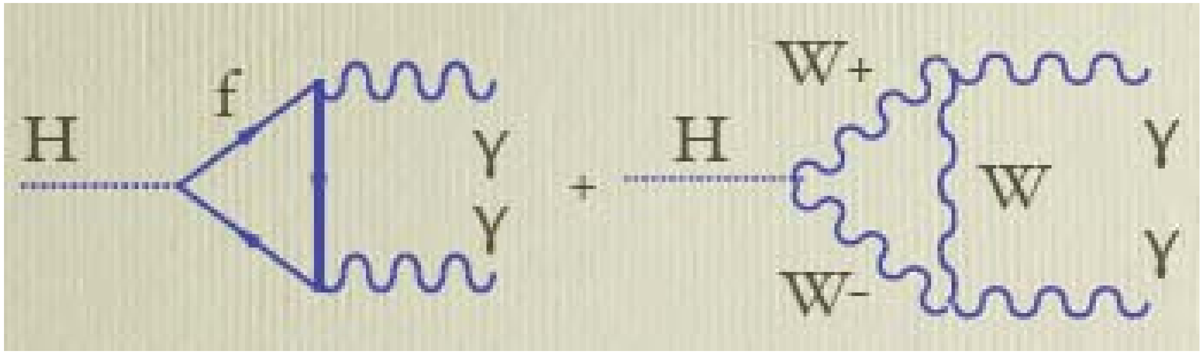


Higgs decay modes

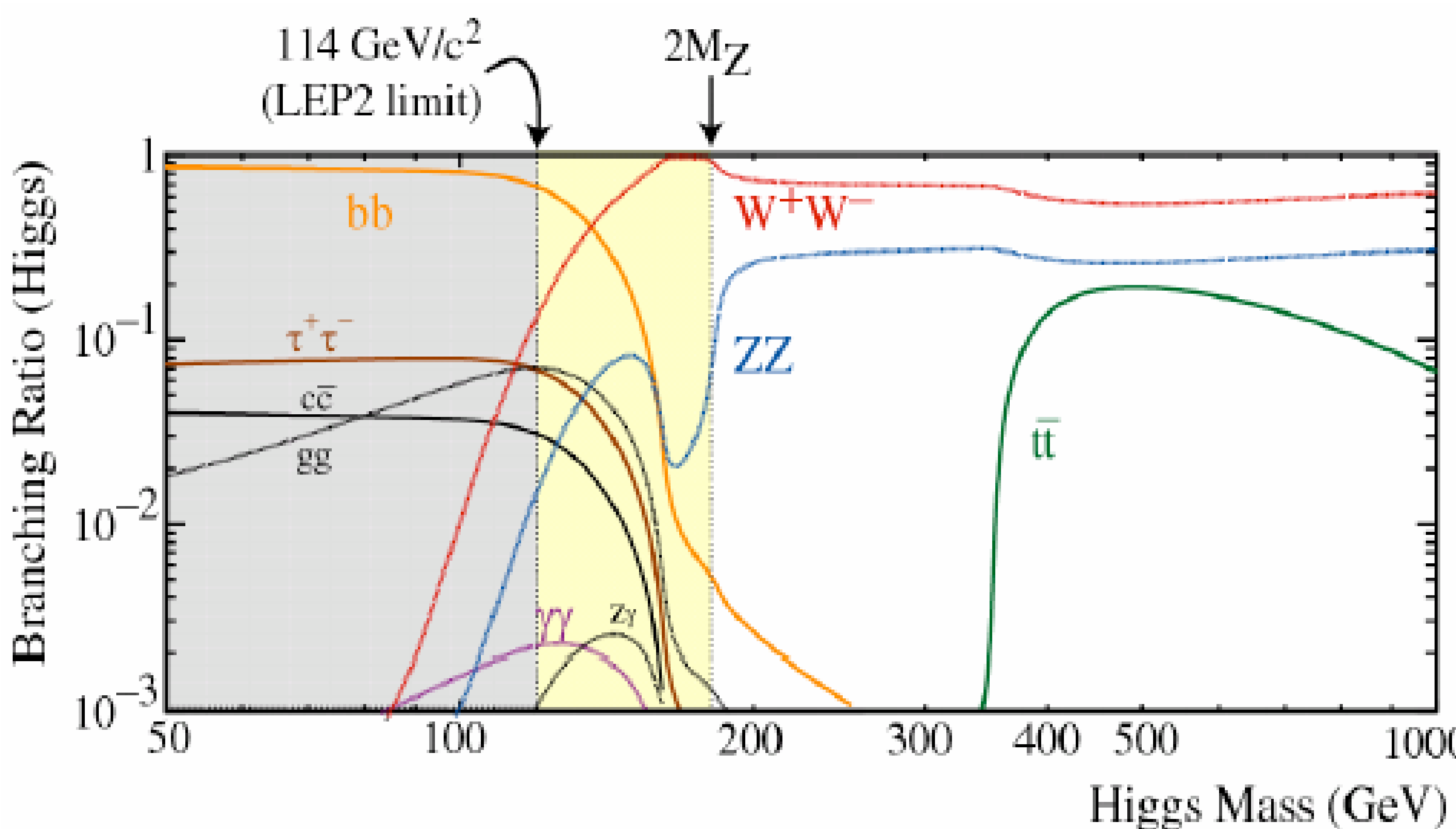






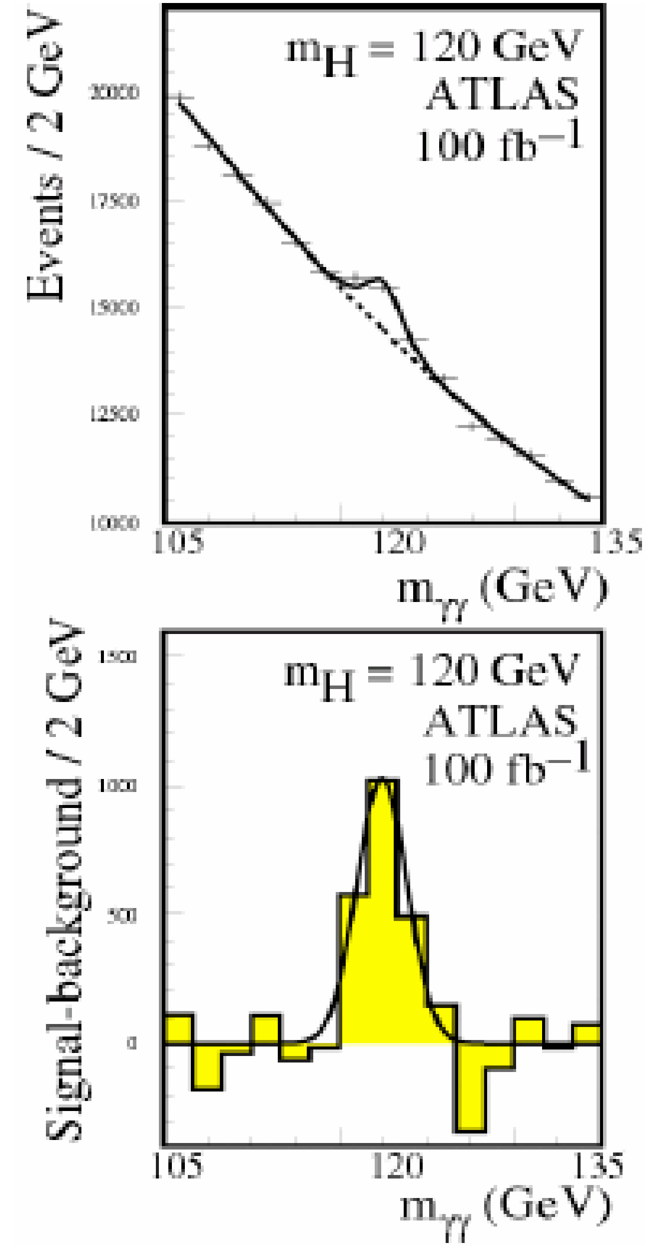


Higgs decay rates



Search channels

- gg$\rightarrow$ H$\rightarrow$ $\gamma\gamma$
- Dominant background:
- QCD continuum production of $\gamma\gamma$
- QCD γ jet production with jet fragmenting into π^0
- Need to calculate these QCD backgrounds precisely



Summary

- High-energy QCD processes must involve both perturbative and nonperturbative dynamics.
- Factorization theorem is a powerful tool for high-energy QCD processes. It is predictive.
- Factorization theorem has been extended to many processes, the PQCD approach.
- Accurate calculation of QCD background is crucial for verifying new physics at LHC
- More topics to study, such as B meson decays, CP asymmetries,...

Quantum Mechanics in B Physics

Outlines

- Introduction
- Oscillation
- Basics of Particle Physics
- Particle Oscillation
- B factory
- Summary

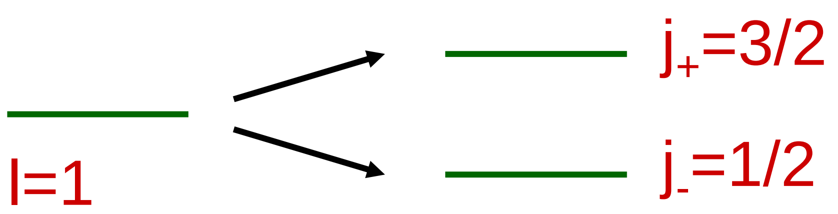
Introduction

- Two-level oscillation is a simple quantum mechanic phenomenon.
- Oscillation frequency reveals the energy difference of the two levels, and the interaction making the splitting.
- This idea can be used to determine fundamental parameters in the standard model of particle physics.

Oscillation

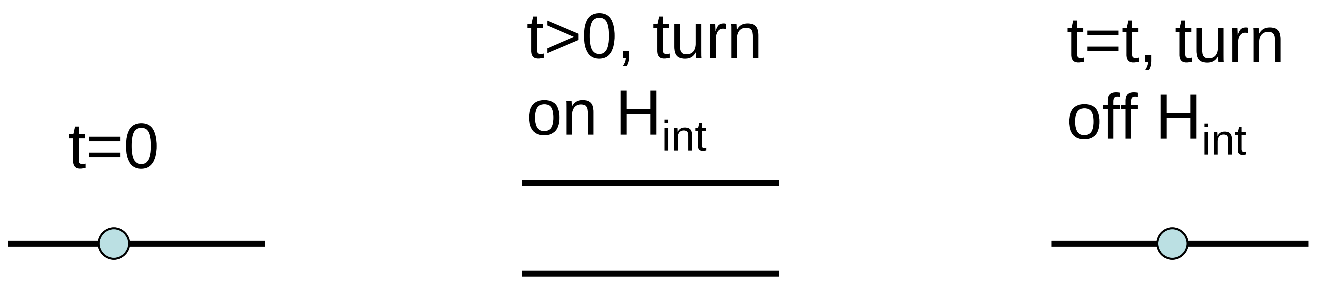
Spin-orbital coupling

- Hamiltonian $H=H_{coul}+H_{int}$, $H_{int}=c\ \mathbf{s}\cdot\mathbf{L}$
- With only H_{coul}, $|l=1,s=1/2\rangle$ are degenerate.
- Adding H_{int}, splitting of degenerate levels.
- Mixing matrix: $\langle l_z,s_z|H|l'_z,s'_z\rangle=\langle H_{coul}\rangle+\langle H_{int}\rangle$
- $\langle H_{coul}\rangle$: diagonal $\propto \delta(l_z,l'_z)\delta(s_z,s'_z)$
- $\langle H_{int}\rangle$: non-diagonal
- Diagonalization gives $|j,j_z\rangle$ as linear combination of $|l_z,s_z\rangle$.



Splitting of energy levels

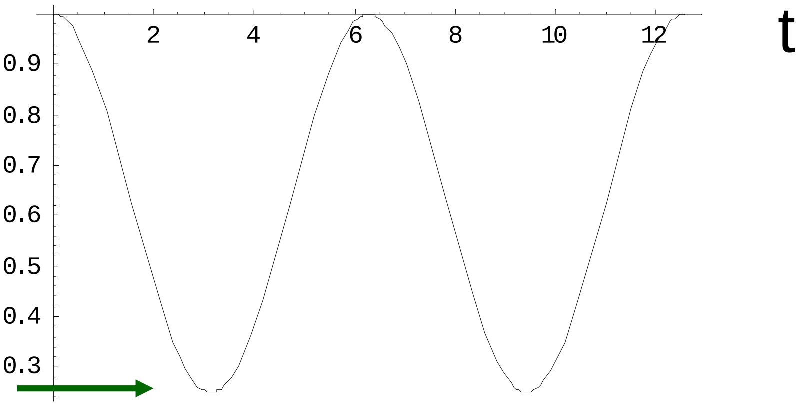
- Small c, small splitting, oscillation.
- Oscillation frequency is related to the splitting, and to c.
- Consider



- Ask for the probability of finding electron at the original state.

Oscillation

- Initial condition,
  $|l_z,s_z,t=0\rangle = a|j_+,t=0\rangle + b|j_-, t=0\rangle$.
- $|l_z,s_z,t\rangle = a\exp(-iE_+t)|j_+,t=0\rangle$
  $+b\exp(-iE_-t)|j_-, t=0\rangle$
- $\langle l_z,s_z,t=0|l_z,s_z,t\rangle = a^2\exp(-iE_+t)+b^2\exp(-iE_-t)$.
- Probability $= a^4+b^4$
  $+2a^2b^2$ $\cos(\Delta E\, t)$
  $\Delta E=E_+-E_-$



Electron goes to other $|l_z,s_z\rangle$

Complex H_{int}

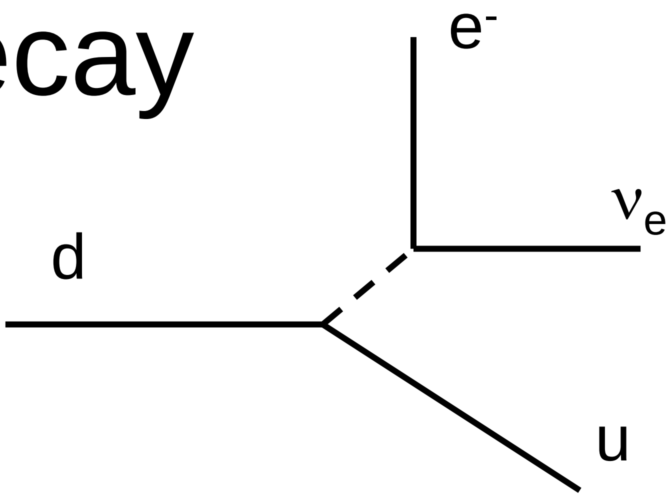
- Imagine complex H_{int}

Hermitian

- $\langle H \rangle = \begin{pmatrix} E & E_{12} + i\varepsilon \\ E_{12} - i\varepsilon & E \end{pmatrix} = \begin{pmatrix} E & E_{12} \\ E_{12} & E \end{pmatrix} + i\varepsilon \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$
- Diagonalization of the first matrix gives the eigenstates $|j_+\rangle$, $|j_-\rangle$.
- The second matrix gives nontrivial mixing between $|j_+\rangle$, $|j_-\rangle$.
- True eigenstates,
  $|j'_+\rangle = |j_+\rangle + \varepsilon\, |j_-\rangle$, $|j'_-\rangle = |j_-\rangle - \varepsilon\, |j_+\rangle$

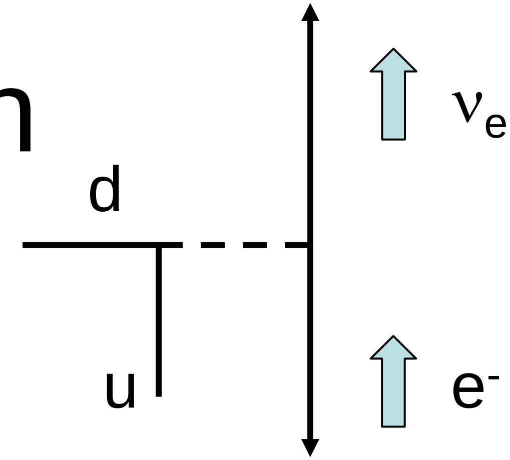
CP violation

Weak decay



- β decay: $n \to p\, e^- \nu_e$
- Quark level $d \to u\, e^- \nu_e$
- Fermi's weak theory inspired by EM
- Decay amplitude: $G[u\gamma_\mu d][e\gamma^\mu \nu_e]$
- G: phenomenological Fermi constant
- The current $u\gamma_\mu d$ conserves parity.
- θ-τ puzzle: same mass, $\theta \to 2\pi$, $\tau \to 3\pi$
- $K^+ \to 2\pi, 3\pi$, parity violation (Lee, Yang 56)

Parity Violation

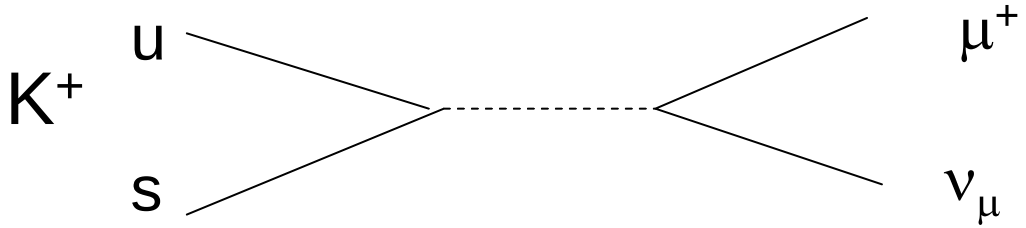


- $u\gamma_\mu d = u\gamma_\mu(1-\gamma_5)d + \cancel{u\gamma_\mu(1+\gamma_5)d}$
- Left-hand ~~right-hand~~

- Exp evidence (Wu): $^{60}Co \rightarrow {}^{60}Ni\ e^-_L\ \nu_{eR}$
- J=5, 4
- Weak theory: $G[u\gamma_\mu(1-\gamma_5)d][e\gamma^\mu(1-\gamma_5)\nu_e]$
- God chose it! No right-handed current.
- SU(2) doublet $(u,d)_L$, $(\nu_e,e^-)_L$, $(\nu_\mu,\mu^-)_L$

Impact from kaon decay

- Naturally, postulate doublet $(c,s)_L$
- Amplitude: $G[c\gamma_\mu(1-\gamma_5)s][l\,\gamma^\mu(1-\gamma_5)\nu_l]$
- G: universal Fermi constant
- $K^+ \rightarrow \mu^+\nu_\mu$ was observed



- u couples to s?
- Introduce a new coupling constant?

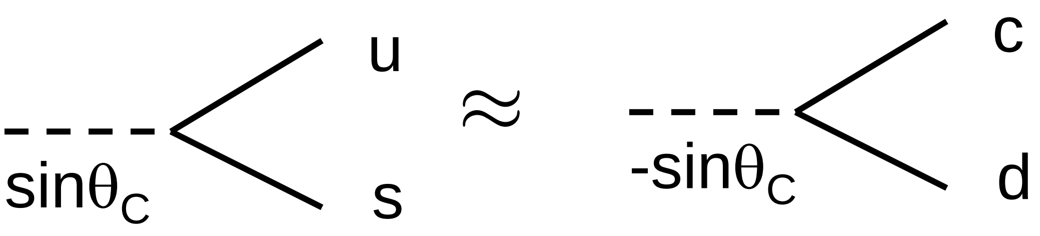
Cabbibo angle

- Instead of new coupling, Cabbibo proposed "quark mixing" (63).
- Weak eigenstate vs. mass eigenstate

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$\theta_C \approx 13^o$
Cabbibo angle

- Doublets $(u,d')_L$, $(c,s')_L$
- Beautiful phenomenology!
- Check

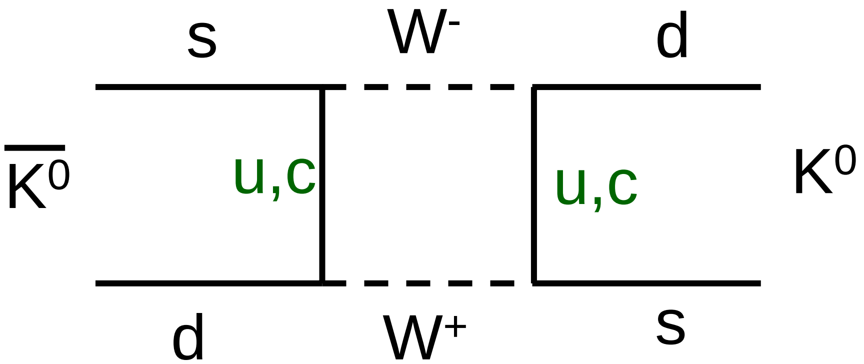


Particle Oscillation

K-$\overline{K}$ oscillation

- C: charge conjugate. $CP|K^0\rangle=|\overline{K^0}\rangle$
- Oscillation between K^0 and $\overline{K^0}$ through a box diagram

real $\langle H_{int}\rangle \sim$



- $|j_+\rangle$: $|K_S\rangle=(|K^0\rangle+|\overline{K^0}\rangle)/\sqrt{2}$, [CP=+1] $\rightarrow 2\pi$
- $|j_-\rangle$: $|K_L\rangle=(|K^0\rangle-|\overline{K^0}\rangle)/\sqrt{2}$, [CP=-1] $\rightarrow 3\pi$
- $K_L\rightarrow 2\pi$ was observed (64).

CKM matrix

- CP violation implies nontrivial admixture, $|K'_S\rangle = |K_S\rangle + \varepsilon|K_L\rangle$, $|K'_L\rangle = |K_L\rangle - \varepsilon|K_S\rangle$
- The mixing matrix must be complex.
- To get it, Kobayashi and Maskawa (73) proposed the third generation of quarks.
- Doublets $(u,d')_L$, $(c,s')_L$, $(t,b')_L$
- Top and bottom were not discovered then.

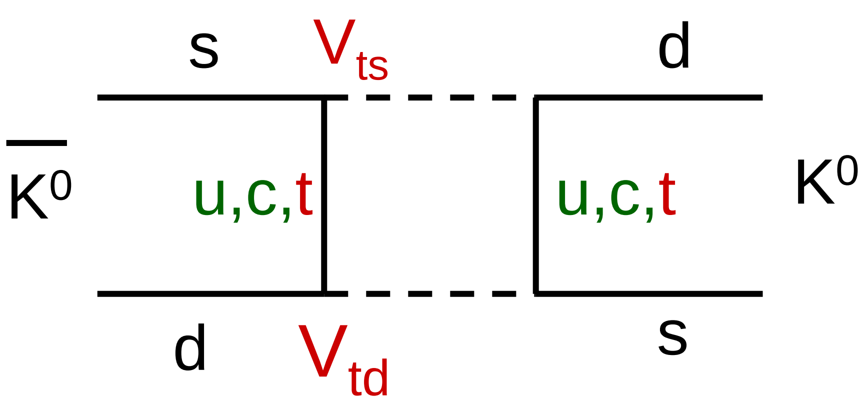
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

V: CKM matrix

Weak phase

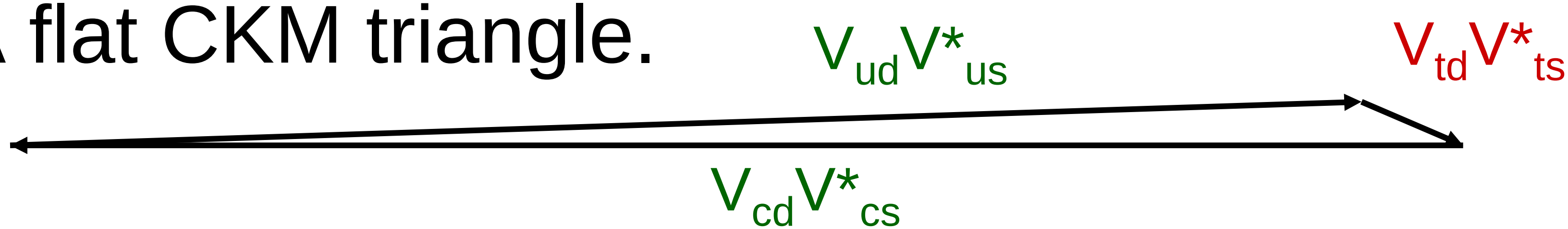
- In 2-generation model, no physical weak phase in mixing matrix, since all phases can be absorbed into quark fields.
- The minimal number of generations for complex mixing matrix is 3.
- 18-9(unitarity)-5(unphysical)=3(rotation)+1
- Again, beautiful phenomenology!

complex
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Measure V_{CKM}

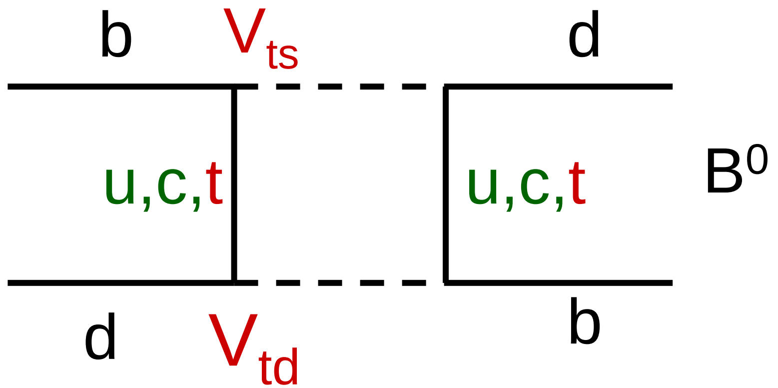
- Re V_{CKM}: splitting or oscillation frequency
- Im V_{CKM}: CP violation
- Measure K-$\bar{K}$ mixing, determine V_{CKM}
- But Im $[V_{td}V^*_{ts}]$ is too small!
- Unitarity: $V^\dagger V=I$ (magnitude of a vector is invariant under rotation).
- $V_{ud}V^*_{us}+V_{cd}V^*_{cs}+V_{td}V^*_{ts}=0$.
- A flat CKM triangle.



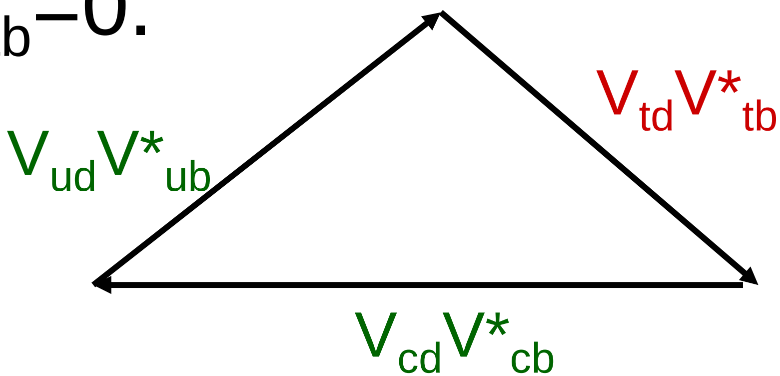
Why B-$\overline{\text{B}}$ mixing?

- B^0 and $\overline{B}^0$ oscillate like K^0 and $\overline{K}^0$.

$$\langle H_{int} \rangle \sim \overline{B}^0$$

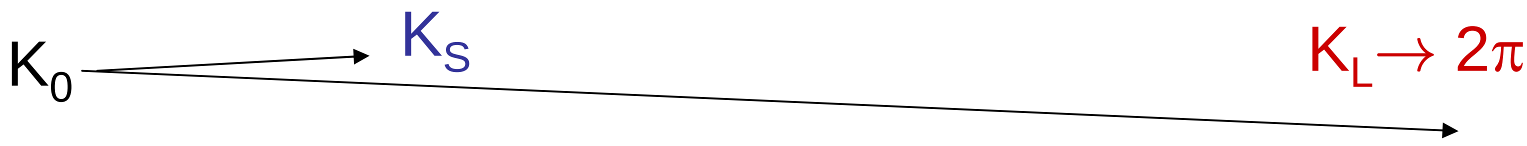


- An ideal but small CKM triangle (Bigi, Sanda).
- $V_{ud}V^*_{ub}+V_{cd}V^*_{cb}+V_{td}V^*_{tb}=0.$
- Relatively large $\text{Im}[V_{td}V^*_{tb}]$



How?

- In kaon case, just produce K_0



- In B meson case, $\tau(B_S) \approx \tau(B_L)$. The above strategy does not work.
- To produce abundant b quarks, use electron collider with E at the threshold. B and $\bar{B}$ are produced at the same time.
- Need a different strategy!

Bigi, Sanda's clever idea

Nuclear Physics B193 (1981) 85–108

Need millions of B, challenge for experimentalists

NOTES ON THE OBSERVABILITY OF *CP* VIOLATION IN B DECAYS

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Received 16 June 1981

We describe a general method of exposing *CP* violations in on-shell transitions of B mesons. Such *CP* asymmetries can reach values of the order of up to 10% within the Kobayashi–Maskawa model for plausible values of the model parameters. Our discussion focuses on those (mainly non-leptonic) decay modes which carry the promise of exhibiting clean and relatively large *CP* asymmetries at the expense of a reduction in counting rates. Accordingly we address the complexities encountered when performing *CP* tests with a high statistics B meson factory like the Z^0 (and a toponium) resonance.

B Factories

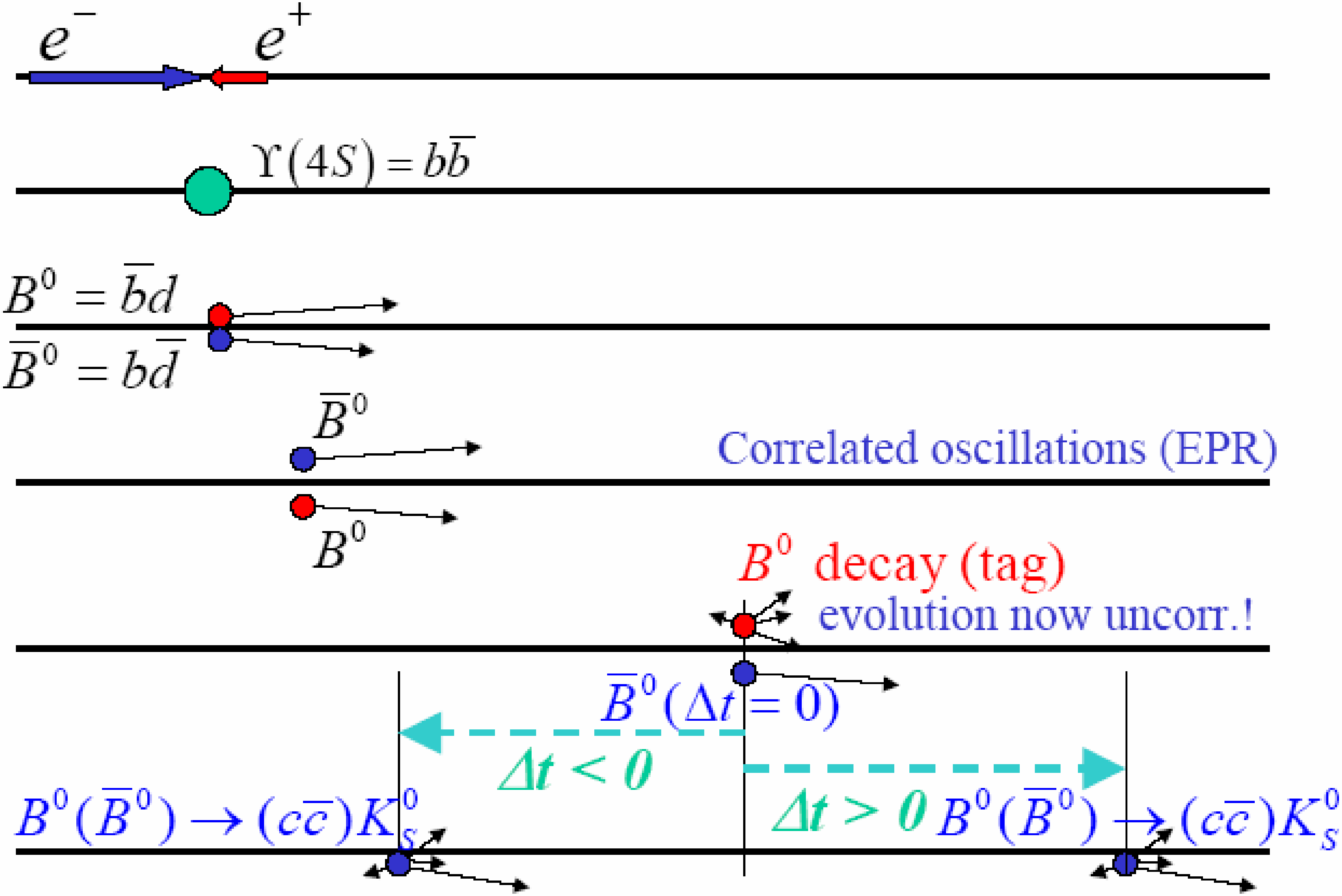
Time-dependent *CP* Violation

- Still measure CP violation, but different

$$A_{CP}(\Delta t) \equiv \frac{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) - \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) + \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}$$

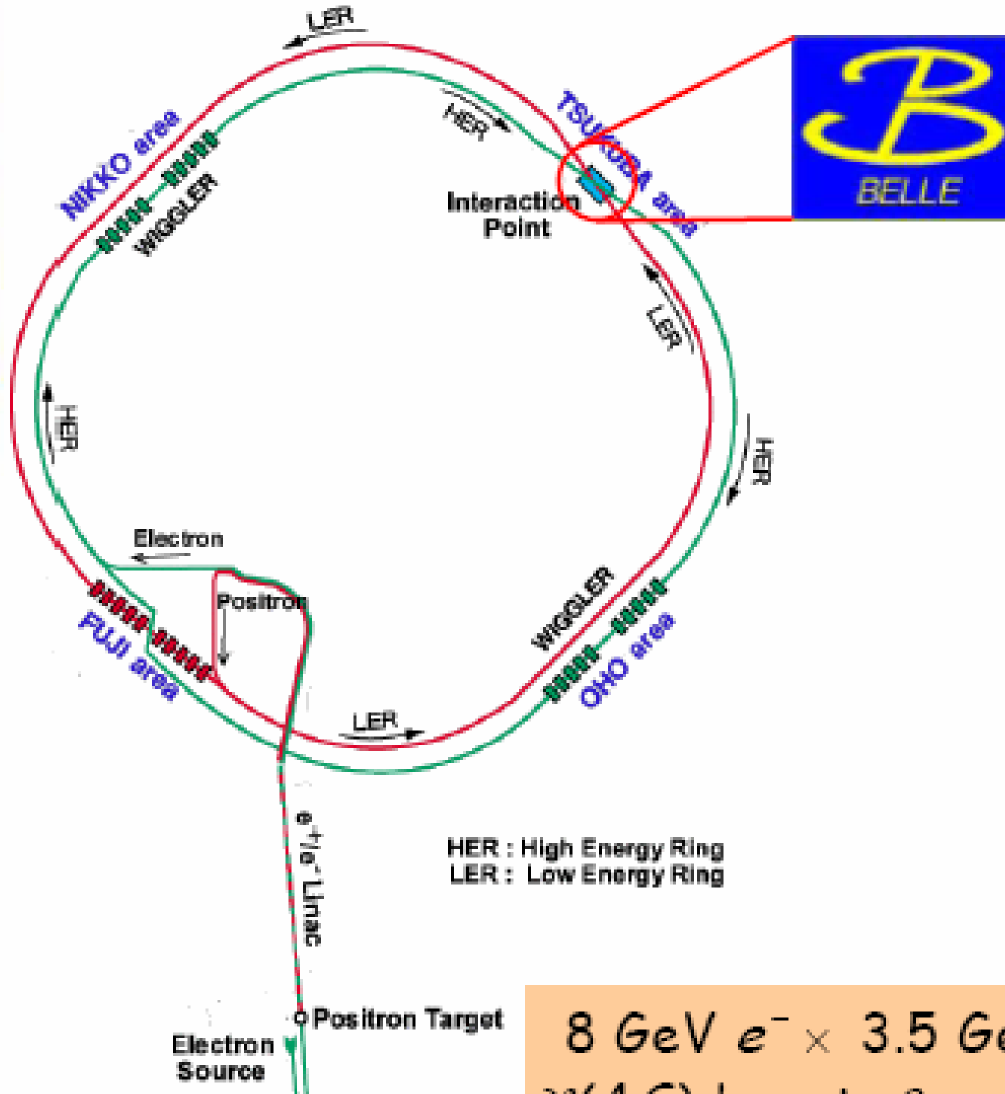
- Recall $K_0=(1+\varepsilon)\,K'_S+(1-\varepsilon)\,K'_L$,
  $\overline{K_0}=(1-\varepsilon)\,K'_S-(1+\varepsilon)\,K'_L$, $A_{CP}\neq 0$.
- To produce abundant B mesons, $E(e^+e^-)=\text{Mass}(B\overline{B})$.
- Then the two B meson sit at rest. How to distinguish B or B meson decay?
- Very clever idea: asymmetric collider!!

Time-dependent CP asymmetry measurement



Babar at SLAC

KEKB & Belle Layout

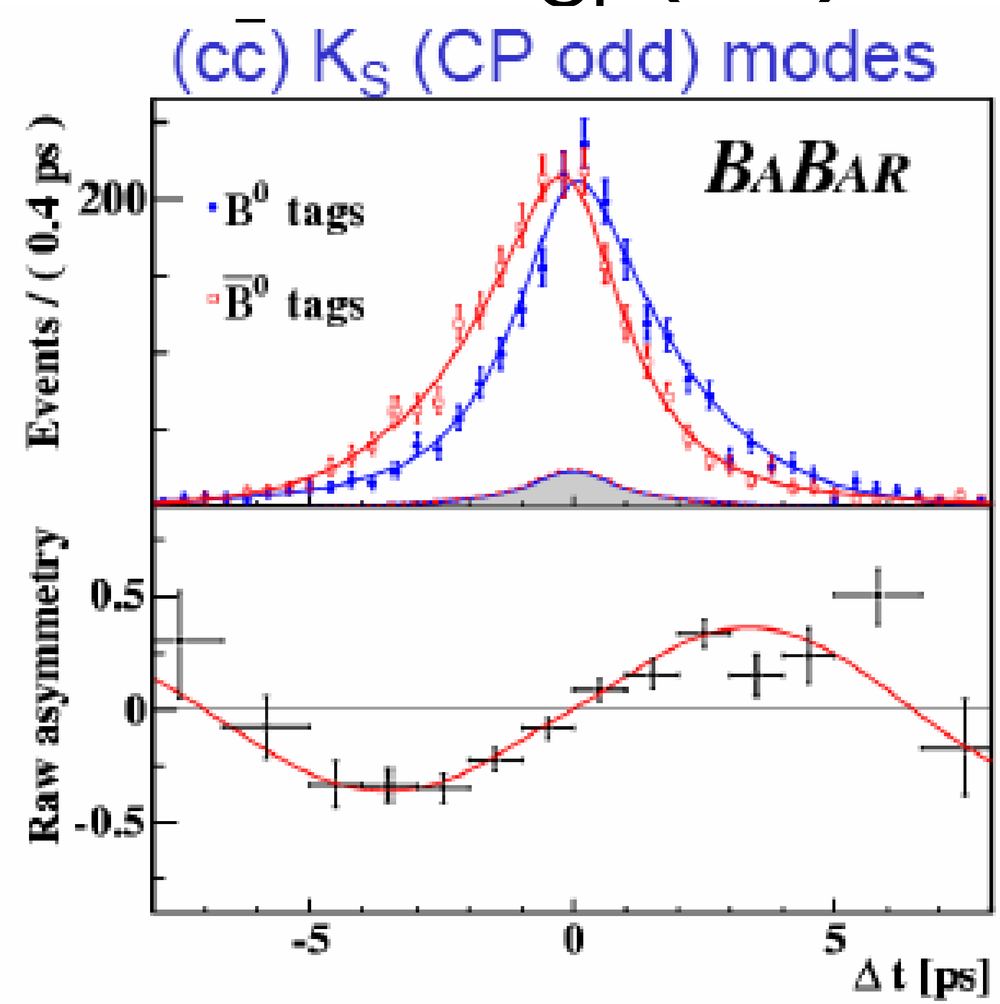


8 GeV e^- × 3.5 GeV e^+

$\Upsilon(4S)$ boost: $\beta\gamma = 0.425$

±11 mrad crossing angle

$A_{CP}(\Delta\ t)$ data



Amplitude (CP violation) related to Im V_{CKM} weak phase $\sin(2\phi_1)$ or $\sin(2\beta)$

Frequency related to mass (energy) difference, Re V_{CKM}

Summary

- Simple Quantum Mechanics is useful in determining fundamental parameters in the standard model.
- Beauty of phenomenology is appreciated in exploring property of fundamental interaction.
- Cabbibo: quark mixing, KM: ~~CP~~ model. All are insightful.
- Measurement of $\sin(2\phi_1)$ from oscillation requires clever theoretical and experimental ideas.