Karlsruhe Institute of Technology

Particle Physics 1
Lecture 5: Symmetries & QCD (Theory)

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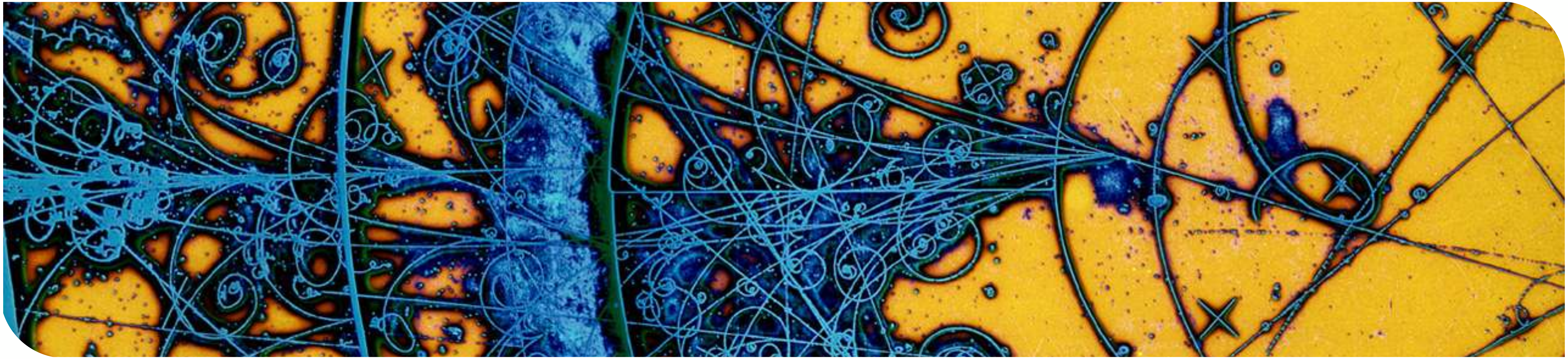
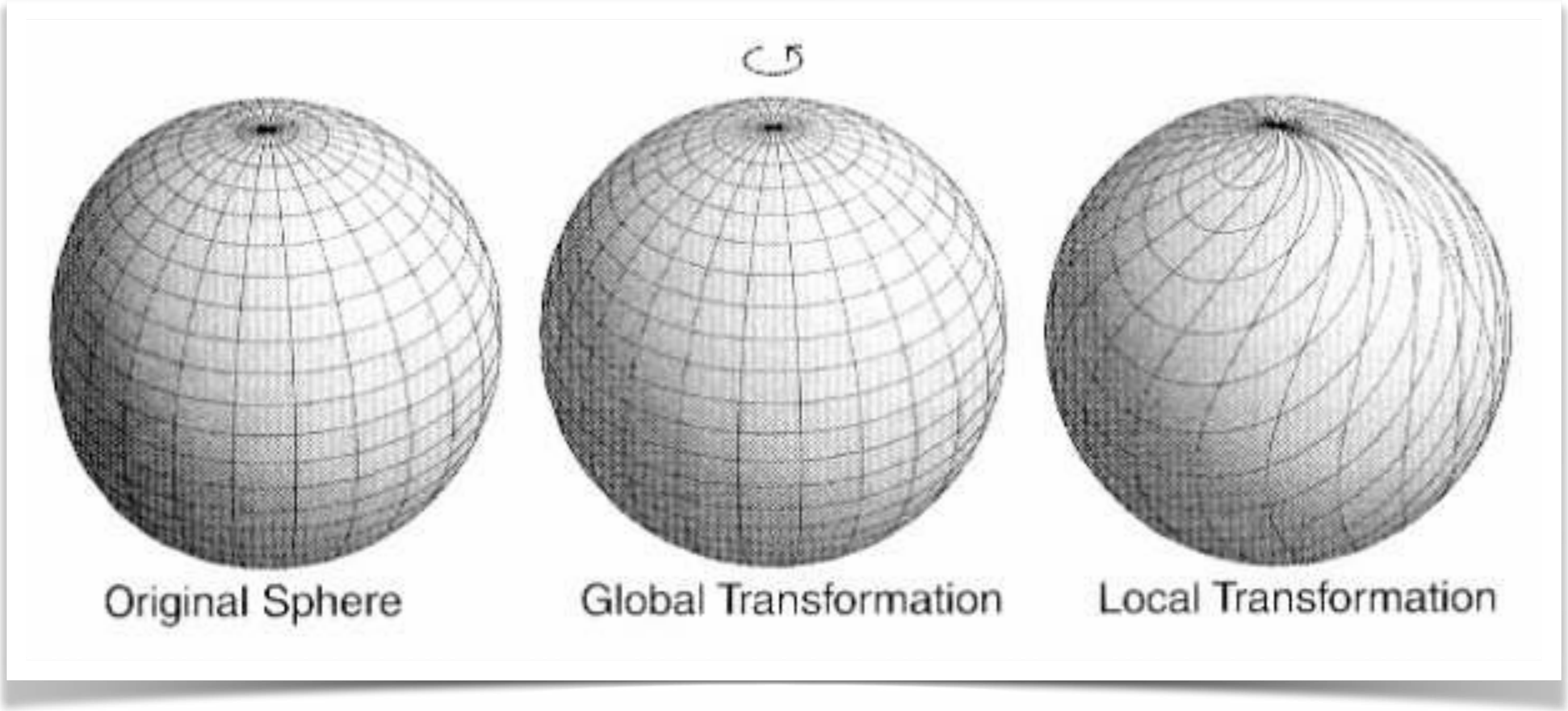


Credit: CERN

Questions from past lectures

Symmetries

- Symmetries are operations performed on a system that leaves it invariant
  - **Global** symmetries are the **same** at all space-time points
  - **Local** symmetries are **different** at different space-time points



Source: https://universe-review.ca/I15-04-gauge2.jpg

Symmetries

- Requires that all physical predictions are invariant under the wavefunction transformation $\psi \rightarrow \psi' = \hat{U}\psi$

- For physical predictions to be unchanged, wavefunction normalizations must remain unchanged

$$\langle \psi | \psi \rangle = \langle \psi' | \psi' \rangle = \langle \hat{U}\psi | \hat{U}\psi \rangle = \langle \psi | \hat{U}^\dagger \hat{U} | \psi \rangle$$

$$U^\dagger U = I \quad \therefore \hat{U} \text{ is unitary}$$

- The eigenstates of the system must also remain unchanged

$$\hat{H} \rightarrow \hat{H}' = \hat{H}$$

$$H\psi_i = E_i \psi_i \Rightarrow \hat{H}'\psi_i' = E_i \psi_i'$$

$$\Updownarrow$$

$$\overset{H}{\hat{H}'}\hat{U}\psi_i = E_i \hat{U}\psi_i = \hat{U}E_i\psi = \hat{U}H\psi$$

$$\therefore \hat{H}\hat{U}\psi_i = \hat{U}\hat{H}\psi_i$$

$$[\hat{H}, \hat{U}] = \hat{H}\hat{U} - \hat{U}\hat{H} = 0$$

$\hat{H}$ must possess the symmetry in question & eigenstates must satisfy

Energies of transformed eigenstates ψ_i will be unchanged

Symmetries

- A finite continuous symmetry operation can be built up from a series of infinitesimal transformations $\hat{U}(\epsilon) = I + i\epsilon\hat{G}$

unitary   infinitesimal parameter   Generator of the transformation

$$\hat{U}(\epsilon)\hat{U}^{\dagger}(\epsilon) = (I + i\epsilon\hat{G})(I - i\epsilon\hat{G}^{\dagger}) = 1 + i\epsilon\underbrace{(\hat{G} - \hat{G}^{\dagger})}_{=0} + \cancel{O(\epsilon^2)}$$

$$\Rightarrow \boxed{G = G^{\dagger}} \quad \text{Hermitian}$$

1. For each symmetry of $\hat{H}$, there is a corresponding unitary symmetry operator $\hat{U}$, with an associated Hermitian generator $\hat{G}$
2. The eigenstates of a Hermitian operator are real $\therefore \hat{G}$ is associated w/an observable quantity G.
3. $[\hat{H}, I - i\epsilon\hat{G}] = 0 \Rightarrow [\hat{H}, \hat{G}] = 0$

Time evolution of the expectation value $\frac{d}{dt}\langle\hat{G}\rangle = i\langle[\hat{H}, \hat{G}]\rangle = 0$

$\Rightarrow$ For each sym. of $\hat{H}$, there is an observable conserved quantity

A simple example

- Translational invariance in 1 dimension $x \to x + \epsilon$

↑ infinitesimal distance x_0

$$\psi'(x) = \psi(x+\epsilon) = \psi(x) + \frac{\partial \psi}{\partial x}\epsilon + \mathcal{O}(\epsilon^2)$$

$$\psi'(x) = \left(1 + \epsilon \frac{\partial}{\partial x}\right)\psi$$

$$\Downarrow \quad \hat{p}_x = -i\frac{\partial}{\partial x}$$

$$\psi'(x) = (1 + i\epsilon\hat{p}_x)\psi(x)$$

↑ generator of the sym. transformation $x \to x + \epsilon$

$$\hat{G} = \{\hat{G}_i\}$$

$$\hat{U}(\vec{\epsilon}) = 1 + i\vec{\epsilon}\cdot\hat{G}$$

$$\vec{x} \to \vec{x} + \vec{\epsilon}$$

3D spatial trans $\Rightarrow \hat{\vec{p}} = (\hat{p}_x, \hat{p}_y, \hat{p}_z)$

associated w/ the generators

Translational invariance of $\hat{H}$ implies momentum conservation

Finite transformations

- Any finite symmetry transformation can be expressed as a series of infinitesimal transformations

$$\hat{U}(\alpha) = \lim_{n\to\infty}\left(1 + i\frac{1}{n}\alpha\cdot\hat{\mathbf{G}}\right)^n = \exp\left(i\alpha\cdot\mathbf{G}\right)$$

$$e^x = \lim_{n\to\infty}\left(1+\frac{x}{n}\right)^n$$

$$e^x = \sum_{n=0}^{\infty}\frac{x^n}{n!}$$

Ex: $x \to x + \epsilon$

$$\hat{U}(x_0) = e^{i x_0 \hat{p}_x} = e^{x_0 \frac{\partial}{\partial x}}$$

$$\psi'(x) = \hat{U}\psi(x) = \exp\left[x_0\frac{\partial}{\partial x}\right]\psi(x) = \underbrace{1 + x_0\frac{\partial}{\partial x} + \frac{x_0^2}{2!}\frac{\partial^2}{\partial x^2} + \dots}_{\text{taylor series expansion}}$$

$$\boxed{\psi(x) \to \psi'(x) = \hat{U}(x_0)\psi = \psi(x+x_0)}$$

Flavor symmetries

- Extend the idea of isospin to the up- and down-quarks.

(1)

$u = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $d = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$, isospin doublet

$\hat{U} = 1 + i\epsilon\hat{G}$

$$\begin{pmatrix} u' \\ d' \end{pmatrix} = \hat{U} \begin{pmatrix} u \\ d \end{pmatrix} = \underbrace{\begin{pmatrix} U_{11} & U_{12} \\ U_{21} & U_{22} \end{pmatrix}}\begin{pmatrix} u \\ d \end{pmatrix}$$

4 complex #'s $\Rightarrow$ 8 real numbers

$U^\dagger U = I \Rightarrow$ 4 parameters

= 4 linearly independent 2×2 matrices

represent the generators of the trans.

$\hat{U} = e^{i\alpha_i \hat{\sigma}_i}$

(2)

$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} e^{i\phi}$

Select the pauli spin matrices

$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, $\sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$, $\sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$\hat{T} = \frac{1}{2}\vec{\sigma}$

$$\boxed{\hat{U} = e^{i\vec{\alpha}\cdot\hat{T}}}$$

A little group theory

- A **group** is a set of objects G on which some "multiplication" operation is defined, s.t.:
  - If a and b are in G, $a \cdot b$ is in G
  - There is an identity element in G s.t. $a \cdot i = a$ for any a in G
  - For any a in G, there is an "inverse" element G s.t. $a \cdot a^{-1} = i$
  - For $a,\ b,\ c$ in G, $(a \cdot b) \cdot c = a \cdot (b \cdot c)$
- A **Lie group** is a group of unitary operators in which the group elements are labeled by a set of continuous parameters
  - Example: the elements $e^{i\alpha_a X_a}$ (a summed) under multiplication.
    - The α_a are the set of continuous parameters, the X_a are operators.
    - The X_a are called **generators** because exponentiating them generates the group

SU(3) flavor symmetry

- Extend the SU(2) flavor symmetry to include the s quark

$$\begin{pmatrix} u' \\ d' \\ s' \end{pmatrix} = \hat{U} \begin{pmatrix} u \\ d \\ s \end{pmatrix} = \underbrace{\begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix}}_{\text{18 real parameters}} \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

$m_s - m_{u/d} \approx 100\,\text{MeV} \ll$ typical binding energy of baryons ($1\,\text{GeV}$)

$U^\dagger U = 1 \Rightarrow$ 9 real parameters or 9 linearly indep. 3×3 matrices

$\Rightarrow I e^{i\phi}$, global phase between flavor states

The remaining 8 form an SU(3) group $\Rightarrow$ expressed in terms of 8 indep Hermitian generators $\hat{T}_i$

$\hat{U} = e^{i\vec{\alpha}\cdot\vec{T}}$

$\hat{\vec{T}} = \frac{1}{2}\vec{\lambda}$ Act on the SU(3) representation of the u, d, s quarks

$u = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$ $d = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$ $s = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$

SU(3) flavor symmetry

- SU(3) uds flavor symmetry contains the subgroup of SU(2) $u \leftrightarrow d$ flavor symmetry

σ_i

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \checkmark$$

$u \leftrightarrow d$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \text{and} \quad \lambda_X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

SU(2) $u \leftrightarrow s$

$$\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \text{and} \quad \lambda_Y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

SU(2) $d \leftrightarrow s$

since $m_u \simeq m_d$, keep λ_3 as one of the generators

$\lambda_8 = \frac{1}{\sqrt{3}} \lambda_X + \frac{1}{\sqrt{3}} \lambda_Y$

treats u+d quarks symmetrically

$\lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$

Hypercharge

- For the case of SU(2), we defined 3 Hermitian generators, each of which corresponds to an observable quantity

$\hat{\vec{T}} = \frac{1}{2}\vec{\sigma}$ $\quad [T_i, T_j] \neq 0$ $\quad \hat{T}^2 = \hat{T}_1^2 + \hat{T}_2^2 + \hat{T}_3^2$, $\hat{T}_3$ SU(2) states defined in terms of their eigenstates.

- In SU(3) there is an analogue of total isospin:

$$\hat{T}^2 = \sum_{i=1}^{8} \hat{T}_i^2 = \frac{1}{4}\sum_{i=1}^{8} \lambda_i^2 = \frac{4}{3}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

only $\hat{T}_3 = \frac{1}{2}\lambda_3$ & $\hat{T}_8 = \frac{1}{2}\lambda_8$ commute ∴ describe compatible observable quantities

Corresponding quantum #'s

3rd component of isospin $\hat{T}_3 = \frac{1}{2}\lambda_3$

$\hat{Y} = \frac{1}{\sqrt{3}}\lambda_8$

additive quantum #'s which specify the flavor of the state

Take 5

Local gauge principle

- Recall gauge invariance form electromagnetism

scalar $\phi \to \phi' = \phi - \frac{\partial \chi}{\partial t}$

vector $\vec{A} \to \vec{A}' = \vec{A} + \vec{\nabla}\chi$

$A_\mu \to A_\mu' = A_\mu - \partial_\mu \chi$

$\Rightarrow$ Fields are invariant under this gauge transformation

- In relativistic QM, the gauge invariance of EM can be related to a local gauge principle

U(1) global phase trans. $\psi \to \psi' = e^{i\phi}\psi$

Local: $\psi(x) \to \boxed{\psi'(x)} = \hat{U}\psi(x) = \boxed{e^{iq\chi(x)}\psi(x)}$

Local gauge principle

- For this local U(1) phase transformation, the free-particle Dirac equation $i\gamma^\mu\partial_\mu\psi = m\psi$ becomes

$$\Downarrow$$

$$i\gamma^\mu\partial_\mu\left(e^{iq\chi(x)}\psi\right) = m e^{iq\chi(x)}\psi$$

$$\Downarrow$$

$$i\gamma^\mu\left[\partial_\mu + \underbrace{iq\partial_\mu\chi(x)}\right]\psi = m\psi$$

now has an extra term which must be "cancelled"

The only way is to add a new degree of freedom A_μ

$$i\gamma^\mu(\partial_\mu + iqA_\mu)\psi = m\psi$$

$$\Downarrow$$

invariant under $\boxed{\psi(x)\to\psi'(x) = e^{iq\chi(x)}\psi(x)}$ U(1)

A_μ: field which corresponds to a massless gauge boson.

$$i\gamma^\mu iqA_\mu = -q\gamma^\mu A_\mu$$

form of the perturbation from min. sub.

Local gauge principle

- The requirement that physics is invariant under local U(1) phase transformations implies the existence of a gauge field with couples to Dirac particles in **exactly** the same way as the photon.

- All of QED can be derived by requiring the invariance of physics under local U(1) transformations of the form $\hat{U} = \exp[iq\chi(x)]$

Thomson, Sec. 10.1

QED →QCD

- QED corresponds to a local U(1) gauge symmetry of the universe
- The QFT of the strong interaction is invariance under SU(3) local phase transformations

$$\psi(x) \to \psi'(x) = \exp\left[ig_S\,\underbrace{\boldsymbol{\alpha}(x)}_{\text{fn. of space time coords.}} \cdot \underbrace{\hat{\mathbf{T}}}_{\text{generators}}\right]\psi(x)$$

$\hat{T} = \{T^a\}$ The 8 generators of SU(3) sym group.

$\hat{T} = \frac{1}{2}\hat{\lambda}$

- Since the generators of SU(3) are represented by 3×3 matrices, the wavefunction must now include 3 additional degrees of freedom represented by a 3 component vector

$r = \begin{pmatrix}1\\0\\0\end{pmatrix}, g = \begin{pmatrix}0\\1\\0\end{pmatrix}; b = \begin{pmatrix}0\\0\\1\end{pmatrix}$ new degree of freedom ⇒ color

Dirac equation becomes

- As before, substitute the expression for ψ' into the free-particle Dirac equation $i\gamma^\mu \partial_\mu \psi = m\psi$ and you obtain:

$$i\gamma^\mu \left[\partial_\mu + ig_S(\partial_\mu \overset{\alpha(x)}{\boldsymbol{\alpha}}) \cdot \hat{\mathbf{T}}\right]\psi = m\psi.$$

- The **required** local gauge invariance can be asserted by introducing 8 new fields (just as we introduced the new A_μ photon field in U(1) QED)

$G_\mu^a(x)$, $a_{1 \dots 8}$ each correspond to one of the 8 generators of SU(3)

Interactions with the new gauge field

$$i\gamma^\mu \left[\partial_\mu + ig_S(\partial_\mu \alpha)\cdot \hat{\mathbf{T}}\right]\psi = m\psi.$$

Dirac eqn including the interaction w/ the new gauge fields

$$i\gamma^\mu \left[\partial_\mu + ig_S \boxed{G^a_\mu} T^a\right]\psi - m\psi = 0,$$

Appears since the generators in SU(3) don't commute. Gives rise to gluon self interaction

Invariant under SU(3) phase trans if the new fields transform as

$$\boxed{G^k_\mu} \to G^{k\prime}_\mu = G^k_\mu - \partial_\mu \alpha_k - g_S \underbrace{f_{ijk}}_{\text{fine structure constants of SU(3)}} \alpha_i G^j_\mu.$$

Summary (so far)

	QED	QCD
	U(1)	SU(3)
Symmetry of the universe that requires the invariance of physics under local phase transformations	$\psi(x) \to \psi'(x) = \hat{U}(x)\psi(x) = e^{iq\chi(x)}\psi(x).$	$\psi(x) \to \psi'(x) = \exp\left[ig_S\boldsymbol{\alpha}(x)\cdot\hat{\mathbf{T}}\right]\psi(x)$
Substitute ψ' into the free particle Dirac eq. $i\gamma^\mu\partial_\mu\psi = m\psi$	$i\gamma^\mu(\partial_\mu + iq\partial_\mu\chi)\psi = m\psi,$	$i\gamma^\mu\left[\partial_\mu + ig_S(\partial_\mu\boldsymbol{\alpha})\cdot\hat{\mathbf{T}}\right]\psi = m\psi.$
Modify $i\gamma^\mu\partial_\mu\psi = m\psi$ to include a new degree of freedom **to re-establish the required invariance**	$i\gamma^\mu(\partial_\mu + iqA_\mu)\psi - m\psi = 0,$	$i\gamma^\mu\left[\partial_\mu + ig_S G^a_\mu T^a\right]\psi - m\psi = 0,$
These equations are invariant under the local phase transformations provided that the new field transforms as:	$A_\mu \to A'_\mu = A_\mu - \partial_\mu\chi,$	$G^k_\mu \to G^{k\prime}_\mu = G^k_\mu - \partial_\mu\alpha_k - g_S f_{ijk}\alpha_i G^j_\mu.$

Neither possess the hypothesized invariance under U(1) & SU(3) local phase trans.

QED: Mediated by massless photon corresponding to the single generator of the U(1) local gauge sym

single charge

antiparticles have opposite electrical charge

QCD: " 8 massless gluons

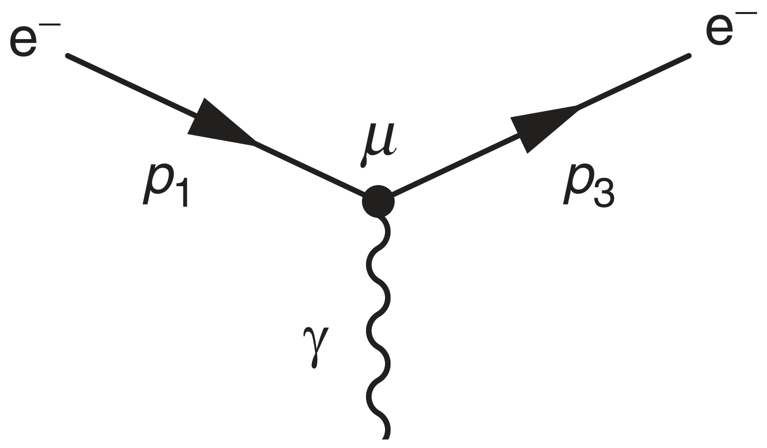
3 conserved color charges

antiquarks have opposite color charge $\bar{r}, \bar{g}, \bar{b}$

	QED	QCD
	U(1)	SU(3)
Interaction term	$-iq\gamma^\mu A_\mu \psi$	$-ig_S \frac{1}{2}\lambda^a \gamma^\mu G^a_\mu \psi$
Vertex factor	$-iq\gamma^\mu$	$-ig_S\gamma^\mu \frac{1}{2}\lambda^a$
4-vector current	$j^\mu_{\mathrm{e}} = \overline{u}_{\mathrm{e}}(p_3)\gamma^\mu u_{\mathrm{e}}(p_1)$	$j^\mu_{\mathrm{q}} = \overline{u}(p_3)c_j^\dagger \left\{-\frac{1}{2}ig_S\,\lambda^a\gamma^\mu\right\} c_i u(p_1),$

3x3

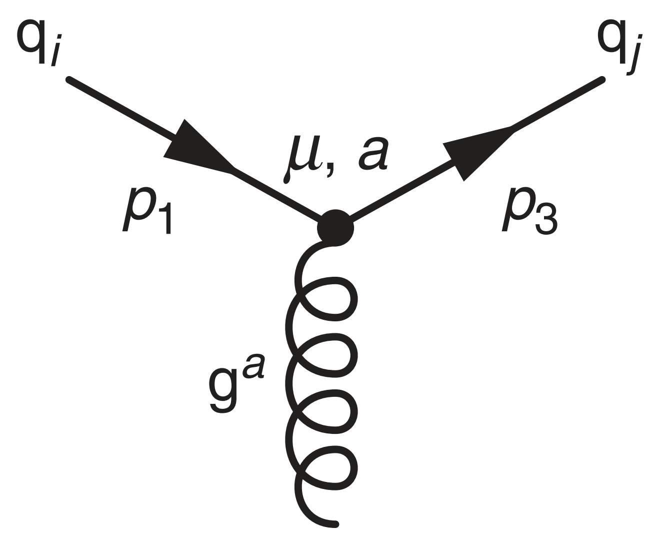
4x4



$c_1 = r = \begin{pmatrix}1\\0\\0\end{pmatrix}$

$c_2 = g = \begin{pmatrix}0\\1\\0\end{pmatrix}$

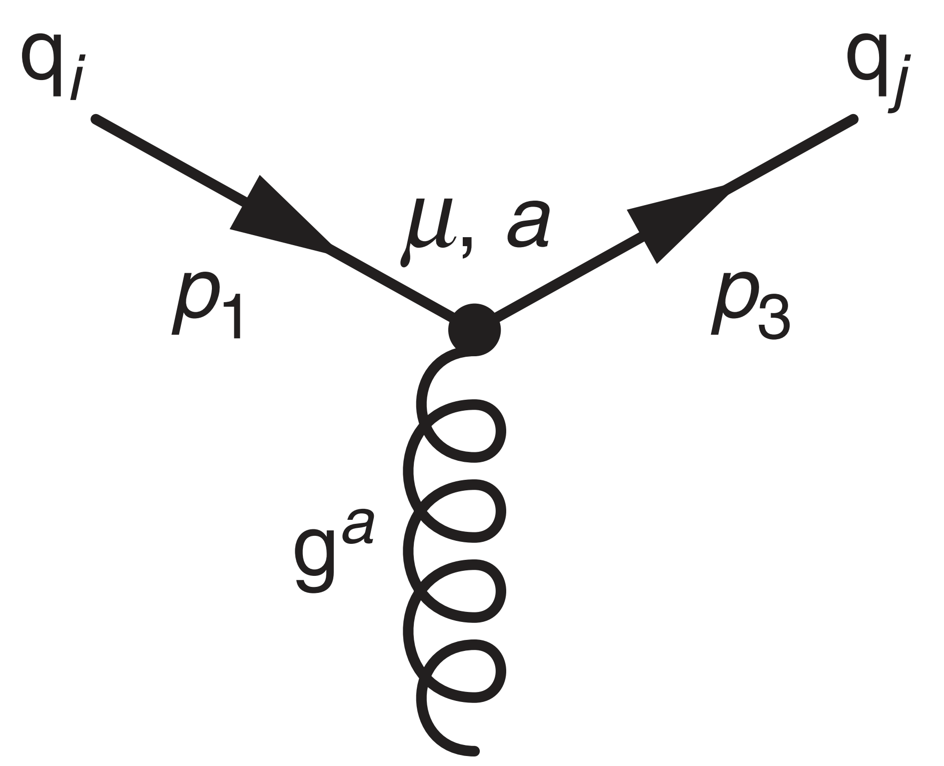
$c_3 = b = \begin{pmatrix}0\\0\\1\end{pmatrix}$



Factorize the qqg vertex

j^μ_q from last slide

$$\bar{u}(p_3)c_j^\dagger\{-\tfrac{1}{2}ig_s\lambda^a\gamma^\mu\}c_i u(p_1) = -\tfrac{1}{2}ig_s\underbrace{\left[c_j^\dagger\lambda^a c_i\right]}_{\text{color part}}\times\left[\bar{u}(p_3)\gamma^\mu u(p_1)\right]$$



$$c_j^\dagger\begin{pmatrix}\lambda^a_{1i}\\ \lambda^a_{2i}\\ \lambda^a_{3i}\end{pmatrix} = \lambda^a_{ji} \Leftarrow$$

This is a number.
The ji^{th} element of λ^a.

Gluons

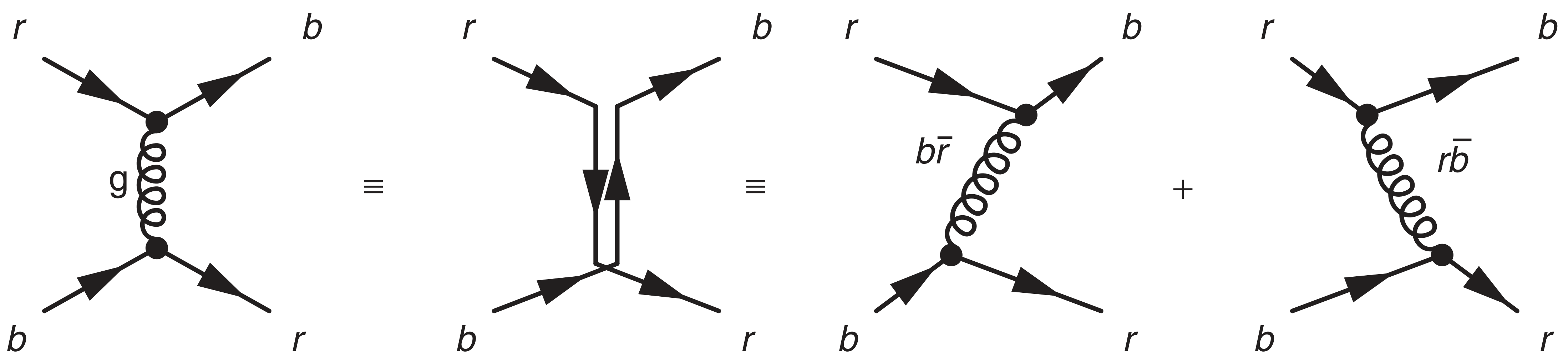
off-diagonal

- QCD interaction vertex includes a factor of λ_{ij}, where i & j label the colors of the quarks
  - $\Rightarrow$ *Gluons corresponding to the non-diagonal GM matrices connect quark states of diff. color*
  - $\Rightarrow$ *Gluons **must** carry color charge (for color to be conserved)*

1 unit of color
1 unit of anti-color

$\vec{T} = \frac{1}{2}\vec{\lambda}$

The 8 gluons correspond to these 8 linear combination of generators



Gell-Mann matrices: The 8 matrices used to represent the **generators** of the SU(3) symmetry

$$\lambda_1 = \begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix},\quad \lambda_4 = \begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix},\quad \lambda_6 = \begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix}$$

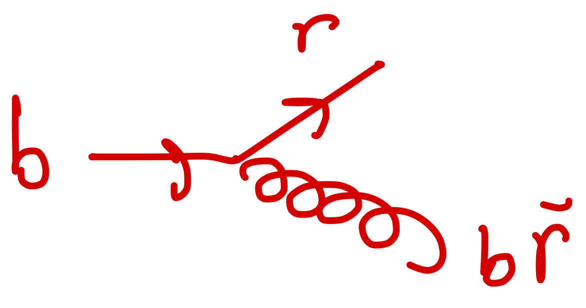
$$\lambda_2 = \begin{pmatrix}0&-i&0\\i&0&0\\0&0&0\end{pmatrix},\quad \lambda_5 = \begin{pmatrix}0&0&-i\\0&0&0\\i&0&0\end{pmatrix},\quad \lambda_7 = \begin{pmatrix}0&0&0\\0&0&-i\\0&i&0\end{pmatrix}$$

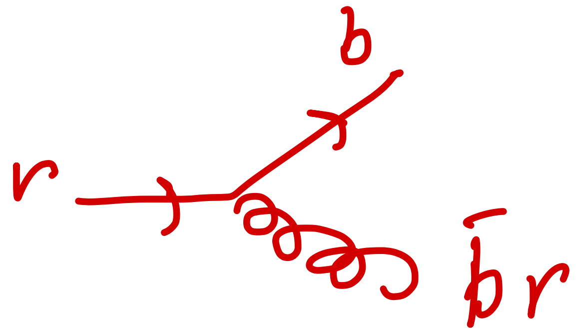
$$\lambda_3 = \begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix},\quad \lambda_8 = \frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}.$$

$$T_4 \pm iT_5 = \frac{1}{2}\begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix} \pm \frac{i}{2}\begin{pmatrix}0&0&-i\\0&0&0\\i&0&0\end{pmatrix} = \begin{pmatrix}0&0&1\\0&0&0\\0&0&0\end{pmatrix}$$

or

$$\begin{pmatrix}0&0&0\\0&0&0\\1&0&0\end{pmatrix}$$



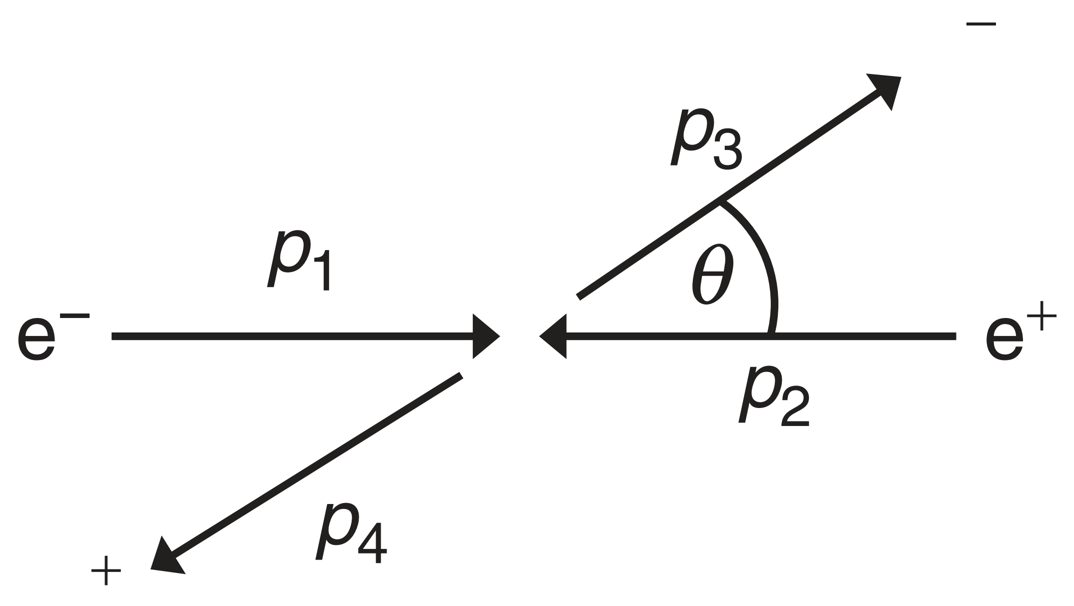


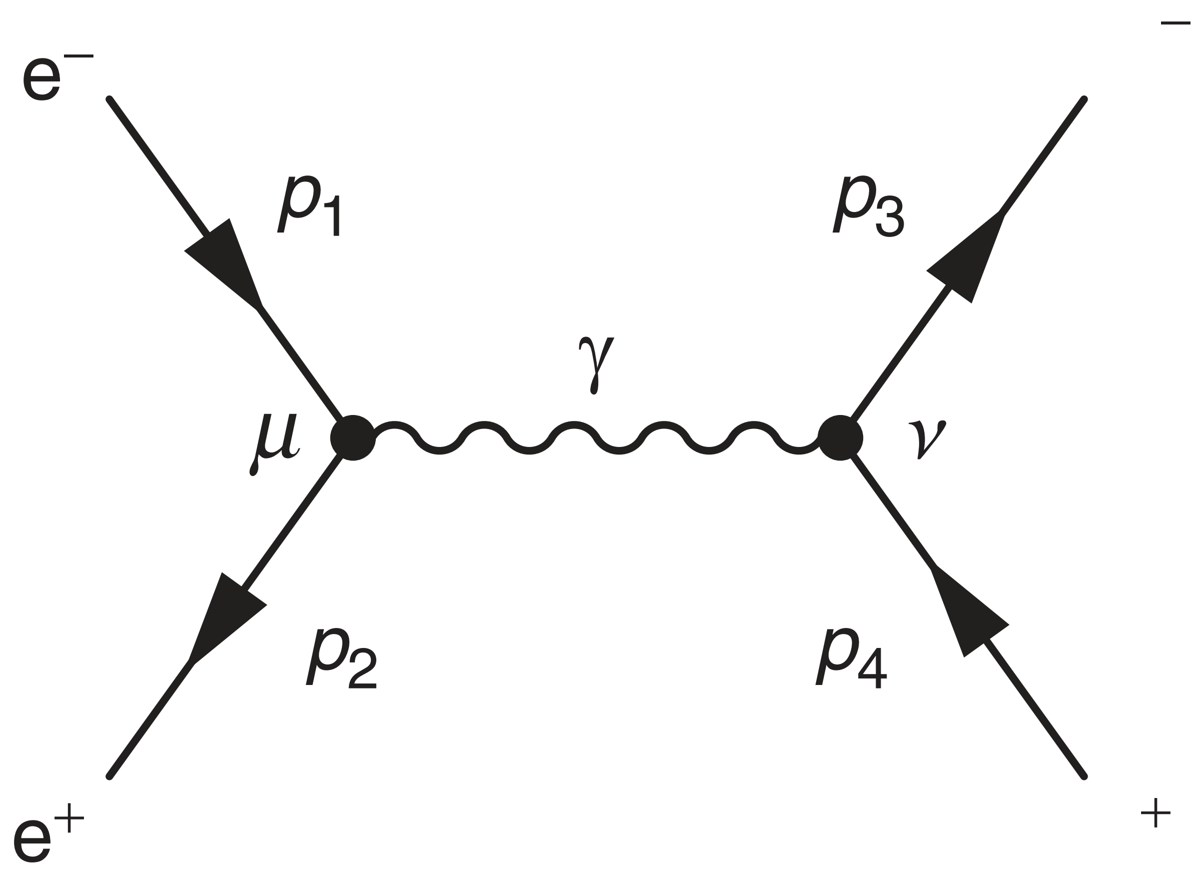
Also have

$T_1 \pm iT_2$, T_3 , T_8

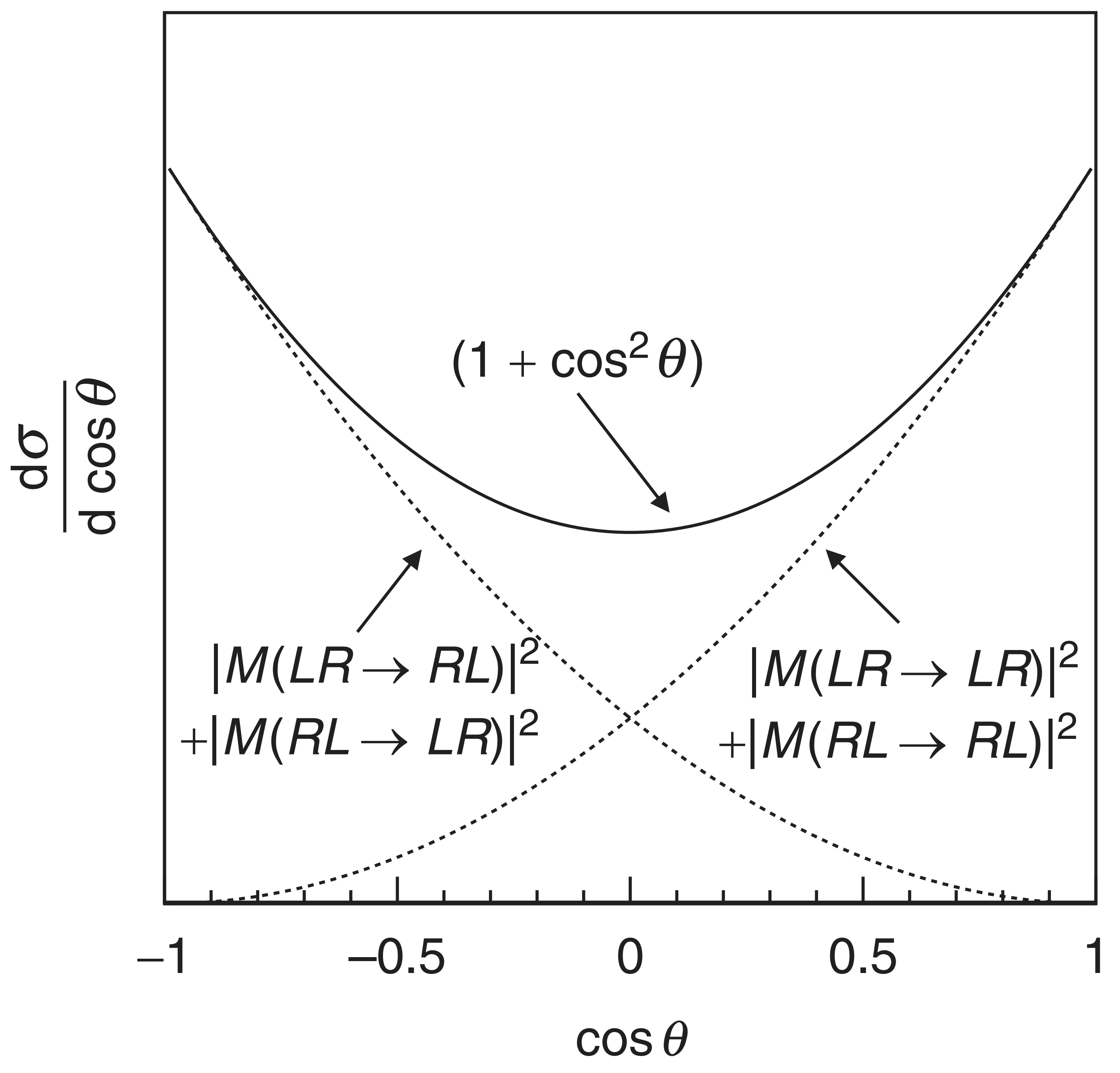
$T_6 \pm iT_7$

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





Thomson Figs. 6.4, 6.7



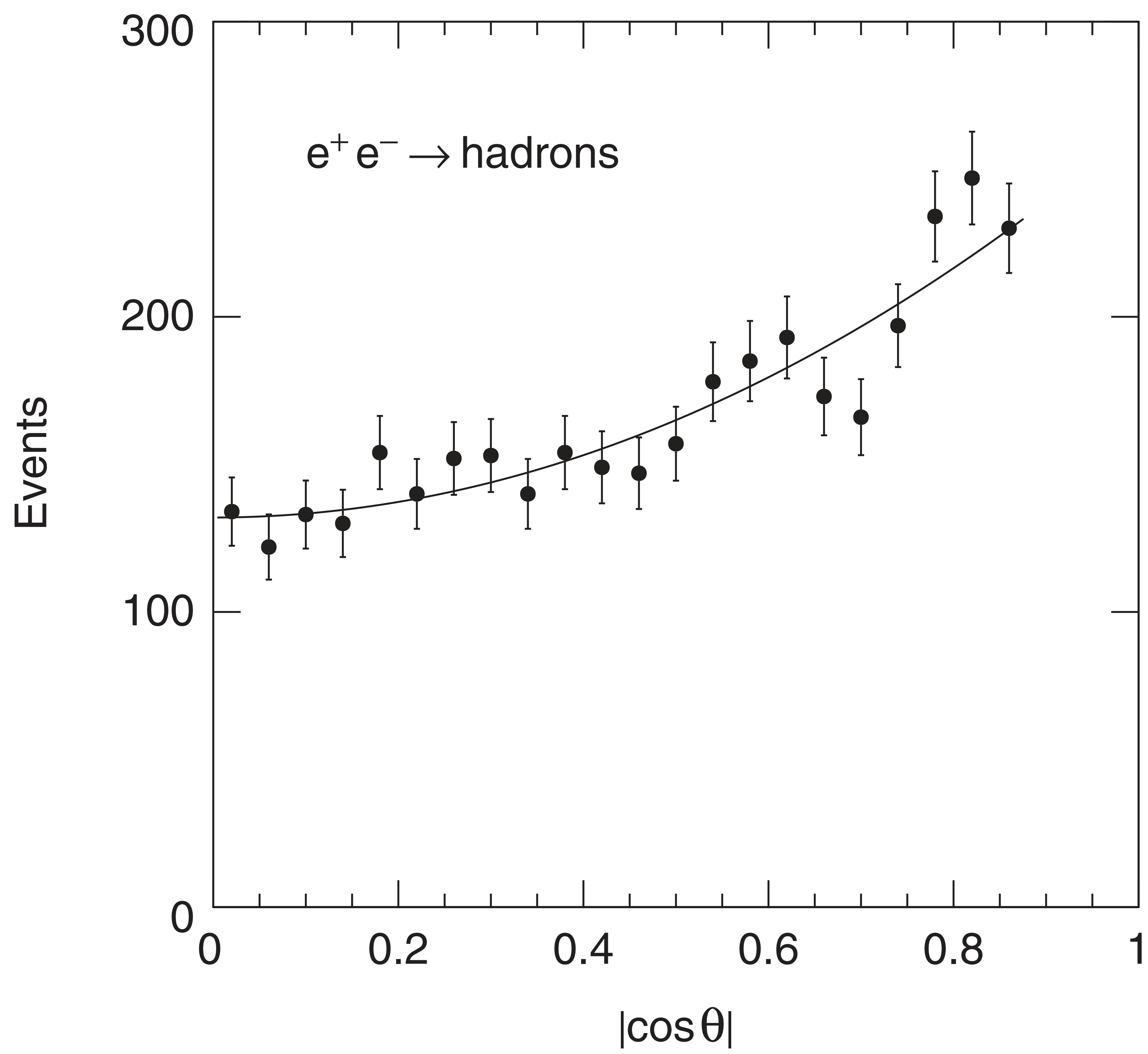
$$\begin{aligned}\langle|\mathcal{M}_{fi}|^2\rangle &= \frac{1}{4}\times\left(|\mathcal{M}_{RL\to RL}|^2+|\mathcal{M}_{RL\to LR}|^2+|\mathcal{M}_{LR\to RL}|^2+|\mathcal{M}^2_{LR\to LR}|\right)\\ &= \frac{1}{4}e^4\left[2(1+\cos\theta)^2+2(1-\cos\theta)^2\right]\\ &= e^4(1+\cos^2\theta).\end{aligned}$$

$$\boxed{\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{4s}(1+\cos^2\theta).}$$

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

- Assuming quarks are spin-half particles, should have the same angular dependence

- However:
  - Generally not possible to ID which flavor of quark was produced, *so express as an inclusive sum over all hadrons $e^+e^- \rightarrow$ hadrons*
  - Usually not possible to ID which jet came from the quark and which from the antiquark, so quote in terms of $|\cos\theta|$



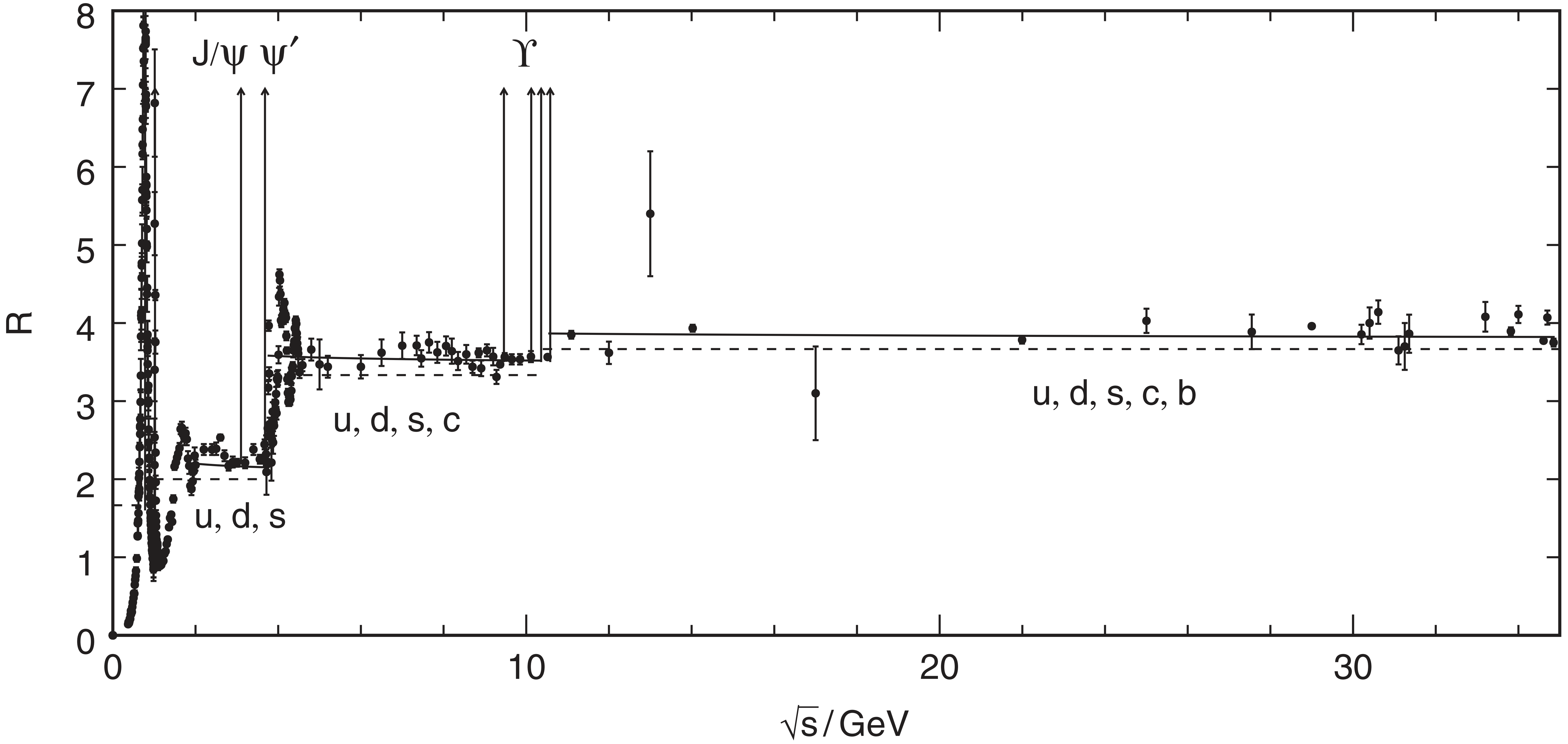
R-ratio

- Determine the number of colors from production and decay processes involving quarks. Compare production of hadrons and $\mu^+\mu^-$ in e^+e^-scattering

- The total QED $e^+e^- \to \mu^+\mu^-$ cross section

- For the inclusive QED production of hadrons

R-ratio



PINGO: R-ratio

- PINGO:
  - Session: Particle Physics 1 (WS 24/25).
  - Accession number: 559016
  - Link: https://pingo.coactum.de/events/559016

PINGO: R-ratio

- What happens to the R-ratio for energies above $\sqrt{s} \gtrsim 350$ GeV?
  - The R-ratio shows a sharp peak because $t\bar{t}$ bound states appear like for all other quarks
  - The R-ratio shows a step and becomes $R = 5$
  - Since there are no $t\bar{t}$ bound states, there is neither a sharp peak nor a step

Cooperative project seminar
“Particle Physics meets Music Informatics"

KIT – Karlsruher Institut für Technologie, ETP – Institut für experimentelle Teilchenphysik / CERN, IMWI – Institut für Musikinformatik und Musikwissenschaft, Hochschule für Musik Karlsruhe

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Grundsätzliches Ziel dieses kooperativen Projektseminars ist es, einen Raum zur Begegnung und gegenseitigen Befruchtung wissenschaftlicher und künstlerischer Praktiken zu schaffen.
Um den Austausch zwischen den Beteiligten und (Teil-)Projekten zu fördern, sollen über das Semester hinweg regelmäßige Treffen, in Form eines Kolloquiums gesetzt werden.

Den Auftakt bilden drei Kick-Off-Veranstaltungen mit Impulsvorträgen und anschließendem Rahmen zur Diskussion. Die daraus resultierenden Ideen können dann in konkrete Projektausarbeitungen münden. Diese sollen in kleinen Arbeitsgruppen mit Beteiligten beider Institutionen unter Betreuung der jeweiligen Lehrenden (ggf. auch als aktiv Mitgestaltende/-entwickelnde) realisiert werden, die relativ autark Teilbereiche einer größeren Projektidee oder kleinere autonome Projekte realisieren können. Die Bandbreite möglicher Projekte kann dabei von freien Kunstwerken wie Elektroakustische Kompositionen oder interaktiven Installationen bis hin zu Forschungstools im Sinne eines Transmodal Data Display reichen.

14.11., HfM Karlsruhe MUT Seminarraum 206, 17 Uhr
Impulsvorträge von Prof. Dr. Markus Klute (KIT) und Lehrenden des IMWI

21.11., HfM Karlsruhe MUT Seminarraum 206, 17 Uhr
Impulsvorträge von Dr. Michale Hoch (CERN) und Lehrenden des IMWI

28.11., HfM Karlsruhe MUT Seminarraum 206, 17 Uhr
Austausch und Ideenfindung

Die weiteren Termine werden dann sukzessive festgelegt.

Zusatztermin:
Di, 19.11., Staatliche Akademie der Bildenden Künste Karlsruhe, 17 Uhr
Prof. Dr. Markus Klute, Vortrag über Raum und Zeit

Reading assignment

- Modern particle physics (Mark Thomson)
  - Chap. 9 (complete)
  - Chap. 10
    - 10.1-10.3
    - 10.6-10.7