Lecture II: QCD scattering theory

- ❖ Physical states of QCD, Feynman rules and color algebra
- ❖ Kinematics, colour structure and amplitudes of typical processes
- ❖ Lorentz-invariant phase space and the parton-level cross section
- ❖ Soft gluon radiation and resummation
- ❖ Hadronisation and confinement

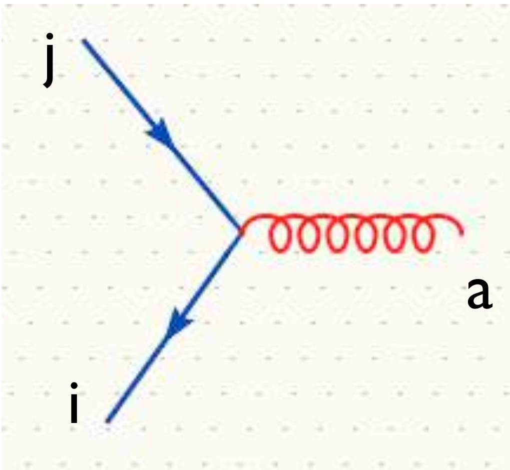
From QED to QCD interactions: 3-gluon vertex

Particles carry non-Abelian charge “color”: they transform under a nontrivial representation R of a non-Abelian group G (=SU(3) for quarks!)

The standard currents operator transforms as $R \otimes \bar{R}$: the only representation that belongs to this product for any R is the adjoint representation of group G

$$3 \otimes 3^* = 1 \oplus 8$$

The field that couples to the current must transforms under adjoint rep of G!



$$q\bar{q} \to gg$$

$$-ig_s t^a_{ij}\gamma^\mu$$

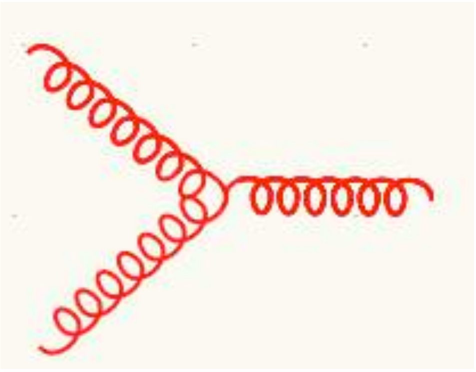
$$[t^a, t^b] = if^{abc}t^c$$

$$\frac{i}{g_s^2}M_g \equiv (t^b t^a)_{ij} D_1 + (t^a t^b)_{ij} D_2$$

$$M_g = (t^a t^b)_{ij} M_\gamma - g^2 f^{abc} t^c_{ij} D_1$$

The gauge invariance must still work: $k_1^\mu {\epsilon_2}^\nu M_g^{\mu,\nu} = k_2^\nu \epsilon_1^\mu M_g^{\mu,\nu} = 0$

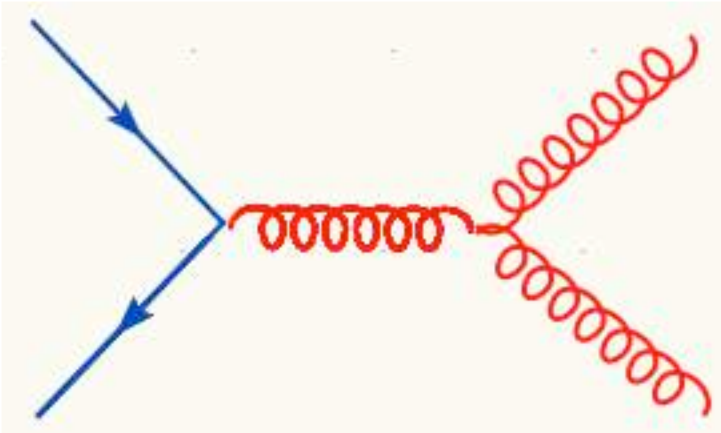
BUT! One piece has to compensated $k_{1\mu} M_g^\mu = i(-g_s f^{abc}\epsilon_2^\mu)(-ig_s t^c_{ij}\bar{v}_i(\bar{q})\gamma_\mu u_i(q))$



$$-g_s f^{abc} V_{\mu_1\mu_2\mu_3}(p_1, p_2, p_3)$$

new 3-gluon vertex!

From QED to QCD interactions: 3-gluon vertex



$$-ig_s^2 D_3 = \left(-ig_s t^a_{ij} \bar{v}_i(\bar{q})\gamma^\mu u_j(q)\right) \times \left(\frac{-i}{p^2}\right) \times$$
$$\left(-g f^{abc} V_{\mu\nu\rho}(-p, k_1, k_2)\epsilon_1^\nu(k_1)\epsilon_2^\rho(k_2)\right)$$

<u>How do we write the Lorentz structure of such a new interaction?</u>

- ❖ Lorentz invariance: built out of the terms of the form $g_{\mu_1\mu_2} p_{\mu_3}$
- ❖ Bose symmetry: V is fully anti-symmetric w.r.t. permutations $(\mu_i, p_i) \leftrightarrow (\mu_j, p_j)$
- ❖ Dimensional analysis: only one power of momentum!
- ❖ Up to an overall factor:

$$V_{\mu_1\mu_2\mu_3}(p_1, p_2, p_3) = V_0 \left[(p_1 - p_2)_{\mu_3} g_{\mu_1\mu_2} + (p_2 - p_3)_{\mu_1} g_{\mu_2\mu_3} + (p_3 - p_1)_{\mu_2} g_{\mu_3\mu_1}\right]$$

$$k_1 \cdot D_3 = g^2 f^{abc} t^c V_0 \left[\bar{v}(\bar{q})\not{\epsilon}_2 u(q) - \frac{k_2 \cdot \epsilon_2}{2k_1 \cdot k_2} \bar{v}(\bar{q})\not{k}_1 u(q)\right]$$

Gauge invariance is satisfied for physical external gluons:

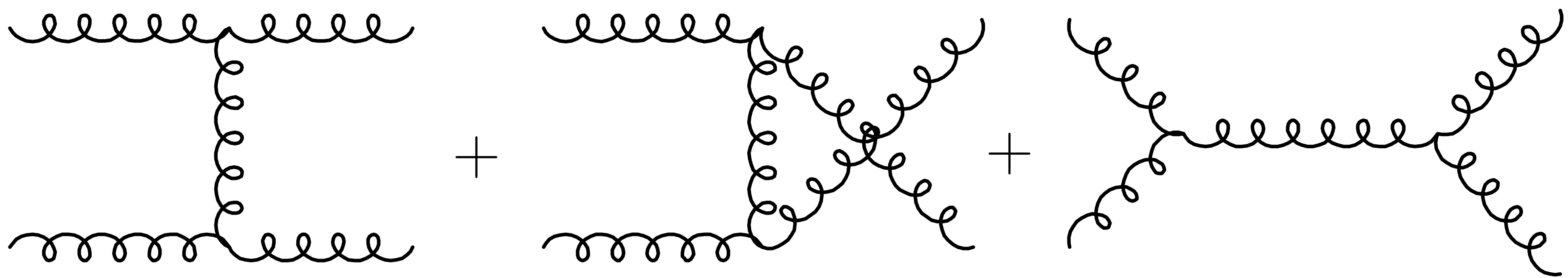
$$k_2 \cdot \epsilon_2 = 0$$

with $V_0 = 1$

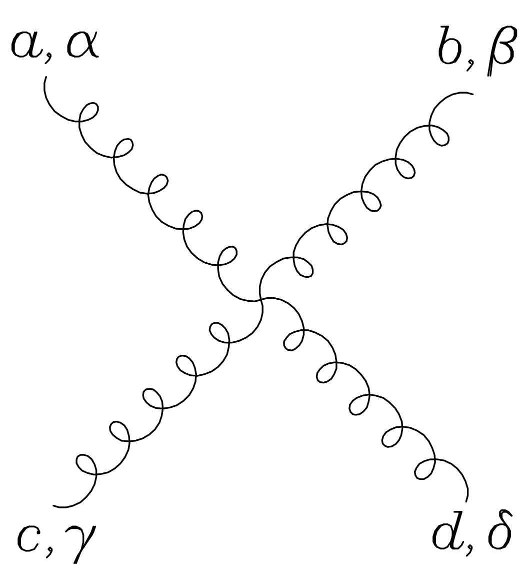
4-gluon vertex

- Similarly to the 3-gluon vertex, the gauge invariance of the gluon scattering

$gg \to gg$



requires the presence of an additional contribution given by the 4-gluon vertex:



$$
\begin{aligned}
= \quad & -ig^2 f^{xac} f^{xbd} \left(g^{\alpha\beta} g^{\gamma\delta} - g^{\alpha\delta} g^{\beta\gamma} \right) \\
& -ig^2 f^{xad} f^{xbc} \left(g^{\alpha\beta} g^{\gamma\delta} - g^{\alpha\gamma} g^{\beta\delta} \right) \\
& -ig^2 f^{xab} f^{xcd} \left(g^{\alpha\gamma} g^{\beta\delta} - g^{\alpha\delta} g^{\beta\gamma} \right)
\end{aligned}
$$

No extra vertices have to be introduced — all QCD amplitudes are automatically gauge-invariant with this set of Feynman rules!

Physical states of QCD

- For Abelian symmetries (such as in QED)

$$\sum_{\epsilon_1} |M|^2 = \left(\sum_{\epsilon_1} \epsilon_1^\mu \epsilon_1^{\nu *} \right) M_\mu M_\nu^*$$

ALL polarisations!

Two independent physical polarisations:

$$\epsilon^\mu_{L,R} = (0; 1, \pm i, 0)/\sqrt{2}$$

$$\epsilon_L \cdot \epsilon_L^* = -1 = \epsilon_R \cdot \epsilon_R^* \qquad \epsilon_L \cdot \epsilon_R^* = 0$$

- Sum over physical polarisations:

$$k = (k_0; 0, 0, k_0) \qquad \bar{k} = (k_0; 0, 0, -k_0)$$

$$k_\mu M^\mu = 0 \qquad M_0 = M_3$$

$$\sum_{i=L,R} \epsilon_i^\mu \epsilon_i^{\nu *} \equiv \begin{pmatrix} 0 & & \vec{0} & \\ & 1 & 0 & 0 \\ \vec{0} & 0 & 1 & 0 \\ & 0 & 0 & 0 \end{pmatrix} = -g_{\mu\nu} + \frac{k_\mu \bar{k}_\nu + k_\nu \bar{k}_\mu}{k \cdot \bar{k}}$$

In QED: can be safely dropped!

$$\sum_{i=L,R} |\epsilon_i \cdot M|^2 = |M_1|^2 + |M_2|^2 = |M_1|^2 + |M_2|^2 + |M_3|^2 - |M_0|^2 \equiv -g^{\mu\nu} M_\mu M_\nu^*$$

Production of space-like and longitudinal photons cancel out: only physical states are produced!

- NOT true in non-Abelian theories such as QCD!!!

$$k_1 \cdot M \propto \epsilon_2 \cdot k_2$$

Vanishes ONLY for physical ϵ_2 !!!

Production of a pair of unphysical gluons is allowed in QCD!

$$\sum_{\mathrm{non-physical}} |\epsilon_1^\mu \epsilon_2^\nu M_{\mu\nu}|^2 = \left| i\, g^2 f^{abc} \lambda^c \frac{1}{2k_1 k_2} \bar{v}(\bar{q}) \not{k}_1\, u(q) \right|^2$$

The role of ghosts

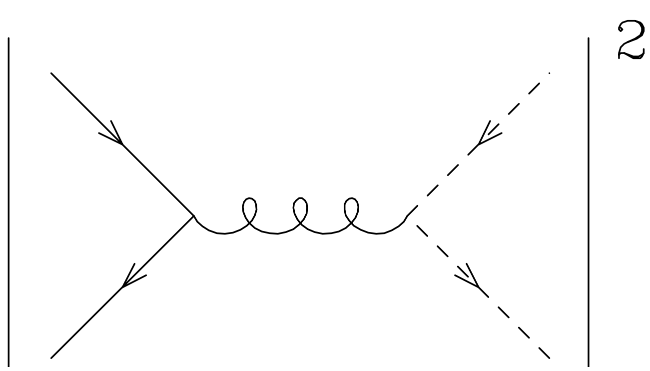
- The choice of physical gauges: remove ALL unphysical d.o.f. from the final states (and off-shell propagators they are coupled to) explicitly imposing

$$\sum \epsilon_\mu \epsilon_\nu^* = -g_{\mu\nu}$$

<u>**Unitarity is imposed!**</u>

- Alternatively, gauge fixing in non-physical gauges (e.g. covariant gauge): appearance of two colour octet scalar d.o.f. only coupling to gluons (their loop comes with -1 as if they obey Fermi statistics!) which are pair-produced and exist in loops

- Due to violation of the spin-statistics theorem, the ghosts lead to negative probability contributions necessary to cancel unphysical gluons' effect!



$$= -\left| i\, g^2\, f^{abc} \lambda^c \; \frac{1}{2k_1 k_2} \bar{v}(\bar{q}) \not{k}_1 \; u(q) \right|^2$$

<u>**Unitarity is restored!**</u>

exactly cancels the unphysical gluon term!

QCD Feynman rules

Free fields:

$u(p,s)$ incoming fermion

$\bar{u}(p,s)$ outgoing fermion

$\bar{v}(p,s)$ incoming antifermion

$v(p,s)$ outgoing antifermion

$\epsilon(p,s)$ incoming vector boson

$\epsilon^*(p,s)$ outgoing vector boson

in order to define the gluon propagator → fix the gauge!

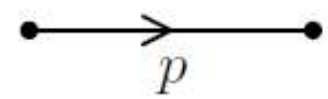
Covariant gauges:

$$\Delta L = -\frac{1}{2a_0}(\partial_\mu A_0^{a\mu})^2 + (\partial^\mu \bar{c}_0^a)(D_\mu c_0^a)$$

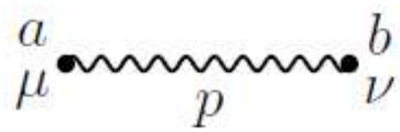
ghost: scalar field obeying Fermi statistics

popular Feynman gauge: $a_0 = 1$

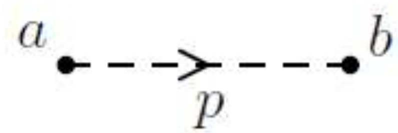
Free propagators in covariant gauges:



$= iS_0(p) \qquad S_0(p) = \frac{1}{\not p} = \frac{\not p}{p^2}$ massless quark!

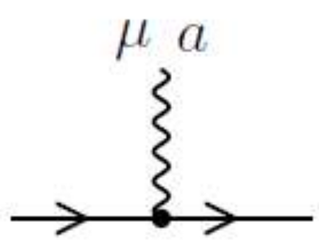


$= -i\delta^{ab} D^0_{\mu\nu}(p) \qquad D^0_{\mu\nu}(p) = \frac{1}{p^2}\left[g_{\mu\nu} - (1-a_0)\frac{p_\mu p_\nu}{p^2}\right]$

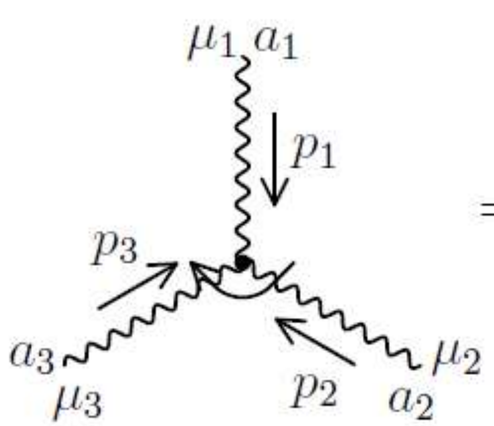


$= i\delta^{ab} G_0(p) \qquad G_0(p) = \frac{1}{p^2}$

Bare vertices:

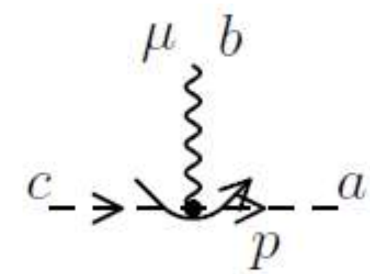


$= t^a \times ig_0\gamma^\mu$

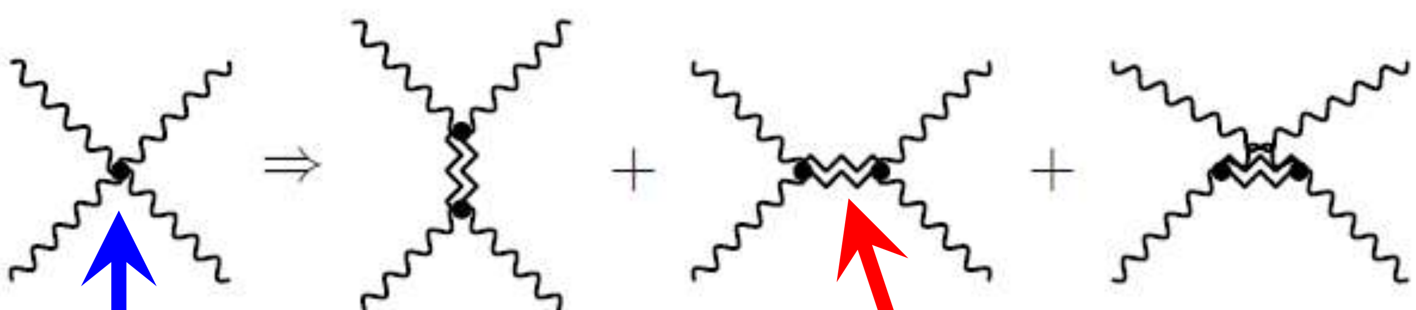


$= if^{a_1a_2a_3} \times ig_0 V^{\mu_1\mu_2\mu_3}(p_1,p_2,p_3)$

$$V^{\mu_1\mu_2\mu_3}(p_1,p_2,p_3) = (p_3-p_2)^{\mu_1} g^{\mu_2\mu_3} + (p_1-p_3)^{\mu_2} g^{\mu_3\mu_1} + (p_2-p_1)^{\mu_3} g^{\mu_1\mu_2}$$

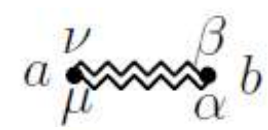


$= if^{abc} \times ig_0 p^\mu$

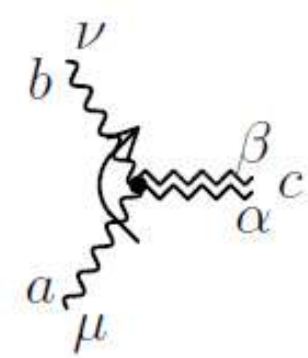


second order in coupling

auxiliary field



$= i\delta^{ab}(g^{\mu\alpha}g^{\nu\beta} - g^{\mu\beta}g^{\nu\alpha})$



$= if^{abc} \times g_0 g^{\mu\alpha} g^{\nu\beta}$

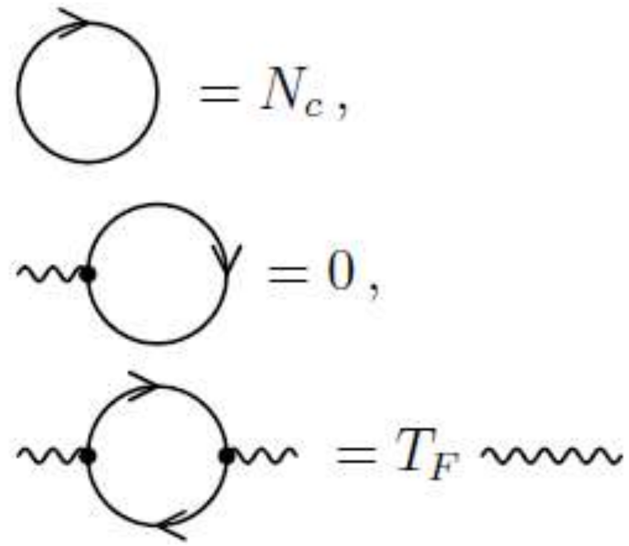
Color factors calculus: Cvitanović algorithm

Graphical representation of the color factors:

$\mathrm{Tr}\,1 = N_c$ or

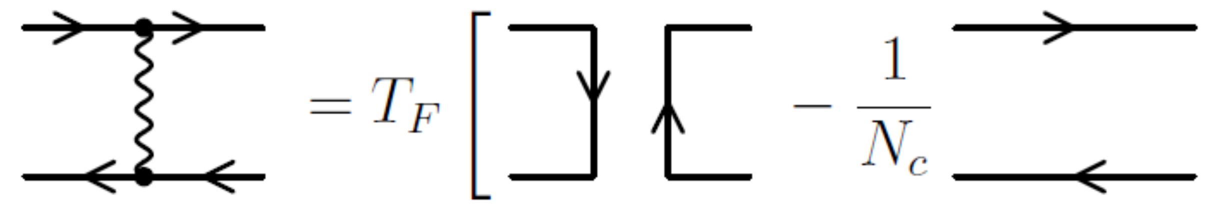
$\mathrm{Tr}\,t^a = 0$ or

$\mathrm{Tr}\,t^a t^b = T_F \delta^{ab}$ or



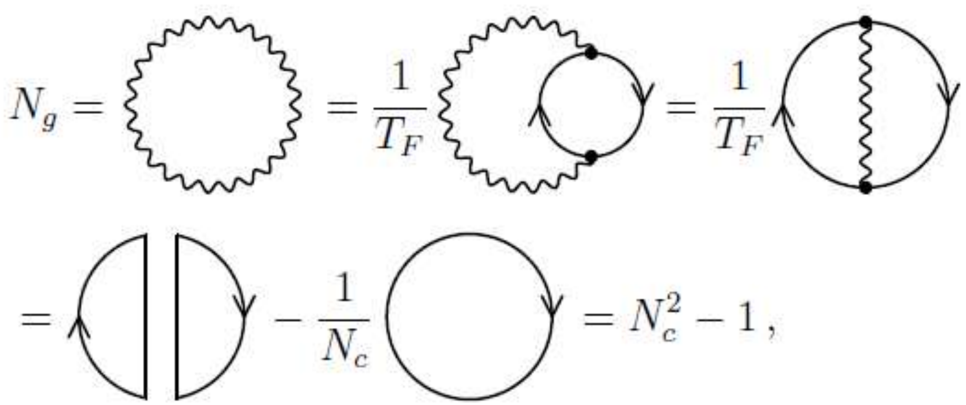
…eliminating gluons from color diagrams!

$$(t^a)^i{}_j (t^a)^k{}_l = T_F \left[\delta^i_l \delta^k_j - \frac{1}{N_c} \delta^i_j \delta^k_l \right]$$

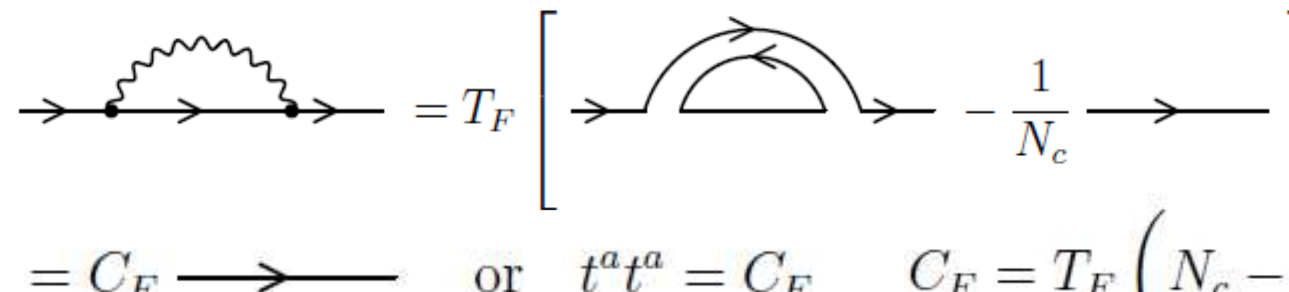


Quark-antiquark Color singlet

Example 1: number of gluons



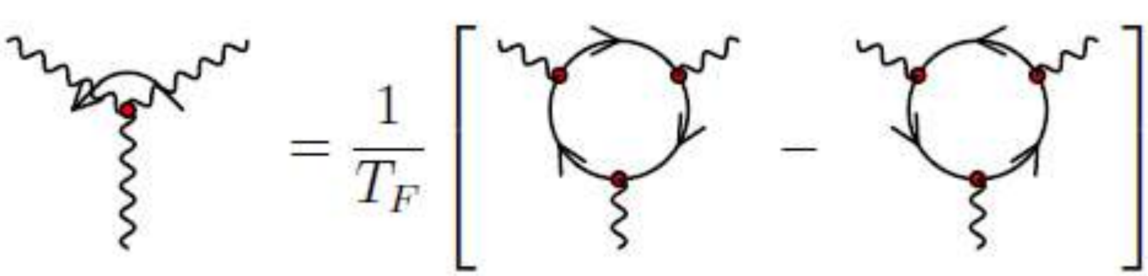
Example 2: Casimir operator in the fundamental rep.



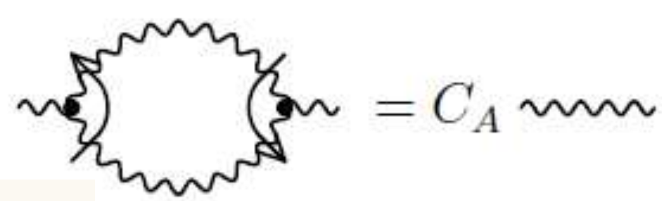
or $t^a t^a = C_F$ $\quad C_F = T_F \left(N_c - \frac{1}{N_c} \right)$

$$(t^a t^a)_{ij} = C_F \delta_{ij}$$

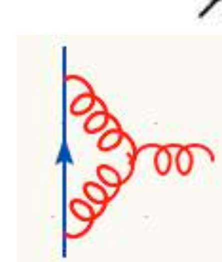
…eliminating 3-gluon vertices!



Example 3: Casimir operator in the adjoint rep.

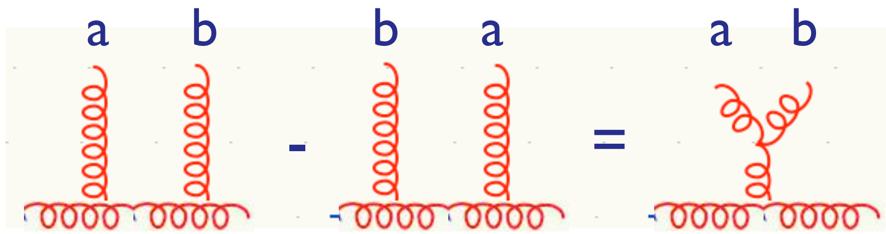


or $i f^{acd} i f^{bdc} = C_A \delta^{ab}$



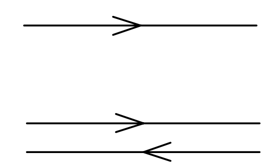
$$i f^{abc} (t^b t^c)_{ij} = \frac{C_A}{2} t^a_{ij} \qquad C_A = 2 T_F N_c$$

More color algebra

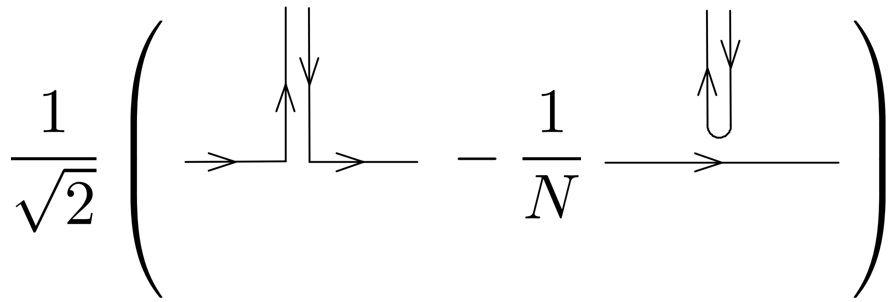


Generators in the adjoint representation satisfy:

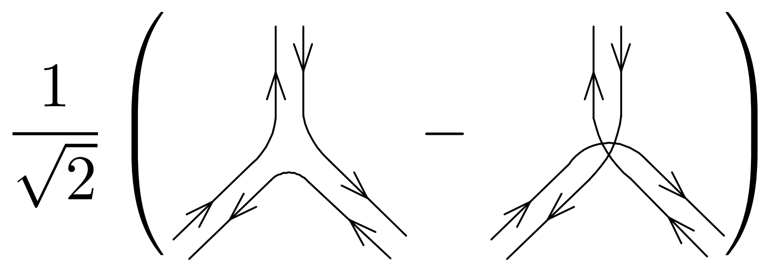
$$[F^a, F^b] = i f^{abc} F^c$$



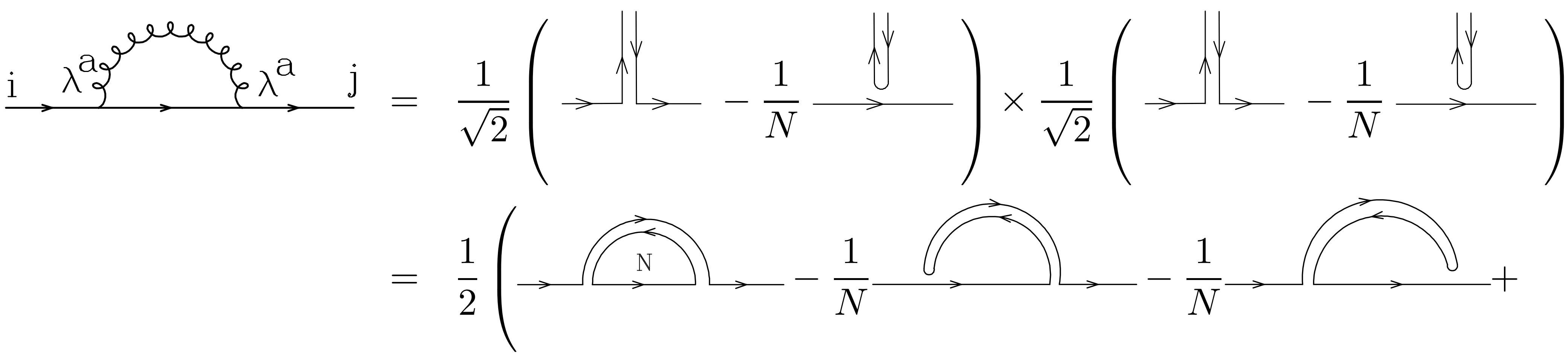
In the large N-limit gluons behaves as a quark-antiquark pair!

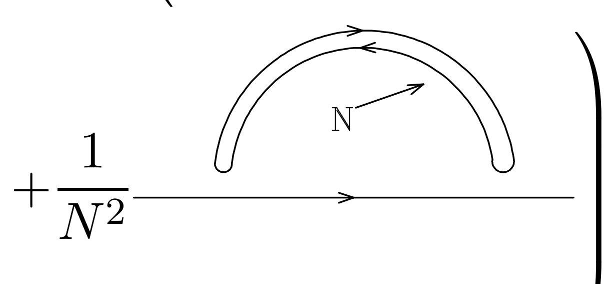


Fermion-Gluon Vertex (t^a)



3-Gluon Vertex (f^{abc})



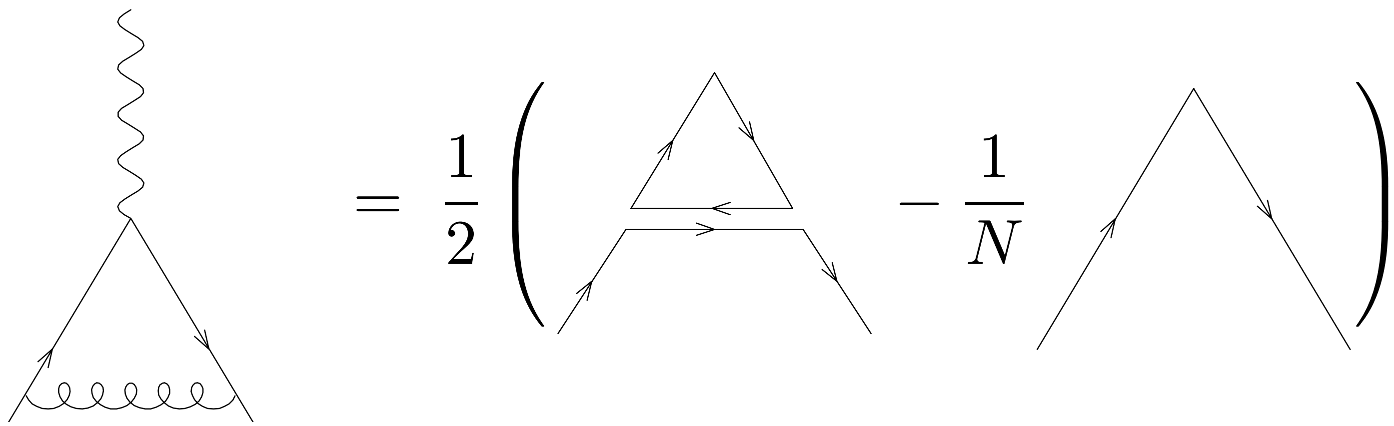


$$= \delta^{ij}\frac{N^2-1}{2N}$$

Many algorithms and codes work in the large-N limit (e.g. parton showers)

Even more color algebra

❖ The gluon exchange between the quark and anti-quark in the color-singlet state:



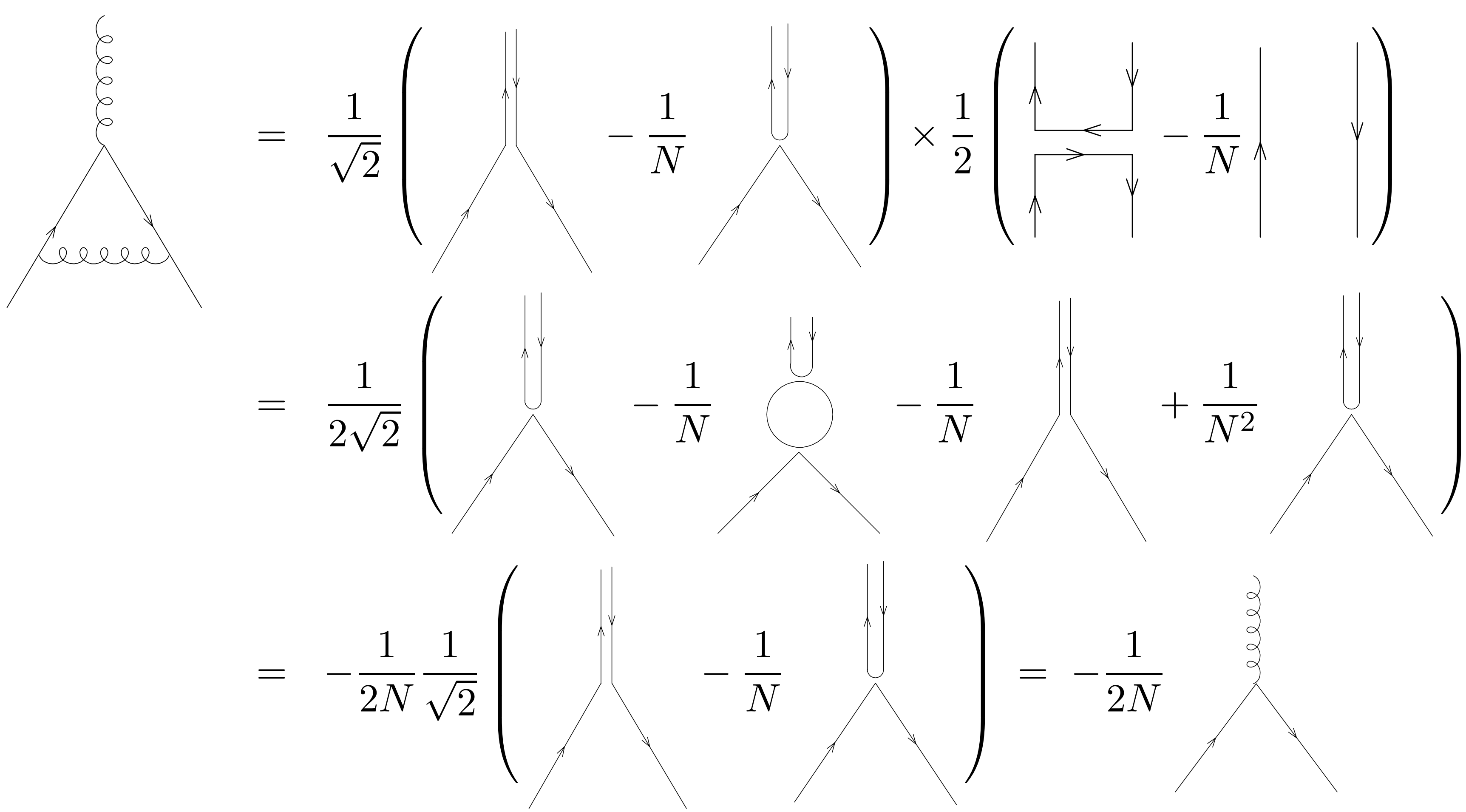
$$= \frac{1}{2}\frac{N^2-1}{N}\delta_{ij} \;=\; C_F\delta_{ij}$$

has positive sign, so the interaction is attractive!

Bound states are formed, with attractive potential

$$V(r) \simeq -C_F\frac{\alpha_S(1/r)}{r}$$

❖ The gluon exchange between the quark and anti-quark in the color-octet state:



has negative sign, so the interaction is repulsive!

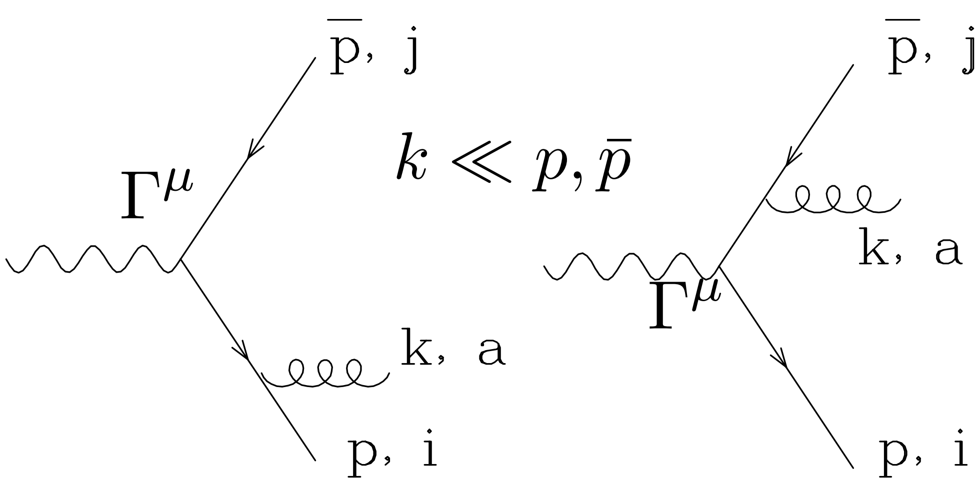
$$(t^b t^a t^b)_{ij} = (C_F - \frac{C_A}{2})t^a_{ij}$$

No colour-octet bound states exist!

Soft gluon emission off a singlet quark-antiquark pair

- ❖ **Emission of soft (=long wavelength) gluons plays a fundamental role in evolution of the final state (e.g. it defines final-state multiplicity of hadrons)**

- ❖ **Soft gluons are insensitive to the spin of the partons and cannot distinguish features of the interactions taking place at time scales shorter than their wavelengths (phenomenon of QCD factorisation)**



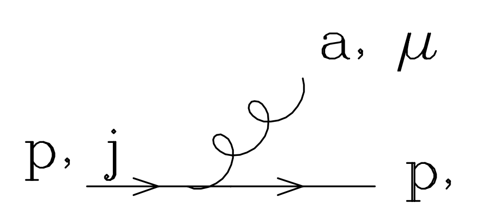
Amplitude:

$$A_{soft} = \bar{u}(p)\epsilon(k)(ig)\,\frac{-i}{\not{p}+\not{k}}\,\Gamma^\mu\, v(\bar{p})\ \lambda^a_{ij} + \bar{u}(p)\,\Gamma^\mu\,\frac{i}{\not{\bar{p}}+\not{k}}\,(ig)\epsilon(k)\,v(\bar{p})\ \lambda^a_{ij}$$

$$= \left[\frac{g}{2p\cdot k}\,\bar{u}(p)\epsilon(k)\,(\not{p}+\not{k})\Gamma^\mu\, v(\bar{p}) - \frac{g}{2\bar{p}\cdot k}\,\bar{u}(p)\,\Gamma^\mu\,(\not{\bar{p}}+\not{k})\epsilon(k)\,v(\bar{p})\right]\lambda^a_{ij}$$

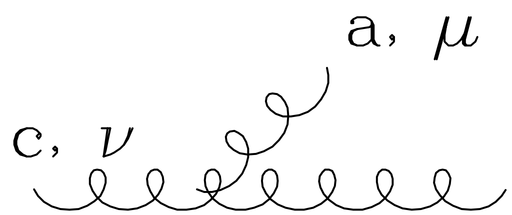
- ❖ **Using the Dirac equation** $A_{soft} = g\lambda^a_{ij}\ \left(\frac{p\cdot\epsilon}{p\cdot k} - \frac{\bar{p}\epsilon}{\bar{p}\cdot k}\right)\ A_{Born}$ **Factorises!**

- ❖ **The Feynman rule for the soft photon radiation**



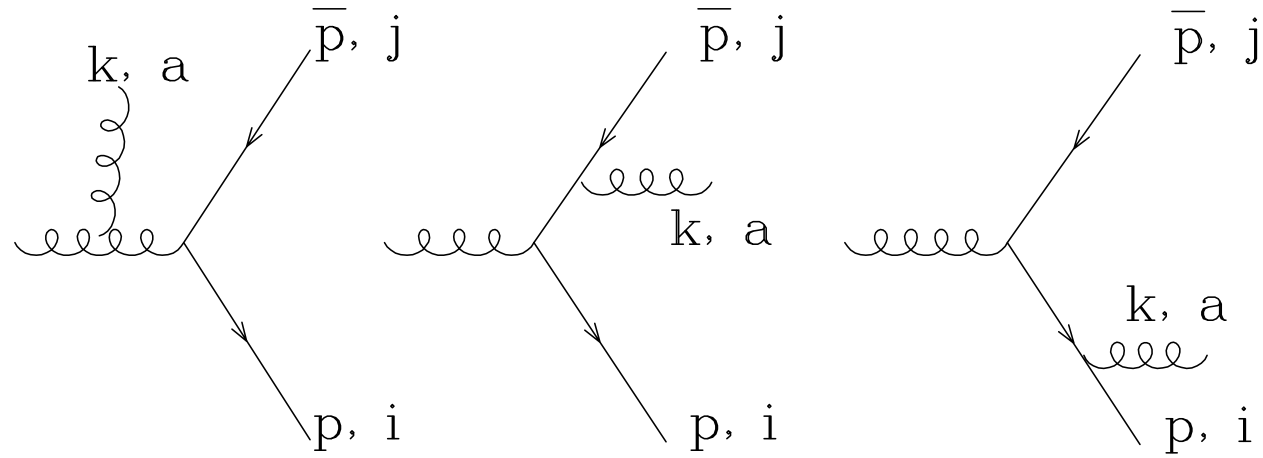
$$= g\ \lambda^a_{ij}\ 2p^\mu$$

- ❖ **Analogically**



$$= igf^{abc}\ 2p^\mu\ g^{\nu\rho}$$

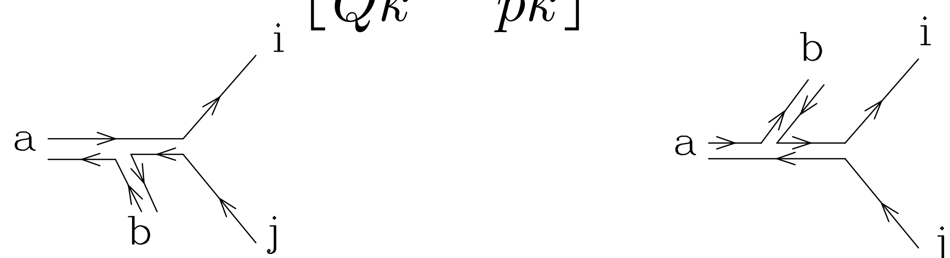
Soft gluon emission off an octet quark-antiquark pair



$$\stackrel{k\to 0}{=} \left[i\ g\ f^{abc}\ \lambda^c_{ij}\ \left(\frac{Q\epsilon}{Qk}\right) + g\ (\lambda^b\,\lambda^a)_{ij}\left(\frac{p\epsilon}{pk}\right) - g\ (\lambda^a\lambda^b)_{ij}\left(\frac{\bar{p}\epsilon}{pk}\right)\right] A_{Born}$$

$$= \quad g\ (\lambda^a\,\lambda^b)_{ij}\left[\frac{Q\epsilon}{Qk} - \frac{\bar{p}\epsilon}{pk}\right] + g\ (\lambda^b\,\lambda^a)_{ij}\left[\frac{p\epsilon}{pk} - \frac{Q\epsilon}{Qk}\right]$$

Color flow:

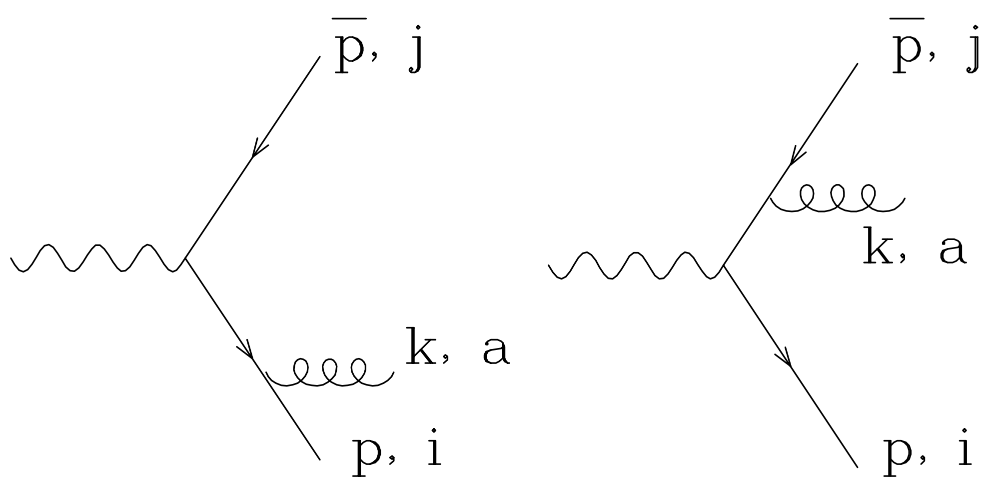


In the emission probability, the interference terms are color-suppressed:

$$\sum_{a,b,i,j} |(\lambda^a\lambda^b)_{ij}|^2 = \sum_{a,b} \mathrm{tr}\ \left(\lambda^a\lambda^b\lambda^b\lambda^a\right) = \frac{N^2-1}{2}\,C_F \ = \ \mathcal{O}(N^3)$$

$$\sum_{a,b,i,j} (\lambda^a\lambda^b)_{ij}[(\lambda^b\lambda^a)_{ij}]^* = \sum_{a,b} \mathrm{tr}(\lambda^a\lambda^b\lambda^a\lambda^b) = \frac{N^2-1}{2}\ \underbrace{(C_F - \frac{C_A}{2})}_{-\frac{1}{2N}} \ = \ \mathcal{O}(N)$$

Angular ordering



$$\theta_{\alpha\beta} = \theta_\alpha - \theta_\beta$$

$$i,\ j,\ k \quad q,\ \bar{q}\ \ g$$

Including the gluon phase space:

$$\begin{aligned} d\sigma_g &= \sum |A_{soft}|^2 \frac{d^3k}{(2\pi)^3 2k^0} \\ &= \sum |A_0|^2 \frac{-2p^\mu \bar{p}^\nu}{(pk)(\bar{p}k)}\ g^2 \sum \epsilon_\mu \epsilon^*_\nu \frac{d^3k}{(2\pi)^3 2k^0} \\ &= d\sigma_0 \frac{2(p\bar{p})}{(pk)(\bar{p}k)}\ g^2\ C_f \left(\frac{d\phi}{2\pi}\right) \frac{k^0 dk^0}{8\pi^2}\ d\ \cos\theta \\ &= d\sigma_0\ \frac{\alpha_s C_F}{\pi}\ \frac{dk^0}{k^0}\ \frac{d\phi}{2\pi} \frac{1-\cos\theta_{ij}}{(1-\cos\theta_{ik})(1-\cos\theta_{jk})} d\cos\theta \end{aligned}$$

The radiation probabilities from the quark and antiquark lines

$$\frac{1-\cos\theta_{ij}}{(1-\cos\theta_{ik})(1-\cos\theta_{jk})} = \frac{1}{2}\left[\frac{\cos\theta_{jk}-\cos\theta_{ij}}{(1-\cos\theta_{ik})(1-\cos\theta_{jk})} + \frac{1}{1-\cos\theta_{ik}}\right] + \frac{1}{2}[i \leftrightarrow j] \equiv W_{(i)} + W_{(j)}$$

Azimuthal average around q-direction

$$\int \frac{d\phi}{2\pi} W_{(i)} = \begin{cases} \frac{1}{1-\cos\theta_{ik}} & \text{if } \theta_{ik} < \theta_{ij} \\ 0 & \text{otherwise} \end{cases}$$

$$\int \frac{d\phi}{2\pi} W_{(j)} = \begin{cases} \frac{1}{1-\cos\theta_{jk}} & \text{if } \theta_{jk} < \theta_{ij} \\ 0 & \text{otherwise} \end{cases}$$

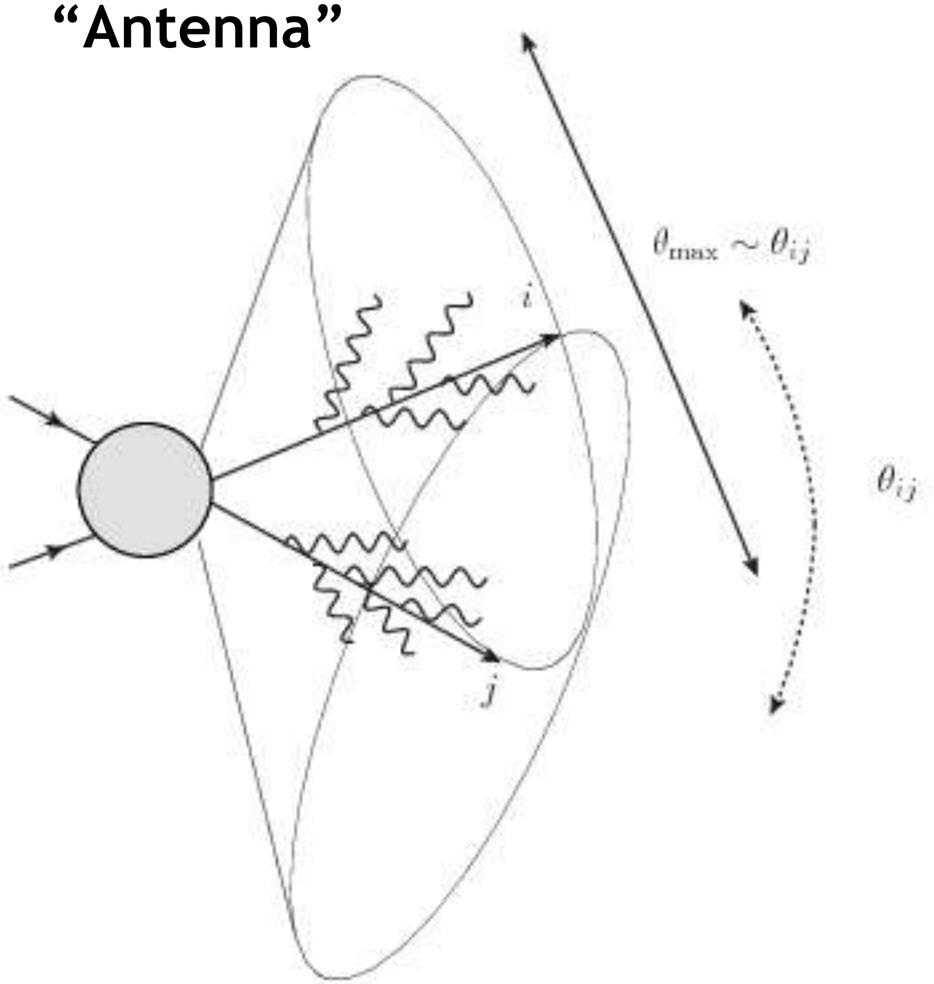
…are singular in the limit of parallel emission off the respective (anti)quark!

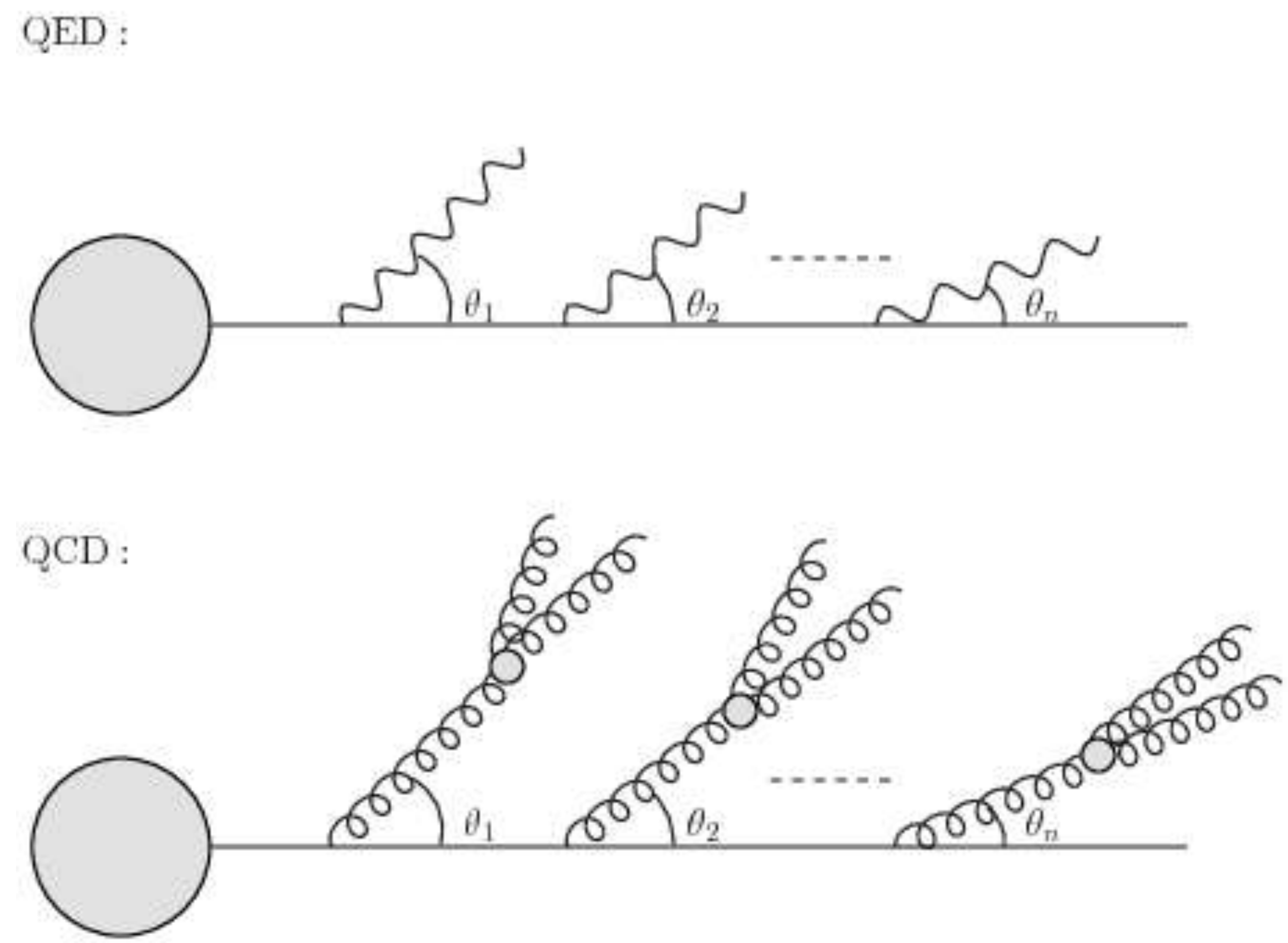
(i) No emission outside the two cones obtained by rotating the antiquark direction around the quark one, and vice versa (quantum coherence)

(ii) Uncorrelated emission inside the cones!

Angular ordering

"Antenna"

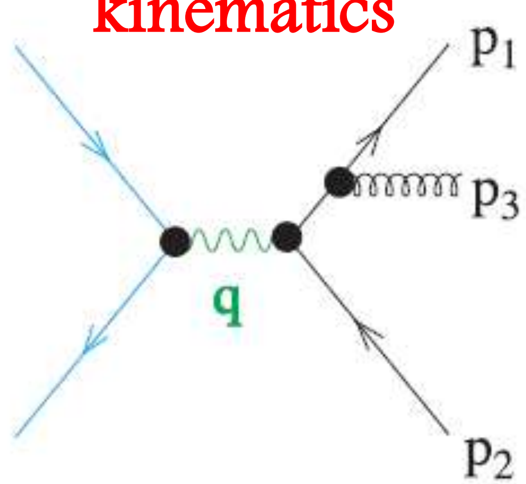




- ❖ **Color always flows directly from the emitting parton to the emitted one**
- ❖ **The radiation gets softer at later stages of the evolution**
- ❖ **Partons forming the color-singlet clusters appear to be close in phase space**
- ❖ **Hadronisation happens locally inside the jet: only pairs of nearby partons are involved!**

Soft and collinear divergences

kinematics



$$q^\mu q_\mu = s$$ *c.m.s energy squared*

$$E_i = p_i^0$$ *final states energies*

energy fractions

$$x_i = \frac{E_i}{\sqrt{s}/2} = \frac{2p_i \cdot q}{s} \qquad 0 \le x_i \le 1$$

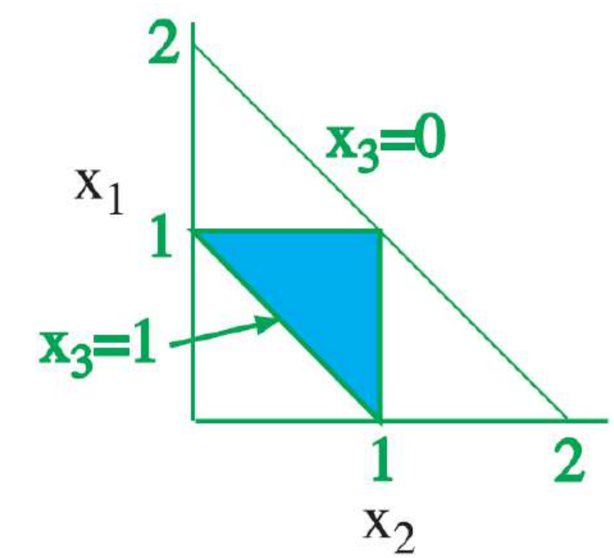
$$\sum_i x_i = \frac{2(\sum p_i)\cdot q}{s} = 2 \qquad x_3 = 2 - x_1 - x_2$$

angles between final momenta

$$x_1 x_2 (1-\cos\theta_{12}) = 2(1-x_3)$$
$$x_2 x_3 (1-\cos\theta_{23}) = 2(1-x_1)$$
$$x_3 x_1 (1-\cos\theta_{31}) = 2(1-x_2)$$

collinear partons

$$\theta_{12} \to 0 \Leftrightarrow x_3 \to 1$$
$$\theta_{23} \to 0 \Leftrightarrow x_1 \to 1$$
$$\theta_{31} \to 0 \Leftrightarrow x_2 \to 1$$



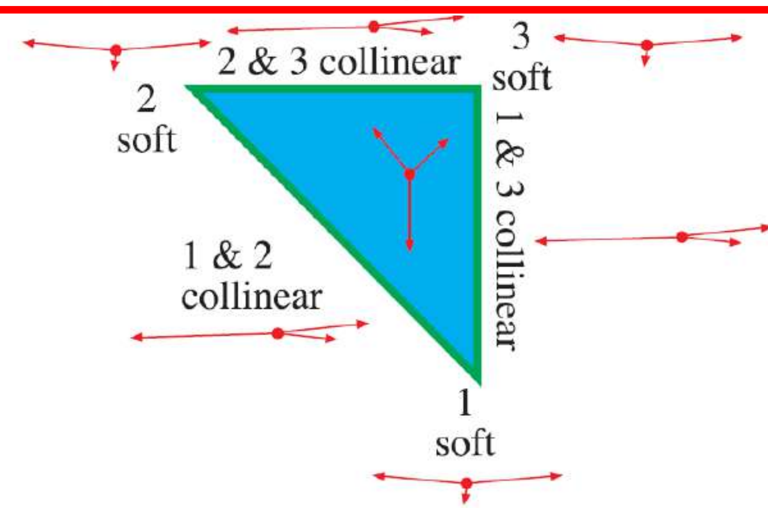
Differential 2→3 cross section

$$\frac{1}{\sigma_0}\frac{d\sigma}{dx_1 dx_2} = \frac{\alpha_s}{2\pi} C_F \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

$$\sigma_0 = (4\pi\alpha^2/s)\sum Q_f^2 \quad C_F = 4/3$$

Collinear divergences

$$(1-x_1) \to 0$$
$$(1-x_2) \to 0$$



Soft divergence

$$x_3 \to 0$$

$$\frac{1}{\sigma_0}\frac{d\sigma}{dE_3\, d\cos\theta_{31}} = \frac{\alpha_s}{2\pi} C_F \frac{f(E_3,\theta_{31})}{E_3(1-\cos\theta_{31})}$$

$$d\sigma \sim \int E_3 dE_3 d\theta_{31}^2 d\phi \left[\frac{\theta_{31}}{E_3\theta_{31}^2}\right]^2 \sim \int \frac{dE_3}{E_3}\frac{d\theta_{31}^2}{\theta_{31}^2}\, d\phi$$

double log behavior!

Cancelation of soft/collinear divergences

- Correction to the $e^+e^- \to q\bar{q}$ cross section due to soft one-gluon emission

$$d\sigma_g = \sigma_0 \frac{2\alpha_s}{\pi} \quad C_F \quad \frac{dk_0}{k_0} \frac{d\cos\theta}{1-\cos^2\theta}$$

soft div. collinear div.

$$q\cdot\bar{q} = 2q_0\bar{q}_0 \ , \quad q\cdot k = q_0 k_0(1-\cos\theta),$$

$$\bar{q}k = \bar{q}_0 k_0 (1+\cos\theta)$$

- Since the total cross section is finite, the soft and collinear divergences must cancel!

- Such cancellation indeed happens when summed together with the virtual contribution which is the soft gluon limit has the form

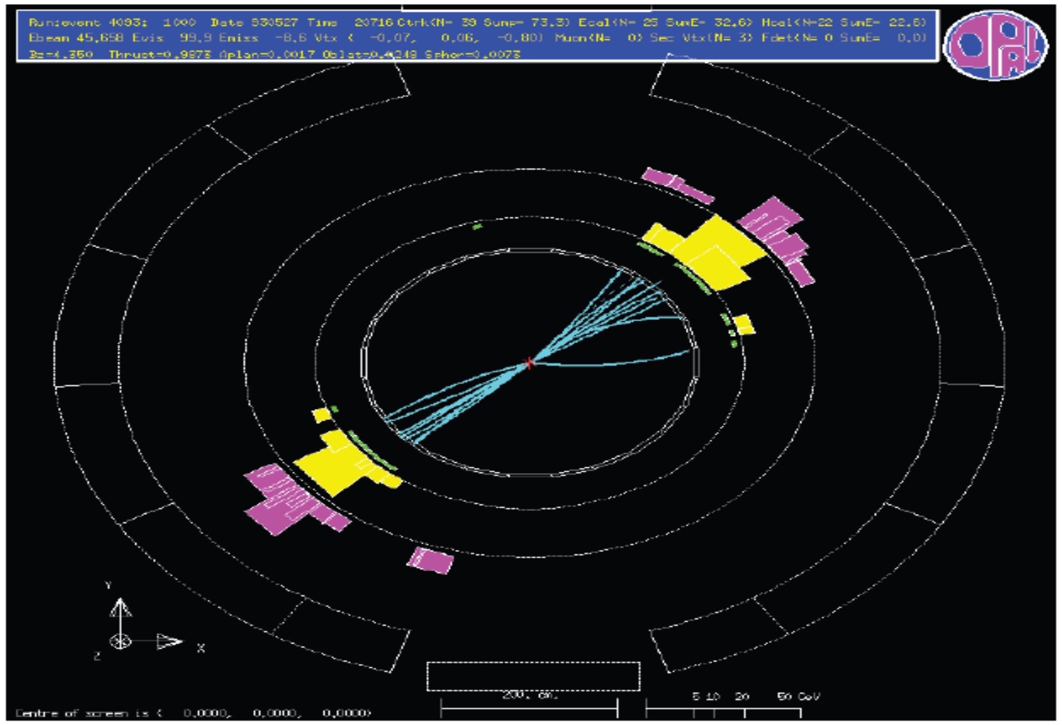
$$\frac{d^2\sigma_v}{dk_0 d\cos\theta} = -\sigma_0 \frac{2\alpha_s}{\pi} C_F \int_0^{\sqrt{s/2}} \frac{dk_0'}{k_0'} \int_{-1}^{1} \frac{d\cos\theta'}{(1-\cos^2\theta')} \times \frac{1}{2}\delta(k_0)\ [\delta(1-\cos\theta)+\delta(1+\cos\theta)]$$

…plus finite terms

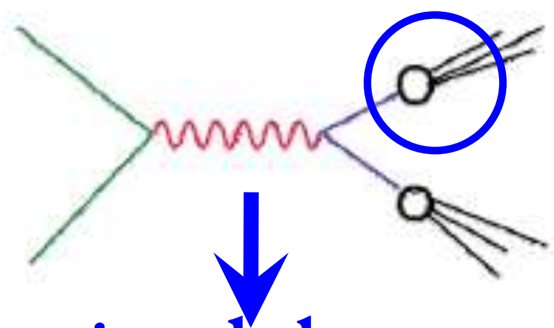
such that $$\int_0^{\sqrt{s/2}} dk_0 \int_{-1}^{1} d\cos\theta \quad \left[\frac{d^2\sigma_g}{dk_0 d\cos\theta} + \frac{d^2\sigma_v}{dk_0 d\cos\theta}\right] = \text{finite}$$

Jets in electron-positron annihilation

Di-jet LEP event

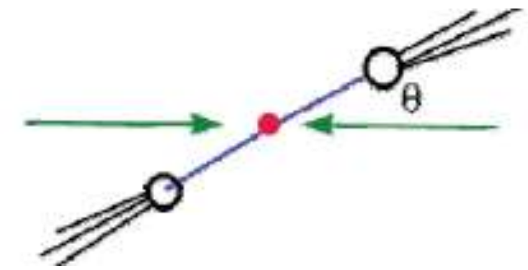


Jet: collinear spray of hadrons!



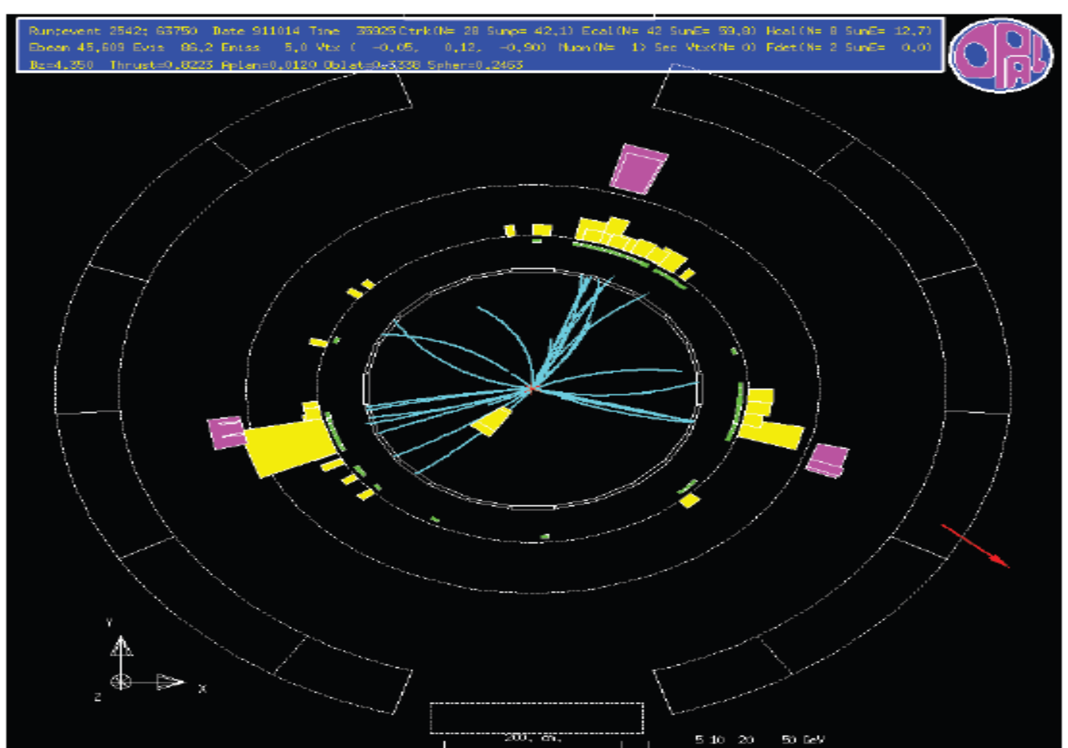
virtual photon
(or Z boson)

hadronisation
of quarks



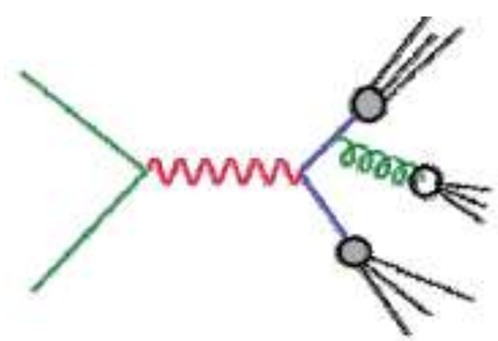
resembles all the features of 2→2 hard process (e.g. angular distribution inherent to spin-1/2 particles)

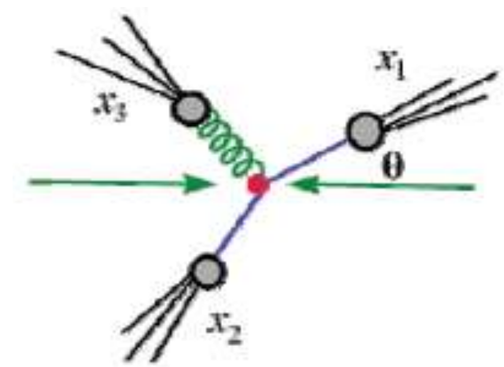
Three-jet LEP event



first observation of gluons!

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

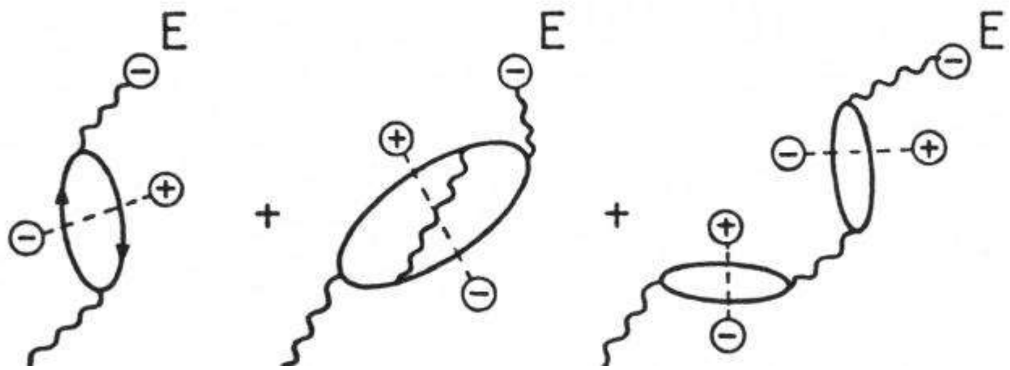


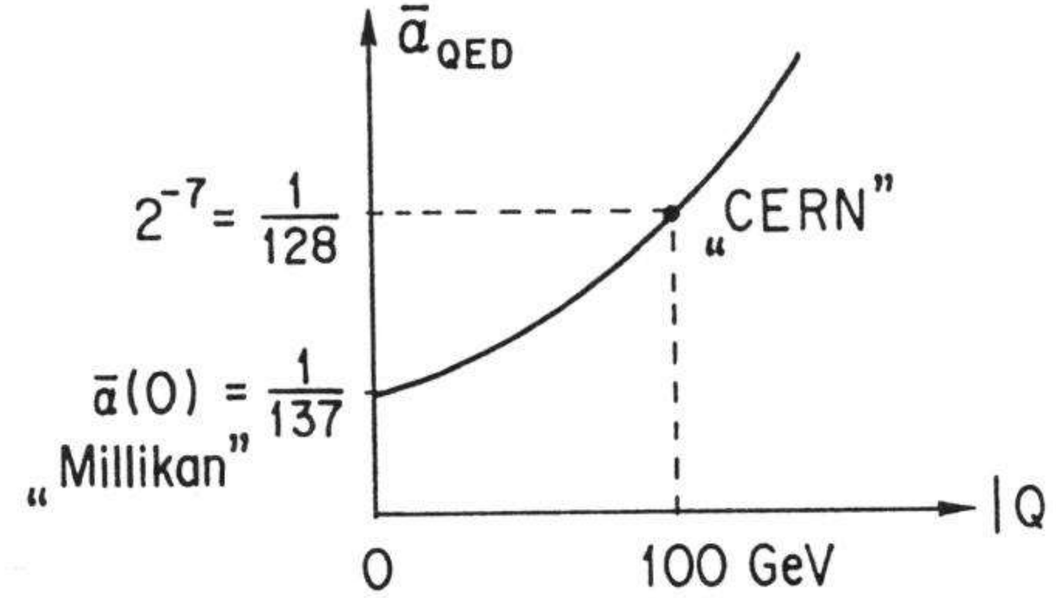


- *of higher order (extra coupling factor) as compared to the previous case (10 % of events)* $\alpha_s \simeq 0.1$
- *angular dependence as expected from spin-1 gluon*

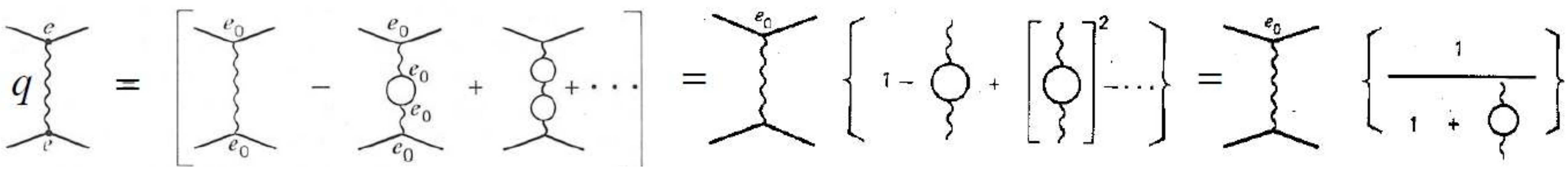
What is the fundamental role of the vacuum polarisation?

Screening of electric charge in QED





Higher-order corrections to the e+e- annihilation

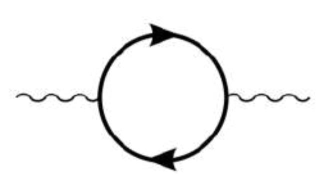


"Running" electric charge $$e^2\left(Q^2=-q^2\right)=e_0^2\left(\frac{1}{1+I\left(Q^2\right)}\right)$$

Long range EM interactions

$$I\left(Q^2\right)=\int_{m_e}^{M}\frac{dp^2}{p^2}\cdots=-\frac{\alpha_0}{3\pi}\log\left(\frac{Q^2}{M^2}\right)$$

UV cut-off

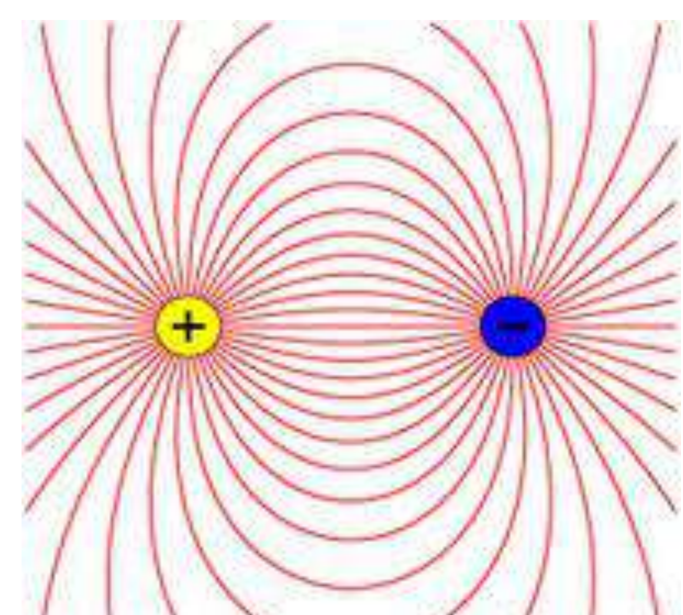


$$\alpha\left(Q^2\right)=\frac{\alpha\left(\mu^2\right)}{1-\frac{\alpha\left(\mu^2\right)}{3\pi}\log\left(\frac{Q^2}{\mu^2}\right)}$$

increases with scale!

At larger distances EM interaction becomes weaker!

$$e \rightarrow e(r) = e\{1 - \frac{\alpha}{3\pi}\ln\frac{r}{r_e} + O(\alpha^2)\}$$



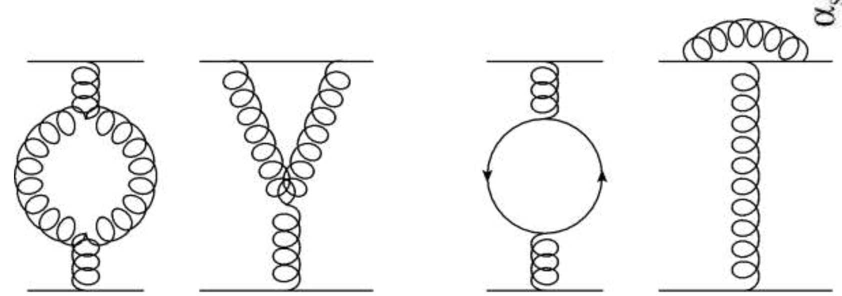
Why we do not see quarks?

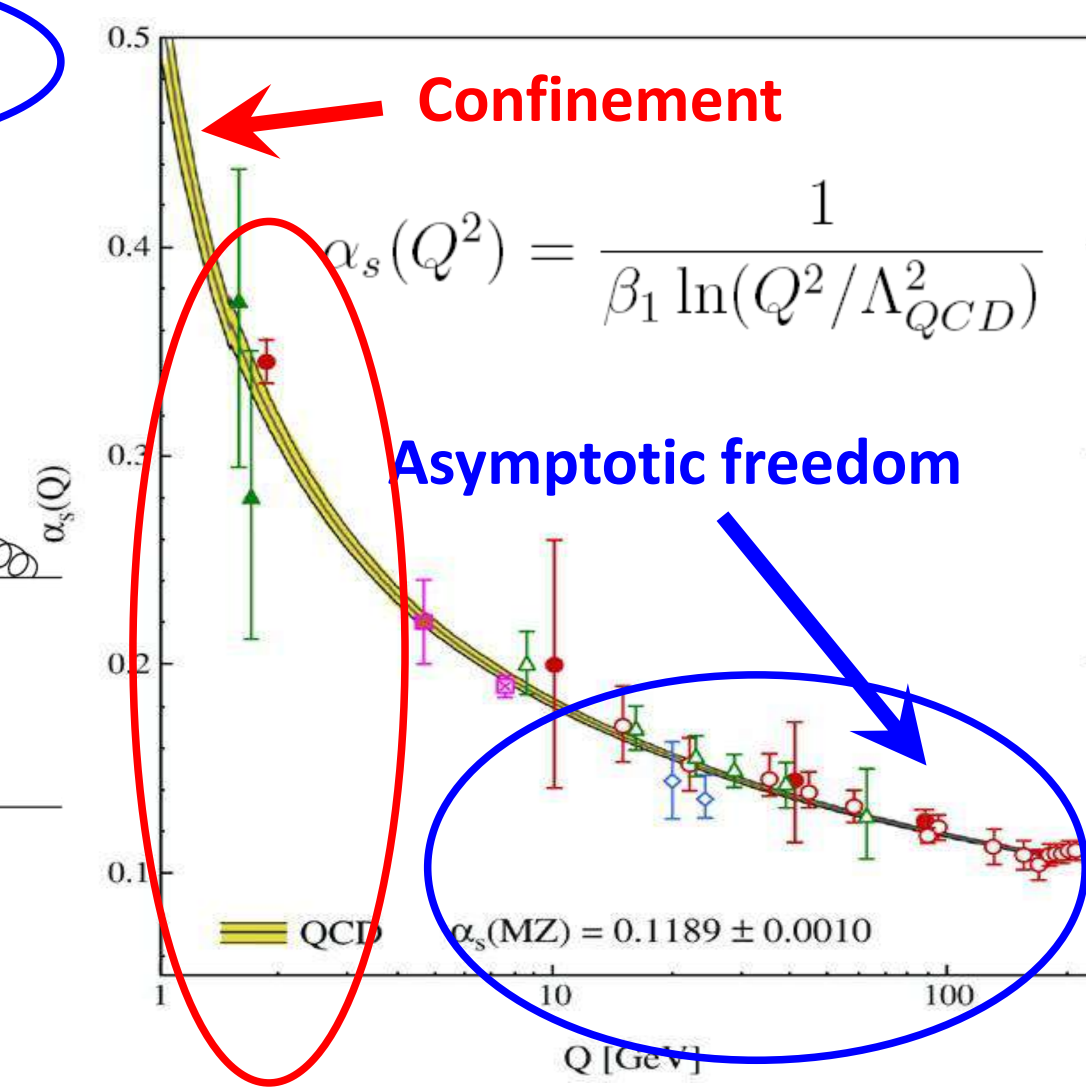
Running QCD coupling $\alpha_s = \frac{g^2}{4\pi}$ **Color charge anti-screening**

$$\mu^2 \frac{d\alpha_s}{d\mu^2} = \beta(\alpha_s). \quad \beta(\alpha_s) = -\left(11 - \frac{2n_f}{3}\right)\frac{\alpha_s^2}{2\pi}$$

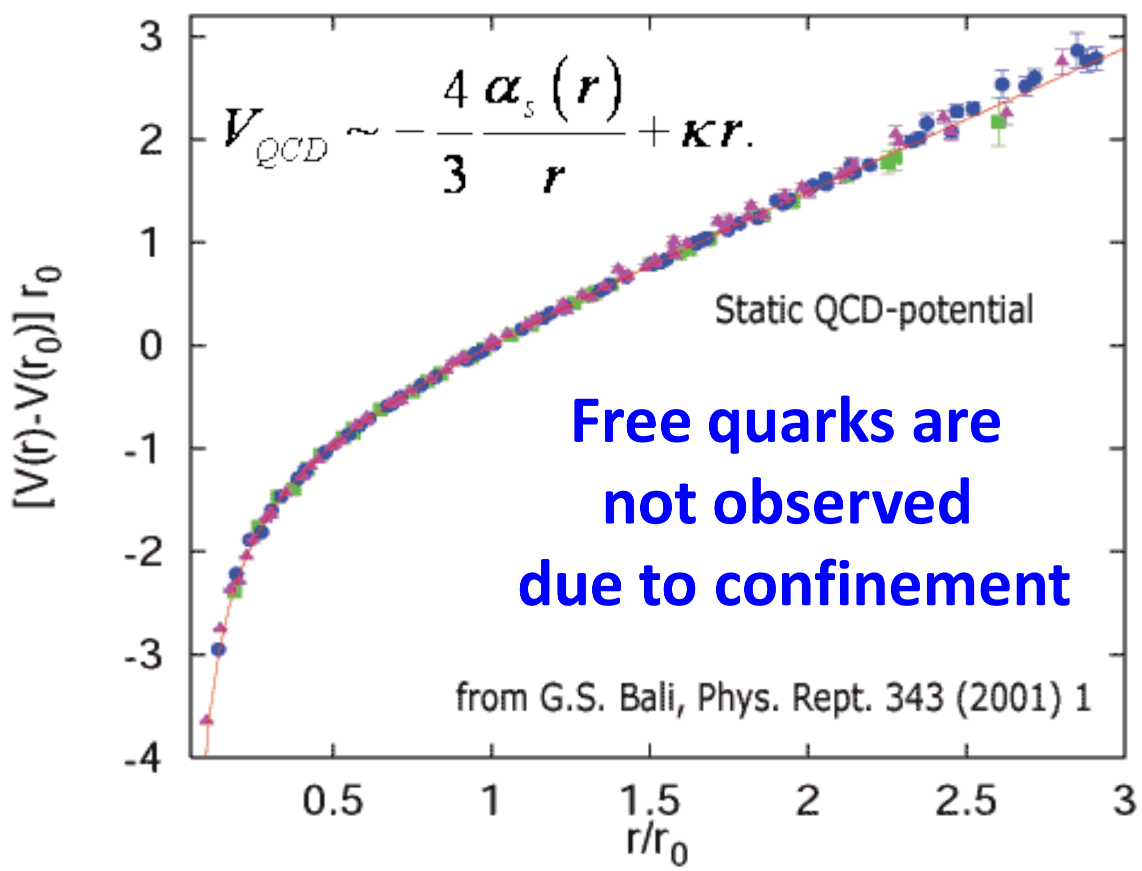
Nobel Prize 2004:

Gross, Wilczek; Politzer

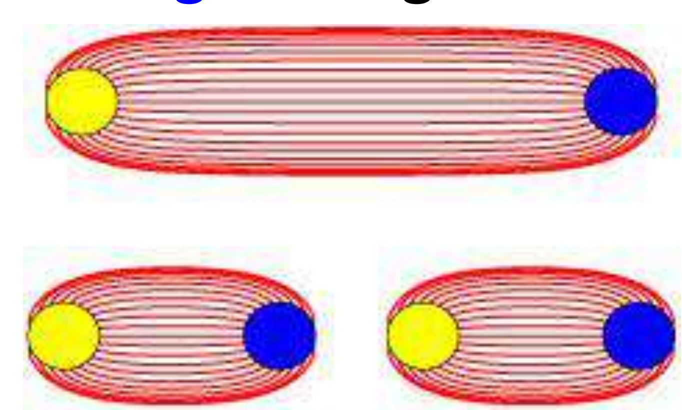




Soft QCD (models) *Hard QCD (PT)*



Short range strong interactions



basis for hadronisation models.....

Thank you

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