

Quantum Chromodynamics

Lecture 1: All about color

Hadron Collider Physics Summer School 2010

John Campbell, Fermilab





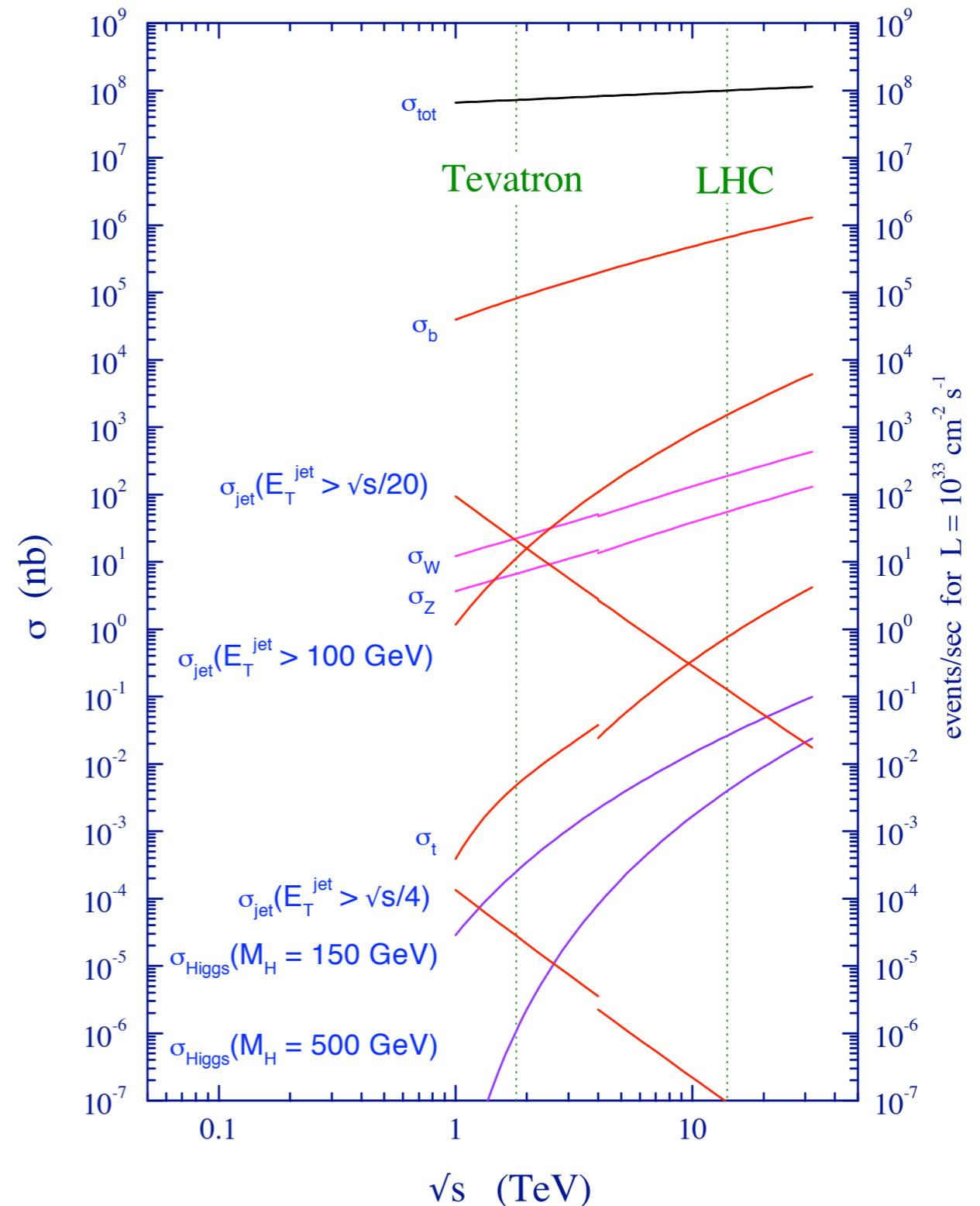
References and thanks

- Useful references for this short course are:
- **QCD and Collider Physics**
R. K. Ellis, W. J. Stirling and B. R. Webber
Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology
- **Hard Interactions of Quarks and Gluons: a Primer for LHC Physics**
J. C., J. W. Huston and W. J. Stirling
Rept. Prog. Phys. 70, 89 (2007) [hep-ph/0611148]
- **Resource Letter: Quantum Chromodynamics**
A. S. Kronfeld and C. Quigg
arXiv:1002.5032 [hep-ph] (for the American Journal of Physics)
- Thanks to R. K. Ellis and G. Zanderighi, for lecture notes from previous schools - upon which much of these lectures will be based.

QCD: why we care

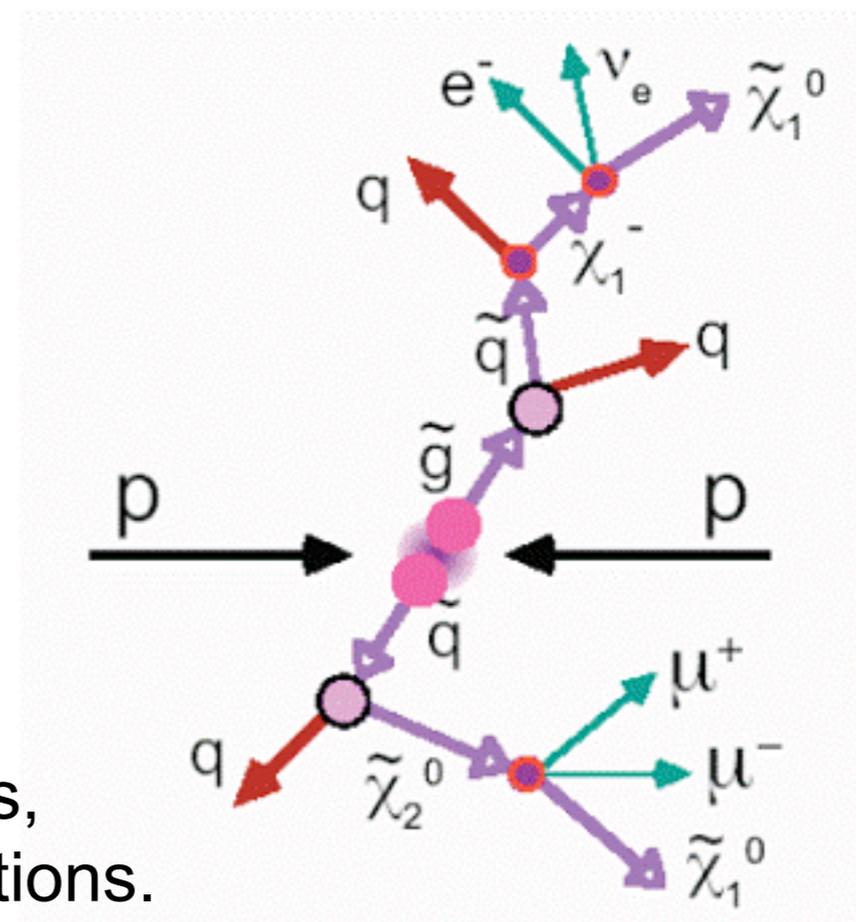
- It is no surprise that hadron colliders require an understanding of QCD.
- This plot demonstrates the extent to which we must have a good understanding,
 - cross sections for inclusive bottom production and final states with jets of hadrons are near the top.
 - Higgs boson cross sections are at the bottom.
- Discovering such New Physics requires a **sophisticated, quantitative understanding of QCD**.
- In these lectures, we will develop the tools necessary for such a task.

proton - (anti)proton cross sections



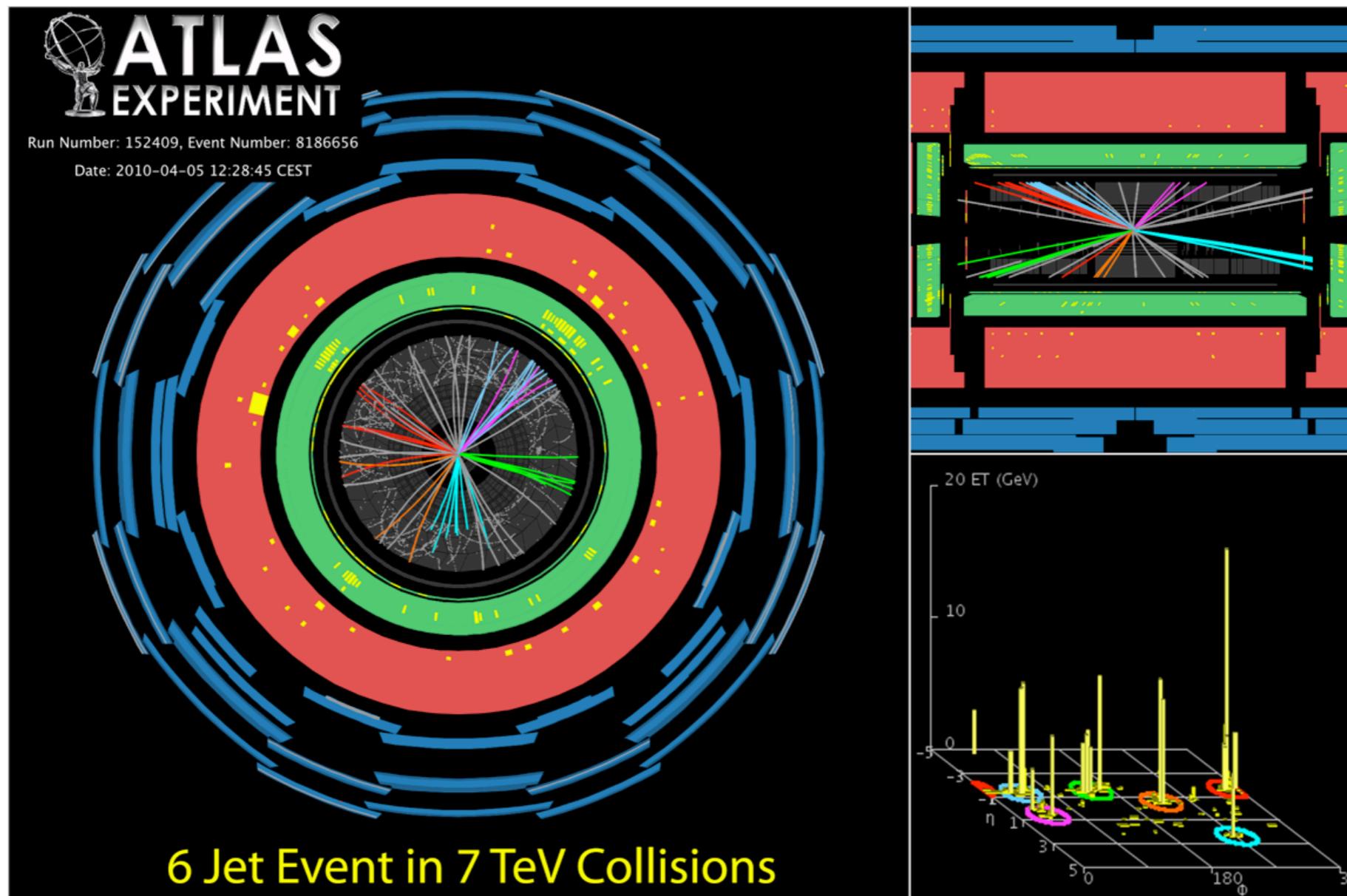
QCD: why we care even more

- If a Higgs-like signal is observed, to confirm its interpretation as the Higgs boson requires measurement of its couplings and quantum numbers.
 - need an accurate understanding of the production/decay mechanisms.
- Hopefully, we will see more than just a Higgs boson.
 - ◆ supersymmetry?
 - ◆ extra dimensions?
 - ◆ technicolor?
- All of these models of New Physics introduce new particles that will (most likely) decay as they traverse the detectors, into “old” colored particles → QCD interactions.



The challenge of QCD

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} F_{\mu\nu}^A F_A^{\mu\nu} + \sum_{\text{flavors}} \bar{q}_i (i\not{D} - m)_{ij} q_j$$





Tasks for today



Tasks for today

- Understand why the Lagrangian looks like this:
 - why color and why $SU(3)$?



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- Understand why the Lagrangian looks like this:
 - why color and why $SU(3)$?
- Understand some features of this Lagrangian:
 - in practical terms, how does QCD differ from QED?



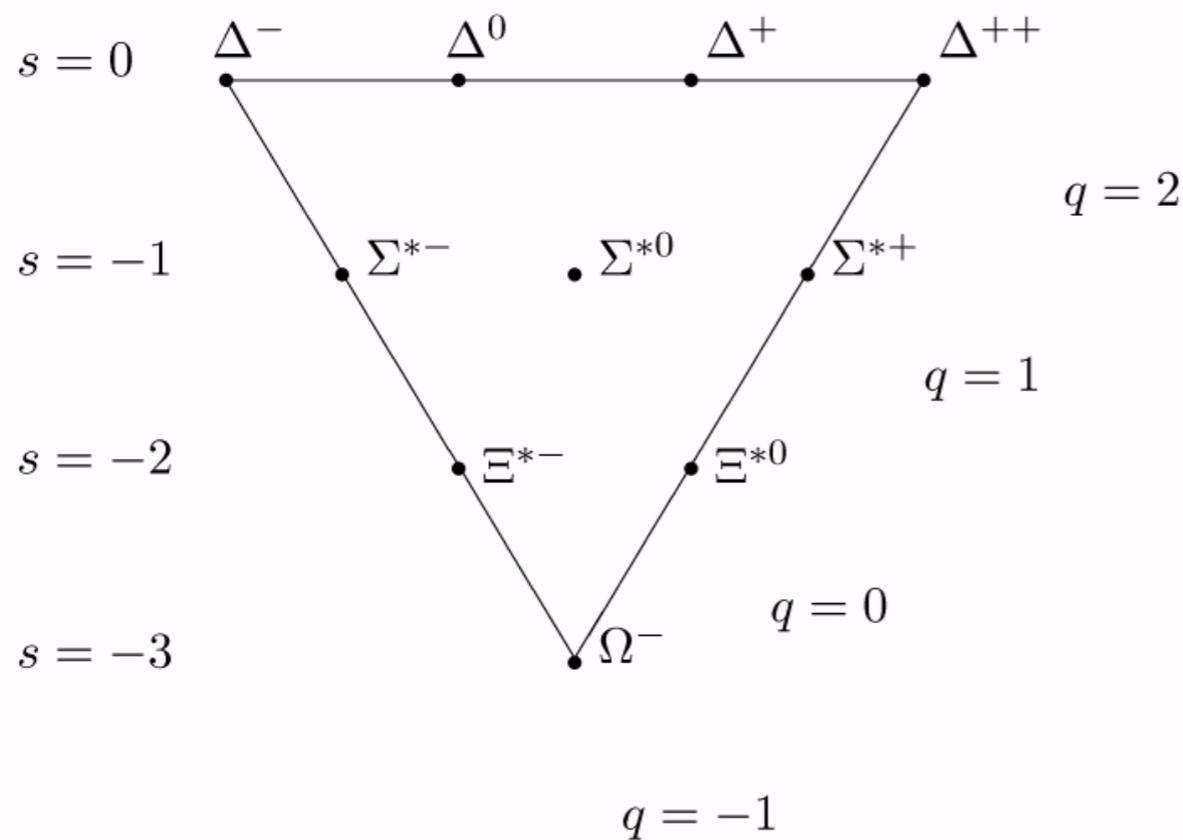
Tasks for today

- Understand why the Lagrangian looks like this:
 - why color and why $SU(3)$?
- Understand some features of this Lagrangian:
 - in practical terms, how does QCD differ from QED?
- Understand how to use this Lagrangian:
 - how can we use it to make predictions?

Quarks and color

- The quark model is a useful way of categorizing mesons (baryons) in terms of two (three) constituent quarks.

Q=+2/3	up $m_u \sim 4 \text{ MeV}$	charm $m_c \sim 1.5 \text{ GeV}$	top $m_t \sim 172 \text{ GeV}$
Q=-1/3	down $m_d \sim 7 \text{ MeV}$	strange $m_s \sim 135 \text{ MeV}$	bottom $m_b \sim 5 \text{ GeV}$



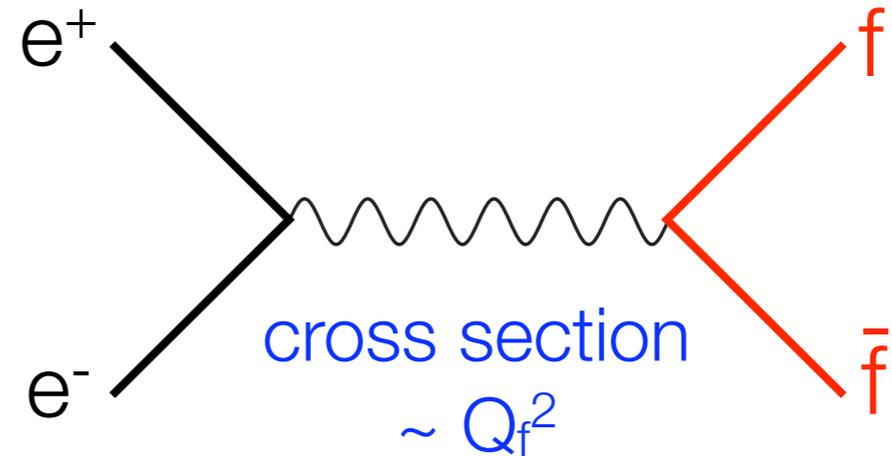
Baryon decuplet ($S=3/2$)

- Simple picture must be amended due to, for example, $\Delta^{++}=(u,u,u)$ in a symmetric spin state.
- The baryons should obey the **Pauli principle**: the overall wavefunction should be antisymmetric.
- In order to accommodate this, the antisymmetry should be carried by another quantum number: **color**.
- Observed particles are **colorless**.

Probing color

- Subsequent realization that color could be probed directly in e^+e^- collisions.

- production of fermion pairs through a virtual photon sensitive to electric charge of fermion and the number of degrees of freedom allowed.



- Hence investigate quarks through “R-ratio”:

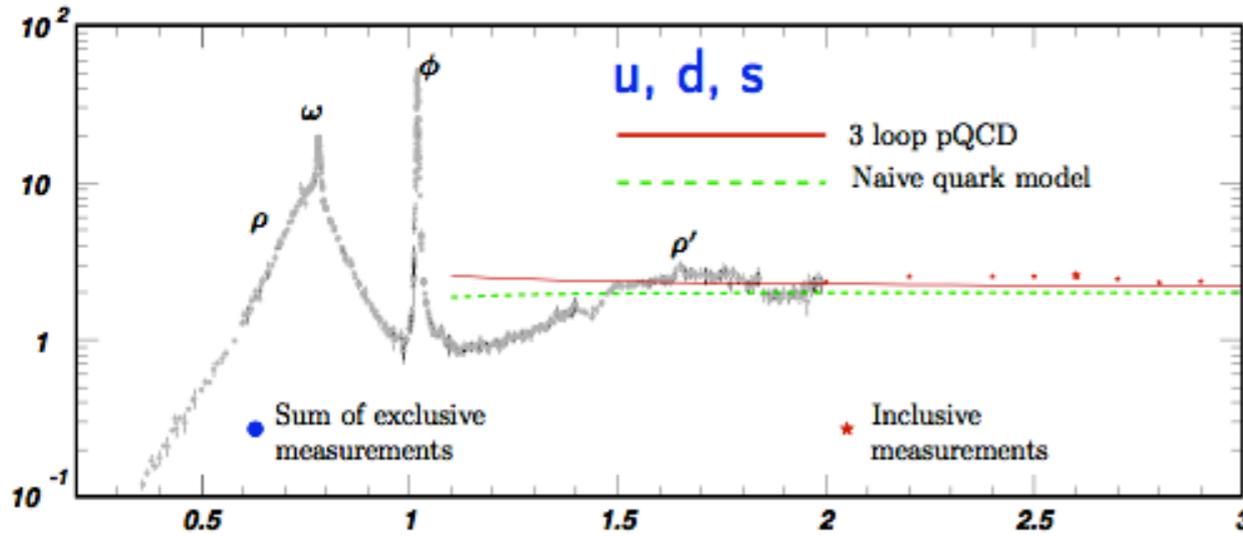
$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = N_c \sum_f Q_f^2$$

← assume N_c colors of quark
← quark charge
← sum over active quarks

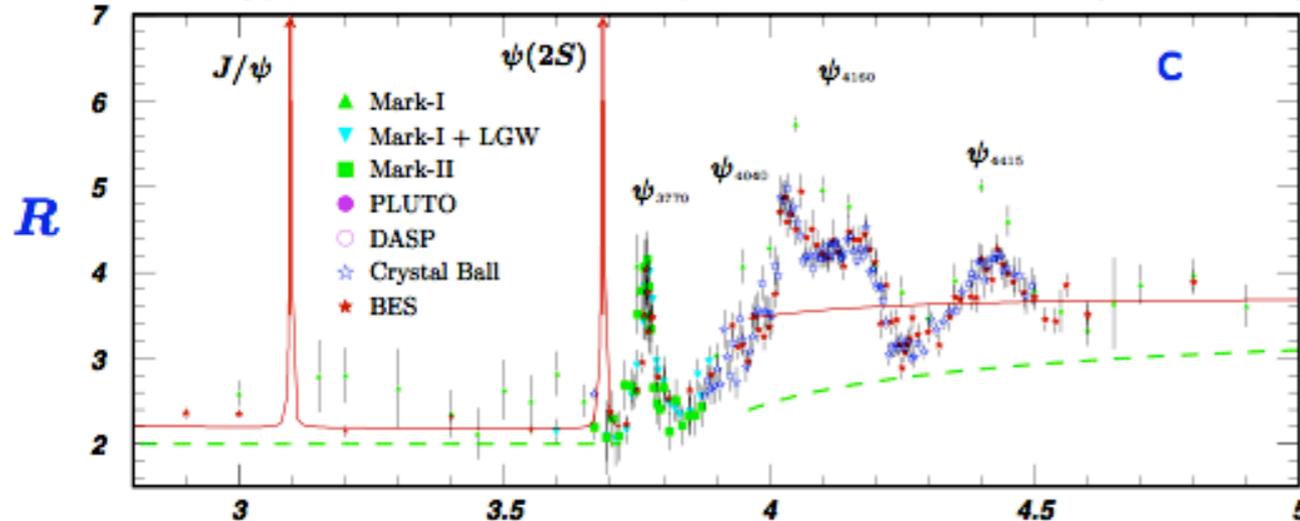
(this is at least the most basic expectation - corrections later)

- Each **active** quark is produced in N_c colors: must be above the kinematic threshold for each quark in the sum, i.e. $\sqrt{s} > 2m_q$.

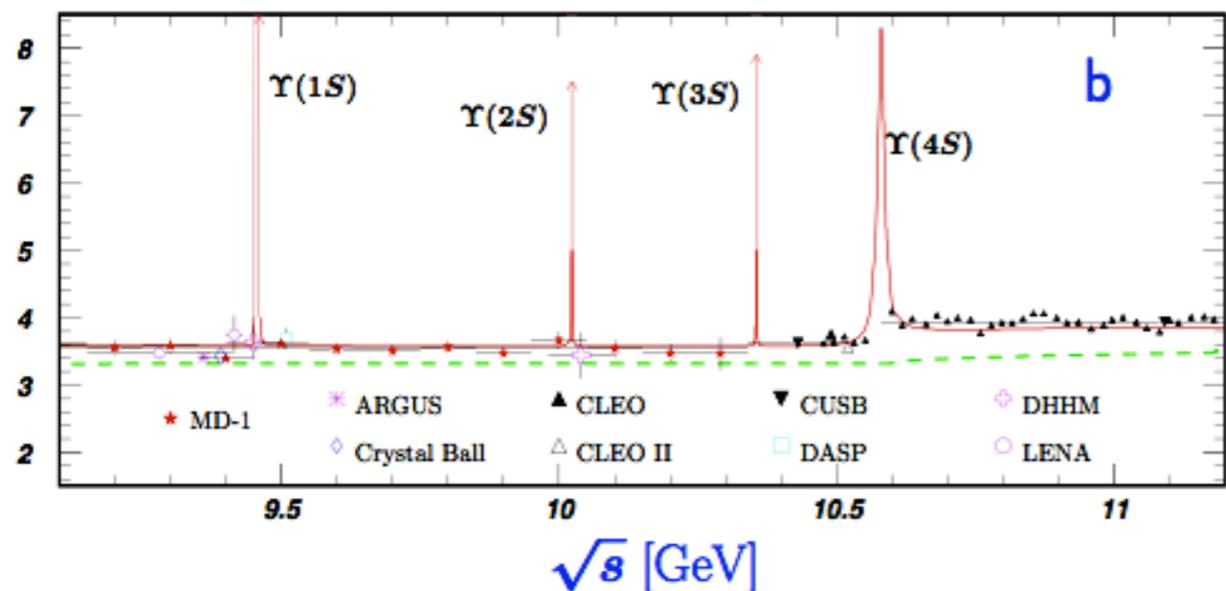
Experimental measurements



$$R_{u,d,s} = 3 \times \left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 \right] = 2$$



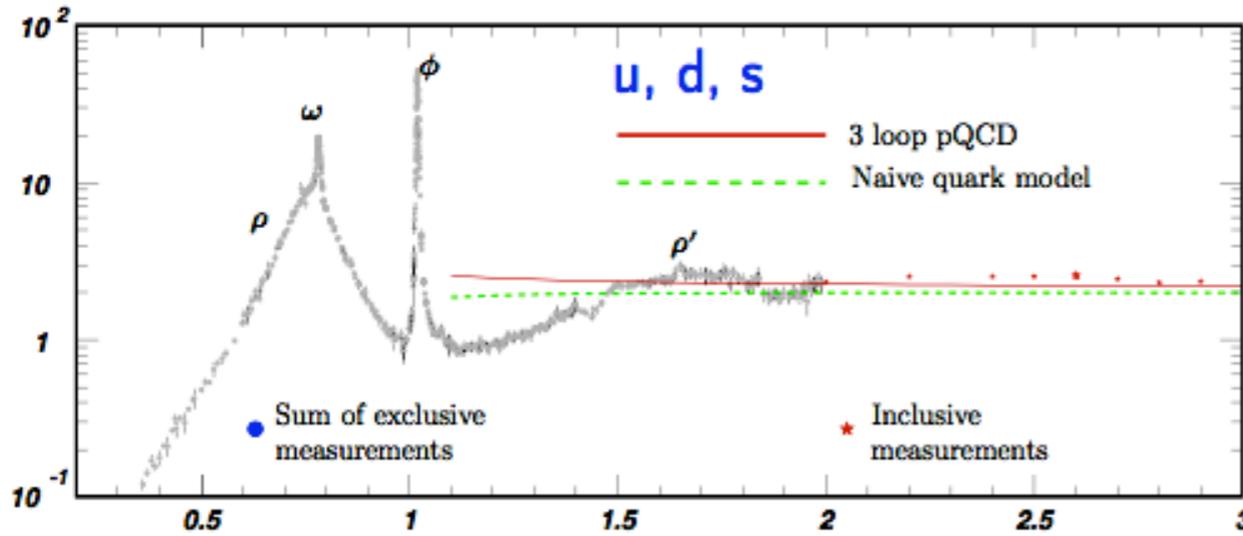
$$R_{u,d,s,c} = R_{u,d,s} + 3 \times \left(\frac{2}{3}\right)^2 = \frac{10}{3}$$



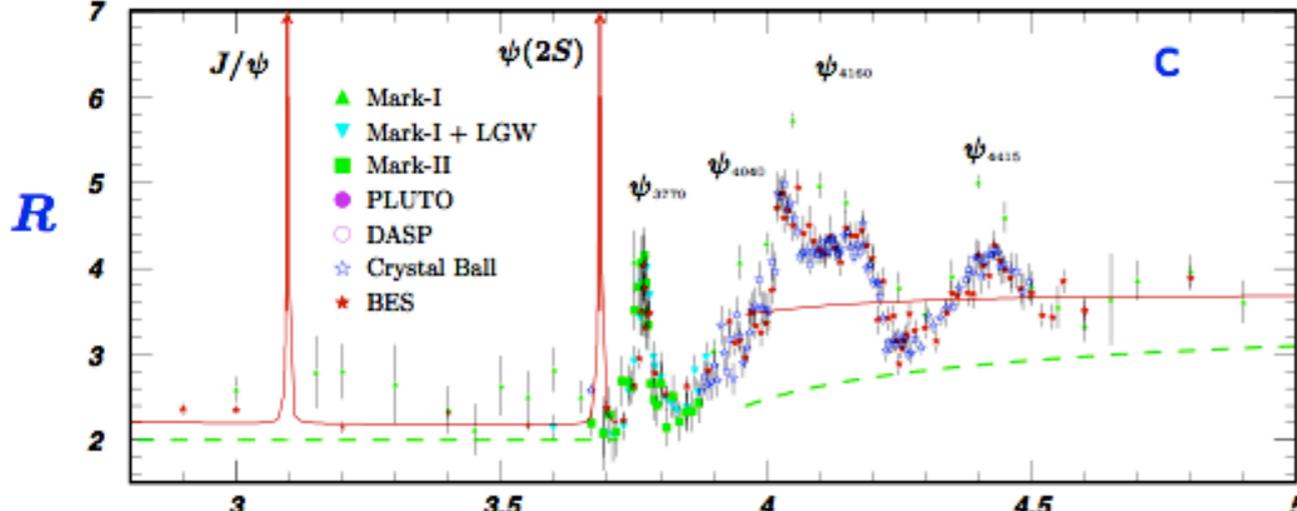
$$R_{u,d,s,c,b} = R_{u,d,s,c} + 3 \times \left(-\frac{1}{3}\right)^2 = \frac{11}{3}$$

Experimental measurements

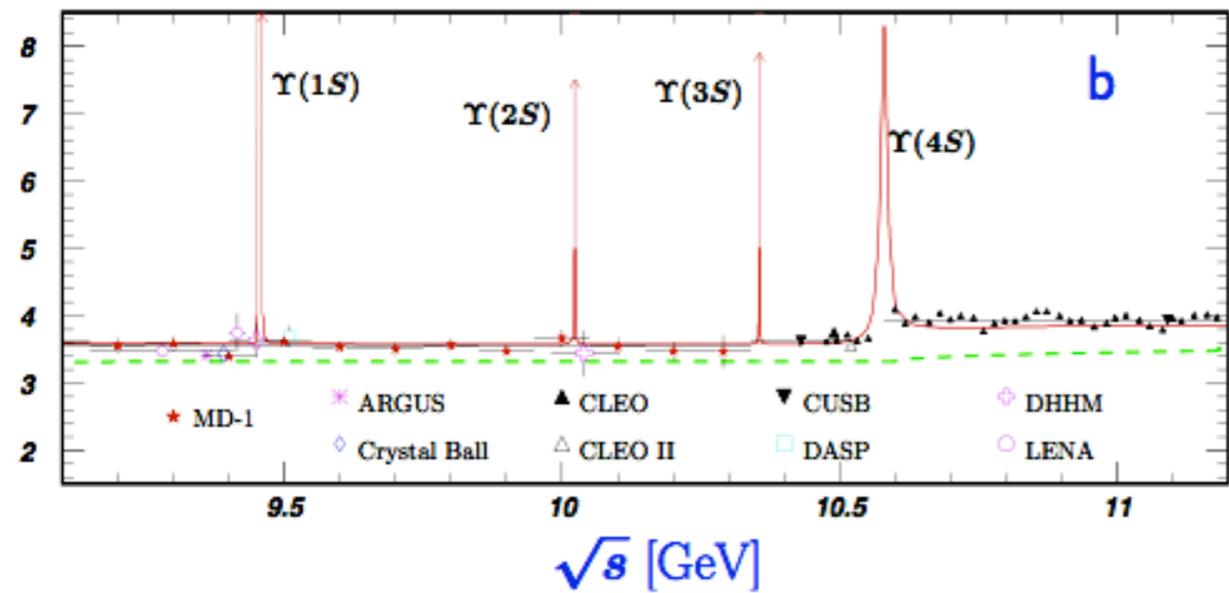
Broad support
for $N_c=3$



$$R_{u,d,s} = 3 \times \left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 \right] = 2$$



$$R_{u,d,s,c} = R_{u,d,s} + 3 \times \left(\frac{2}{3}\right)^2 = \frac{10}{3}$$



$$R_{u,d,s,c,b} = R_{u,d,s,c} + 3 \times \left(-\frac{1}{3}\right)^2 = \frac{11}{3}$$

QCD interactions

- In QCD, the **color** quantum number is mediated by the **gluon**, analogous to the photon in QED.
 - it will be responsible for changing quarks from one color to another; as such it must also carry a color charge (not neutral, as in QED).
- 1st try**: mediating quark and anti-quark of 3 different colors $\rightarrow 3 \times 3 = 9$ **gluons**.



- In fact we should take six such combinations, plus three mutually orthogonal combinations of same-color states.

$$\bar{R}B \quad \bar{R}G$$

$$\bar{G}B \quad \bar{G}R$$

$$\bar{B}R \quad \bar{B}G$$

$$(\bar{R}R - \bar{B}B)/\sqrt{2}$$

$$(\bar{R}R + \bar{B}B - 2\bar{G}G)/\sqrt{6}$$

$$(\bar{R}R + \bar{B}B + \bar{G}G)/\sqrt{3}$$



QCD interactions

- Since color is an internal degree of freedom, we expect invariance of the theory under rotations in this color space.
 - this requires that eight of our color combinations share the same coupling:

$$\bar{R}B \quad \bar{R}G$$

$$(\bar{R}R - \bar{B}B)/\sqrt{2}$$

$$\bar{G}B \quad \bar{G}R$$

$$(\bar{R}R + \bar{B}B - 2\bar{G}G)/\sqrt{6}$$

$$\bar{B}R \quad \bar{B}G$$

- the remaining combination only transforms into itself - it is a **color singlet**:

$$(\bar{R}R + \bar{B}B + \bar{G}G)/\sqrt{3}$$

- Such a combination is not present in QCD: we are left with **8 gluons**.
- The color charge of each gluon is represented by a matrix in color space.
 - the eight combinations result in eight matrices, T^A , with $A=1,\dots,8$.
 - a conventional choice is to write these in terms of the **Gell-Mann matrices**, which are just an extension of Pauli Matrices:

$$T^A = \frac{1}{2}\lambda^A$$

Gell-Mann matrices

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda^8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

- These matrices are **Hermitian**, $(\lambda^A)^\dagger = \lambda^A$, and **traceless**.
 - only two diagonal matrices: the color singlet would not have been traceless.
- They obey the two relations:

$$\text{Tr} (\lambda^A \lambda^B) = 2\delta^{AB} , \quad [\lambda^A, \lambda^B] = 2if^{ABC} \lambda^C$$

completely antisymmetric
set of real constants, f^{ABC}



Color matrices

- Translating back to color matrices, we have:

$$[T^A, T^B] = if^{ABC}T^C, \quad \text{Tr}(T^A T^B) = T_R \delta^{AB} \quad (\text{with } T_R = 1/2)$$

- The first of these relations reflects that fact that:
 - the matrices T^A are the **generators of the SU(3) group**, $A=1, \dots, 8$;
 - the antisymmetric set, f^{ABC} , contains the **SU(3) structure constants**.
- The second relation is just a normalization convention.
- The group structure is also characterized by two other relations:

$$\sum_{C,D} f^{ACD} f^{BCD} = C_A \delta^{AB} \quad \text{with } C_A = N_c = 3$$

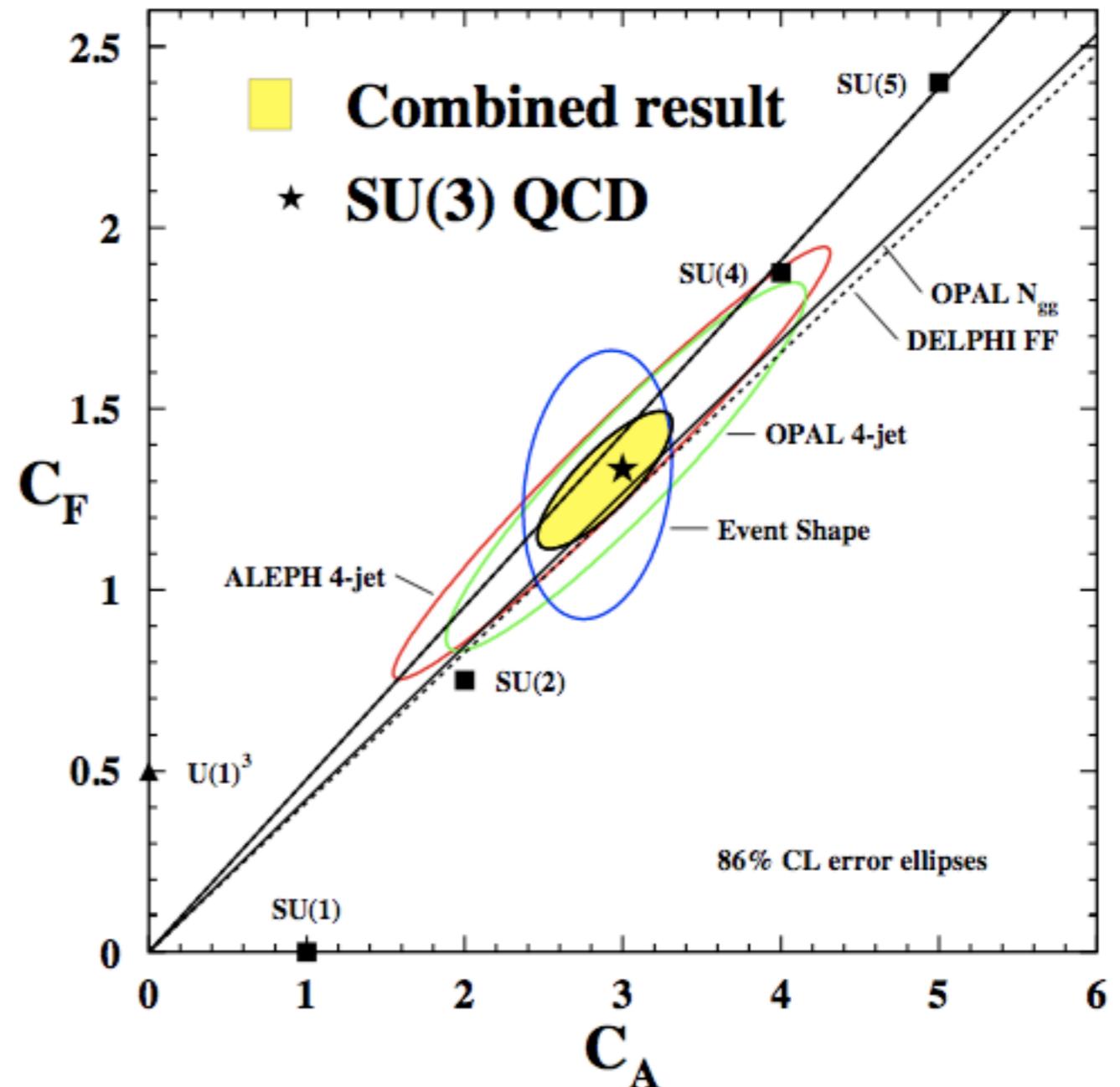
$$\sum_A T^A T^A = C_F \mathbf{1} \quad \text{with } C_F = \frac{N_c^2 - 1}{2N_c} = \frac{4}{3}$$

3x3 identity matrix

“Casimir”

Further support for SU(3)

- These **color sums** are exactly the quantities which will appear when we compute cross sections involving QCD.
- In particular, the cross section for 4-jet production in e^+e^- annihilation at LEP is **sensitive to both C_A and C_F** .
- At this point, no one expected that SU(3) was not the correct description.
- However, demonstrates that the **group structure is an important phenomenological aspect** - not just math!





The QCD Lagrangian

- The quantum field theory of QCD is then based on the Lagrangian:

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} F_{\mu\nu}^A F_A^{\mu\nu} + \sum_{\text{flavors}} \bar{q}_i (iD_\mu \gamma^\mu - m)_{ij} q_j$$

field strength tensor, gluon degrees of freedom

in the non-interacting case, the Dirac term for quark d.o.f.

- Color** plays a crucial role in the Lagrangian:

$$F_{\mu\nu}^A = \partial_\mu A_\nu^A - \partial_\nu A_\mu^A - g_s f^{ABC} A_\mu^B A_\nu^C$$

A_μ^A : field for the spin-1 gluon (just like the photon in QED, but with an extra color label)

self-interaction term for gluon fields: called “non-Abelian” since it arises from the SU(3) structure



QCD gauge transformations

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} F_{\mu\nu}^A F_A^{\mu\nu} + \sum_{\text{flavors}} \bar{q}_i (iD_\mu \gamma^\mu - m)_{ij} q_j$$

- Color also appears in the definition of the **covariant derivative**:

$$(D_\mu)_{ij} = \partial_\mu \delta_{ij} + ig_s (T^A A_\mu^A)_{ij}$$

which couples together quarks and gluons in the interacting theory.

- Such a definition ensures that the QCD Lagrangian remains invariant under **local gauge transformations** of the form,

$$q_i(x) \rightarrow q'_i(x) = \Omega_{ij}(x) q_j(x) \quad \left(\Omega_{ik}^\dagger(x) \Omega_{kj}(x) = \delta_{ij} \right)$$

$$(D_\mu)_{ik} q_k(x) \rightarrow (D'_\mu)_{ik} q'_k(x) = \Omega_{ij}(x) (D_\mu)_{jk} q_k(x)$$

- Covariant means that it **transforms in the same way** as the quark field itself.
- Imposing these transformation laws ensures invariance of the second term.



QCD gauge transformations

- To apply the argument on the first term relies upon the specific form we have introduced for the covariant derivative.
- This is easiest to see by manipulating the field strength tensor into a new form,

$$T^A F_{\mu\nu}^A = \partial_\mu (T^A A_\nu^A) - \partial_\nu (T^A A_\mu^A) - g_s T^A f^{ABC} A_\mu^B A_\nu^C \quad (\text{use comm. relation})$$

$$= \partial_\mu T^A A_\nu^A - (T^A A_\nu^A) \partial_\mu - \partial_\nu T^A A_\mu^A + (T^A A_\mu^A) \partial_\nu + ig_s [(T^B A_\mu^B)(T^C A_\nu^C) - (T^C A_\nu^C)(T^B A_\mu^B)] \quad (\text{consider action on a field})$$

$$= [\partial_\mu + ig_s (T^B A_\mu^B)] \left[T^A A_\nu^A + \frac{1}{ig_s} \partial_\nu \right] - [\partial_\nu + ig_s (T^B A_\nu^B)] \left[T^A A_\mu^A + \frac{1}{ig_s} \partial_\mu \right]$$

$$= \frac{1}{ig_s} [D_\mu, D_\nu]$$

- Lastly, exploit the fact that the commutator transforms in the same way as the covariant derivative itself:

$$[D_\mu, D_\nu]_{ik} q_k(x) \rightarrow \Omega_{ij}(x) [D_\mu, D_\nu]_{jk} q_k(x)$$

QCD gauge transformations

- Putting it all together:

$$(T^A F_{\mu\nu}^A)_{ij} q_j(x) \rightarrow (T^A F'^A_{\mu\nu})_{ij} q'_j(x)$$

$$\Omega_{ij}(x) (T^A F_{\mu\nu}^A)_{jk} q_k(x) = (T^A F'^A_{\mu\nu})_{ij} \Omega_{jk}(x) q_k(x)$$

so that the field strength transforms as,

$$(T^A F_{\mu\nu}^A)_{ij} \rightarrow \Omega_{ik}(x) (T^A F_{\mu\nu}^A)_{k\ell} \Omega_{\ell j}^{-1}(x)$$

- The field strength is no longer gauge invariant as in QED, a reflection of the self-interacting nature of gluons.
- However the combination that appears in the **Lagrangian is invariant**, as required:

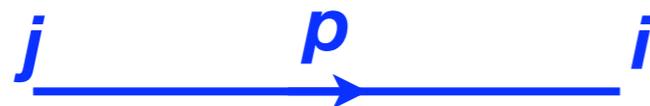
$$\begin{aligned} -\frac{1}{4} F_{\mu\nu}^A F_A^{\mu\nu} &= -\frac{1}{2} \text{Tr} (T^A F_{\mu\nu}^A T^B F_B^{\mu\nu}) \\ &\rightarrow -\frac{1}{2} \text{Tr} (\Omega T^A F_{\mu\nu}^A T^B F_B^{\mu\nu} \Omega^{-1}) \end{aligned}$$

Using the QCD Lagrangian

- Armed with a Lagrangian that is invariant under gauge transformations, we can investigate many features of QCD.
- **In these lectures**, we're interested in **perturbative QCD** and cross sections computed from Feynman diagrams: **convert Lagrangian into Feynman rules**.
- Simplest place to start: free, or non-interacting Lagrangian ($g_s \rightarrow 0$).
- Prescription: make the replacement $\partial_\mu \rightarrow -ip_\mu$ (c.f. Fourier expansion) and then multiply by i to obtain inverse propagator.

$$\bar{q}_i (i\partial_\mu \gamma^\mu - m) \delta_{ij} q_j \rightarrow iq_i (p_\mu \gamma^\mu - m) \delta_{ij} q_j$$

quarks



$$\frac{i(\not{p} + m)}{p^2 - m^2} \delta_{ij}$$

trivial color factor

gluons

$$-\frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu) (\partial^\mu A^\nu - \partial^\nu A^\mu) \rightarrow \frac{i}{2} A_\mu (p^2 g^{\mu\nu} - p^\mu p^\nu) A_\nu$$

Cannot invert!

Gauge fixing

- The solution is to **fix a gauge**: add an additional term to the Lagrangian which depends upon an arbitrary **gauge parameter** λ .

$$\mathcal{L}_{\text{gauge-fixing}} = -\frac{1}{2\lambda} (\partial^\mu A_\mu^A)^2$$

- This contributes an extra term: $\frac{i}{2\lambda} A_\mu p^\mu p^\nu A_\nu$ such that an inverse now exists.

gluons A, μ p B, ν



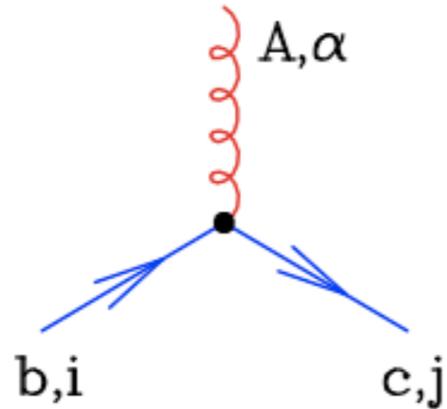
$$\frac{-i}{p^2} \left(g^{\mu\nu} - (1 - \lambda) \frac{p^\mu p^\nu}{p^2} \right) \delta^{AB}$$

- Different gauges may be useful in different calculations, but ultimately must all give the same result.
 - a particularly simple choice is often the **Feynman gauge**, $\lambda=1$.
- Further complication: covariant gauge-fixing introduces **unphysical d.o.f.** that must be cancelled by **ghost contributions** - we will not discuss them here.

QCD interactions

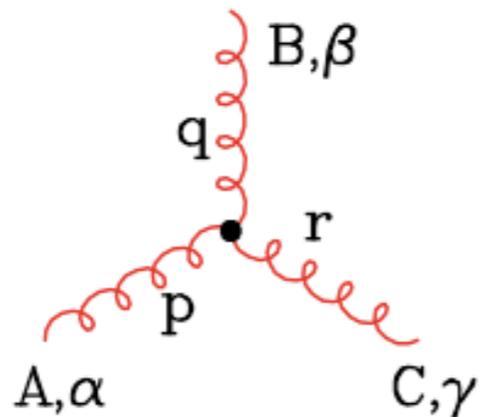
- Interactions between the quarks and gluons can be read off from the terms of order g_s and higher.

quark-gluon
(from covariant derivative)



$$-ig (t^A)_{cb} (\gamma^\alpha)_{ji}$$

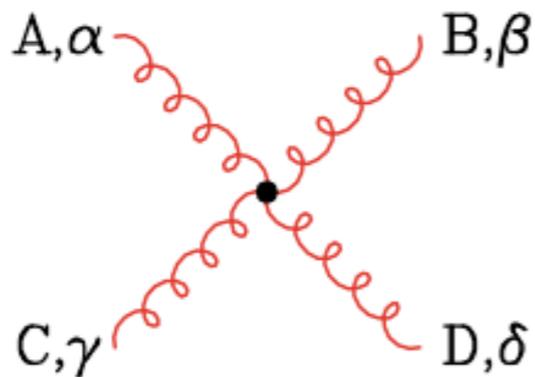
NB: sum over quark colors
→ trace over T strings



$$-g f^{ABC} [(p-q)^\gamma g^{\alpha\beta} + (q-r)^\alpha g^{\beta\gamma} + (r-p)^\beta g^{\gamma\alpha}]$$

(all momenta incoming)

self interactions
(from additional terms in the field strength)

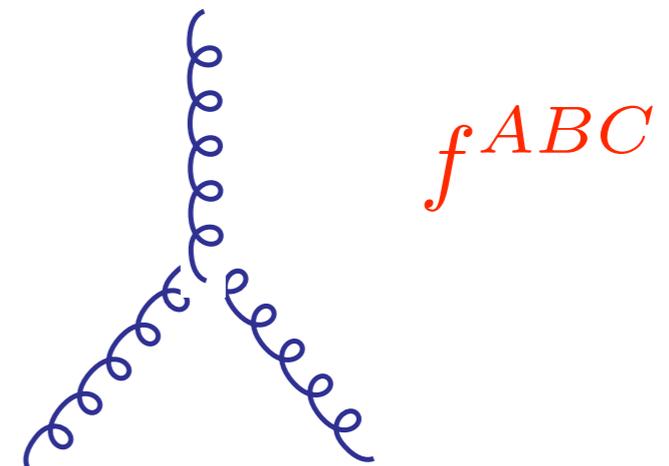
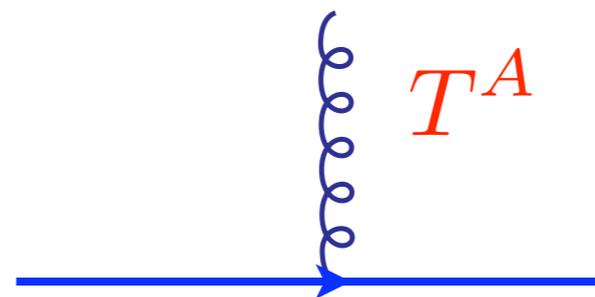


$$\begin{aligned}
 & -ig^2 f^{XAC} f^{XBD} [g^{\alpha\beta} g^{\gamma\delta} - g^{\alpha\delta} g^{\beta\gamma}] \\
 & -ig^2 f^{XAD} f^{XBC} [g^{\alpha\beta} g^{\gamma\delta} - g^{\alpha\gamma} g^{\beta\delta}] \\
 & -ig^2 f^{XAB} f^{XCD} [g^{\alpha\gamma} g^{\beta\delta} - g^{\alpha\delta} g^{\beta\gamma}]
 \end{aligned}$$

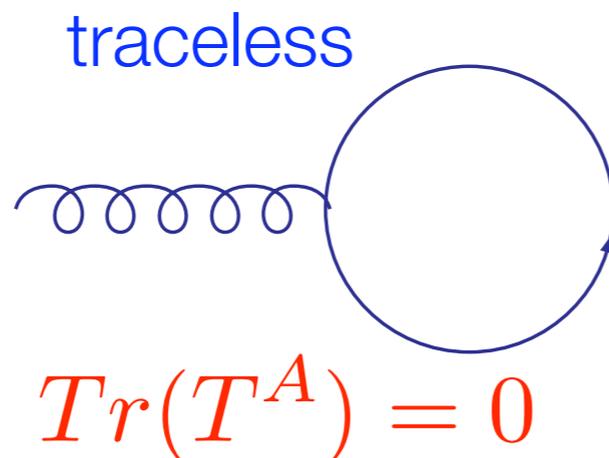
Quantum number management

- Since color is a completely separate degree of freedom, it is often useful to **factorize out any dependence on color** at an early stage of the calculation.
- Each Feynman diagram will be associated with a particular **color factor**, which it is often useful to calculate and account for separately.
- A pictorial way of doing this can be very useful.

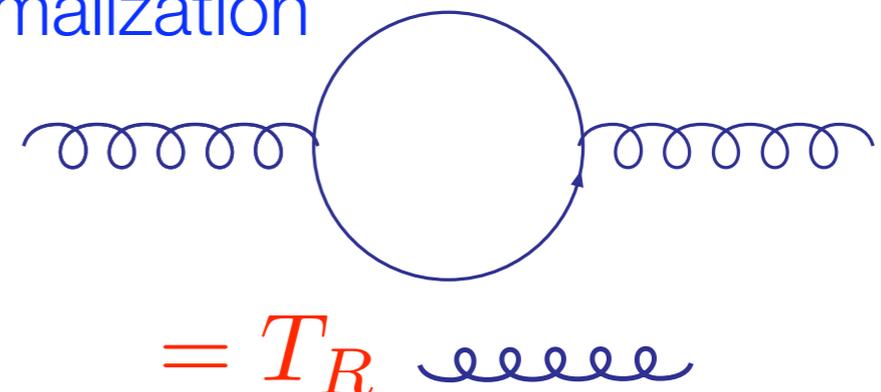
from the
Feynman rules



properties of the
color matrices

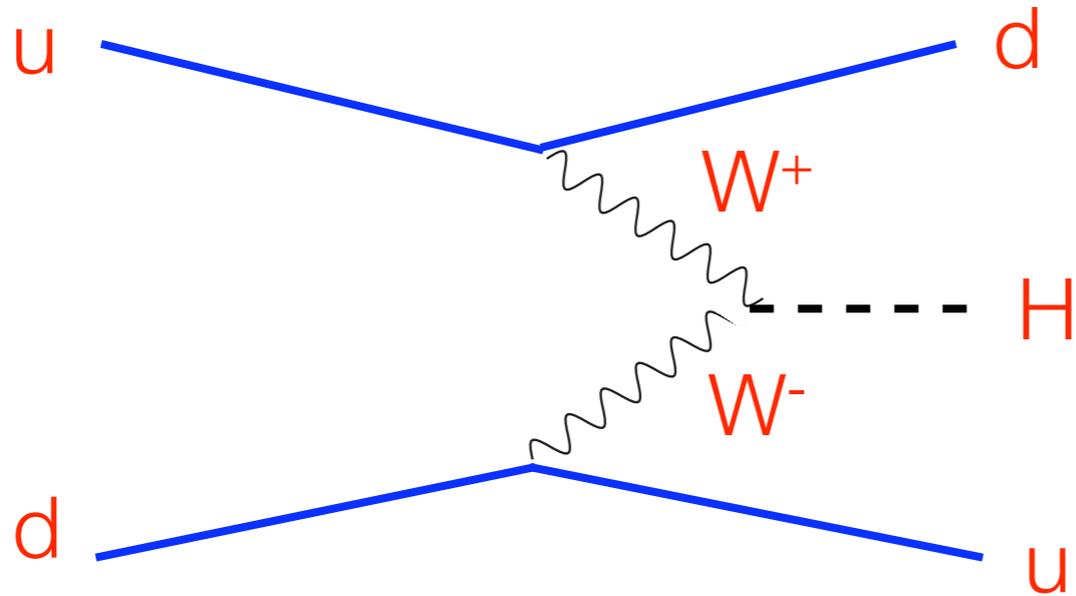


normalization



Simple loop calculation

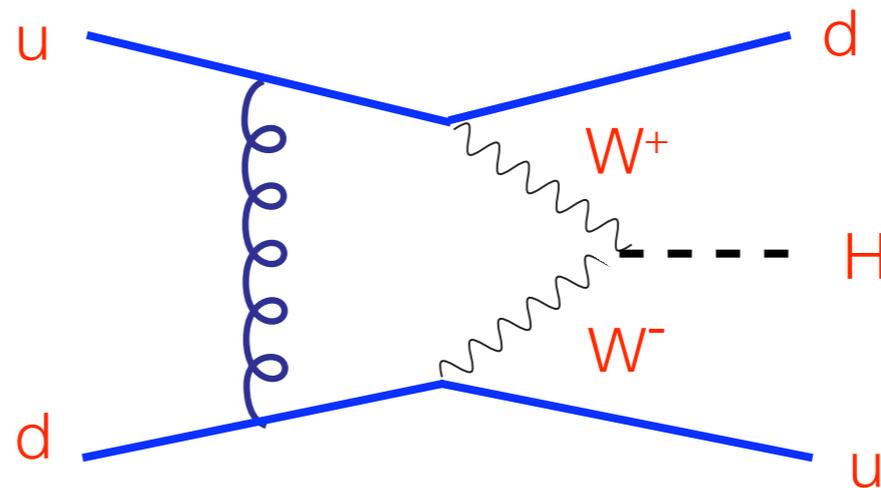
- Vector boson fusion is an important Higgs search channel at the LHC.



Basic idea: incoming quarks radiate W (or Z) bosons without changing direction much.

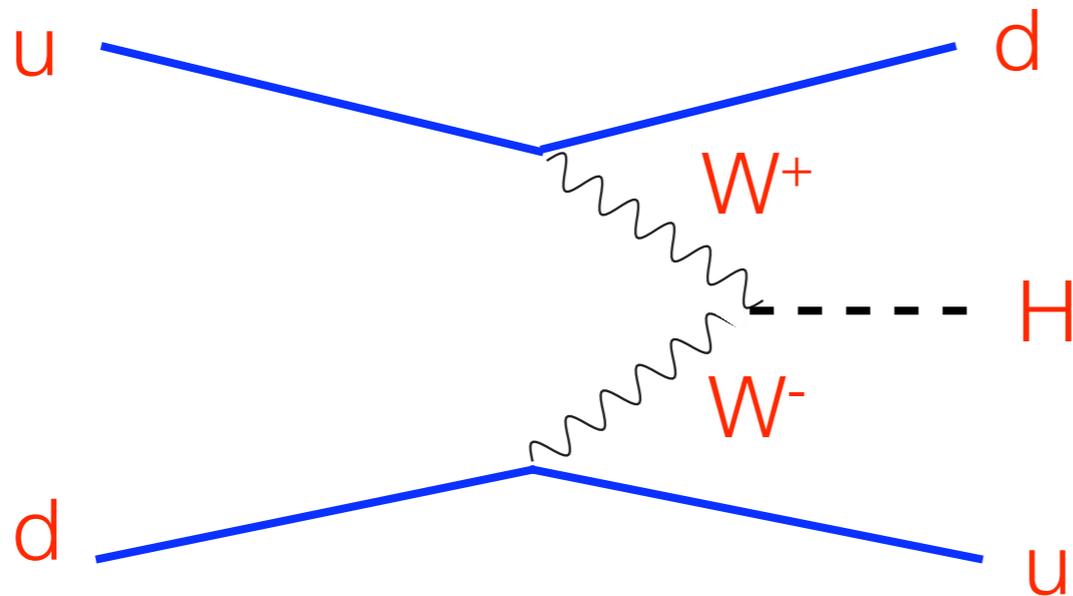
Higgs boson is produced in the central area of the detector relatively cleanly.

Simple picture corrected by gluon emission and absorption by the quarks:



Simple loop calculation

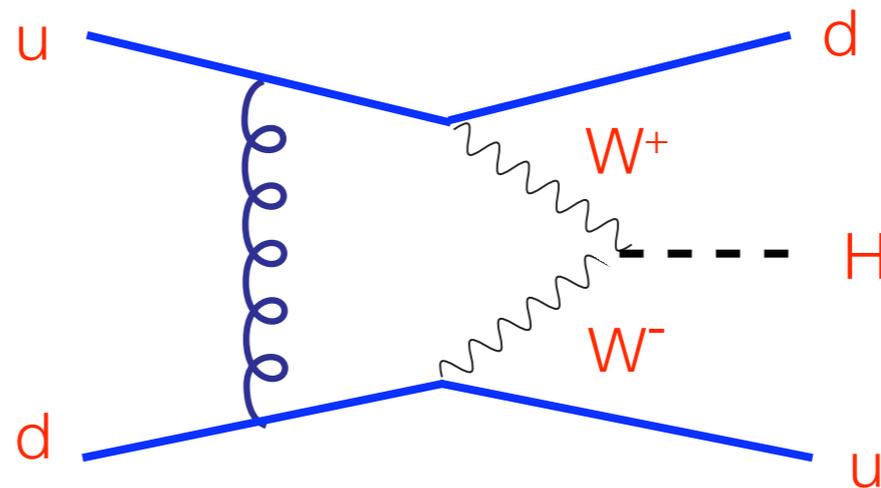
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Basic idea: incoming quarks radiate W (or Z) bosons without changing direction much.

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Simple picture corrected by gluon emission and absorption by the quarks:



$= 0$ when interfered with diagram above!

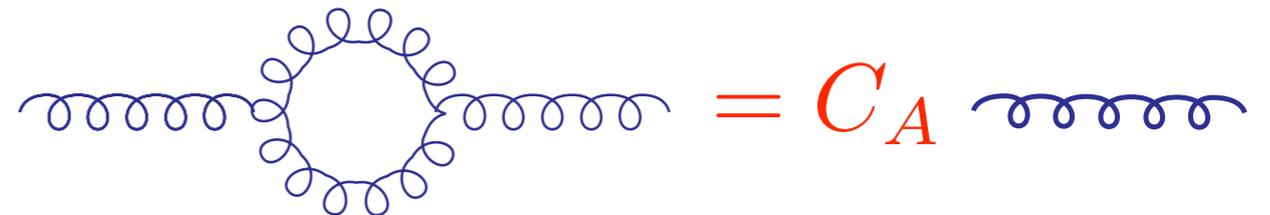
Other color identities

- Identities we have already seen:

$$\sum_A T^A T^A = C_F \mathbf{1}$$

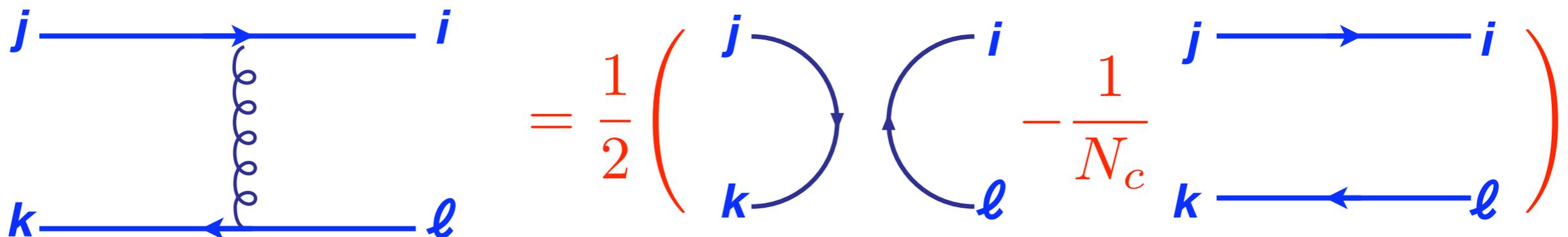


$$\sum_{C,D} f^{ACD} f^{BCD} = C_A \delta^{AB}$$



- A new relation, the **Fierz identity**:

$$\sum_A (T^A)_{ij} (T^A)_{kl} = \frac{1}{2} \left(\delta_{il} \delta_{jk} - \frac{1}{N_c} \delta_{ij} \delta_{kl} \right) \quad \text{(note direction of arrows)}$$



Color at work

H. Ita, Blackhat (June 2010)

W+4 jets on its way

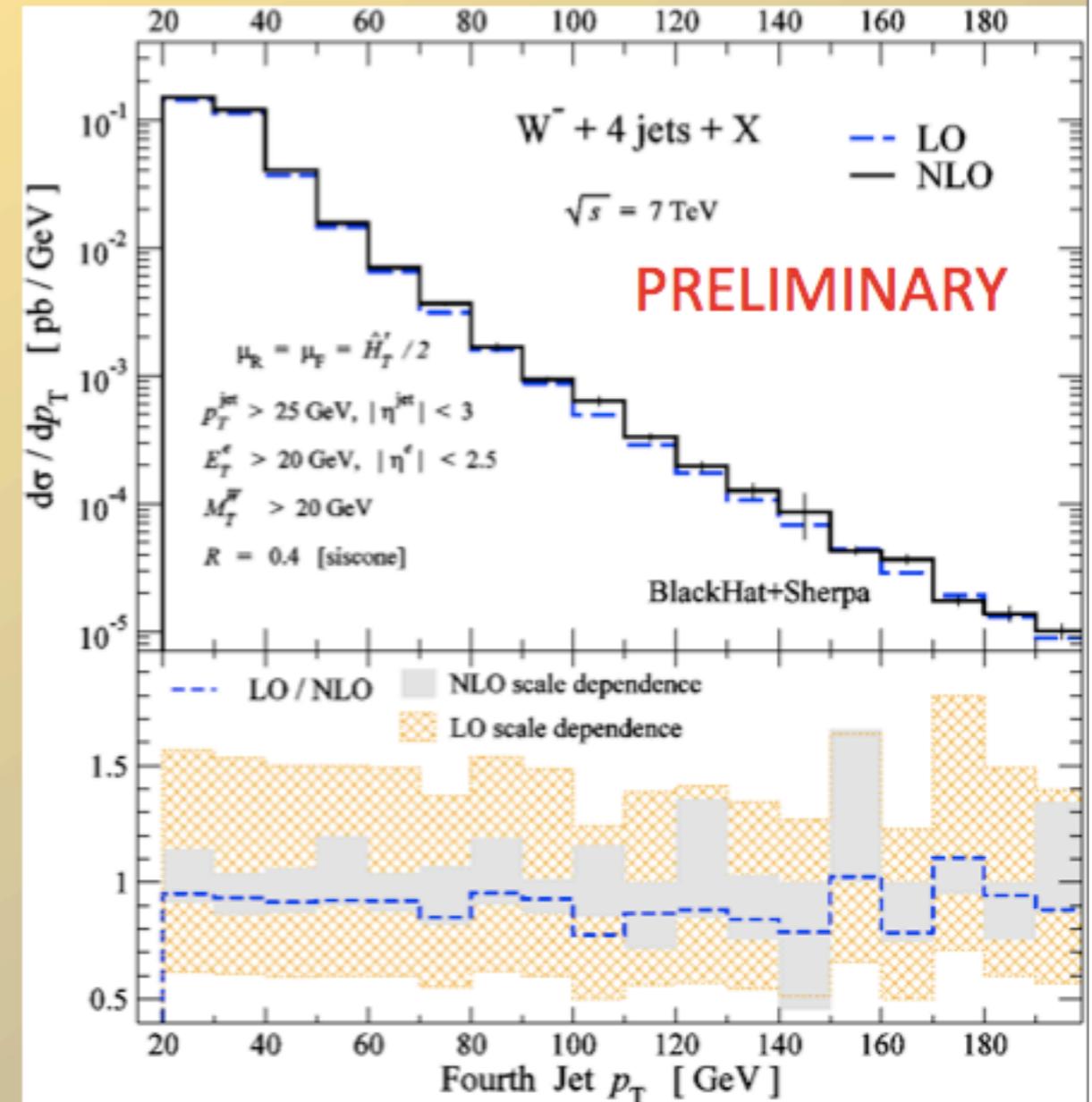
W⁻+4jets+X

Cuts: $\mu_R = \mu_f = \hat{H}_T / 2$
 $p_T^{\text{jet}} > 25 \text{ GeV}$ $|\eta^{\text{jet}}| < 3$
 $E_T^e > 20 \text{ GeV}$ $|\eta_e| < 2.5$
 $M_{TW} > 20 \text{ GeV}$ $R > 0.4$ [siscone]

Leading color approximation:

- 8-point virtual amplitudes
- Off-shell W
- in virtual keep up to n_f/N_c terms drop order $1/(N_c)^2$ terms and 6q real contribution

Under good control for physics!



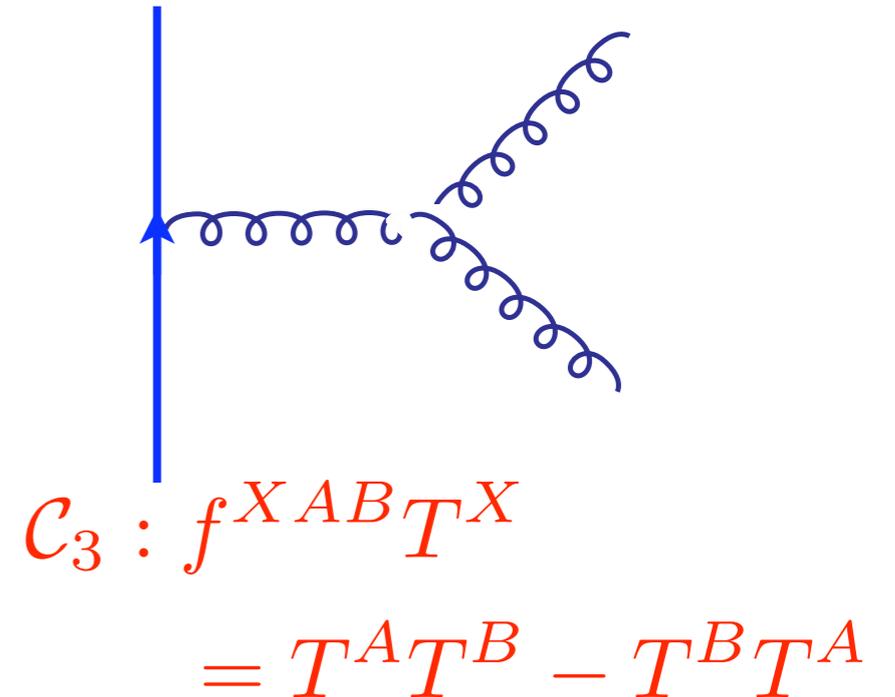
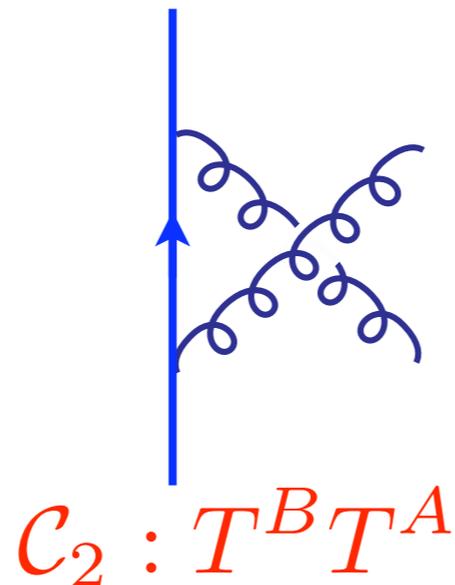
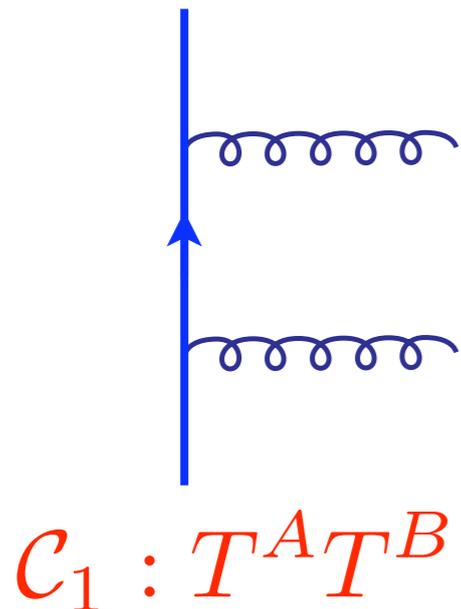
4th jet p_T

How is approx. made?

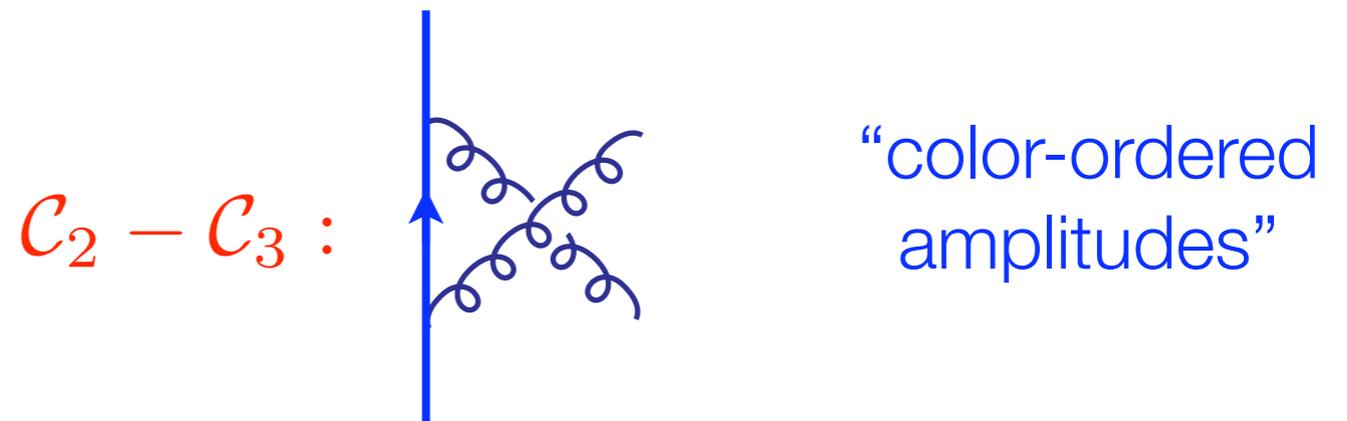
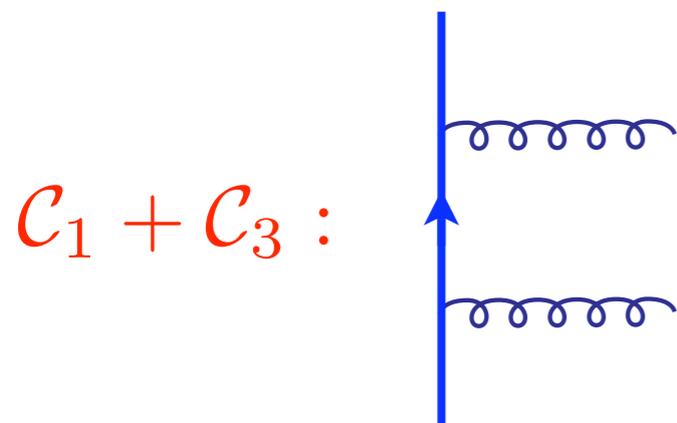
What is being dropped?

Simpler example

- **quark+antiquark \rightarrow W + 2 gluons** is enough to see the main features.
 - in fact, we will drop the W in the pictures, since it is color-neutral.
- There are then three types of contribution, with the following color diagrams:

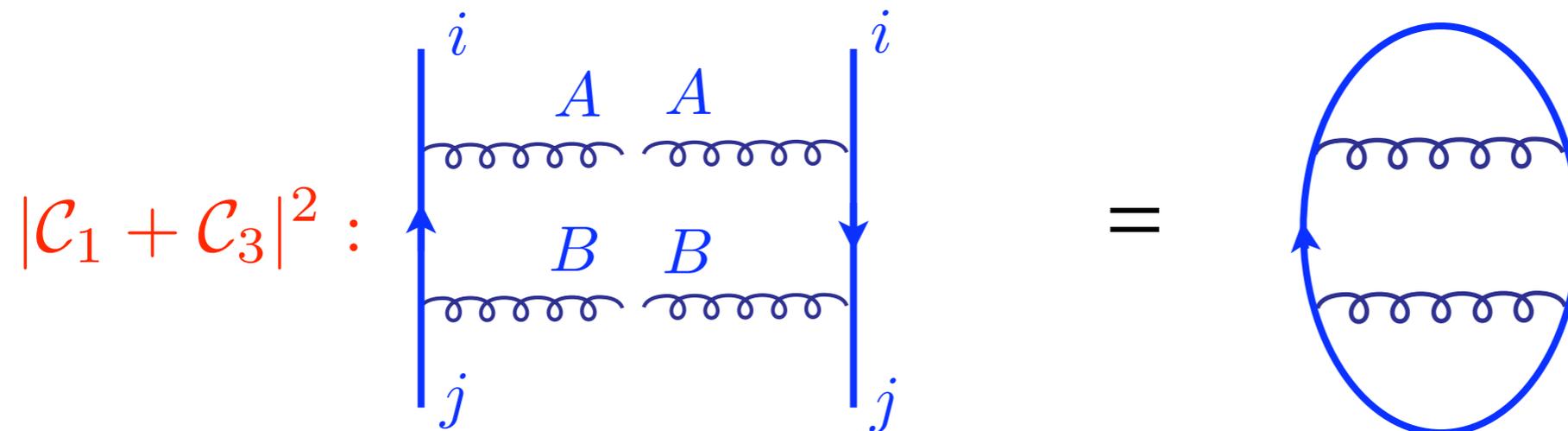


- Hence we can already simplify our calculation to:



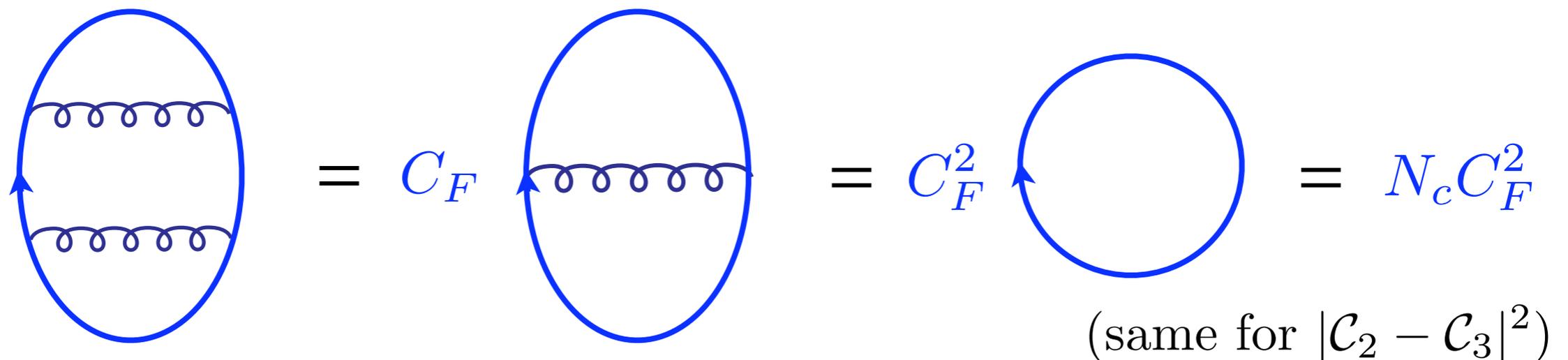
Color factors

- To compute the cross section we need the amplitude squared.



[recall: $(T_{ij}^A)^* = T_{ji}^A$]

- Now we simplify using our pictorial rules:



Color factors

- The interference term is a little more complicated (use Fierz).

$$(\mathcal{C}_1 + \mathcal{C}_3)(\mathcal{C}_2 - \mathcal{C}_3)^* : \quad \text{[Diagram: circle with two internal gluon lines crossing]} = -\frac{1}{2N_c} \text{[Diagram: circle with one internal gluon line]} = -\frac{C_F}{2}$$

- Sum all contributions, keeping one overall factor of C_F but expanding other.

$$\frac{N_c^2 C_F}{2} \left(|\mathcal{C}_1 + \mathcal{C}_3|^2 + |\mathcal{C}_2 - \mathcal{C}_3|^2 - \frac{1}{N_c^2} |\mathcal{C}_1 + \mathcal{C}_2|^2 \right)$$

this is the leading-color contribution

sub-leading: does not contain any remnant of the triple-gluon diagrams (i.e. QED-like)

(color-ordered contributions)

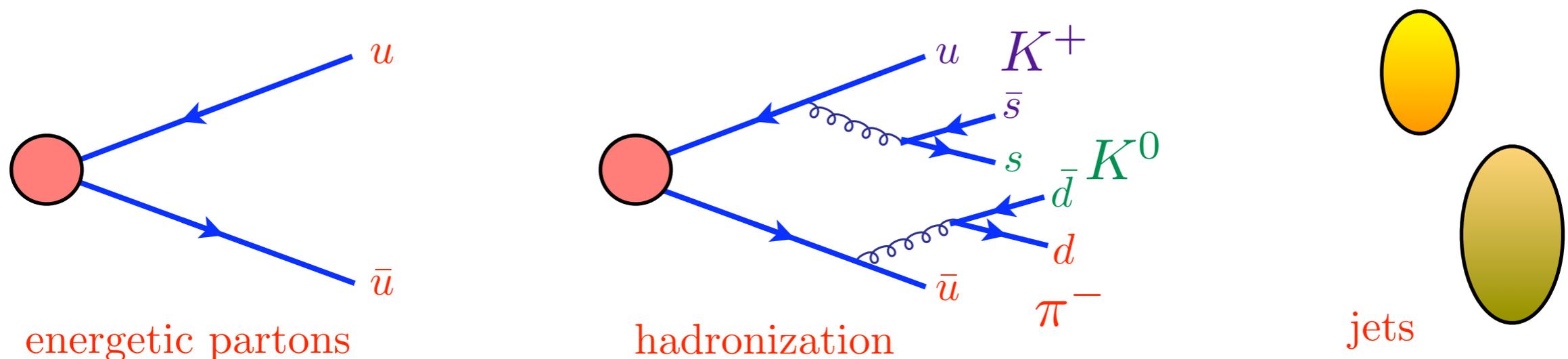


Recipe for QCD cross sections

1. **Identify the final state** of interest, e.g. leptons, photons, quarks, gluons.
2. **Draw the relevant Feynman diagrams** and begin calculating.
 - take care of QCD color factors using color algebra.
 - compute the rest of the diagram using the usual Gamma-matrix algebra.
3. This gives us the **squared matrix elements**.
4. To turn into a cross section, we need to integrate over momentum degrees of freedom → **phase space integration**.
 - for final state momenta, this is just like QED.
 - in the initial state, we have the additional complication that we are colliding protons and not quarks/gluons.
 - more on this later.
 - this step almost always performed numerically - **“Monte Carlo integration”**.

Identifying the final state

- From the beginning, we noted that all particles observed in experiments should be color neutral \rightarrow no quarks or gluons.
- How then can we mesh experimental observations with the QCD Lagrangian, which necessarily involves the fundamental quark and gluon fields?
- A scattering can be described in terms of energetic quarks and gluons (**partons**) that subsequently **hadronize**, combining into color-neutral mesons and baryons, without too much loss of energy.
- This concept is often referred to as **local parton-hadron duality**.



- This naturally accommodates the replacement of jets of particles in the final state by an equivalent number of quarks or gluons.



Leading order tools

- The **leading order** estimate of the cross section is obtained by computing all relevant **tree-level** Feynman diagrams (i.e. no internal loops).
- Nowadays this is practically a solved problem - many suitable tools available.

ALPGEN

M. L. Mangano et al.

<http://alpgen.web.cern.ch/alpgen/>

AMEGIC++

F. Krauss et al.

<http://projects.hepforge.org/sherpa/dokuwiki/doku.php>

CompHEP

E. Boos et al.

<http://comphep.sinp.msu.ru/>

HELAC

C. Papadopoulos, M. Worek

<http://helac-phegas.web.cern.ch/helac-phegas/helac-phegas.html>

Madevent

F. Maltoni, T. Stelzer

<http://madgraph.roma2.infn.it/>



Madgraph

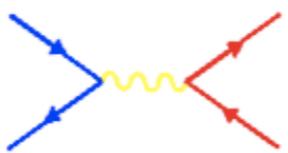
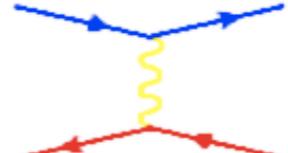
[MadGraph](#) / [MadEvent](#) is a software that allows you to generate amplitudes and events for any process (with up to 9 external particles) in any model. Implemented models are the [Standard Model](#), [Higgs effective couplings](#), [MSSM](#), the general [Two Higgs doublet model](#), and several minor models, and there is an easy-to-use interface for [implementing model extensions](#). In

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[Generate Process](#) [Register](#) [Tools](#) [My Database](#) [Cluster Status](#) [Downloads \(needs registration\)](#) [Wiki/Docs](#) [Admin](#)

[UCL UIUC Fermi](#)
by the [MG/ME Development team](#)

MadGraph Version 4

Generate Code On-Line

To improve our web services we now request that you register. Registration is quick and free. You may register for a password by clicking [here](#)

Code can be generated either by:

I. Fill the form:

MadGraph Version : [What is MadGraph 5?](#)

Model: [Model descriptions](#)

Input Process:

Max QCD Order:

Max QED Order:

p and j definitions:

sum over leptons:



Recap

- The role of color in the theory of QCD is experimentally measurable.
 - good evidence for $N_c=3$.
- The Lagrangian of QCD is based on the SU(3) gauge group.
 - QCD interactions can be represented by a relatively short list of Feynman rules, which can be read off from the Lagrangian.
 - color leads to self-interaction between gluons (triple- and 4-gluon) vertices.
 - more profound differences between QCD and QED we will discuss later.
- Accounting for color is performed using Gell-Mann matrices, whose properties can be used to write amplitudes in terms of color factors $C_F=4/3$ and $C_A=N_c=3$.
 - a pictorial method for computing color factors is a handy tool.
- The computation of leading order cross sections is a solved problem.
 - many tools available to do the work for you.