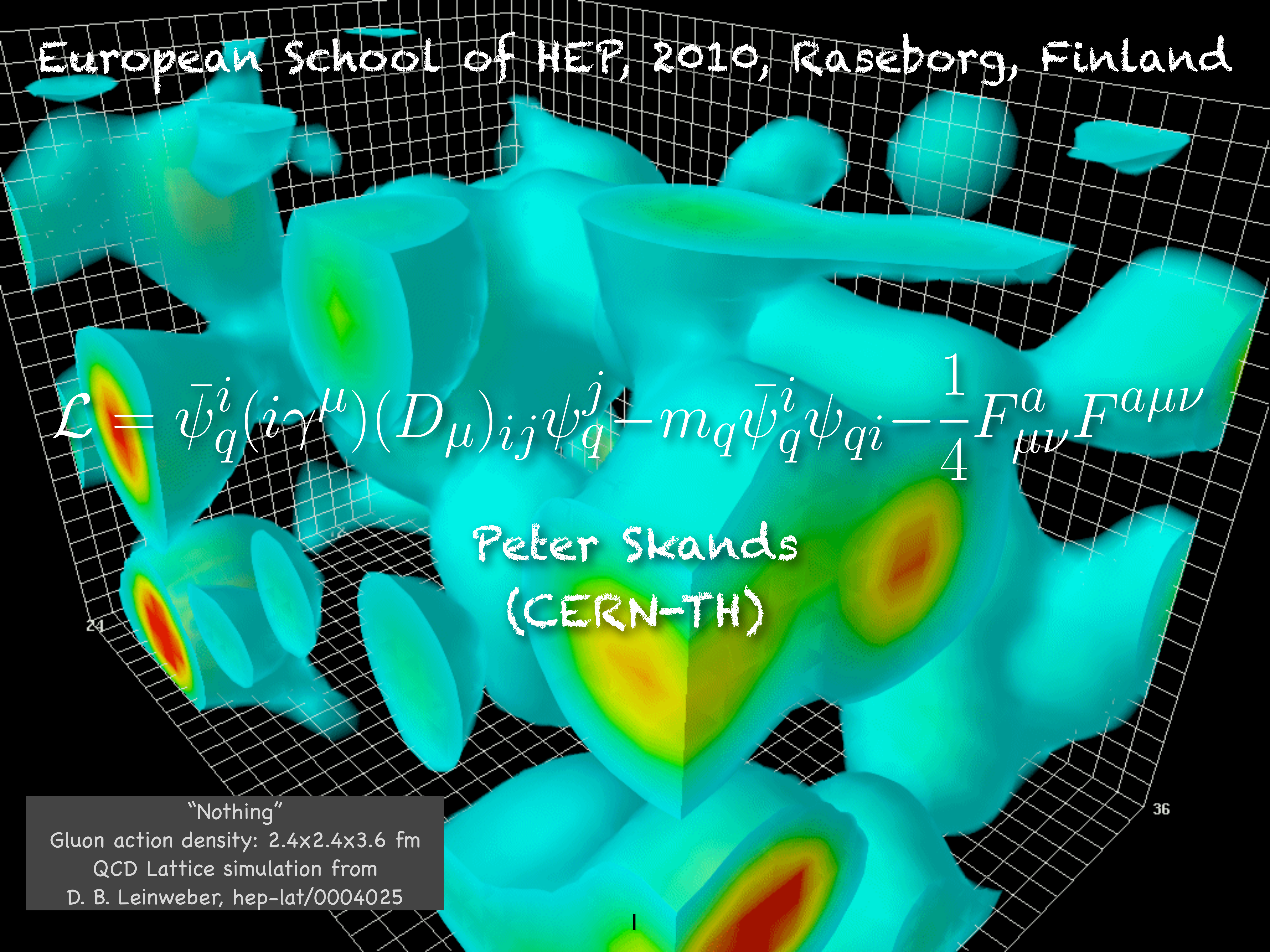
European School of HEP, 2010, Raseborg, Finland

$$\mathcal{L} = \bar{\psi}_q^i (i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}$$

Peter Skands
(CERN-TH)



"Nothing"
Gluon action density: 2.4x2.4x3.6 fm
QCD Lattice simulation from
D. B. Leinweber, hep-lat/0004025

A huge variety of phenomena

$$\mathcal{L} = \bar{\psi}_q^i (i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q\bar{\psi}_q^i\psi_{qi} - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$$

Still only partially solved ...

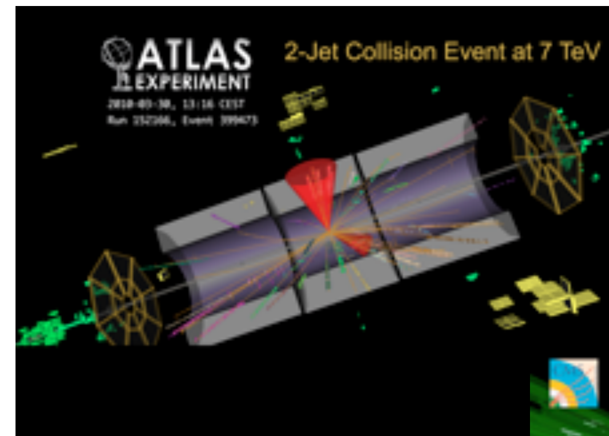
Data ↔ Theory

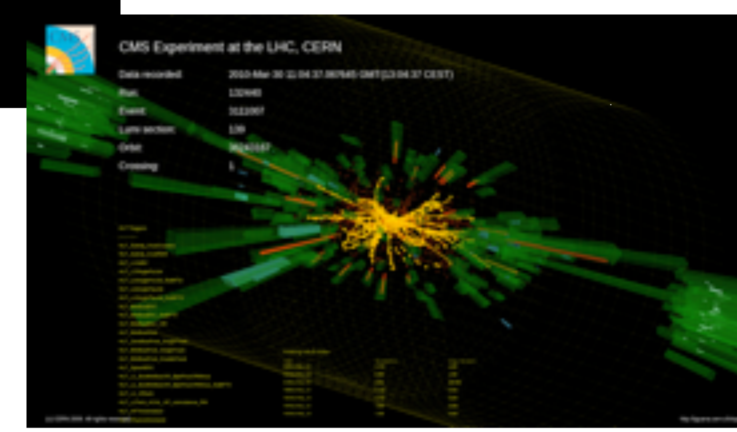
*“**It is a** huge mistake to theorize before one has data - One tends to twist fact to suit theory, instead of theory to suit fact”*

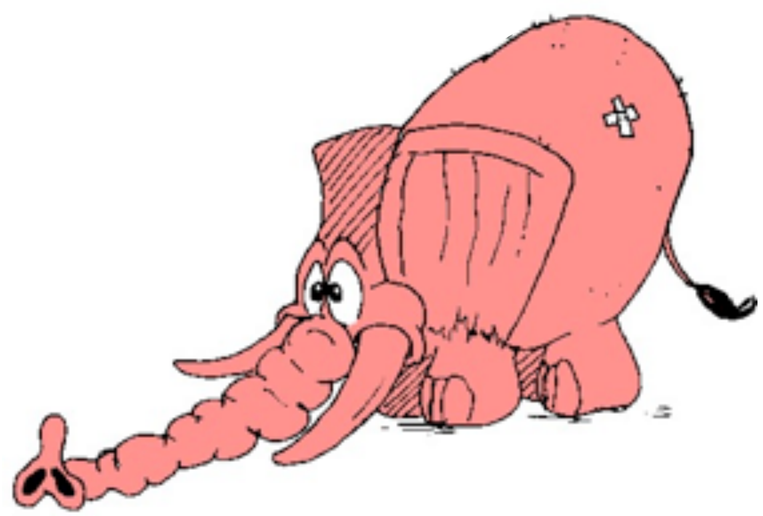
Sherlock Holmes (2009)

Collider Physics

Comparisons
to Collider
observables



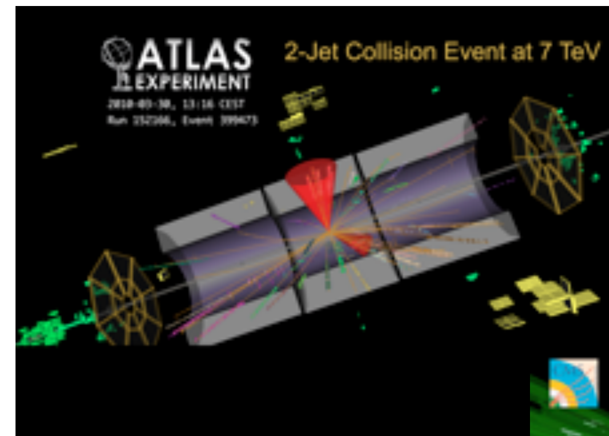


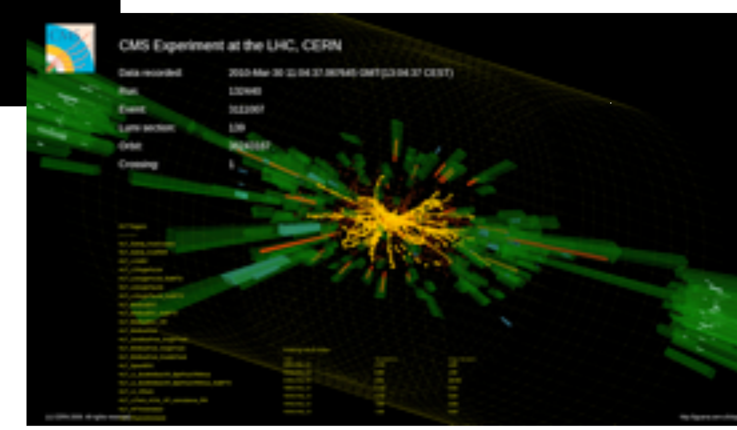


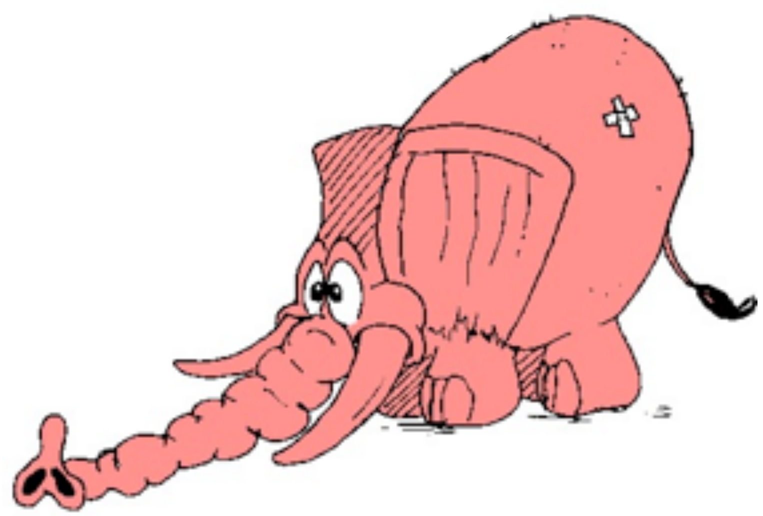
L=...

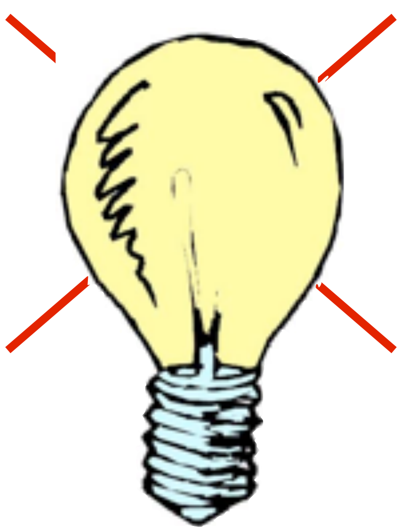
Collider Physics

Comparisons to Collider observables







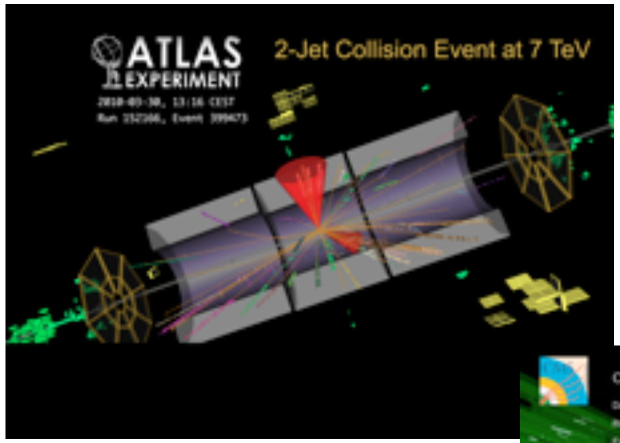


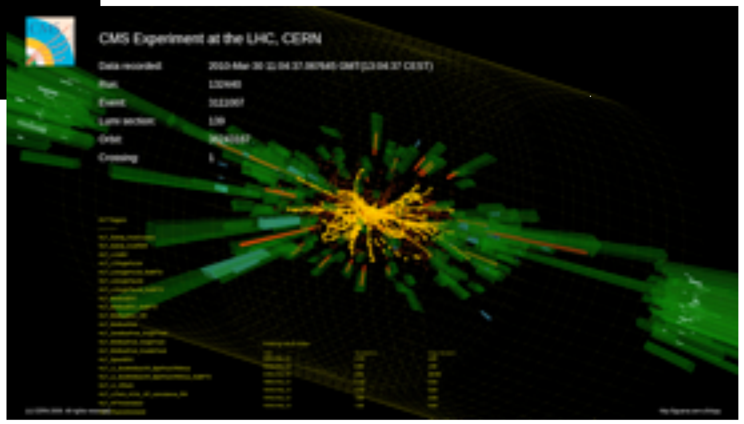
L=...

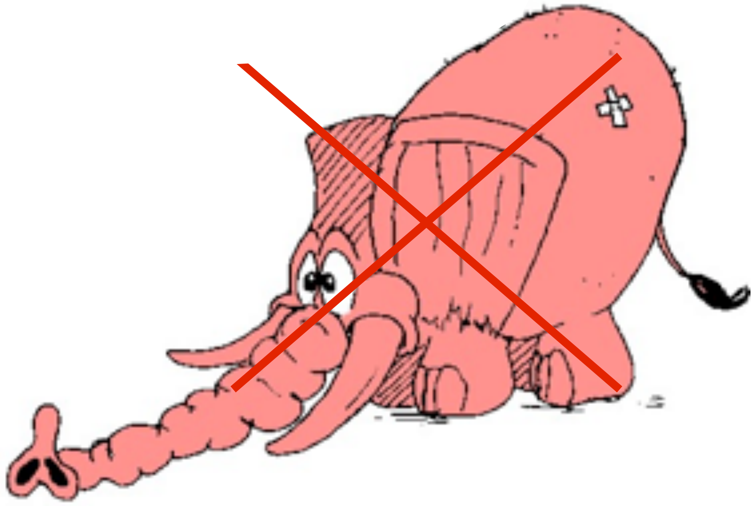
A) Theoretical Idea is wrong

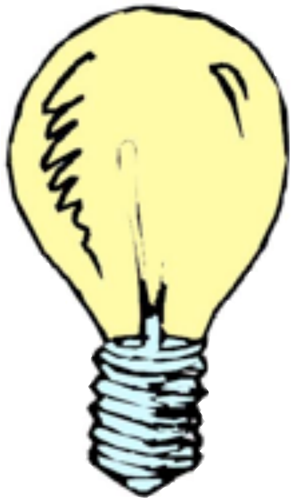
Collider Physics

Comparisons to Collider observables









L=...

A) Theoretical Idea

B) SM Physics Model is wrong

Disclaimer

Focus on QCD for collider physics

- Factorization, Hard Processes
- Jets and Matching
- Monte Carlo Event Generators
- Underlying Event, Hadronization, Min-Bias, ...

Still, some topics not touched, or only briefly

- Heavy flavor physics (e.g., B mesons, J/Psi, ...)
- Physics of hadrons, Lattice QCD
- Heavy ion physics
- DIS
- New Physics
- Prompt photon production, polarized beams, forward physics, diffraction, BFKL, ...

Overview

1. Fundamentals of QCD
2. QCD in the Ultraviolet
3. QCD in the Infrared
4. Monte Carlo Generators
5. Jets & Matching
6. Getting (kick)started with PYTHIA 8

QCD
Lecture 1

Fundamentals

Before QCD

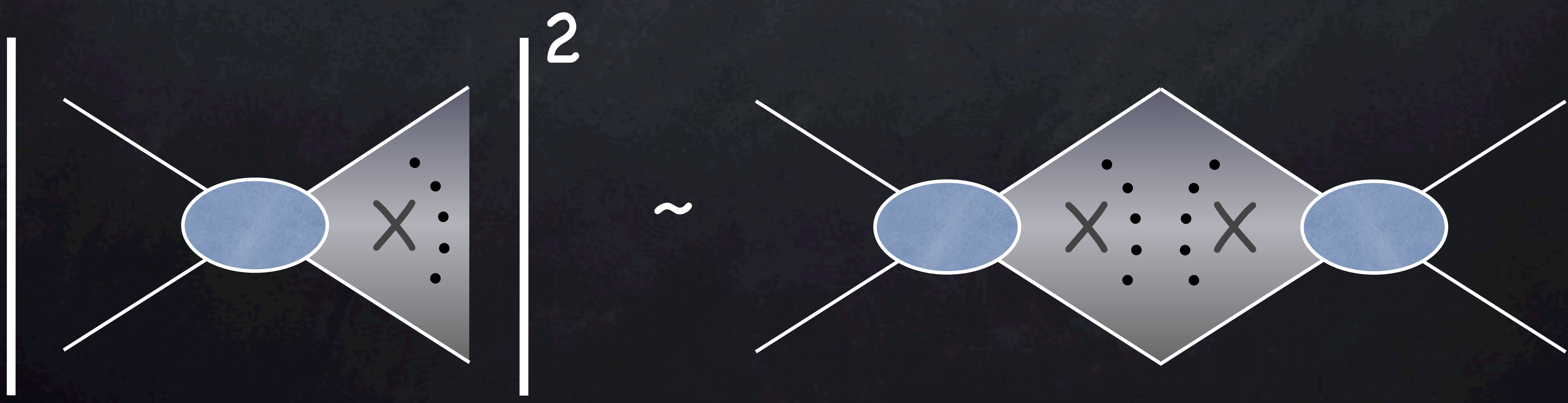
Some Theorems

E.g., Lorentz inv., unitarity and the optical theorem

$$SS^\dagger = 1 \quad \Rightarrow \quad \sigma_{\rm tot}(s) = \sum_X \int {\rm d}\Phi_X |M_X|^2 = \frac{8\pi}{\sqrt{s}} \, {\rm Im}\left[M_{\rm el}(\theta = 0)\right]$$

"something **will** happen"
note: includes "no" scattering

Total σ = Sum over everything that can happen = "Square Root" of nothing happening



Before QCD

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"something **will** happen"
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Total σ = Sum over everything that can happen = "Square Root" of nothing happening

+ Some models

E.g., potential models, Regge theory, Pomerons, string models, the early parton model, ...

After QCD

Some Theorems

E.g., Lorentz inv., unitarity and the optical theorem

$$SS^\dagger = 1 \quad \Rightarrow \quad \sigma_{\rm tot}(s) = \sum_X \int {\rm d}\Phi_X |M_X|^2 = \frac{8\pi}{\sqrt{s}} {\rm Im}\left[M_{\rm el}(\theta=0)\right]$$

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note: includes "no" scattering

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More Theorems

$$\mathcal{L} = \bar{\psi}_q^i (i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$

+ Factorization, Perturbative Quantum Field Theory,
  - ⇒ Resummation, Coherence, Infrared Safety, ...
+ Lattice Discretization

+ Phenomenological Models

+ Some models

E.g., potential models, Regge theory, Pomerons, string models, constituent quark model, …

+ More models

Soft / non-perturbative effects

- Fragmentation models
- Diffraction models, Min-Bias models, soft Underlying-Event models
- Soft final-state interactions, hydrodynamics, …

Approximations to higher-order perturbative effects

- Jet (sub)structure and multiple emissions: shower models
- Multiple parton interactions: "hard" UE models
- Hard Diffraction (e.g., diffractive Higgs), …

work in progress
interesting inputs from LHC

QCD as Discovery Physics

1951: the first hint of colour

Discovery of the
Δ^{++} baryon

Meson-Nucleon Scattering and Nucleon Isobars*

KEITH A. BRUECKNER
Department of Physics, Indiana University, Bloomington, Indiana
(Received December 17, 1951)

Phys.Rev.86(1952)106

satisfactory agreement with experiment is obtained. It is concluded that the apparently anomalous features of the scattering can be interpreted to be an indication of a resonant meson-nucleon interaction corresponding to a nucleon isobar with spin $\frac{3}{2}$, isotopic spin $\frac{3}{2}$, and with an excitation of 277 Mev.

~ 1960: Eightfold Way

$|\Delta^{++}\rangle = |\, u_\uparrow\, u_\uparrow\, u_\uparrow \,\rangle$???

Isospin: Wigner, Heisenberg
Strangeness ('53): Gell-Mann, Nishijima
Eightfold Way ('61): Gell-Mann, Ne'eman
Quarks ('63): Gell-Mann, Zweig, (Sakata)

Symmetric in space, spin & flavor
Antisymmetric in ???

The Δ Baryon

1951: the first hint of colour

14 years ...

Discovery of the Δ^{++} baryon

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1965: $|\Delta^{++}\rangle = \varepsilon_{ijk}\, | u_i\uparrow u_j\uparrow u_k\uparrow \rangle$

Additional SU(3): Han, Nambu, Greenberg

Symmetric in space, spin & flavor

Antisymmetric in a new (≥3D) Quantum Number

+ postulate only overall singlets observed in nature

E.g., $| u_R u_R \rangle$ not a "physical" particle

The Width of the π^0

Δ^{++}, Δ^-, and Ω^-

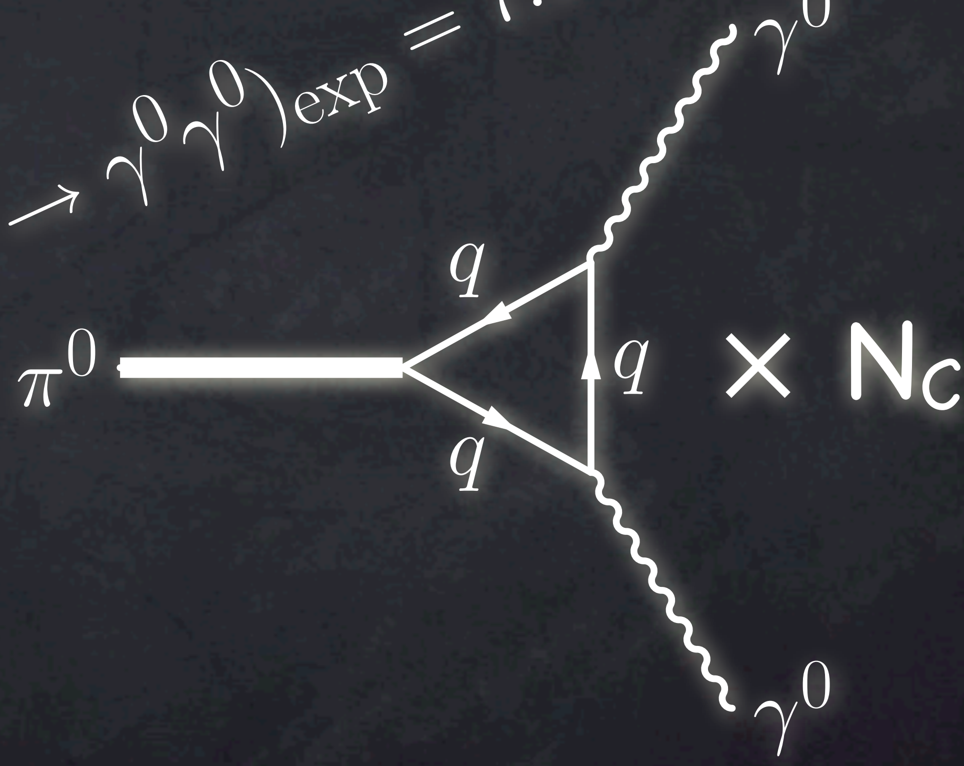
Strictly speaking, we only know N ≥ 3

$\pi \to \gamma\gamma$ decays

Get pion decay constant f_π from

$\pi^- \to \mu^- \nu_\mu$

$$\Gamma(\pi^0 \to \gamma^0\gamma^0)_{\rm exp} = 7.7 \pm 0.6 {\rm eV}$$

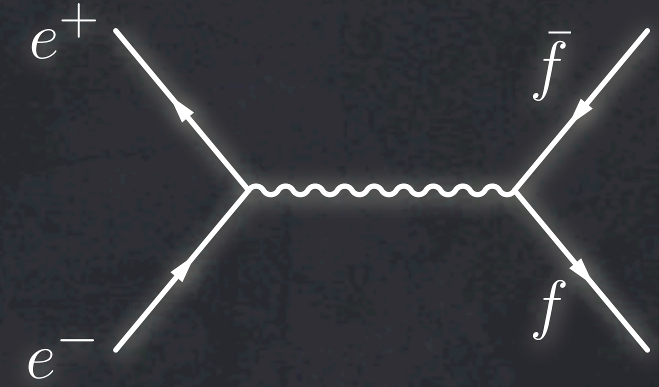


$$\Rightarrow \quad \Gamma(\pi^0 \to \gamma^0\gamma^0)_{\rm th} = \frac{N_C^2}{9}\frac{\alpha_{\rm em}^2}{\pi^2}\frac{1}{64\pi}\frac{m_\pi^3}{f_\pi^2} = 7.6\left(\frac{N_C}{3}\right)^2 {\rm eV}$$

See, e.g., Ellis, Stirling, & Webber, "QCD and Collider Physics", Cambridge Monographs

"R"

$$R = \frac{\sigma(e^+e^- \to \mathrm{q\bar{q}})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



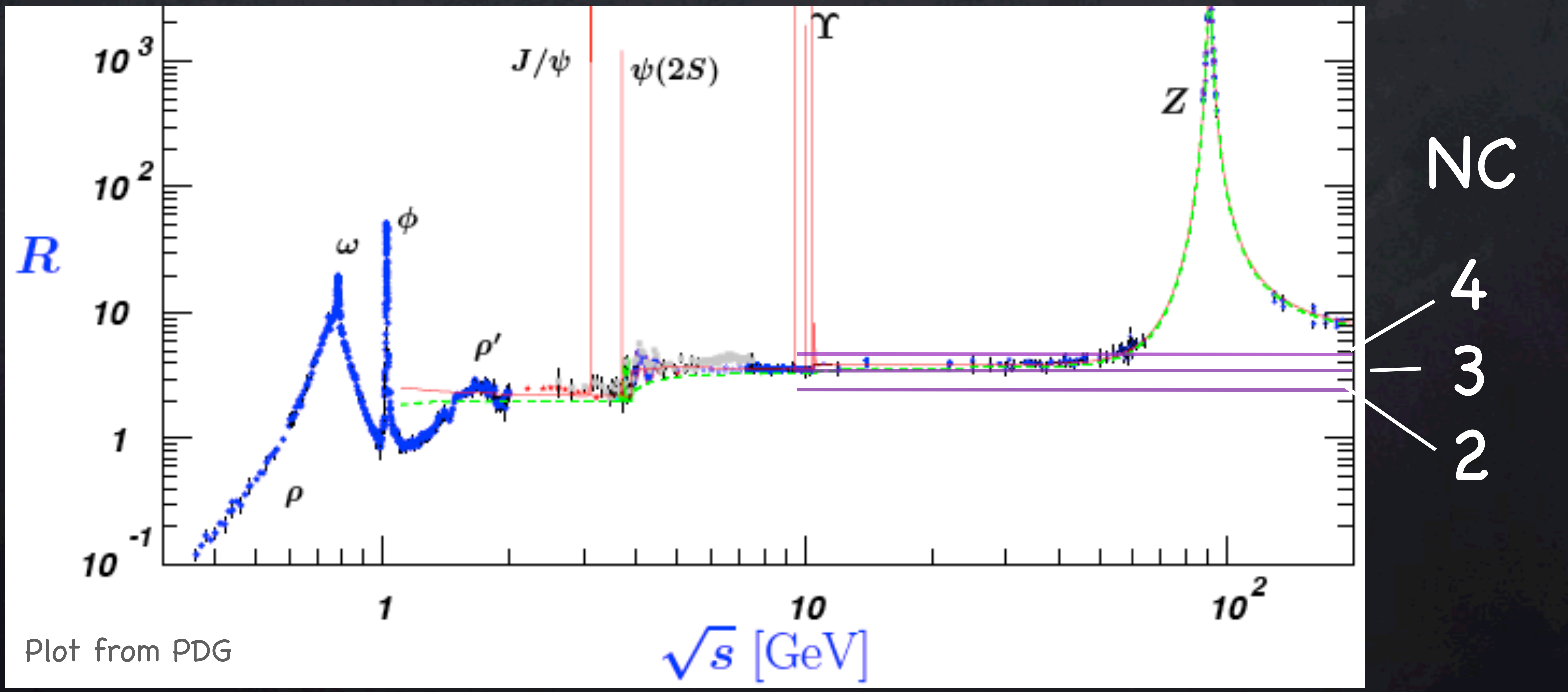
$$= n_u \left(\frac{2}{3}\right)^2 + n_d \left(-\frac{1}{3}\right)^2$$

Question: why does $\pi^0 \to \gamma^0\gamma^0$ go with N_C^2 and R only with N_C?

$$= \begin{cases} 2\,(N_C/3) & q = u, d, s \\ 3.67\,(N_C/3) & q = u, d, s, c, b \end{cases}$$

"R"

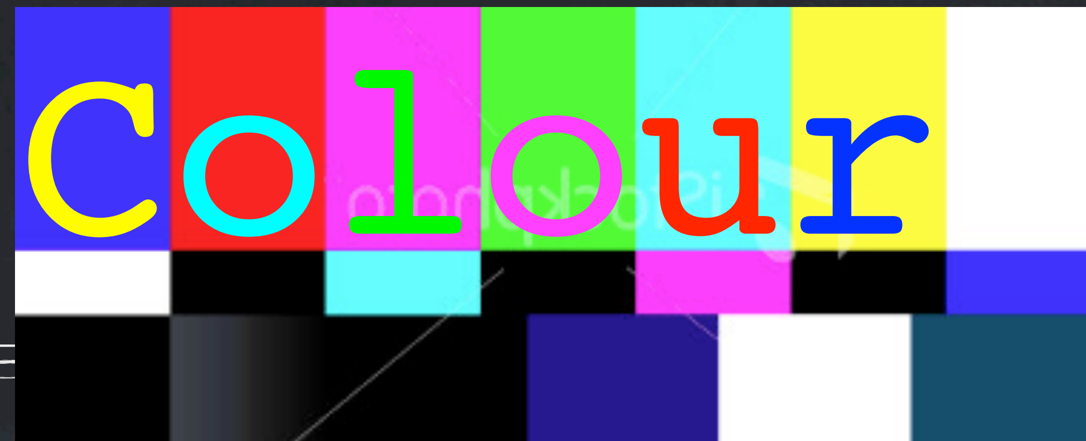
$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \begin{cases} 2\,(N_C/3) & q = u, d, s \\ 3.67\,(N_C/3) & q = u, d, s, c, b \end{cases}$$



So What?

New Physics Pipeline

Data		Phenomenological Models	↔	(Solvable) Theory
Discriminating Observables	↔	Individual Essential Features		Complete description
Fits		Quark Model, Eightfold Way, …		Quantum Chromo-Dynamics



Gauge Group (= local internal space)

Special Unitary group in 3 (complex) dimensions, SU(3)

(Group of 3x3 unitary complex matrices with det=1)

Gluons

One gauge boson for each linearly independent such matrix

3^2-1 = 8 : gluons are octets

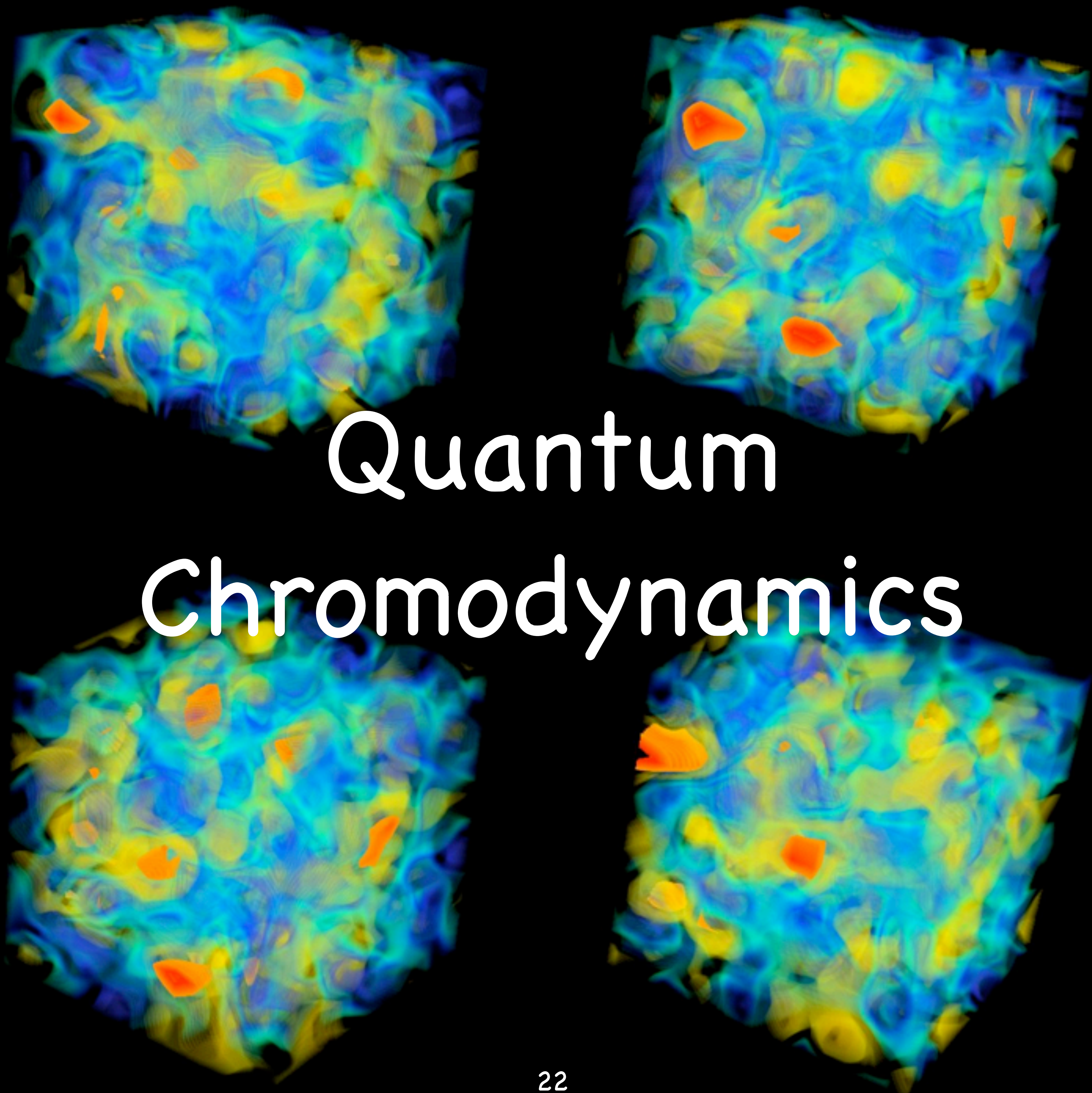
Quarks

One quark color for each degree of SU(3)

3 : quarks are triplets (e.g., vectors on which matrices operate)

(Vacuum Topological Charge, Data courtesy of M. McGuigan BNL-CSC, T. Izubuchi RIKEN-BNL, and S. Tomov University of Tennessee)

Quantum Chromodynamics



$$\mathcal{L} = \bar{\psi}_q^i (i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}$$

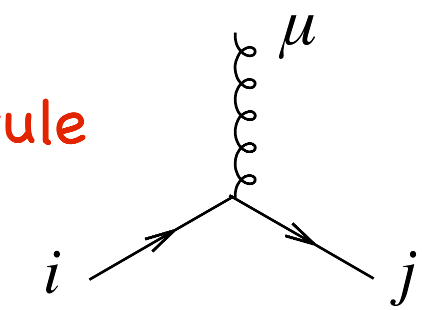
Quark fields

$$\psi_q^j = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$$

Covariant Derivative

$$D_{\mu ij} = \delta_{ij}\partial_\mu - i g_s T_{ij}^a A_\mu^a$$

⇒ Feynman rule



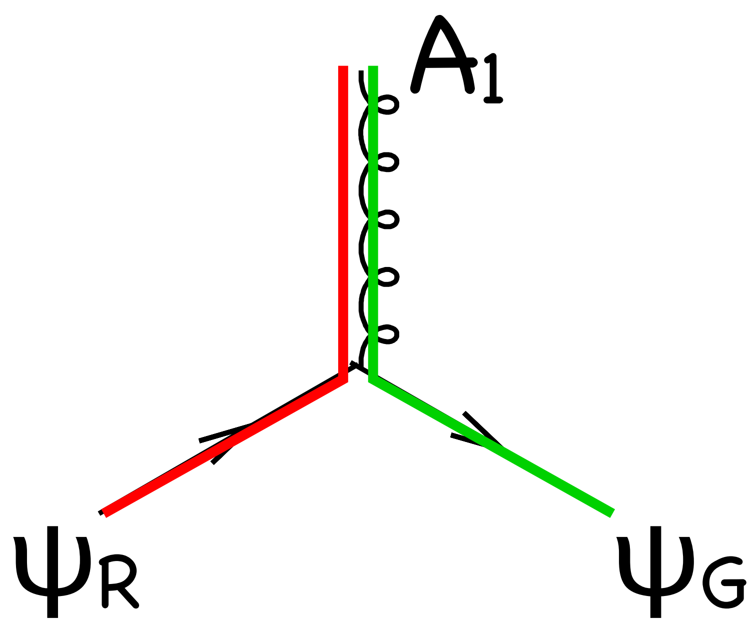
Gell-Mann Matrices $(T^a = \lambda^a/2)$

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & \frac{-2}{\sqrt{3}} \end{pmatrix}$$

Interactions in Colour Space

Quark-Gluon interactions

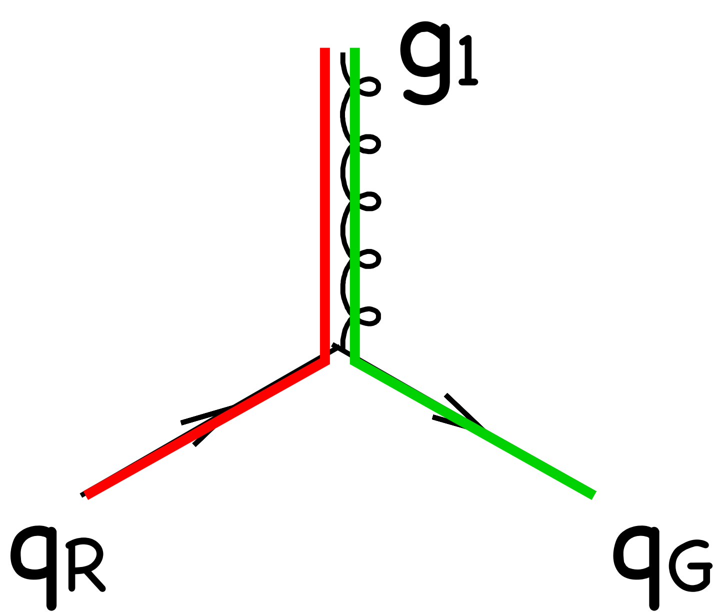


$$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

A_1 ψ_R ψ_G

Interactions in Colour Space

Quark-Gluon interactions



$$\underbrace{\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{g_1} \underbrace{\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}}_{q_R} = \underbrace{\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}}_{q_G}$$

Interactions in Colour Space

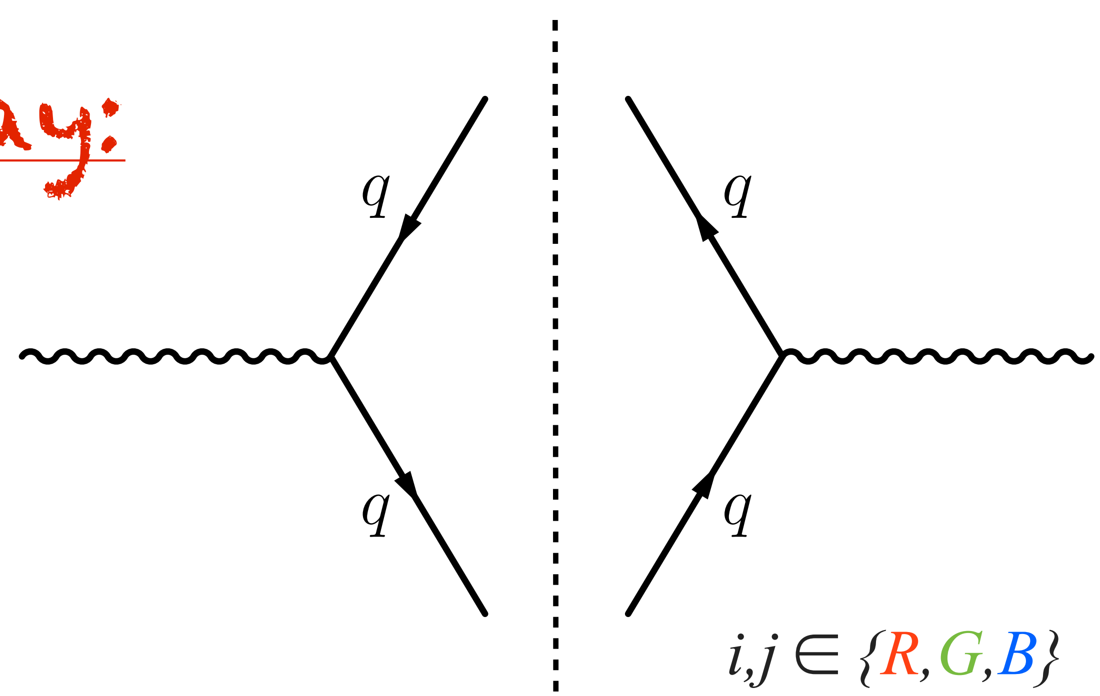
Colour Factors

We already saw pion decay and the "R" ratio depended on how many "color paths" we could take

All QCD processes have a "colour factor". It counts the enhancement from the sum over colours.

Z Decay:

$$\sum_{\text{colours}} |M|^2 =$$



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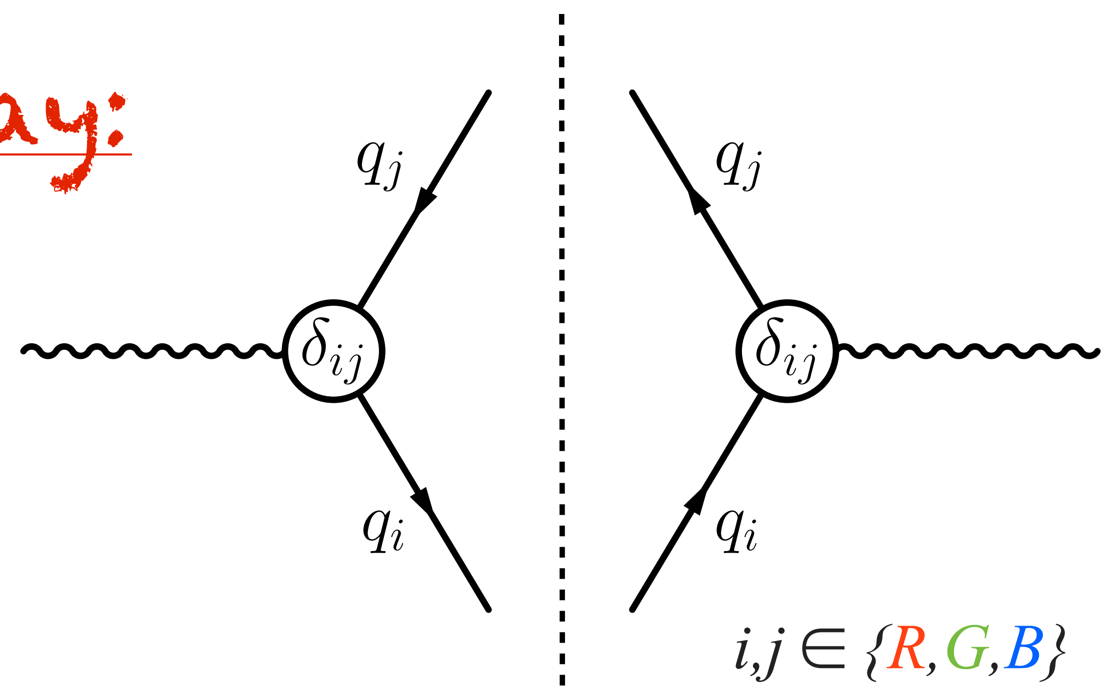

$i,j \in \{R, G, B\}$

$$\propto \delta_{ij}\delta^*_{ji}$$
$$= \mathrm{Tr}[\delta_{ij}]$$
$$= N_C$$

Interactions in Colour Space

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Drell-Yan

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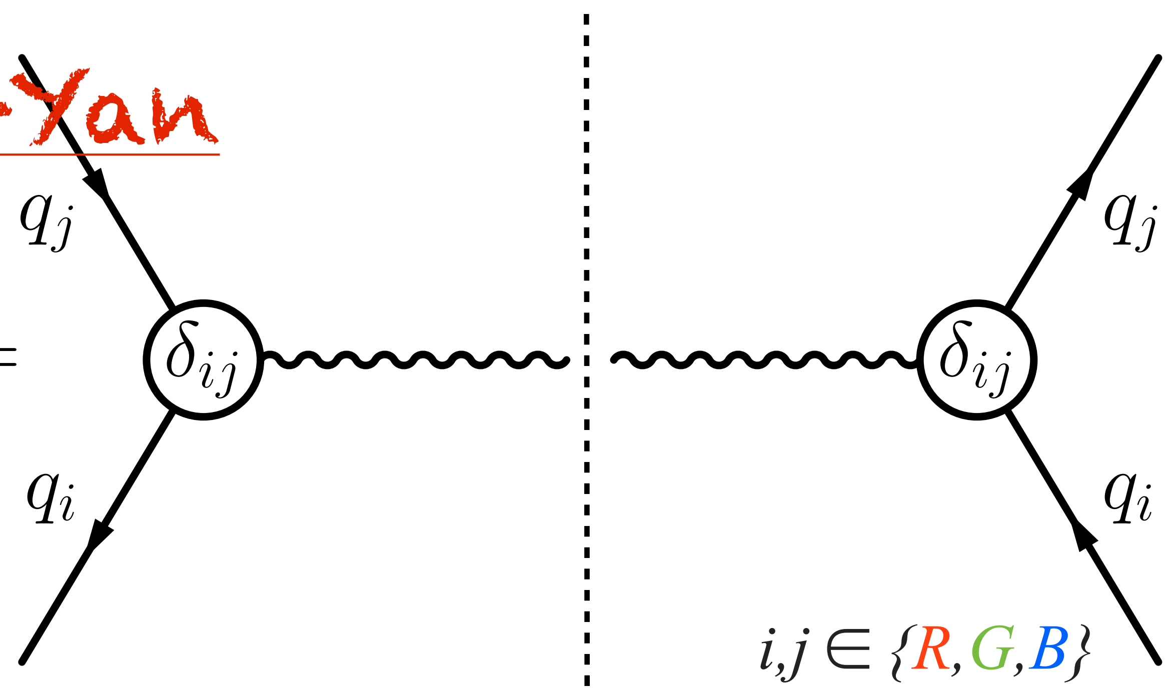

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Interactions in Colour Space

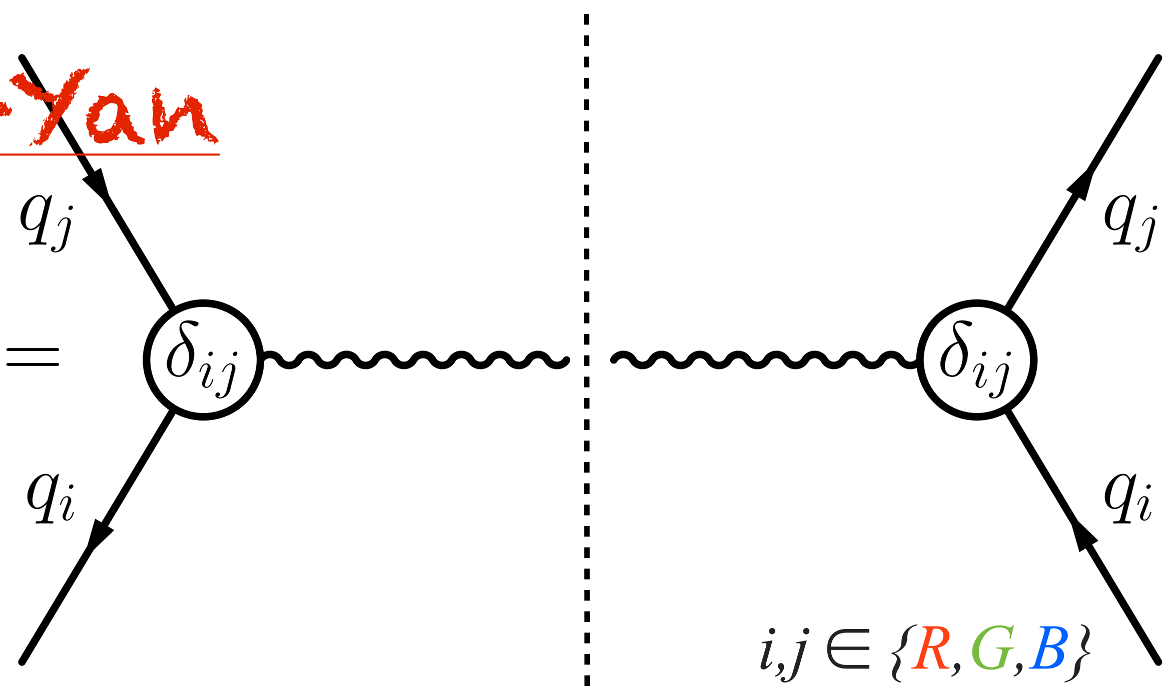
Colour Factors

We already saw pion decay and the "R" ratio depended on how many "color paths" we could take

All QCD processes have a "colour factor". It counts the enhancement from the sum over colours.

Drell-Yan

$$\frac{1}{9}\sum_{\text{colours}} |M|^2 =$$



$$\propto \delta_{ij}\delta^*_{ji} = \mathrm{Tr}[\delta_{ij}] = N_C$$

Interactions in Colour Space

Colour Factors

We already saw pion decay and the "R" ratio depended on how many "color paths" we could take

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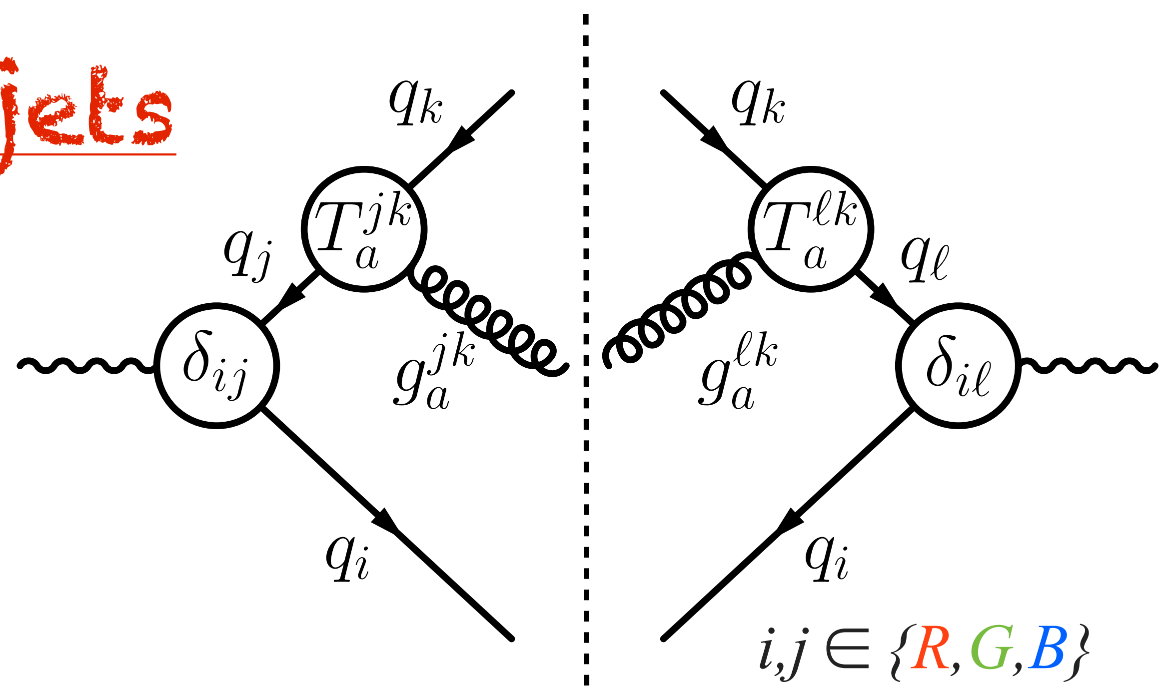
Z→3 jets

$$\sum_{\text{colours}} |M|^2 =$$



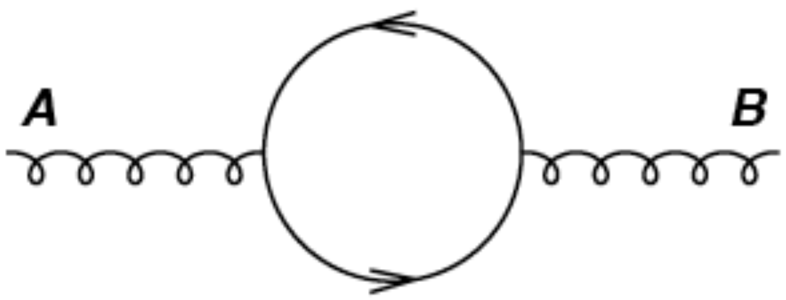
$i,j \in \{R,G,B\}$
$a \in \{1,\ldots,8\}$

$$\propto \delta_{ij} T_a^{jk} (T_a^{\ell k} \delta_{i\ell})^*$$
$$= \mathrm{Tr}[T_a T_a]$$
$$= \frac{1}{2}\mathrm{Tr}\delta_{ab}$$
$$= 4$$

Quick Guide to Colour Algebra

Colour factors squared produce traces

$$\mathrm{Tr}(t^A t^B) = T_R \delta^{AB}, \quad T_R = \frac{1}{2}$$



(from lectures by G. Salam)

Quick Guide to Colour Algebra

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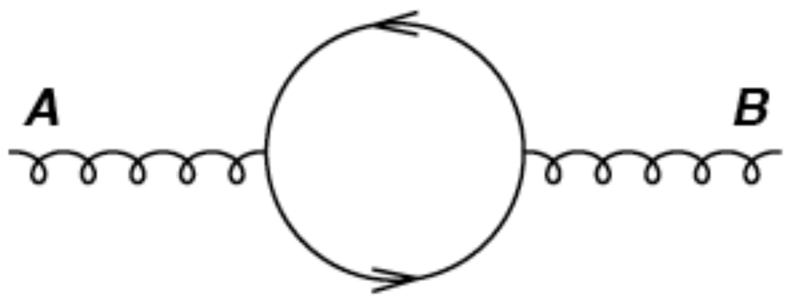
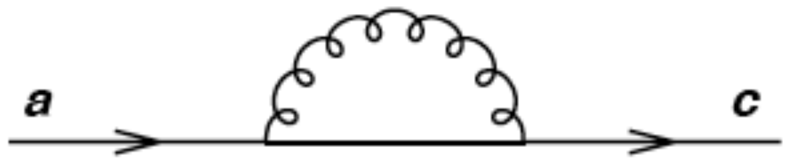


$$\sum_A t^A_{ab} t^A_{bc} = C_F \delta_{ac}\,, \quad C_F = \frac{N_c^2 - 1}{2N_c} = \frac{4}{3}$$



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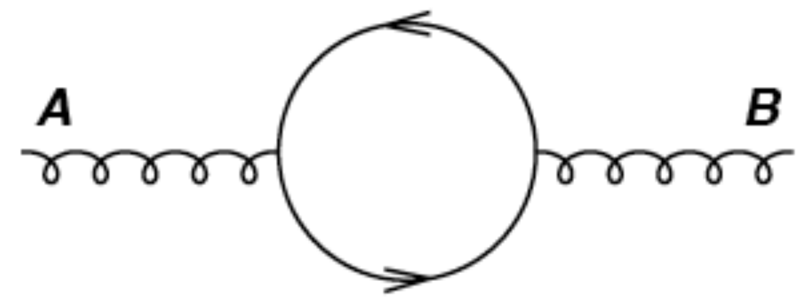

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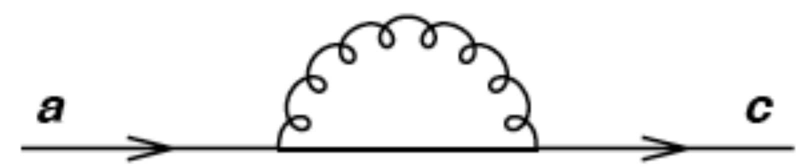
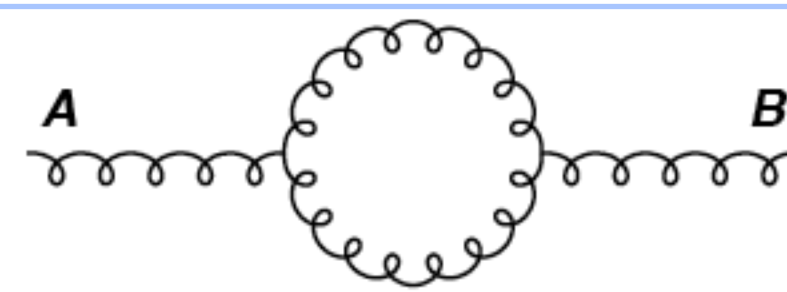
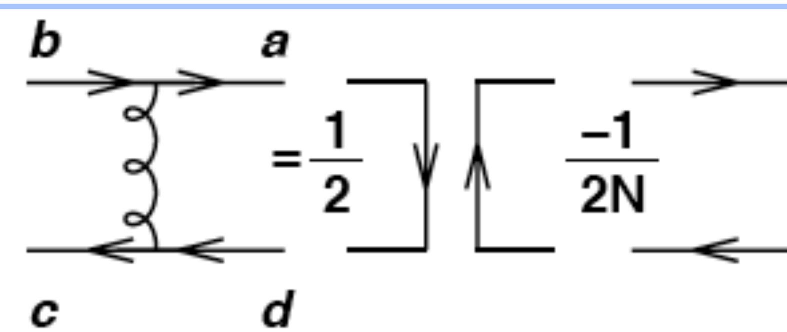


$$\sum_{C,D} f^{ACD} f^{BCD} = C_A \delta^{AB}\,, \quad C_A = N_c = 3$$



$$t^A_{ab} t^A_{cd} = \frac{1}{2}\delta_{bc}\delta_{ad} - \frac{1}{2N_c}\delta_{ab}\delta_{cd} \quad \text{(Fierz)}$$



(from lectures by G. Salam)

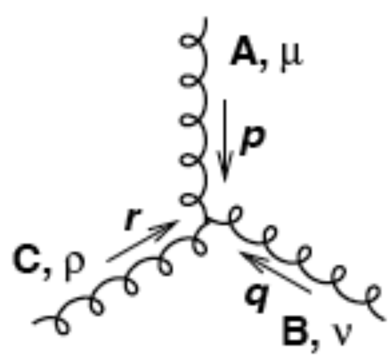
The Gluon

Gluon-Gluon Interactions

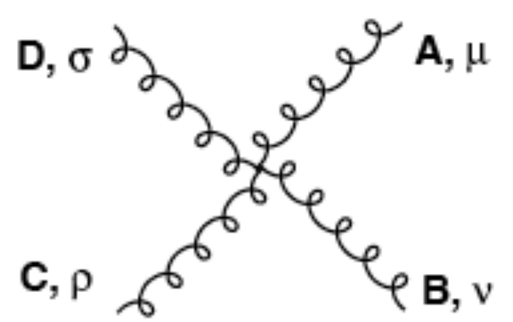
$$\mathcal{L} = \bar{\psi}^i_q (i\gamma^\mu)(D_\mu)_{ij}\psi^j_q - m_q \bar{\psi}^i_q \psi_{qi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$

Gluon field strength tensor:

$$F^a_{\mu\nu} \;=\; \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s f^{abc} A^b_\mu A^c_\nu$$



$$-g_s f^{ABC}[(p-q)^\rho g^{\mu\nu} + (q-r)^\mu g^{\nu\rho} + (r-p)^\nu g^{\rho\mu}]$$



$$-ig_s^2 f^{XAC} f^{XBD}[g^{\mu\nu} g^{\rho\sigma} - g^{\mu\sigma} g^{\nu\gamma}] + (C,\gamma) \leftrightarrow (D,\rho) + (B,\nu) \leftrightarrow (C,\gamma)$$

Structure constants of SU(3):

$$f_{123} = 1$$

$$f_{147} = f_{246} = f_{257} = f_{345} = \frac{1}{2}$$

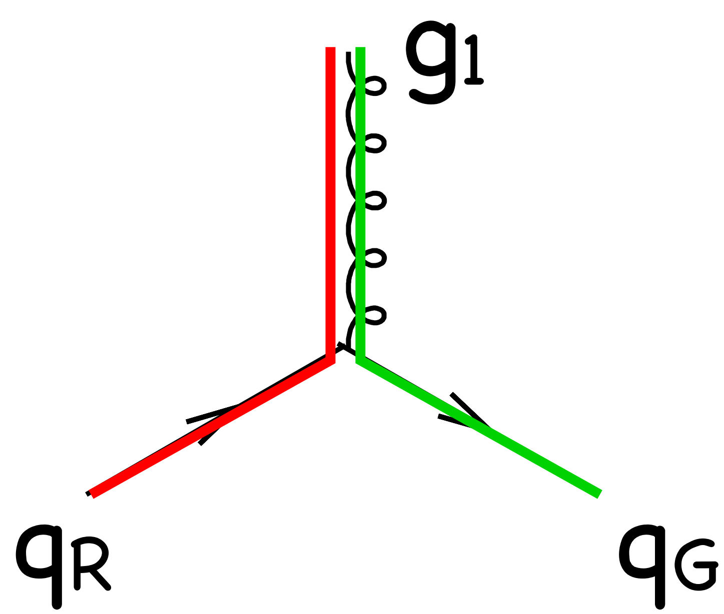
$$f_{156} = f_{367} = -\frac{1}{2}$$

$$f_{458} = f_{678} = \frac{\sqrt{3}}{2}$$

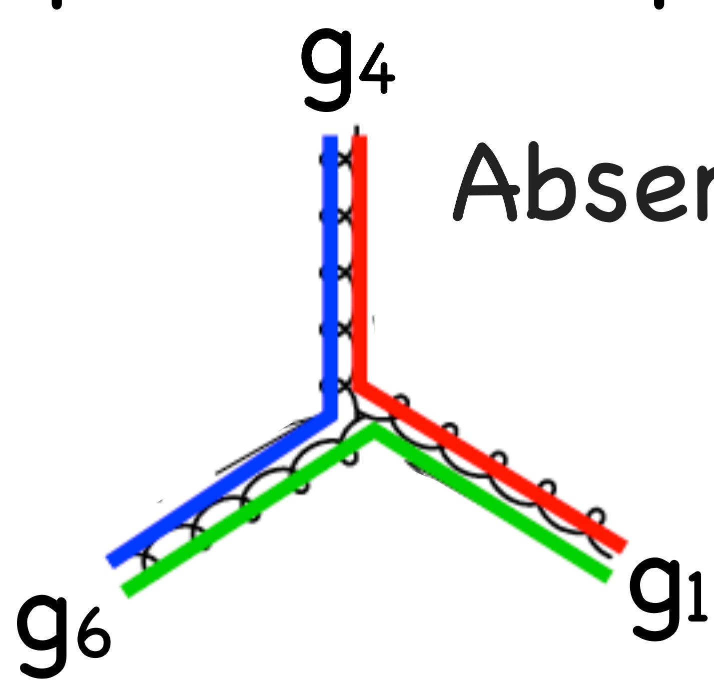
Antisymmetric in all indices

All other $f_{ijk} = 0$

Gluon self-interaction



$$\underbrace{\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}}_{g_1}\underbrace{\begin{pmatrix}1\\0\\0\end{pmatrix}}_{q_R}=\underbrace{\begin{pmatrix}0\\1\\0\end{pmatrix}}_{q_G}$$



Absent in QED

Twice as large as quark

The Strong Coupling

<u>Bjorken scaling</u>

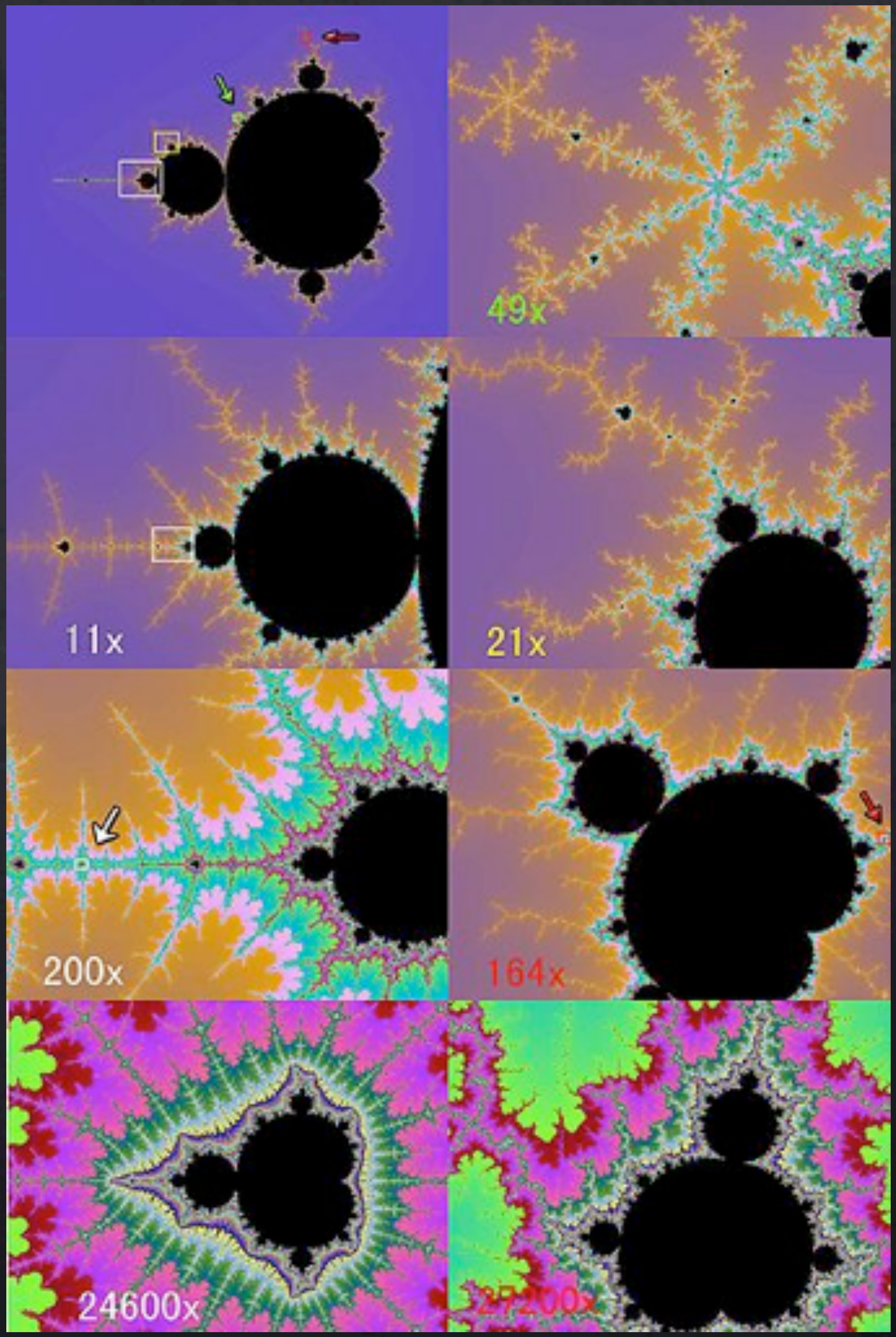
To first approximation, QCD is SCALE INVARIANT

(a.k.a. conformal)

A jet inside a jet inside a jet inside a jet ...

If the strong coupling did not run, this would be absolutely true

(e.g., N=4 SYM)

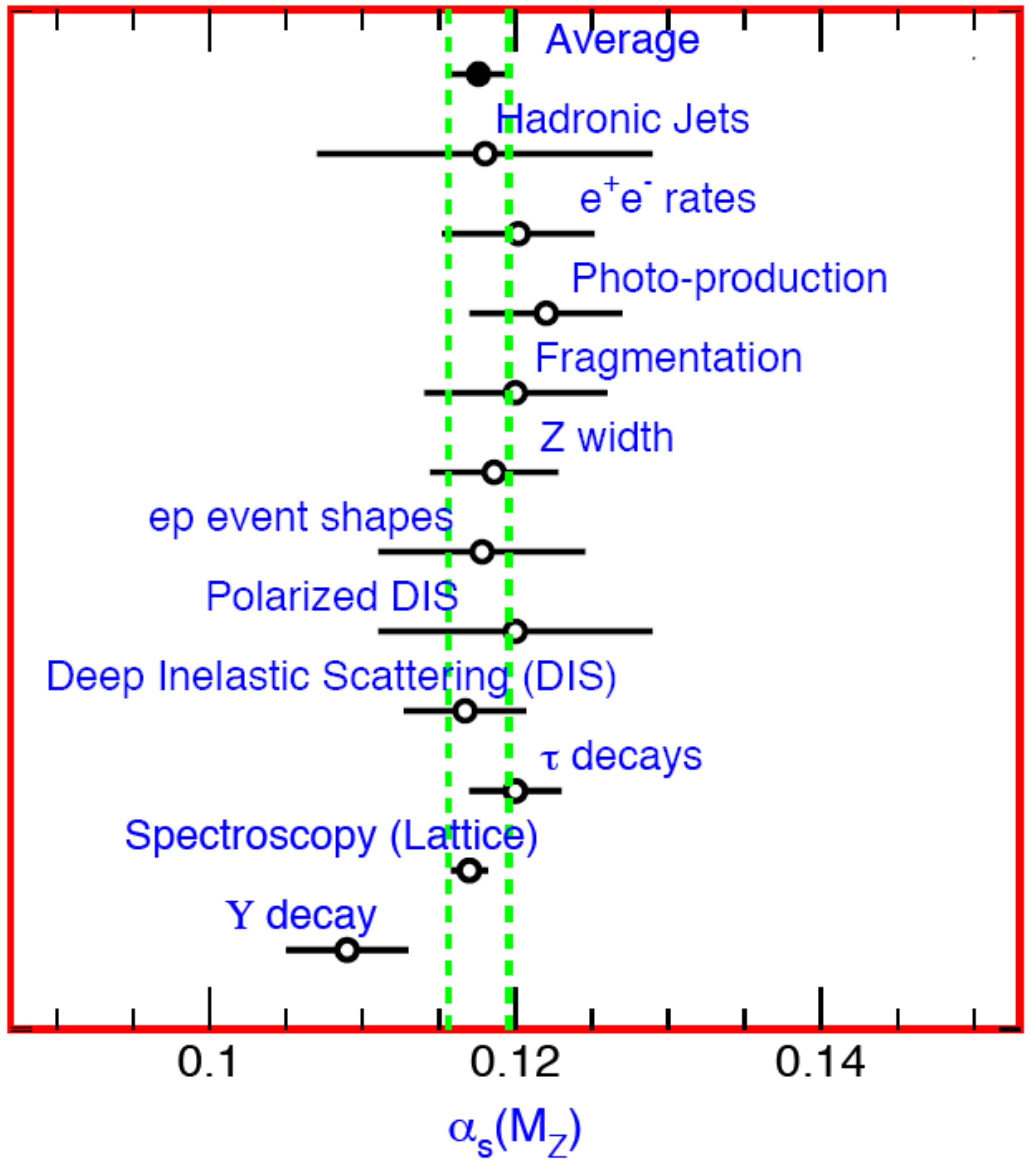


Conformal QCD

No running

$$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = \beta(\alpha_s)\,, \qquad \beta(\alpha_s) = 0$$

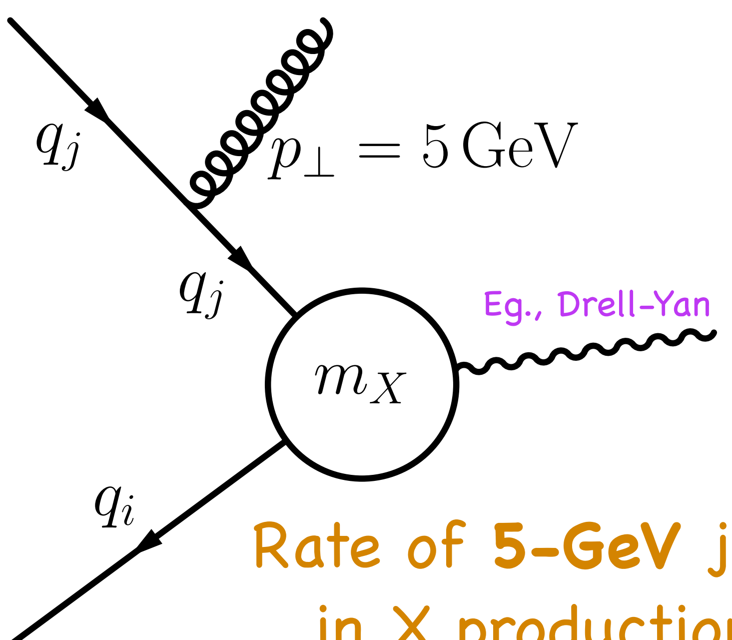
This simplification (QCD at fixed coupling) already captures some of the important properties of QCD



Conformal QCD

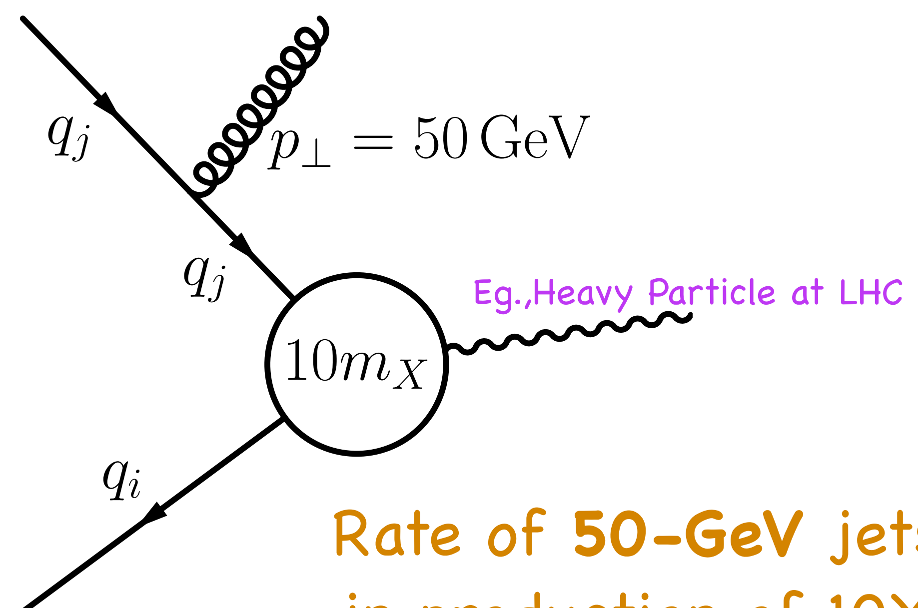
Bremsstrahlung

Rate of bremsstrahlung jets mainly depends on the **RATIO** of the jet p_T to the "hard scale"



Rate of **5-GeV** jets in X production

$\approx$



Rate of **50-GeV** jets in production of 10X

See, e.g.,

Plehn, Rainwater, PS: PLB645(2007)217
Plehn, Tait: 0810.2919 [hep-ph]
Alwall, de Visscher, Maltoni: JHEP 0902(2009)017

Scaling Violation

In real QCD

$$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = \beta(\alpha_s), \qquad \beta(\alpha_s) = -\alpha_s^2 (b_0 + b_1 \alpha_s + b_2 \alpha_s^2 + \ldots),$$

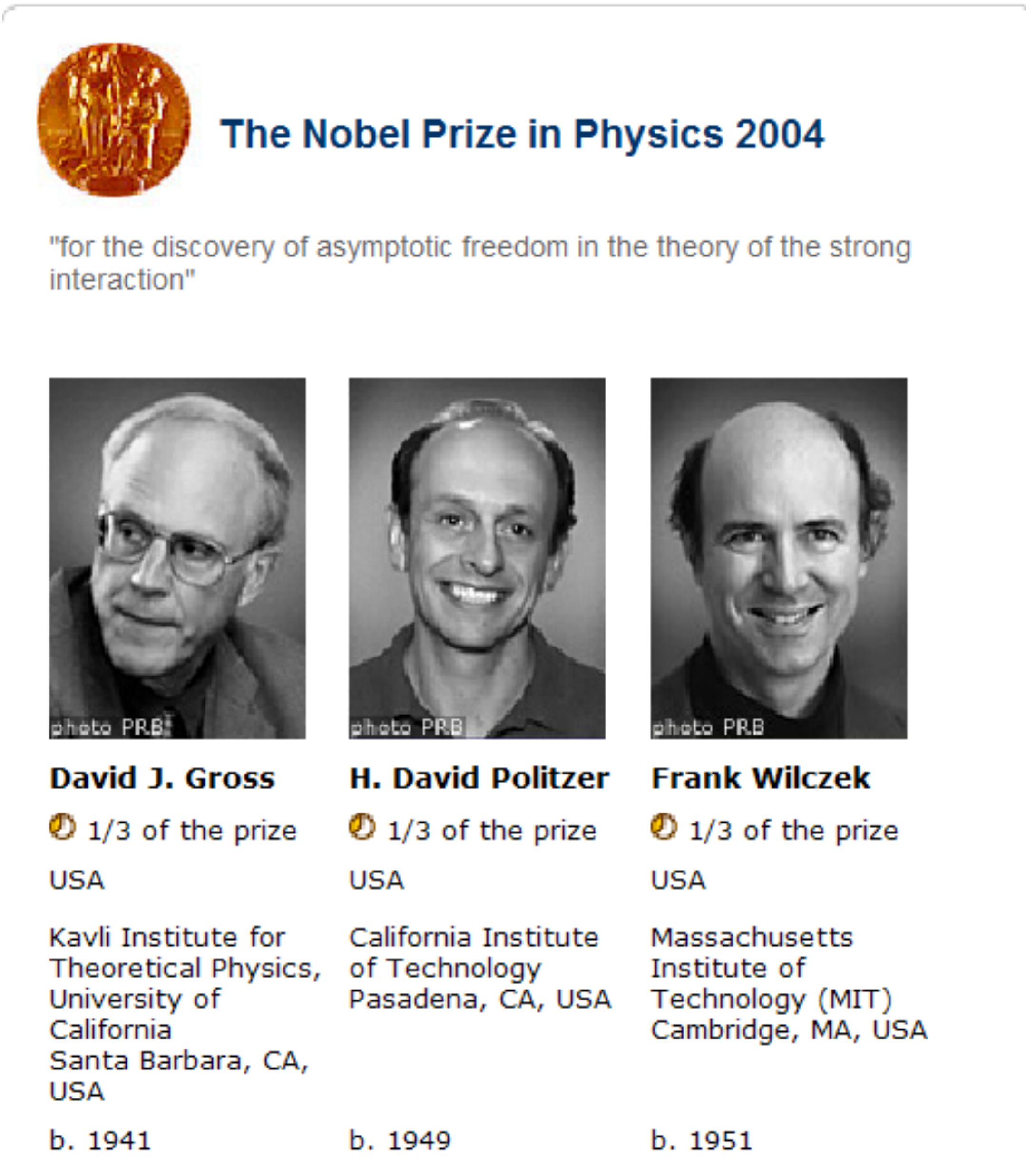
$$b_0 = \frac{11 C_A - 2 n_f}{12\pi}, \qquad b_1 = \frac{17 C_A^2 - 5 C_A n_f - 3 C_F n_f}{24\pi^2} = \frac{153 - 19 n_f}{24\pi^2}$$

The coupling runs logarithmically with the energy

Asymptotic freedom in the ultraviolet

Infrared slavery (confinement) in the IR

Asymptotic Freedom

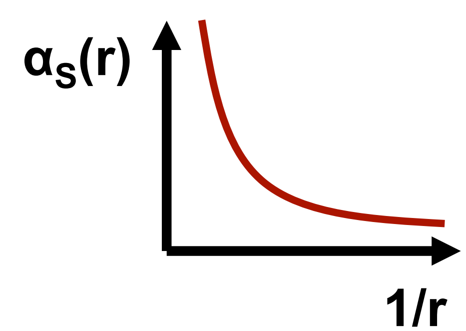


The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

David J. Gross	H. David Politzer	Frank Wilczek
1/3 of the prize	1/3 of the prize	1/3 of the prize
USA	USA	USA
Kavli Institute for Theoretical Physics, University of California Santa Barbara, CA, USA	California Institute of Technology Pasadena, CA, USA	Massachusetts Institute of Technology (MIT) Cambridge, MA, USA
b. 1941	b. 1949	b. 1951

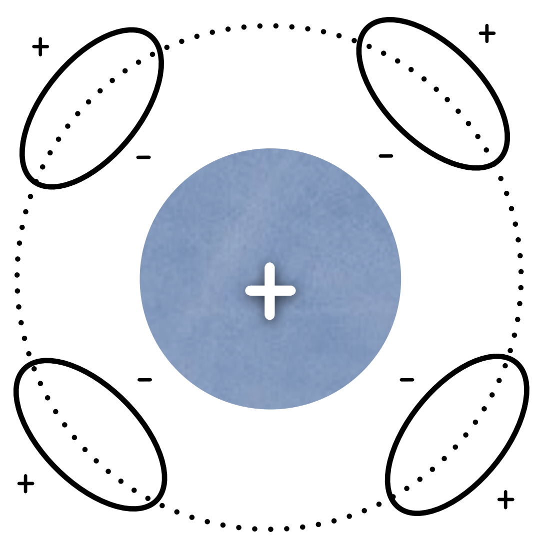
"What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the *weaker* is the 'colour charge'. When the quarks are really close to each other, the force is so weak that they behave almost as free particles. This phenomenon is called 'asymptotic freedom'. The converse is true when the quarks move apart: the force becomes stronger when the distance increases."



Asymptotic Freedom

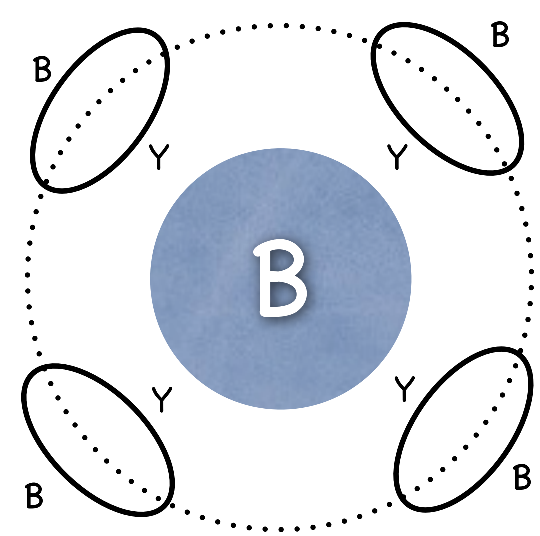
QED:

charge screening



QCD:

also has charge screening



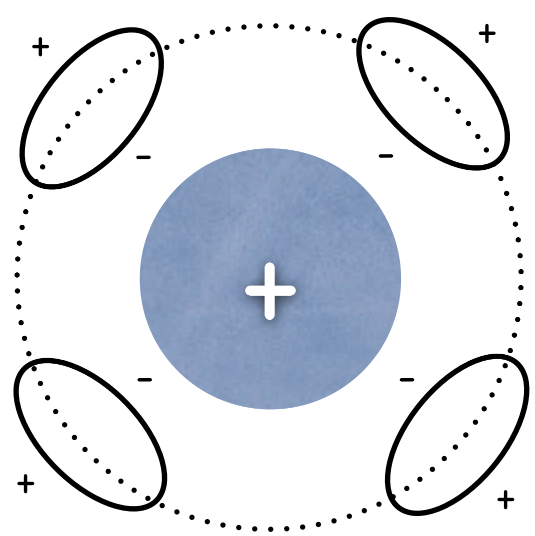
Quark loops

But only dominant if > 16 flavors!

Asymptotic Freedom

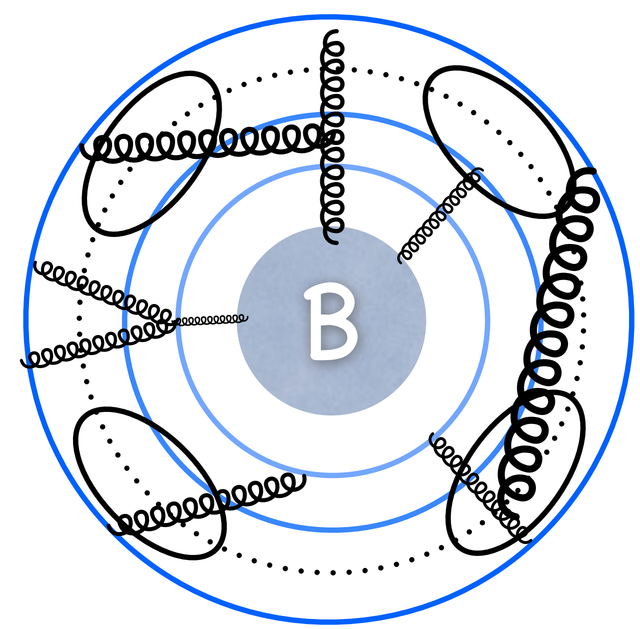
QED:

charge screening



QCD:

color “leaking”



Gluons carry color

Dominant if < 16 flavors!

Asymptotic Freedom

At High Energies

QCD is weak → quarks and gluons almost free

Smaller coupling

→ Perturbation theory better behaved

Lecture 2: QCD in the ultraviolet

→ Changes in jet shapes

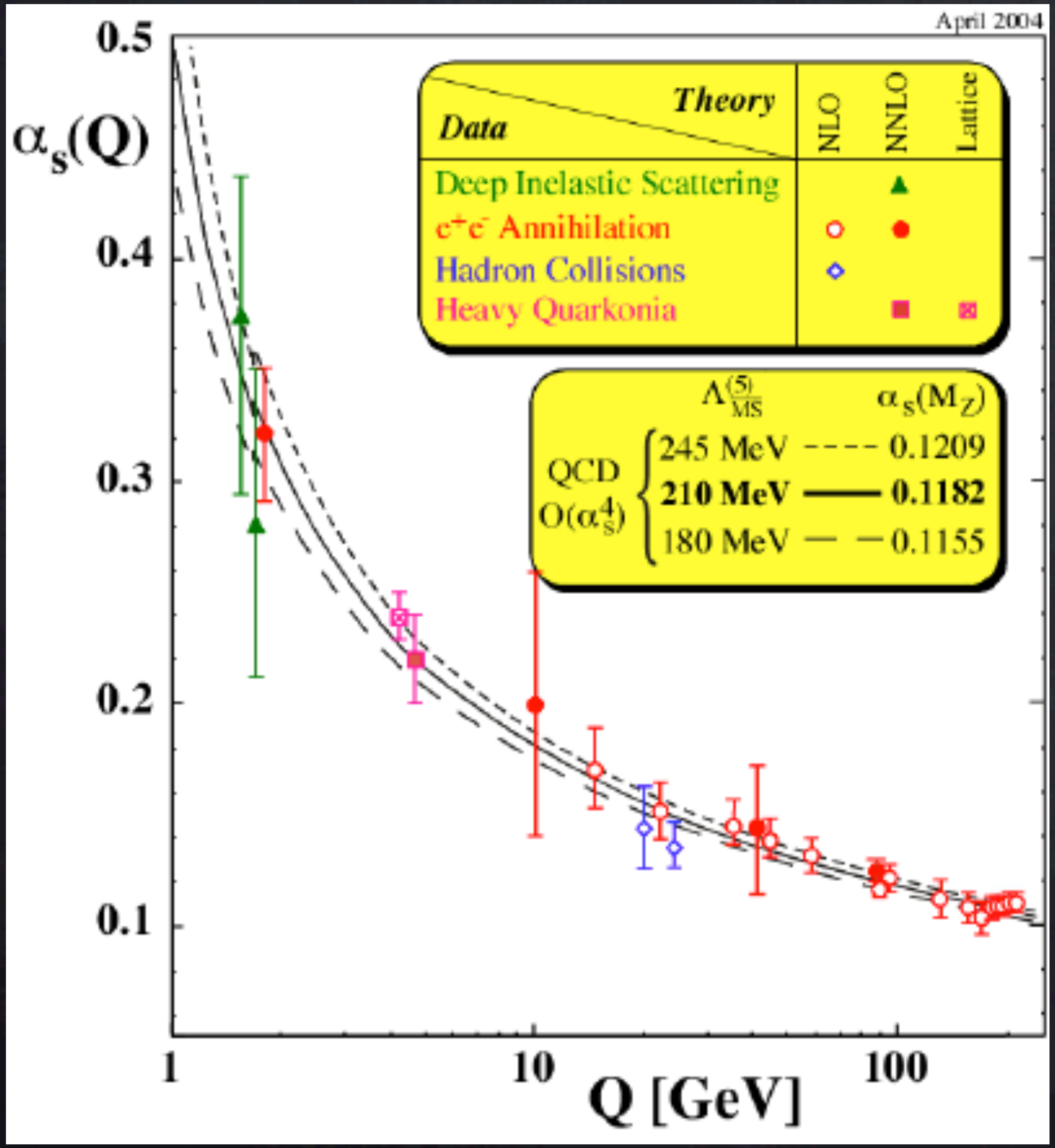
High-$p_\perp$ jets narrower than low-$p_\perp$ ones

Important for jet calibration (e.g., smaller "out-of-cone" corrs)

(Freedom or Unification?)

Decreasing coupling approaches EW ones …

UV and IR



At current scales

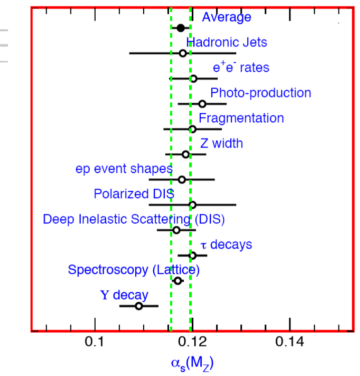
Coupling actually runs rather fast

Explodes at a scale somewhere below

≈ 1 GeV

So we usually give its value at a unique reference scale that everyone agrees on

The Fundamental Parameter(s)



QCD has one fundamental parameter

$\alpha_s(m_Z)^{\overline{\text{MS}}}$

$$\alpha_s(Q^2) = \alpha_s(m_Z^2)\frac{1}{1 + b_0\ \alpha_s(m_Z)\ln\frac{Q^2}{m_Z^2} + \mathcal{O}(\alpha_s^2)}$$

$$b_0 = \frac{11N_C - 2n_f}{12\pi}$$

… and its sibling

$\Lambda_{\text{QCD}}^{(n_f)\overline{\text{MS}}}$

$$\alpha_s(Q^2) = \frac{1}{b_0\ \ln\frac{Q^2}{\Lambda^2}}$$

$\Lambda \sim 200\,\text{MeV}$

… And all their cousins

$\alpha_s(m_Z)_{\text{LO}}$ $\alpha_s(m_Z)_{\text{N}^n\text{LO}}$ $\alpha_s(m_Z)_{\text{N}^n\text{LO+N}^n\text{LL}}$ $\alpha_s(m_Z)^{\text{DIS}}$ $\alpha_s(m_Z)^{\text{DR}}$, …

$\Lambda^{(3)}$ $\Lambda^{(4)}$ $\Lambda^{(5)}$ Λ_{CMW} Λ_{FSR} Λ_{ISR} Λ_{MPI}, …

Other parameters

<u>The number of flavors</u>

(and quark masses)

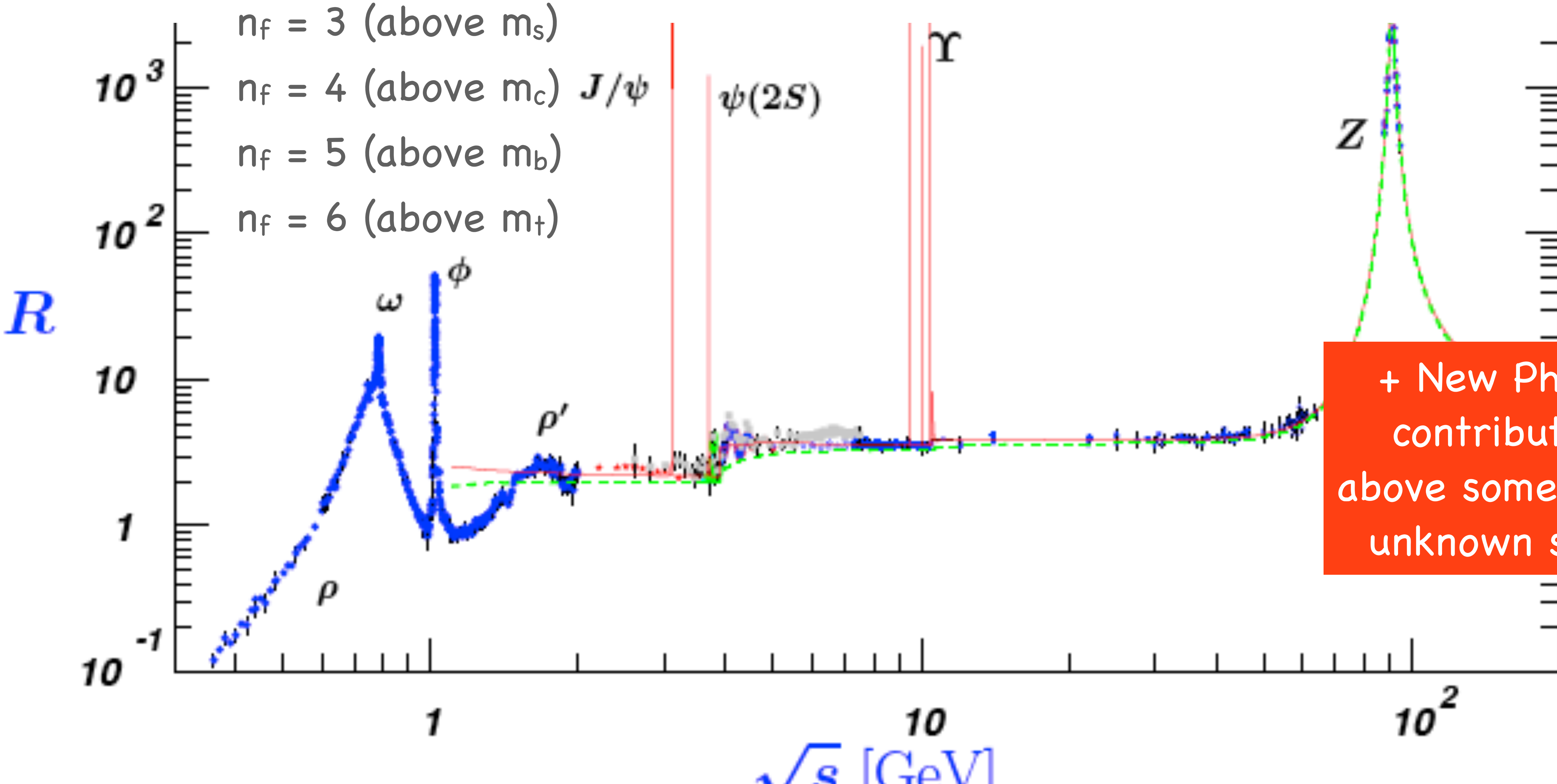
$$b_0 = \frac{11N_C - 2n_f}{12\pi}$$

n_f = 3 (above m_s)

n_f = 4 (above m_c)

n_f = 5 (above m_b)

n_f = 6 (above m_t)



+ New Physics contributions above some as yet unknown scale?

Other parameters

> The emergent is unlike its components insofar as … it cannot be reduced to their sum or their difference."
>
> *G. Lewes (1875)*

Emergent phenomena

Cannot guess non-perturbative phenomena from perturbative QCD → "Emerge" due to confinement

Hadron masses,

Decay constants,

Fragmentation functions

Parton distribution functions,...

Difficult/Impossible to compute given only knowledge of perturbative QCD

→ Lattice QCD (only for "small" systems)

→ Experimental fits (for reference)

→ Phenomenological models (for everything else)

Image Credits: Yeimaya

The Way of the Chicken

- Who needs QCD? I'll use leptons
  - Sum inclusively over all QCD
    - Leptons almost IR safe by definition
    - WIMP-type DM, Z', EWSB → may get some leptons

The Way of the Chicken

- **Who needs QCD? I'll use leptons**
  - Sum inclusively over all QCD
    - Leptons almost IR safe by definition
    - WIMP-type DM, Z', EWSB → may get some leptons
  - Beams = hadrons for next decade (RHIC / Tevatron / LHC)
    - At least need well-understood PDFs
    - High precision = higher orders → enter QCD (and more QED)
  - Isolation → indirect sensitivity to QCD
  - Fakes → indirect sensitivity to QCD
  - Not everything gives leptons
    - Need to be a lucky chicken …
- **The unlucky chicken** → Next Lectures
  - Put all its eggs in one basket and didn't solve QCD