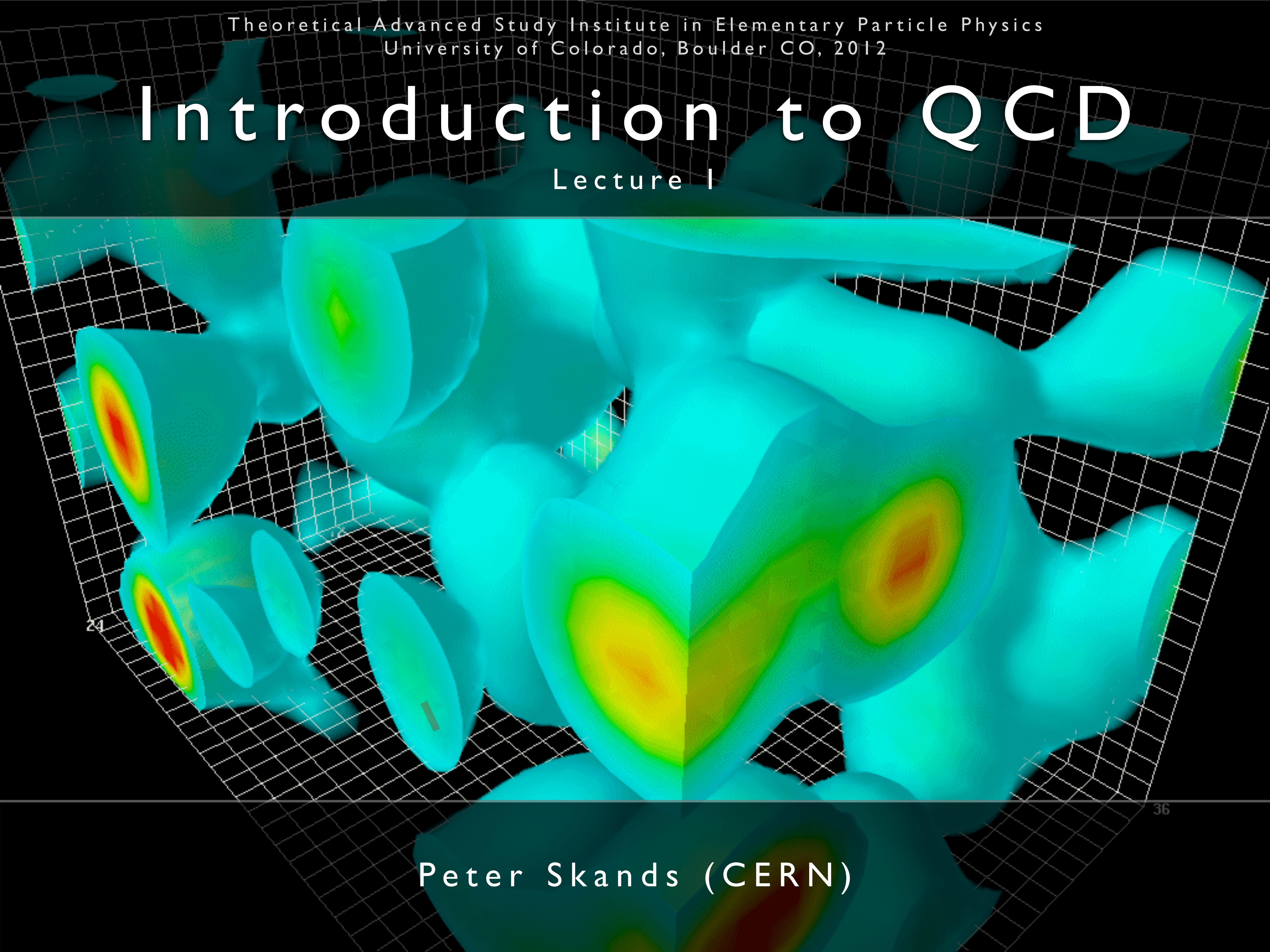
Theoretical Advanced Study Institute in Elementary Particle Physics
University of Colorado, Boulder CO, 2012

Introduction to QCD

Lecture I



Peter Skands (CERN)

Theoretical Advanced Study Institute in Elementary Particle Physics
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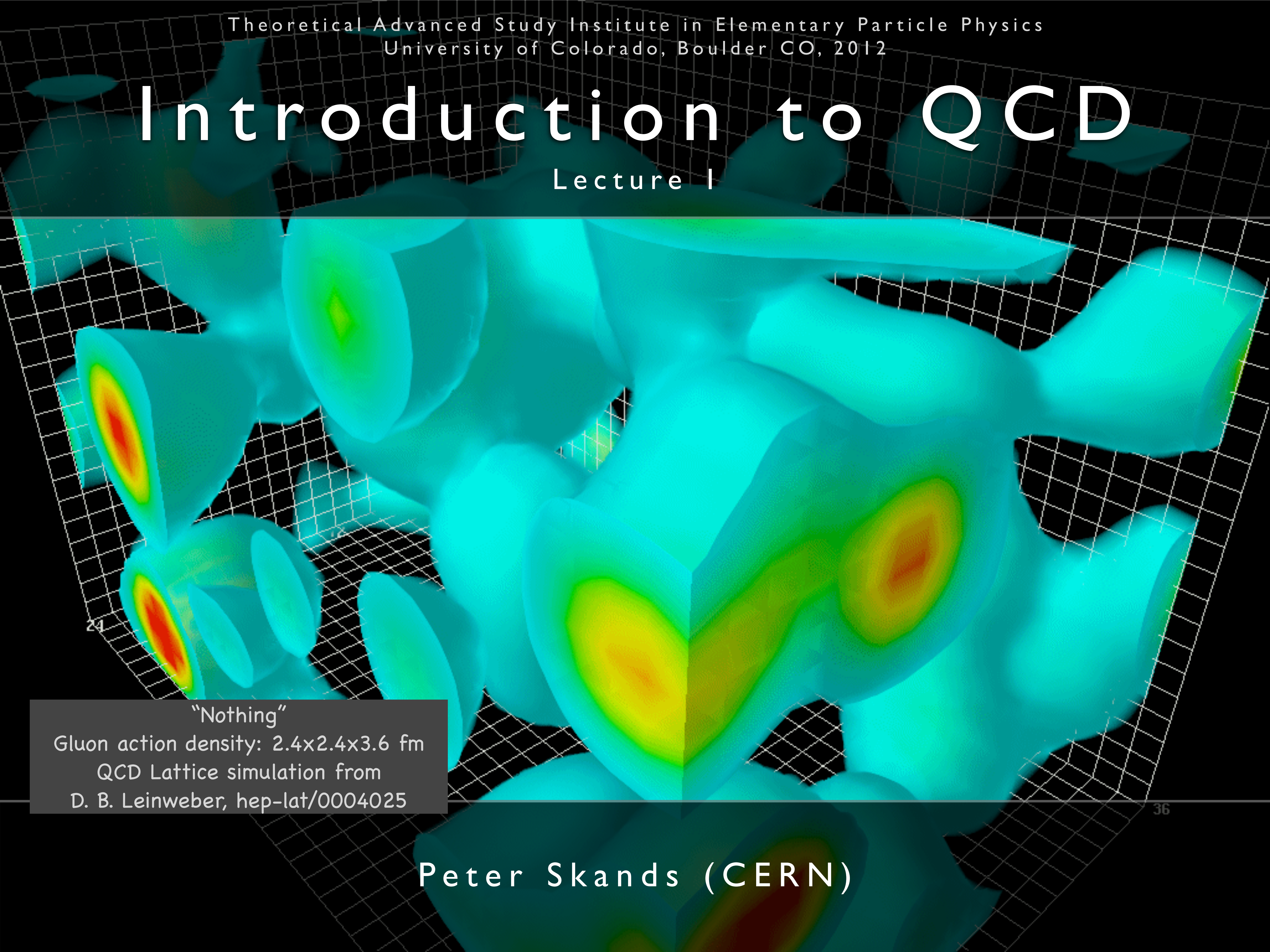

"Nothing"
Gluon action density: 2.4x2.4x3.6 fm
QCD Lattice simulation from
D. B. Leinweber, hep-lat/0004025

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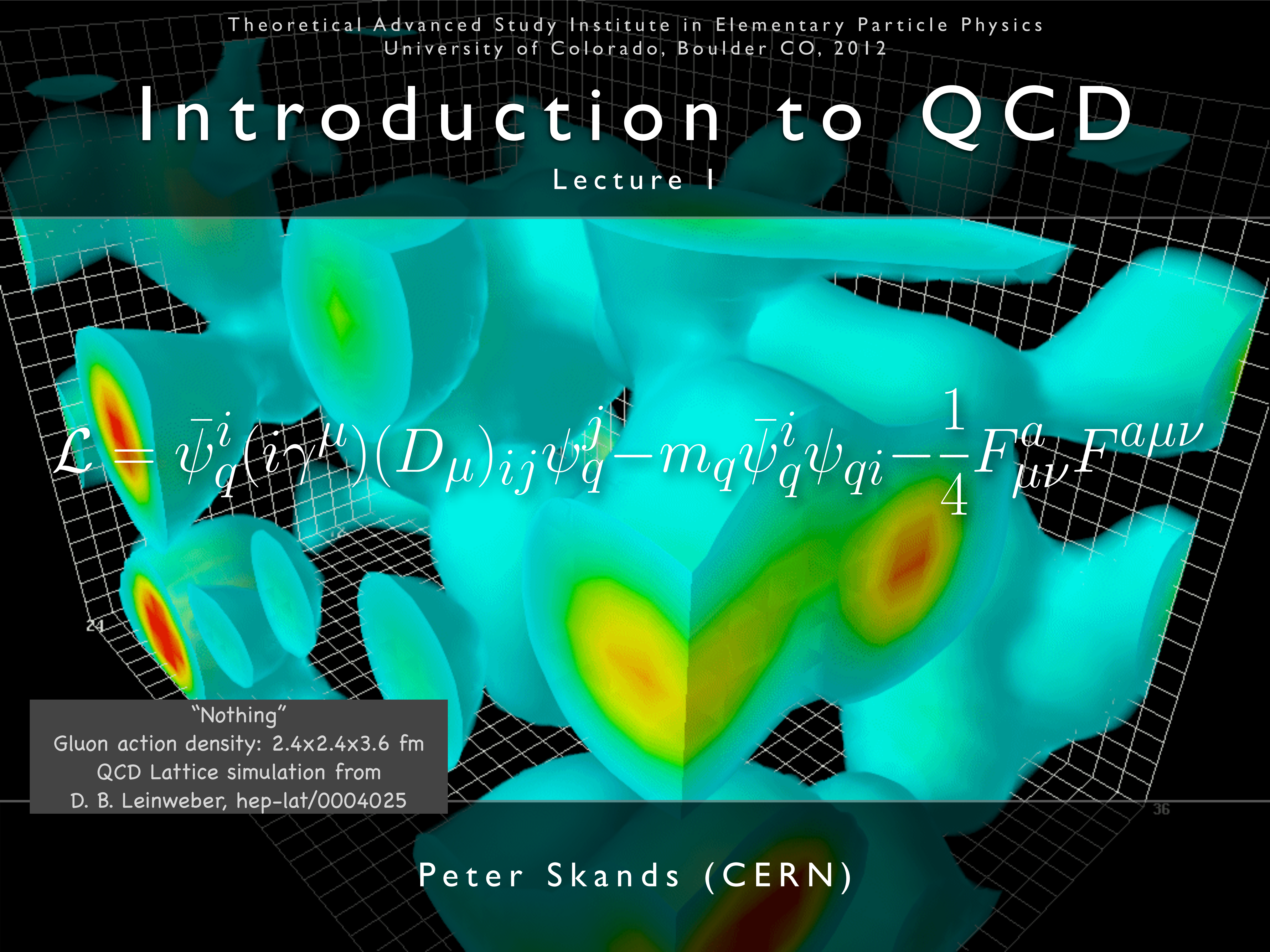

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A huge variety of phenomena

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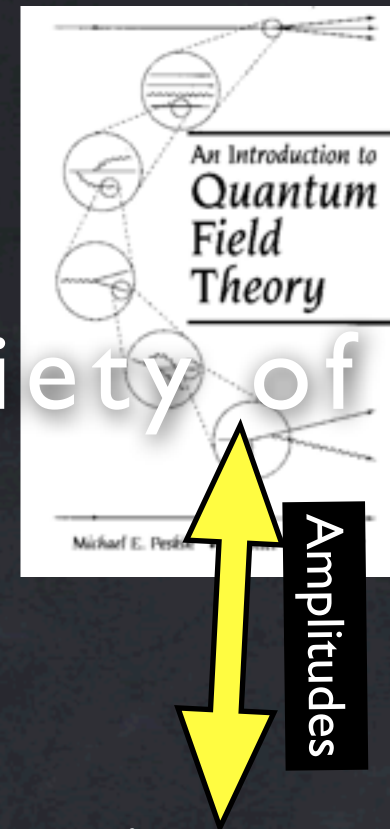
Still only partially solved ...

A huge variety of phenomena



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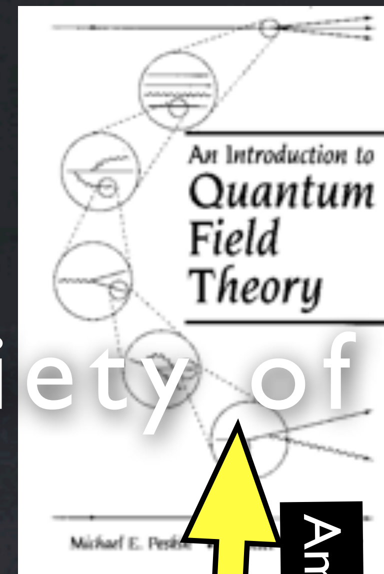
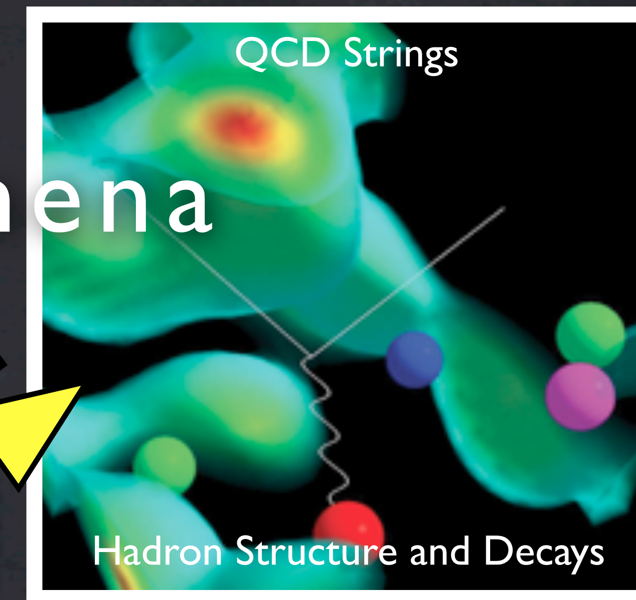


Amplitudes



Confinement

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

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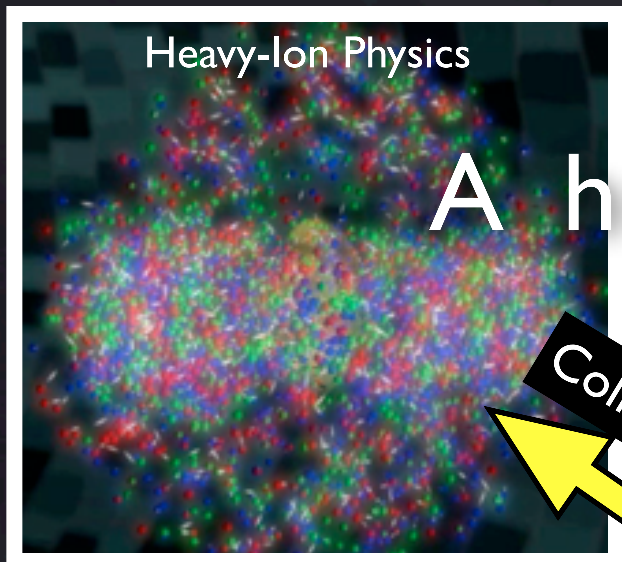

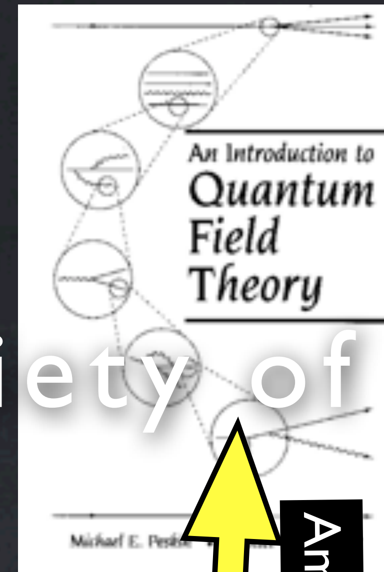

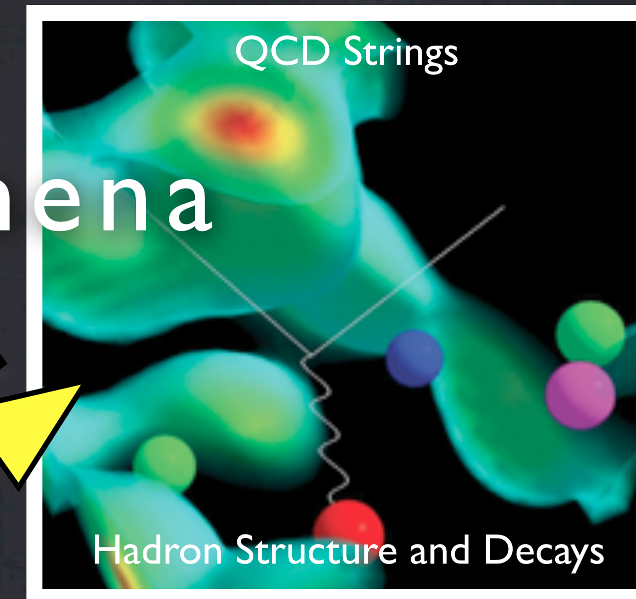

Collective Effects

Amplitudes

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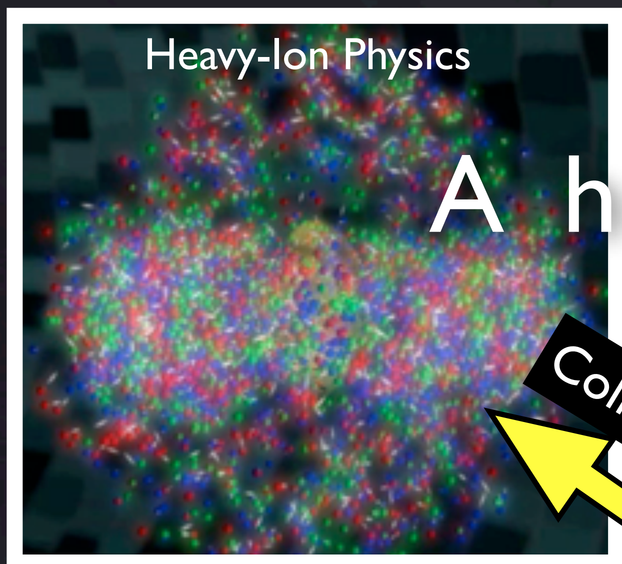

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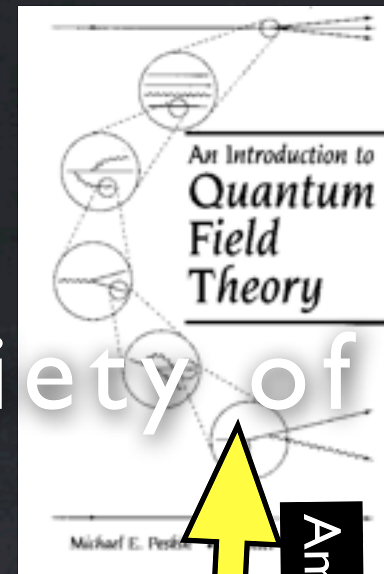

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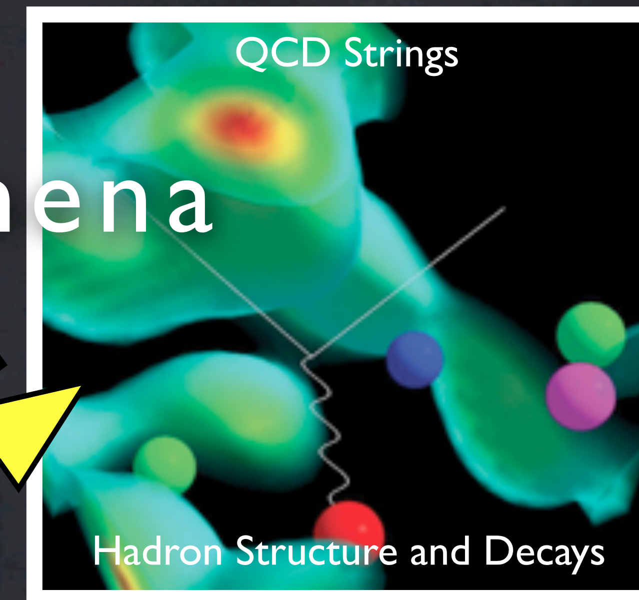

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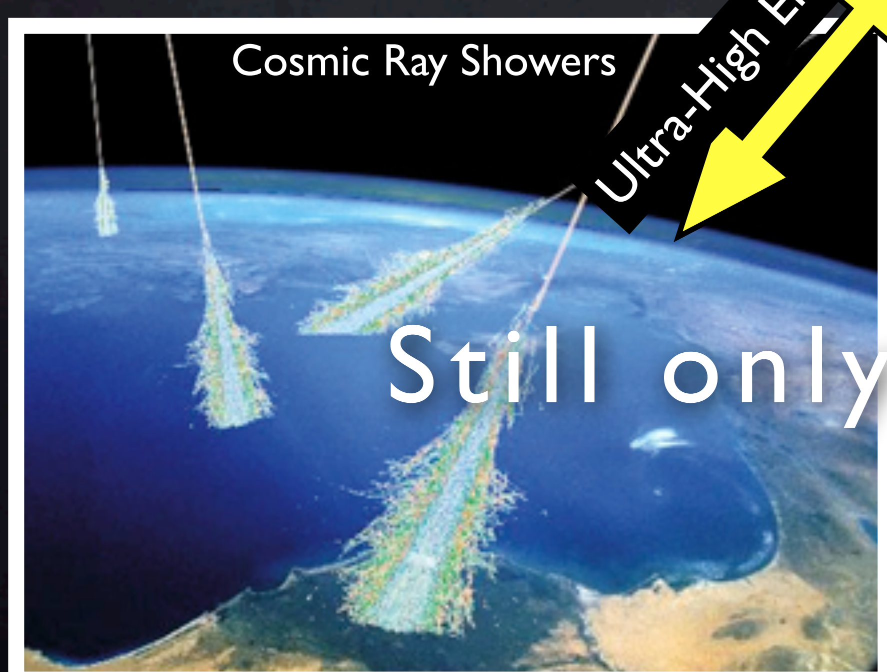
Ultra-High Energies



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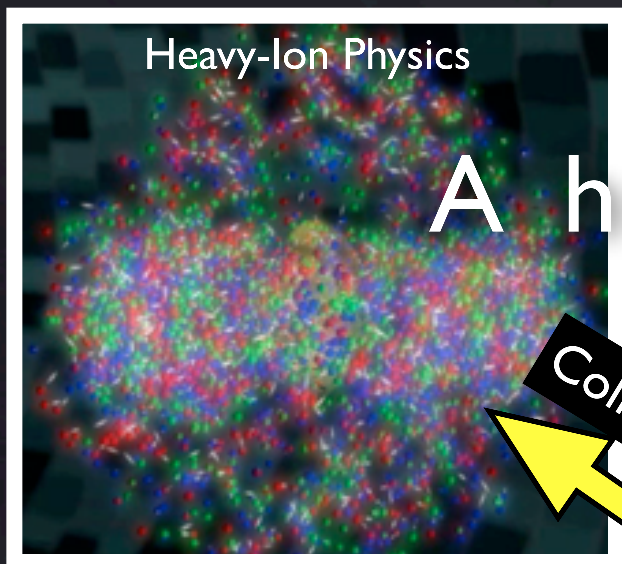

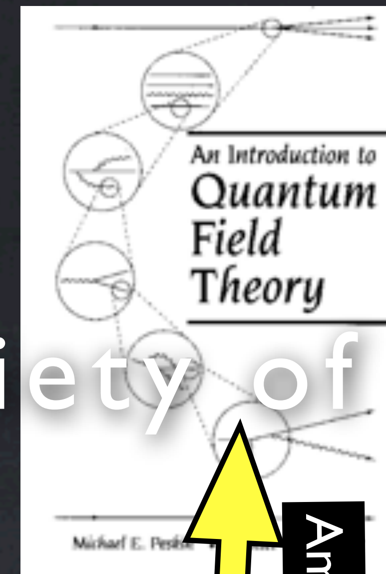

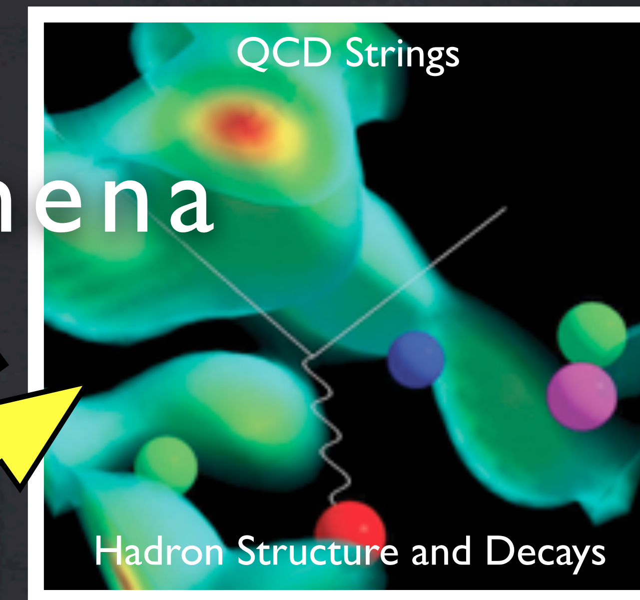

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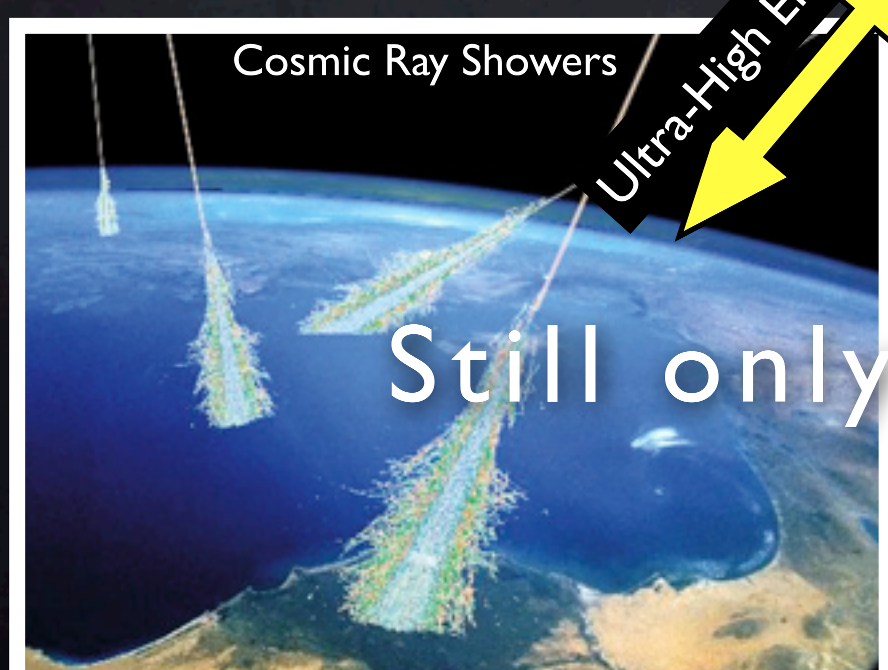
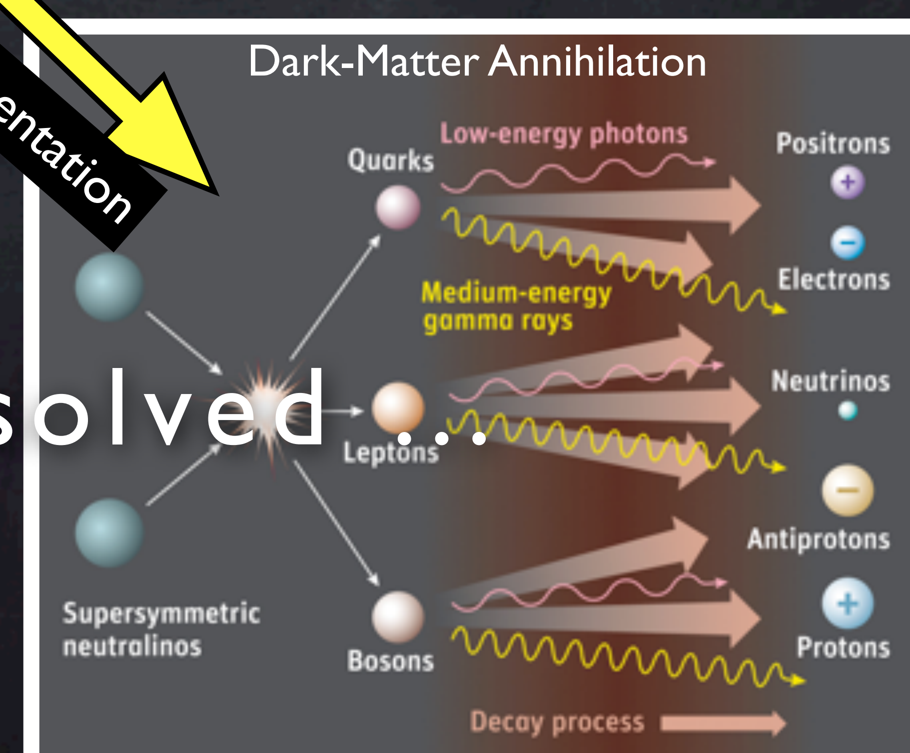
Ultra-High Energies

Fragmentation





Still only partially solved...

Disclaimer

Focus on QCD for collider physics

- Quantum Chromodynamics
- The Ultraviolet (hard processes and jets)
- The Infrared (hadronization and underlying event)
- Monte Carlo Event Generators (shower Markov chains and matching)

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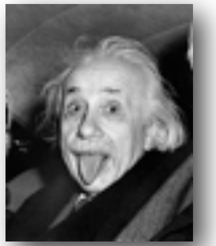
Still, some topics not touched, or only briefly

- Physics of hadrons (Lattice QCD, Heavy flavor physics, diffraction, …)
- Heavy ion physics
- New Physics
- + Many specialized topics (DIS, prompt γ, polarized beams, low-x, …)

Introduction to QCD

1. **Fundamentals of QCD**
2. **Jets and Fixed-Order QCD**
3. **Monte Carlo Generators**
4. **Matching at LO and NLO**
5. **QCD in the Infrared**

QCD as Discovery Physics



1951: the first hint of color

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)

K. A. Brueckner
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.

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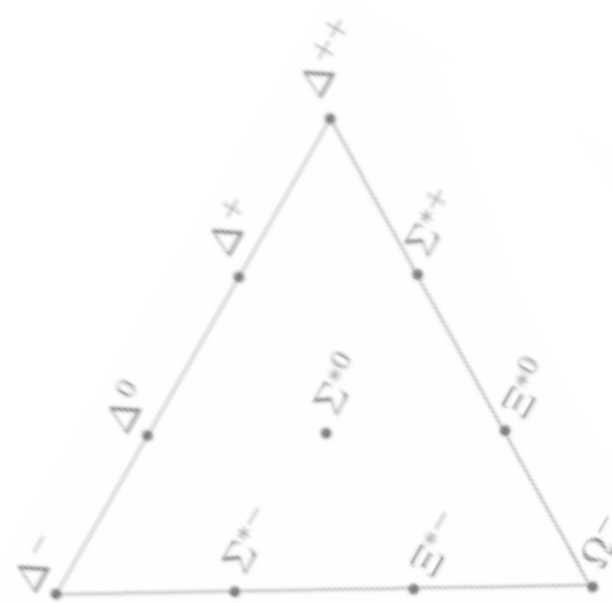
~ 1960: Eightfold Way

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

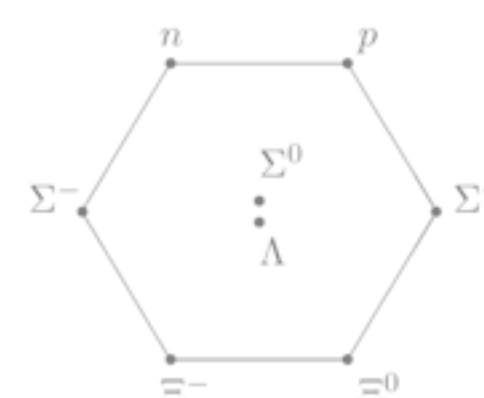
Fermion (spin-3/2).

Symmetric in space, spin & flavor

Antisymmetric in ???



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



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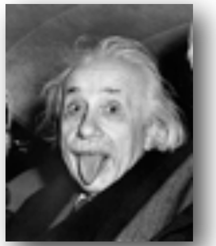

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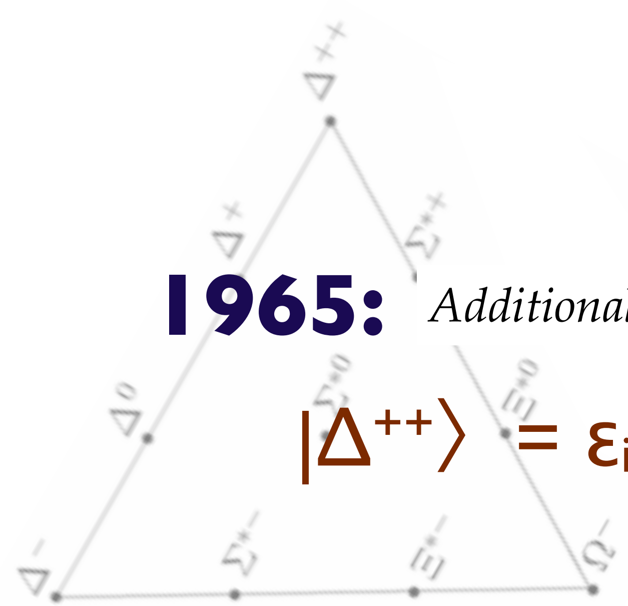

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1965: *Additional SU(3): Han, Nambu, Greenberg*

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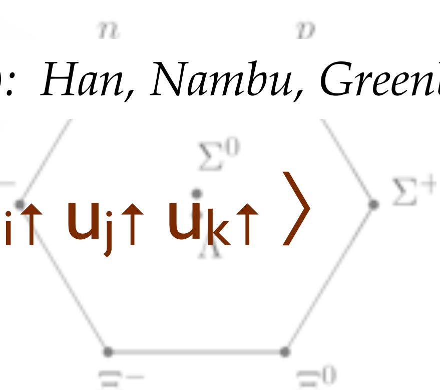

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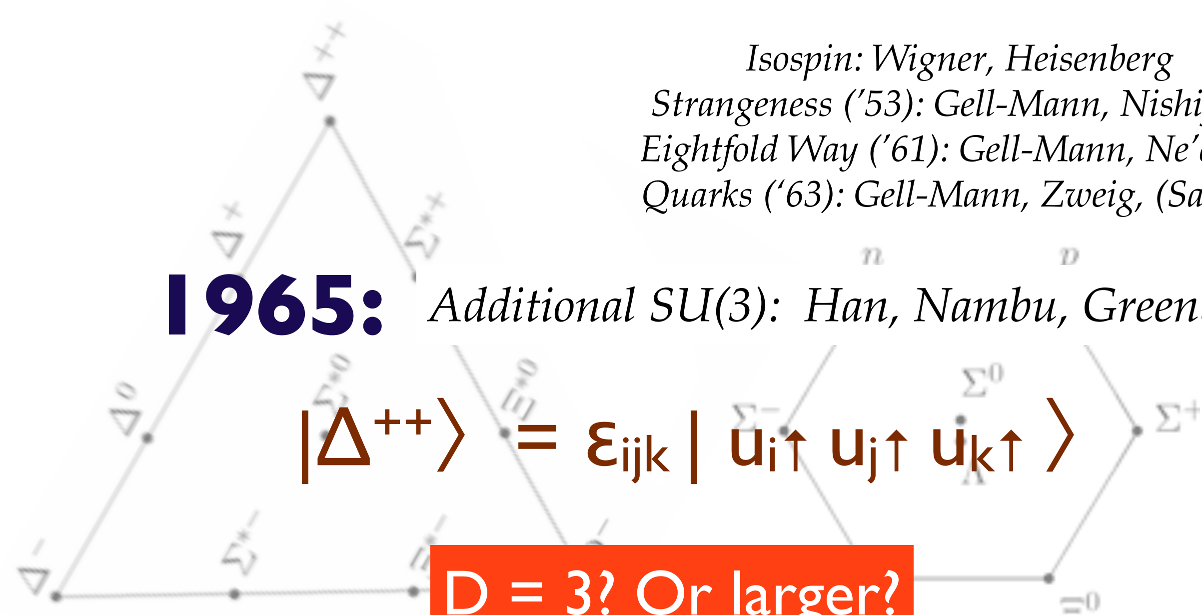

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D = 3? Or larger?

QCD
Lecture I

The Width of the π^0

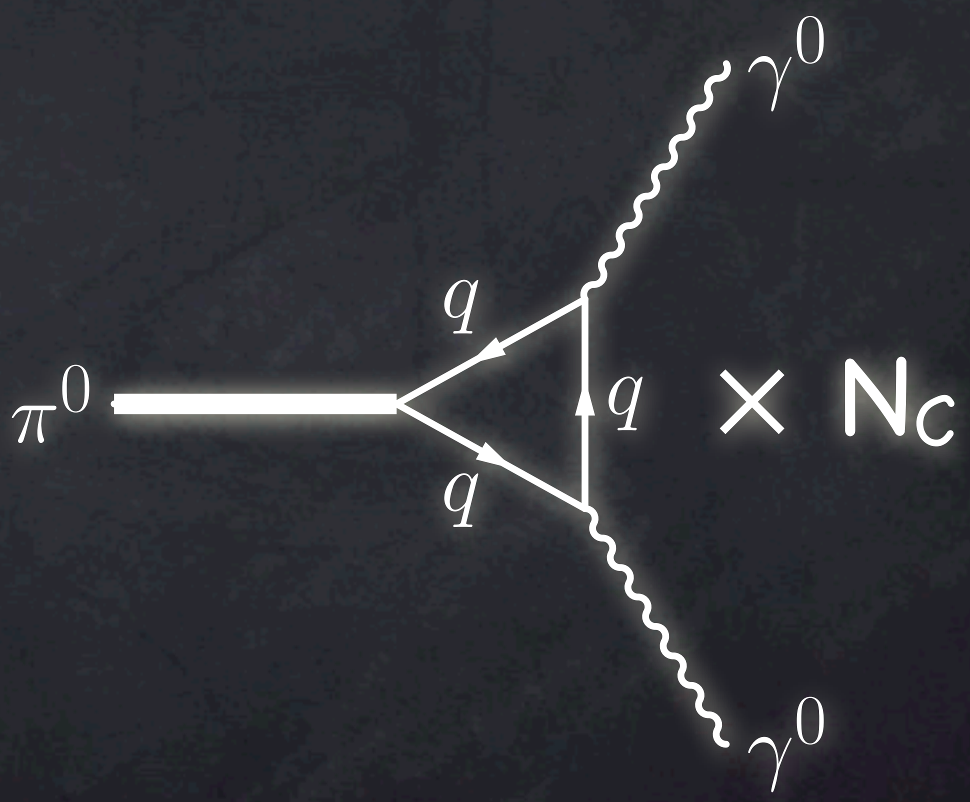
Δ^{++}, Δ^-, and Ω^-

Strictly speaking, we only know N ≥ 3

$\pi \to \gamma\gamma$ decays

Get pion decay constant f_π from

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



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

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

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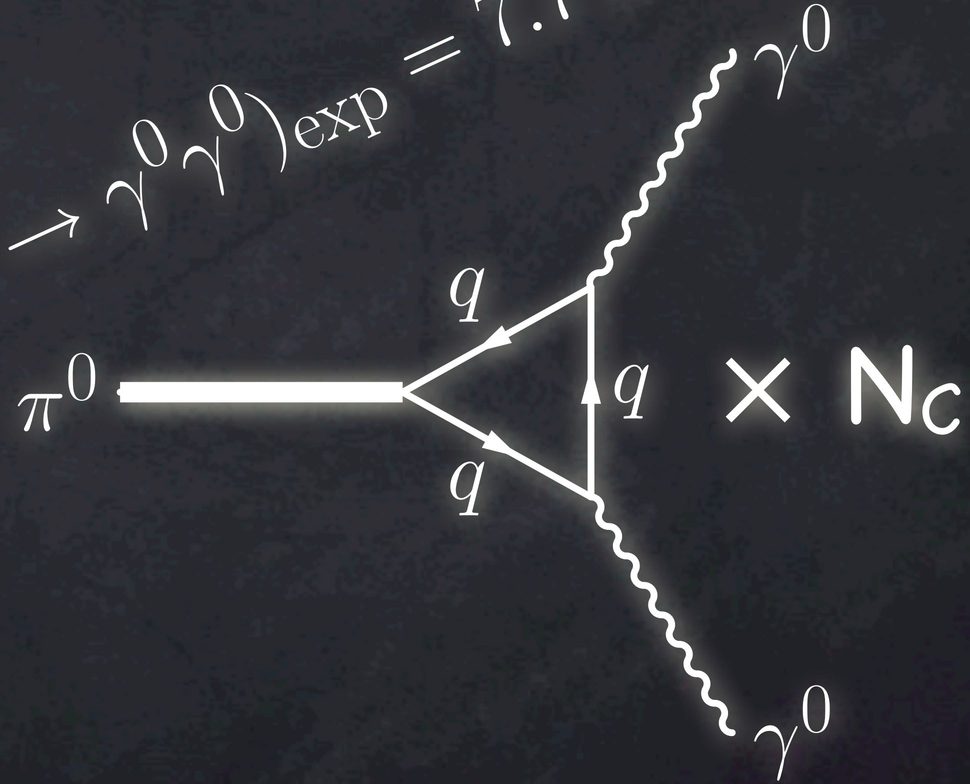
$$\Gamma(\pi^0 \to \gamma^0\gamma^0)_{\mathrm{exp}} = 7.7 \pm 0.6\mathrm{eV}$$



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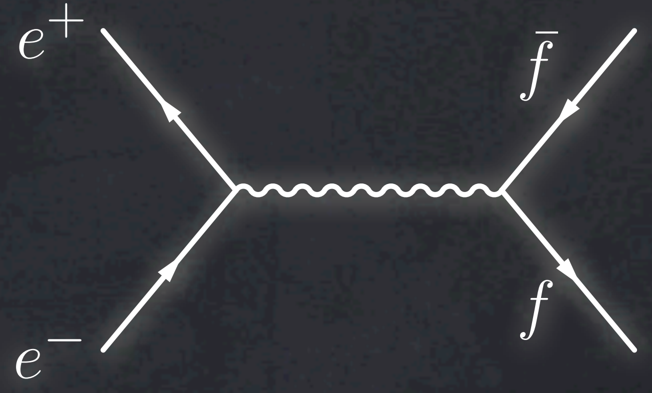
$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



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

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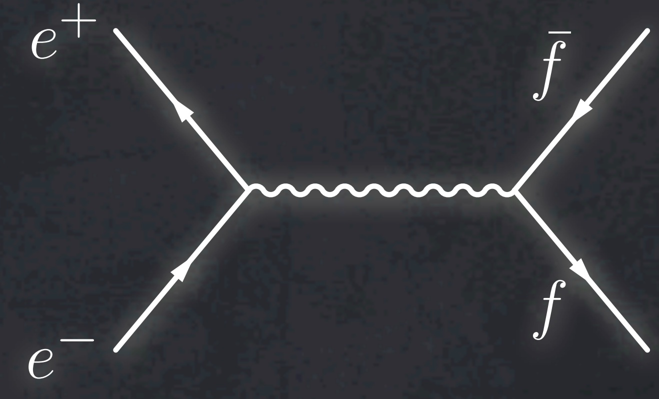

$$= n_u \left(\frac{2}{3}\right)^2 + n_d \left(-\frac{1}{3}\right)^2$$

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

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

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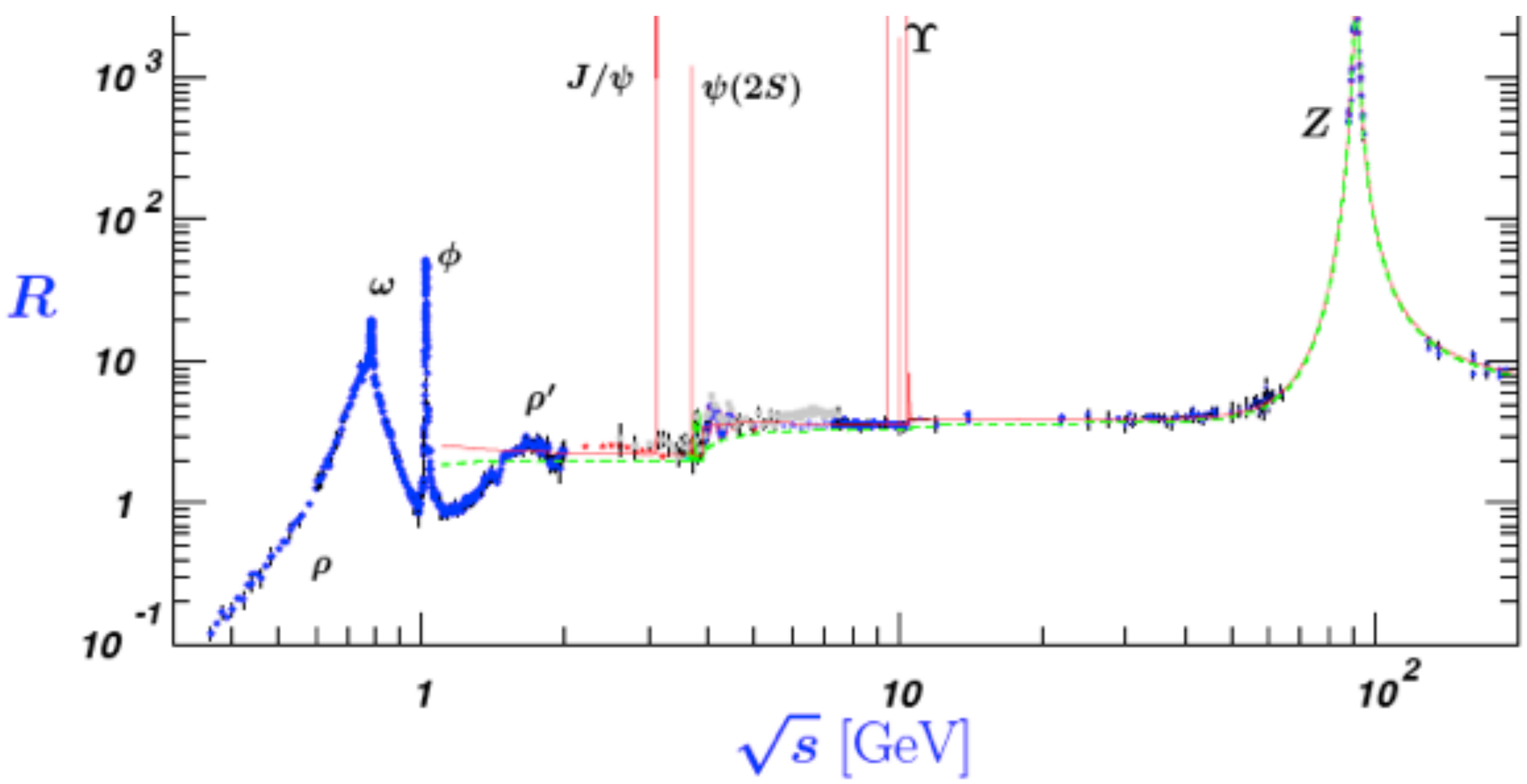

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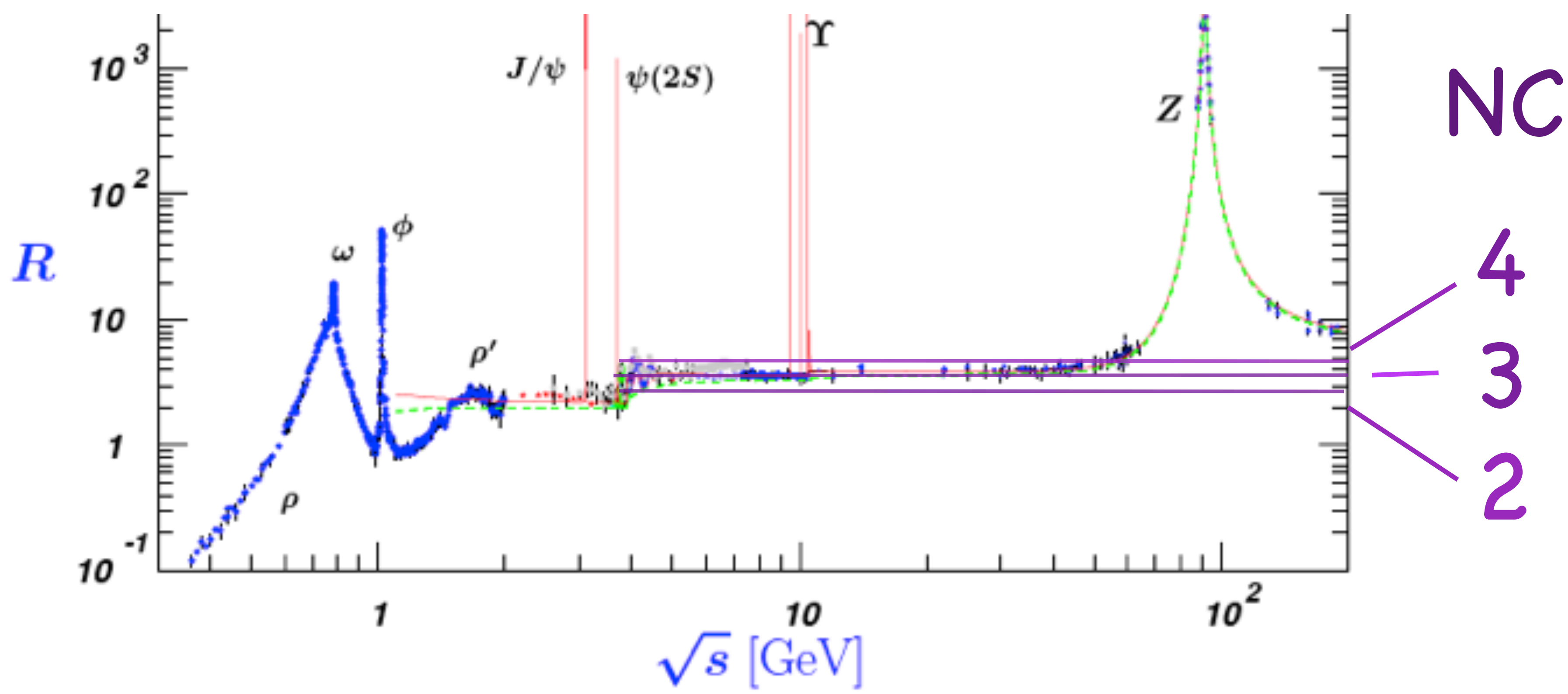
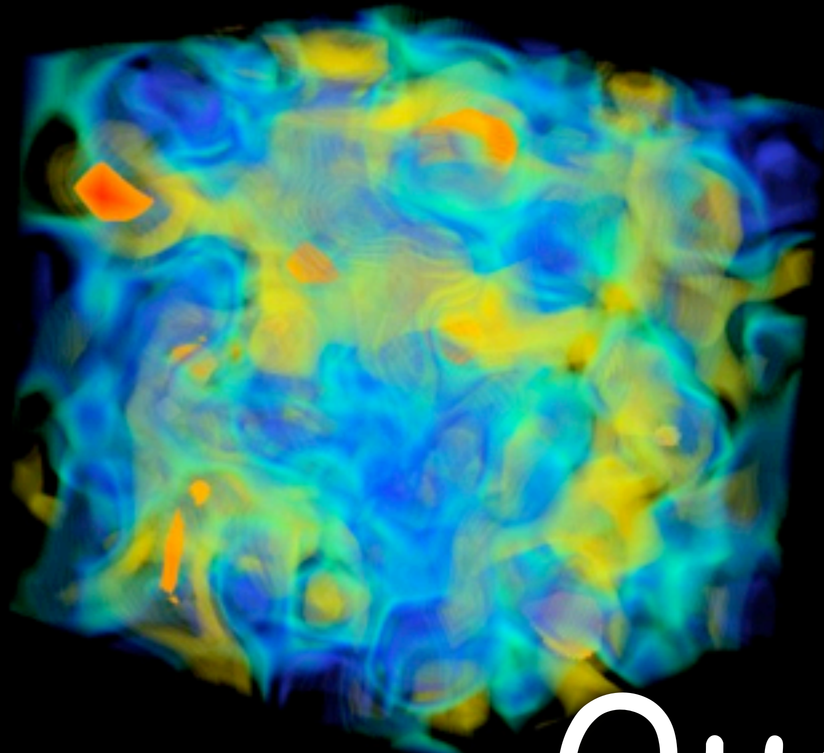
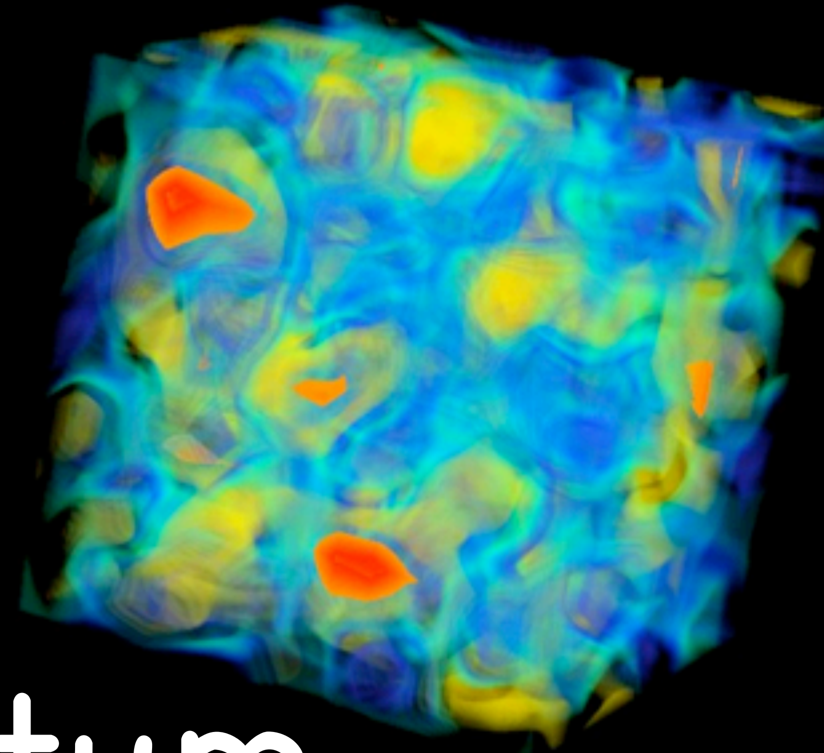
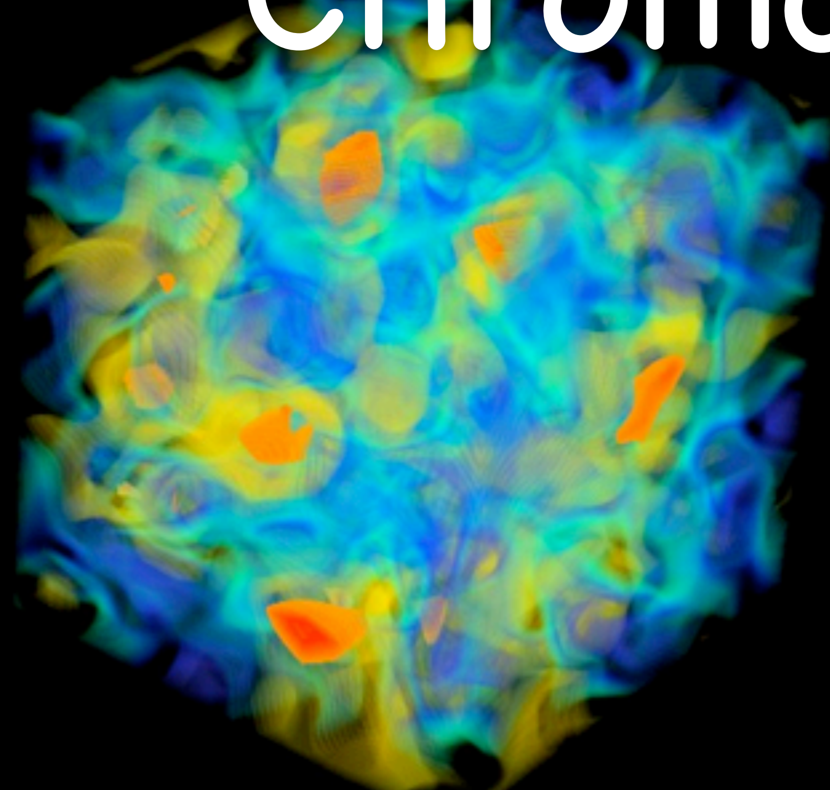


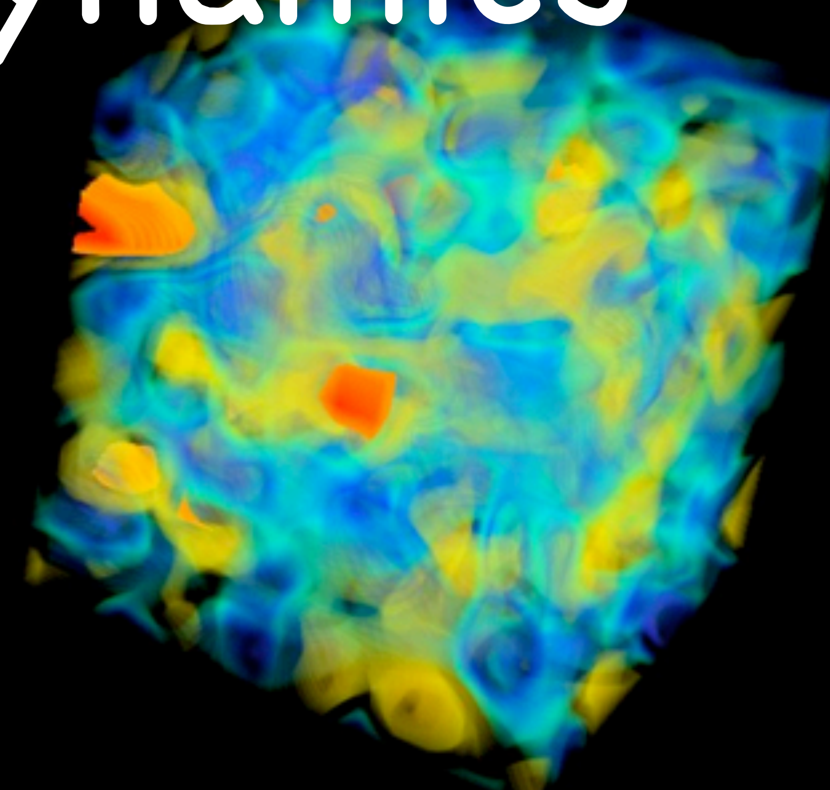
Vacuum Topological Charge, Data courtesy of M. McGuigan BNL-CSC, T. Izubuchi RIKEN-BNL, and S. Tomov University of Tennessee





Quantum Chromodynamics





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Quark fields

$$\psi^j_q = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$$

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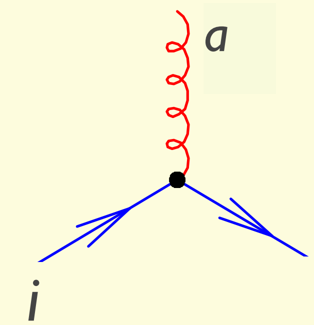
Covariant Derivative

$$D_{\mu ij} = \delta_{ij}\partial_\mu - i g_s T^a_{ij} A^a_\mu$$

⇒ Feynman rules



a∈[1,8]

i,j∈[1,3]

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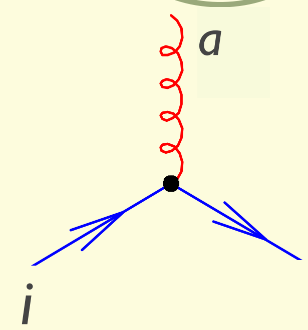


$a \in [1,8]$

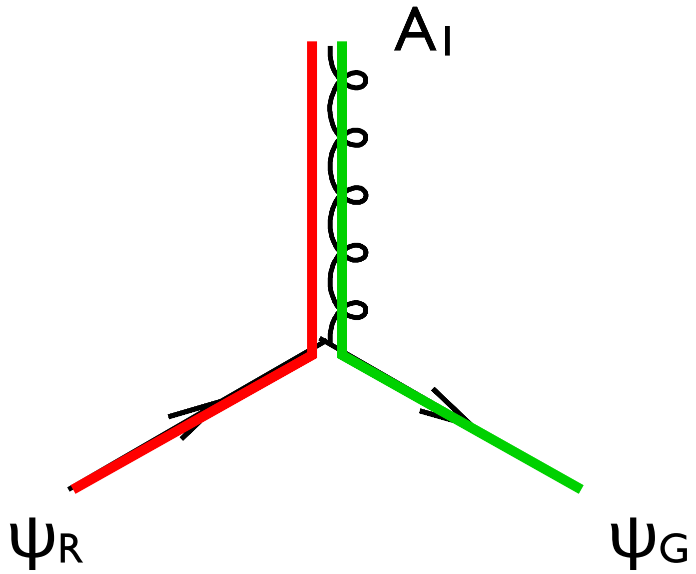
$i,j \in [1,3]$

Gell-Mann Matrices *($T^a = \frac{1}{2}\lambda^a$)*

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

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

Quark-Gluon interactions



$$\underbrace{\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{A_1} \underbrace{\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}}_{\psi_R} = \underbrace{\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}}_{\psi_G}$$

Interactions in Color Space

Color Factors

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

All QCD processes have a "color factor". It counts the enhancement from the sum over colors.

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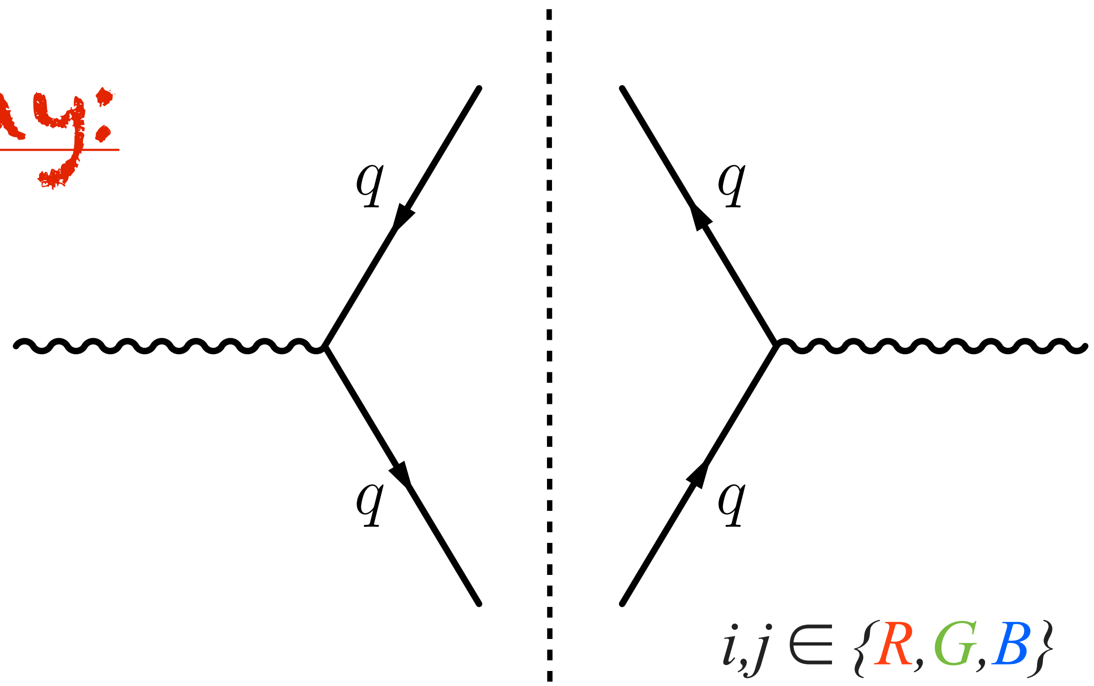

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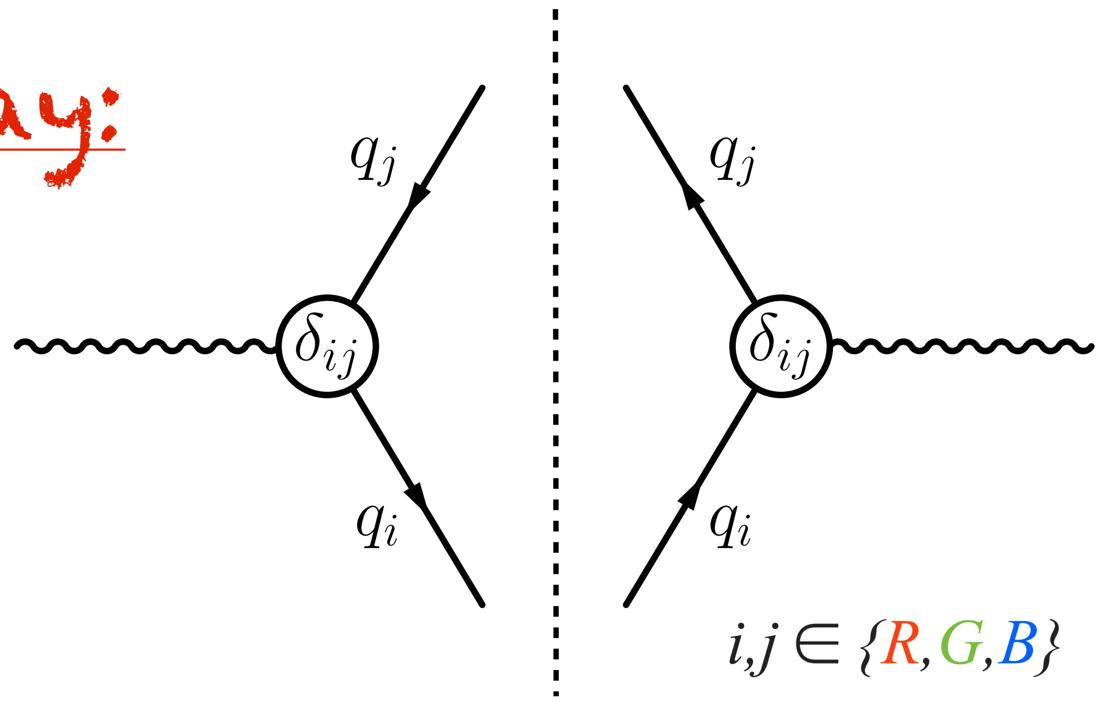

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Drell-Yan

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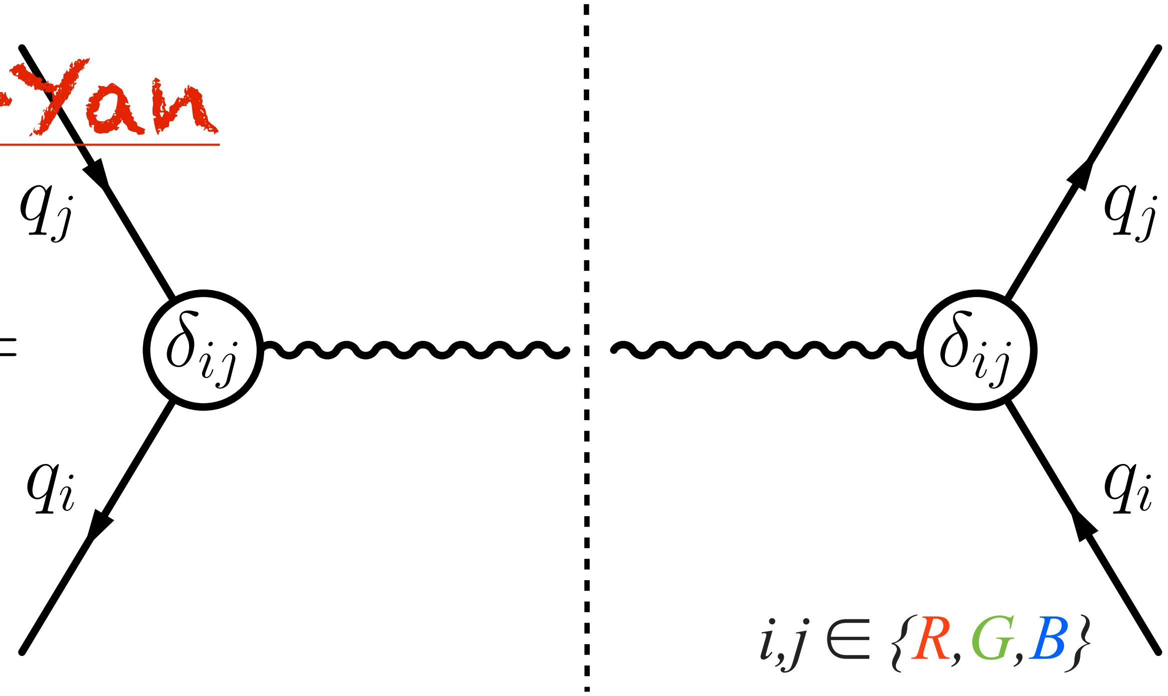

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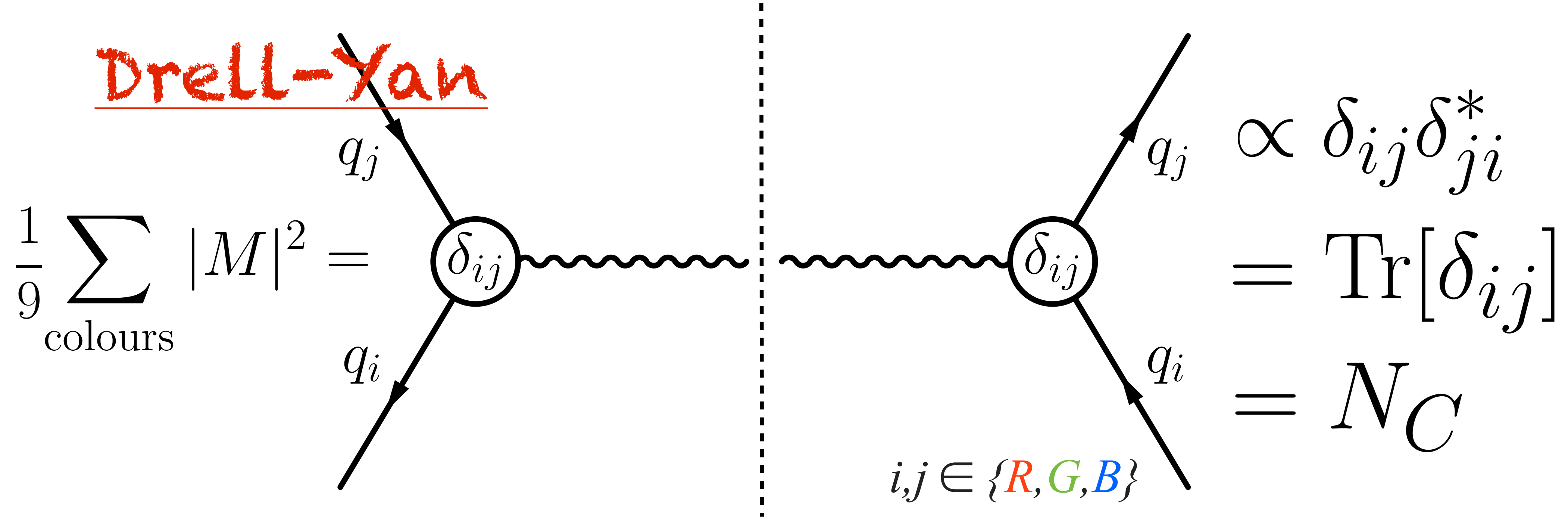

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Z→3 jets

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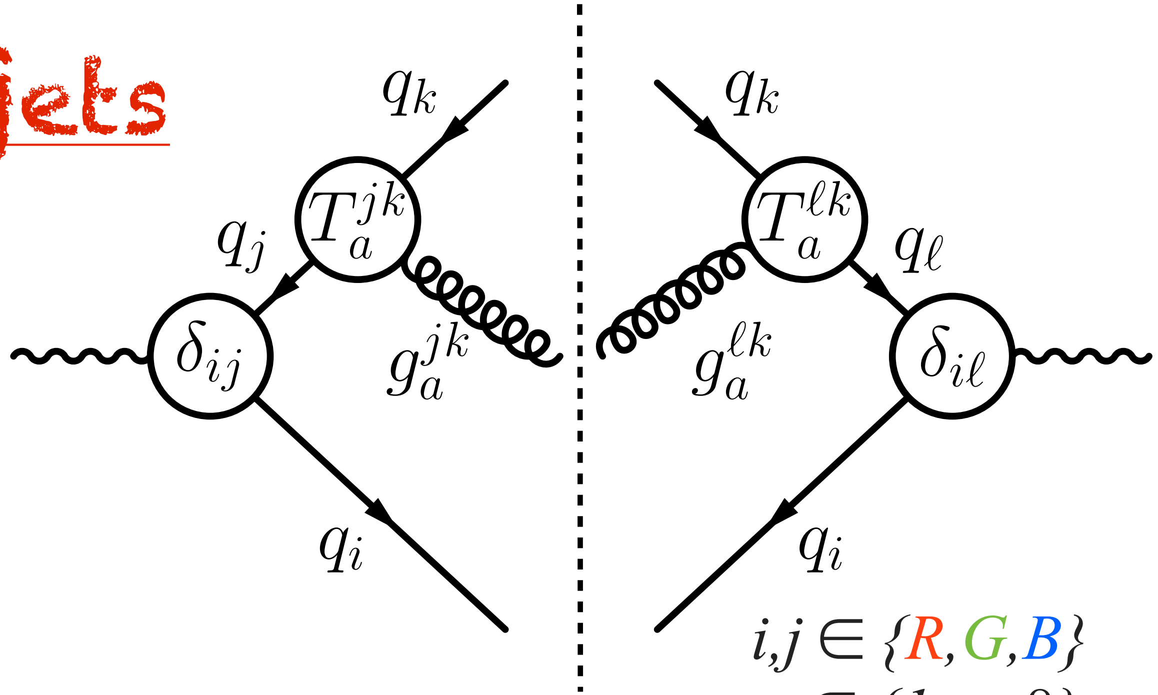


$i,j \in \{R,G,B\}$
$a \in \{1,\ldots,8\}$

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

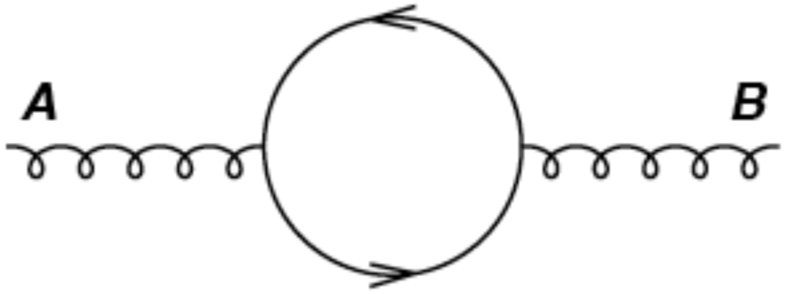
Quick Guide to Color Algebra

Color factors squared produce traces

Trace Relation

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

Example Diagram



(from ESHEP lectures by G. Salam)

Quick Guide to Color Algebra

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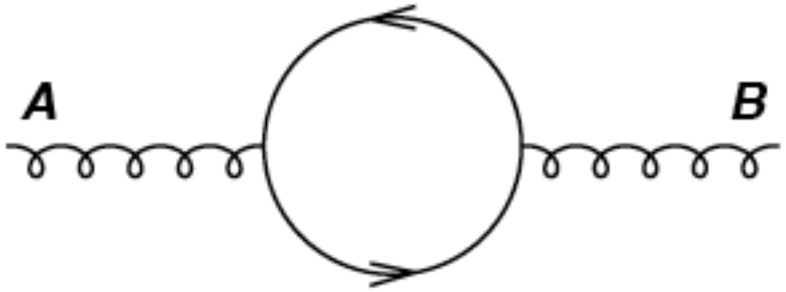
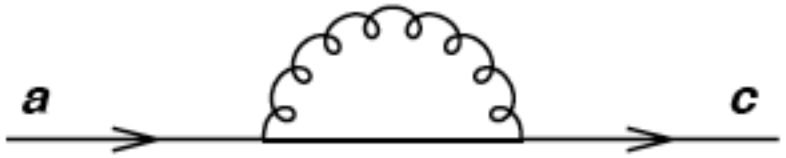
$\mathrm{Tr}(t^A t^B) = T_R \delta^{AB}\,, \quad T_R = \frac{1}{2}$	
$\sum_A t^A_{ab} t^A_{bc} = C_F \delta_{ac}\,, \quad C_F = \frac{N_c^2 - 1}{2N_c} = \frac{4}{3}$	

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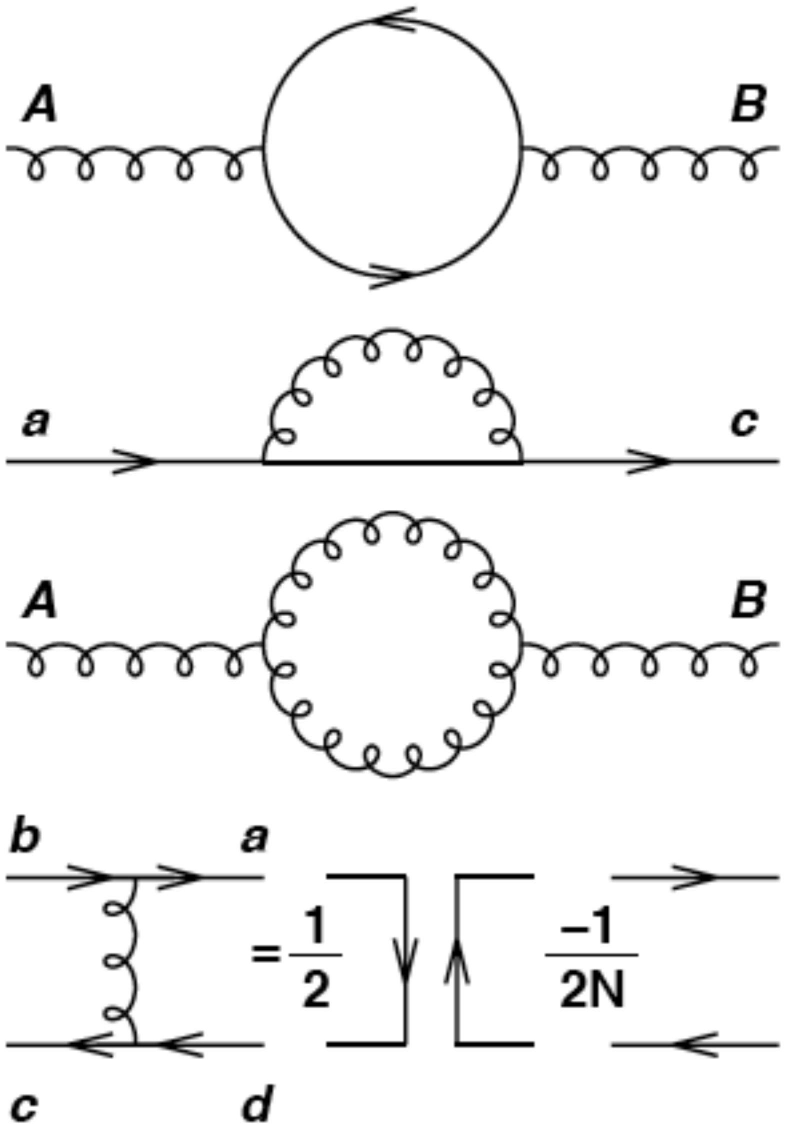
Example Diagram



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QCD
Lecture I

Quick Guide to Color Algebra

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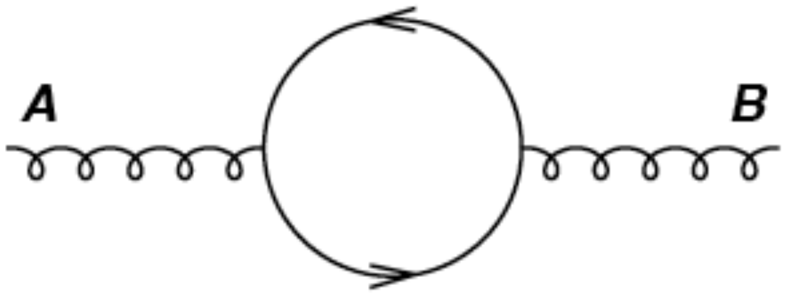
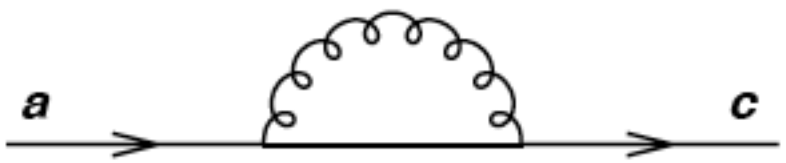
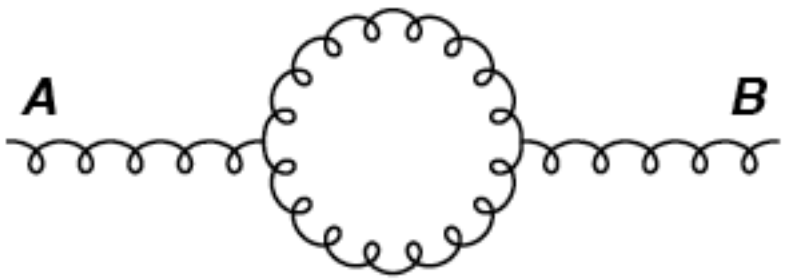
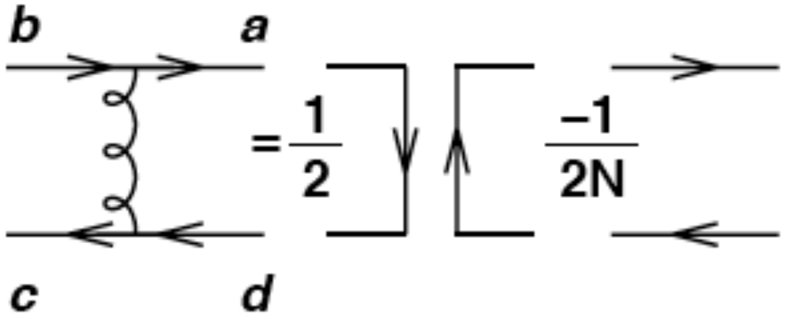
$\mathrm{Tr}(t^A t^B) = T_R \delta^{AB}\,, \quad T_R = \frac{1}{2}$	
$\sum_A t^A_{ab} t^A_{bc} = C_F \delta_{ac}\,, \quad C_F = \frac{N_c^2-1}{2N_c} = \frac{4}{3}$	
$\sum_{C,D} f^{ACD} f^{BCD} = C_A \delta^{AB}\,, \quad C_A = N_c = 3$	
$t^A_{ab} t^A_{cd} = \frac{1}{2}\delta_{bc}\delta_{ad} - \frac{1}{2N_c}\delta_{ab}\delta_{cd}$ (Fierz)	

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The Gluon

Gluon-Gluon Interactions

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

QCD

Lecture I

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Gluon field strength tensor:

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f^{abc} A_\mu^b A_\nu^c$$

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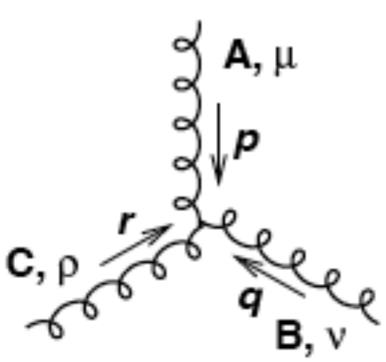
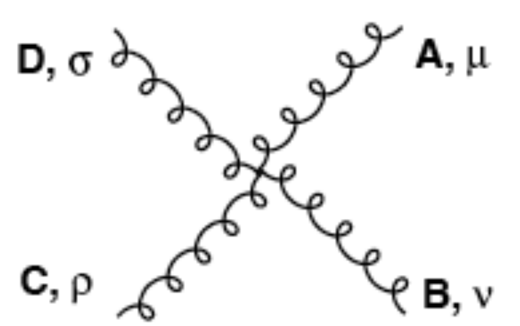


$-g_s f^{ABC}[(p-q)^\rho g^{\mu\nu} + (q-r)^\mu g^{\nu\rho} + (r-p)^\nu g^{\rho\mu}]$



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

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 $f_{ijk} = 0$

The Strong Coupling

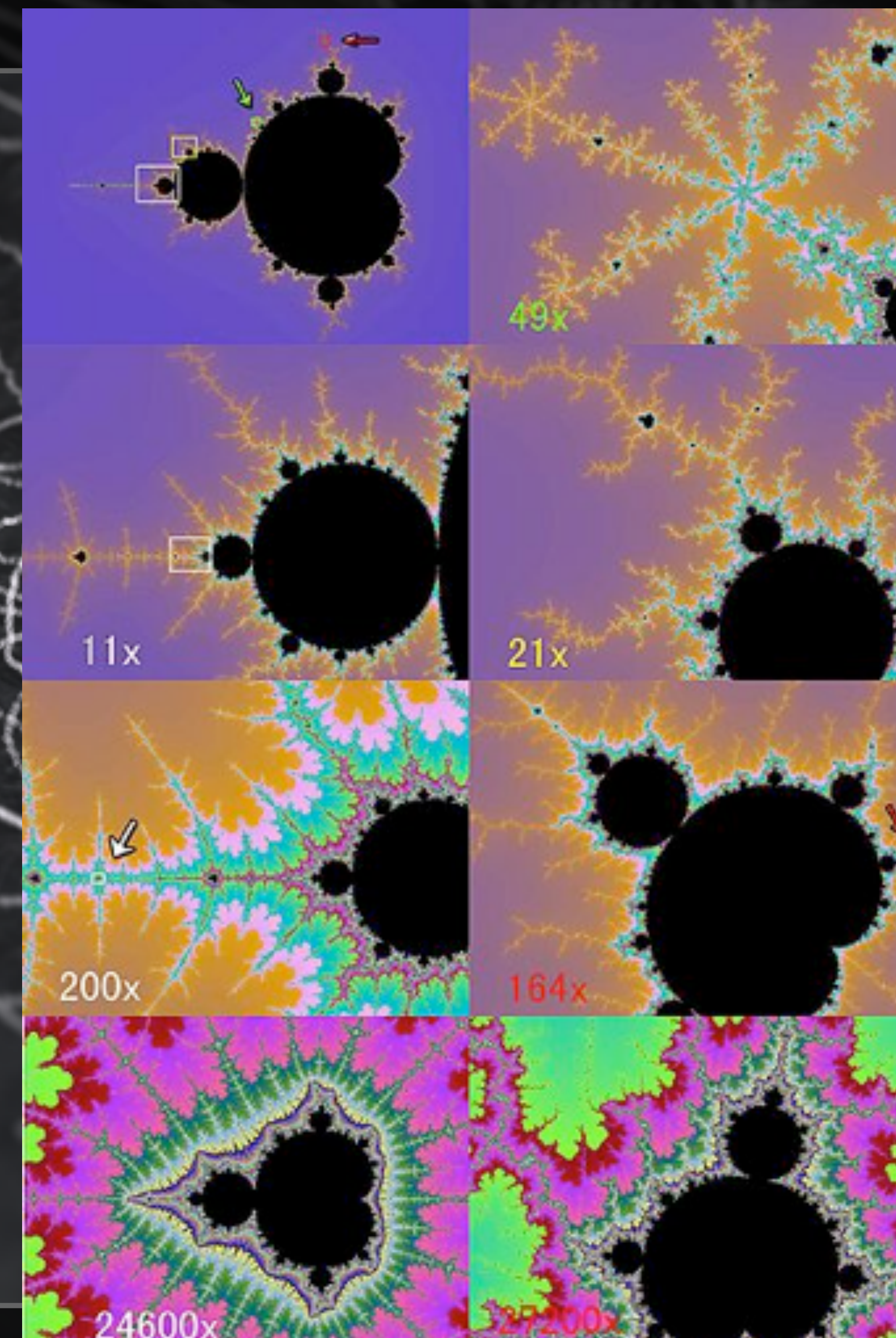
Bjorken scaling

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 didn't "run", this would be absolutely true (e.g., N=4 Supersymmetric Yang-Mills)

As it is, α_s only runs slowly (logarithmically) → can still gain insight from fractal analogy



Note: I use the terms "conformal" and "scale invariant" interchangeably

Strictly speaking, conformal (angle-preserving) symmetry is more restrictive than just scale invariance

But examples of scale-invariant field theories that are not conformal are rare (eg 6D noncritical self-dual string theory)

Conformal QCD

Bremsstrahlung

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

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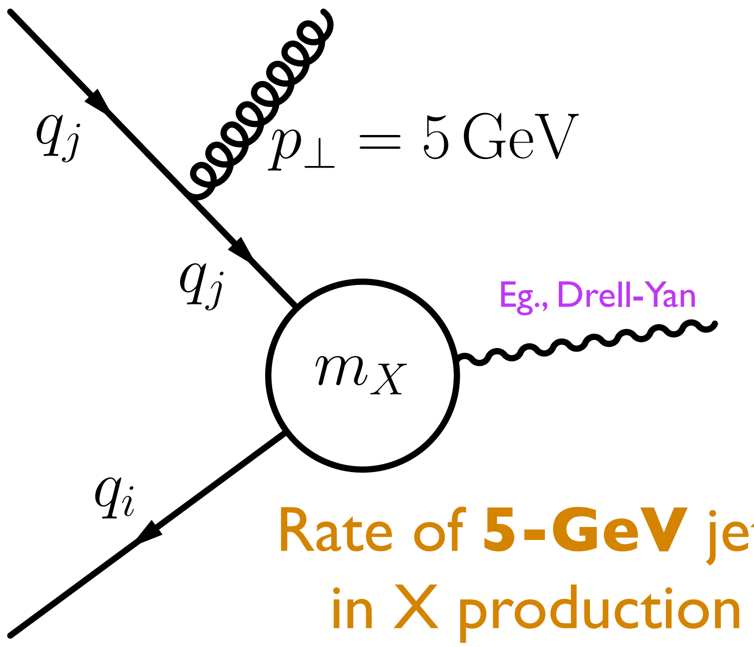

Rate of **5-GeV** jets in X production

Bremsstrahlung

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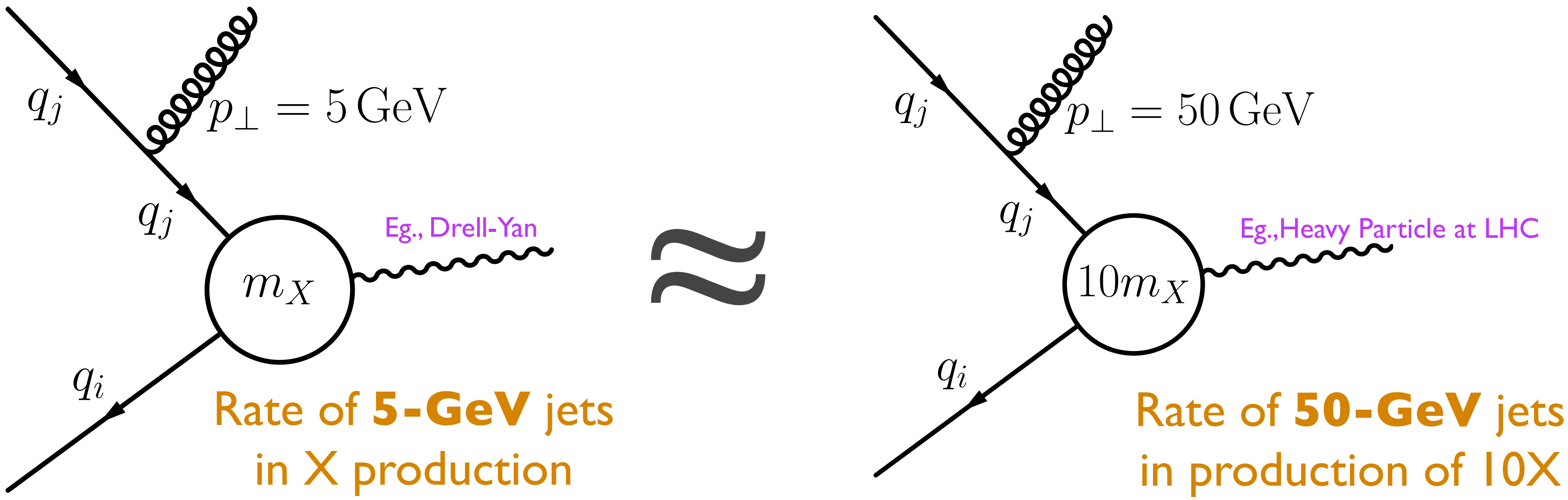

Conformal QCD in Action

Naively, QCD radiation suppressed by $\alpha_s \approx 0.1$

Truncate at fixed order = LO, NLO, …

But beware the jet-within-a-jet-within-a-jet …

Example:

SUSY pair production at 14 TeV, with $M_{SUSY} \approx 600$ GeV

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LHC - sps1a - m~600 GeV

Plehn, Rainwater, PS PLB645(2007)217

FIXED ORDER pQCD	σ_{tot}[pb]	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$	$\tilde{u}_L\tilde{u}_L^*$	$\tilde{u}_L\tilde{u}_L$	TT
$p_{T,j} >$ 100 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
inclusive X + 1 "jet" →	σ_{1j}	2.89	2.74	0.136	0.145	0.73
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σ for X + jets much larger than naive estimate

QCD

Lecture I

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(Computed with SUSY-MadGraph)

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→ More on this in lectures on Jets, Monte Carlo, and Matching

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Scaling Violation

Real QCD isn't conformal

The coupling runs logarithmically with the energy scale

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

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

1-Loop β function coefficient

2-Loop β function coefficient

$$b_2 = \frac{2857 - 5033 n_f + 325 n_f^2}{128\pi^3}$$

$$b_3 = \text{known}$$

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Asymptotic freedom in the ultraviolet

QCD

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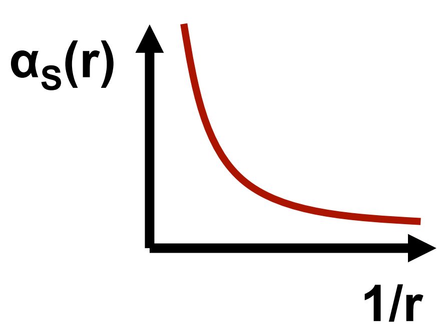
Asymptotic freedom in the ultraviolet

Confinement (IR slavery?) in the infrared

Asymptotic Freedom

“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.”



Nobelprize.org
The Official Web Site of the Nobel Prize

The Nobel Prize in Physics 2004
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David J. Gross


H. David Politzer


Frank Wilczek

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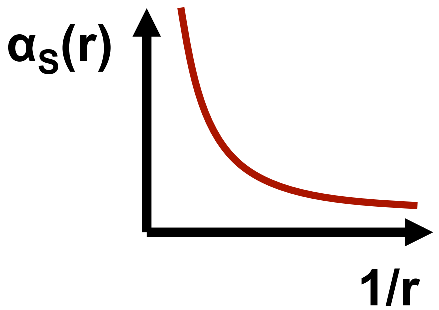


*1 The force still goes to ∞ as r → 0 (Coulomb potential), just less slowly

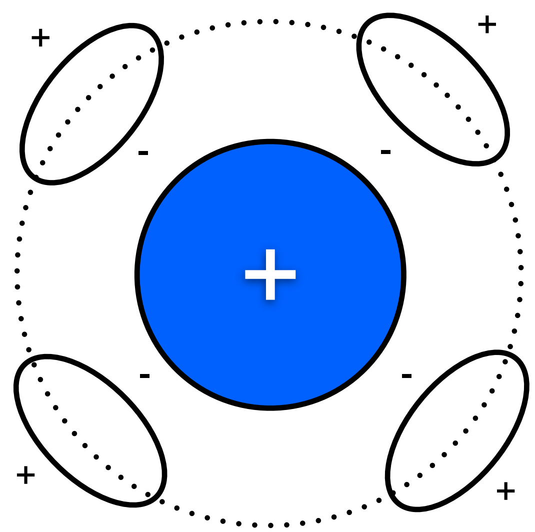
*2 The potential grows linearly as r → ∞, so the force actually becomes constant (even this is only true in “quenched” QCD. In real QCD, the force eventually vanishes for r>>1fm)

Asymptotic Freedom

QED:

Vacuum polarization

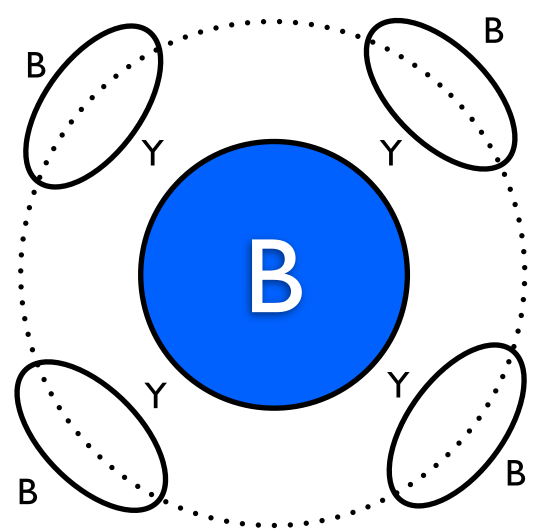
→ Charge screening



QCD:

Quark Loops

→ Also charge screening



But only dominant if > 16 flavors!

Asymptotic Freedom

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Vacuum polarization

→ Charge screening

QCD:

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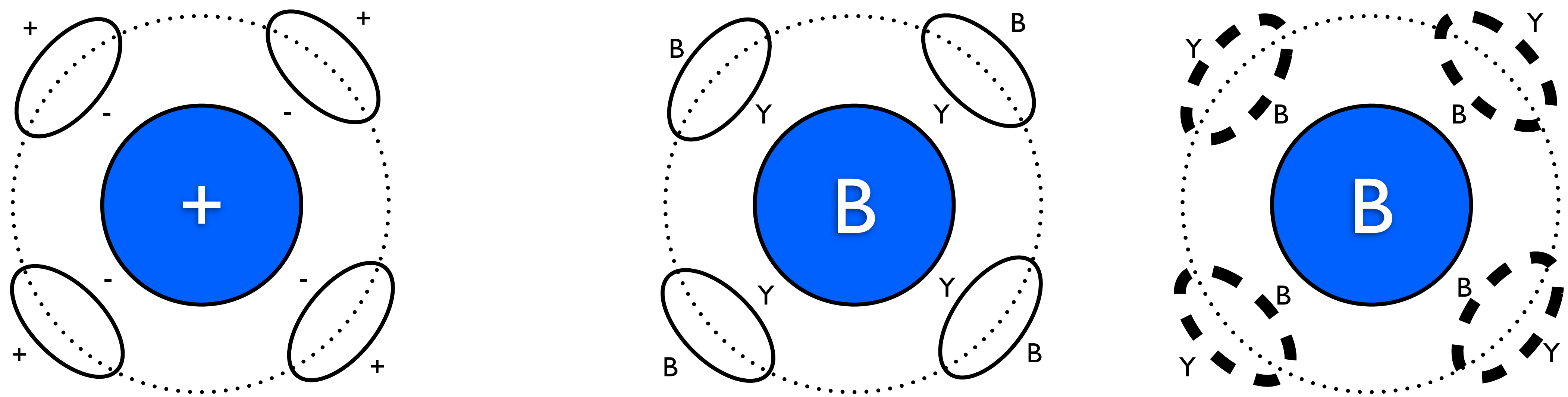
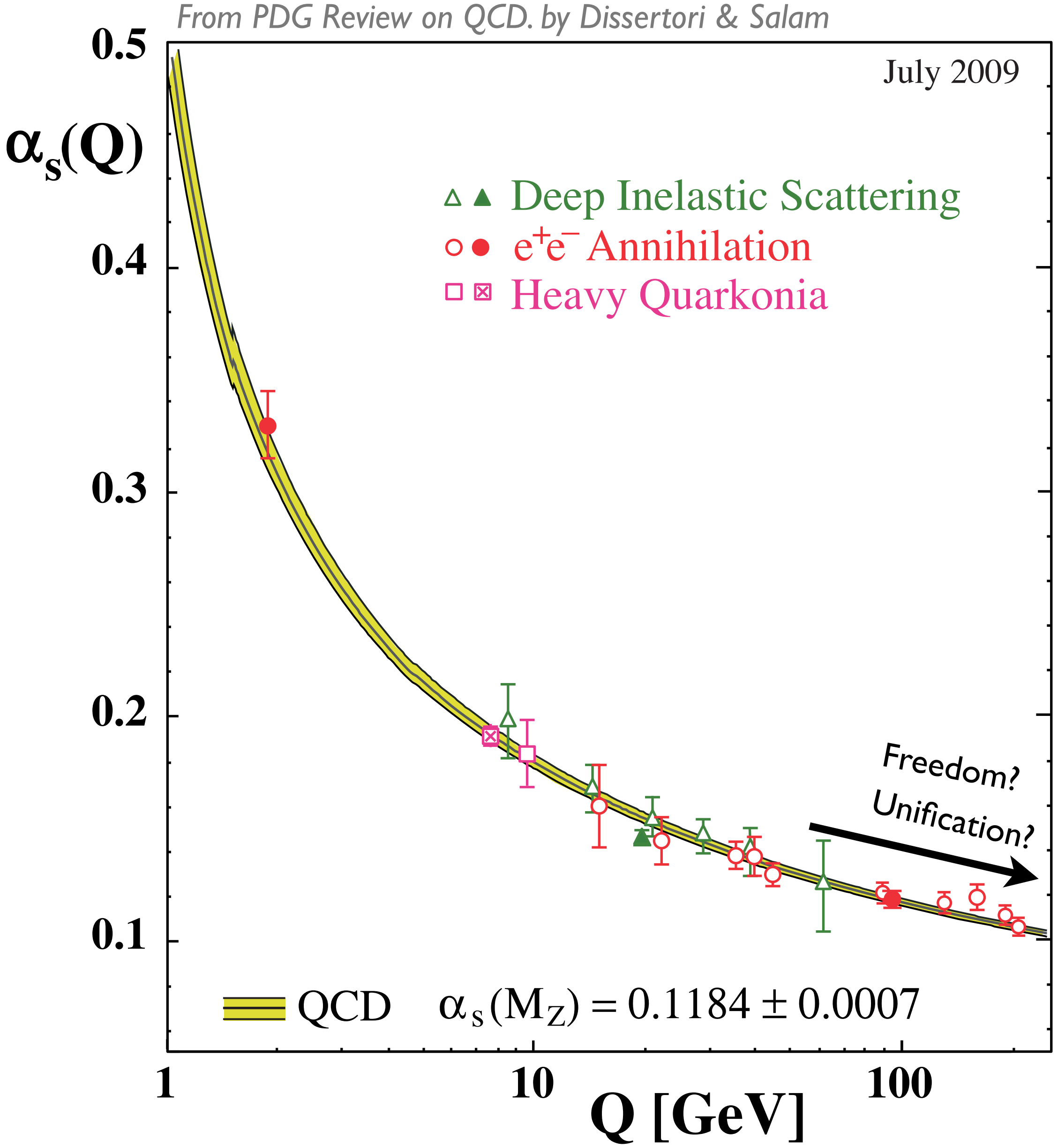
Gluon Loops

Dominate if ≤ 16 flavors



Spin-1 → Opposite Sign

UV and IR



At low scales

Coupling $\alpha_s(Q)$ actually runs rather fast with Q

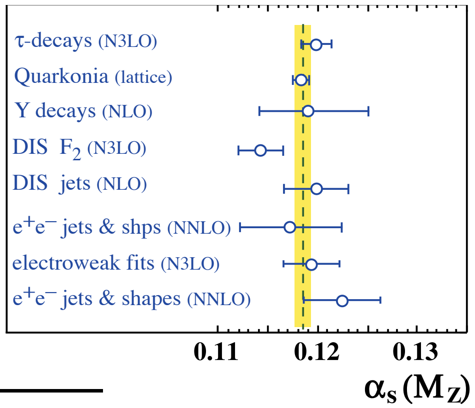
Perturbative solution diverges at a scale Λ_{QCD} somewhere below

$\approx$ 1 GeV

So, to specify the strength of the strong force, we usually give the value of α_s at a unique reference scale that everyone agrees on: M_Z

The Fundamental Parameter(s)

From PDG Review on QCD. by Dissertori & Salam



QCD has one fundamental parameter

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

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

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

… + n_f and quark masses

QCD

Lecture I

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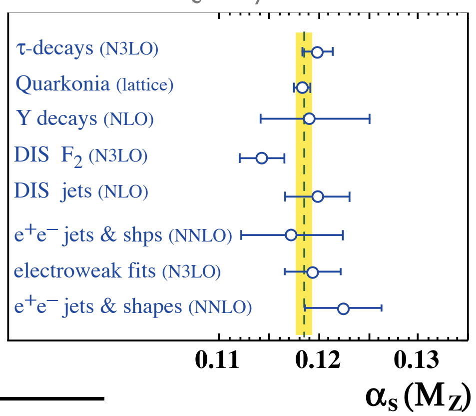

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… and its sibling

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

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

(depends on n_f, scheme, and # of loops)

$\Lambda \sim 200\ \mathrm{MeV}$

… + n_f and quark masses

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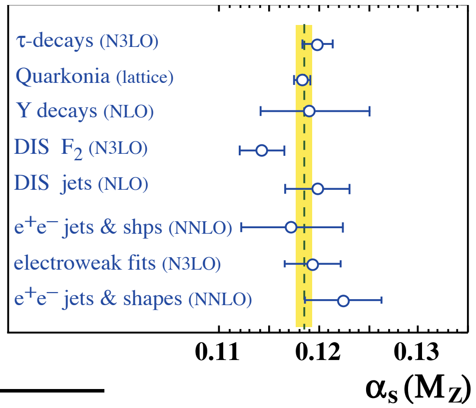

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… And all its cousins

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

… + n_f and quark masses

Uncalculated Orders

Naively $O(\alpha_s)$ - True in e^+e^- !

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Generally larger in hadron collisions

Typical "K" factor in pp (= σ_{NLO}/σ_{LO}) ≈ 1.5 ± 0.5

Why is this? Many pseudoscientific explanations

Uncalculated Orders

Naively O(α_s) - True in e^+e^- !

$$\sigma_{\rm NLO}(e^+e^- \to q\bar{q}) = \sigma_{\rm LO}(e^+e^- \to q\bar{q}) \left(1 + \frac{\alpha_s(E_{\rm CM})}{\pi} + \mathcal{O}(\alpha_s^2)\right)$$

Generally larger in hadron collisions

Typical "K" factor in pp (= σ_{NLO}/σ_{LO}) ≈ 1.5 ± 0.5

Why is this? Many pseudoscientific explanations

- Explosion of # of diagrams ($n_{Diagrams} \approx n!$)
- New initial states contributing at higher orders (E.g., $gq \to Zq$)
- Inclusion of low-x (non-DGLAP) enhancements
- Bad (high) scale choices at Lower Orders, …

Theirs not to reason why // Theirs but to do and die

Tennyson, The Charge of the Light Brigade

Changing the scale(s)

Why scale variation ~ uncertainty?

Scale dependence of calculated orders must be canceled by contribution from uncalculated ones (+ non-pert)

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

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→ $$\left(\alpha_s(Q'^2) - \alpha_s(Q^2)\right)|M|^2 = \alpha_s^2(Q^2)|M|^2 + \ldots$$

→ Generates terms of higher order, but proportional to what you already have ($|M|^2$)→ a first naive* way to estimate uncertainty

*warning: some theorists believe it is the only way … but be agnostic! There are other things than scale dependence …

Dangers

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Complicated final states

Intrinsically Multi-Scale problems

with Many powers of α_s

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E.g., W + 3 jets in pp

$$\alpha_s^3(m_W^2) < \alpha_s^3\left(m_W^2 + \langle p_\perp^2 \rangle\right) < \alpha_s^3\left(m_W^2 + \sum_i p_{\perp i}^2\right)$$

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Global Scaling: jets don't care about m_W

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Dangers

$p_{\perp 1}$= 50 GeV
$p_{\perp 2}$= 50 GeV
$p_{\perp 3}$= 50 GeV

Complicated final states

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E.g., W + 3 jets in pp

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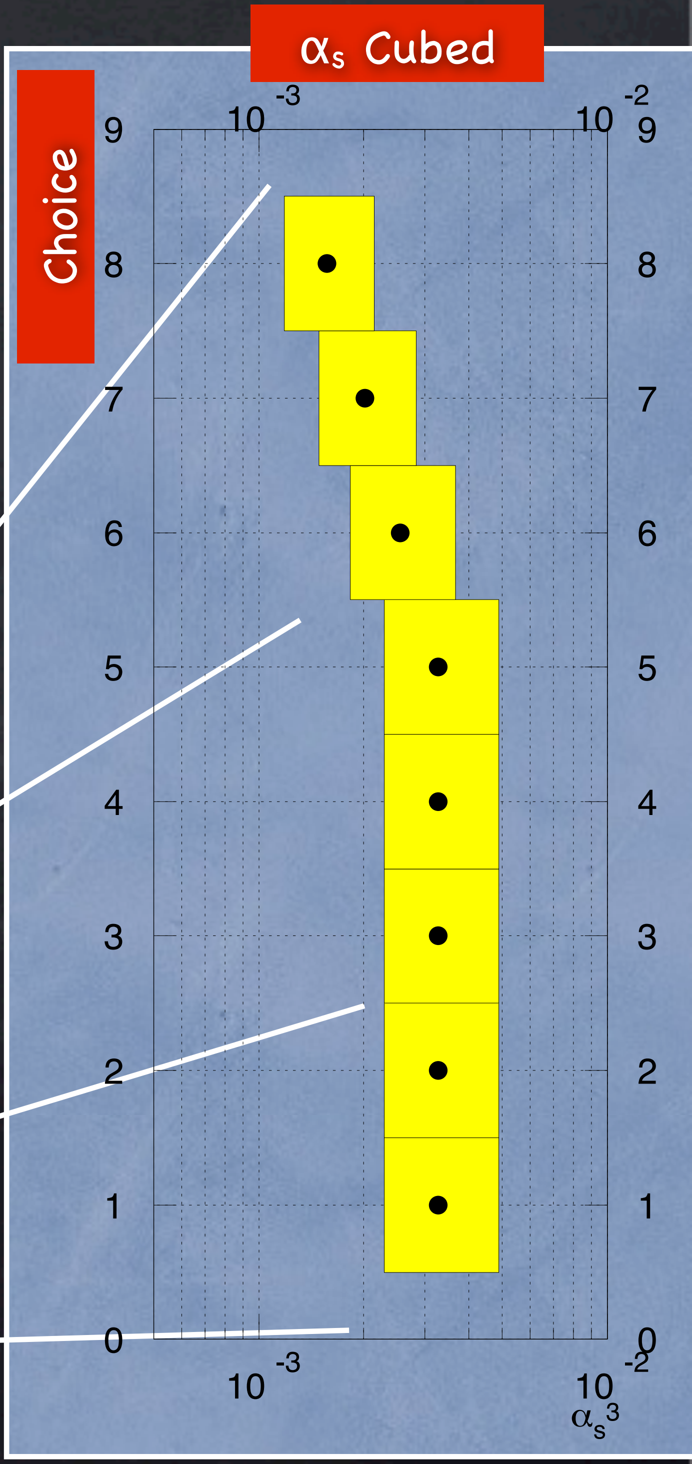
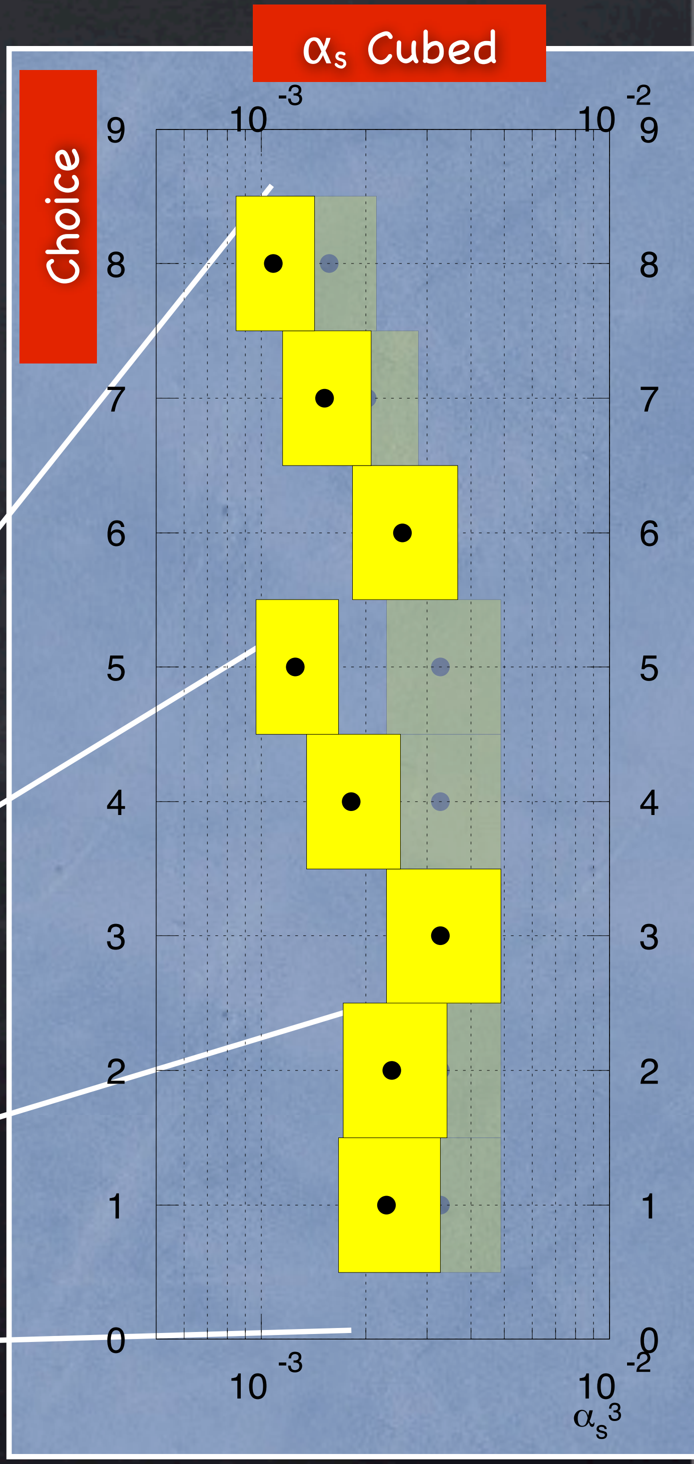


Dangers

$p_{\perp 1}$= 500 GeV
$p_{\perp 2}$= 100 GeV
$p_{\perp 3}$= 30 GeV



Complicated final states

Intrinsically Multi-Scale problems

with Many powers of α_s

If you have multiple QCD scales

→ variation of μ_R by factor 2 in each direction not good enough! (nor is × 3, nor × 4)

Need to vary also functional dependence on each scale!

Other parameters

The emergent is unlike its components insofar as … it cannot be reduced to their sum or their difference."

G. Lewes (1875)

Image Credits: Yeimaya

Other parameters

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Emergent phenomena

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

Image Credits: Yeimaya

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Decay constants,

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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

From Partons to Pions

General-Purpose Monte Carlo models

Start from pQCD *(still mostly LO)*. Extend towards Infrared.

HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

Elastic & Diffractive ← *Towards Soft-QCD Interactions* ······ *Hard Physics*

Elastic — Min-Bias — Jets/W/Z/H/Top/…

0 — Λ_{QCD} — 5 GeV — ∞

Elastic & Diffractive Treated as separate class Little predictivity	Color Screening Regularization of pQCD Hadronization	Unitarity Showers (ISR+FSR) Multiple 2→2 (MPI)	Hard Process Perturbative 2→2 (ME) Resonance Decays

PYTHIA uses **string fragmentation**,
HERWIG, SHERPA use **cluster fragmentation**

(N)LL

(N)LO Matching

(Also possible to start from non-perturbative QCD (via optical theorem) and extend towards UV)
E.g., PHOJET, DPMJET, QGSJET, SIBYLL, … (But will not cover here)

Factorization

Subdivide a calculation

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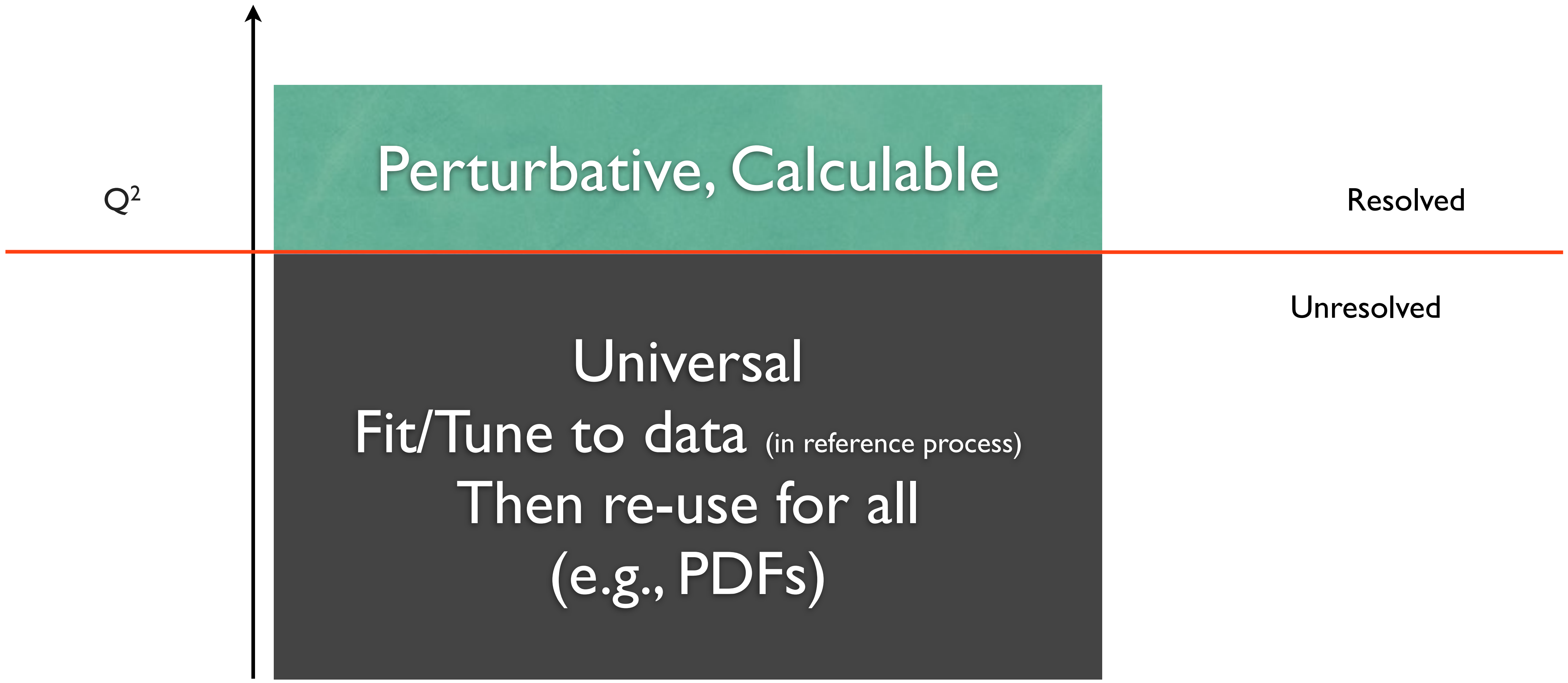

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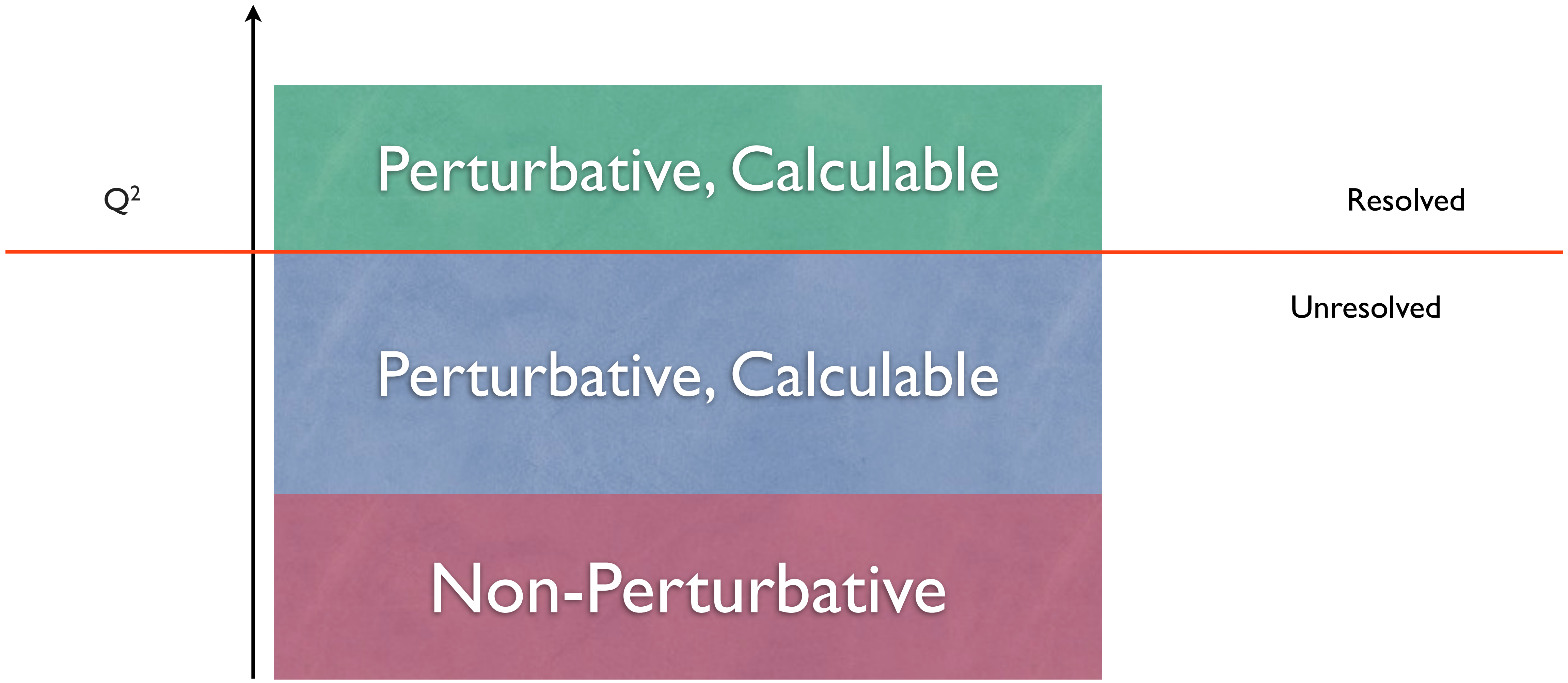

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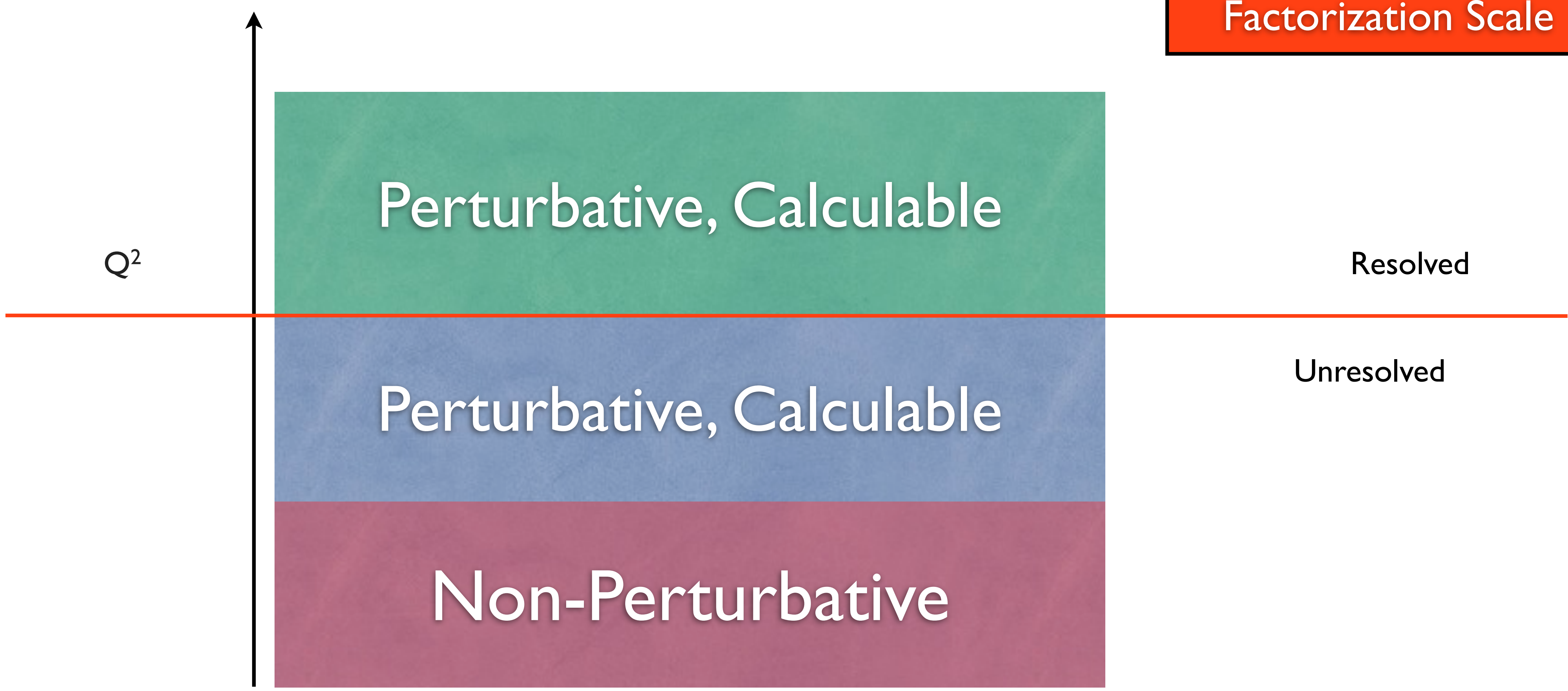
Dependence on
Factorization Scale



Factorization

Subdivide a calculation

Dependence on

Factorization Scale

Q^2

Perturbative, Calculable

Resolved

Unresolved

Single-Scale problems:

$Q_F \approx Q_{hard} \approx m$ and/or $p_\perp$

Multi-Scale problems:

No unique agreement

More later ...

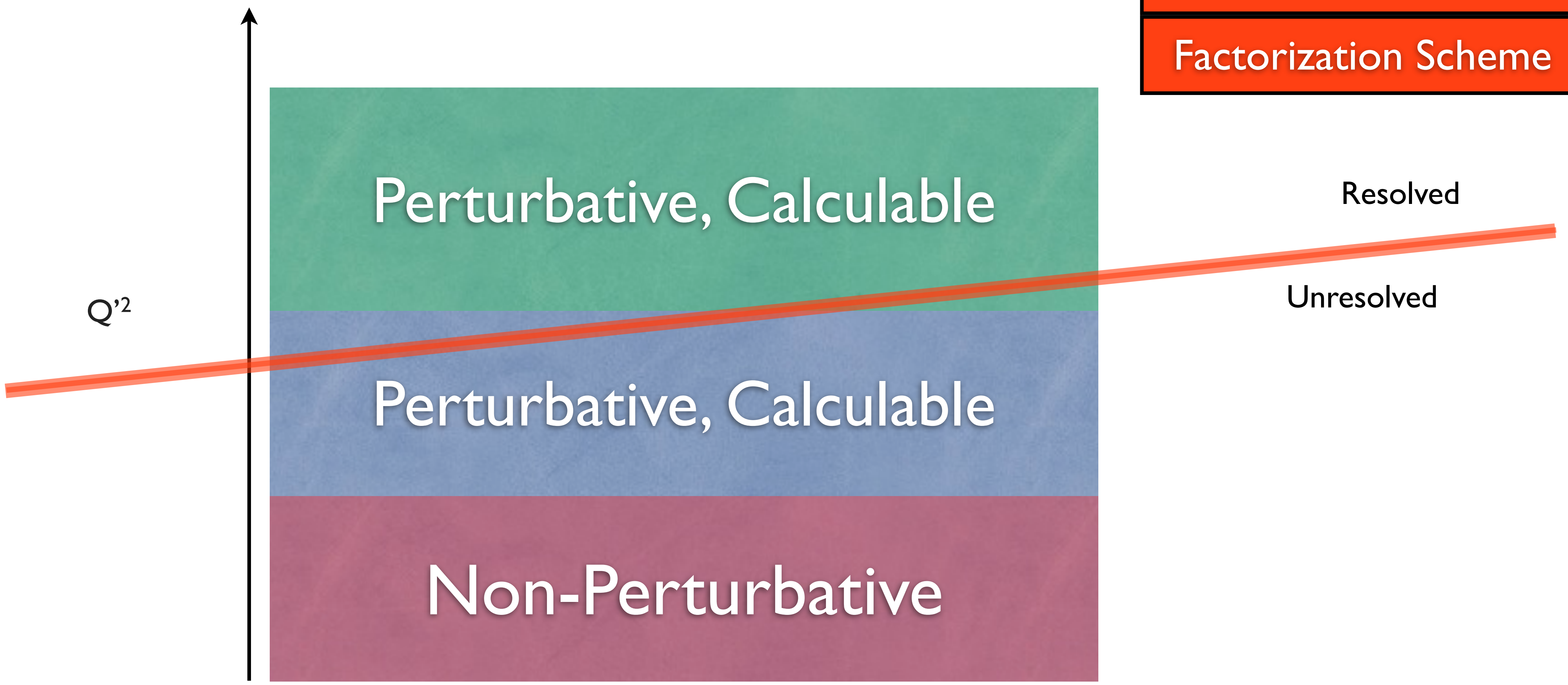
QCD

Lecture I

Factorization

Subdivide a calculation

Dependence on
Factorization Scale
Factorization Scheme



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

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- Beams = hadrons for next decade (RHIC / Tevatron / LHC)
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  - High precision = higher orders → enter QCD (and more QED)
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→ Next Lectures

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Questions

1. Why is the color factor for $\pi^0 \to \gamma\gamma$ proportional to N_C^2 while the one for $e^+e^- \to$ quarks is proportional to N_C ?

(Note: treat the π^0 as a fundamental pseudoscalar)

2. What is the color factor for QCD Rutherford scattering, $qq \to qq$ via t-channel gluon exchange?