Understanding the Strong Interactions with Effective Theories

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MIT Colloquium, 2005

Outline

- QED, Effective Field Theory, Hydrogen
- Introduction to QCD, $\alpha_s(\mu)$
- Energetic Particles & Soft-Collinear Effective Theory
- Weak Decays of B mesons
- Outlook

Introduction to QED

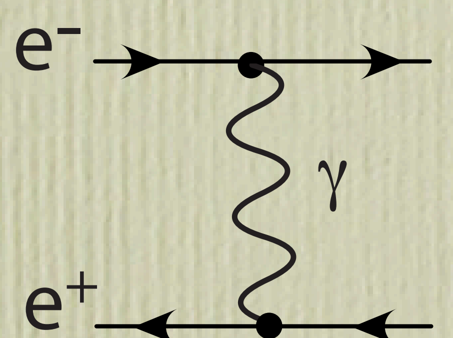
(quantum electromagnetism)

QED $\begin{cases} \text{Special Relativity:} & \text{spacetime,} \quad v \leq c \\ \text{Quantum Mechanics:} & \text{quantization,} \quad \Delta x \Delta p \geq \dfrac{\hbar}{2} \end{cases}$

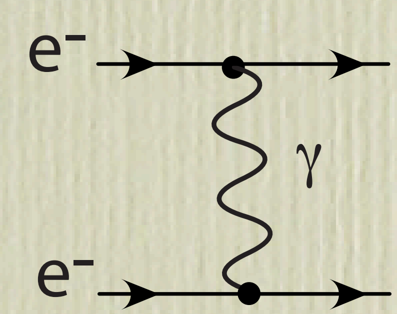
$\Rightarrow$ antiparticles, spin, gauge-theory

$\Rightarrow$ parameters: charge & masses

Interactions

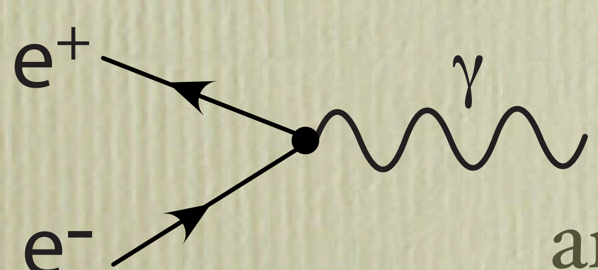


$$V = -\frac{e^2}{r}$$

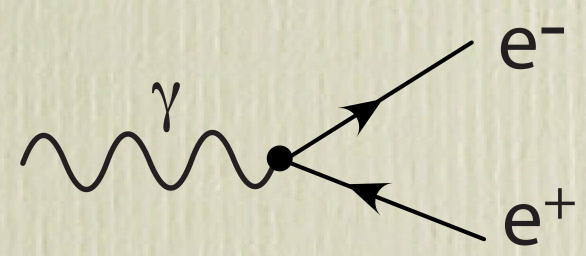


$$V = +\frac{e^2}{r}$$

two factors of the coupling



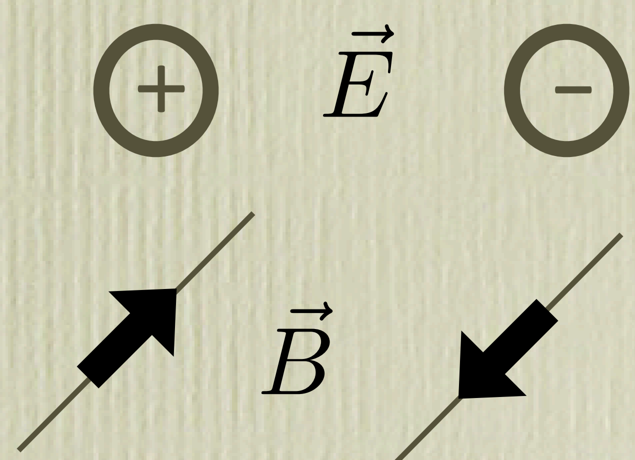
pair annihilation



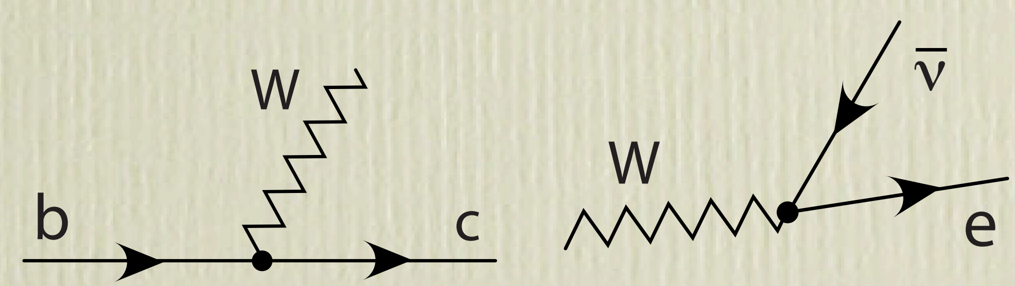
pair creation

The Standard Model Interactions

(leave out gravity and the higgs)

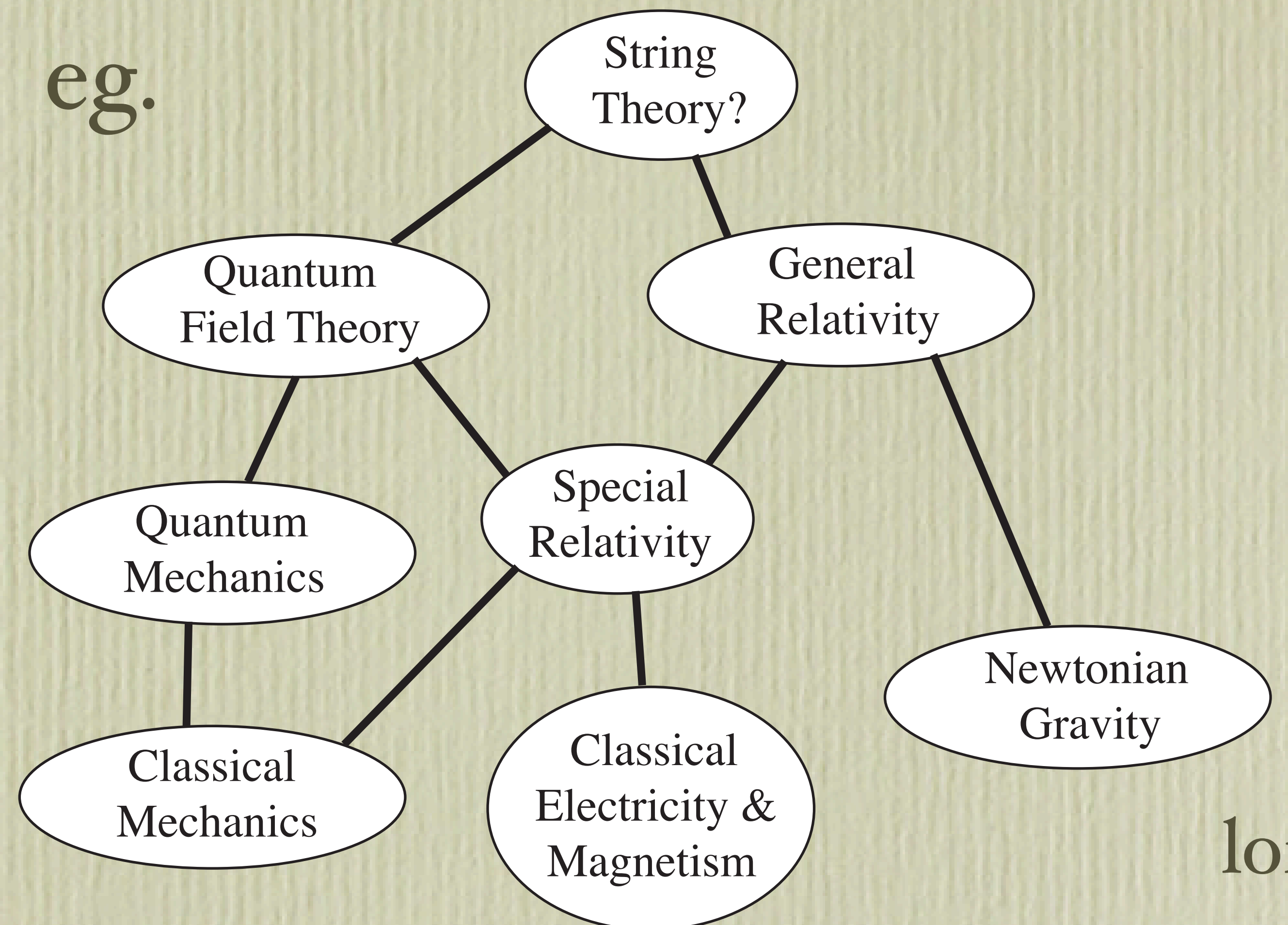
	Strong	Electromagnetism	Weak
	QCD	QED	
mediator:	gluons	photons	$W^{\pm},\ Z^0$
typical strength:	~ 1	$\sim 10^{-2}$	$\sim 10^{-6}$
range:	~ 1 fm	∞	$\frac{1}{m_W} \rightarrow \sim 10^{-3}$ fm
	 proton		$n \longrightarrow pe\bar{\nu}$, radioactive decay

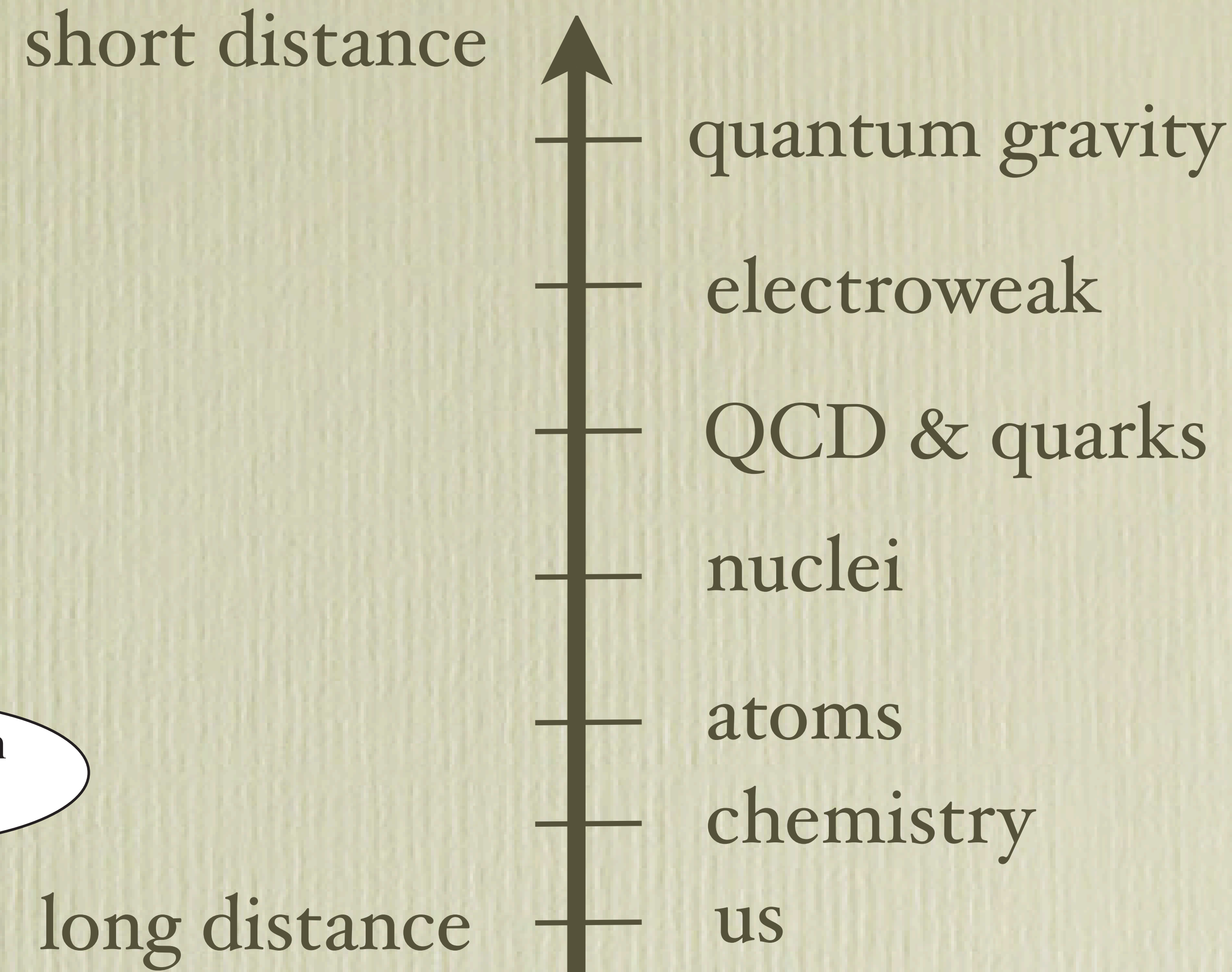
Other forces can (in principle) be derived from these



Physics compartmentalized

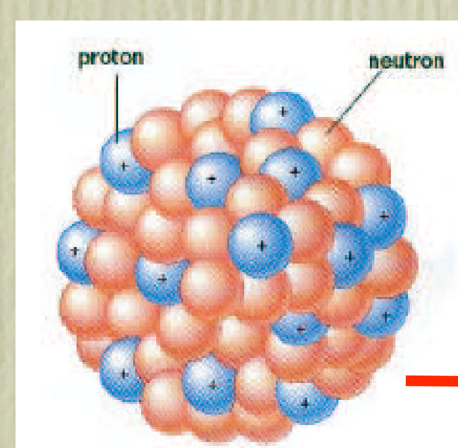
eg.





But, one doesn't need nuclear physics to build a boat

Generality
vs.
Precision



→ Dynamics at long distance does not depend on the details of what happens at short distance

In the quantum realm, $\lambda \sim \frac{1}{p}$, wavelength and momentum are related, so

→ Low energy interactions do not depend on the details of high energy interactions

Bad:

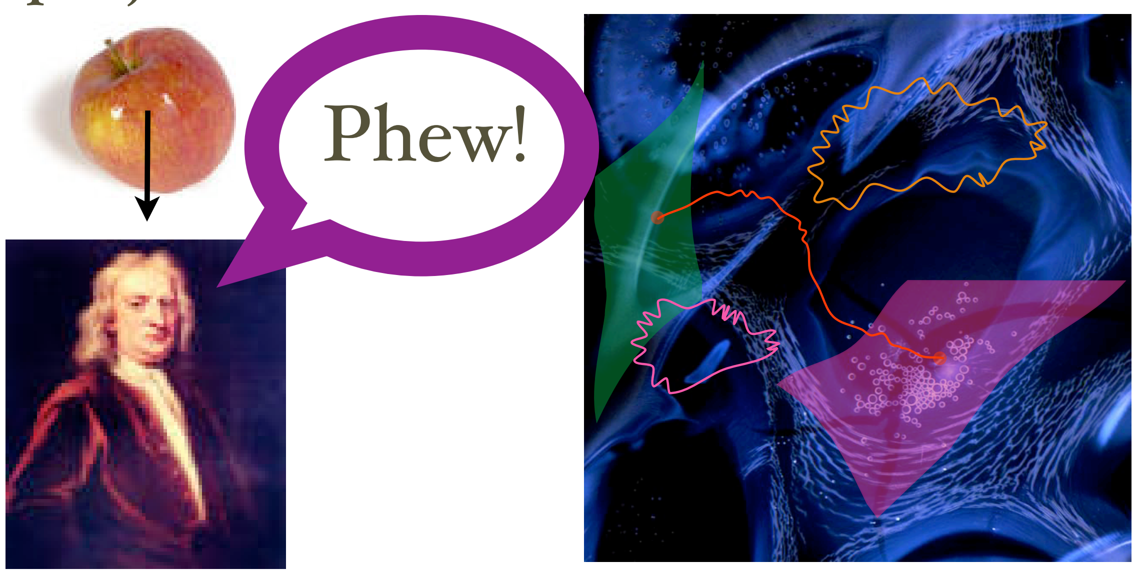
- we have to work harder to probe the interesting physics at short distances

Good:

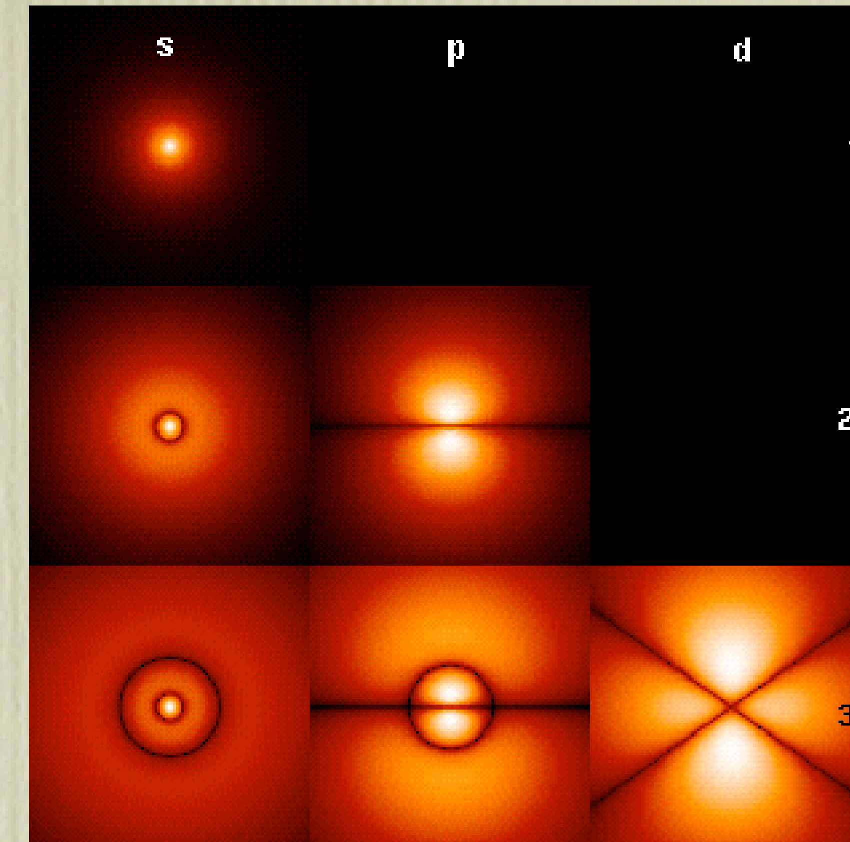
- we can focus on the relevant interactions & degrees of freedom

- calculations are simpler

Newton didn't need quantum gravity for projectile motion



Example: Hydrogen

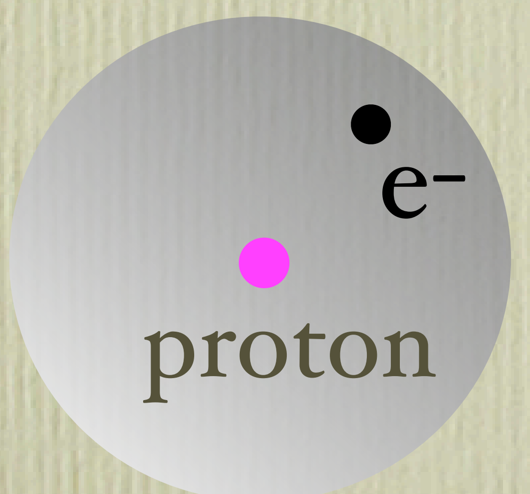


non-relativistic quantum mechanics

parameters:

	mass	m_e
	charges	$Q_e\,,Q_p$
	coupling	$\alpha = \dfrac{1}{137}$

degrees of freedom:



scales:

$$m_p = 938\,\text{MeV} \quad \longrightarrow \infty$$

$$m_e = 0.511\,\text{MeV}$$

$$p \sim m_e\alpha = 3.7\,\text{keV} \qquad \sim (a_{\text{Bohr}})^{-1}$$

$$E_n = -\frac{m_e\alpha^2}{2n^2} = -\frac{13.6\,\text{eV}}{n^2} \qquad + \ \ldots$$

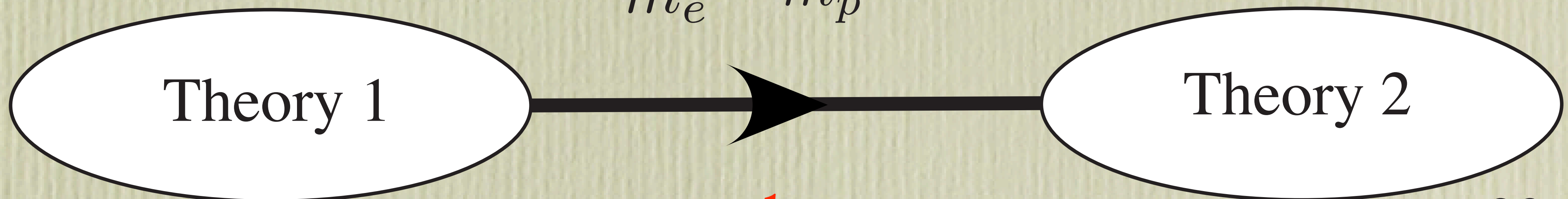
Did not need: QED (e^+, relativity, spin) , m_{proton}
QCD (quarks, ...), weak force, ... } corrections

Effective Field Theory Idea:

short distance theory
is more general

expand in
$\frac{p}{m_e}$, $\frac{m_e}{m_p}$, α

long distance theory
where its easier
to compute



match to
give H_m

$$H = H_0 + \sum_{m=1}^{\infty} \epsilon^m \ H_m$$

exact answer is irrelevant, work to
the desired level of precision

Degrees of freedom can change:

$$e^+ \longrightarrow \text{no } \ e^+$$

QCD, quarks $\longrightarrow$ proton

Effective Field Theory Idea:

short distance theory
is more general

expand in

$$\frac{p}{m_e}\,,\ \frac{m_e}{m_p}\,,\ \alpha$$

long distance theory
where its easier
to compute

Theory 1 $\longrightarrow$ Theory 2

match to
give H_m

$$H = H_0 + \sum_{m=1}^{\infty} \epsilon^m \, H_m$$

exact answer is irrelevant, work to
the desired level of precision

Symmetries of Theory 1 constrain the form of Theory 2:

Charge conjugation ($e^+ \leftrightarrow e^-$)
Parity ($\vec{x} \longrightarrow -\vec{x}$)
Time-Reversal ($t \longrightarrow -t$)

$\Longrightarrow$ constrain the H_m 's

Spin-Statistics Theorem

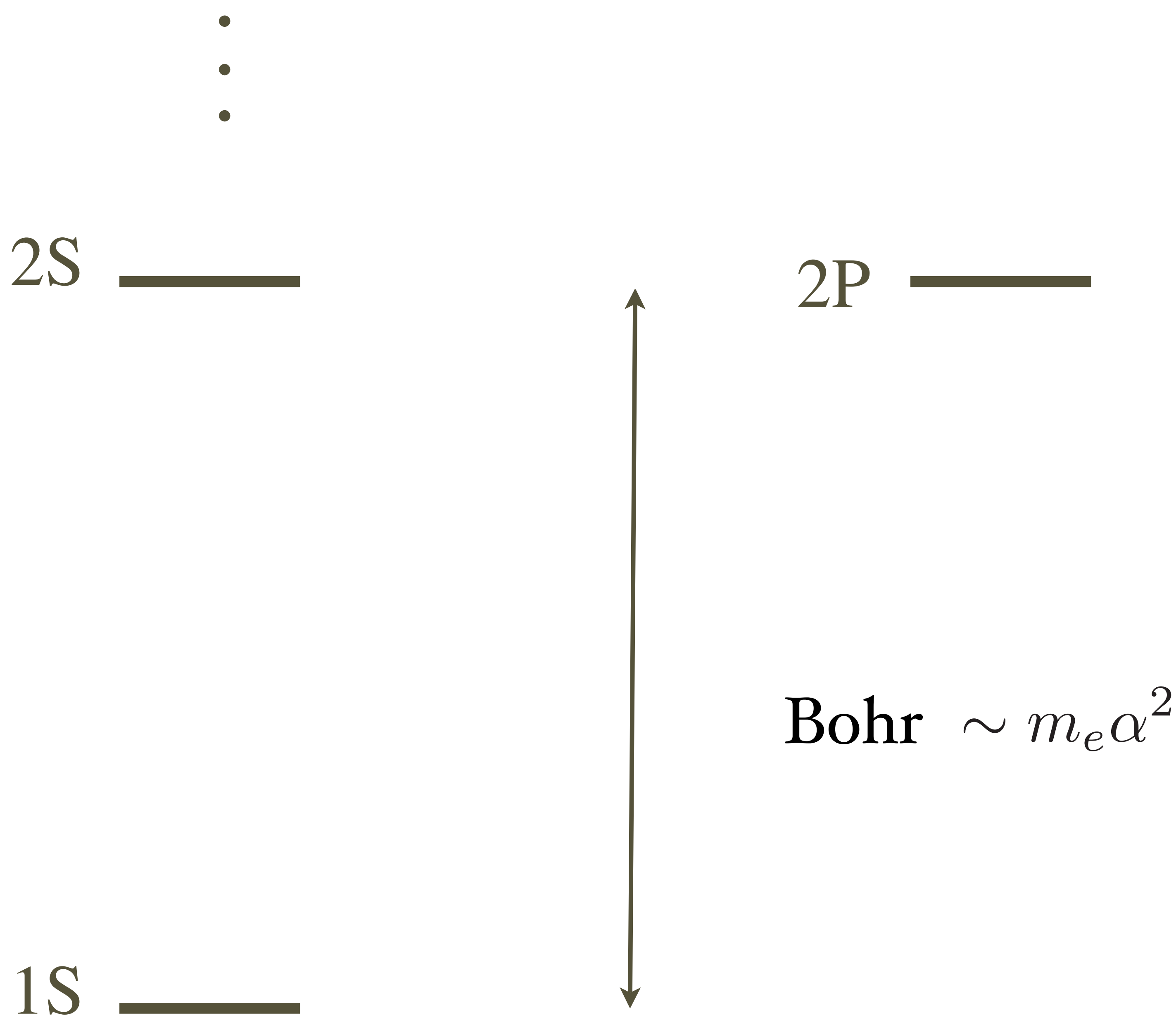
NRQED

Effective Field Theory for Non-relativistic bound states

nL_J

$F = J + S_p$

spectrum



NRQED

Effective Field Theory for Non-relativistic bound states

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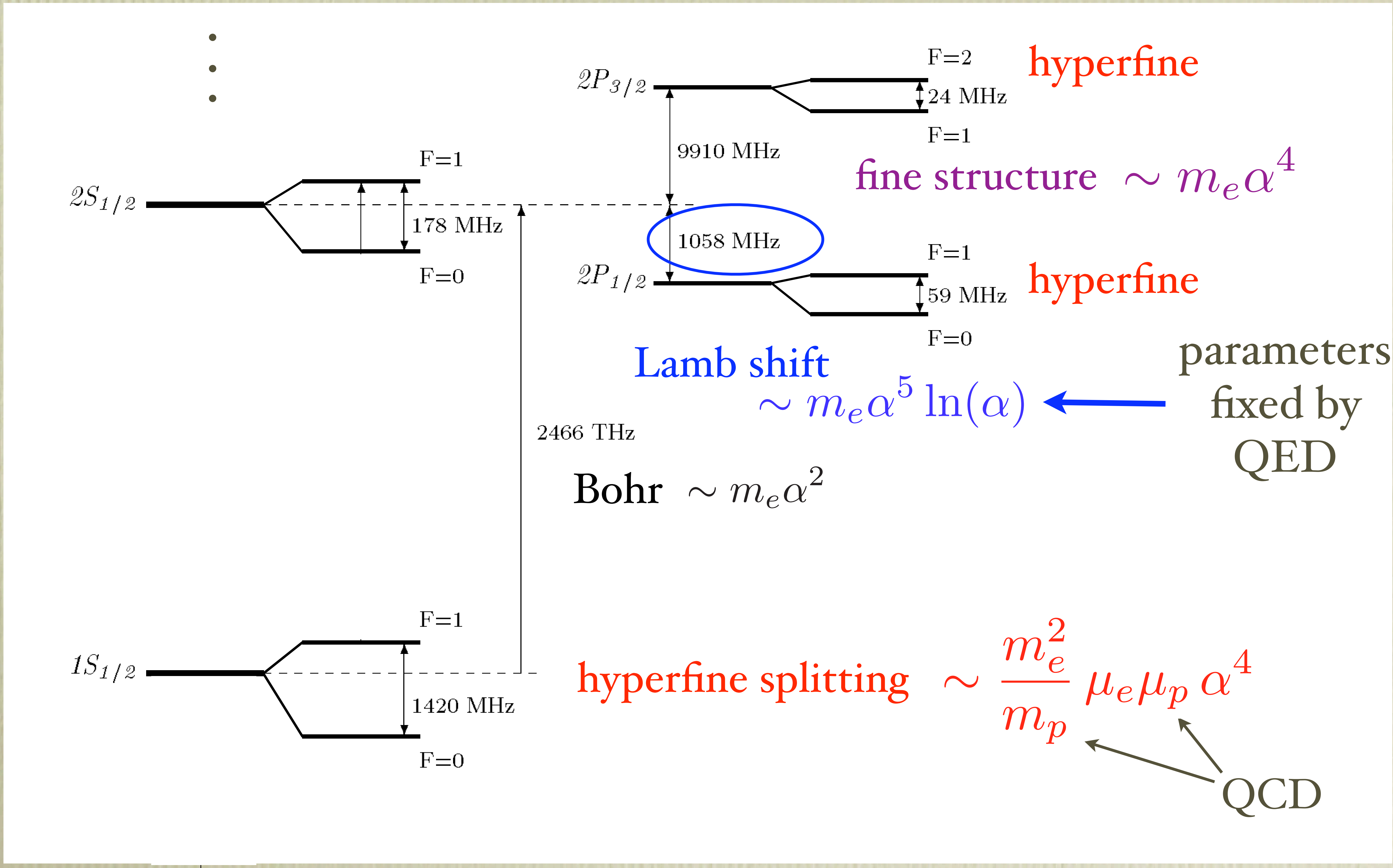
$F = J + S_p$



Compute the H_m :

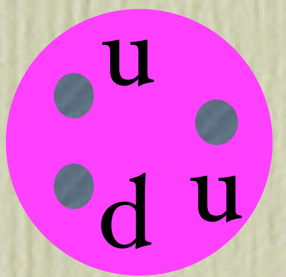
$$H = H_0 + \sum_{m=1}^{\infty} \epsilon^m \, H_m$$

Relativity: $\dfrac{p^4}{8m_e^3} + \ldots$

QED: $\mu_e \,, \quad \vec{L} \cdot \vec{S} \quad , \ldots$ (coefficients determined by $\alpha \,, m_e$)

What about quarks?

size $\sim 1\,\mathrm{fm} \longrightarrow 200\,\mathrm{MeV} \gg p_\gamma$



$Q_u = +2/3$

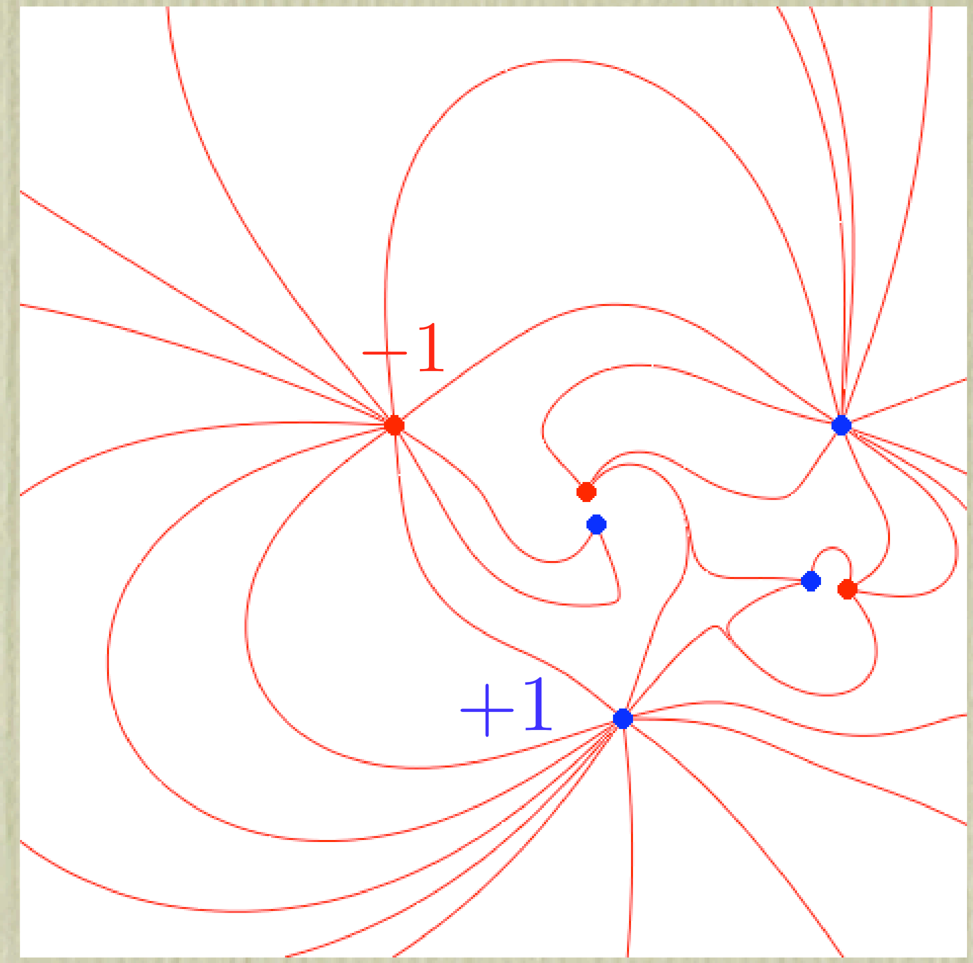
$Q_d = -1/3$

low momentum photons do not resolve the quarks

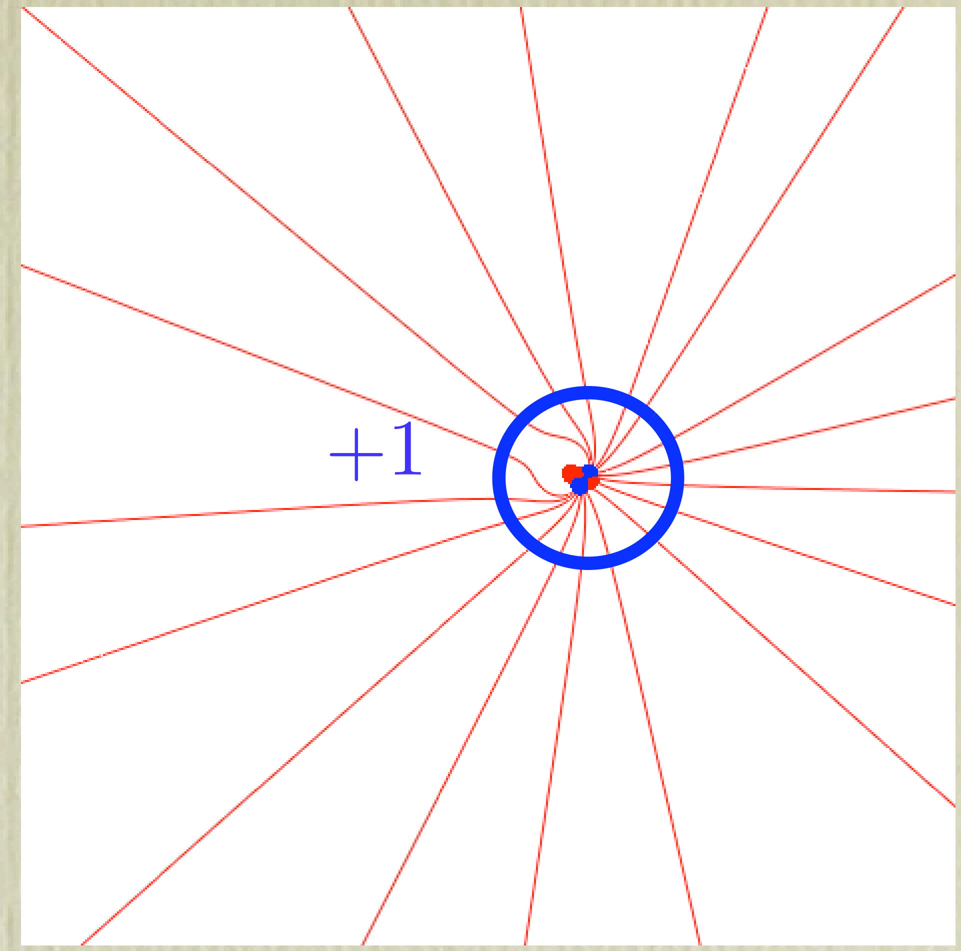
When matching

couplings change too: $Q_{u,d} \longrightarrow Q_p$

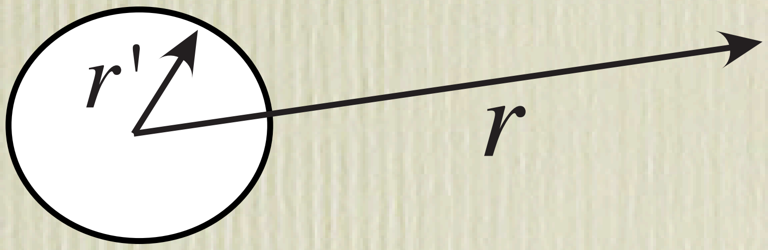
short distance



long distance



This is just an application of the multipole expansion, familiar from electromagnetism:



$$\mathcal{V}(\vec{r}) = \frac{1}{r}\underbrace{\int \rho \, d^3 r'}_{\text{total charge}} + \frac{1}{r^2}\int r' cos\theta \rho \, d^3 r' + \ldots$$

$$200 \, \text{MeV} \gg \underset{\nwarrow \text{keV}}{p_\gamma} \Leftrightarrow r' \ll r$$

Compute the H_m :

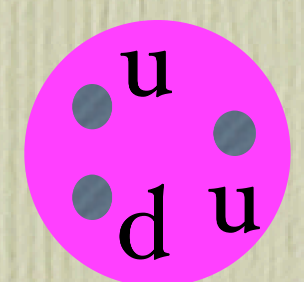
$$H = H_0 + \sum_{m=1}^{\infty} \epsilon^m \, H_m$$

Relativity: $\dfrac{p^4}{8m_e^3} + \dots$

QED: $\mu_e \, , \quad \vec{L} \cdot \vec{S} \quad , \dots$ (coefficients determined by $\alpha \, , m_e$)

What about quarks?

size ~ 1 fm $\longrightarrow$ 200 MeV $\gg p_\gamma$



$Q_u = +2/3$

$Q_d = -1/3$

low momentum photons do not resolve the quarks

When matching

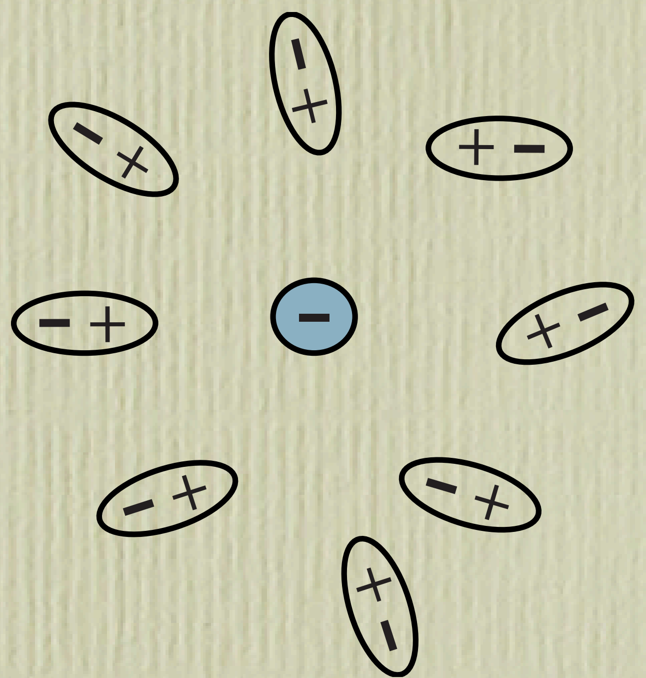
couplings change too: $Q_{u,d} \rightarrow Q_p$

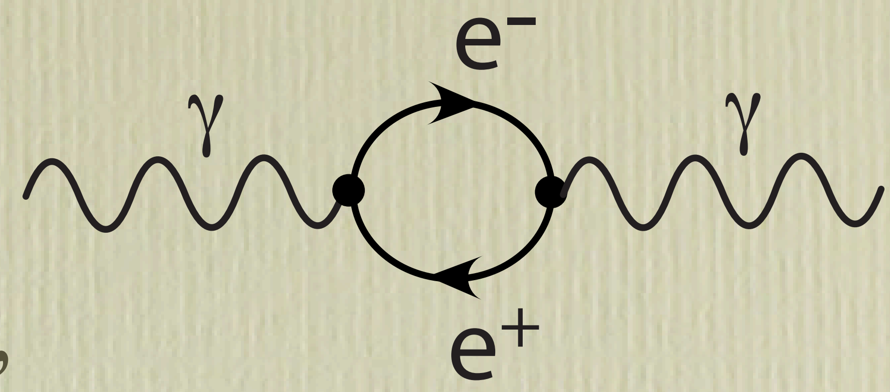
other parameters: $m_p, \mu_p \, , \dots$

in principle fixed by QCD, but it is more accurate to use experimental measurements

measure a parameter in one place, then use it in others = universality

Vacuum Polarization





like a dielectric,
gives screening

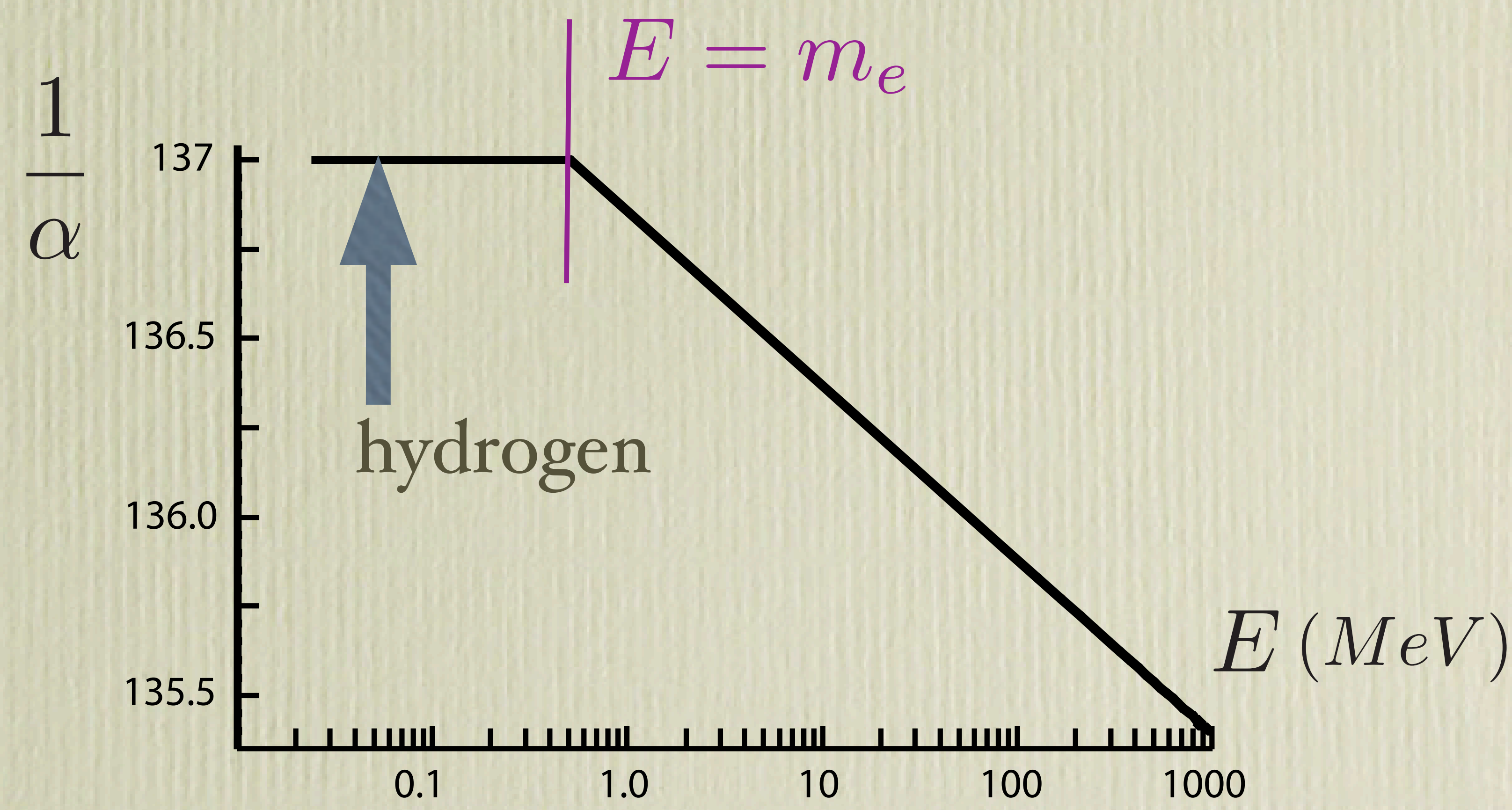
$$\alpha = \frac{e^2}{4\pi}$$

coupling is
renormalized

resolution $\mu = E$

$$\mu \frac{d}{d\mu}\alpha(\mu) = \frac{2}{3\pi}\alpha^2(\mu)$$

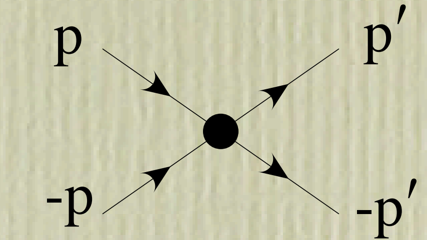
at larger energy E, we
probe shorter distances
and see a larger charge

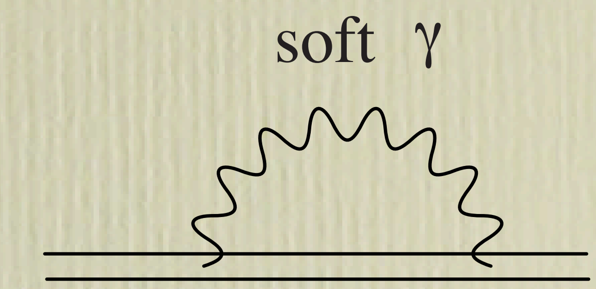


$$\alpha(E) = \frac{\alpha(0)}{1 - \frac{\alpha(0)}{3\pi}\ln\left(\frac{E^2}{m_e^2}\right)}$$

Lamb Shift in NRQED

Two parts:





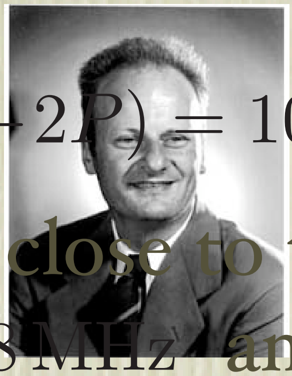
i) effective potentials (short distance)

ii) radiation in the bound state (long distance)

$$\delta E_n = \left[\frac{4\alpha^2}{3m_e^2}|\psi_n(0)|^2 \ln\left(\frac{\mu}{m_e}\right)+\ldots\right]+\left[\frac{1}{m_e^2}\sum_{k\neq n}|\langle n|\hat{p}|k\rangle|^2(E_k-E_n)\ln\left(\frac{\mu}{|E_n-E_k|}\right)+\ldots\right]$$

μ dependence cancels, but allows us to give separate meaning to the two pieces

History:



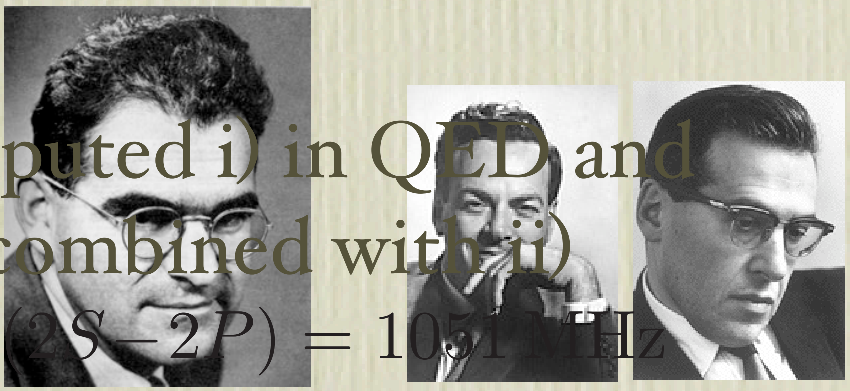
$\Delta E(2S-2P) = 1040\,\mathrm{MHz}$

close to the 1058 MHz answer

- 1947 Bethe computed ii), with $\mu = m_e$

  → large log: $\sim \ln\left(\frac{m_e}{m_e\alpha^2}\right) = -2\ln(\alpha)$

- 1949 French & Weisskopf
  Lamb & Kroll
  (Feynman, Schwinger)



computed i) in QED and combined with ii)

$\Delta E(2S-2P) = 1051\,\mathrm{MHz}$

The structure of QED logs can be derived from a non-relativistic renormalization group

Manohar, I.S.

$$E = \frac{p^2}{2m}$$

energy resolution μ_E

momentum resolution μ_p

$$\mu_E \sim \frac{\mu_p^2}{m}$$

Correction	Observable	System	Comparison
$\alpha^8 \ln^3 \alpha$	Lamb shift	H	agrees*
		μ^+e^-, e^+e^-	new
	(no h.f.s., no $\Delta\Gamma/\Gamma$)		
$\alpha^7 \ln^2 \alpha$	h.f.s.	H, μ^+e^-, e^+e^-	agrees
	Lamb shift	H, μ^+e^-, e^+e^-	agrees
$\alpha^3 \ln^2 \alpha$	$\Delta\Gamma/\Gamma$	e^+e^- ortho and para	agrees
$\alpha^6 \ln \alpha$	Lamb shift	H, μ^+e^-, e^+e^-	agrees
	h.f.s.	H, μ^+e^-, e^+e^-	agrees
$\alpha^2 \ln \alpha$	$\Delta\Gamma/\Gamma$	e^+e^- ortho and para	agrees
$\alpha^5 \ln \alpha$	Lamb shift	H, μ^+e^-, e^+e^-	agrees

all from one equation

LO anomalous dimension: $\alpha^4(\alpha \ln \alpha)^k$ stops at $k = 1$

NLO anomalous dimension: $\alpha^5(\alpha \ln \alpha)^k$ stops at $k = 3$

The structure of QED logs can be derived from a non-relativistic renormalization group

Manohar, I.S.

$$E = \frac{p^2}{2m}$$

energy resolution μ_E

momentum resolution μ_p

$$\mu_E \sim \frac{\mu_p^2}{m}$$

NRQED methods are also used for the non-logarithmic terms

		Expt.(MHz)	Theory(MHz)	Agree?
H	Lamb	$1057.845(9)$	$1057.85(1)$	$< r_p^2 >$
	h.f.s	$1420.405751768(1)$	$1420.399(2)$	G_E, G_M
$\mu^+ e^-$	h.f.s	$4463.30278(5)$	$4463.30288(55)$	m_e/m_μ
$e^+ e^-$	Lamb	$13012.4(1)$	$13012.41(8)$	agree
	h.f.s	$203389.10(74)$	$203391.70(50)$	3σ
	Γ_{para}	$7990.9(1.7)\ \mu s^{-1}$	$7989.62(4)\ \mu s^{-1}$	agree
	Γ_{ortho}	$7.0404(13)\ \mu s^{-1}$	$7.03996(2)\ \mu s^{-1}$	agree

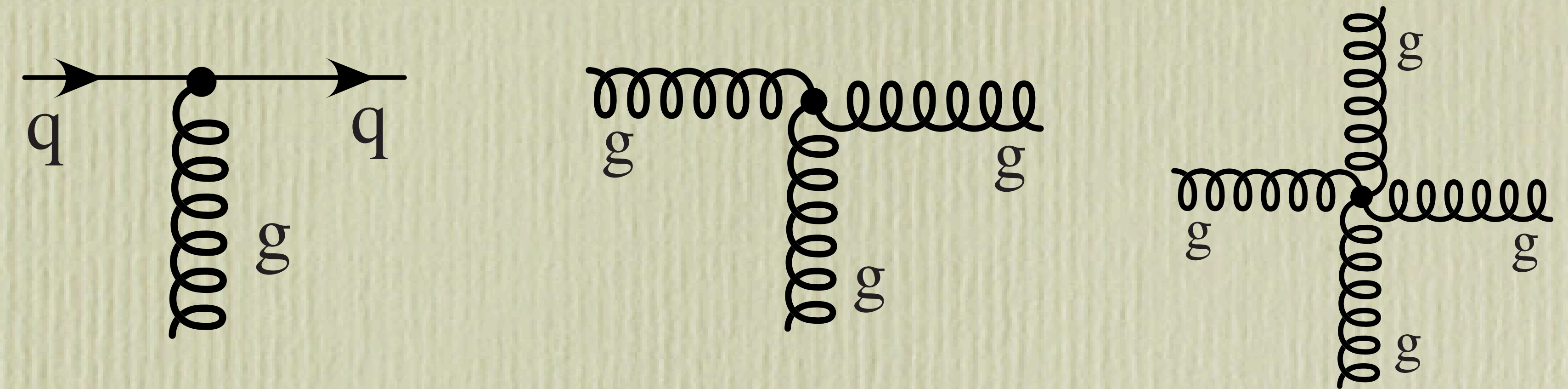
The ideas we've discussed in QED:

- resolution μ
- changes in degrees of freedom & couplings
- expansions, multiple scales
- universality

become even more crucial for QCD

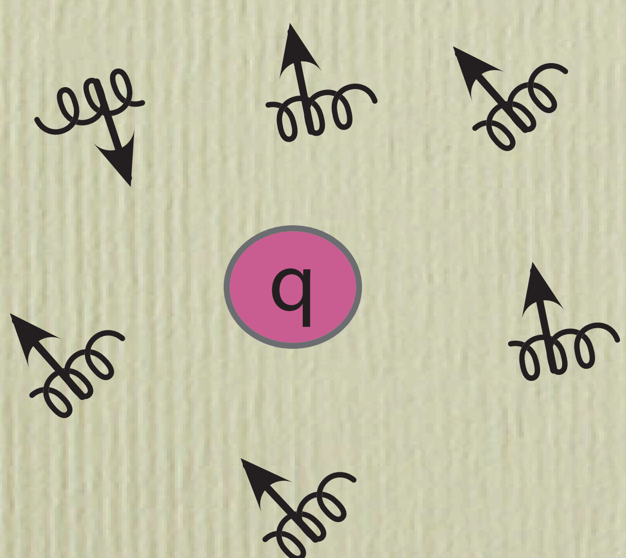
QCD Interactions are more complicated than QED:

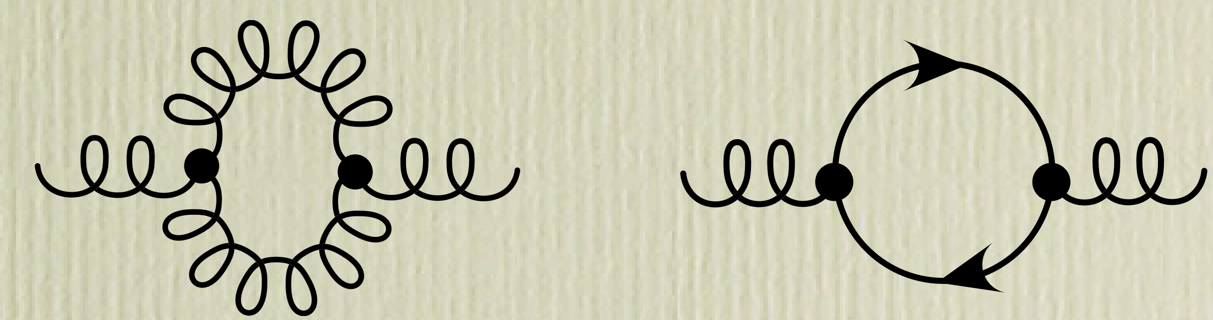
strong coupling: $g(\mu)$ $\qquad \alpha_s(\mu) = \frac{g(\mu)^2}{4\pi}$



these interactions involve the same coupling (gauge symmetry)

Vacuum response?





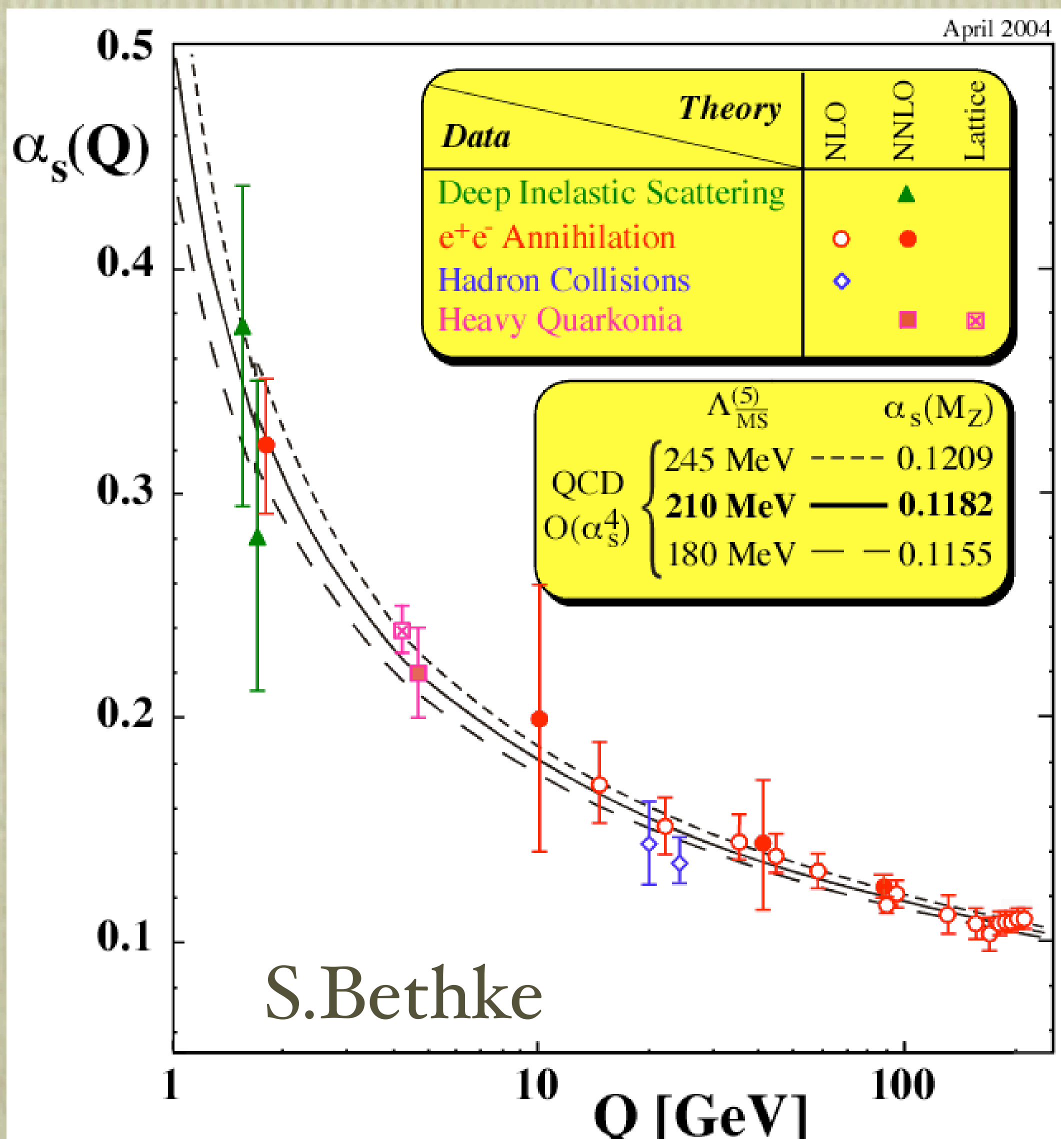
gluons have spin, carry color charge

behave like a permanent magnet
anti-screen the charge

$$\beta(g) = \mu \frac{d}{d\mu} g(\mu) = -\frac{g(\mu)^3}{16\pi^2}\left(11 - \frac{2}{3} n_f\right) \quad < 0$$

In QCD, the coupling , $g(\mu)$, behaves in the opposite way to QED, it gets weaker at short distances

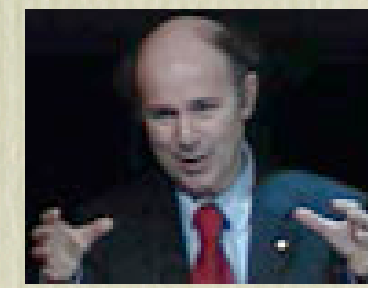
slope is negative



large change in the value

$$\alpha_s(\mu) = \frac{g(\mu)^2}{4\pi} \qquad \beta(g) = \mu \frac{d}{d\mu} g(\mu) < 0$$

Gross, Politzer, Wilczek



Nobel Prize, 2004

Asymptotic freedom

large $\mu = Q$, small α_s , free quarks

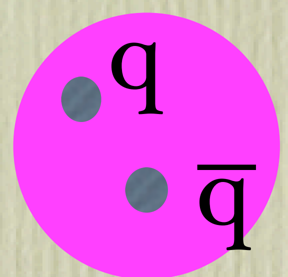
Infrared slavery

as $\mu = Q$ approaches a few $100\,\mathrm{MeV}$ $(r \to 1\,\mathrm{fm})$, the coupling gets large an expansion in $\alpha_s(\mu < 1\,\mathrm{GeV})$ is no good

→ coupling gets so strong that quarks never escape unless they form a color singlet (bound) state with other quarks, ie. they are confined

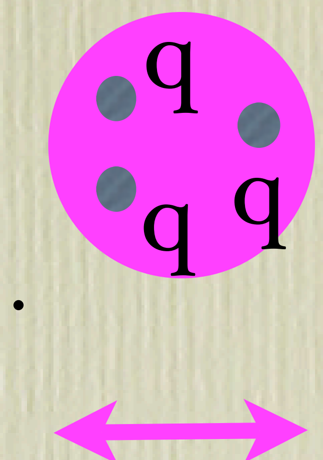
Mesons

$\pi,\ K,\ \rho,\ \ldots$



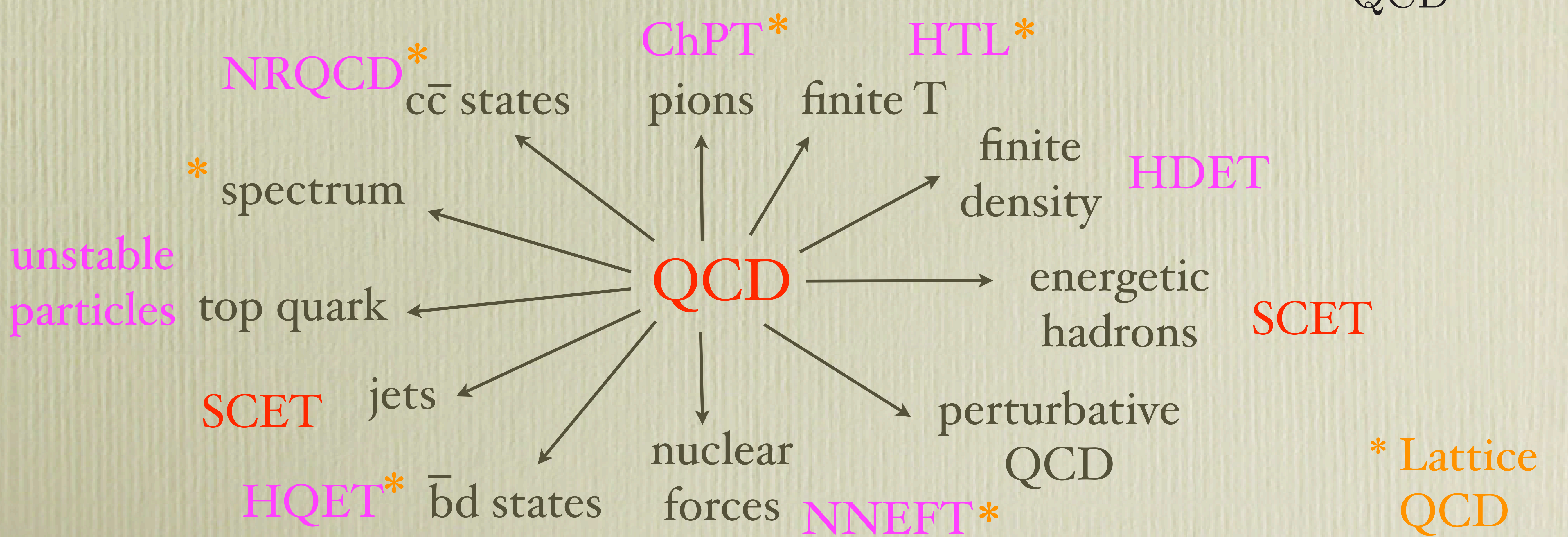
Baryons

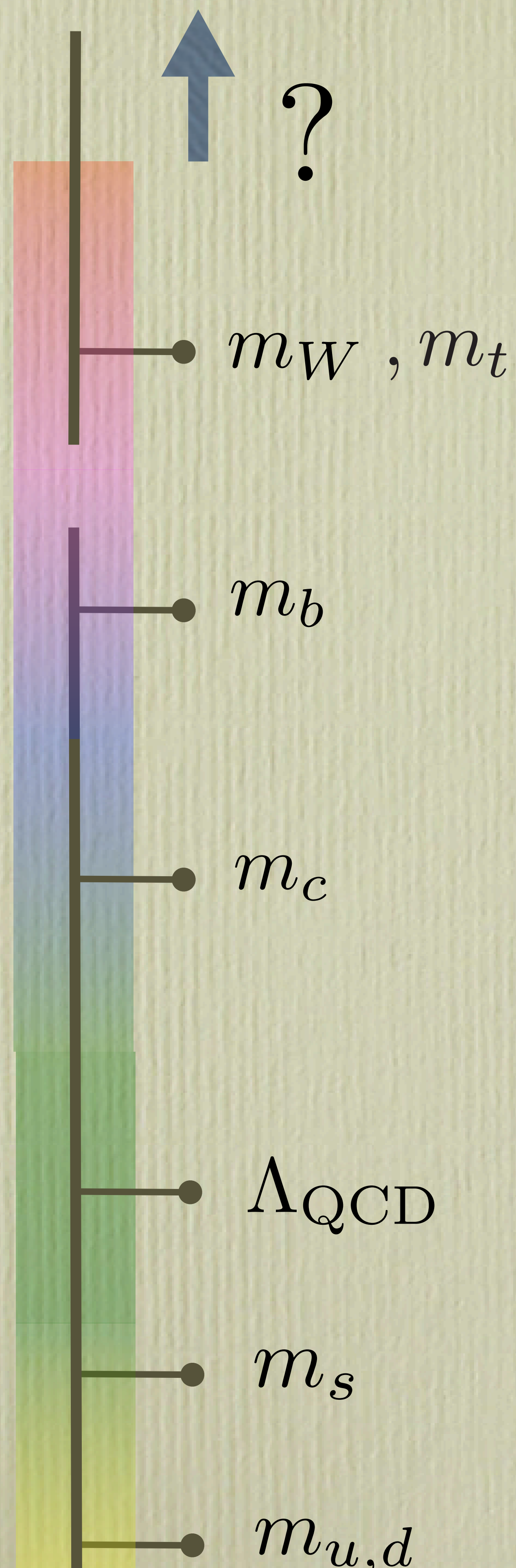
$p,\ n,\ \Sigma,\ \Delta,\ \ldots$



$r = \Lambda_{\mathrm{QCD}}^{-1}$

degrees of freedom change





Is there a "Hydrogen Atom" for QCD?

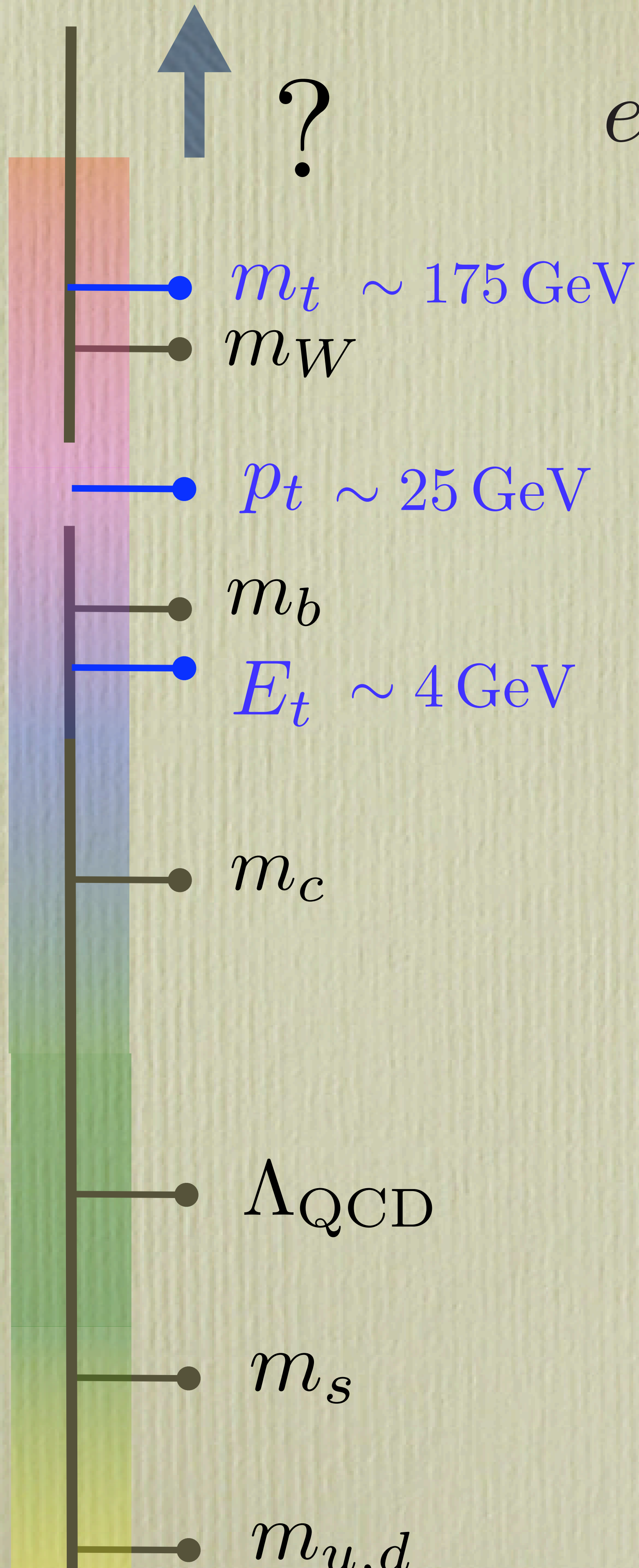
candidates:

i) top quarks: $t\,\bar{t}$

ii) proton

iii) B mesons

Nonrelativistic QCD bound states?



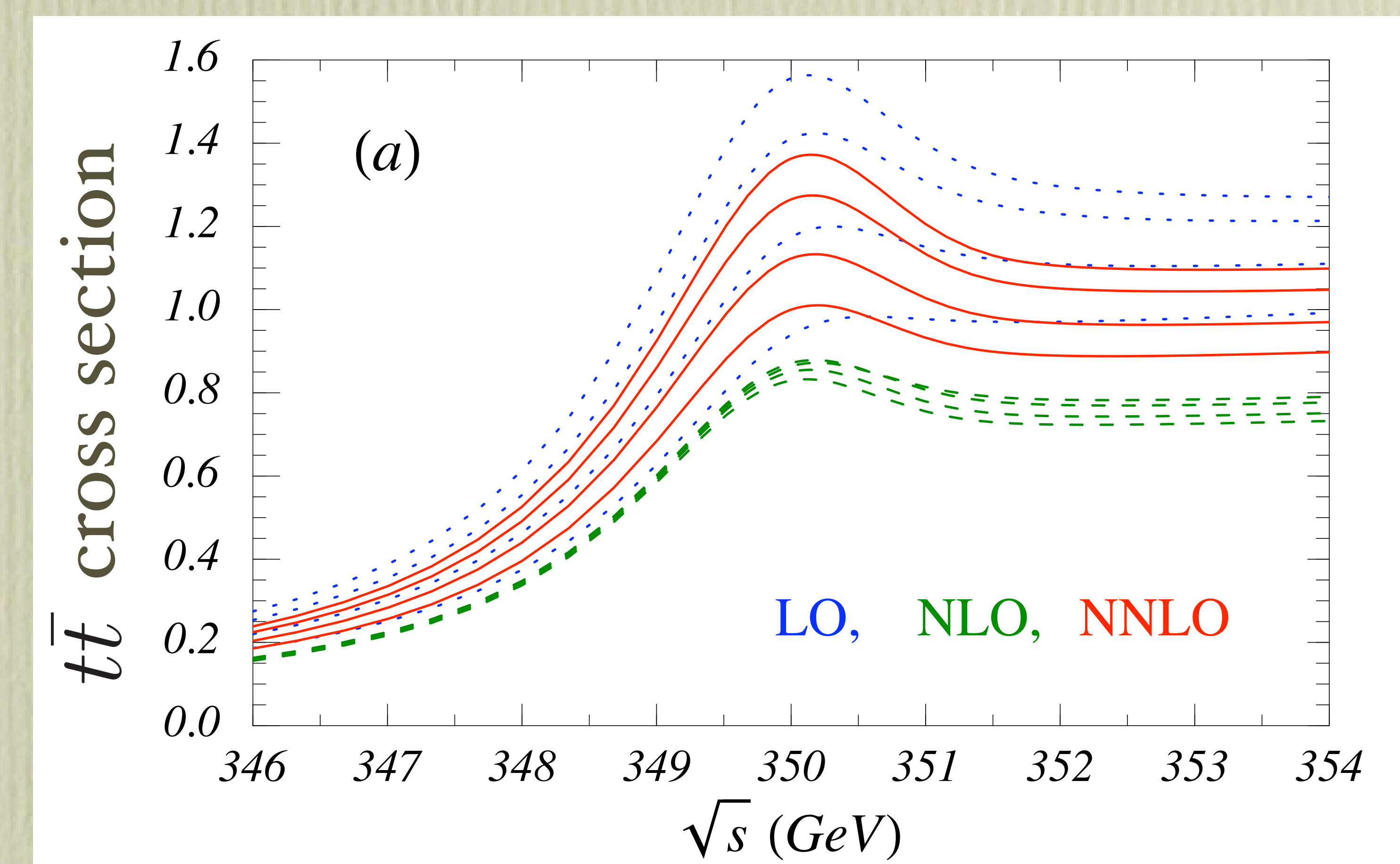
$$e^+e^- \to t\bar{t}$$

$$\Gamma_t = 1.4\,\mathrm{GeV} \gg \Lambda_{\mathrm{QCD}}$$

top decays before it hadronizes

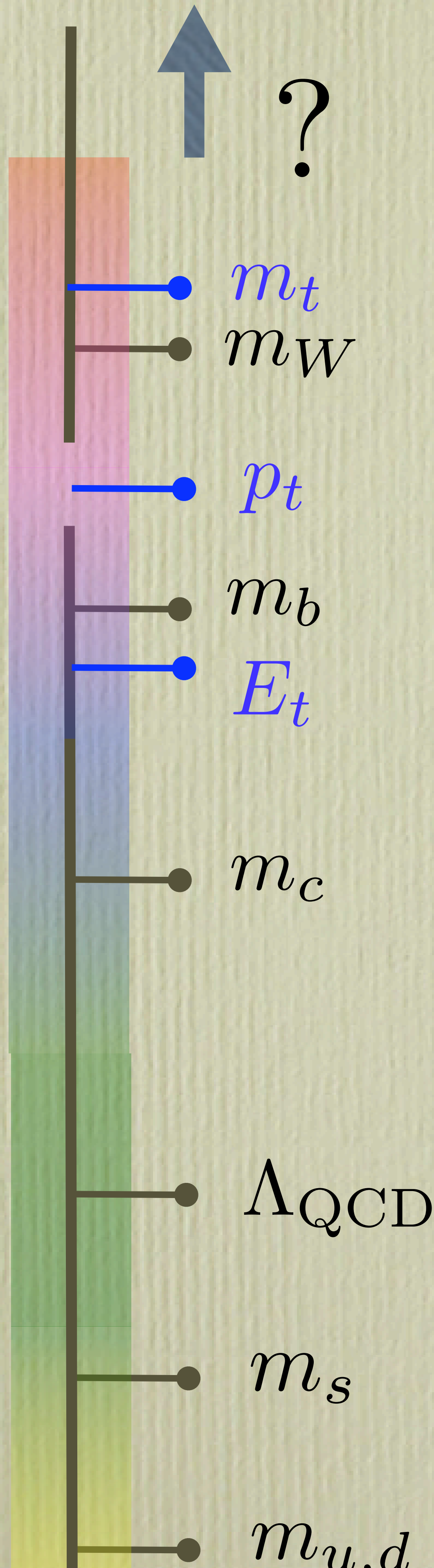
Coulombic, expansion in $\alpha_s(\mu)$:

$$\mathrm{LO} + \mathrm{NLO} + \mathrm{NNLO} + \ldots$$



vary μ

$\mu = m_t, p_t, E_t$?



$$e^+e^- \to t\bar{t}$$

Nonrelativistic QCD bound states?

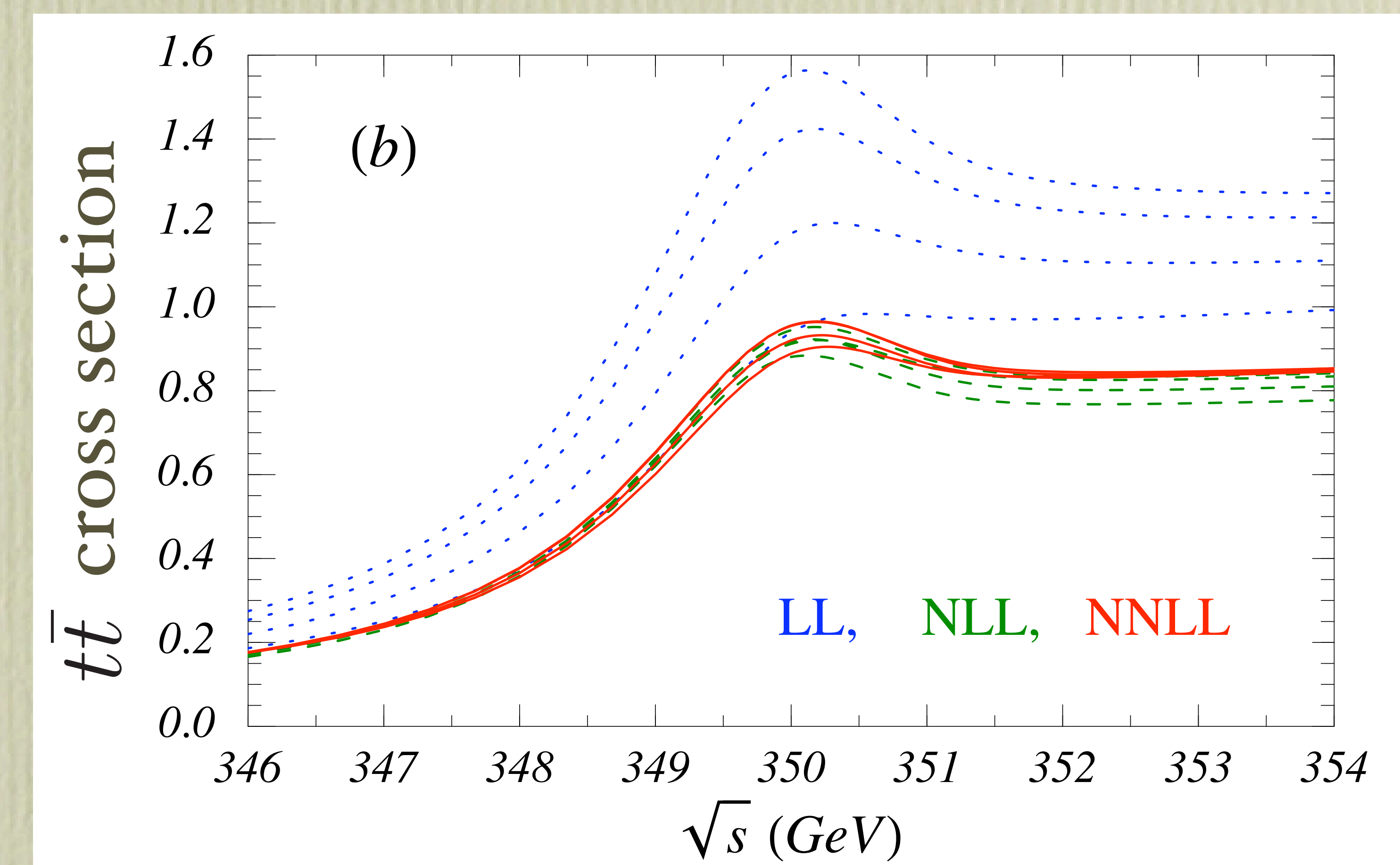
$$\Gamma_t = 1.4\,\mathrm{GeV} \gg \Lambda_{\rm QCD}$$

top decays before it hadronizes

Determine the right scales

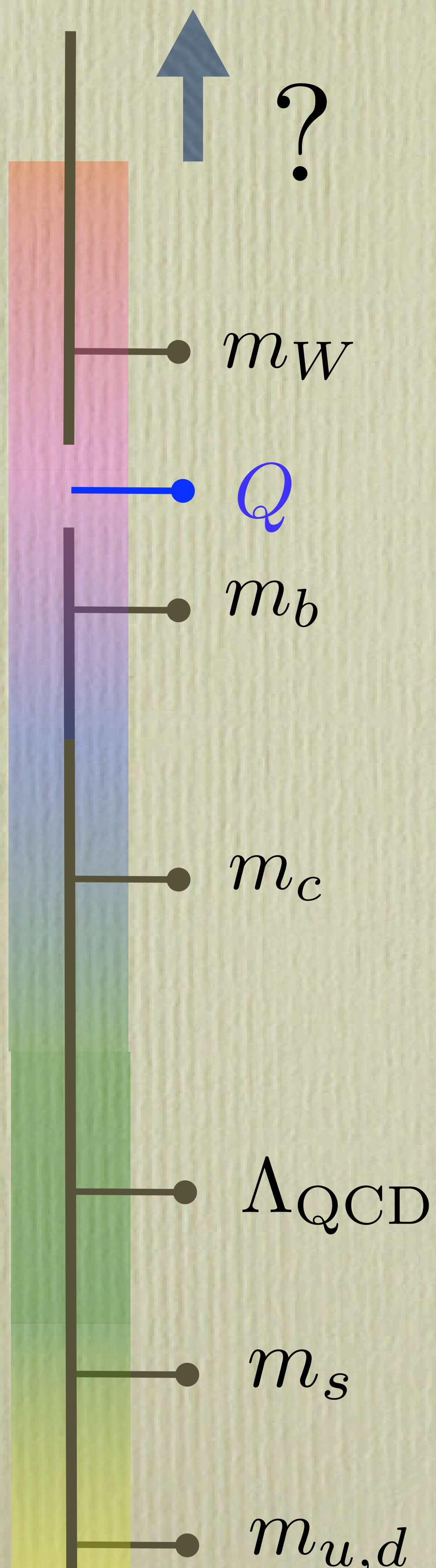
$$\mu \frac{d}{d\mu} C_i(\mu) = \ldots$$

Hoang, Manohar, I.S., Teubner



vary μ

$\rightarrow m_t, y_t, \Gamma_t$



$$e^- p \to e^- X$$

Deep Inelastic Scattering on a proton

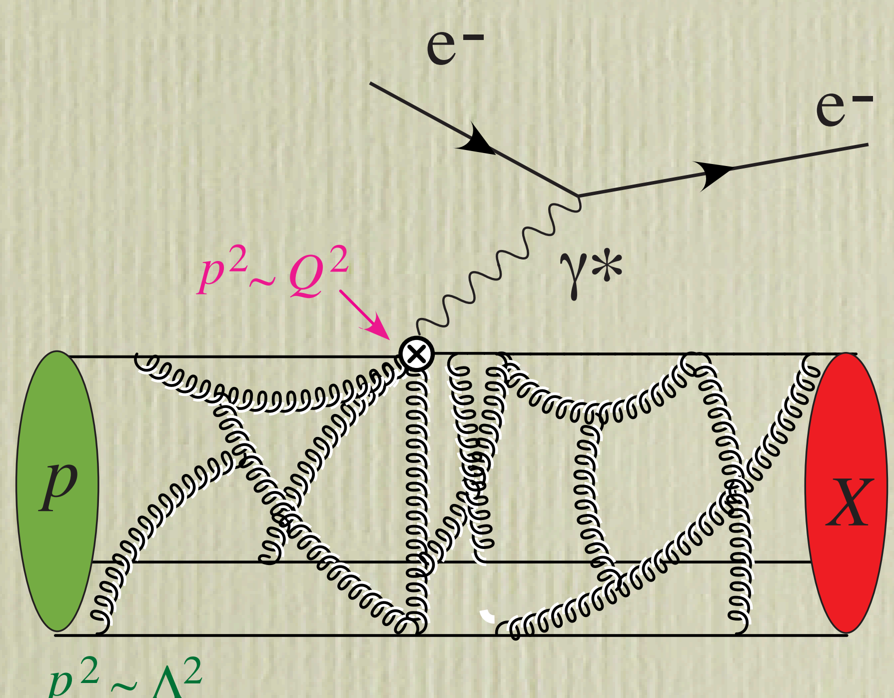
A factorization theorem

$$F_1(x, Q^2) = \frac{1}{x}\int_x^1 d\xi \; H(\xi/x, Q, \mu) \; f_{i/p}(\xi, \mu)$$

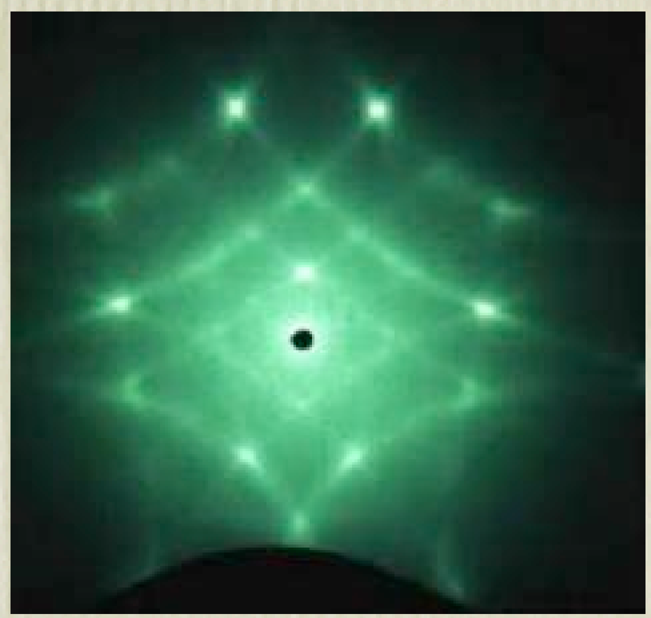
short distance process $p^2 \sim Q^2$

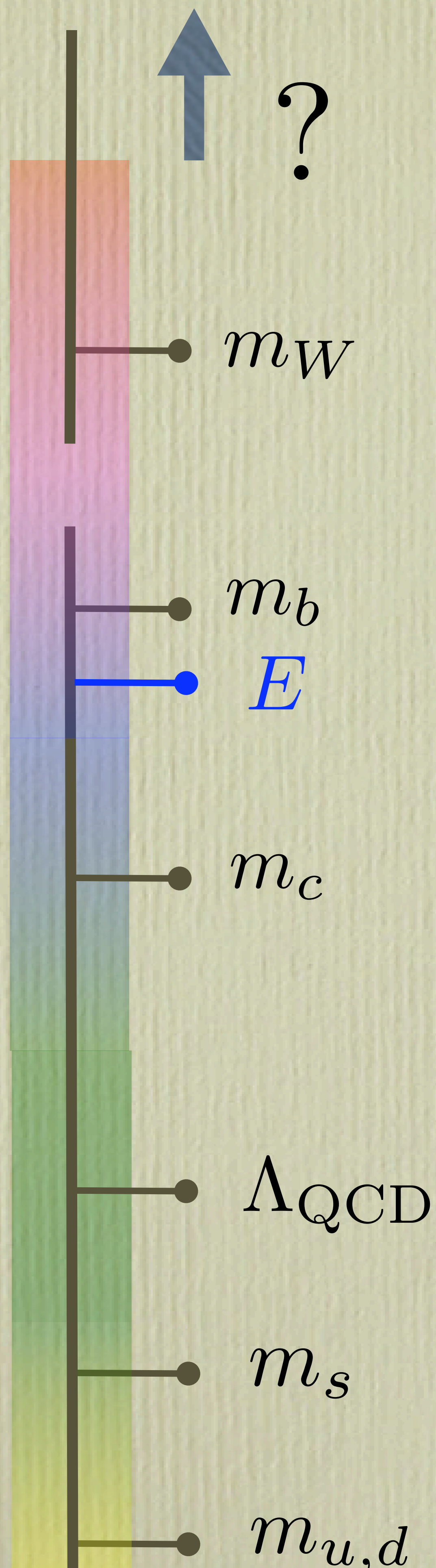
universal nonperturbative function

$p^2 \sim \Lambda^2_{\mathrm{QCD}}$

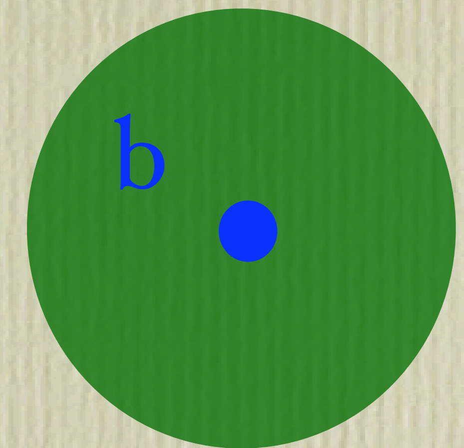


analogy: Bragg scattering of X-rays on a crystal, for this time scale the atoms are at rest





B-meson



$m_b \gg \Lambda_{\rm QCD}$

heavy quark symmetry

Isgur & Wise

Decay by weak interactions; long lived

$B \to X_u \ell \bar{\nu}$ $\quad B \to D\pi \quad B \to K^*\gamma$

$B \to \pi \ell \bar{\nu} \quad B \to X_s \gamma \quad B \to \rho\gamma$

$B \to D^* \eta' \quad B \to \rho\rho \quad B \to \pi\pi \quad B \to K\pi \quad B \to \gamma \ell \bar{\nu}$

Precision studies are sensitive to scales > m_W

The B is heavy, so many of its decay products are energetic, E

eg. $B \to D\, e\, \bar{\nu}$, $\quad M_W^2 \gg m_b^2 \gg \Lambda^2$

1) Short Distance

2) Intermediate Distance

3) Very Long Distance

4) Long Distance

$\mu = M_W \simeq 80\,\mathrm{GeV}$

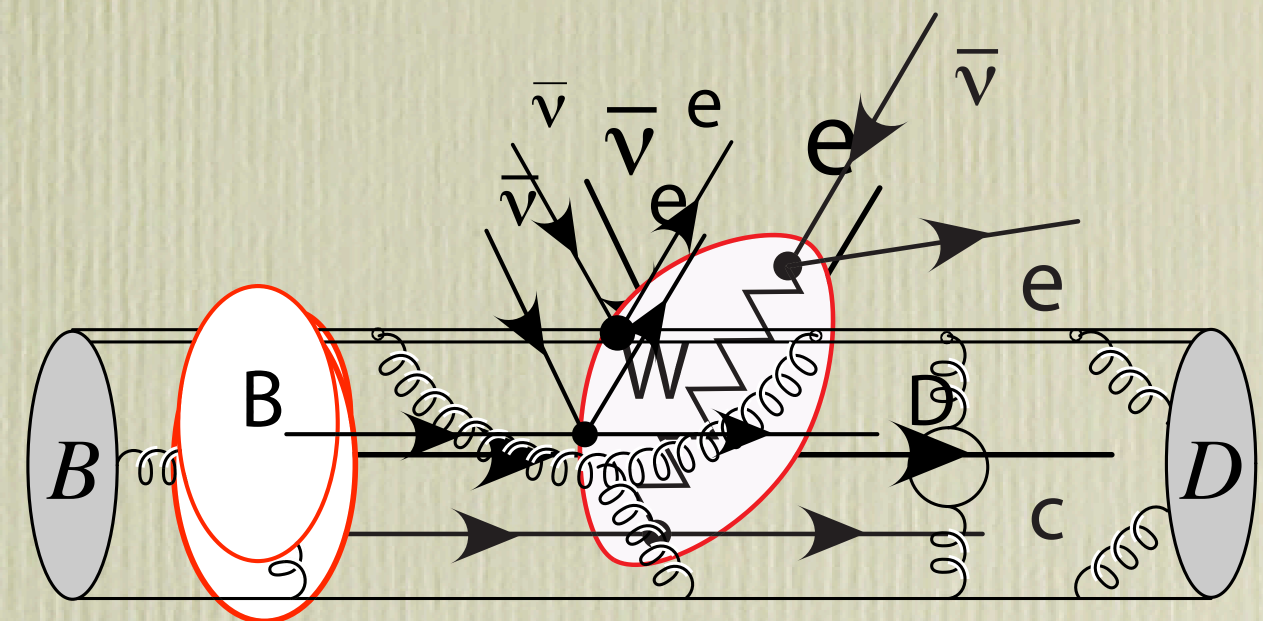
$\mu = m_b \simeq 5\,\mathrm{GeV}$

$\mu \ll m_b$

$\mu = \Lambda \simeq 0.5\,\mathrm{GeV}$

gluons perturbative

gluons nonperturbative



-
- $\mathcal{L}_1 \to \mathcal{L}_2 \to \mathcal{L}_3 \to \mathcal{L}_4$
- μ

expansion parameters $\quad \dfrac{m_b^2}{m_W^2} \simeq \dfrac{1}{250}, \quad \alpha_s(m_b) \simeq 0.2, \quad \dfrac{\Lambda}{m_b} \simeq 0.1$

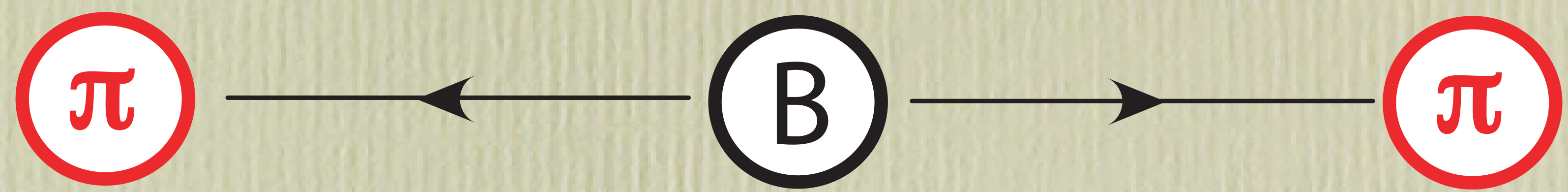
Soft - Collinear Effective Theory

Bauer, Pirjol, I.S.
Fleming, Luke

An effective field theory for energetic hadrons & jets

$$E \gg \Lambda_{\mathrm{QCD}}$$

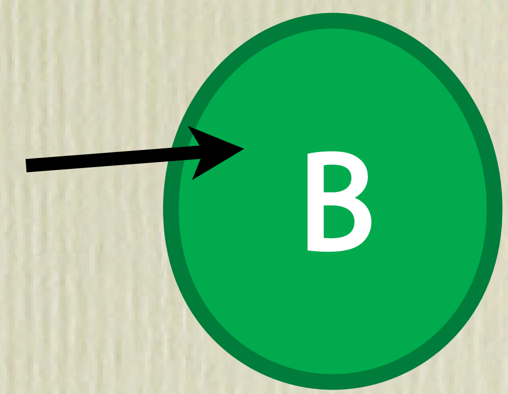
Soft Collinear Effective Theory (SCET)

eg. 

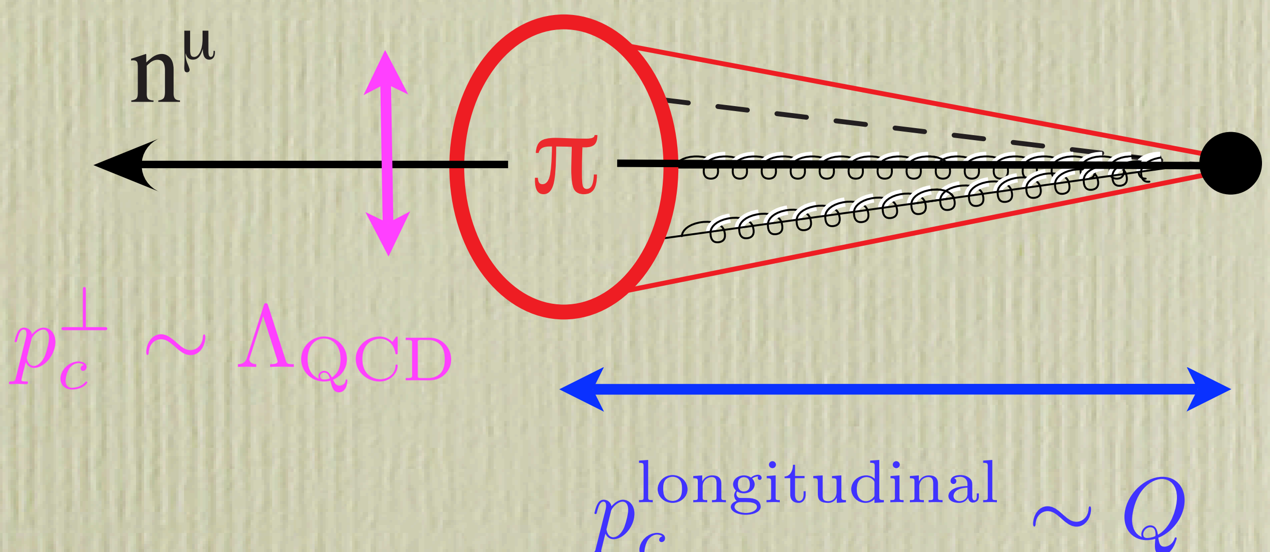
$E_\pi = 2.6\,\mathrm{GeV} \gg \Lambda_{\mathrm{QCD}} \sim 0.3\,\mathrm{GeV}$

B has Soft constituents:

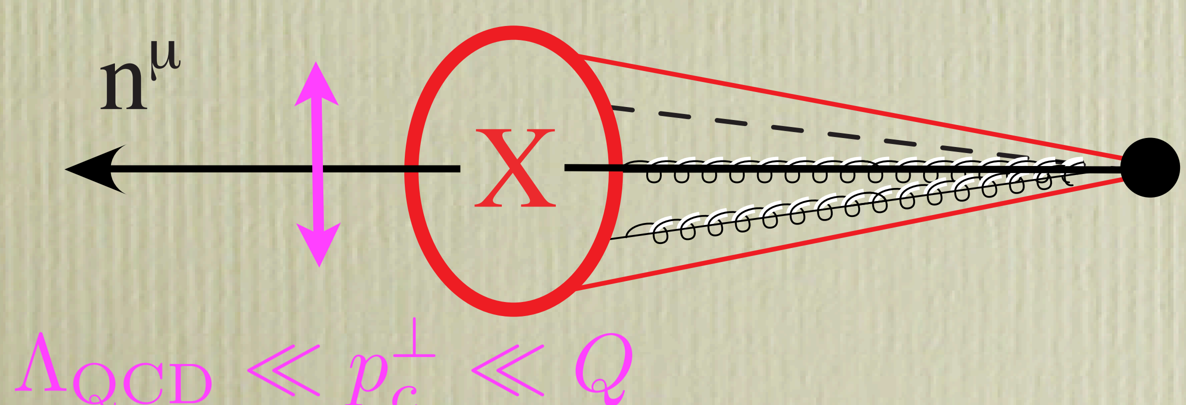
$p_s^\mu \sim \Lambda_{\mathrm{QCD}}$



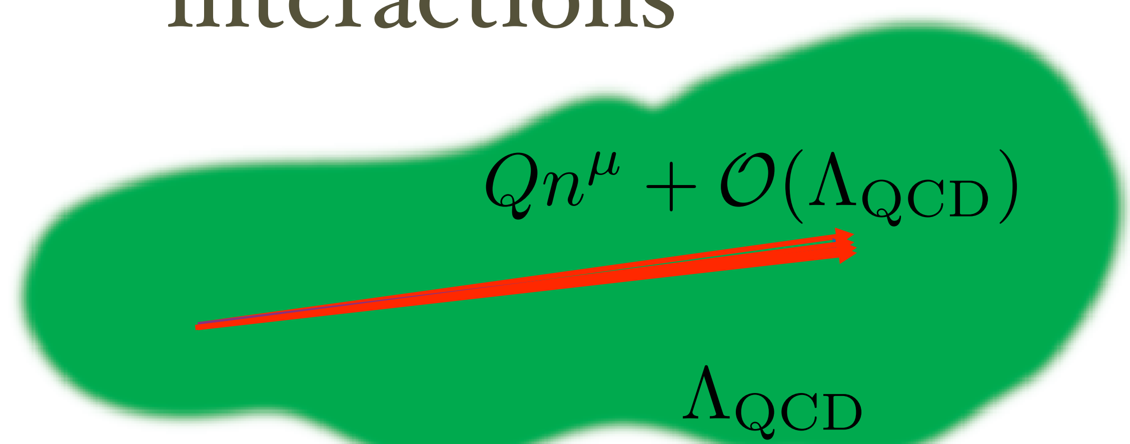
π has Collinear constituents:



or replace π by a jet of many hadrons



A field theory for
Soft & Collinear
interactions

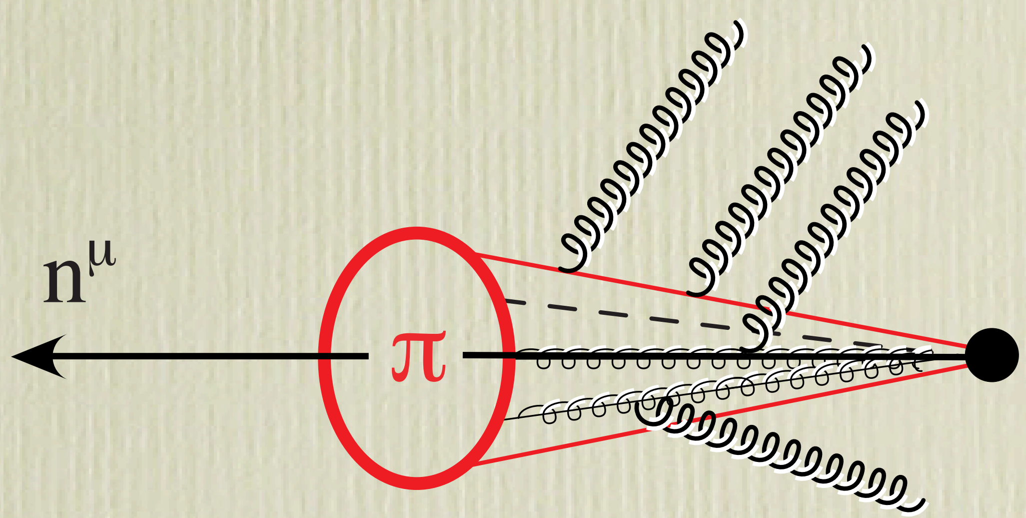


SCET is a field theory which:

- explains how these degrees of freedom communicate with each other, and with hard interactions
- organizes the interactions in a series expansion in $\dfrac{\Lambda_{\rm QCD}}{E}$
- provides a simple operator language to derive factorization theorems in fairly general circumstances

eg. unifies the treatment of factorization for exclusive and inclusive QCD processes

- new symmetry constraints
- scale separation & decoupling



How is SCET used?

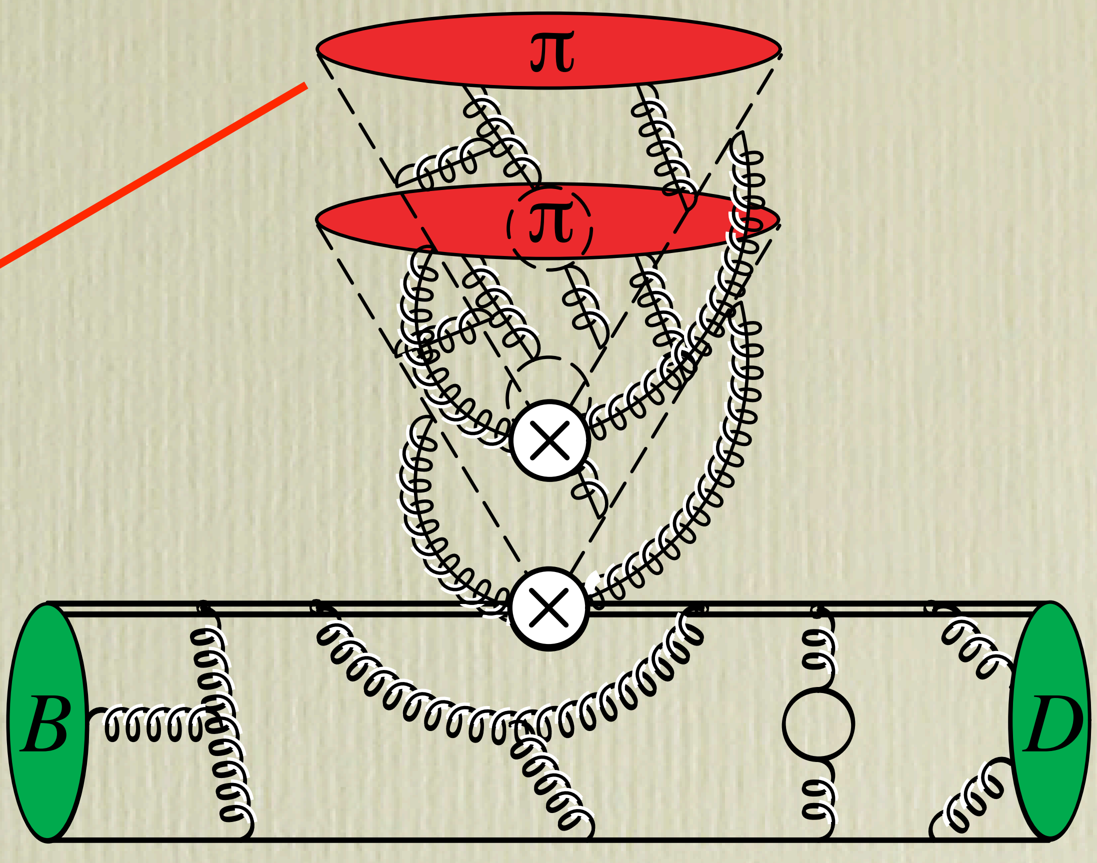
- cleanly separate short and long distance effects in QCD
  - ➡ derive new factorization theorems
  - ➡ find universal hadronic functions, exploit symmetries & relate different processes
- model independent, systematic expansion
  - ➡ study power corrections
- keep track of μ dependence
  - ➡ sum logarithms, reduce uncertainties

Factorization Example

$\bar{B}^0 \to D^+\pi^-$, $B^- \to D^0\pi^-$

B, D are soft , π collinear

$$\langle D\pi | H_{\rm weak} | B\rangle = N\xi(v\cdot v') \int_0^1 dx\, T(x,\mu)\ \phi_\pi(x,\mu)$$



$$\mathcal{L}_{\rm SCET} = \mathcal{L}_s^{(0)} + \mathcal{L}_c^{(0)}$$

Factorization if $H_{\rm weak} = O_s \times O_c$

Universal functions:

$$\langle D^{(*)} | O_s | B\rangle = \xi(v\cdot v')$$

$$\langle \pi | O_c(x) | 0\rangle = f_\pi \phi_\pi(x)$$

Calculate T, $\alpha_s(Q)$

$$Q = E_\pi, m_b, m_c$$

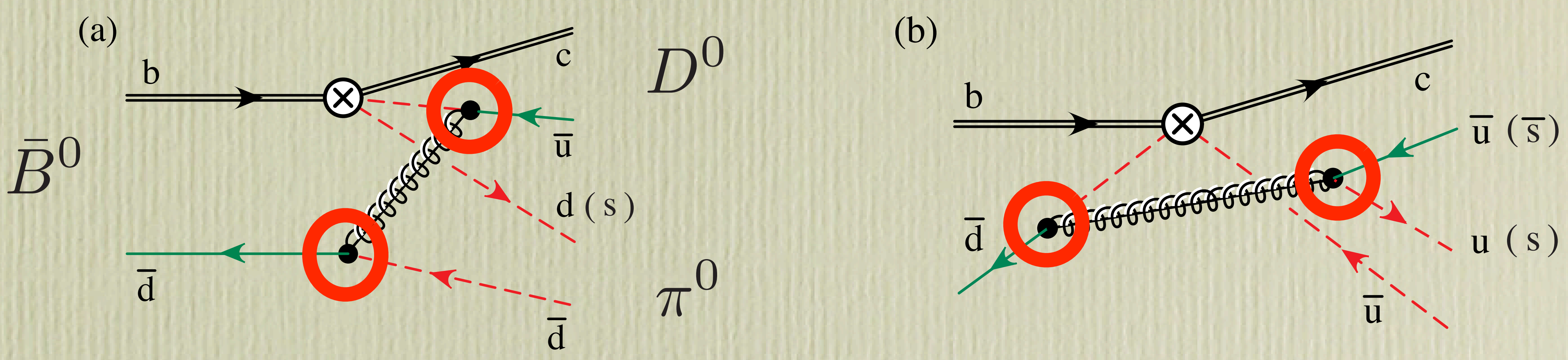
corrections will be $\Lambda/m_c \sim 30\%$

Color Suppressed Decays

Mantry, Pirjol, I.S.

$\bar{B}^0 \to D^0 \pi^0$ Intractable without SCET

subleading interaction



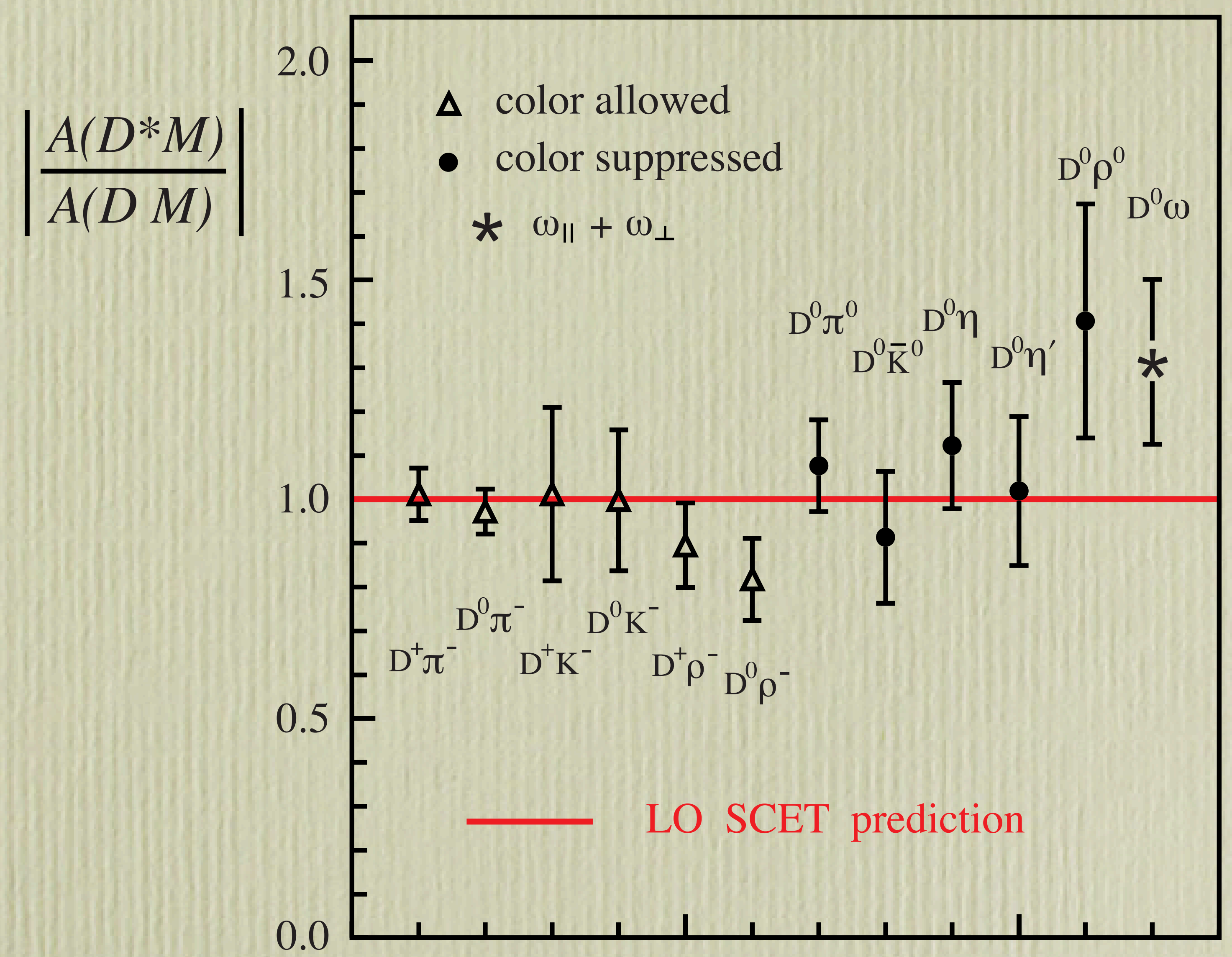
$$A_{00}^{D^{(*)}} = N_0^{(*)} \int dx\, dz\, dk_1^+ dk_2^+ \underbrace{T^{(i)}(z)}_{Q^2} \gg \underbrace{J^{(i)}(z, x, k_1^+, k_2^+)}_{Q\Lambda} \gg \underbrace{S^{(i)}(k_1^+, k_2^+)}_{\Lambda^2} \phi_M(x)$$

$Q = m_b, E_\pi, m_c$

prove S is same for D and D*

Comparison to Data

(Cleo, Belle, Babar)



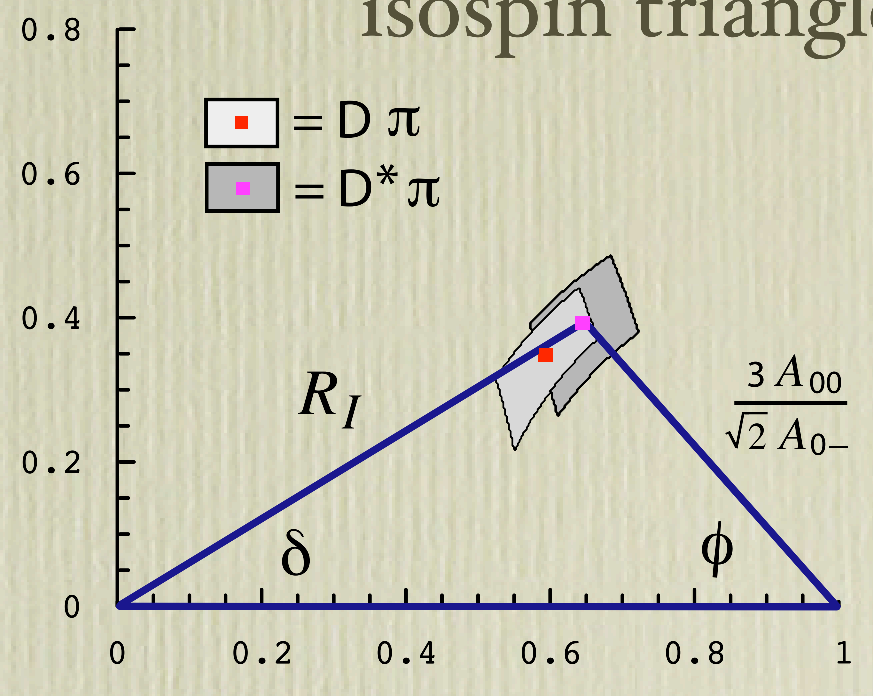
Extension to isosinglets:

Blechman, Mantry, I.S.

Extension to baryons (Λ_b) :

Leibovich, Ligeti, I.S., Wise

isospin triangle

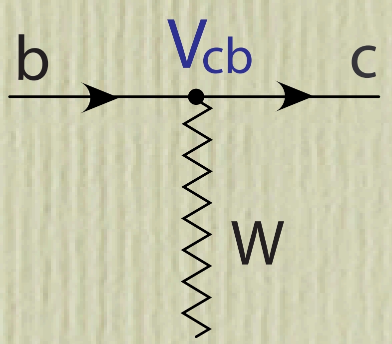


$$\delta(D\pi) = 30.4 \pm 4.8^\circ$$
$$\delta(D^*\pi) = 31.0 \pm 5.0^\circ$$

Not yet tested:

- $Br(D^*\rho^0_{\parallel}) \gg Br(D^*\rho^0_{\perp})$, $Br(D^{*0}K^{*0}_{\parallel}) \sim Br(D^{*0}K^{*0}_{\perp})$
- equal ratios $D^{(*)}K^*$, $D_s^{(*)}K$, $D_s^{(*)}K^*$; triangles for $D^{(*)}\rho$, $D^{(*)}K$

$B \to \pi\pi$ Decays & Weak Interactions



CKM Matrix

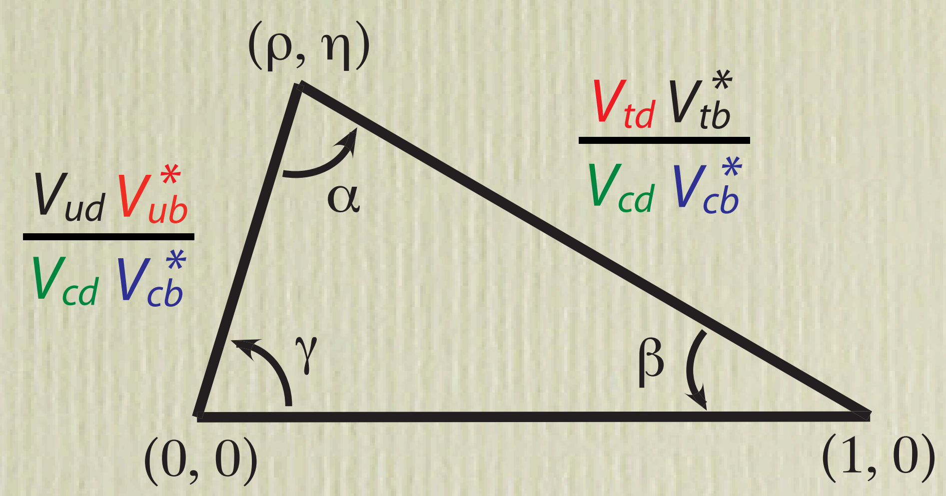
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

<u>Violate</u>

C: exchange of particles & antiparticles

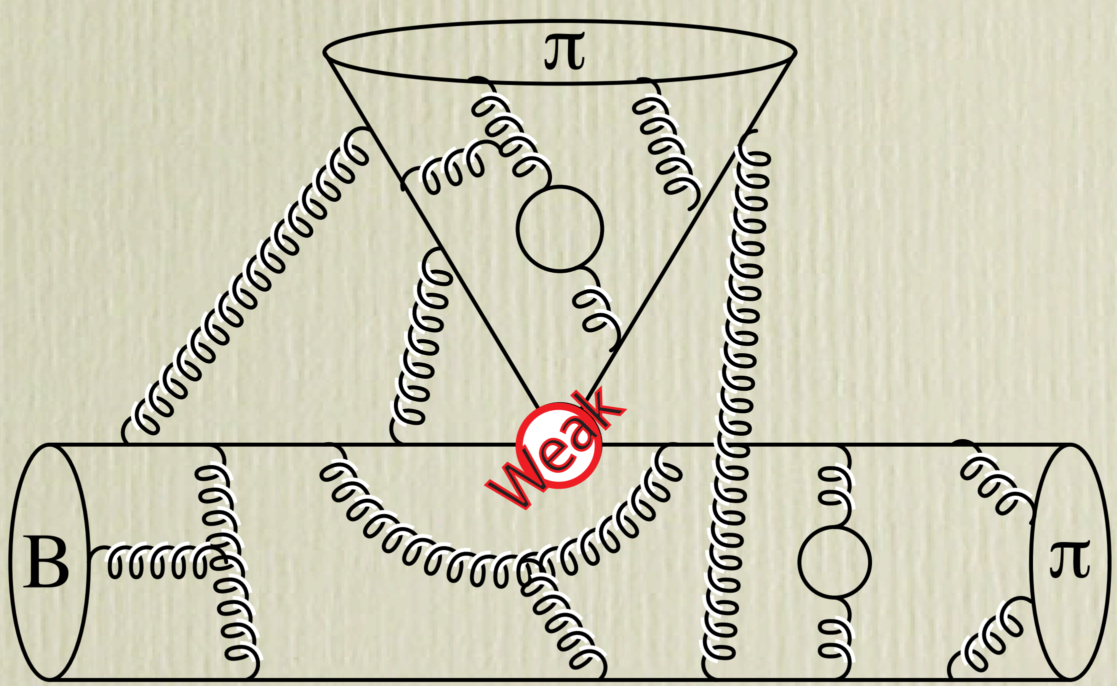
P: parity $\vec{x} \to -\vec{x}$

CP:



Can use CP-violating observables in $B \to \pi\pi$ to measure γ ,

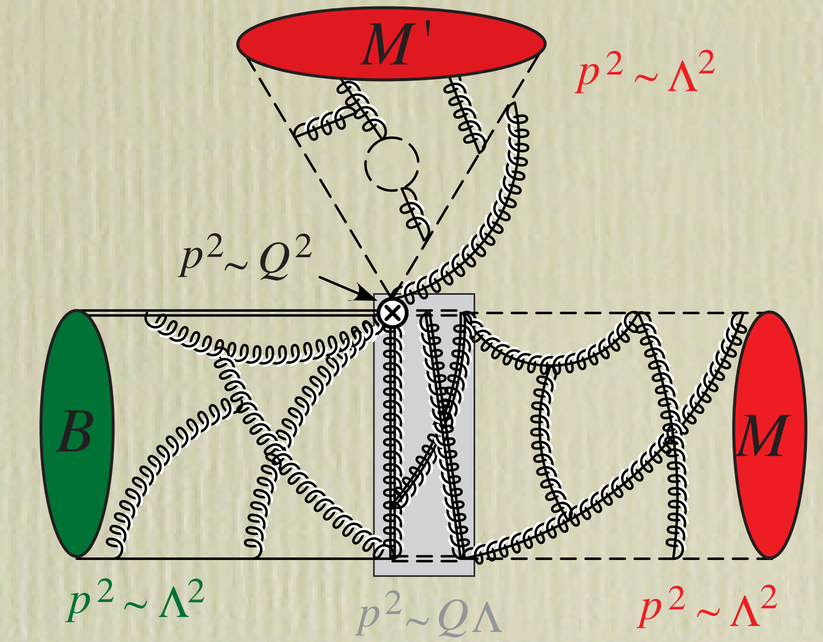
but need to control QCD interactions



Factorization with SCET

Bauer, Pirjol, Rothstein, I.S.;

Beneke, Buchalla, Neubert, Sachrajda



Resolution $\mu = m_b$

Nonleptonic $\quad B \to M_1 M_2 \quad$ ($\sim$ 120 channels)

$$A(B \to M_1 M_2) = A^{c\bar{c}} + N\Big\{ f_{M_2} \zeta^{BM_1} \int du\, T_{2\zeta}(u) \phi^{M_2}(u) + f_{M_2} \int du dz\, T_{2J}(u,z) \zeta_J^{BM_1}(z) \phi^{M_2}(u) + (1 \leftrightarrow 2) \Big\}$$

Form Factors

$$f(E) = \int dz\, T(z,E)\, \zeta_J^{BM}(z,E)$$
$$+\, C(E)\, \zeta^{BM}(E)$$

$B \to \pi \ell \bar{\nu}$,
$B \to K^* \ell^+ \ell^-$,
$B \to \rho\gamma$, ...

universality at $E\Lambda$

Resolution $\mu = \sqrt{E\Lambda}$, expansion in $\alpha_s(\sqrt{E\Lambda})$

$$\zeta_J^{BM}(z) = f_M f_B \int_0^1 dx \int_0^\infty dk^+ J(z,x,k^+,E) \phi_M(x) \phi_B(k^+)$$

$\zeta^{BM} = ?$ (left as a form factor)

Beneke, Feldmann
Bauer, Pirjol, I.S.
Becher, Hill, Lange, Neubert

$\boxed{B \to \pi\pi}$

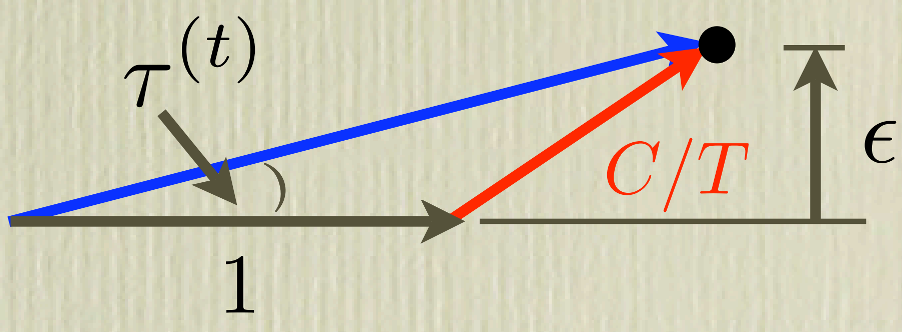
$$\bar{B}^0 \to \pi^+\pi^-, \quad B^- \to \pi^0\pi^-, \quad \bar{B}^0 \to \pi^0\pi^0,$$
$$B^0 \to \pi^+\pi^-, \quad B^0 \to \pi^0\pi^0$$

- $C_{\pi^0\pi^0} = -0.28 \pm 0.39$, uncertainty precludes measuring γ here
  (Belle & Babar)

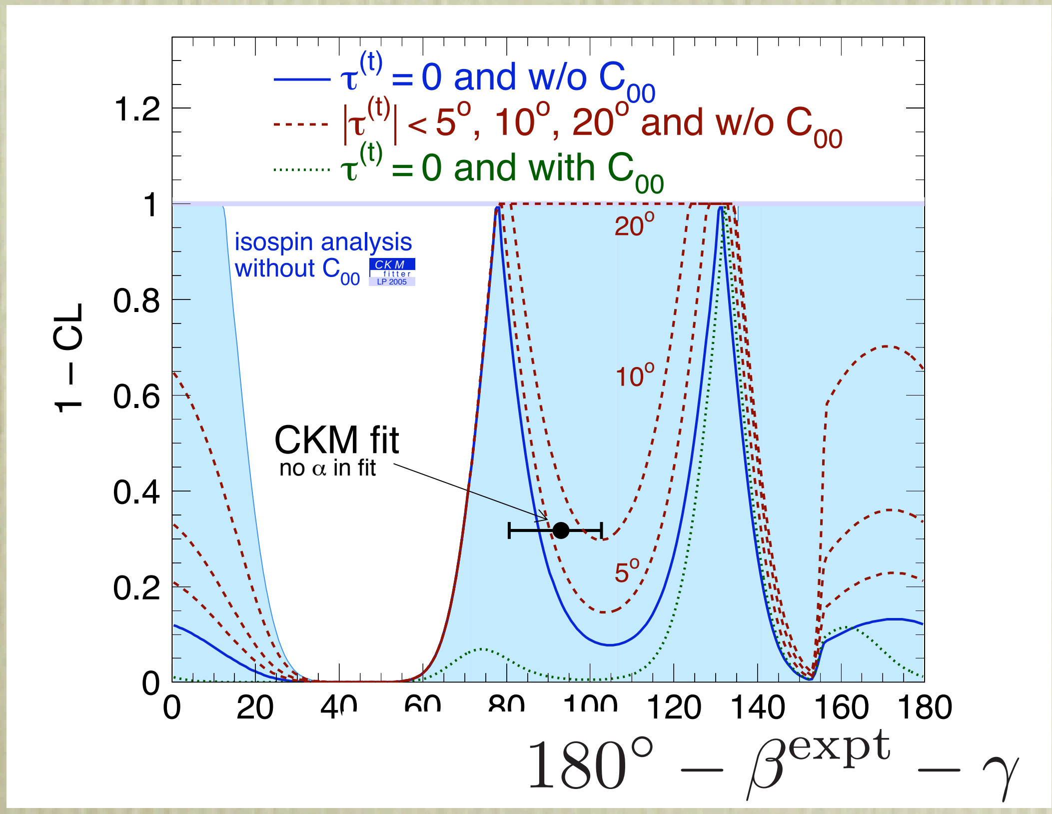
- $\frac{\Lambda_{\rm QCD}}{E_\pi} \ll 1$ Factorization predicts a **small relative phase** for two amplitudes $\epsilon \sim 0,\ \tau^{(t)} \sim 0$

Bauer, Rothstein, I.S.

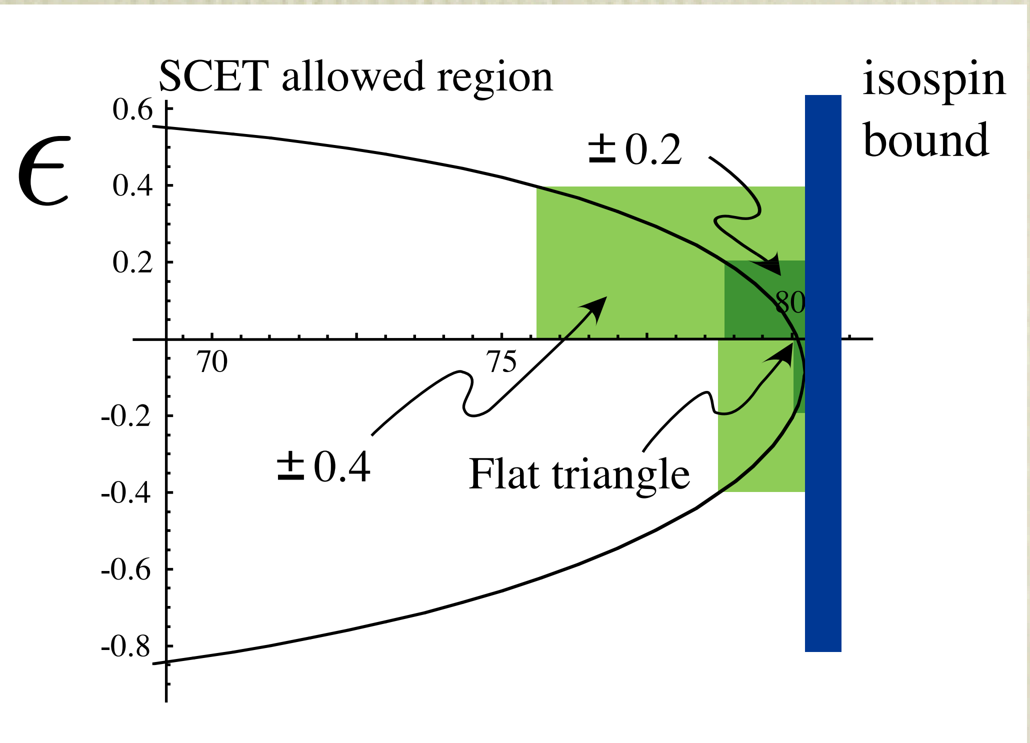
$$\epsilon = \mathrm{Im}\Big(\frac{C}{T}\Big) = \mathcal{O}\Big(\alpha_s(m_b), \frac{\Lambda}{E}\Big) \lesssim 0.2$$

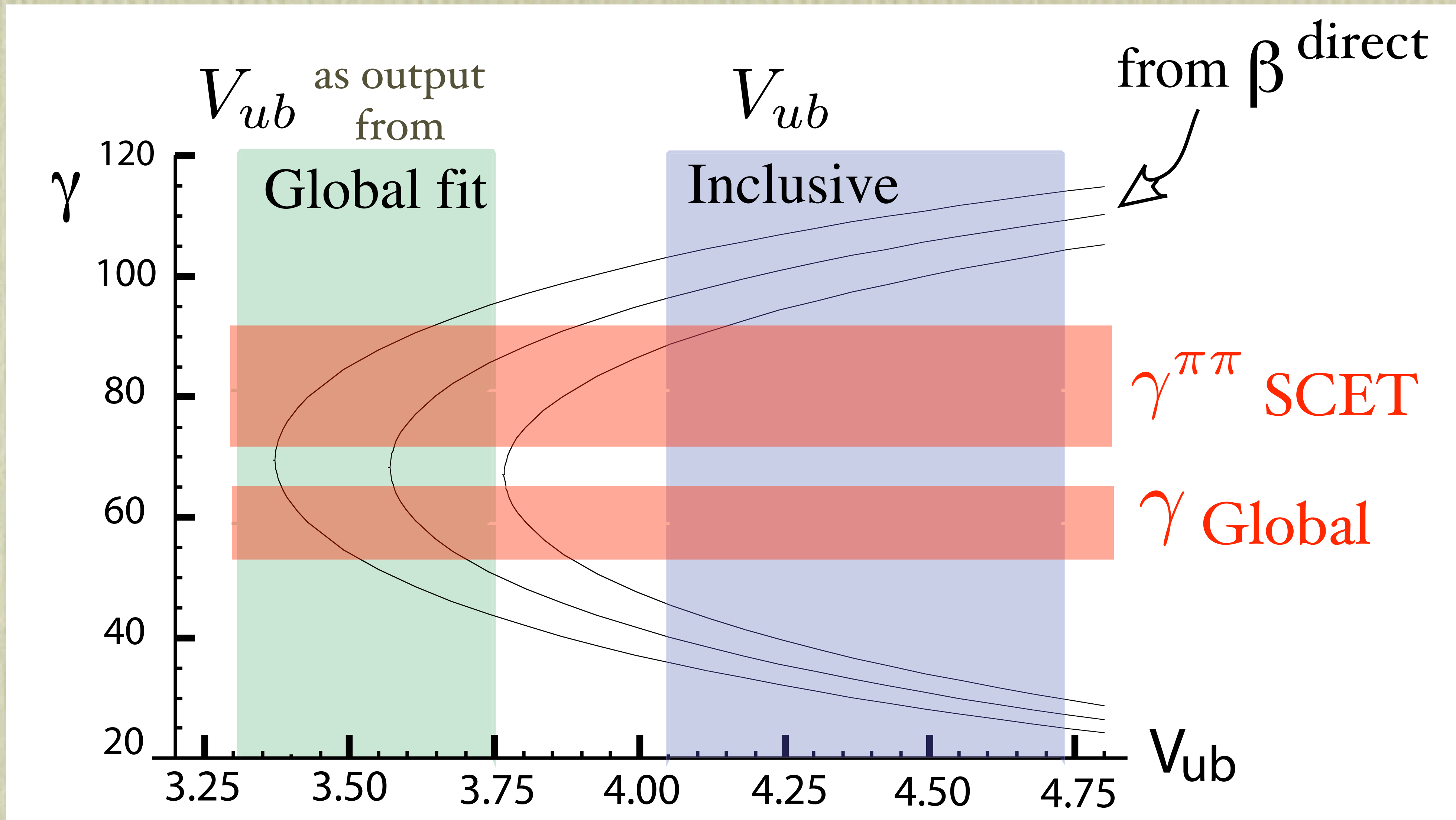


Use this to get α without $C_{\pi^0\pi^0}$.

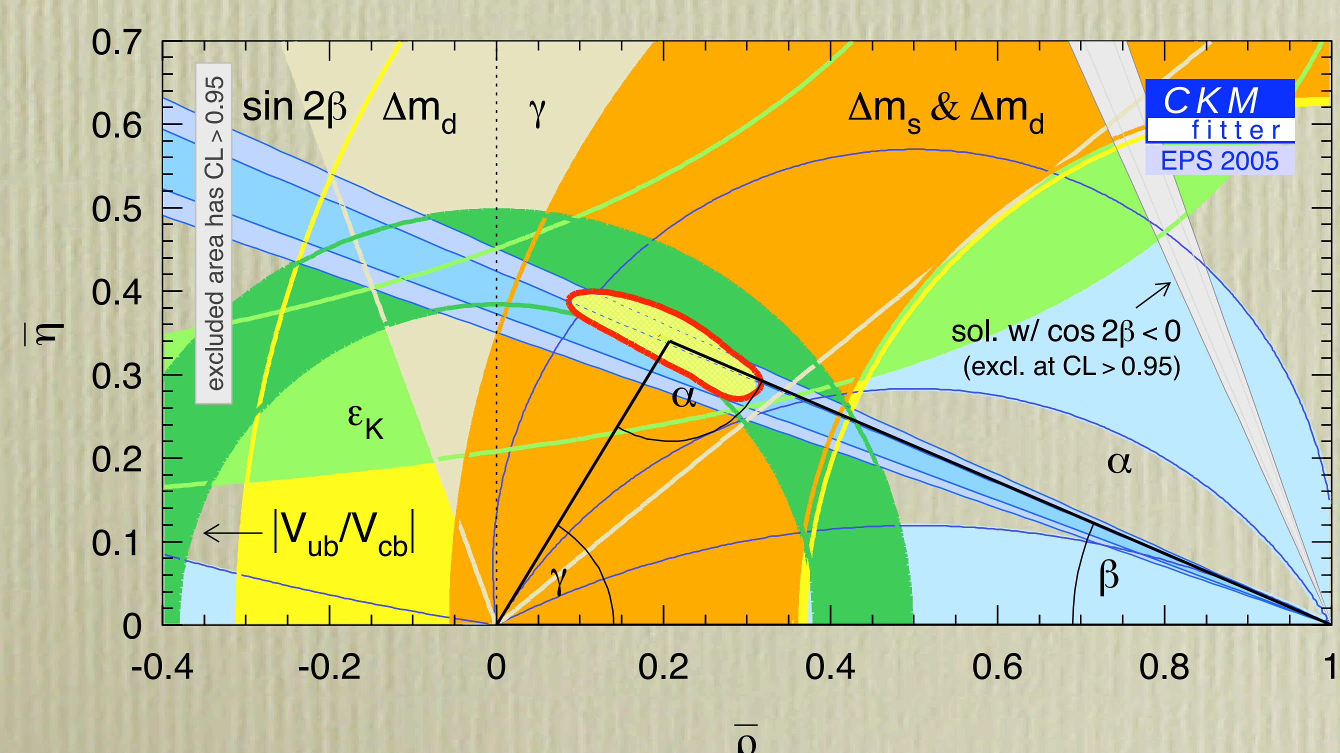


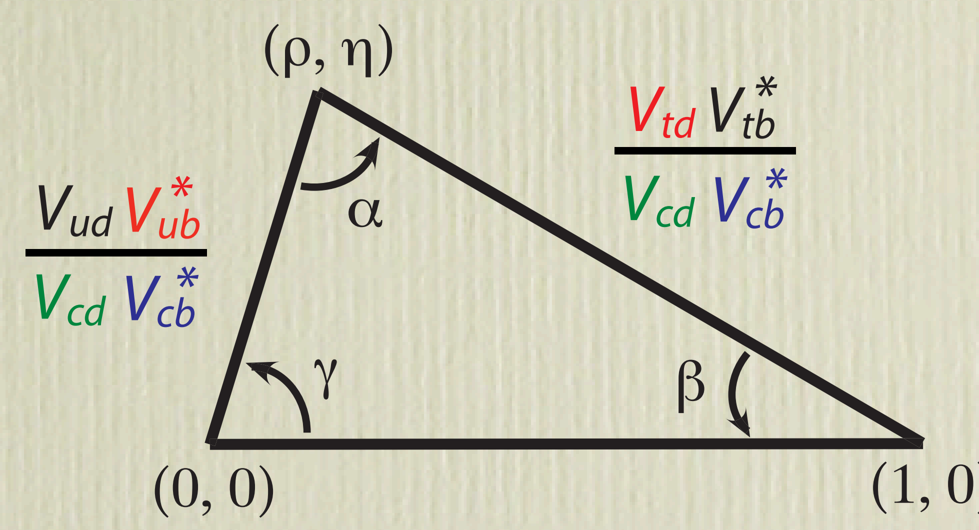
Grossman, Hoecker, Ligeti, Pirjol





expt. errors dominate



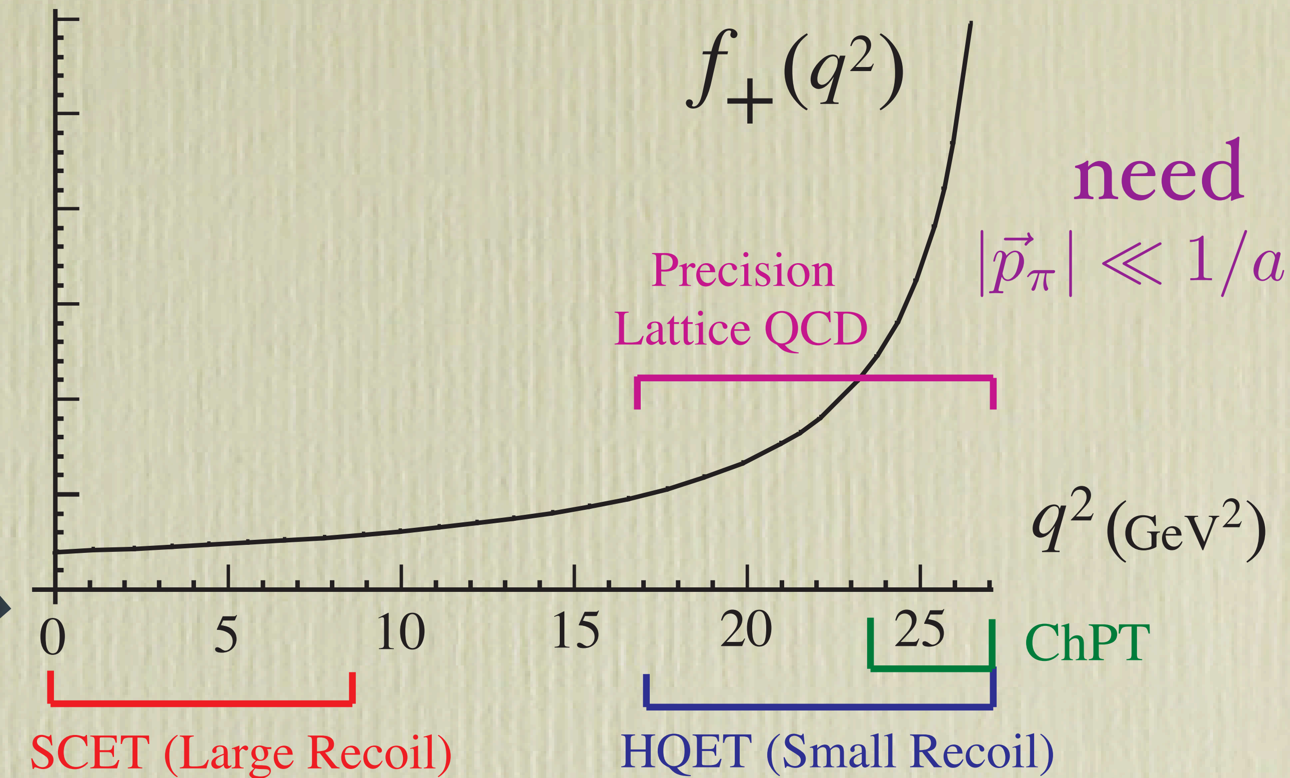


Test Factorization with Semileptonic decays $B \to \pi \ell \bar{\nu}$

$$\frac{d\Gamma(\bar{B}^0 \to \pi^+ \ell \bar{\nu})}{dq^2} = \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} |V_{ub}|^2 \, |f_+(q^2)|^2$$

SCET & $B \to \pi\pi$ data predicts

$$\boxed{|V_{ub}| f_+(0) = (7.2 \pm 1.8) \times 10^{-4}}$$



Using Lattice QCD, data, dispersion relations, and analyticity:

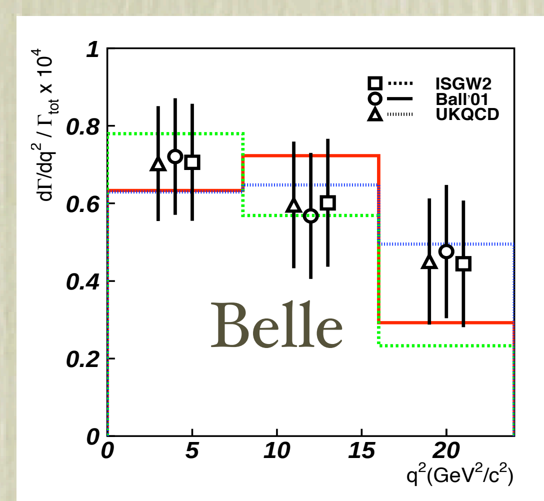
$$\boxed{|V_{ub}| f_+(0) = (9.8 \pm 2.4) \times 10^{-4}}$$

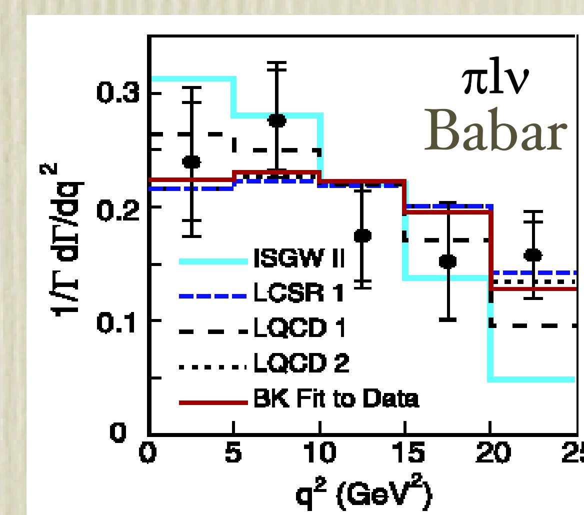
Arnesen, Grinstein, Rothstein, I.S.

&

measure an electroweak parameter

$$\boxed{10^3 \times |V_{ub}| = 3.92 \pm 0.52 \quad 13\% \text{ total error}}$$





SCET has been applied to many processes

Process	Non-Pert. functions	Utility
$\bar{B}^0 \to D^+\pi^-, \ldots$	$\xi(w)$, ϕ_π	study QCD
$\bar{B}^0 \to D^0\pi^0, \ldots$	$S(k_j^+)$, ϕ_π	study QCD
$B \to X_s^{endpt}\gamma$	$f(k^+)$	new physics, measure f
$B \to X_u^{endpt}\ell\nu$	$f(k^+)$	measure $\lvert V_{ub}\rvert$
$B \to \pi\ell\nu, \ldots$	$\phi_B(k^+)$, $\phi_\pi(x)$, $\zeta_\pi(E)$	measure $\lvert V_{ub}\rvert$, study QCD
$B \to \gamma\ell\nu$, $\gamma\ell^+\ell^-$	ϕ_B	measure ϕ_B, new physics
$B \to \pi\pi$, $K\pi$, $\ldots$	ϕ_B, ϕ_π, $\zeta_\pi(E)$	new physics, CP violation, γ
	$\phi_{\bar{K}}$, $\zeta_K(E)$	study QCD
$B \to K^*\gamma$, $\rho\gamma$	ϕ_B, ϕ_K, $\zeta_{K^*}^\perp(E)$	measure $\lvert V_{td}/V_{ts}\rvert$,
	ϕ_ρ, $\zeta_\rho^\perp(E)$	new physics
$B \to X_s\ell^+\ell^-$	$f(k^+)$	new physics
$e^-p \to e^-X$	$f_{i/p}(\xi)$, $f_{g/p}(\xi)$	study QCD , measure p.d.f's
$p\bar{p} \to X\ell^+\ell^-$	$f_{i/p}(\xi)$, $f_{g/p}(\xi)$	study QCD
$e^-\gamma \to e^-\pi^0$	ϕ_π	measure ϕ_π
$\gamma^*M \to M'$	ϕ_M, $\phi_{M'}$	study QCD
$e^+e^- \to j_1 + \text{jets}$	$\tilde{S}(k^+)$	event shapes & universality
$e^+e^- \to J/\Psi X$	$S^{(8,n)}(k^+)$	study QCD
$\Upsilon \to X\gamma$	$S^{(8,n)}(k^+)$	study QCD
$\vdots$	$\vdots$	$\vdots$

At MIT: C.Arnesen, D.Pirjol, A.Jain, B.Lange, K.Lee, S.Mantry

Future

Who needs to understand QCD?

Immediate future:

Babar, Belle

- For many channels, control of hadronic uncertainties is crucial to test standard model & look for new physics.

$$B \to X_s \ell^+ \ell^-, B \to \pi\pi, B \to K\pi, B \to \rho\pi, \ldots$$
$$B \to \rho\gamma, B \to K^*\gamma, B \to \phi K_s, B \to \eta' K_s$$

CDF, DØ

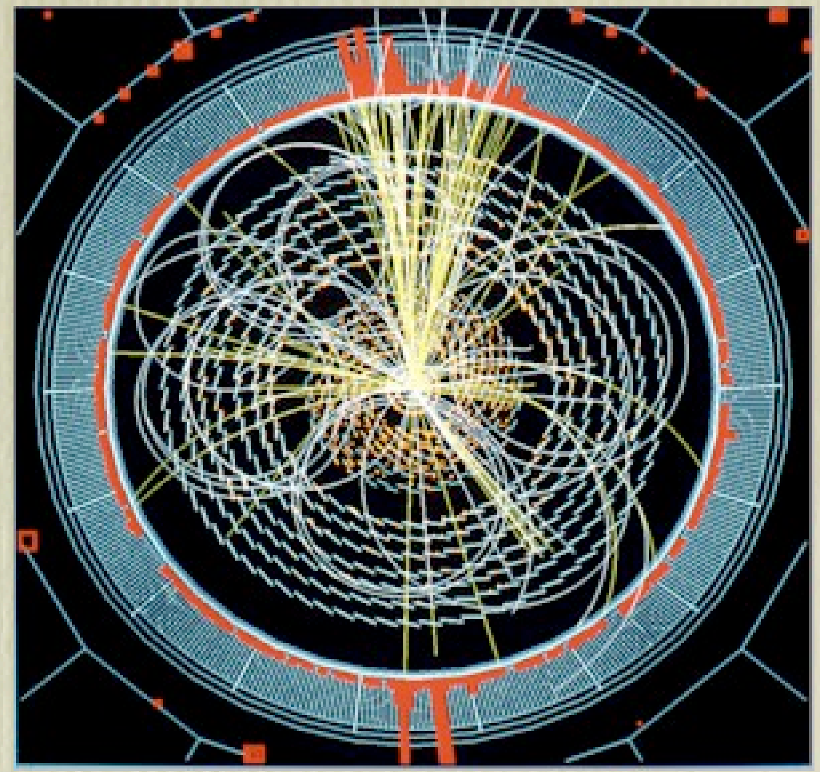
- Test standard model / new physics in $B_s, \Lambda_b, \ldots$
- Heavy quark production, jets, ...

LHC era:

pp collider with $E_{cm} = 14\,\mathrm{TeV}$

scales: $m_W, m_t, E_T^{\mathrm{jet}}$

→ Energetic QCD (SCET)



Effective theory concepts will be helpful whether we're:

- exploring QCD,
- computing precision standard model cross sections (resolution scales or resummation of logs),
- or puzzling out signals of unexplored particle physics

Concluding Remarks

- QED fundamental parameters & precision quantum field theory

- QCD today is as rich & diverse as ever

  many subfields which focus on different degrees of freedom
  and different relevant interactions

- SCET a new approach to derive factorization theorems
  and treat power corrections for energetic hadrons & jets

  Nonleptonic B-decays

  ➡ predictions for the size of amplitudes

  ➡ universal hadronic parameters, strong phases

  ➡ γ (or α) from individual $B \to M_1 M_2$ channels

- A lot of theory and phenomenology left to study ...