Disentangling the strong force:

QCD, Factorization and the b quark

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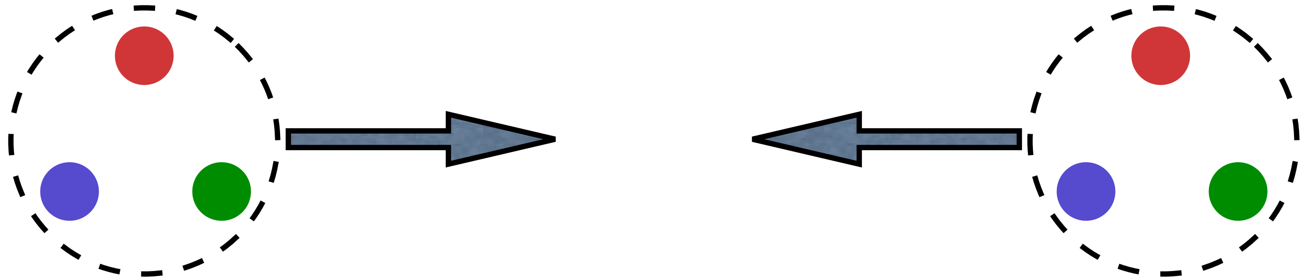
Outline

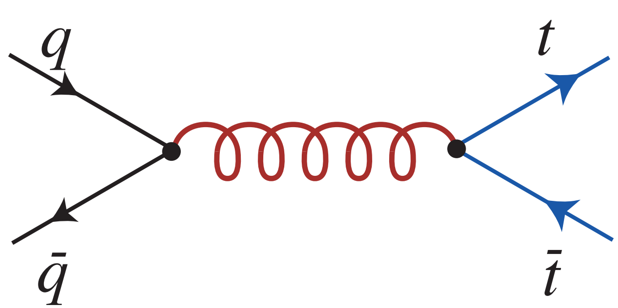
0. Prologue - factorization and the parton model
1. Why study b quarks?
2. Effective field theory and the heavy quark expansion
3. Applications ... where these ideas have led
4. New directions

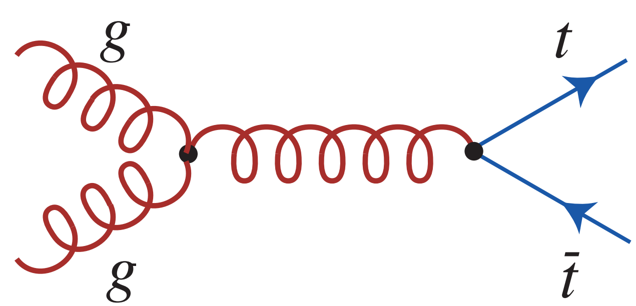
Prologue: How do we do physics at proton colliders at all? (i.e. Tevatron, LHC)



Colliding protons → Colliding quarks and gluons

i.e. top production at Fermilab:





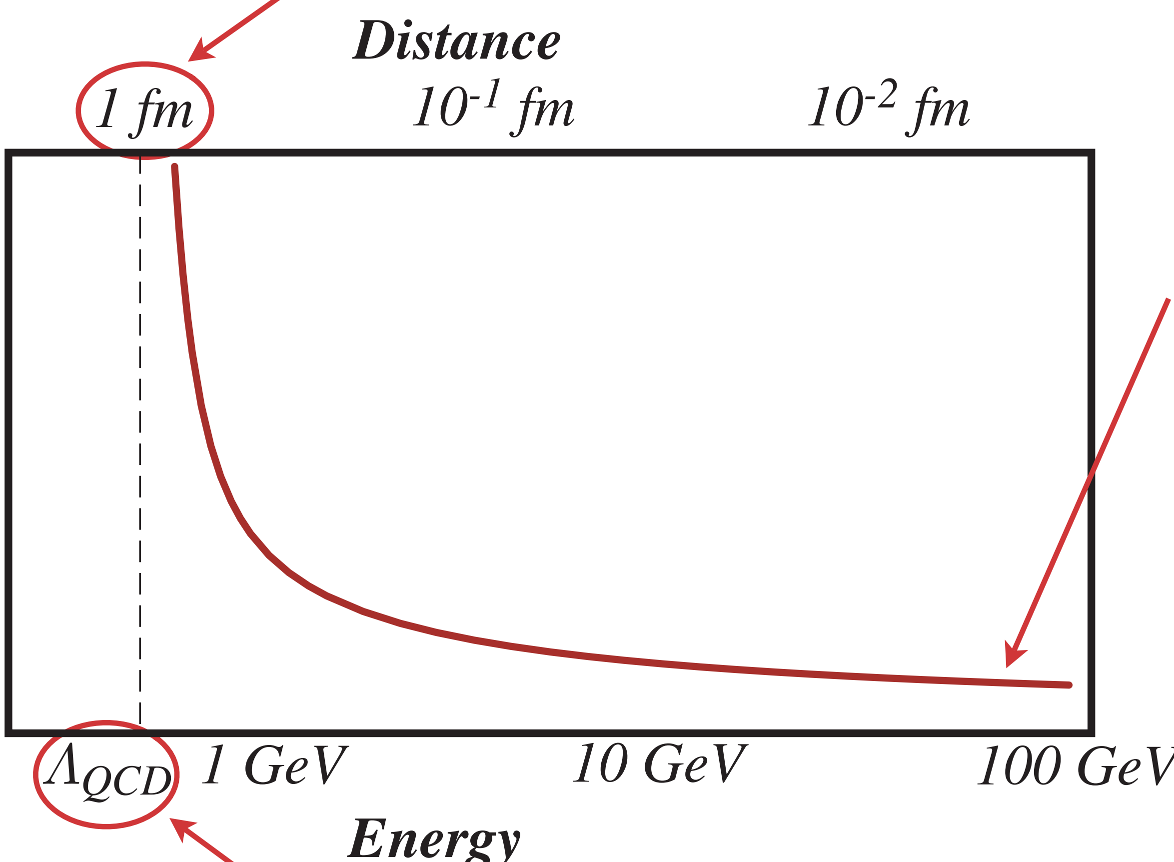
... this is the physics we want to study

... but protons aren't so simple ...

"Quantum Chromodynamics" (QCD)

(Gross, Politzer, Wilczek - Nobel Prize, 2004)

1 fm = 10^{-15} m ~ radius of proton



"asymptotic freedom":

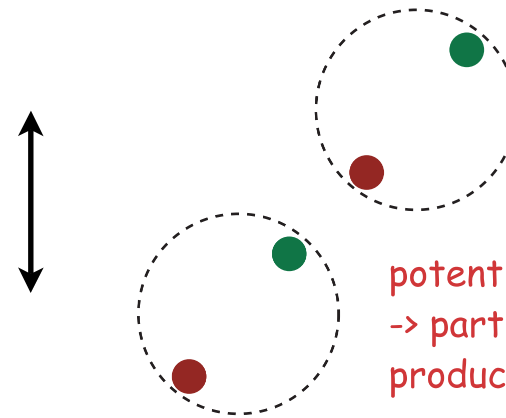
effective QCD CHARGE of quarks/gluons under is small at SHORT distances (large energies), large at LONG distances (low energies)

Λ_{QCD} ~300 MeV sets the scale for nonperturbative effects

$$\Lambda_{\rm QCD} \sim 300\,\text{MeV} \sim \frac{1}{3} m_{\rm proton} \qquad \frac{1}{\Lambda_{\rm QCD}} \sim 1\,\text{fm} \sim r_{\rm proton}$$

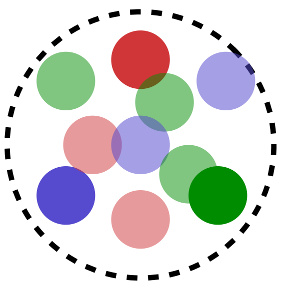
(1) sets the maximum size of a hadron

$1\ \text{fm}$



potential energy -> particle production

(2)

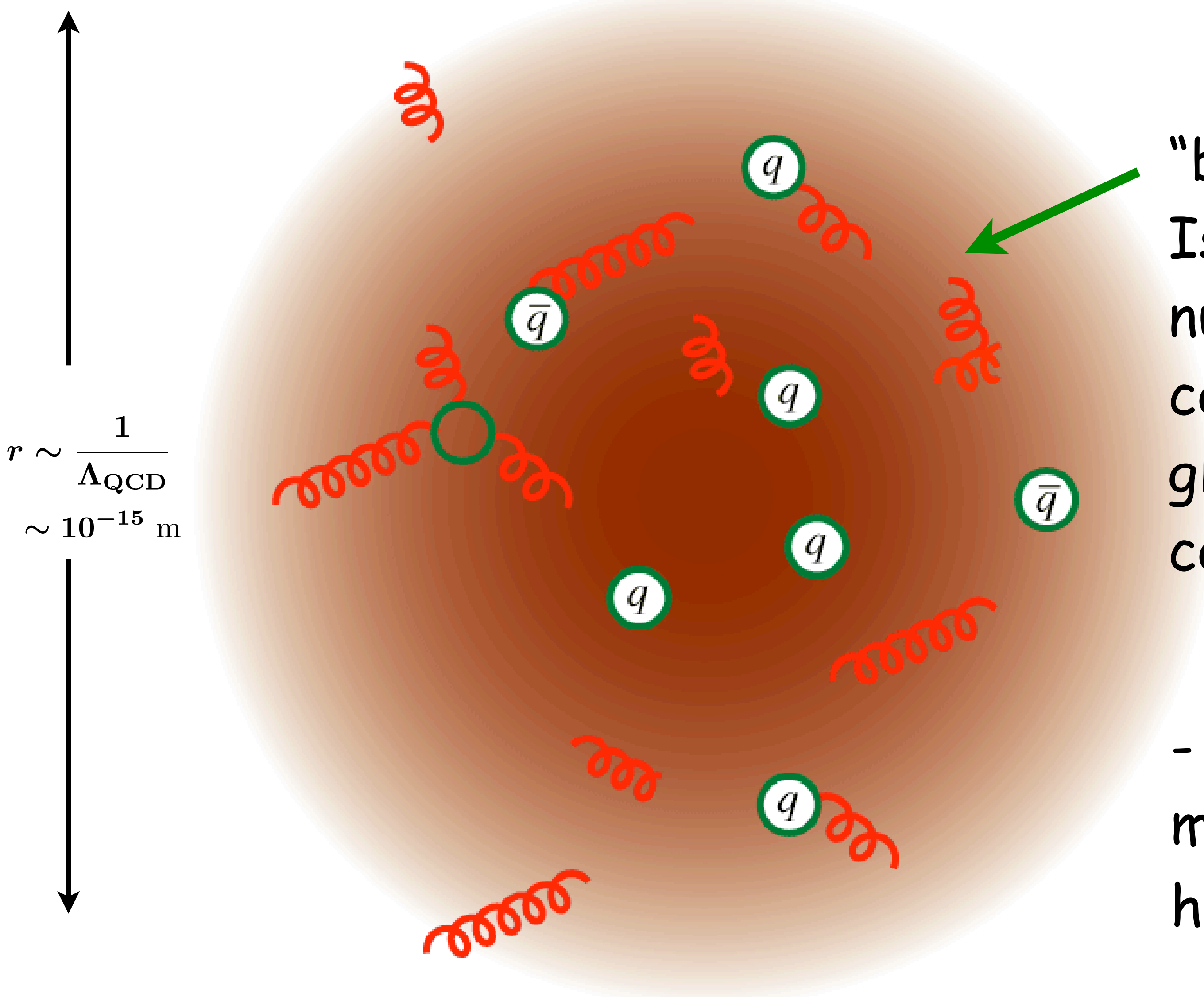


$$m_{\rm up} \sim 5\ \text{MeV}$$
$$m_{\rm down} \sim 10\ \text{MeV}$$
$$\ll \Lambda_{\rm QCD}$$

but Heisenberg: $\Delta p \sim \frac{1}{\Delta x} \sim \Lambda_{\rm QCD} \gg m_{u,d}$

-> particle production! Indeterminate number of quarks in proton

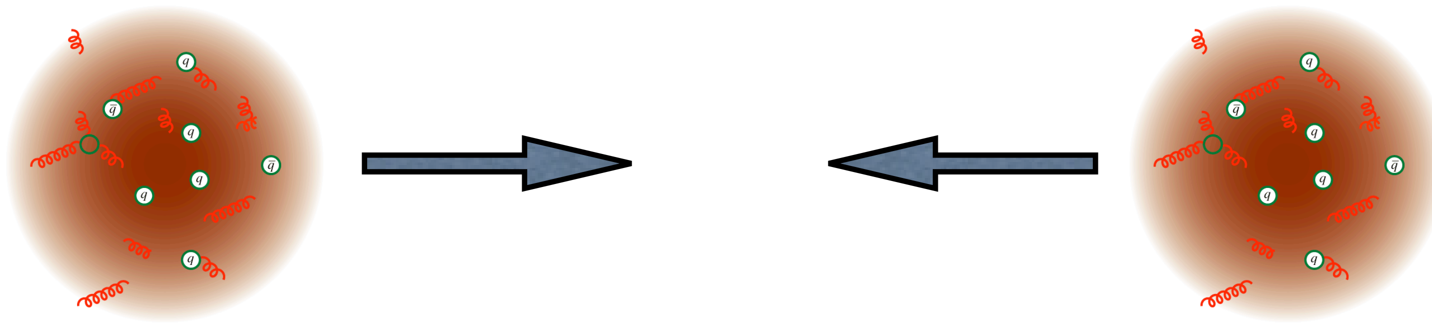
So a proton looks something like this:



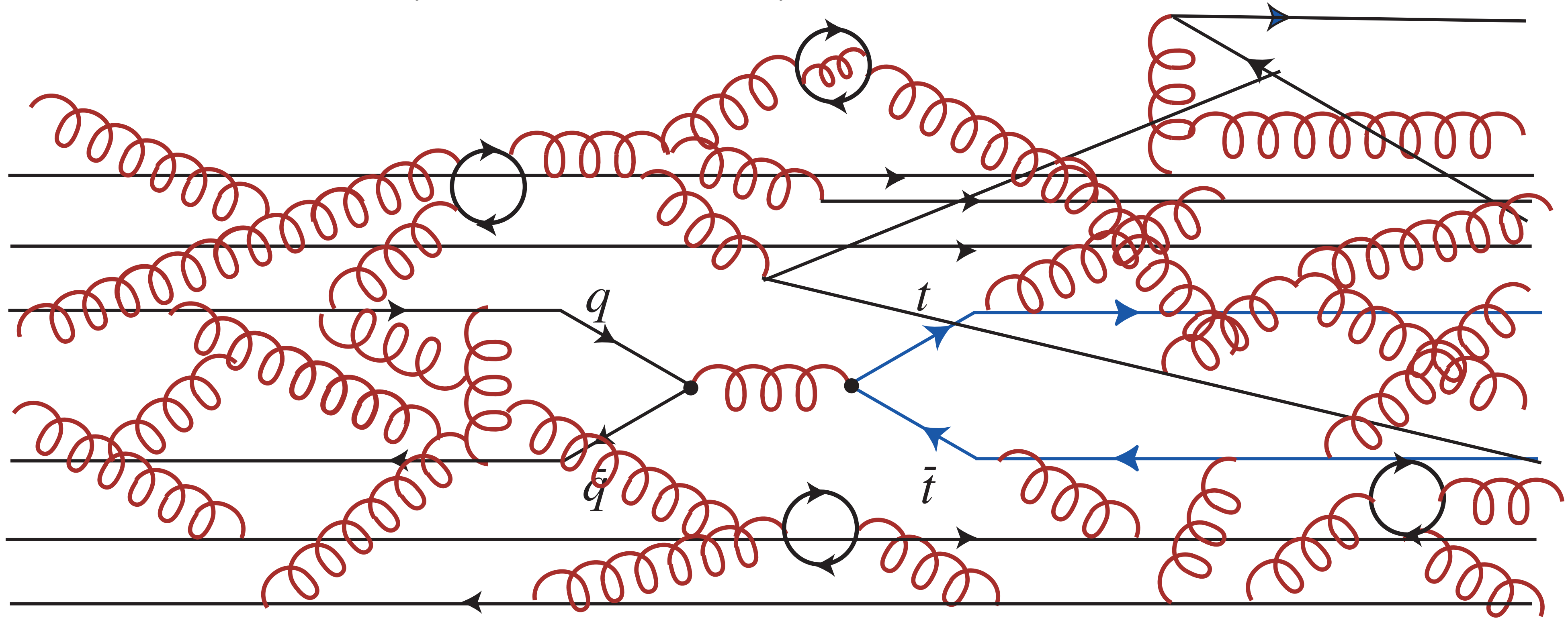
"brown muck" of QCD (N. Isgur) - an indeterminate number of strongly coupled light quarks and gluons (horrible strongly-coupled mess)

- quarks & gluons all have momentum ~Λ_{QCD}~few hundred MeV

(Actually, it's a linear superposition of all these states ...)



... and our simple quark-level process



... is buried in the muck.

How can we calculate anything without solving QCD?

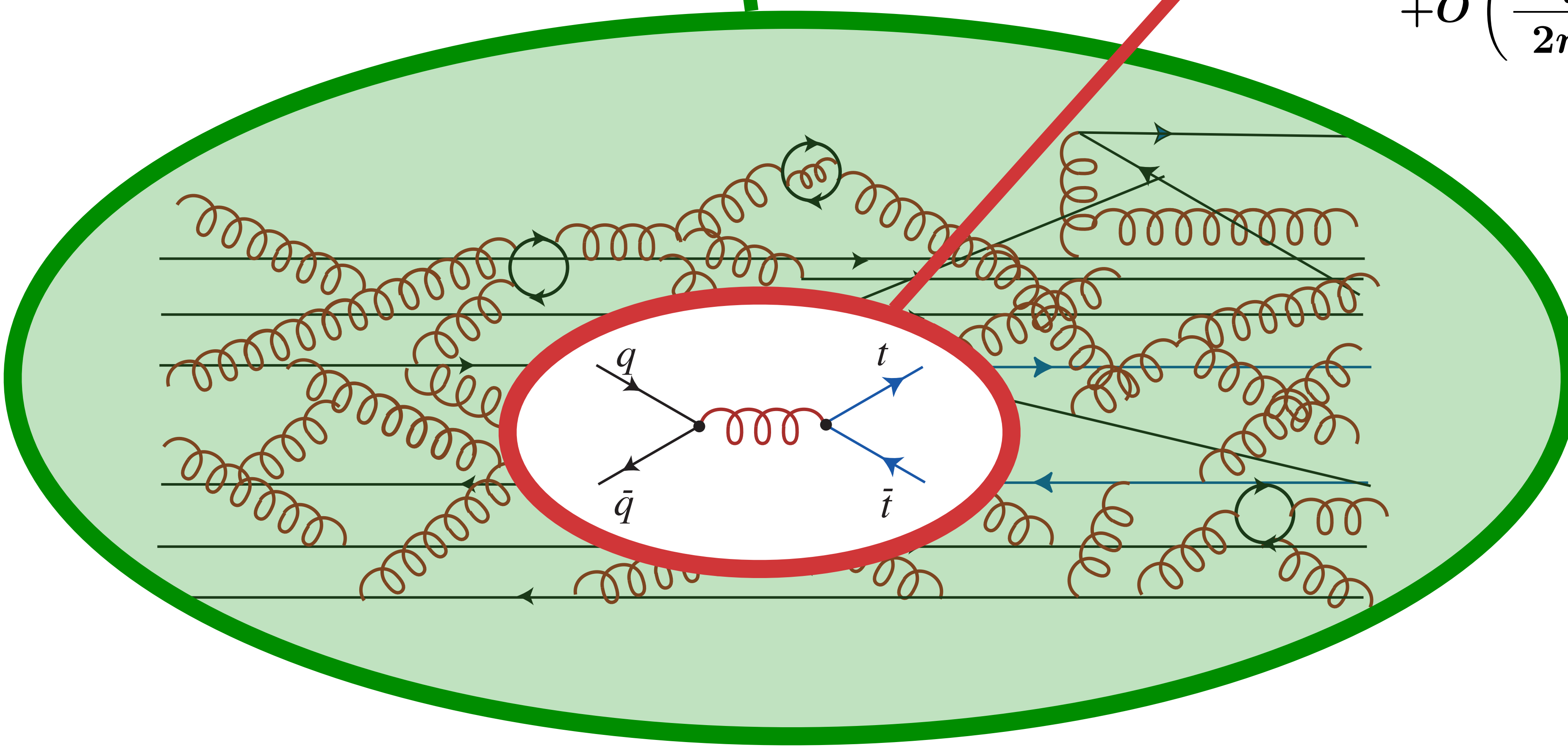
A miracle occurs .... "Factorization"

$$\sigma(p(P_1) + p(P_2) \to t\bar{t} + X)$$

(NB for simplicity, neglecting top quark decay)

$$= \int_0^1 dx_1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \to t\bar{t})$$

$$+ O\left(\frac{\Lambda_{\rm QCD}}{2m_t}\right)$$

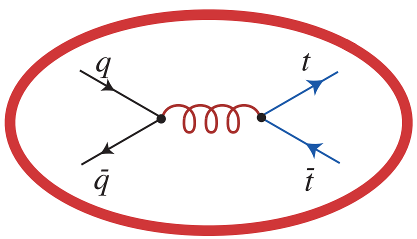


(Feynman, Bjorken)

but then a miracle occurs .... "Factorization"

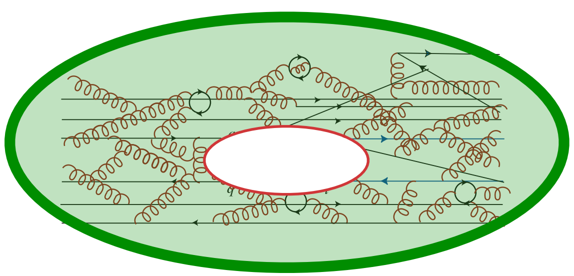
$$\sigma(p(P_1) + p(P_2) \to t\bar{t} + X)$$

$$= \int_0^1 dx_1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \to t\bar{t})$$



cross section for free quarks (and gluons)

- can calculate in perturbation theory

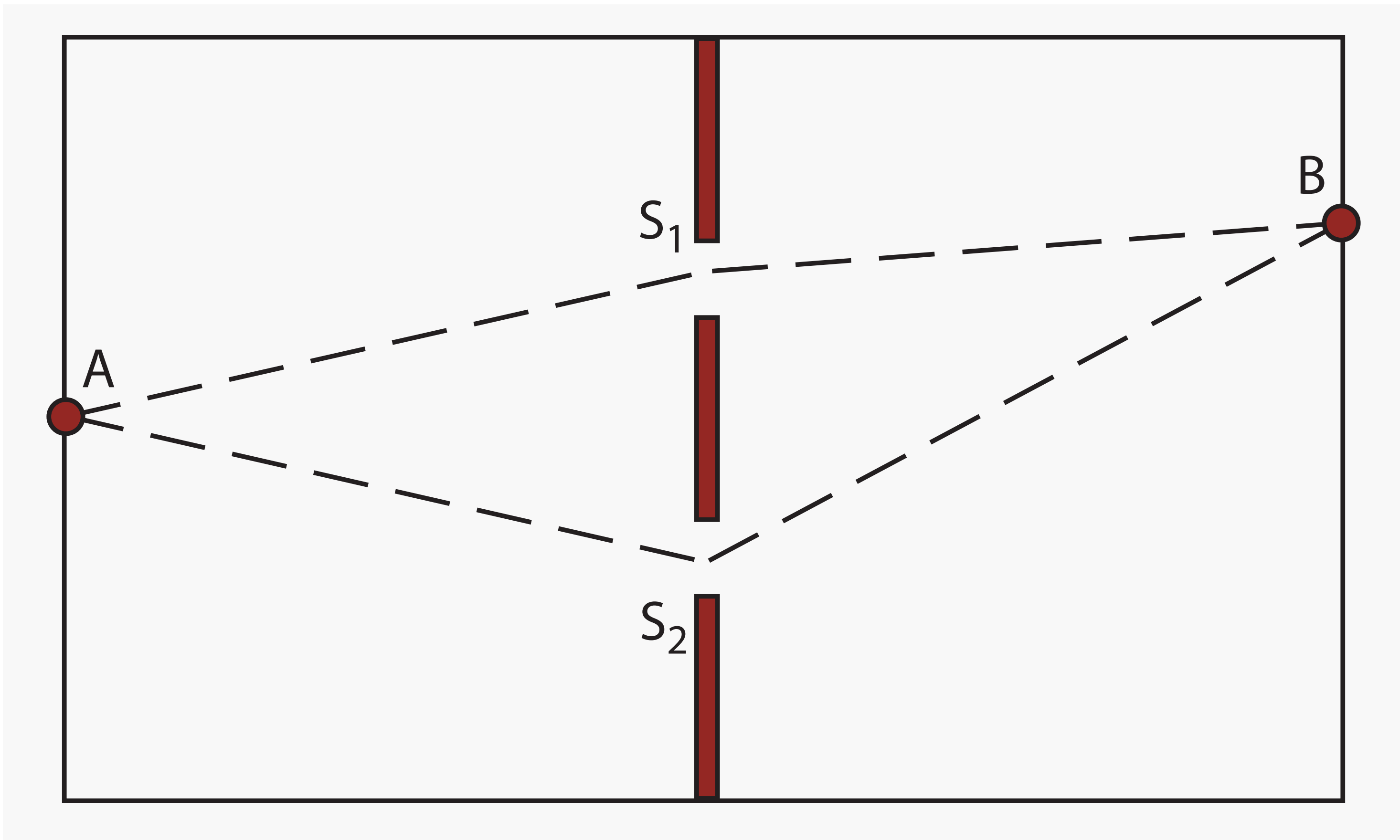


$f_f(x_1)$: probability to find parton f with fraction x_1 of longitudinal momentum of proton ("parton distribution function") - property of the PROTON

- can't calculate ... but UNIVERSAL (can measure in another process)

This is not obvious!

A patently false factorization formula:

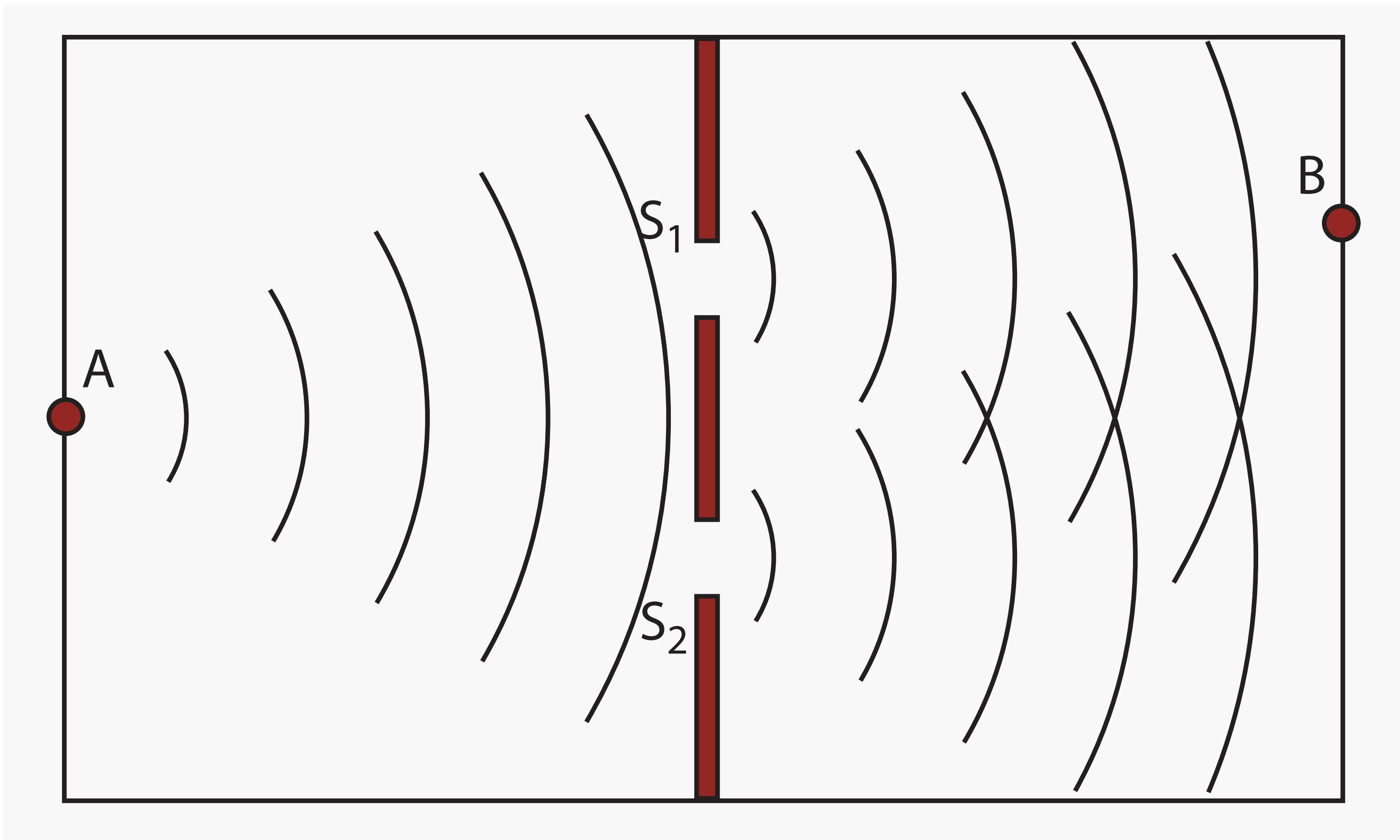


$$P(A \to B) = \sum_i P(A \to S_i) P(S_i \to B)$$

(subprocesses: travel through slits, propagate)

This is not obvious!

A patently false factorization formula:



$$P(A \to B) = \sum_i P(A \to S_i) P(S_i \to B)$$

Interference - can't in general disentangle the probabilities!

The proofs of factorization are long and complicated ...

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FACTORIZATION FOR SHORT DISTANCE HADRON-HADRON SCATTERING

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(Revised 17 May 1985)

We show that factorization holds at leading twist in the Drell-Yan cross section $d\sigma/dQ^2\,dy$ and related inclusive hadron-hadron cross sections

We review the heuristic arguments for factorization, as well as the difficulties which must be overcome in a proof We go on to give detailed arguments for the all order cancellation of soft gluons, and to show how this leads to factorization

1. Introduction

Factorization theorems [1] show that QCD incorporates the phenomenological successes of the parton model at high energy and provide a systematic way to refine parton model predictions. The term "factorization" refers to the separation of short-distance from long-distance effects in field theory The program of factorization is to show that such a separation may be carried out order-by-order in field theoretic perturbation theory. In practice, this means analyzing the Feynman diagrams which contribute to a given process, and showing that they may be written as products of functions with the desired properties.

Such an analysis has been carried out in e^+e^- annihilation [2–4] and deeply inelastic scattering [1,5]. The purpose of this paper is to extend the analysis to

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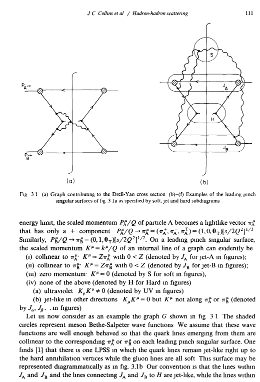

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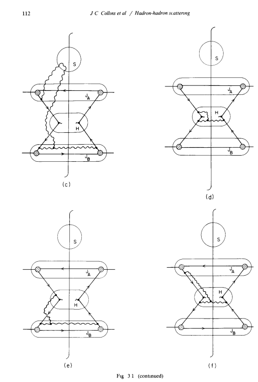

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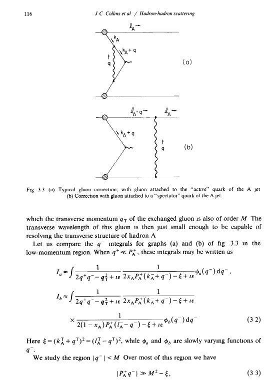

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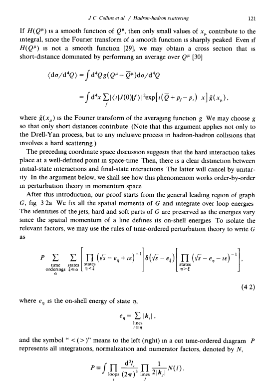

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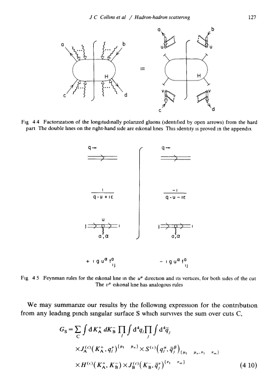

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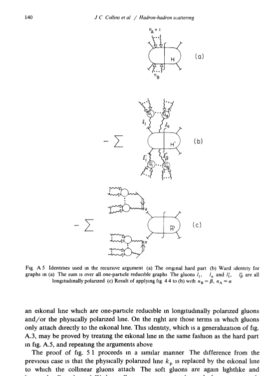

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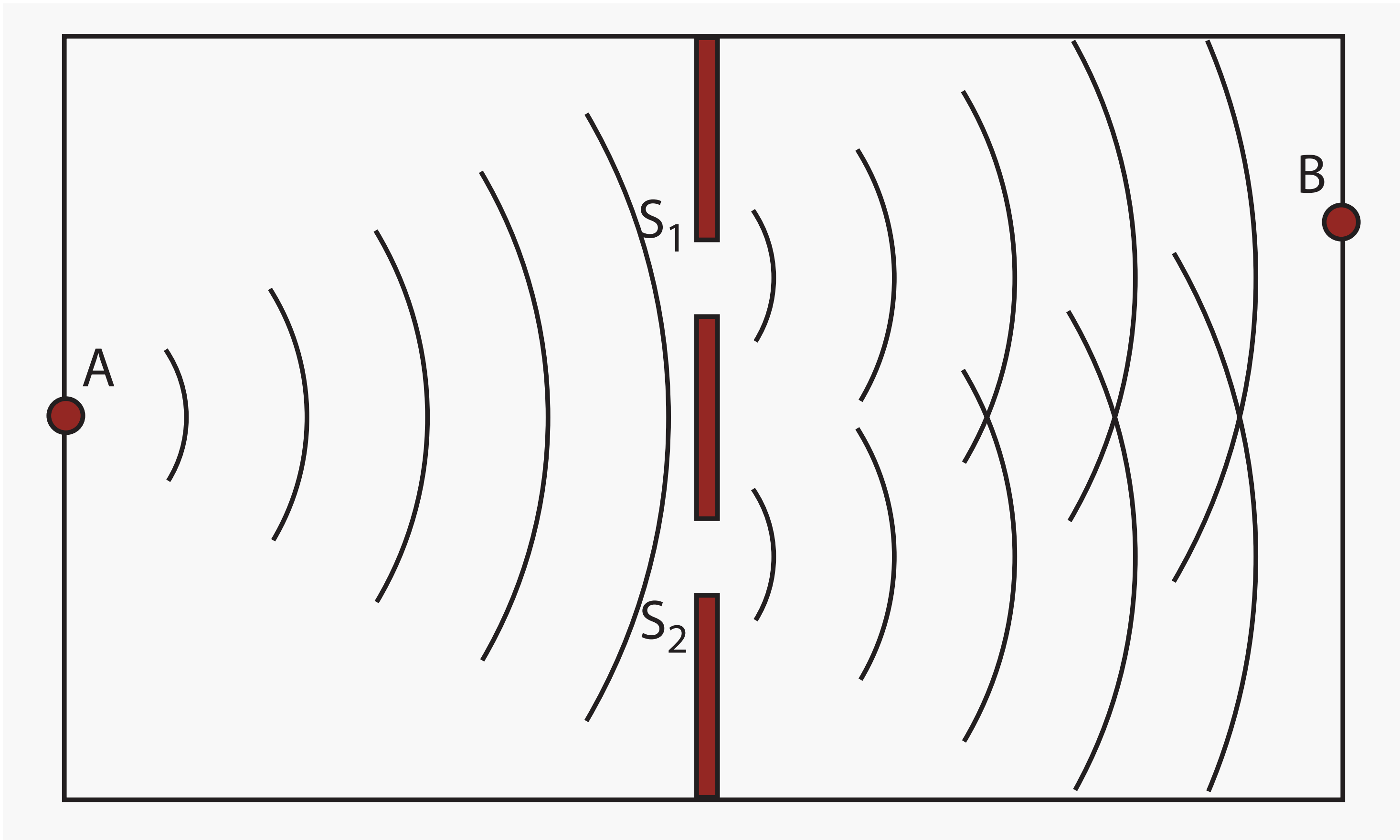
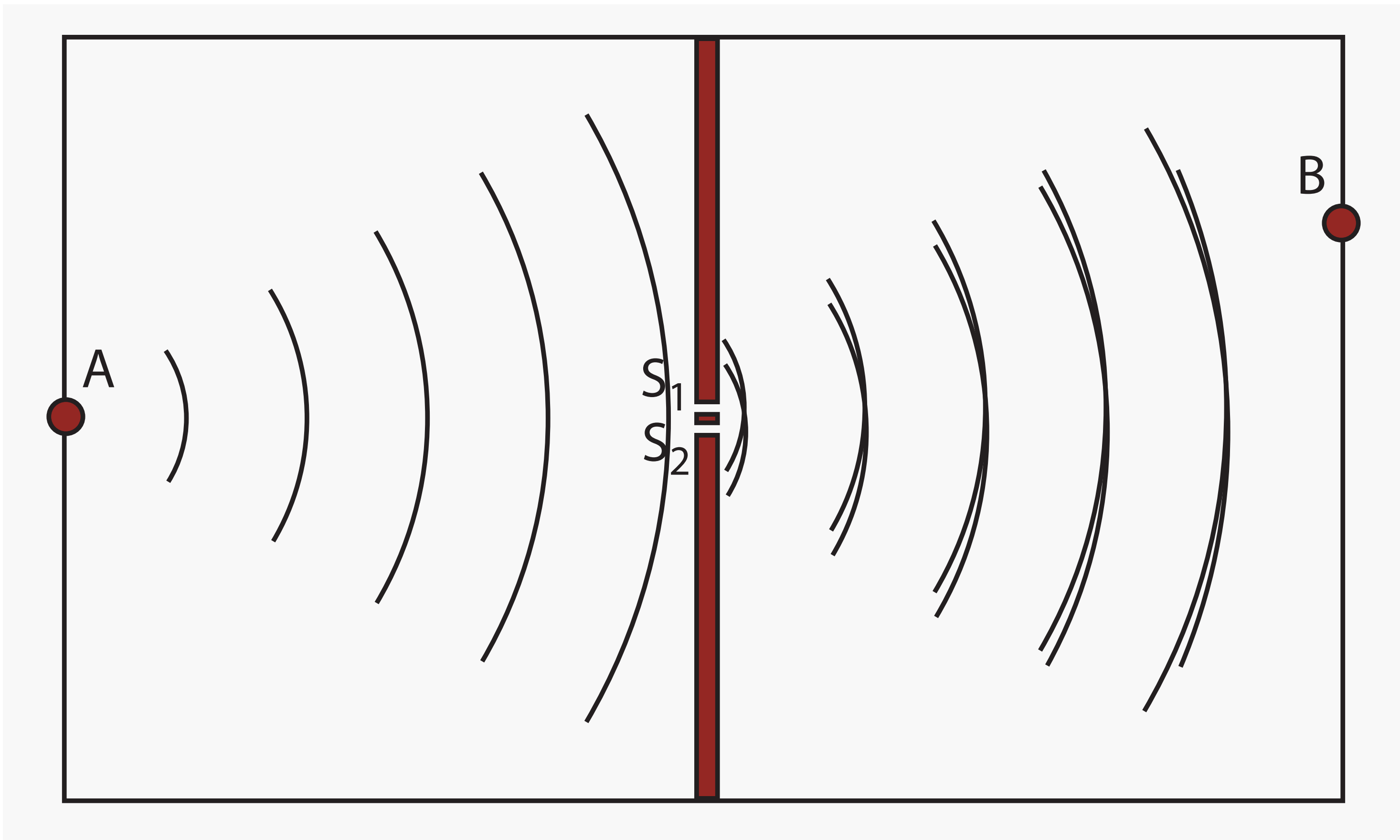
(Collins, Soper, Sterman, 1980's)

... but the physics is simple



... but the physics is simple



Separation of Scales

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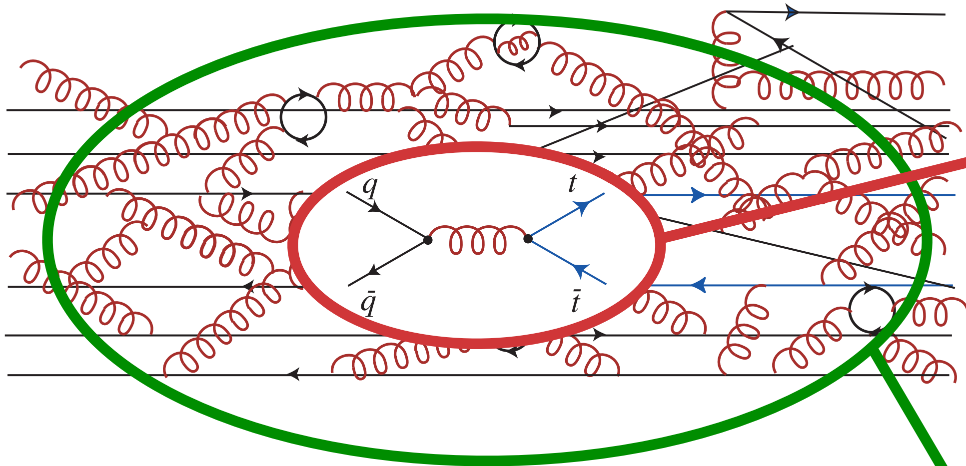
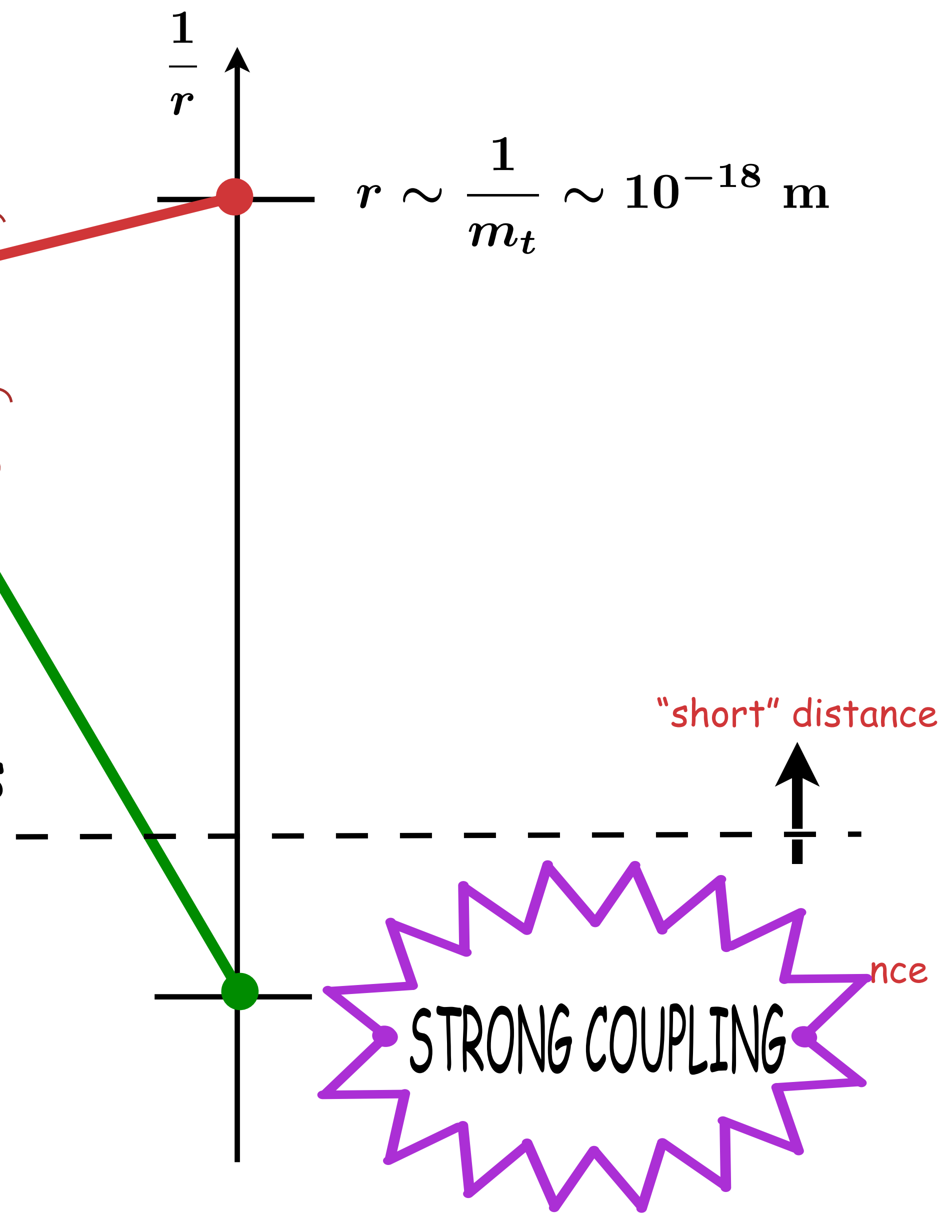




- top quark production is a short-distance process, hadronic physics is long-distance
- hadronic physics cannot resolve details of short-distance physics - hadronization is independent of details of scattering

COMMENTS:

$$\sigma(p(P_1) + p(P_2) \to t\bar{t} + X) \ = \int_0^1 dx_1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \to t\bar{t}) + O\left(\frac{\Lambda_{\rm QCD}}{2m_t}\right)$$

- form of the factorization formula (convolution over light-cone momentum fraction) is non-trivial

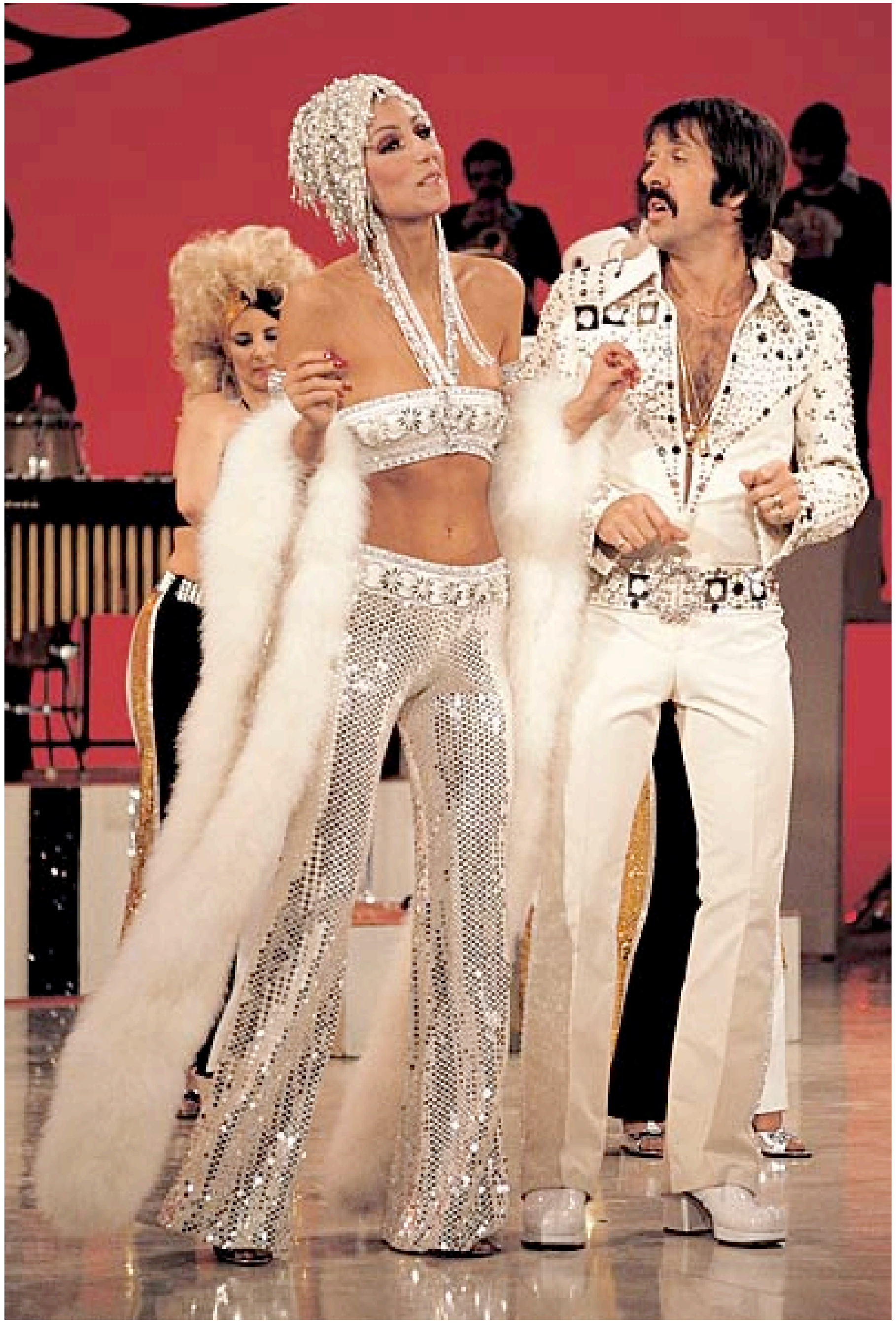
- final hadronic state unspecified - sum over all of them ("+X") - probability to hadronize = 1! **"inclusive"**

- subleading ($O(\Lambda_{QCD}/Q)$) terms (**"power corrections"**) don't factorize in this way ... fortunately, these are small for $Q \sim 2m_t$.

MORAL:

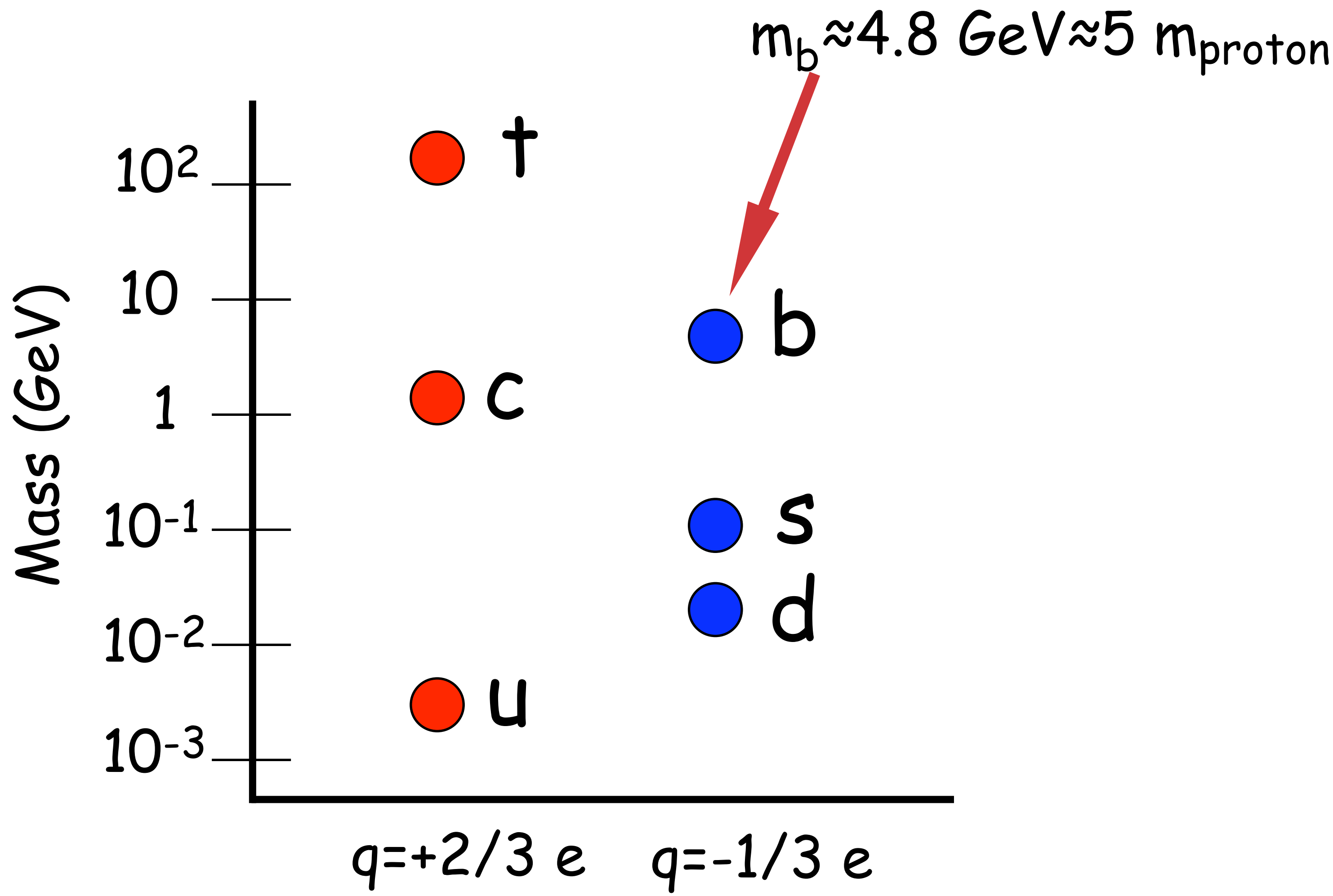
- to the degree that the distance scales can be separated (i.e. to LEADING ORDER in Λ_{QCD}/Q), hard scattering factorizes into a short-distance scattering and long distance parton distribution functions

- short-distance physics can be calculated in QCD (perturbative) .. long-distance physics is incalculable, but universal - can be measured in other processes

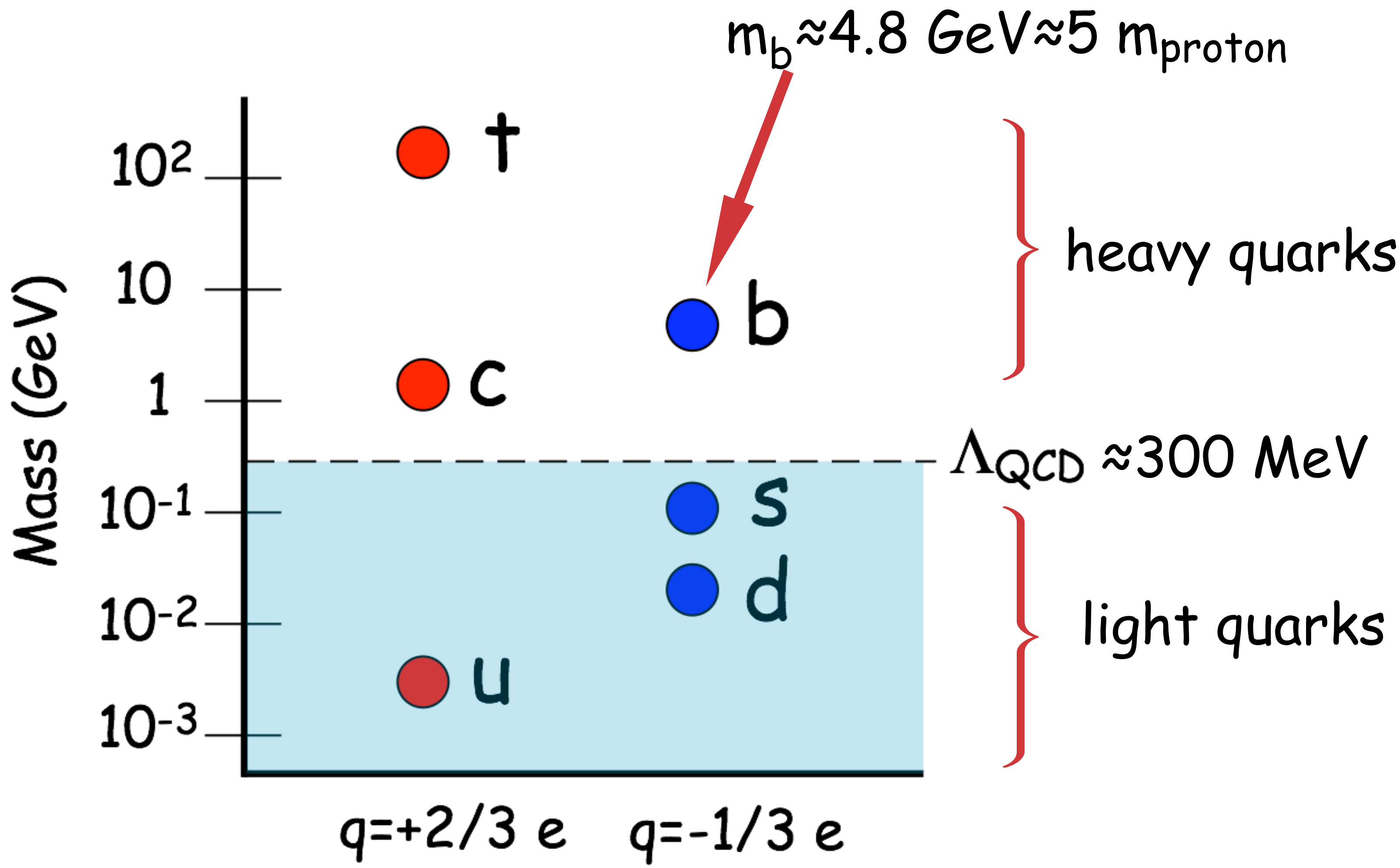


1970's ----------------------------------> now

Why study b quarks?

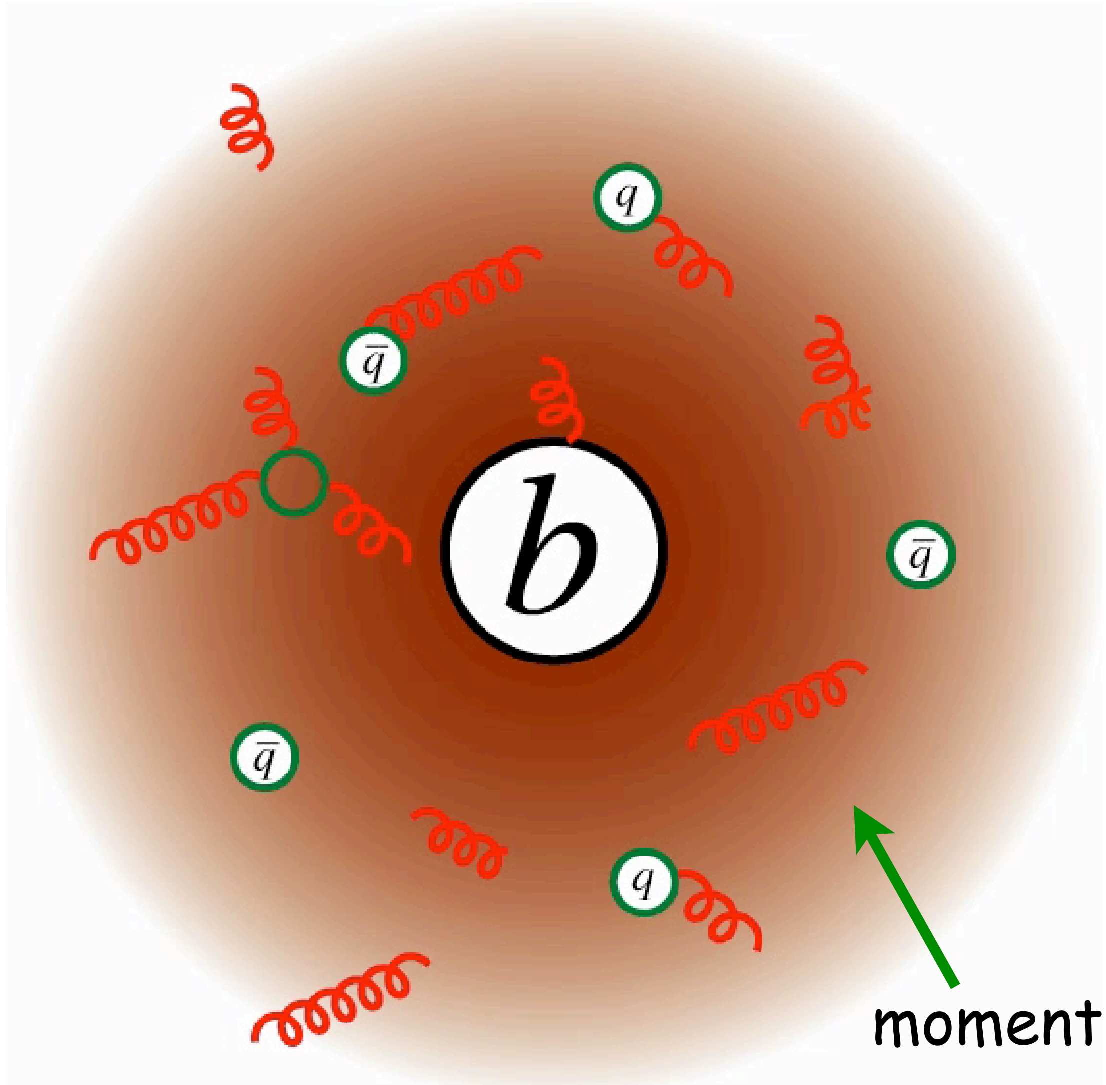


Why study b quarks?



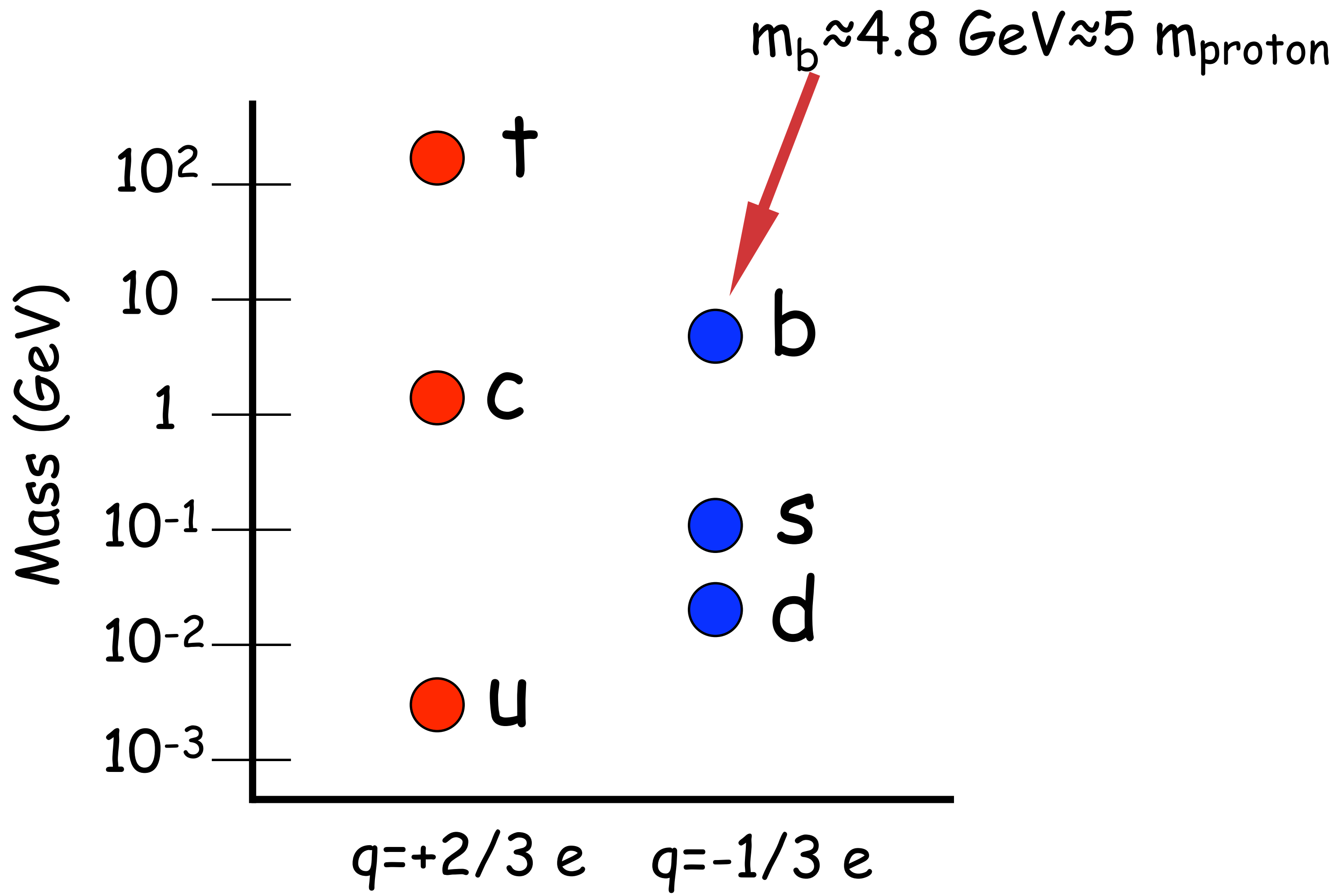
A B ($b\bar{q}$) meson

q=u, d, s

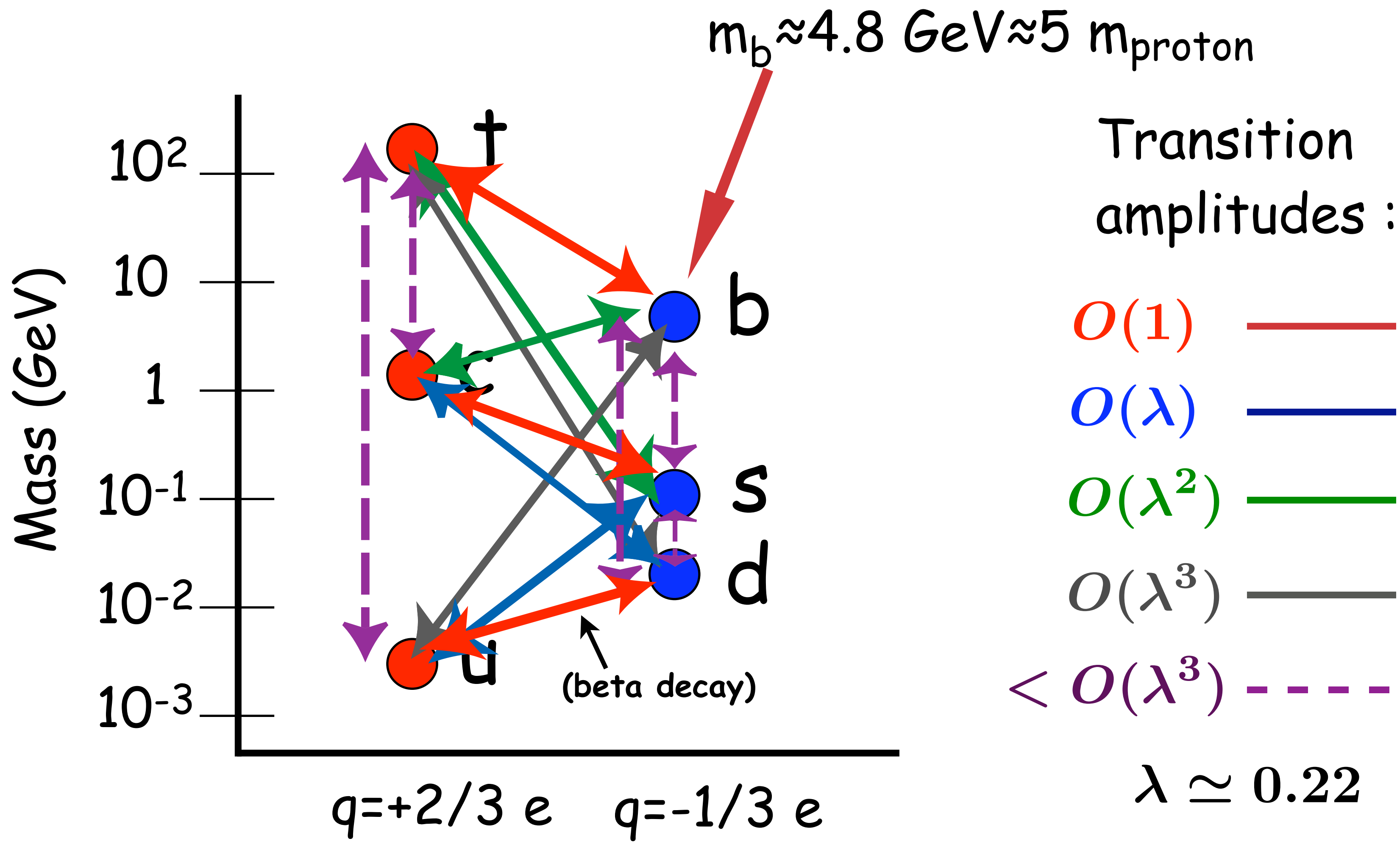


momentum ~$\Lambda_{QCD} \ll m_b$

Why study b quarks?

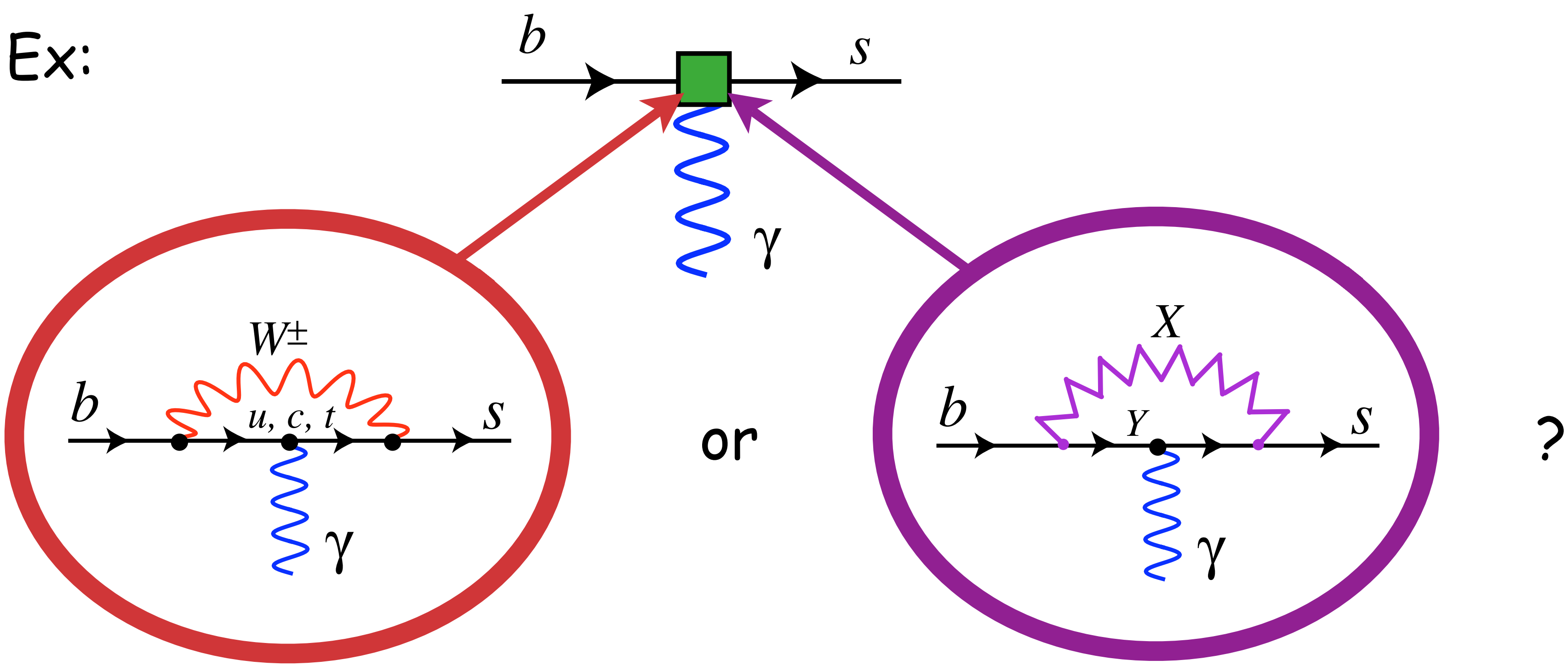


Why study b quarks?



b quarks are a natural microscope ... decays are determined by very SHORT distance physics, where we expect new particles/ interactions:

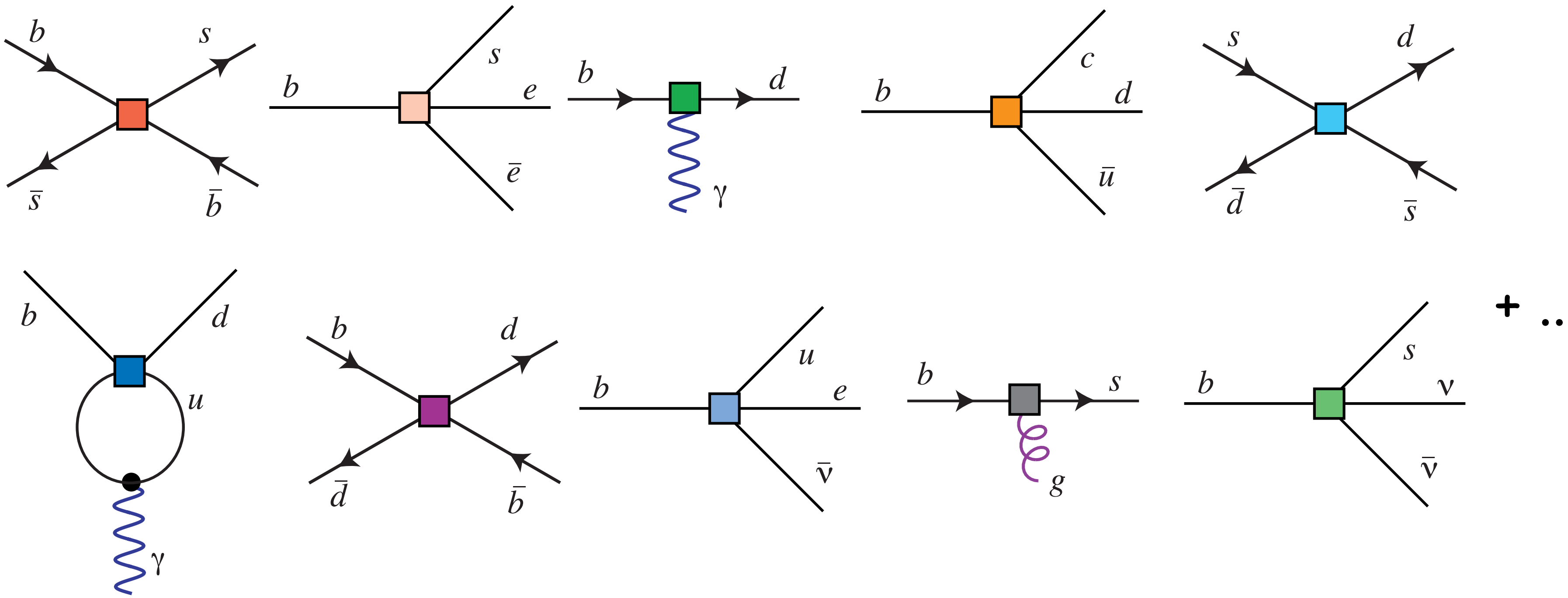
Ex:



known physics (boring) new physics (exciting!)

NB: $m_W, m_X >> m_b$ -> seeing heavy particles VIRTUALLY

There are many possible flavour-changing interactions ...



... and by measuring as many as we can and requiring consistency with the Standard Model (highly constrained!) we can search for signs of new physics.

(NB: this sort of thing has worked in the past ...)

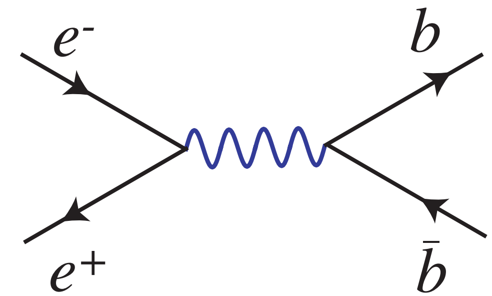
"B Factories" (SLAC, KEK):

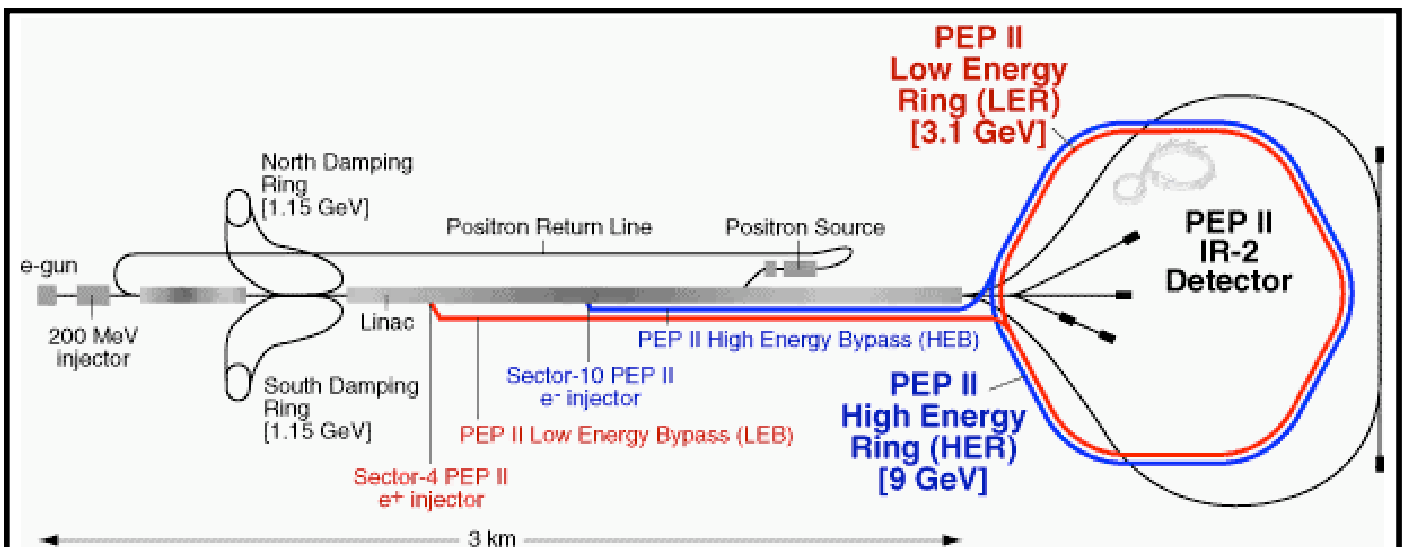
- dedicated machines producing ~10^8 $b\bar{b}$ pairs/year (on-line since 1999) - designed for high precision studies of B meson properties

(also: **CLEO**, LEP, FNAL, ATLAS)

BaBar detector:
SLAC, California

Belle detector,
KEK, Japan

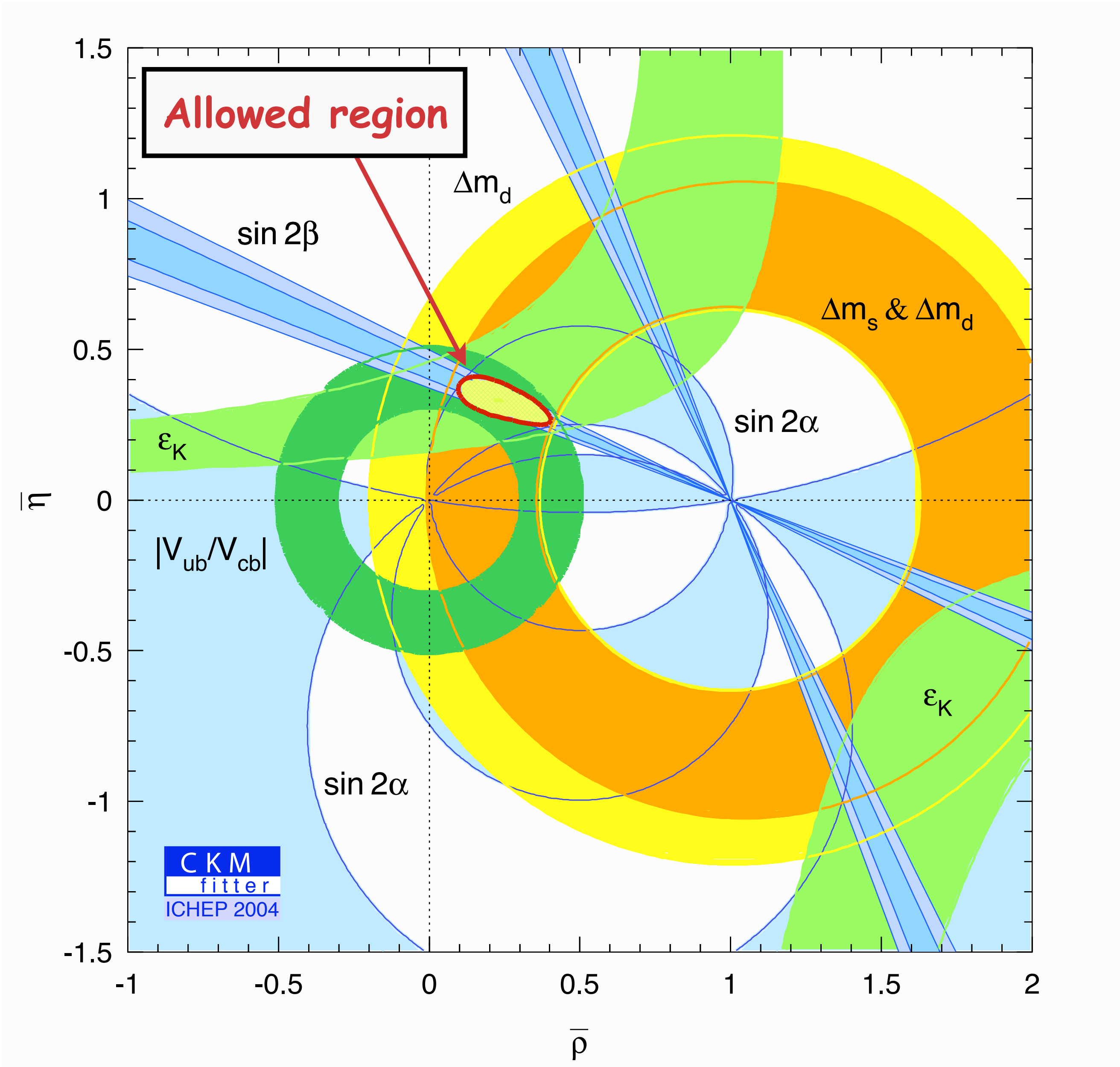




- LOW energy, HIGH luminosity machines (~10 GeV c.o.m. energy for virtual study of 100 GeV scale)

Consistency of the Standard Model (so far)

(from ICHEP, summer 2004)



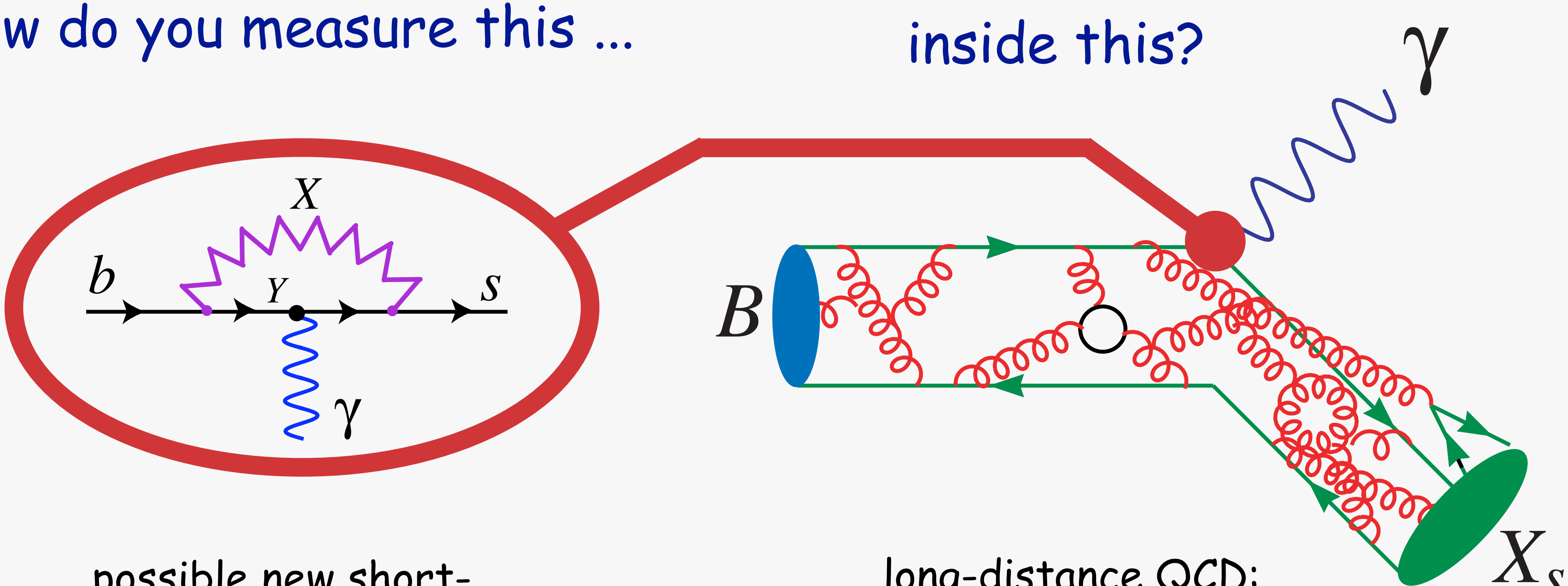
All constraints overlap in one region ...

(1) the Standard Model provides the right first-order description of flavour-changing transitions

(2) discrepancies will require precision theory/measurements to find (probably ...)

Precision physics with b decays is tricky ...

how do you measure this ... inside this?



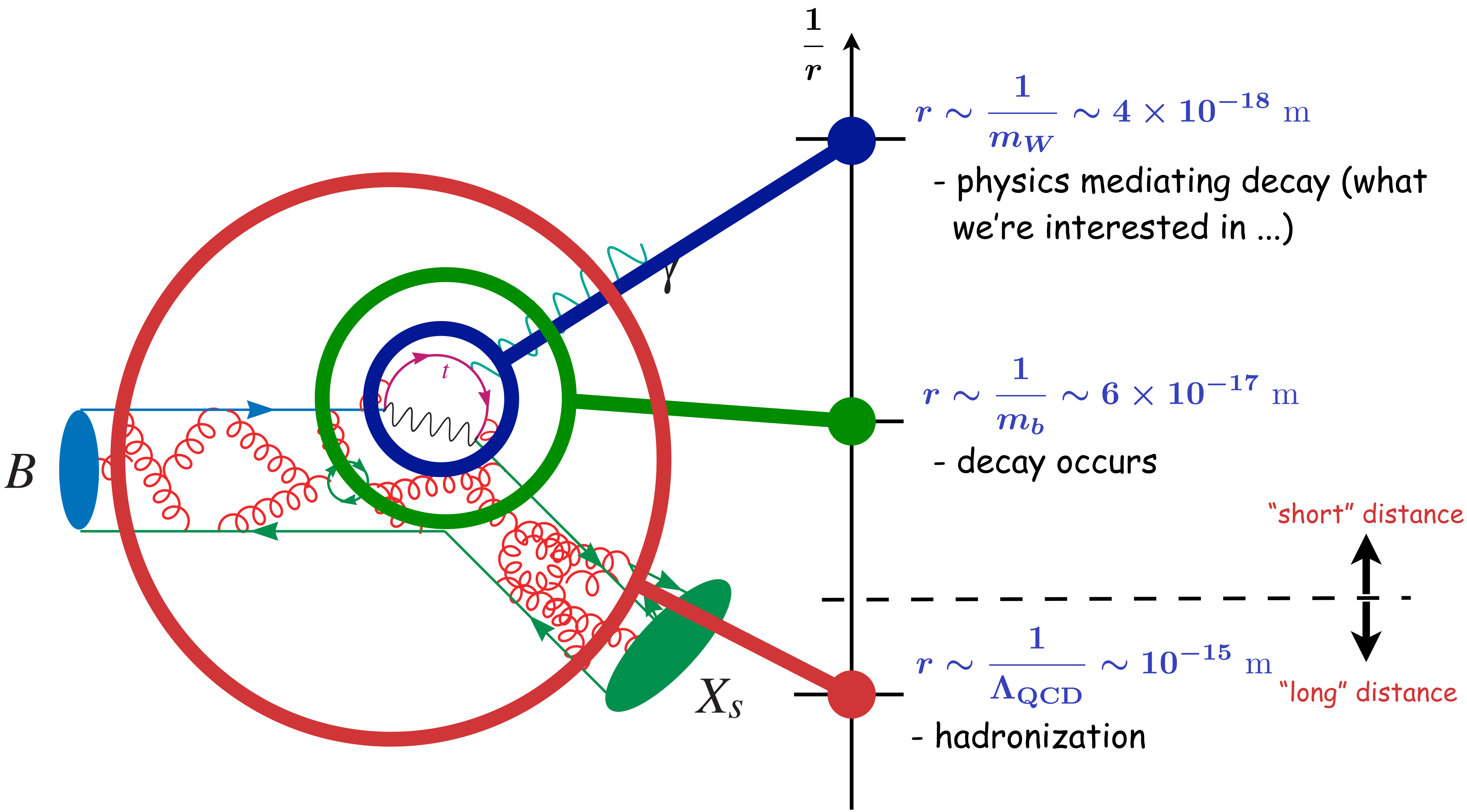
possible new short-distance physics mediated by X particle

long-distance QCD: hadrons, nonperturbative form factors ...

(and to believe small discrepancy = new physics, need model independent predictions - challenge for theory! ... cf g-2 for muon)

Does the process factorize in a useful way?

(Obvious) Scales in B Decay:

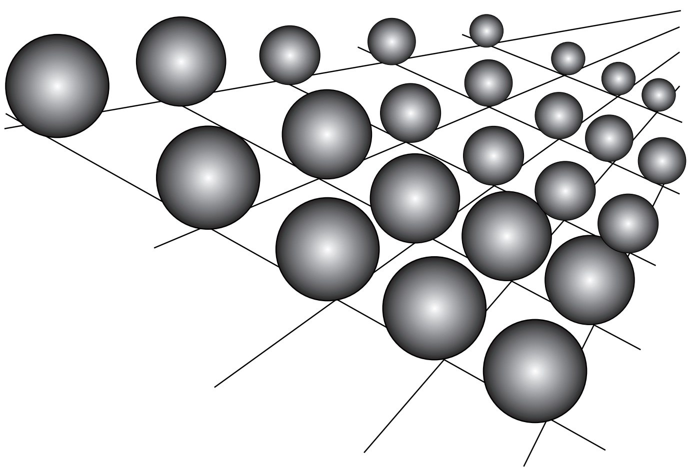


- Multiscale problem - want to unravel physics at different scales
- $\Lambda_{QCD}/m_b \sim 1/10$, so we need to understand power corrections

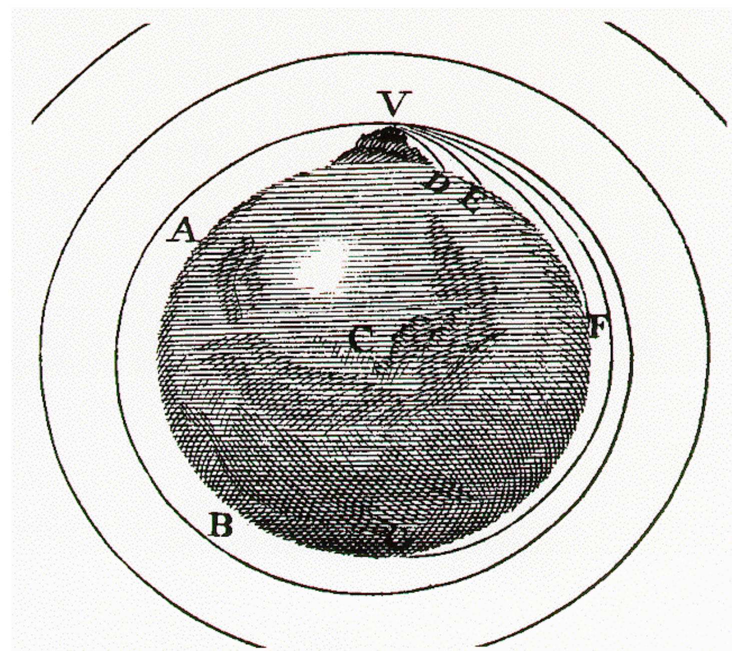
The Tool: Effective Field Theory ("EFT")

"sufficient unto the day is the evil thereof" (Mt. 6:34)

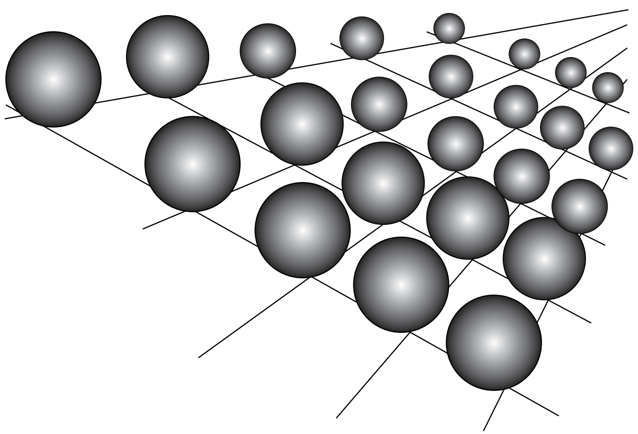
Use the degrees of freedom appropriate to energy/distance scale of problem!

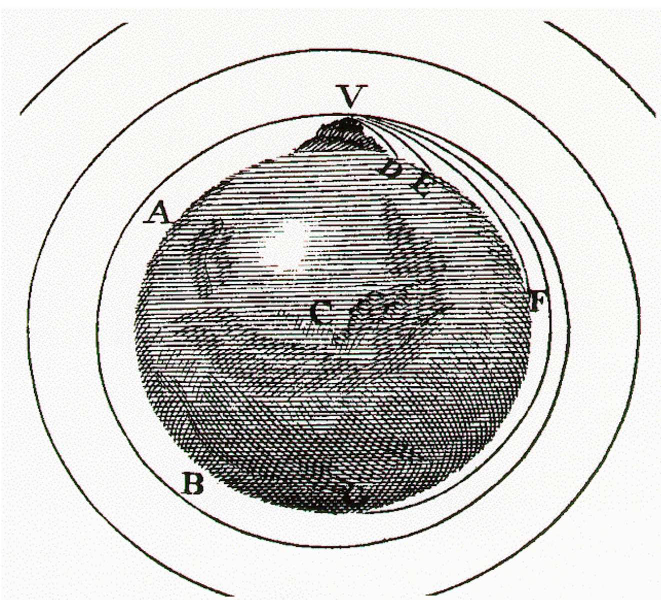


i.e. you shouldn't use quantum gravity ...



... to calculate projectile motion





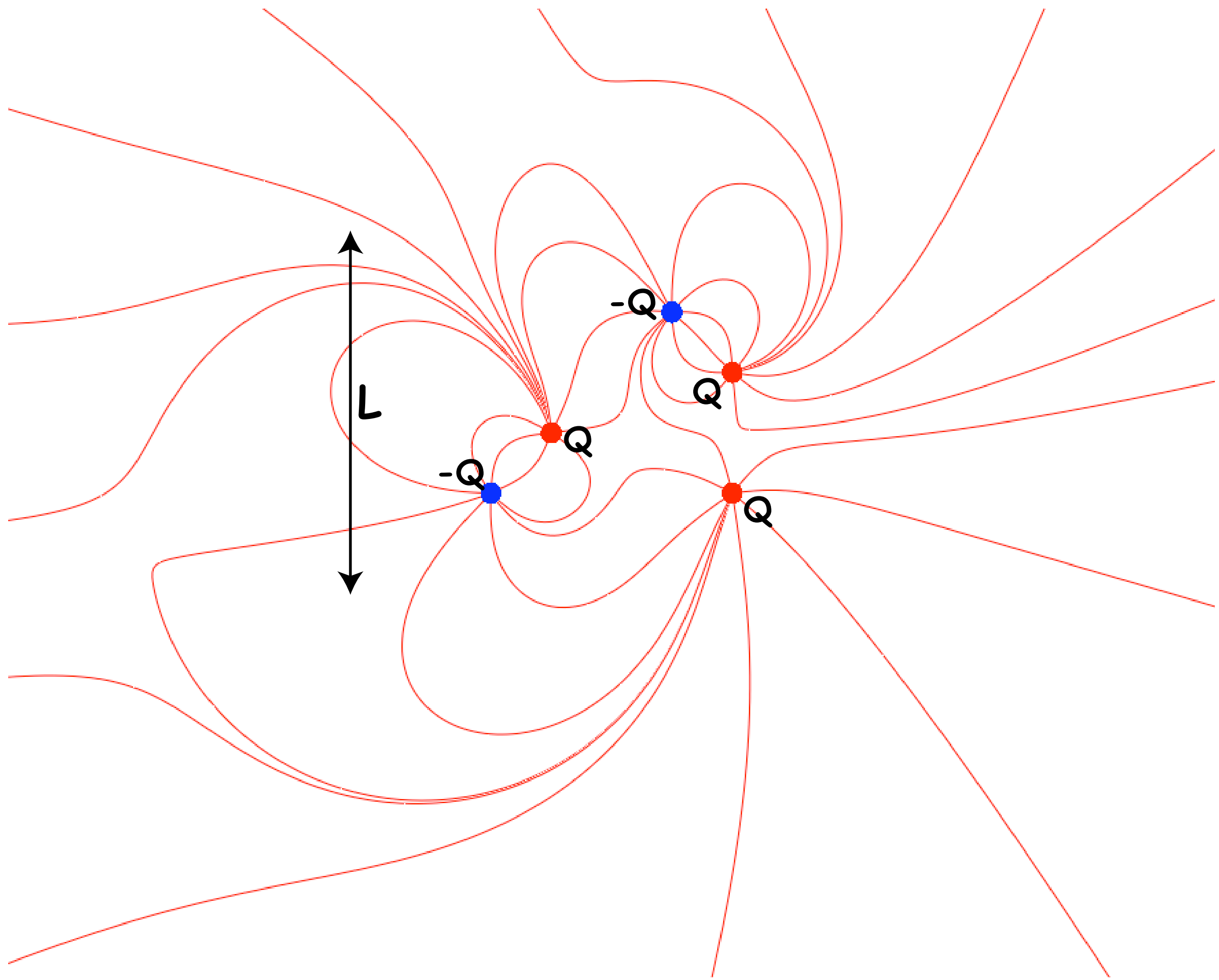
It's HARD:

- the calculation is MUCH more complicated
- appropriate degrees of freedom are obscured in "fundamental" theory
- we don't even know what quantum gravity is

and POINTLESS:

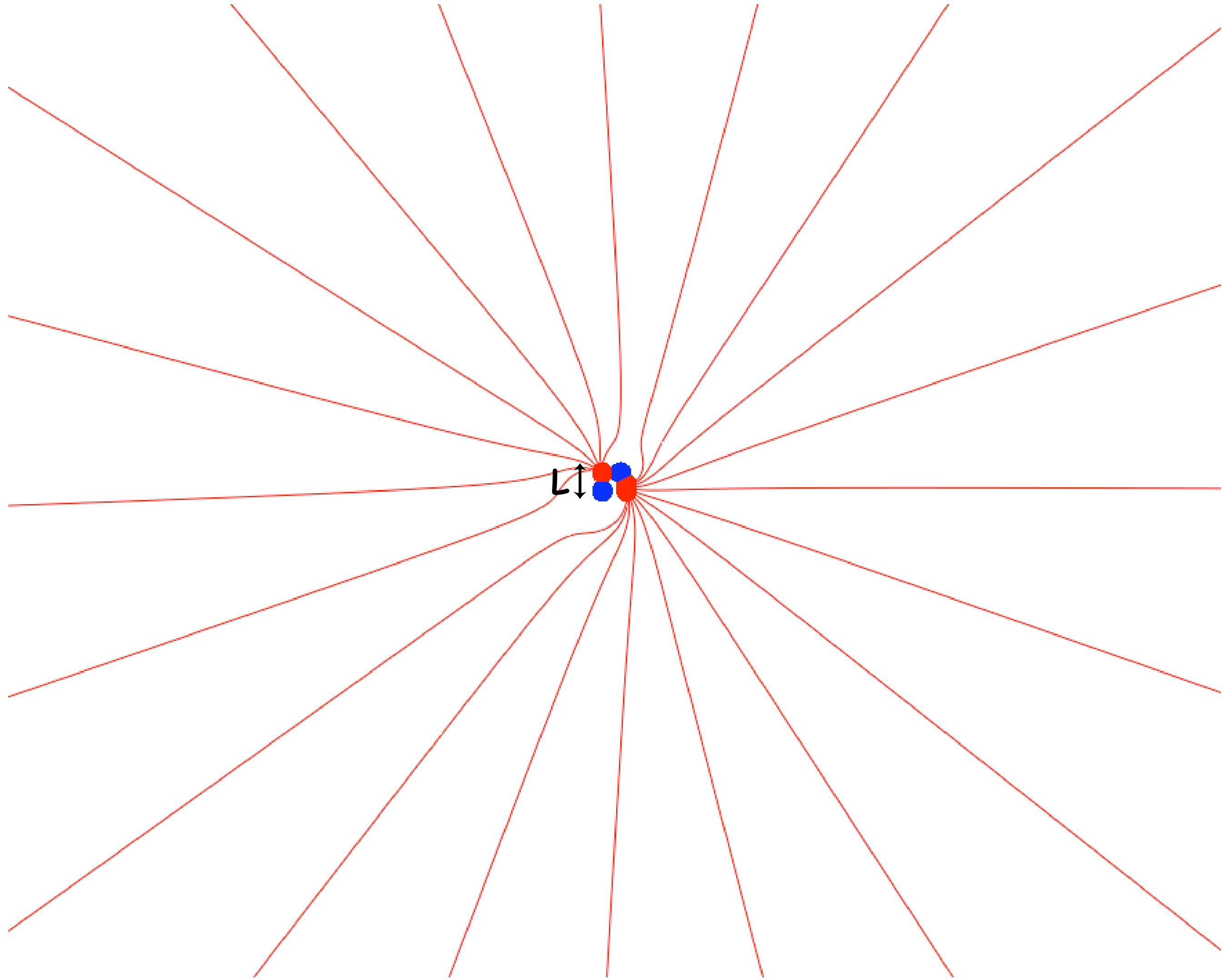
- quantum effects are TINY (corrections ~10^{-33} cm/r)
- if we need corrections, much simpler to expand QG in powers of r_{PLANCK}/r, take linear correction

Ex: the multipole expansion:



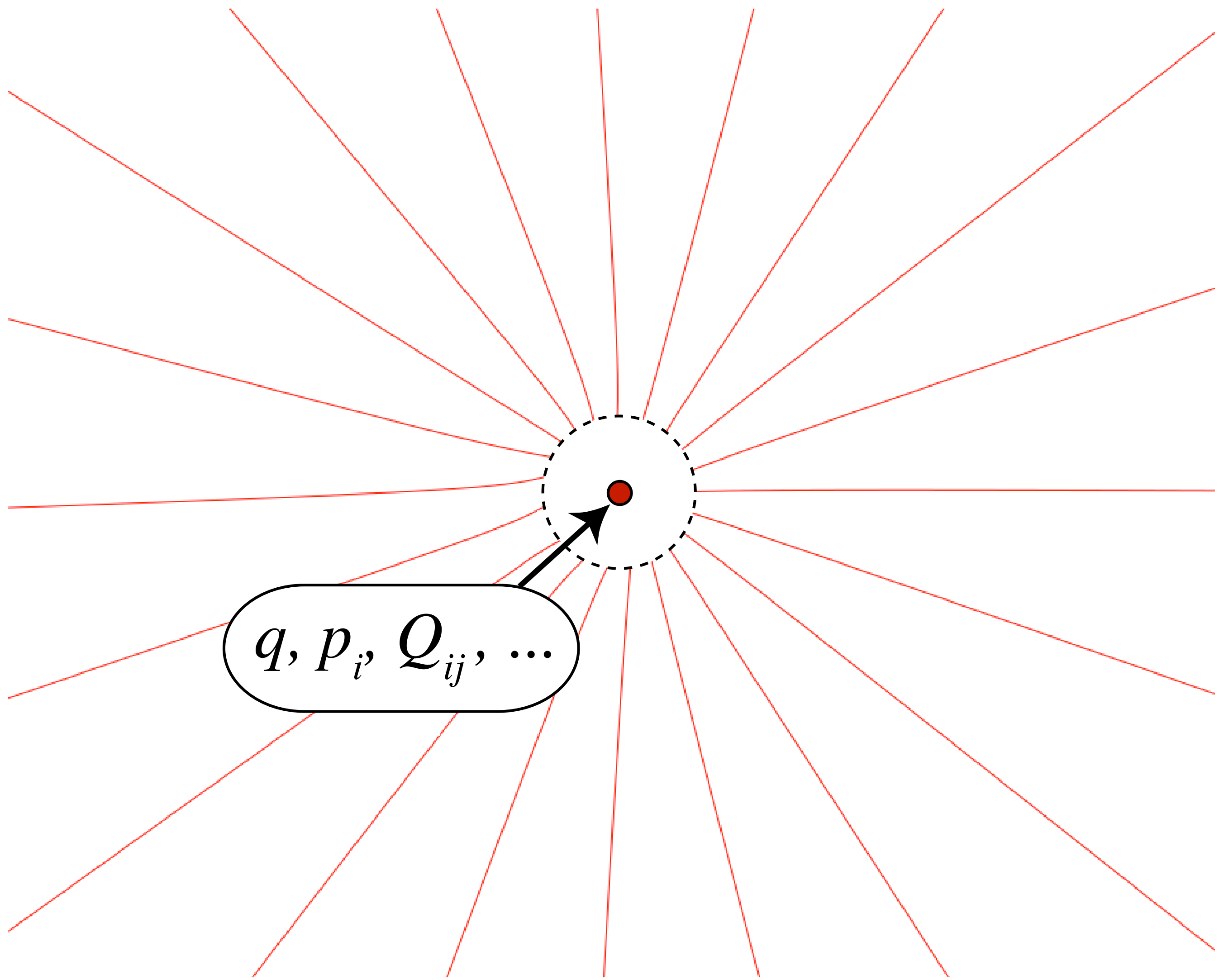
Physics at r~L is complicated - depends on details of charge distribution

Ex: the multipole expansion:



BUT ... if we are interested in physics at r>>L, things are much simpler ...

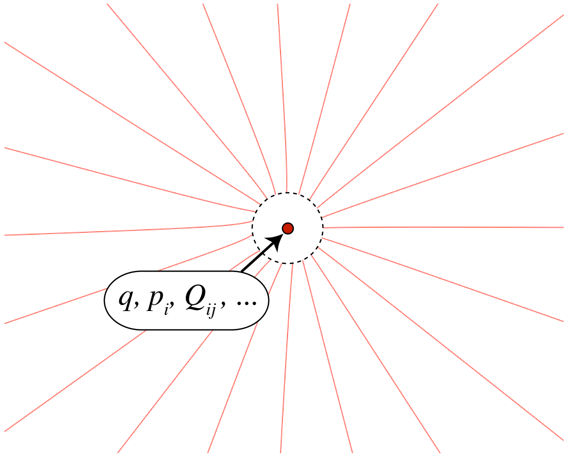
Ex: the multipole expansion:



... can replace complicated charge distribution by a POINT source with additional interactions (multipoles)...

Multipole expansion:

$$V(r) = \frac{q}{r} + \frac{\vec{p}\cdot\vec{x}}{r^3} + \frac{1}{2}Q_{ij}\frac{x_i x_j}{r^5} + \cdots$$



$q,\ p_i,\ Q_{ij},\ \cdots$: short distance quantities

$\left\langle \frac{1}{r} \right\rangle,\ \left\langle \frac{x_i}{r^3} \right\rangle,\ \left\langle \frac{x_i x_j}{r^5} \right\rangle,\ \cdots$: long distance quantities

FACTORIZATION!

higher order terms in multipole expansion suppressed by powers of (L/r) - for r>>L, only need first few terms. To get more accuracy, need more parameters.

Effective Field Theory ("EFT"): more generally, any theory at momentum p<<M can be described by an effective Hamiltonian,

$$H_{\text{eff}} = H_0 + \sum_i \frac{C_i}{M^{n_i}} \mathcal{O}_i$$

Hamiltonian in M->∞ limit

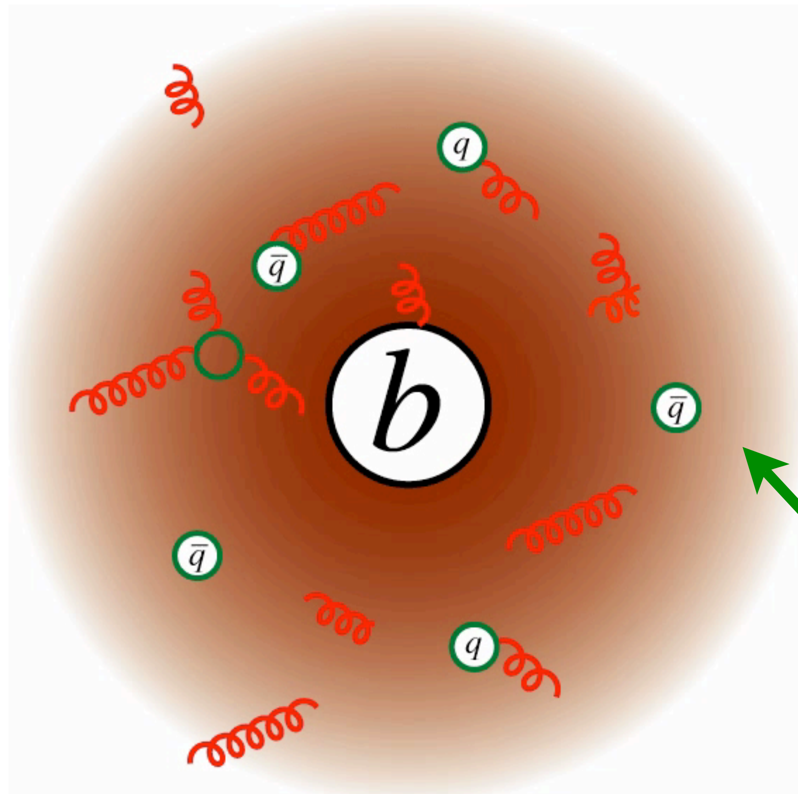
corrections determined by matrix elements of operators O_i - power counting determined by dimensional analysis

C_n's : short distance quantities (in QCD: perturbatively calculable if $M \gg \Lambda_{QCD}$)

$\langle \mathcal{O}_n \rangle$'s : long distance quantities (in QCD: nonperturbative ... need to get them elsewhere)

- Effective Field Theory automatically factorizes the calculation
- by keeping more terms, can work to arbitrary accuracy in 1/M

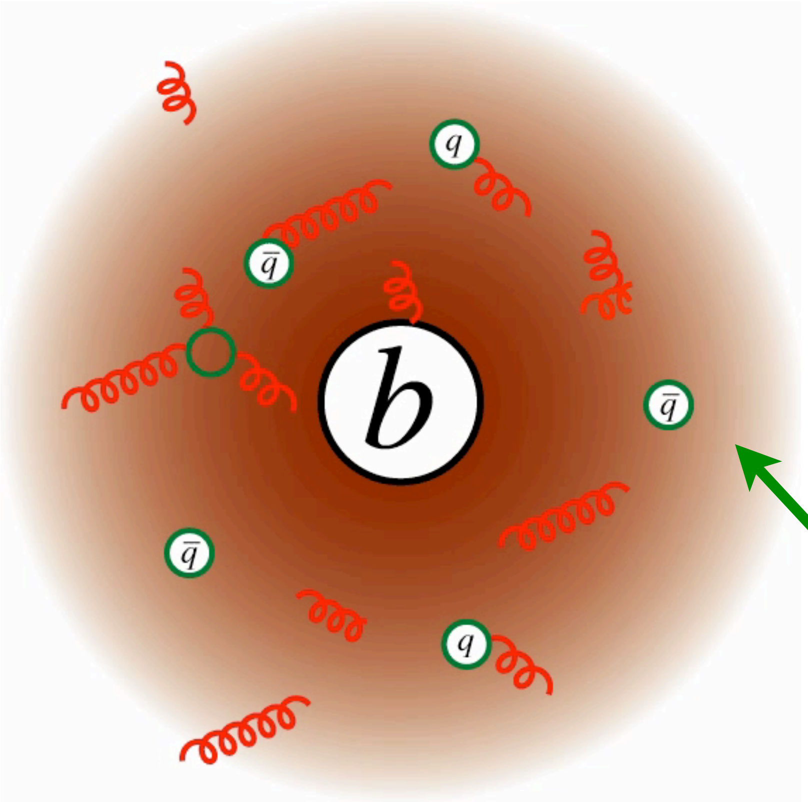
EFT for a b quark at low momentum transfer:



momentum ~Λ_{QCD} << m_b

B meson dynamics

EFT for a b quark at low momentum transfer:



momentum $\sim\Lambda_{QCD} \ll m_b$

B meson dynamics in the limit $\Lambda_{QCD}/m_b \to 0$

- at low ($\sim \Lambda_{QCD}$) momentum transfers, a heavy ($m_Q \gg \Lambda_{QCD}$) quark behaves as a **static colour source** .. **essentially NO dynamics** (cf. proton in H atom)

(Isgur & Wise, 1989)

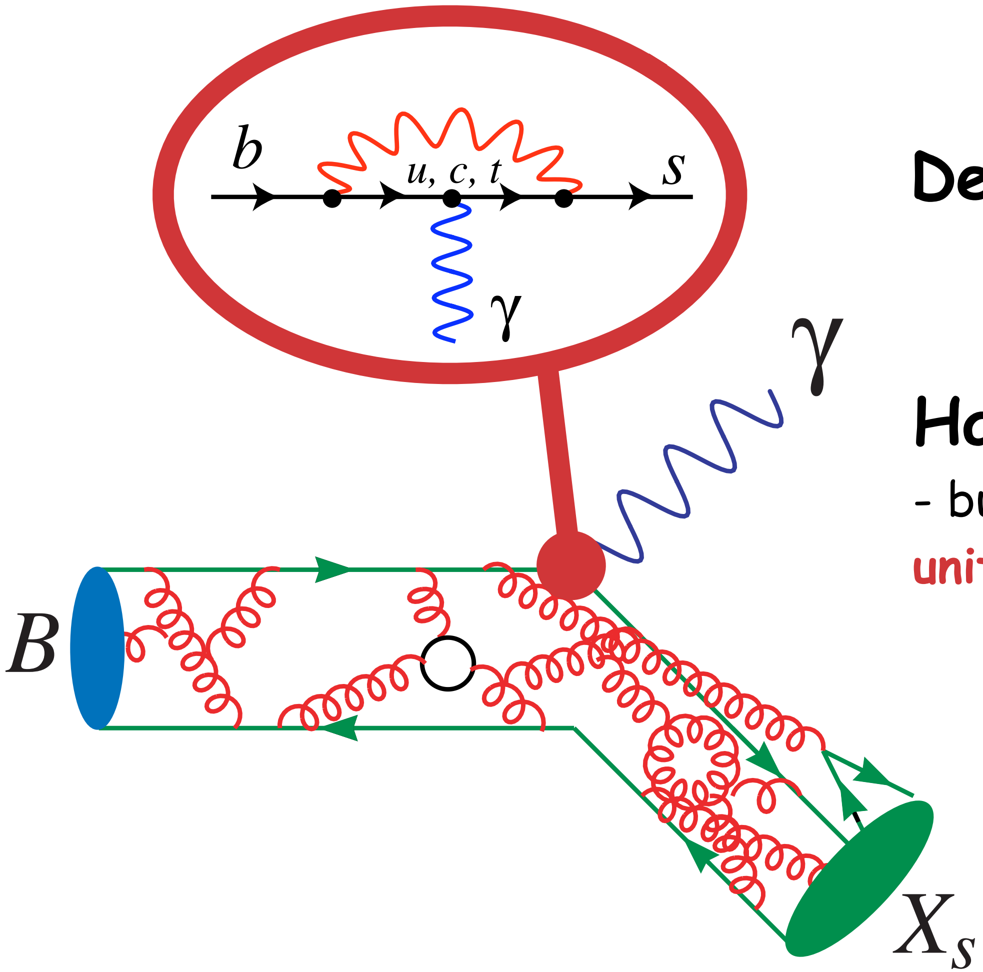
This field became suddenly fashionable in the early 1990's ...

(Isgur, Wise; Voloshin, Shifman; Eichten, Hill; Georgi; ...)

- in EFT, heavy quark ~ static colour source => many of its properties (mass, spin, magnetic moment, "Fermi motion") are IRRELEVANT at leading order in Λ_{QCD}/m_b ... EFT has lots of symmetry
- in a FEW cases, symmetries constrain the dynamics so strongly that at leading order there is NO unknown hadronic physics => absolute predictions!

"Classic" Application: INCLUSIVE decays (sum over all possible hadronic final states)

(Bigi, Shifman, Uraltsev, Vainshtein, Voloshin, Shifman; Chay, Georgi, Grinstein; Manohar, Wise; Falk, ML, Savage ...)



Decay: short distance (calculable)

Hadronization: long distance (nonperturbative)

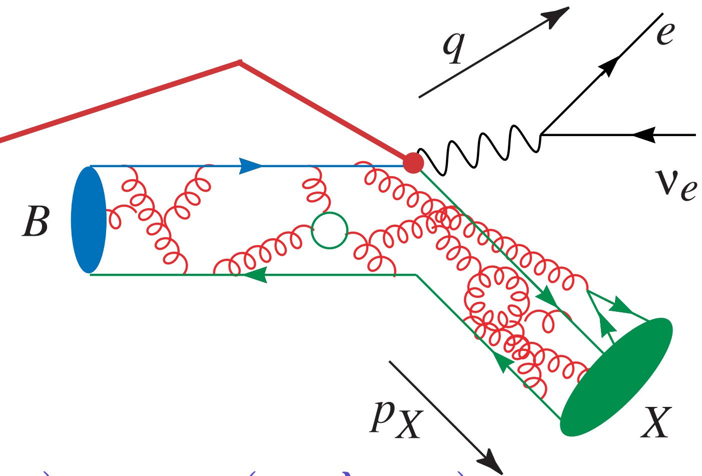
- but probability to hadronize (to SOMETHING) is **unity - nothing to calculate!**

- if all final hadronic states are included ("inclusive"), hadron decay is given by **free quark** decay (at leading order in $1/m_b$)

Similar to inclusive processes in proton collisions, but since the initial b quark is ~ at rest, the factorization is MUCH simpler (no convolution over momentum fraction) ... straightforward to calculate power corrections

Inclusive semileptonic b->c decay:

(need to determine b->c weak coupling constant V_{cb})



$$\Gamma(B \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3}(0.534)\left(\frac{m_\Upsilon}{2}\right)^5 \times$$

$$\Big[1 - 0.22\left(\frac{\Lambda_{1S}}{500\ \mathrm{MeV}}\right) - 0.011\left(\frac{\Lambda_{1S}}{500\ \mathrm{MeV}}\right)^2 - 0.052\left(\frac{\lambda_1}{(500\ \mathrm{MeV})^2}\right) - 0.071\left(\frac{\lambda_2}{(500\ \mathrm{MeV})^2}\right)$$

$$-0.006\left(\frac{\lambda_1 \Lambda}{(500\ \mathrm{MeV})^3}\right) + 0.011\left(\frac{\lambda_2 \Lambda}{(500\ \mathrm{MeV})^3}\right) - 0.006\left(\frac{\rho_1}{(500\ \mathrm{MeV})^3}\right) + 0.008\left(\frac{\rho_2}{(500\ \mathrm{MeV})^3}\right)$$

$$+0.011\left(\frac{T_1}{(500\ \mathrm{MeV})^3}\right) + 0.002\left(\frac{T_2}{(500\ \mathrm{MeV})^3}\right) - 0.017\left(\frac{T_3}{(500\ \mathrm{MeV})^3}\right) - 0.008\left(\frac{T_4}{(500\ \mathrm{MeV})^3}\right)$$

$$-0.096\,\epsilon - 0.030\,\epsilon^2_{BLM} + 0.015\,\epsilon\left(\frac{\Lambda_{1S}}{500\ \mathrm{MeV}}\right) + \dots\Big]$$

$O(\Lambda_{QCD}/m_b)$: ~20% correction

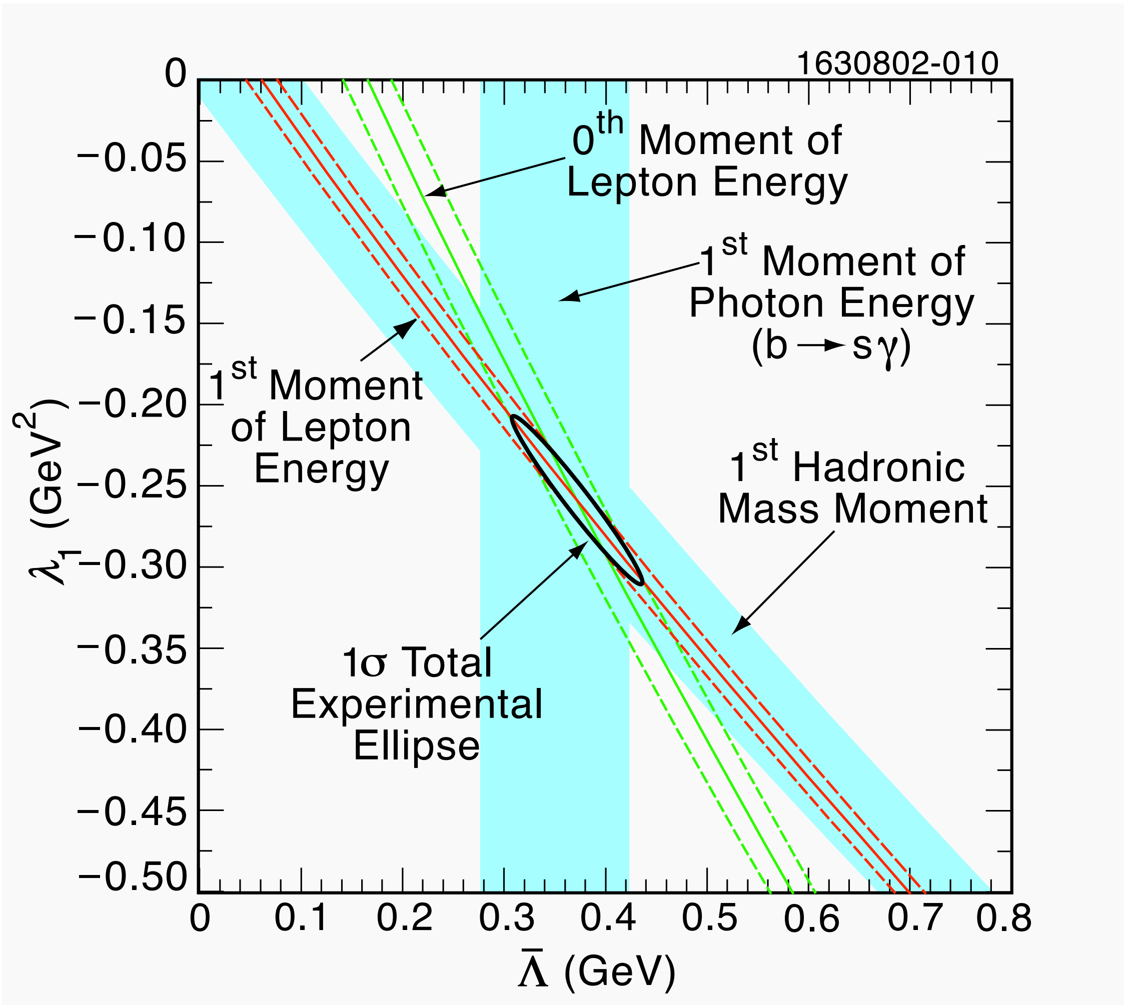
$O(\Lambda^3_{QCD}/m^3_b)$: ~1-2% correction

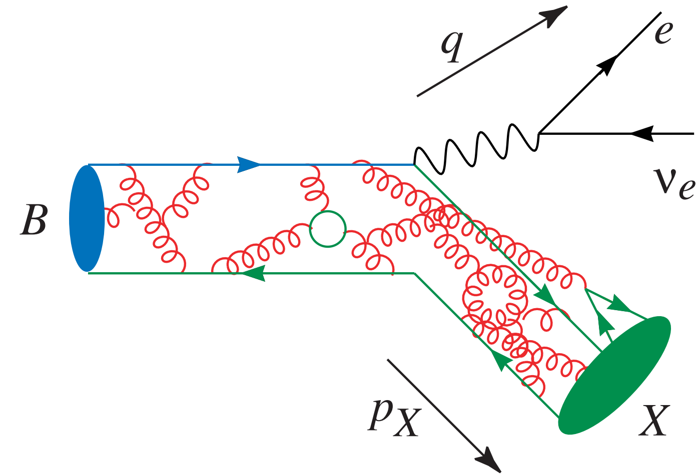
$O(\Lambda^2_{QCD}/m^2_b)$: ~5-10% correction

Perturbative: ~few %

-> This is now a PRECISION field!

Nonperturbative parameters can be determined from other observables (spectral moments):





(CLEO, PRD67:072001, 2003)

$\bar{\Lambda}$, λ_1: only unknown hadronic parameters for inclusive decays up to $O(\Lambda_{QCD}/m_b)^2$

Applications:

- spectroscopy
- semileptonic decays (measure parameters of Standard Model - calibration)
  - inclusive (sum over all hadronic states)
  - exclusive (decays to specific final states - particular those with charm quarks - "Heavy Quark Symmetry")
- nonleptonic decays (lifetimes)
- rare (inclusive) decays i.e. $b \to s\gamma$, $b \to s\mu^+\mu^-$

All can be handled in an expansion in $\Lambda_{QCD}/m_b \sim 1/10$ ... remarkable success over past decade

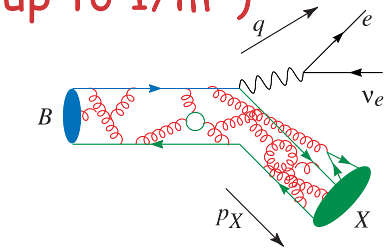
Much of this theory was developed in early-mid 1990's ... since then:

1. Much better data! (B factories, CDF, CLEO).
   - We now work to sub-sub-subleading order ($O(\Lambda_{QCD}/m_b)^3$) in some cases
   - worry (& argue) hard about theoretical uncertainties, effects at the few % level
2. Effective Field Theory ideas extended to more complex situations - including much more complex forms of factorization

Global fits (summer '02 - updated '04):

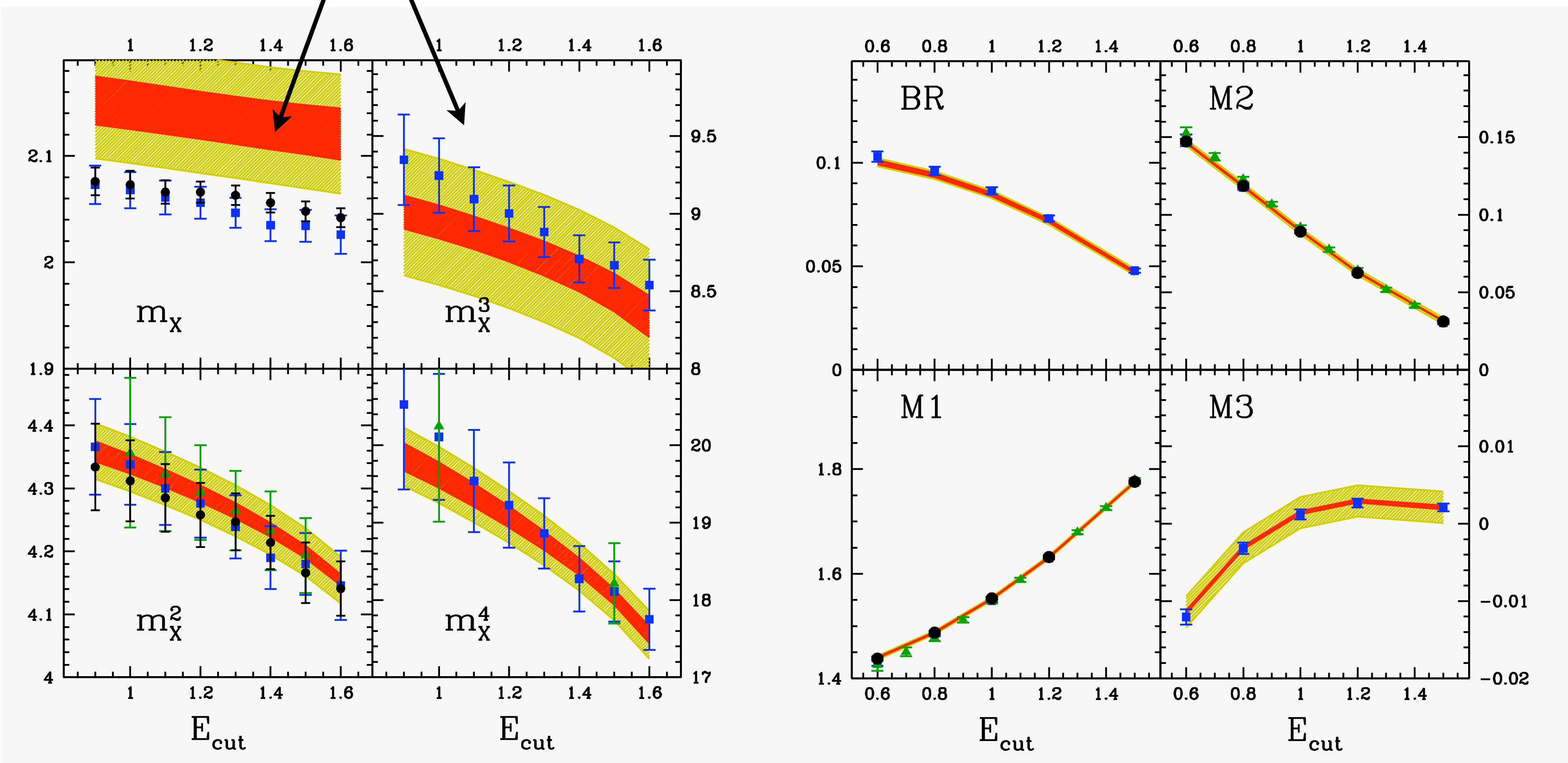
(Bauer, Ligeti, ML, Manohar and Trott)

(up to $1/m^3$)



- fit 92 data points (spectral moments with varying lepton energy cuts) with 7 free parameters

(These two are expected to be problematic for reasons I won't get into ...)



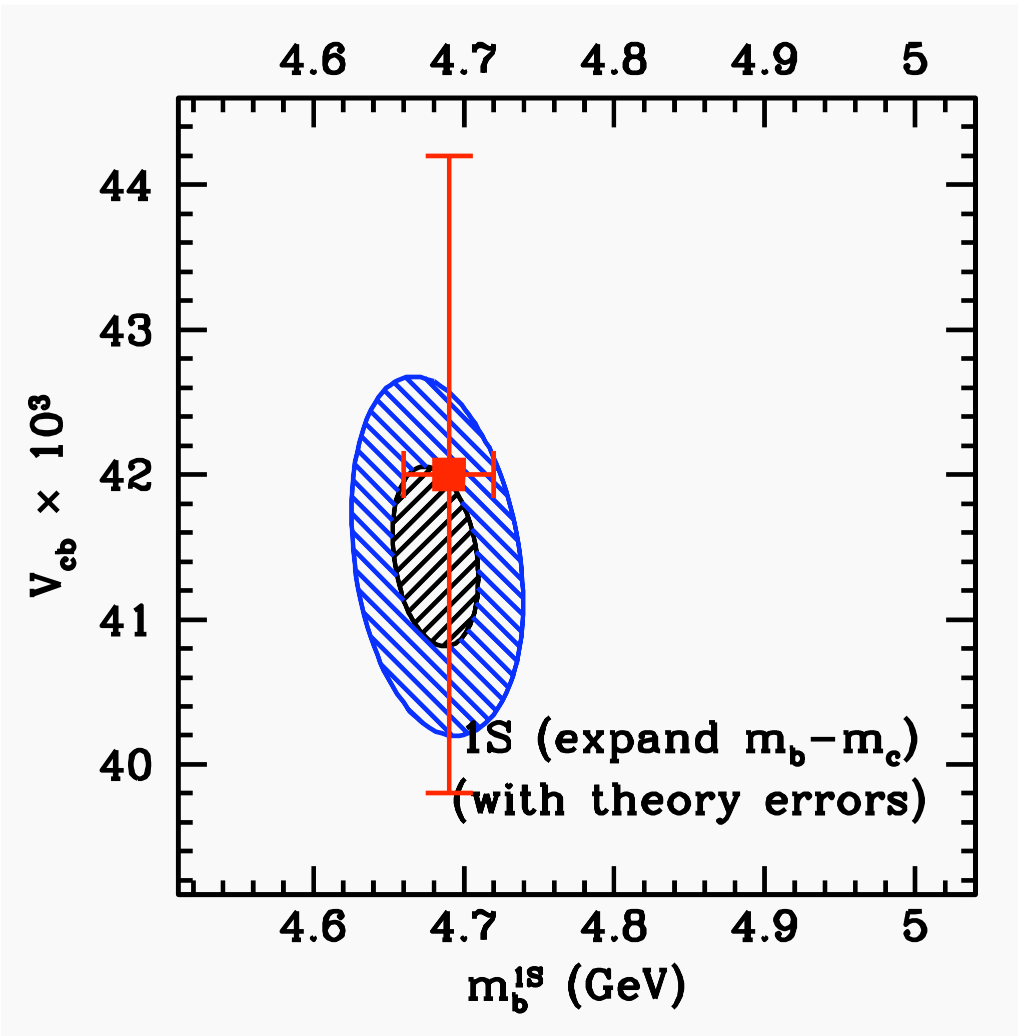
hadronic invariant mass moments

lepton energy moments

Global fits (summer '02 - updated '04):

(Bauer, Ligeti, ML, Manohar and Trott)

(up to $1/m^3$)



mass of b quark to 30 MeV!

$$m_b^{1S} = 4.68 \pm 0.03\,\mathrm{GeV}$$
$$m_c = m_b - (3.41 \pm 0.01\,\mathrm{GeV})$$
$$|V_{cb}| = (41.4 \pm 0.6) \times 10^{-3}$$

b-c weak coupling at % level!

■ V_{cb} from exclusive decays, m_b from sum rules (Hoang)

Global fits (summer '02 - updated '04):

(Bauer, Ligeti, ML, Manohar and Trott)

(up to $1/m^3$)

The fit also allows us to make precise predictions of other moments as a cross-check:

$$D_3 \equiv \frac{\int_{1.6\,\mathrm{GeV}} E_\ell^{0.7} \frac{d\Gamma}{dE_\ell}\, dE_\ell}{\int_{1.5\,\mathrm{GeV}} E_\ell^{1.5} \frac{d\Gamma}{dE_\ell}\, dE_\ell} = \begin{cases} 0.5190 \pm 0.0007 & \text{(theory)} \\ 0.5193 \pm 0.0008 & \text{(experiment)} \end{cases}$$

$$D_4 \equiv \frac{\int_{1.6\,\mathrm{GeV}} E_\ell^{2.3} \frac{d\Gamma}{dE_\ell}\, dE_\ell}{\int_{1.5\,\mathrm{GeV}} E_\ell^{2.9} \frac{d\Gamma}{dE_\ell}\, dE_\ell} = \begin{cases} 0.6034 \pm 0.0008 & \text{(theory)} \\ 0.6036 \pm 0.0006 & \text{(experiment)} \end{cases}$$

(some fractional moments of lepton spectrum are very insensitive to $O(1/m^3)$ effects, and so can be predicted very accurately)

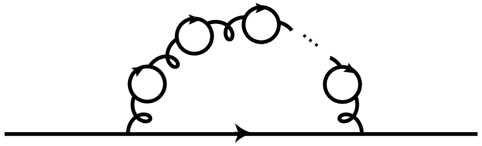
(C. Bauer and M. Trott)

NB: these were REAL PREdictions (not postdictions)

Hadronic physics with < 1% uncertainty!

There are lots of other theoretical issues arising in this game ...

- ☑ phase space boundaries - experimental cuts can ruin usual 1/m expansion
  - in some restricted regions, infinite series can be summed into nonperturbative "shape function" (Bigi, Uraltsev, Shifman, Vainsthein; Neubert)
  - recently shown to generalize to all orders in 1/m (cf subleading twist parton distribution functions) (Bauer, ML and Mannel; Leibovich, Ligeti and Wise)
- ☑ perturbation theory

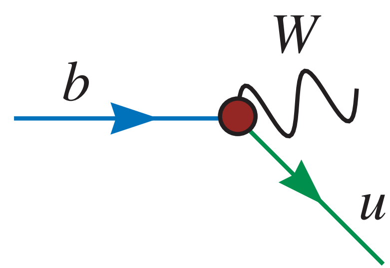


  - "renormalons" (apparently bad behaviour when unphysical parameters used) (Bigi et. al., Beneke, ML, Manohar and Savage, Neubert and Sachrajda)
- ☑ enhanced $1/m^3$ corrections ("weak annihilation") (Bigi and Uraltsev, Voloshin)
- ☑ long-distance physics - fragmentation, light quark loops
- ☑ "quark-hadron duality"
- ☑ ...

... useful as this is, in the B factory era it only touches a small fraction of the interesting decays

We'd like to understand more complex situations (particularly 2 body, nonleptonic decays - important for CP violation studies)

Ex: want to measure the COMPLEX PHASE of the b-u coupling (this is the kind of measurement the B Factories were built to make)



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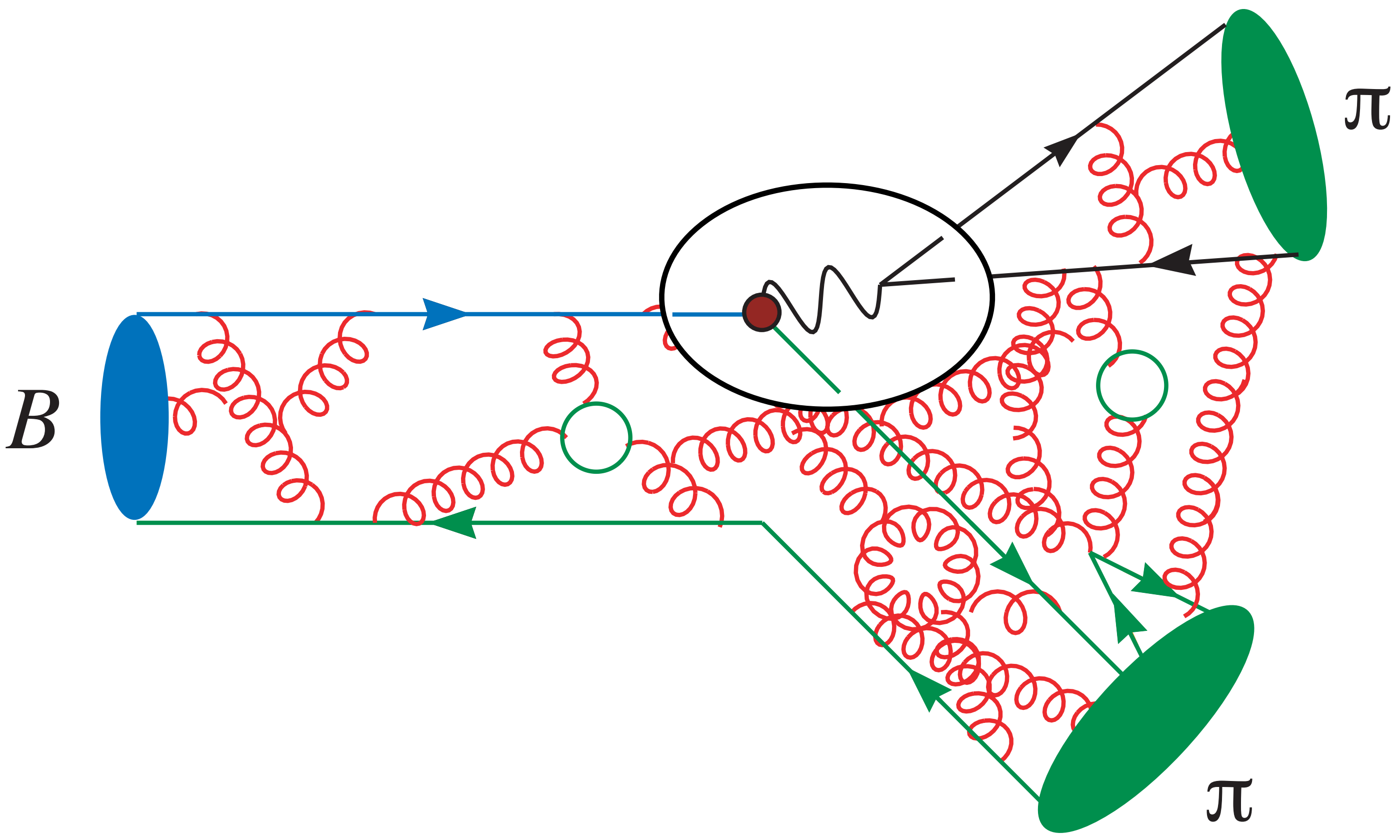
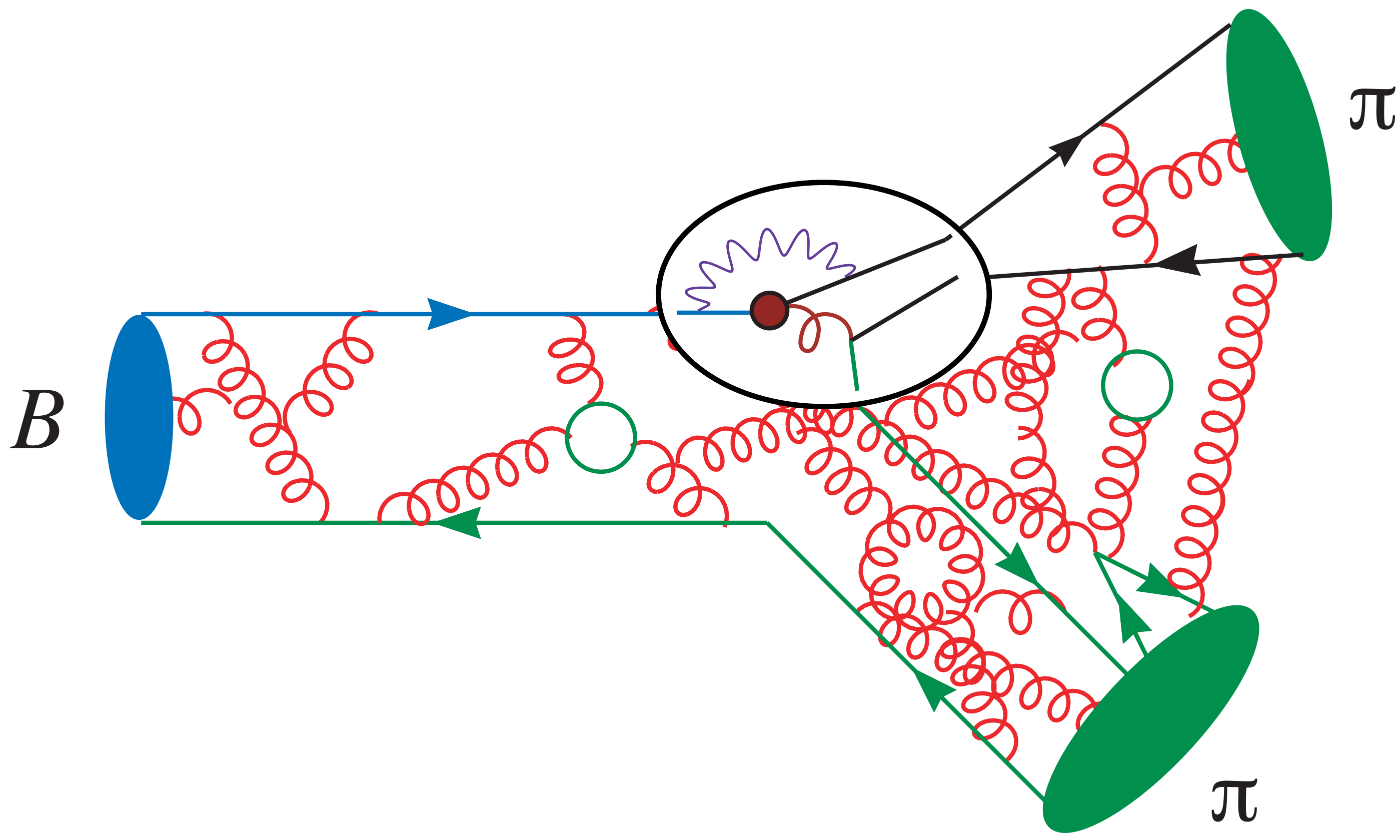


The best place to get this is in B -> $\pi\pi$ decays. None of the preceding allows us to pull this apart into anything simpler.

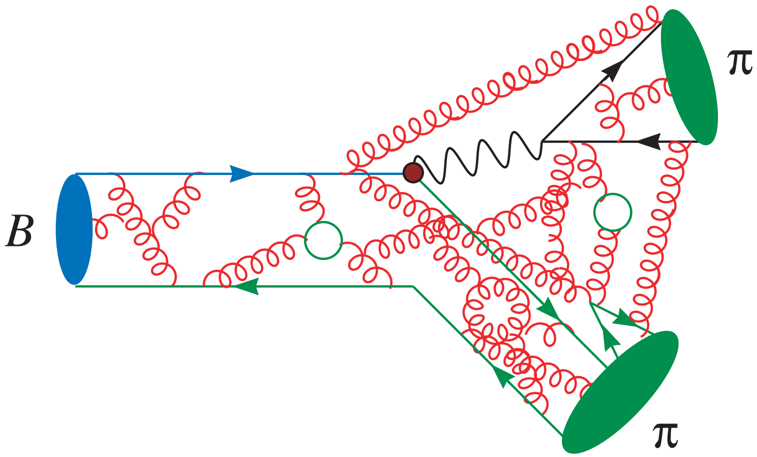
In addition, other short-distance contributions contribute to the same decay! ("penguin pollution") - need to disentangle



The best place to get this is in B -> $\pi\pi$ decays. None of the preceding allows us to pull this apart into anything simpler.

"QCD Factorization" proposal (not an EFT)

(Beneke, Buchalla, Neubert, Sachrajda)



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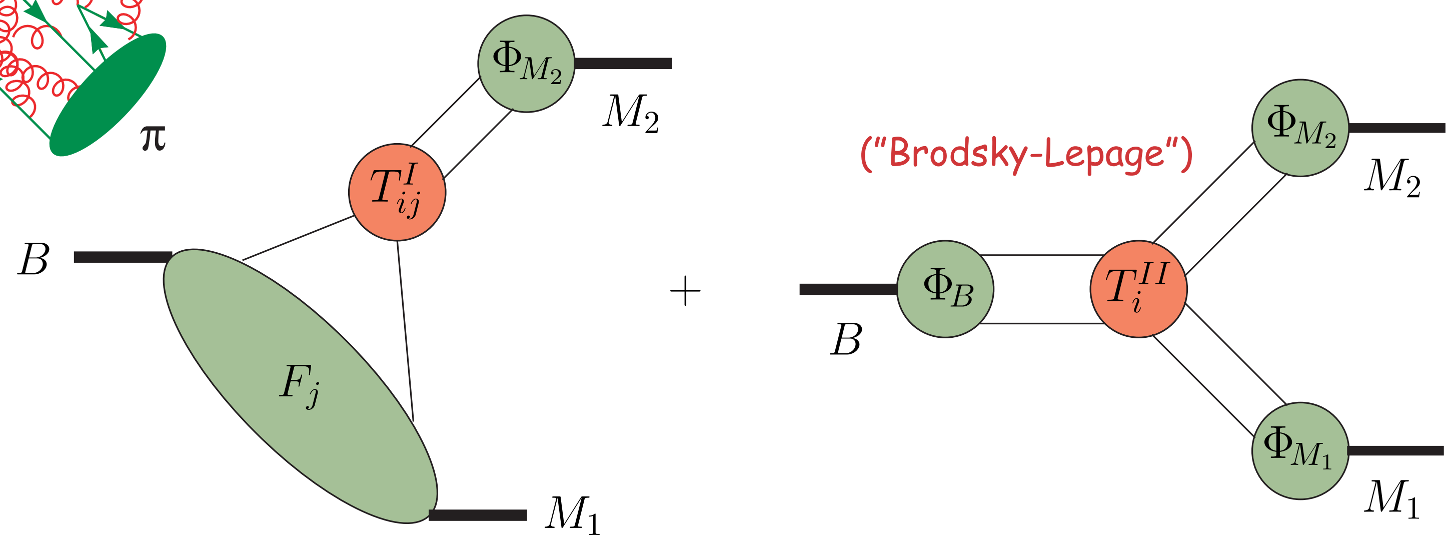
("Brodsky-Lepage")



complicated convolutions (cf. parton model)

$+O(\Lambda_{QCD}/m_b)$

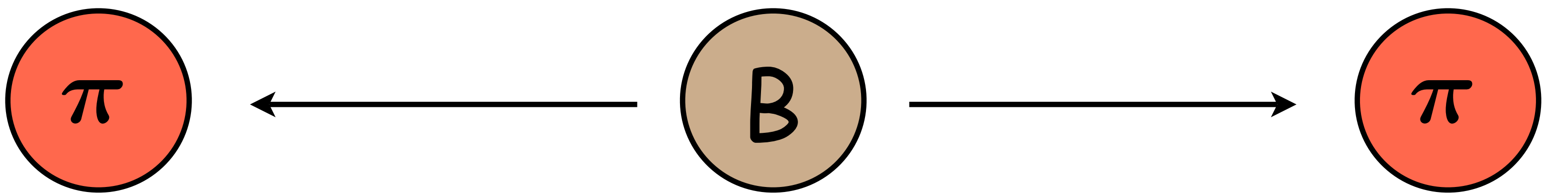
subprocesses:

Short-distance QCD

Long-distance form factor/wave function

"Soft-Collinear Effective Theory" (SCET)

Bauer, ML, Fleming, Pirjol, Stewart, ...

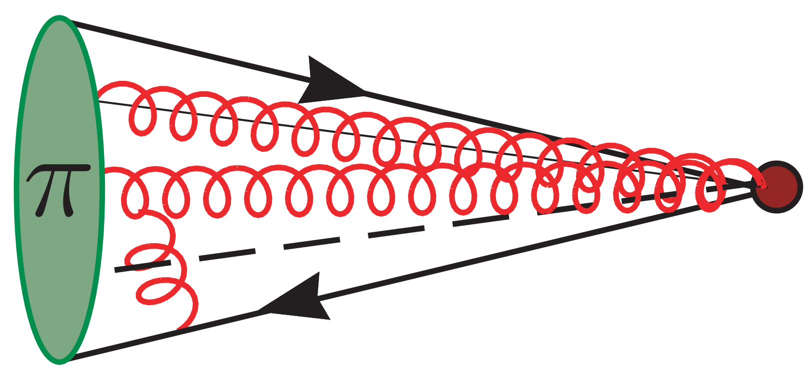


- pions have LARGE energy ($\sim m_b/2 \gg \Lambda_{QCD}$), LOW mass ($\sim \Lambda_{QCD}$)

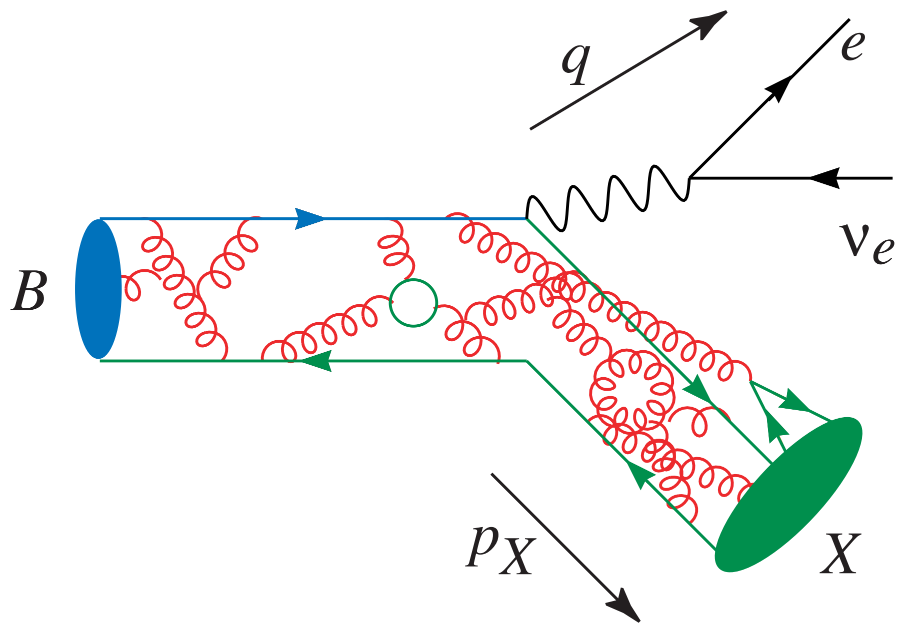
"SOFT" constituents $p^\mu = (p^+, p^-, p^\perp) \sim (\Lambda_{\rm QCD}, \Lambda_{\rm QCD}, \Lambda_{\rm QCD})$

"Collinear" constituents $p^\mu = (p^+, p^-, p^\perp) \sim \left(\frac{\Lambda^2_{\rm QCD}}{m_b}, m_b, \Lambda_{\rm QCD}\right)$

SCET is a "Large energy" expansion - complicated because of extra scales ..



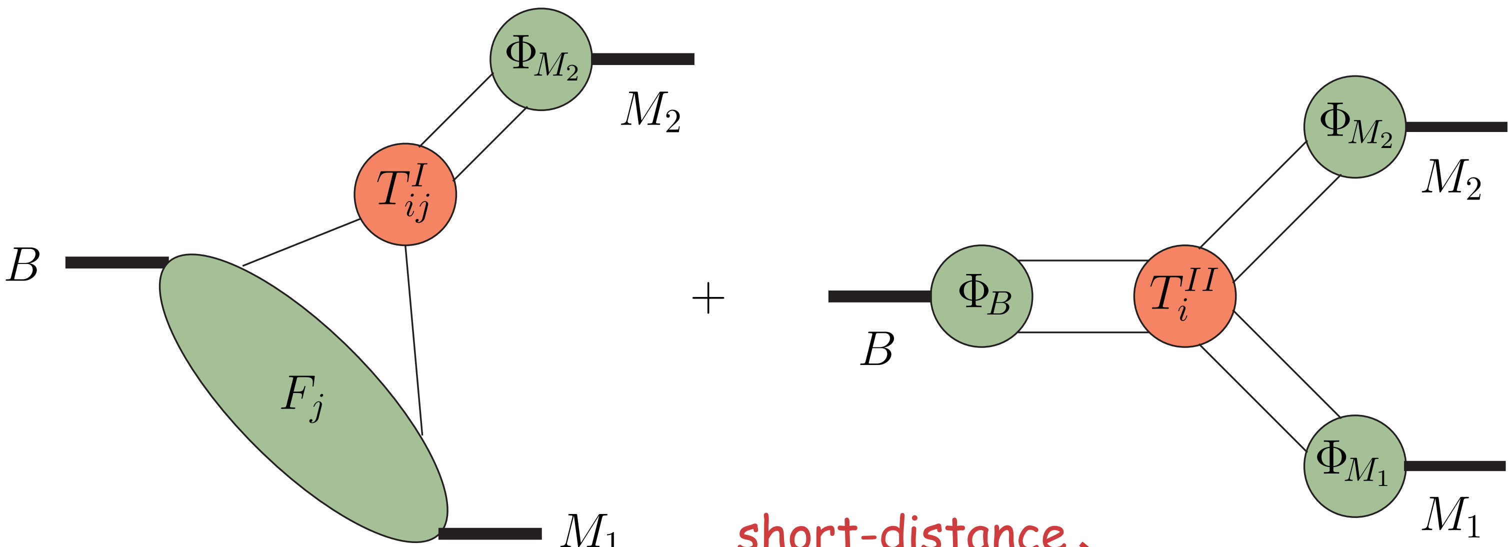
Factorization in B Decays (c. 1994):



$$\frac{1}{\Gamma_0}\Gamma(B\to X_c\ell\bar{\nu}_\ell)=0.369\left[1-1.54\frac{\alpha_s(m_b)}{\pi}+3.35\frac{\bar{\Lambda}}{m_B}+5.81\frac{\bar{\Lambda}^2}{m_B^2}-5.69\frac{\lambda_1}{m_B^2}-7.47\frac{\lambda_2}{m_B^2}+O\left(\frac{\Lambda_{QCD}}{m_B}\right)^3\right]$$

Factorization in B Decays (c. 2004):

(Beneke, Buchalla, Neubert Sachraja; Bauer, Pirjol, Rothstein, Stewart)



short-distance

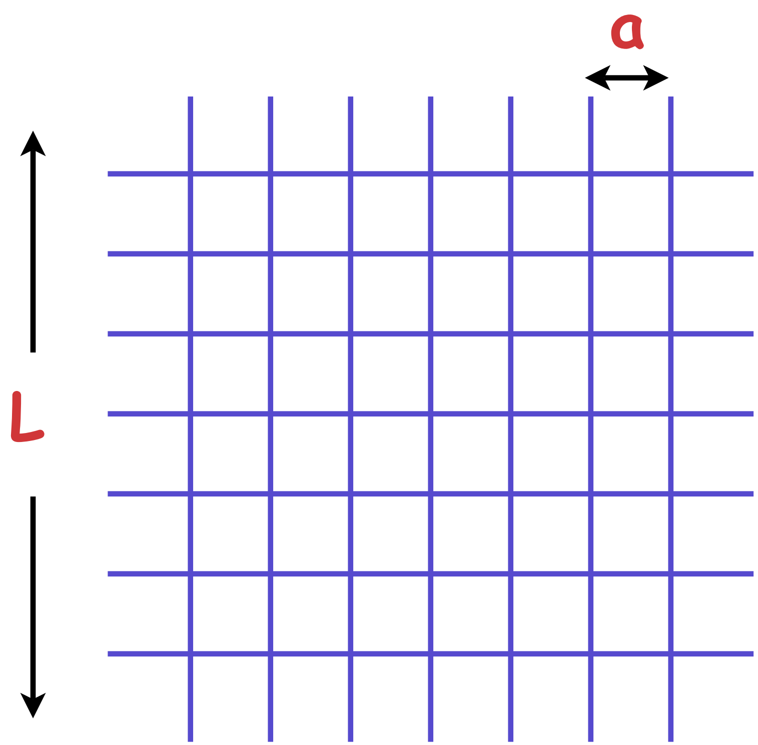
long-distance

controversial

$$A(\bar{B} \to M_1 M_2) = \lambda_c^{(f)} A_{c\bar{c}}^{M_1 M_2} + \frac{G_F m_B^2}{\sqrt{2}} \Big\{ f_{M_2}\, \zeta^{BM_1} \int_0^1 du\, T_{2\zeta}(u)\, \phi^{M_2}(u)$$
$$+ f_{M_1}\, \zeta^{BM_2} \int_0^1 du\, T_{1\zeta}(u)\, \phi^{M_1}(u) + \frac{f_B f_{M_1} f_{M_2}}{m_b} \int_0^1 du \int_0^1 dx \int_0^1 dz \int_0^\infty dk_+\, J(z, x, k_+)$$
$$\times \Big[T_{2J}(u,z) \phi^{M_1}(x) \phi^{M_2}(u) + T_{1J}(u,z) \phi^{M_2}(x) \phi^{M_1}(u) \Big] \phi_B^+(k_+) \Big\} + O\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

Final Comment

This is always going to be with us ... need to factorize problems for nonperturbative lattice QCD calculations as well!



- need $L>1$ fm to simulate proton
- need $a<1/Q$ to simulate short-distance physics w/momentum Q

- extremely inefficient to simulate short-distance (perturbative) physics on the lattice!

Factorization -> do short-distance physics analytically, long-distance physics numerically with lattice spacing $a\gg 1/Q$

Summary:

- Factorization allows us to separate short-distance (interesting) physics from long-distance QCD in a model-independent way
- effective field theory systematizes the calculation
- in the heavy quark limit, exact results can be proven which allow us to finesse nonperturbative QCD for b decays (in some cases)
- this is now a precision field - limiting effects are at the $O(1/m^3)$ level (few percent in many cases)
- new approaches to EFT are allowing us to study more complicated situations

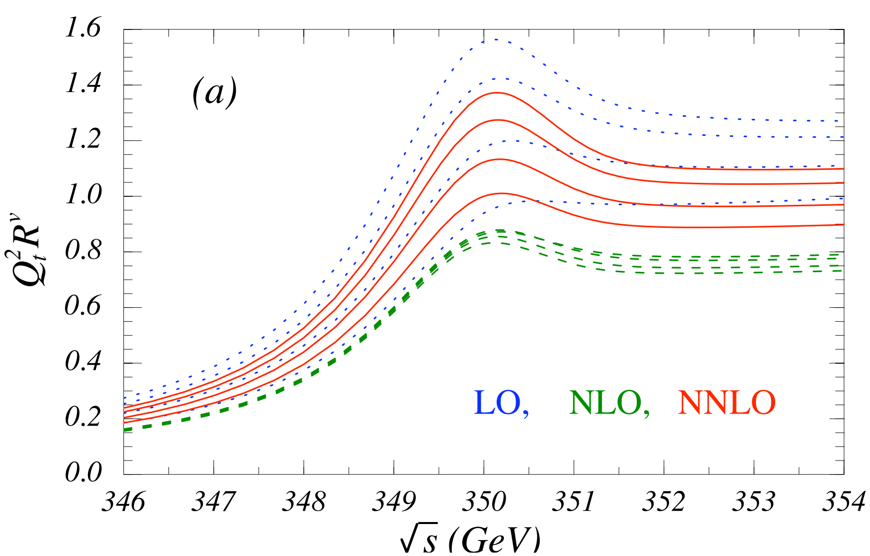

STOP

Other Applications and Directions:

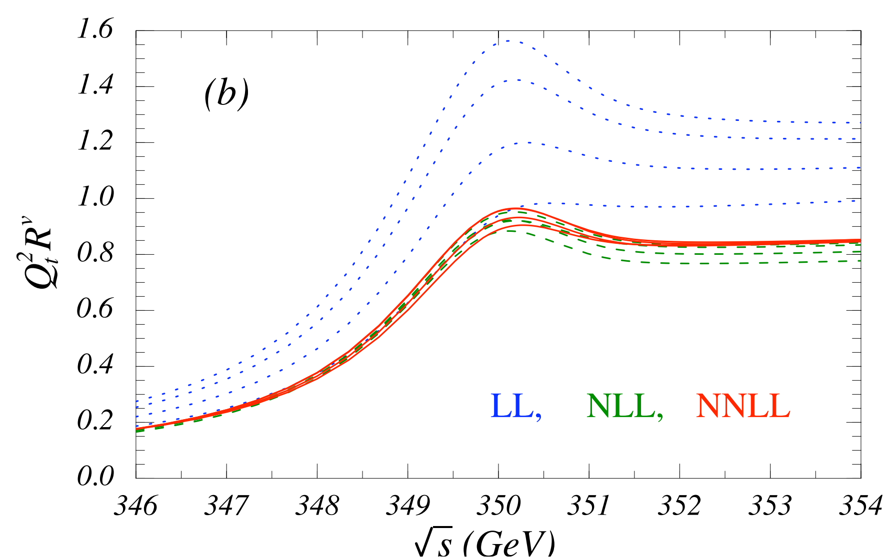
NRQCD: "Non-relativistic QCD" - EFT for systems with two heavy quarks (i.e. $b\bar{b}$ bound states) (more complicated due to correlated scales)

- $b\bar{b}$, $c\bar{c}$ production and decay (fixed huge discrepancy with exp't)
- b quark mass to 50-100 MeV

Ex: $t\bar{t}$ production near threshold



no RGE



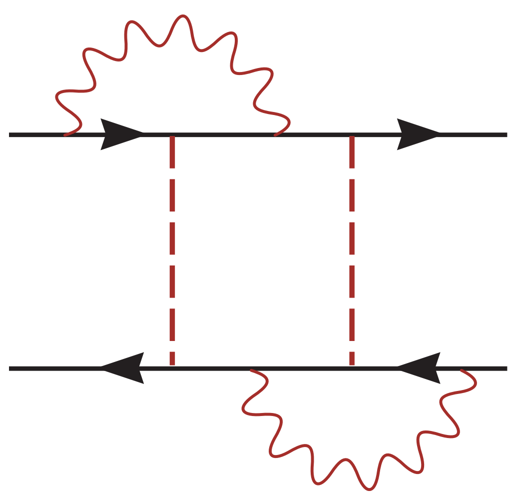
RGE-improved

(from Hoang et al, PRD65:014014, 2002)

Other Applications and Directions:

NRQCD

NRQED: EFT simplifies high precision QED calculations - can get state-of-the-art results with a few Feynman diagrams ...



$\alpha^8 \ln^3 \alpha$	Lamb	H	agree/new
		$\mu^+ e^-,\ e^+ e^-$	new
	(no h.f.s)		agree
$\alpha^4 \ln^3 \alpha$	(no $\Delta\Gamma/\Gamma$)		agree
$\alpha^7 \ln^2 \alpha$	Lamb	$H,\ \mu^+ e^-,\ e^+ e^-$	agree
	h.f.s.	$H,\ \mu^+ e^-,\ e^+ e^-$	agree
$\alpha^3 \ln^2 \alpha$	$\Delta\Gamma/\Gamma$	$e^+ e^-$ ortho and para	agree
$\alpha^6 \ln \alpha$	Lamb, h.f.s.	$H,\ \mu^+ e^-,\ e^+ e^-$	agree
$\alpha^2 \ln \alpha$	$\Delta\Gamma/\Gamma$	$e^+ e^-$ ortho and para	agree

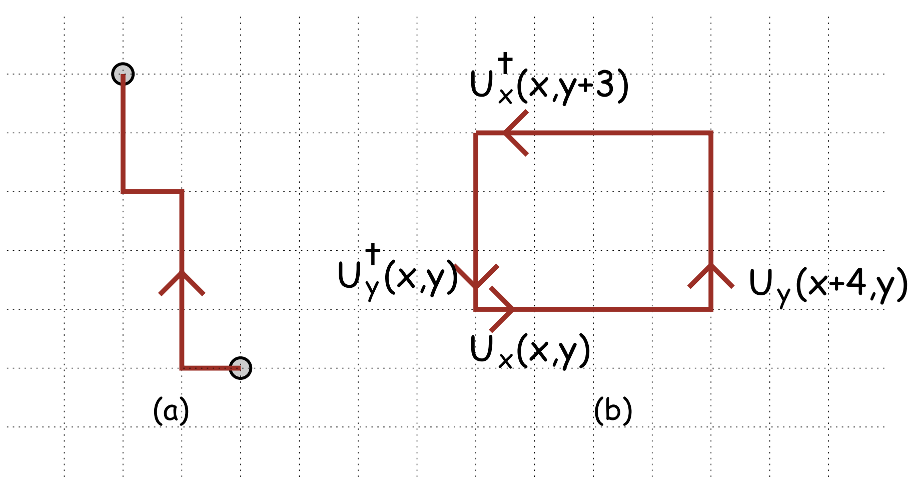
(from A. Manohar, Ringberg Workshop '03)

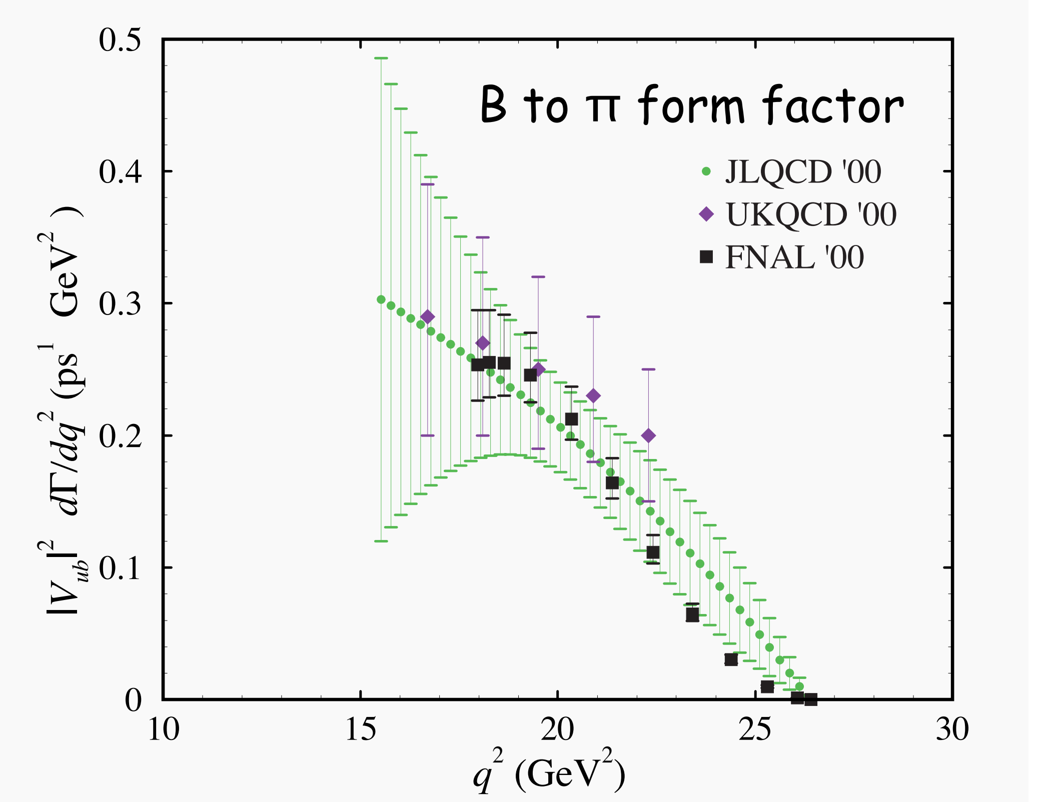
Other Applications and Directions:

NRQCD

NRQED

Lattice QCD: **NONPERTURBATIVE** (numerical) - but hard to handle multiscale problems! (need fine lattice spacing $\sim 1/m_b \ll 1/\Lambda_{QCD}$ - computationally demanding) - EFT removes short-distance dynamics so it doesn't have to be simulated





(from A. Kronfeld, hep-ph/0010074)

Other Applications and Directions:

NRQCD

NRQED

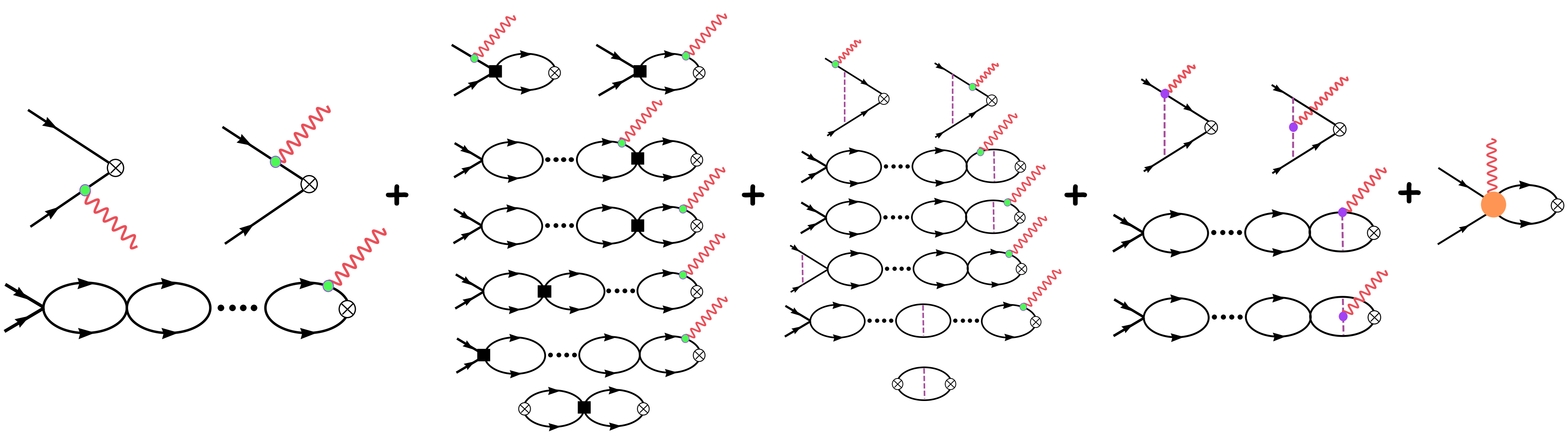
Lattice QCD

Nuclear Physics: NN scattering, model-independently

- renormalization and counterterms instead of potential models, off-shell ambiguities, ...

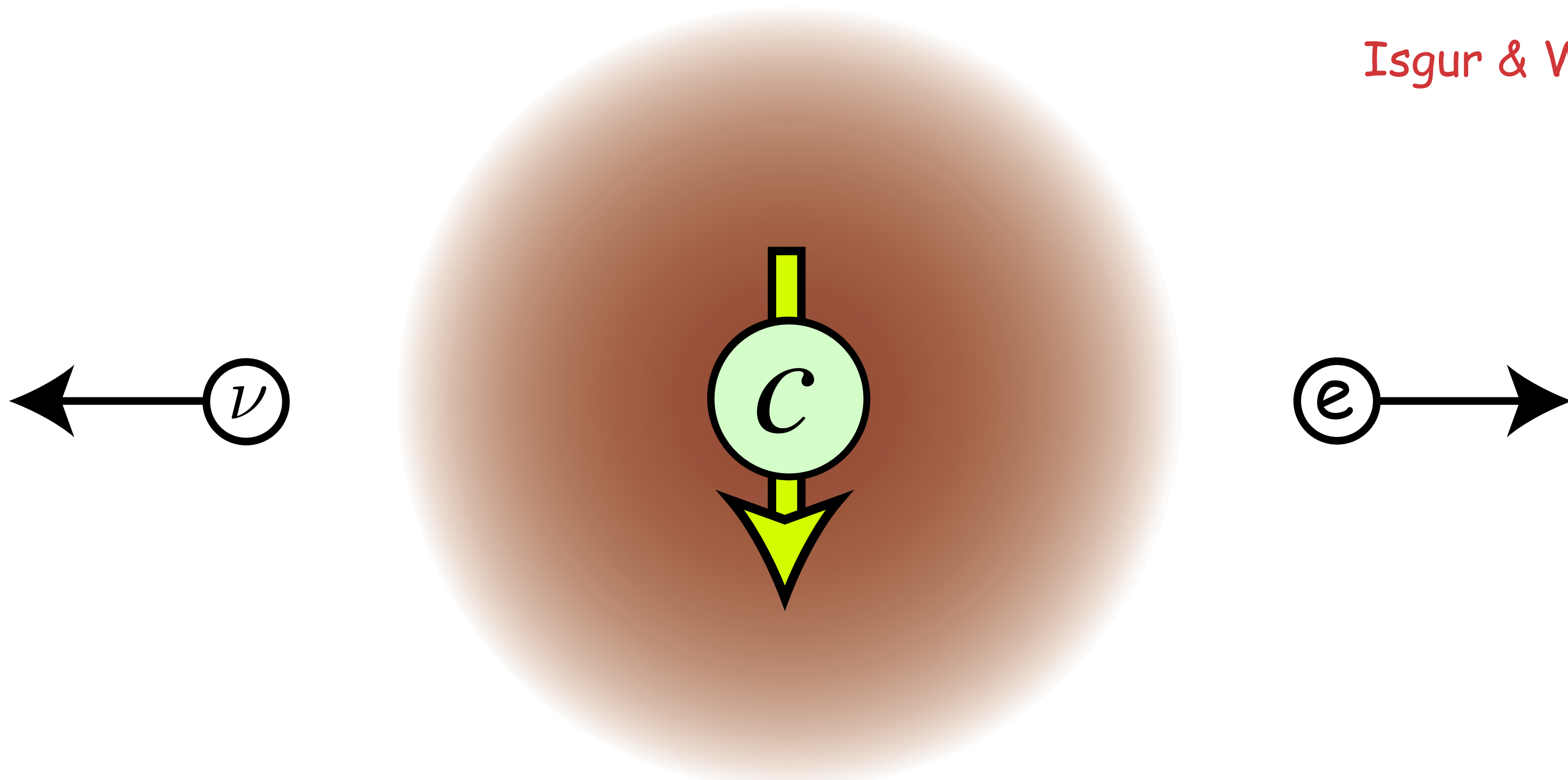
Ex: np->dγ at NNLO:

(Savage, Scaldeferri and Wise, Nucl. Phys. A652:273-286,1999)



"Classic" Application: Heavy Quark Symmetry in B->D*eν decay

Isgur & Wise, 1989



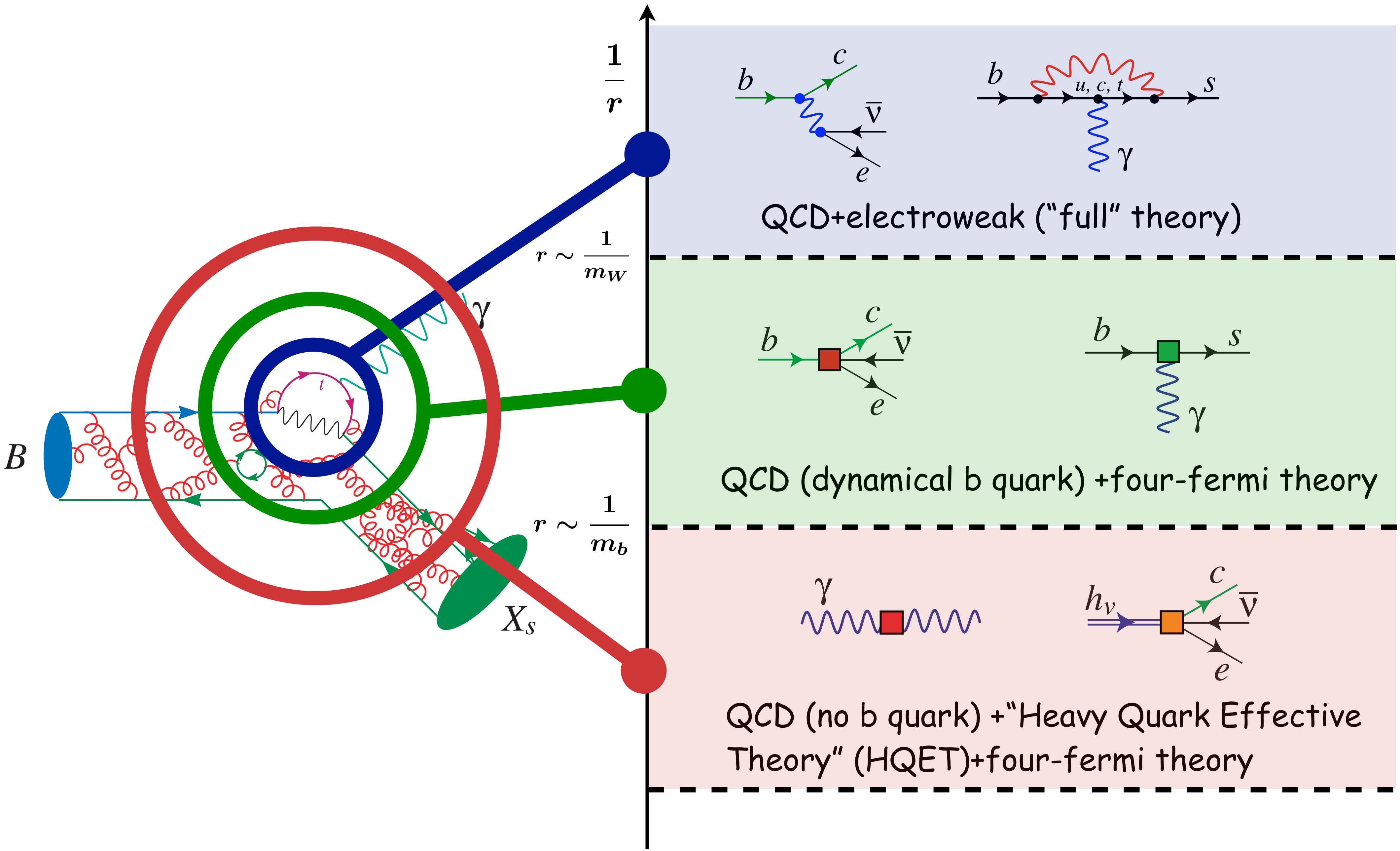
- at zero recoil kinematic point, brown muck doesn't know decay has occurred! - form factor is ONE (fixed by symmetry)

What does this buy us?

- "turn-the-crank" FACTORIZATION
- calculation organized as a power series in Λ_{QCD}/m_b ("power counting") - $\Lambda_{QCD}/m_b \sim 1/10$, so higher order corrections essential for precision (good expansion parameter for theorists!)
- **virtual** excitations (at all energy scales) are systematically included ("renormalization")

EFT is allowing us to do as much of the problem as we can, and isolate the nonperturbative physics

B decay requires a hierarchy of **effective theories** ... at each threshold, degrees of freedom are “integrated out” and a new theory is constructed:



Global fits (summer '02 - updated '04):

(Bauer, Ligeti, ML, Manohar and Trott)

(up to $1/m^3$)

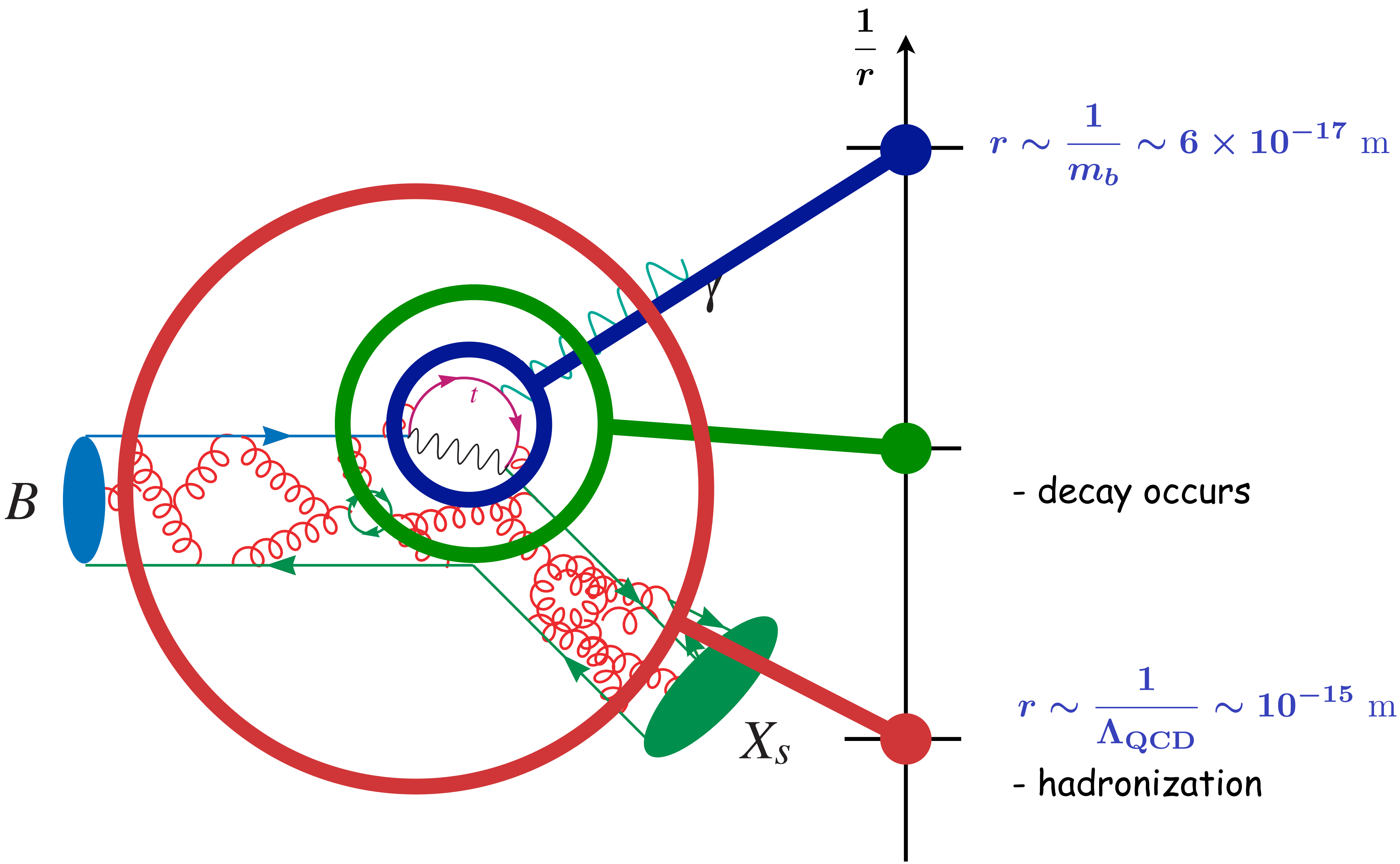
- lepton energy and hadronic invariant mass moments ($\bar{B} \to X_c \ell \bar{\nu}$) , photon energy spectrum moments ($\bar{B} \to X_s \gamma$)
- measured with varying cutoffs by DELPHI, CLEO, CDF, BABAR and BELLE
- simultaneously fit for hadronic matrix elements, **m_b**, V_{cb}

$$R_0(E_0, E_1) = \frac{\displaystyle\int_{E_1} \frac{d\Gamma}{dE_\ell}\, dE_\ell}{\displaystyle\int_{E_0} \frac{d\Gamma}{dE_\ell}\, dE_\ell}, \qquad R_n(E_0) = \frac{\displaystyle\int_{E_0} E_\ell^n \frac{d\Gamma}{dE_\ell}\, dE_\ell}{\displaystyle\int_{E_0} \frac{d\Gamma}{dE_\ell}\, dE_\ell}, \; n = 1,\; 2$$

$$S_1(E_0) = \langle m_X^2 - \bar{m}_D^2 \rangle \Big|_{E_\ell > E_0}, \qquad S_2(E_0) = \Big\langle (m_X^2 - \langle m_X^2 \rangle)^2 \Big\rangle \Big|_{E_\ell > E_0}$$

$$T_1(E_0) = \langle E_\gamma \rangle \Big|_{E_\gamma > E_0}, \qquad T_2(E_0) = \Big\langle (E_\gamma - \langle E_\gamma \rangle)^2 \Big\rangle \Big|_{E_\gamma > E_0}$$

Scales in B Decay relevant for SCET:



add - sqrt[Lam mb], sqrt[Lam^2/mb]