Stretching QCD perturbation theory into the non-perturbative limit.

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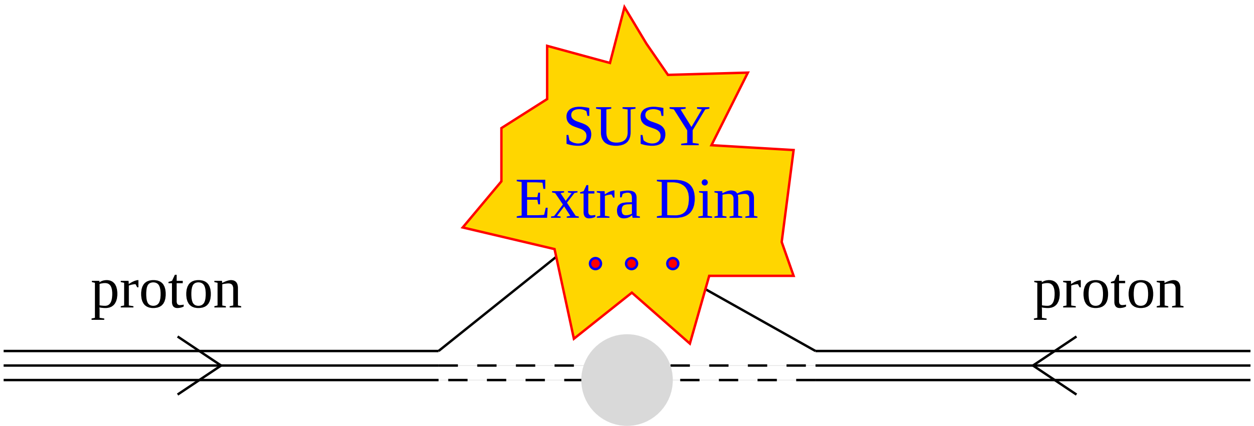
The aim of this talk is to give an overview of some techniques and recent developments

- ✗ in the calculation of the high-order properties of QCD perturbation theory
- ✗ and the associated estimation of non-perturbative effects.

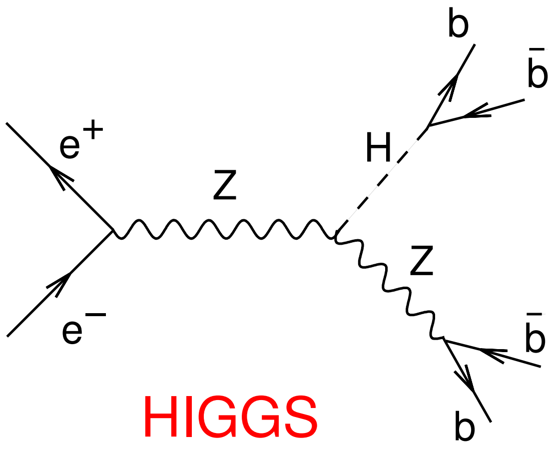
Why study QCD?

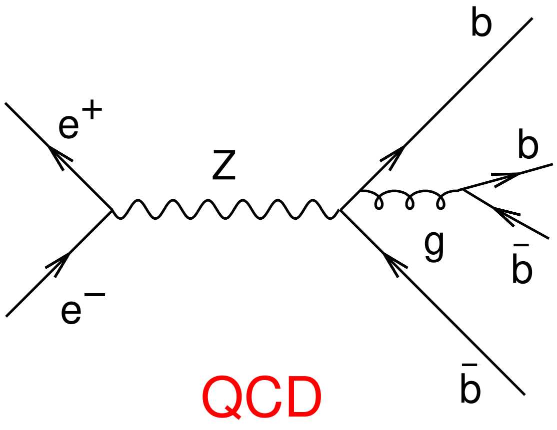
QCD is at the base of any search/study of *new physics*.

✗ If you're colliding hadrons (Tevatron, LHC), you have to understand *what goes in to the collision* — $i.e.$ hadron



✗ You need to understand QCD *backgrounds*, which can mimic signatures of new particles





✗ Once you've discovered something, QCD is vital for *understanding its properties* (recent example: threshold corrections for top cross section ↔ top mass).

QCD is also very rich in itself

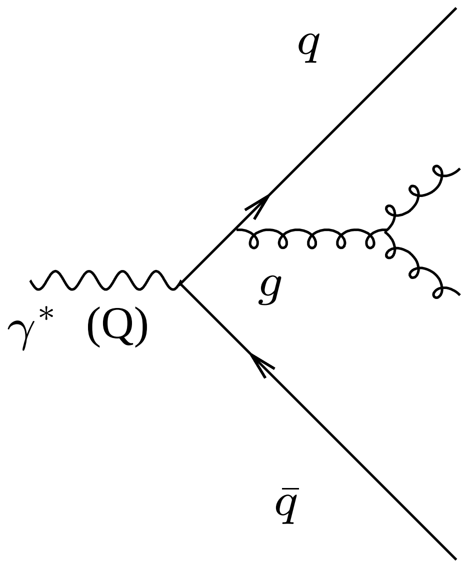
✗ Non-Abelian

✗ α_s is not so small ($0.2 \to 0.1$), so *fixed-order perturbation theory (PT) is often unsatisfactory* (and very hard work!)

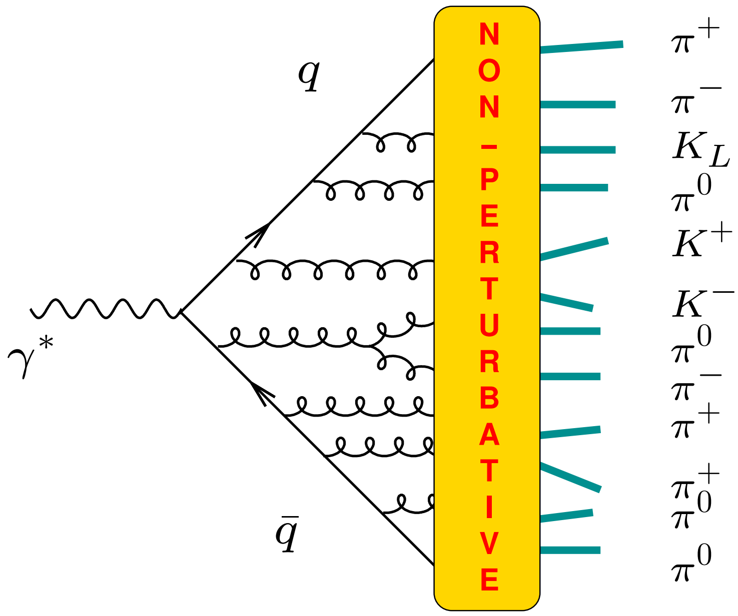
Observable	Series
$\frac{1}{6}\int_0^1 dx\, F_3(x,Q)$	$1 - \frac{\alpha_s}{\pi}(1 + 1.1\,\alpha_s + 1.9\,\alpha_s^2 + \dots)$
$\langle 1 - T \rangle$	$0.33\,\alpha_s\,(1 + 3.4\,\alpha_s + \dots)$

$\Rightarrow$ we need techniques for studying high orders of PT.

✗ The *interface between the perturbative and non-perturbative* (NP) regimes is a vital part of the game.



What we calculate exactly



What goes on!

Lattice is (not yet) the solution

In principle the only way of getting an exact answer in QCD is through a *lattice calculation.*

The lattice is getting good at

- ✗ Static, Euclidean problems (few particles)
- ✗ Problems with a limited range of scales (at most $m_b = 5\,\text{GeV}$, $\Lambda = 0.1\,\text{GeV}$).

But many of the problems in QCD involve

- ✗ Wide ranges of scales ($e.g.$ $Q = 100\,\text{GeV}$, $\Lambda = 0.1\,\text{GeV}$)
- ✗ Dynamics of many final-state particles — Minkowskian.

This means that there are both *number-crunching difficulties* (computing power needed scales at least as $(Q/\Lambda)^4$) and severe *conceptual problems* ($e.g.$ formulation of Minkowskian problems).

This talk

The aim of this talk is to give an overview of some techniques and recent developments in the understanding of the high-order properties of *perturbation theory* and the associated estimation of non-perturbative effects.

✗ Consider a particular set of graphs (bubble insertions) and examine their behaviour at high orders:

- factorially divergent set of terms.

✗ What does this mean for the sum of terms?

- power corrections.

✗ Then we will concentrate on a particular set of observables, *event shapes:*

- higher orders are particularly large
- there is a wealth of data.

Health warning

To determine the high-order behaviour of PT you need to *identify sets of graphs* whose contributions grow systematically large.

Mathematical rigour does not *as yet* exist in this game!

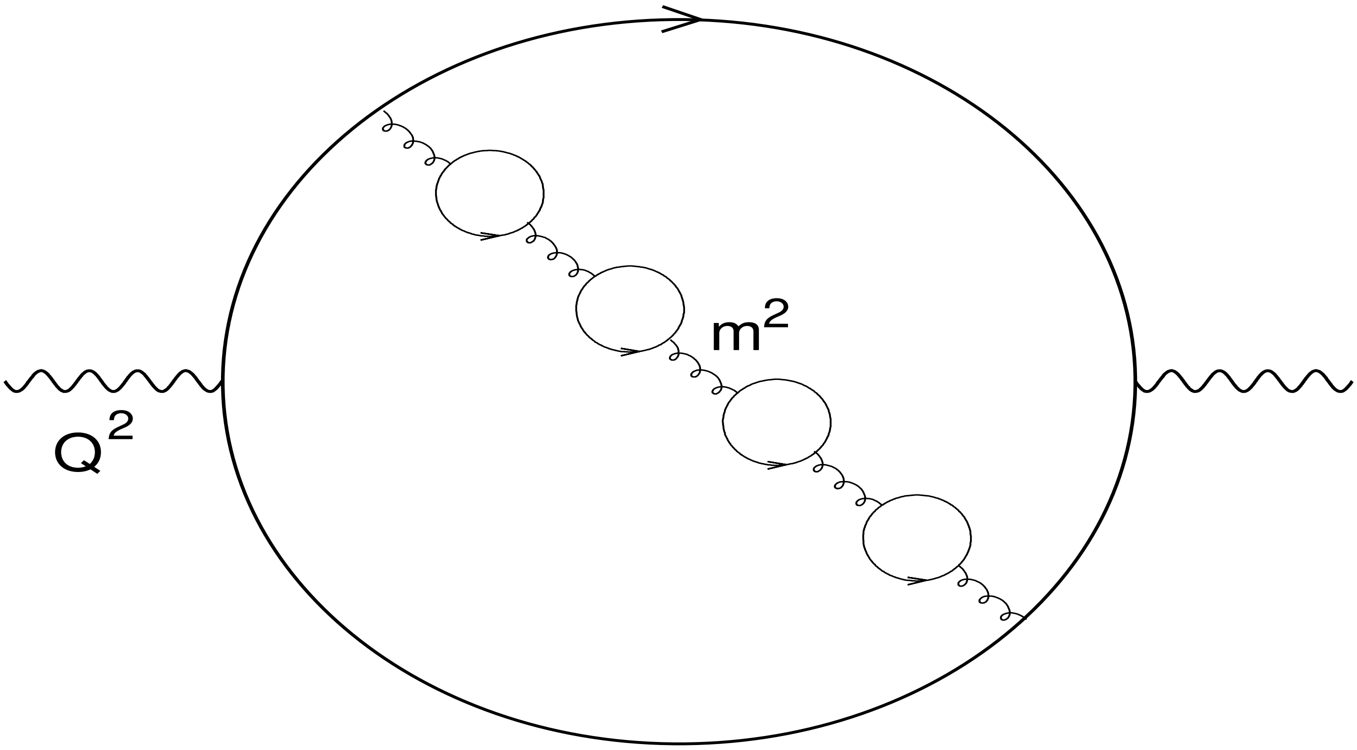
This is because a priori you cannot be sure that you have the *right set of graphs.*

One of the purposes of this talk is to illustrate that
there are however constraints.

A schematic introduction to renormalons

There are many sources of higher-order corrections. For studying general properties of high orders they have to be *classified.*

A class that has attracted much interest is that of *fermion loop insertions* (QED/QCD):



We will be fixing the gluon virtuality m^2 and choosing a renormalisation scale $\mu^2 = Q^2$. After renormalisation each loop essentially gives a factor

$$\alpha_s \underbrace{\left(-\frac{2n_f}{12\pi}\right)}_{n_f \text{ part of } \beta_0 \equiv \beta_{0f}} \ln \frac{Q^2}{m^2}$$

Effect on observable

We will *take some generic observable $\mathcal{V}$.* We integrate the observable and amplitudes over all momenta. We write this in a form showing explicitly only the integral over m^2

$$\mathcal{V}^{(n)} = \alpha_{\mathsf{s}} \int_0^\infty \frac{dm^2}{m^2} f_{\mathcal{V}}\left(\frac{m^2}{Q^2}\right) \cdot \left(\alpha_{\mathsf{s}}\, \beta_{0f}\, \ln \frac{Q^2}{m^2}\right)^n .$$

The function $f_{\mathcal{V}}\left(\frac{m^2}{Q^2}\right)$ embodies *observable's dependence on m^2.* (Characteristic function).

Then suppose that for $m^2 \ll Q^2$,

$$f_{\mathcal{V}}\left(\frac{m^2}{Q^2}\right) \sim c \cdot \left(\frac{m^2}{Q^2}\right)^p$$

where the constants c and p are specific to the observable. The integration gives us

$$\mathcal{V}^{(n)} \simeq \alpha_{\mathsf{s}} \int_0^{Q^2} \cdots \simeq \boxed{\frac{\alpha_{\mathsf{s}} c}{p} \left(\frac{\alpha_{\mathsf{s}}\, \beta_{0f}}{p}\right)^n n!}$$

and the PT series *diverges* for any value of the coupling.

This is referred to as an *infrared renormalon.*

Gross & Neveu 1974, Lautrup 1977, 't Hooft 1977

Renormalons

Renormalons are a general feature of perturbation theory

There exist also *ultraviolet renormalons* coming from similar integrals but with $m^2 \gg Q^2$. We will not discuss them because they turn out to be practically much less important than the infrared variety.

What about gluon loops?

This is one of the stumbling blocks for renormalon approaches.

The non-Abelian nature of QCD makes it difficult to identify the classes of diagrams that are needed:

✗ loops on their own are not sufficient (not gauge invariant — though the pinch technique helps address the problem).

✗ vertex corrections are also needed — but it is much harder to see how to organise them systematically.

At the same time *physically it seems clear what is happening.* If we expand the running of the coupling we have

$$\alpha_s(m^2) = \frac{\alpha_s(Q^2)}{1 - \alpha_s \beta_0 \ln Q^2/m^2} = \alpha_s(Q^2) \sum_{n=0} \left(\alpha_s \, \beta_0 \ln \frac{Q^2}{m^2} \right)^n$$

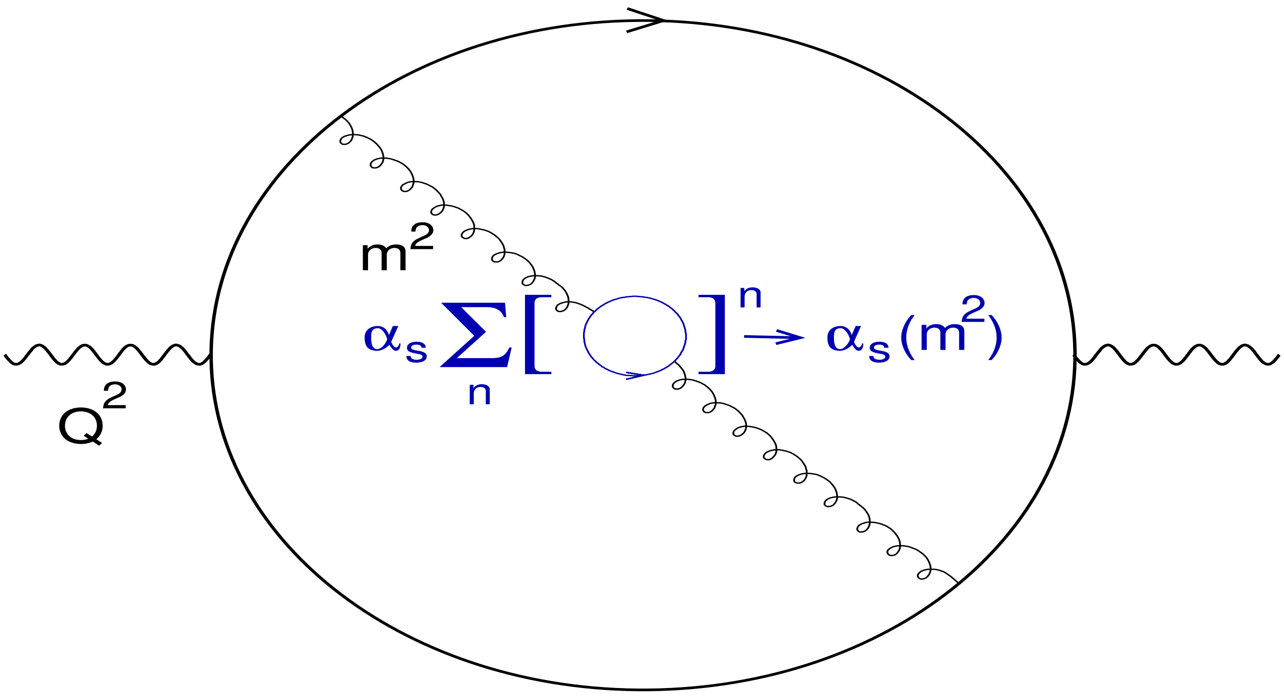
The fermionic loops seem to be giving us just the pure n_f-dependent part of this:

$$\alpha_s(Q^2) \sum_{n=0} \left(\alpha_s \, \beta_{0f} \ln \frac{Q^2}{m^2} \right)^n$$

So people have suggested the following replacement (*Naive non-abelianisation*)

$$\boxed{\beta_{0f} \to \beta_0 = \frac{11N_c - 2n_f}{12\pi}}$$

It corresponds to replacing the sum over fermion loops with the full running of the coupling:



This is formally *ad hoc.* BUT

✗ Physically very natural.

✗ There is also circumstantial evidence supporting it:

- Fixed order calculations.
- All order calculations that examine terms $N_c n_f^{n-1}$.

✗ Many predictions may not depend too strongly on an exact reconstruction of the running coupling.

What can we do with a divergent series?

Substitution of β_{0f} with β_0 still leaves us with a divergent series:

$$\mathcal{V}(Q^2) \sim \frac{\alpha_s c}{p} \sum_{n=0} \left(\frac{\alpha_s \beta_0}{p}\right)^n n!$$

Standard procedure from theory of *asymptotic series*:

✗ truncate the sum at the smallest term

✗ the smallest term is an estimate of the uncertainty on the sum

This means we truncate at

$$\frac{\alpha_s \beta_0}{p} = \frac{1}{n}$$

Uncertainty is (recall Stirling: $n! \simeq \sqrt{2\pi n}\,(\frac{n}{e})^n$)

$$\delta\mathcal{V} \sim \left(\frac{1}{n}\right)^n n! \;\sim\; e^{-n} \;=\; e^{-\frac{p}{\alpha_s \beta_0}}$$

This is known as a *power correction*:

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln Q^2/\Lambda^2} \Rightarrow \boxed{\delta F \sim \left(\frac{\Lambda^2}{Q^2}\right)^p}$$

Physical interpretation?

The sum of many terms is equivalent to an integral over the running coupling (interchanging order of sum and integration):

$$\mathcal{V}(Q^2) \sim \int \frac{dm^2}{m^2} f_{\mathcal{V}}(m^2)\, \alpha_s(m^2)$$

$$\sim \int_0^{Q^2} \frac{dm^2}{m^2} c \cdot \left(\frac{m^2}{Q^2}\right)^p \frac{1}{\beta_0 \ln m^2/\Lambda^2}$$

The uncertainty in the sum is (loosely) equivalent to the *ambiguity in integrating over the Landau pole:*

$$\delta\mathcal{V} \sim \frac{c}{\beta_0} \cdot \left(\frac{\Lambda^2}{Q^2}\right)^p$$

So the high-order factorial divergence of perturbation theory (infrared renormalons) seems to be linked to ambiguities in the infrared and therefore to non-perturbative physics.

In many respects power corrections are simply a consequence of the functional dependence of the observable on infrared scales — in this sense the problems relating to the reconstruction of the full β_0 are irrelevant.

Universality

Suppose we have many observables $\mathcal{V}_i$ which at small m^2 all go as the same power of m^2, but with different coefficients

$$f_{\mathcal{V}_i}(m^2) \sim c_i \cdot \left(\frac{m^2}{Q^2}\right)^p$$

Since they have the same dependence on the infrared, we say that they belong to the same *class.*

There is a *Universality Hypothesis:*

For variables in the same class, while it is impossible to predict the absolute size of the power correction, *it is possible to predict the relative size of the power correction* from one variable to the next — *i.e.* it should be proportional to c_i:

$$\delta\mathcal{V}_i \simeq c_i \cdot \left(\frac{\Lambda^2_{\text{eff},p}}{Q^2}\right)^p$$

$\Lambda_{\text{eff},p}$ is some effective scale. It is a priori uncalculable, but should be the same for all variables in the same class.

Intermediate summary

- ✗ We believe we can extract the dominant high-order behaviour of the PT series *(factorial growth).*

- ✗ It leads to *ambiguities which are power suppressed,* $(\Lambda^2/Q^2)^p$, and these can be interpreted as being associated with the infrared and *non-perturbative* physics.

- ✗ For observables having the same class of power correction (same p) there is a *universality hypothesis* — it should be possible to predict the relative size of the power corrections to different observables.

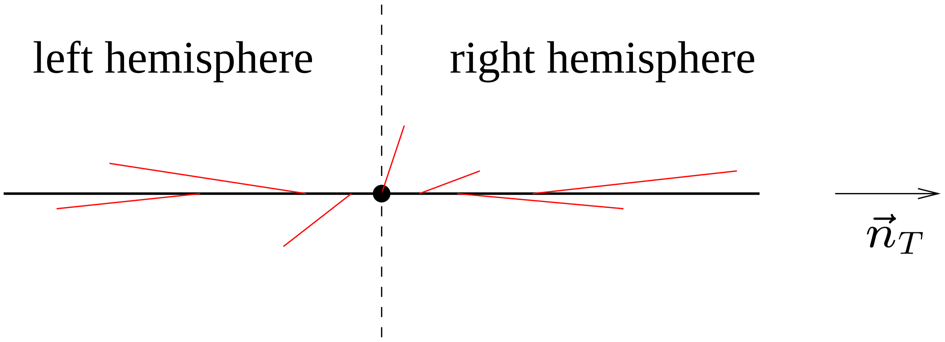
Phenomenology?

These ideas have been applied to a wide range of phenomenological problems. This extract from the table of contents of a review by Beneke, hep-ph/9807443, gives an idea of the variety of applications.

We shall concentrate on *event shapes* because there is a large amount of data and because renormalon effects are big.

Event shapes

Event shapes measure overall properties of QCD final states ($i.e.$ they are not especially sensitive to the fate of individual particles, but rather to the *general flow of energy*). We study them for the process $e^+e^- \to$ *hadrons*, but they exist also in DIS and hadron-hadron collisions.



$$\text{thrust} \quad T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i.\vec{n}|}{\sum_i |\vec{p}_i|}\,, \qquad \tau = 1 - T\,,$$

$$C\text{-parameter} \quad C = \frac{3}{2}\frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{\left(\sum_i |\vec{p}_i|\right)^2}\,,$$

$$\text{jet-mass} \quad \rho = \frac{\left(\sum_{i\in\text{hemisphere}} p_i\right)^2}{\left(\sum_i E_i\right)^2}\,,$$

$$\text{broadening} \quad B_T = \frac{\sum_i p_{ti}}{\sum_i |\vec{p}_i|}\,.$$

Define also:

$$\text{heavy-jet mass} \quad \rho_h = \max\{\rho_{\text{left}}, \rho_{\text{right}}\}\,,$$

$$\text{wide-jet broadening} \quad B_W = \max\{B_{\text{left}}, B_{\text{right}}\}\,.$$

Infrared properties

Let's take the *thrust* and study it in more detail.

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i.\vec{n}|}{\sum_i |\vec{p}_i|}\,, \qquad \tau = 1 - T\,.$$

Fundamental point is that it is a function of momenta to the first power: *linear dependence on momenta*.

This carries through to the infrared and implies *linear power correction:*

$$\langle \delta\tau \rangle \sim c_\tau \frac{\Lambda}{Q}$$

Webber 1994a; Manohar & Wise 1995

All the variables are sensitive to the first power of momenta and so they *all have a linear power correction*. The coefficients $c_\mathcal{V}$ in a simple renormalon analysis come out as

$\mathcal{V}$	τ	C	ρ	ρ_h	B_T	B_W
$c_\mathcal{V}$	2 or 3.66	3π	1	2	$4\ln Q$	$4\ln Q$

Results exist for some analogous DIS event shapes as well.

Webber 1994; Dokshitzer & Webber 1995;
Akhoury & Zakharov 1995; Korchemsky & Sterman 1995;
Beneke & Braun 1995; Dasgupta & Webber 1997 (DIS)

Systematic approaches

There are essentially two systematic approaches to renormalon-based analyses of event-shape data.

Maximal approach:

Make use of renormalons to generate all uncalculated orders of the perturbative series — to this add a $1/Q$ power correction.

It corresponds to trying to do the 'best possible job'. But it involves a lot of work for each new observable. So far only the thrust has been fully studied.

Minimal approach:

Take just the first two perturbative orders (known exactly) and to those add a $1/Q$ term — *check* the fitted coefficient of the $1/Q$ is consistent with *universality* across many observables.

This involves perhaps fewer assumptions and in practice is a lot simpler allowing the study of many variables. But there is a question of how it would be modified by the inclusion of higher orders in α_s.

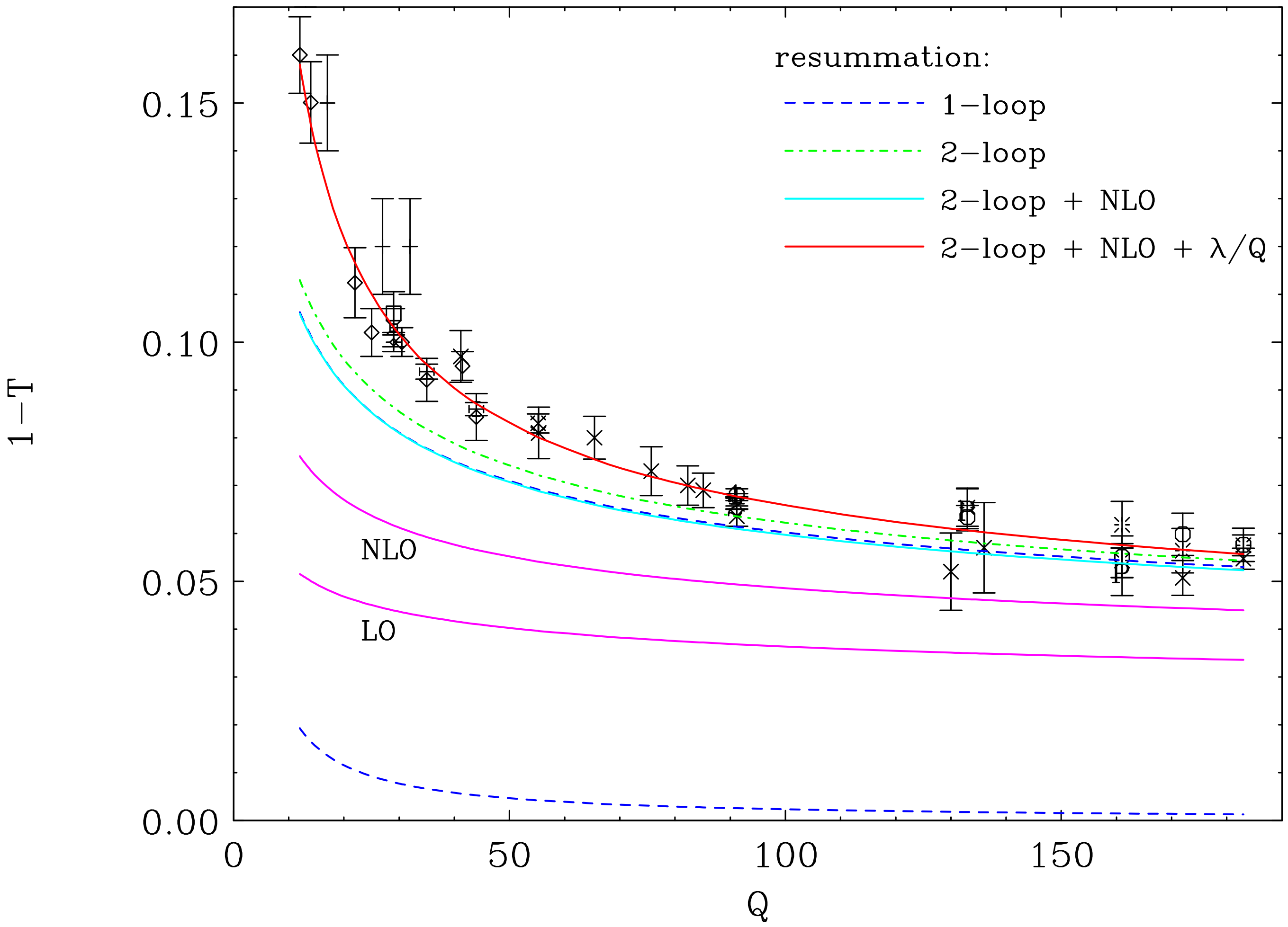
For the thrust, *the data cannot distinguish between the two approaches.*

Thrust in the 'maximal' approach

$$\mathcal{V} = \underbrace{A\alpha_s + B\alpha_s^2}_{\text{exact}} + \underbrace{\sum_{n=3} n!\beta_0^n\alpha_s^n}_{\text{renormalons}} + c_{\mathcal{V}}\frac{\Lambda_{\text{eff},1/2}}{Q}$$

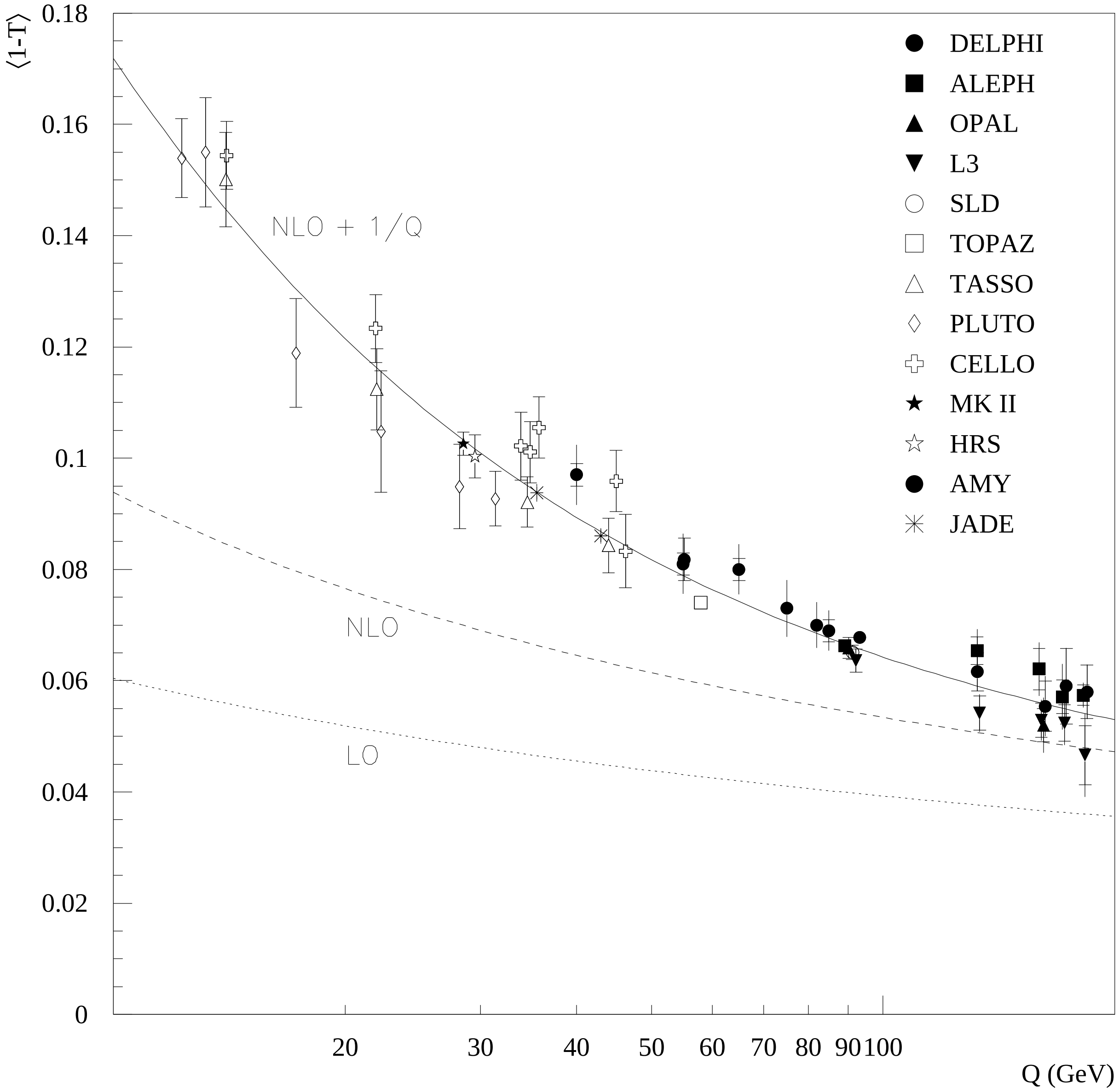
Gardi & Grunberg 1999
Gardi & Rathsman 2001

One needs a prescription for the resummation of the factorials — the plot shows a principal value prescription.



Thrust in the 'minimal' approach

$$\mathcal{V} = A\alpha_{\mathsf{s}} + B\alpha_{\mathsf{s}}^2 + c_{\mathcal{V}}\frac{\Lambda_{\mathsf{eff},1/2}}{Q}$$



Dokshitzer–Webber method

This has become the 'industry-standard' way of fitting event-shape power corrections. Similar to minimal approach but exploits the idea that the power correction comes from an *integral over a full infrared-finite (NP) running coupling*

$$\delta\mathcal{V} = \frac{2C_F}{\pi}\int^{\mu_I}\frac{dm}{m}\frac{m}{Q}\left(\alpha_s^{\mathsf{NP}}(m) - \alpha_s^{\mathsf{PT}}(m)\right)\cdot c_{\mathcal{V}}$$

One subtracts off α_s^{PT}, the fixed-order perturbative expansion of the coupling *so as not to double count contributions that are already included in the fixed-order PT coefficients* (one cancels the PT renormalon ambiguity).

$$\boxed{\mathcal{V} = A\alpha_s + B\alpha_s^2 + c_{\mathcal{V}}\frac{2C_F}{\pi}\frac{\mu_I}{Q}\left(\alpha_0(\mu_I) - \langle\alpha_s^{\mathsf{PT}}\rangle_{\mu_I}\right)}$$

α_0 is first moment of the NP coupling:

$$\alpha_0 = \frac{1}{\mu_I}\int_0^{\mu_I} dm\,\alpha_s^{\mathsf{NP}}(m)$$

$$\langle\alpha_s^{\mathsf{PT}}\rangle_{\mu_I} = \alpha_s(Q) + \beta_0\frac{\alpha_s^2}{2\pi}\left(\ln\frac{Q}{\mu_I} + \frac{K}{\beta_0} + 1\right)$$

One compares next-to-leading PT plus NP predictions to data, fitting for α_s and α_0. If universality holds then both α_s and α_0 should be *independent of the observable.*

e^+e^- event-shape results

D. Decamp *et al.* (ALEPH Collaboration), Phys. Lett. **B284** (1992) 163;
D. Buskulic *et al.* (ALEPH Collaboration), Z. Phys. **C55** (1992) 209;
I. H. Park *et al.* (AMY Collaboration), Phys. Rev. Lett. **62** (1989) 1713;
Y. K. Li *et al.* (AMY Collaboration), Phys. Rev. **D 41** (1990) 2675;
H. J. Behrend *et al.* (CELLO Collaboration), Z. Phys. **C44** (1989) 63;
D. Bender *et al.* (HRS Collaboration), Phys. Rev. **D 31** (1985) 1;
P. A. Movilla Fernandez, O. Biebel, S. Bethke, S. Kluth and P. Pfeifenschneider (JADE Collaboration), Eur. Phys. J. **C1** (1998) 461 [hep-ex/9708034];
B. Adeva *et al.* (L3 Collaboration), Z. Phys. **C55** (1992) 39;
M. Acciarri *et al.* (L3 Collaboration), Phys. Lett. **B411** (1997) 339;
D. P. Barber *et al.* (Mark J Collaboration), Phys. Rev. Lett. **43** (1979) 830;
A. Petersen *et al.* (Mark II Collaboration), Phys. Rev. **D 37** (1988) 1;
S. Bethke *et al.* (Mark II Collaboration), Z. Phys. **C43** (1989) 325;
P. D. Acton *et al.* (OPAL Collaboration), Z. Phys. **C59** (1993) 1;
G. Alexander *et al.* (OPAL Collaboration), Z. Phys. **C72** (1996) 191;
K. Ackerstaff *et al.* (OPAL Collaboration), Z. Phys. **C75** (1997) 193;
C. Berger *et al.* (PLUTO Collaboration), Z. Phys. **C12** (1982) 297;
K. Abe *et al.* (SLD Collaboration), Phys. Rev. **D 51** (1995) 962 [hep-ex/9501003];
W. Braunschweig *et al.* (TASSO Collaboration), Phys. Lett. **B214** (1988) 286;
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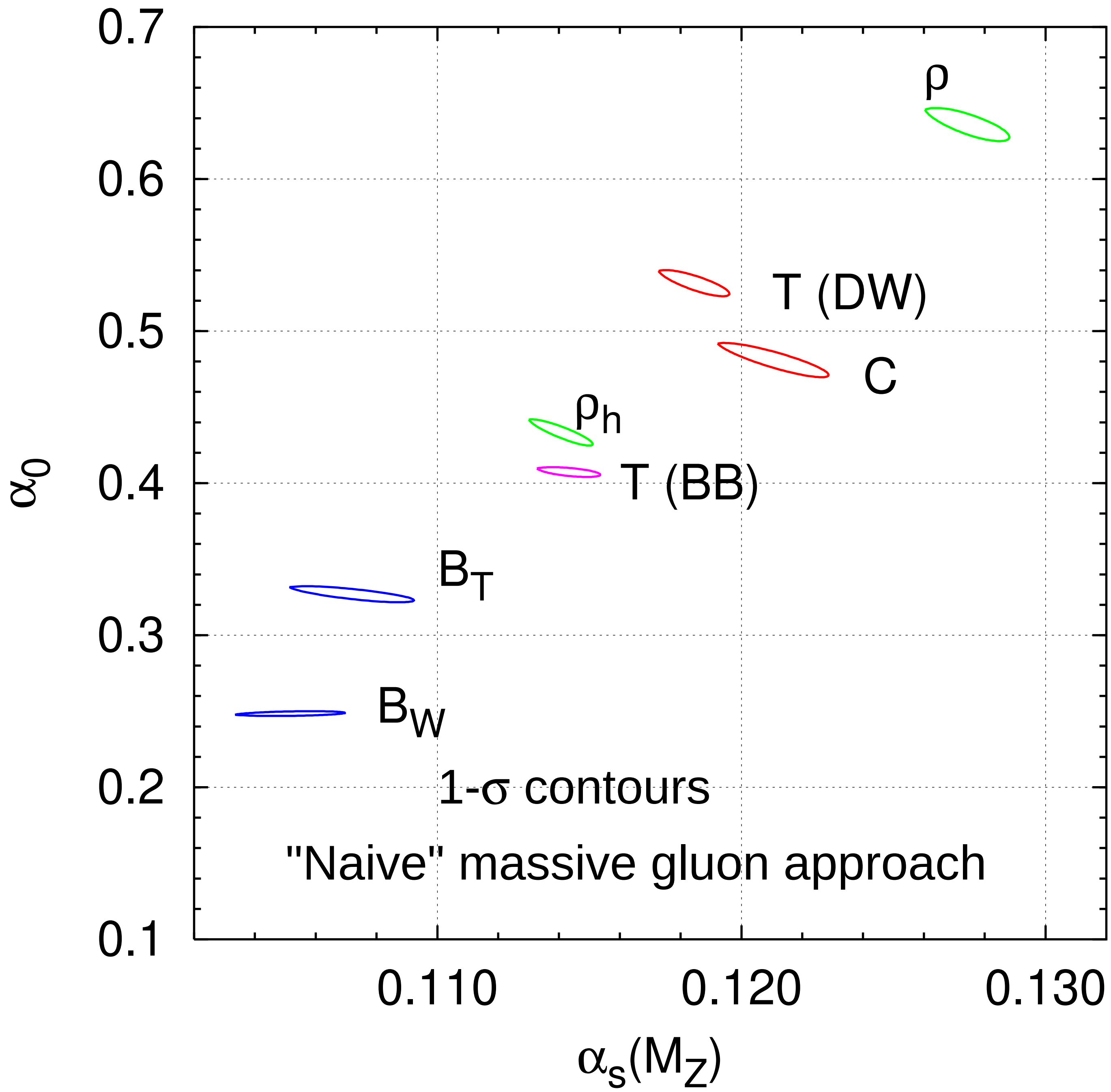
I. Adachi *et al.* (TOPAZ Collaboration), Phys. Lett. **B227** (1989) 495;
K. Nagai *et al.* (TOPAZ Collaboration), Phys. Lett. **B278** (1992) 506;
Y. Ohnishi *et al.* (TOPAZ Collaboration), Phys. Lett. **B313** (1993) 475.

DIS event-shape results

C. Adloff *et al.* (H1 Collaboration), Phys. Lett. **B406** (1997) 256 [hep-ex/9706002];
C. Adloff *et al.* (H1 Collaboration), Eur. Phys. J. **C14** (2000) 255 [hep-ex/9912052], erratum *i*bid. **C18** (2000) 417.

G. J. McCance (for the H1 and ZEUS collaborations), Talk given at *35th Rencontres de Moriond: QCD and High Energy Hadronic Interactions* (March 2000), hep-ex/0008009;
H. Martyn (for the H1 and ZEUS Collaborations), Talk given at *30th International Conference on High-Energy Physics* (ICHEP 2000), hep-ex/0010046.

Fits with 'simple' coefficients



DW Dokshitzer & Webber (1995): $c_\tau = 2$
BB Beneke & Braun (1995): $c_\tau = 3.66$

THIS IS SUPPOSED TO BE UNIVERSALITY?!

NB: a lot of the data were not yet available at the time of the early calculations.

What is missing?

It turns out that various effects need to be taken into account beyond what is in the simple analyses:

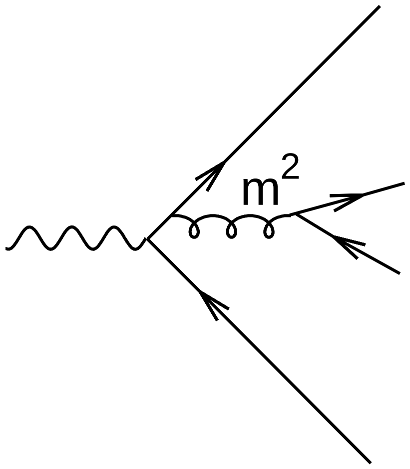
- ✗ sometimes predicted by theory.
- ✗ sometimes worked out after data showed inconsistencies in existing predictions.

The three main classes of effect so far been discovered are:

- ✗ Non-inclusiveness (theory)
- ✗ Large logs (theory for ρ_h, expt. for B's)
- ✗ Hadron mass effects (expt)

Non-inclusiveness

Correct method for determining renormalon involves integrating over all momenta while fixing gluon virtuality $\to f_{\mathcal{V}}(m^2/Q^2)$.



The naive calculations assumed that observable is inclusive, *i.e.* depends only on m^2, not on the configuration of the decayed partons.

Nason & Seymour (1995) *showed this was wrong.*

Different assumptions about variables' dependence on m^2 led to different answers (*cf.* the two values for c_τ).

This problem was solved by explicitly integrating the variables' dependence on the configuration of virtual-gluon decay products.

Beneke Braun & Magnea (1997)
Dokshitzer Lucenti Marchesini & GPS (1997,1998)
Dasgupta & Webber (1998)
Dasgupta Magnea & Smye (1999); Smye (2001)

After this is done there is a unique answer for each variable and the coefficient of the power correction is rescaled by

Milan factor: $\mathcal{M} = 1.49$

This is technically important, but still within the renormalon framework.

Large logs

It turns out that for some variables a single renormalon chain is insufficient.

Recall, term $\alpha_s(\beta_0\alpha_s/p)^n n!$ comes from

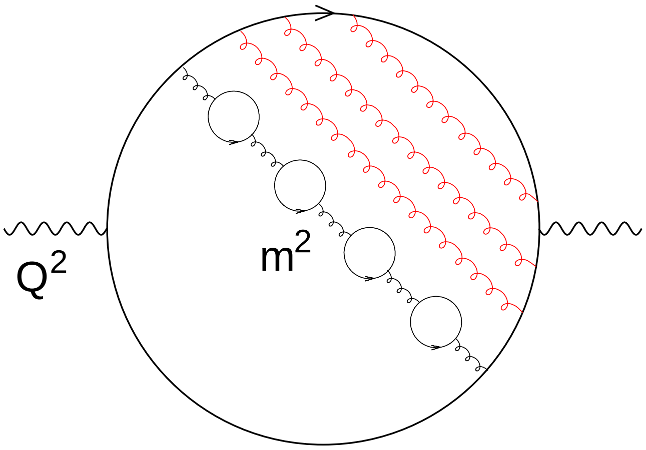
$$\beta_0^n \alpha_s^{n+1} \int \frac{dm^2}{m^2} \left(\frac{m^2}{Q^2}\right) \ln^n \frac{Q^2}{m^2}$$

Integral is dominated by small scales

$$\bar{m}_n^2 = e^{-n/p} Q^2$$

In perturbation theory when there are two scales in a problem one can have *large logs of the ratio*. Accordingly

$$\alpha_s \left(\frac{\alpha_s\beta_0}{p}\right)^n n! \to \alpha_s \left(\frac{\alpha_s\beta_0}{p}\right)^n n! \sum_{i=0} a_i \left(\alpha_s \ln^2 \frac{Q^2}{\bar{m}_n^2}\right)^i$$



Double logs come from this kind of diagram.

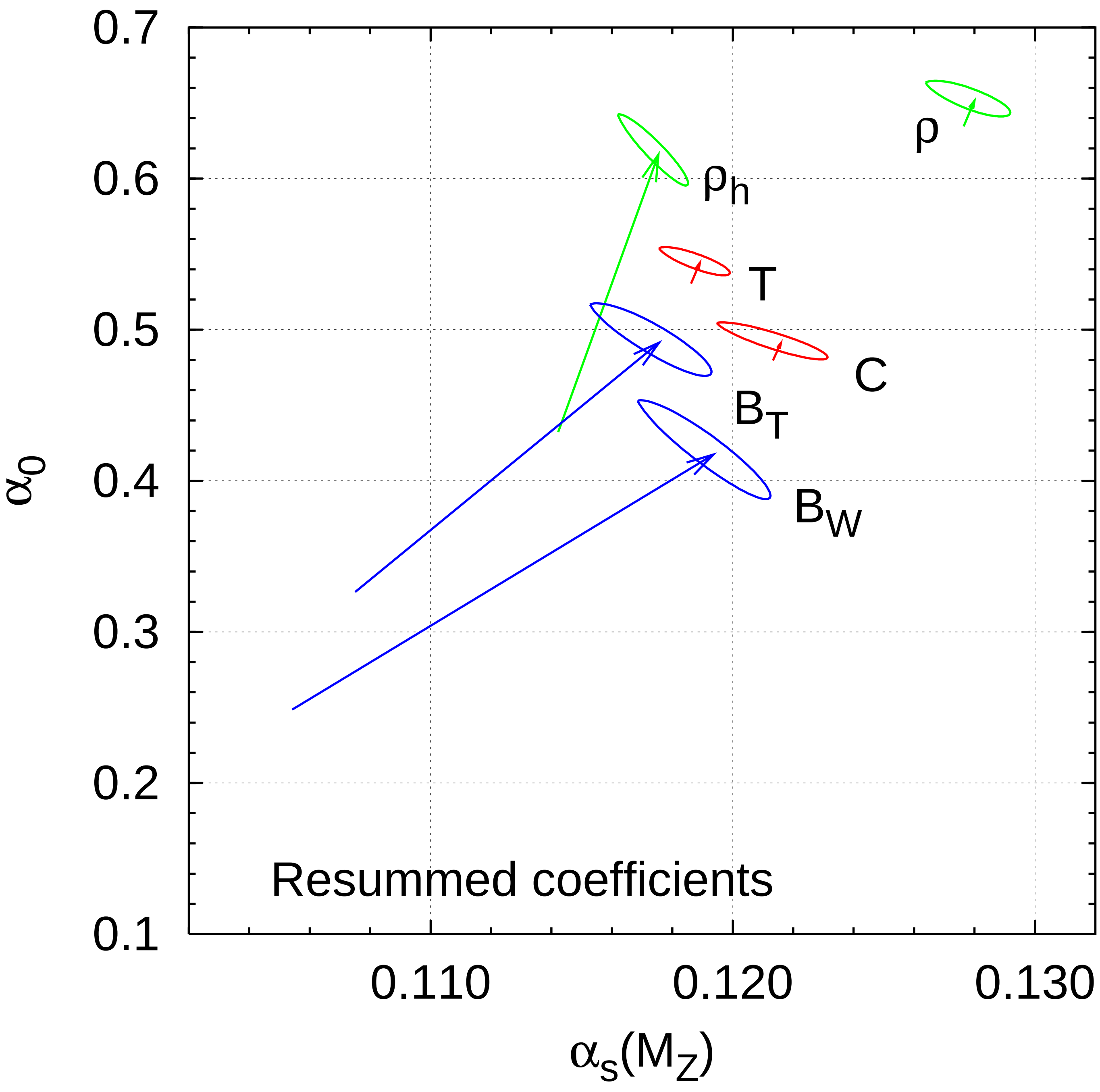
They are only relevant for certain variables: ρ_h, B_T, B_W, T_m.

Akhoury & Zakharov (1995)
Dokshitzer Lucenti Marchesini & GPS (1998, 1999)
Korchemsky & Tafat (2000)
Banfi Dokshitzer Marchesini Zanderighi (2001)

New coefficients with resummed double logs

$\mathcal{V}$	τ	C	ρ	ρ_h	B_T	B_W
$c_{\mathcal{V}}/\mathcal{M}$	2	3π	1	1	$\frac{\pi}{2\sqrt{C_F\alpha_s}}+O(1)$	$\frac{\pi}{4\sqrt{2C_F\alpha_s}}+O(1)$

Repeating fits with these new coefficients gives:



NB: included also a redefinition of α_0 leading to an extra factor of $2/\pi$ in the formula for $\delta\mathcal{V}$.

Hadron mass effects

It turns out that there can be $1/Q$ corrections associated with hadron masses. These are not directly related to renormalons, *but must be accounted for if one is to test universality*.

GPS & Wicke 2001

Simplest source mass effects is related to the fact that most variables are defined in terms of *3-momenta*, while the jet masses (ρ, ρ_h) are defined in terms of *energies and 3-momenta.*

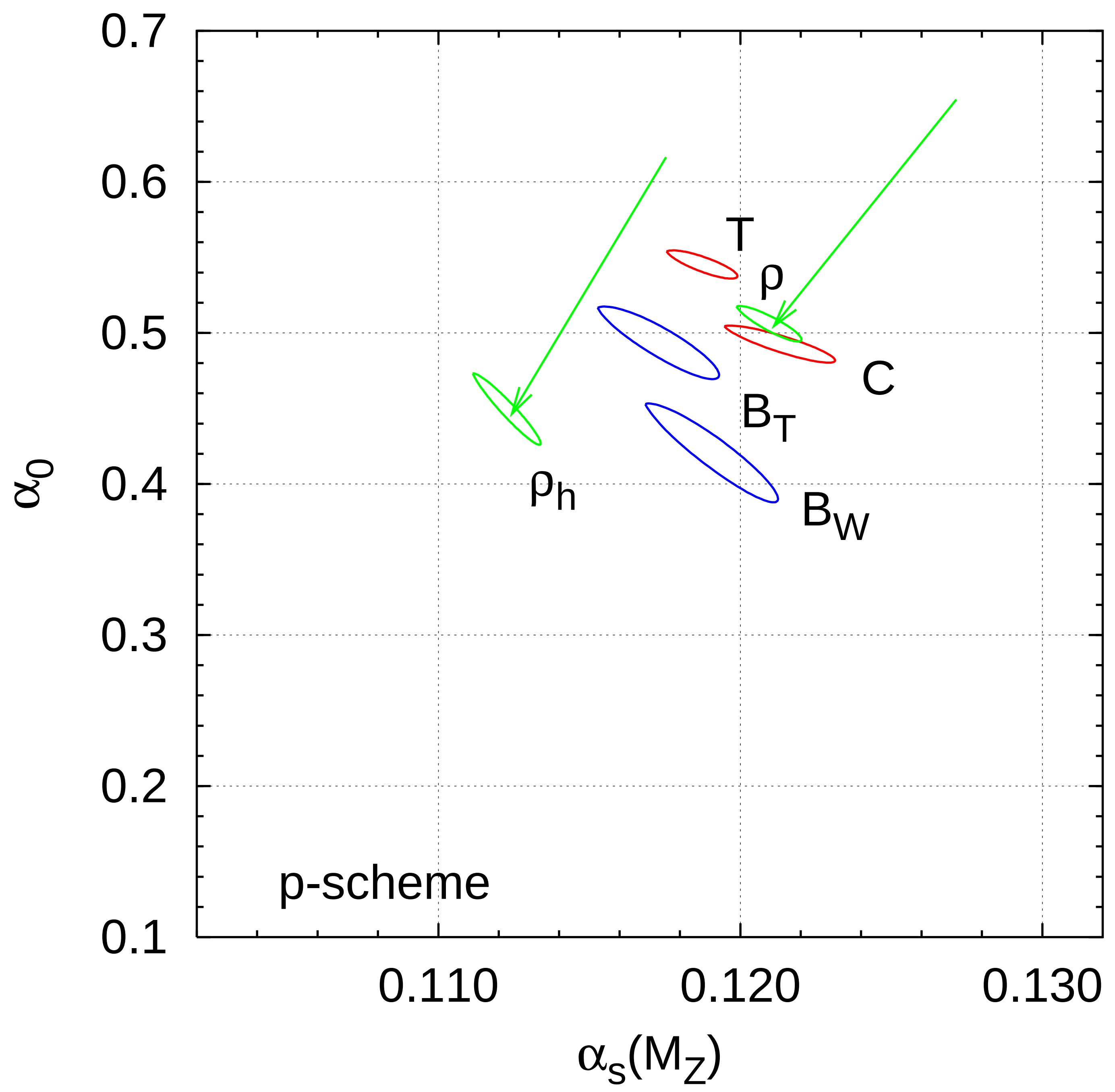
This gives rise to additional corrections of the form

$$\delta_m \mathcal{V} \sim \frac{\Lambda}{Q} \ln^A \frac{Q}{\Lambda}, \qquad A = \frac{N_{\mathrm{c}}}{\pi \beta_0} \simeq 1.6$$

Note the logarithmic energy-dependence, associated with the scaling of hadron multiplicities, arising from non-Abelian gluon branching. (Comes from a *resummation of single logs).*

These terms break universality, but can mostly be eliminated by *redefining the jet masses* in terms of just 3-momenta ($i.e.$ $E \to |\vec{p}|$): a "*p-scheme*" definition.

p-scheme fits for α_s, α_0



Universality holds to within $\pm 15\%$.

Summary

Because of the *factorial growth* of its coefficients QCD perturbation theory does not converge.

The resulting ambiguity in the PT sum is associated with the *infrared* and so the non-perturbative regime.

We can use this information to make phenomenological estimates of higher order and non-perturbative effects — a key ingredient is *universality.*

Experimental data allow non trivial tests of this picture.

They reveal that *a single renormalon chain, alone, often gives the wrong answer* for the high-order behaviour of the PT series. A proper treatment requires an additional resummation of large logs from other classes of diagrams.

For event shapes we know how to resum double logs. *Universality starts to look reasonable.*

The future?

Have we fully understood large logs in connection with renormalons?

For double logs perhaps *yes.*

But *there may still be whole classes of single logs as yet undiscovered* ($cf.$ hadron mass effects). Perhaps they will affect mainly the Q dependence rather than universality?

What is the relevance of large logs for *other classes of power correction?* ($1/Q^2$, $\ldots$)