The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

SMR/1842-25

International Workshop on QCD at Cosmic Energies III

28 May - 1 June, 2007

Lecture Notes

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QCD and jets

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Trieste, 1 June 2007

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Outline

- The QCD conundrum – from partons to jets.
- Scales, observables and IRC safety.
- Ins and outs of QCD jets –some examples.
- Jets as a window on QCD dynamics.
- Important questions still open.

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QCD – a field theory of strong interactions.

QCD is THE theory of strong interactions. A field theory formulated in terms of quarks and gluons.

$$L = \frac{-1}{4} F^A_{\alpha\beta} F^{\alpha\beta}_A + \sum_{\text{flavours}} \bar{q}_a (i\not{D} - m)_{ab} q_b$$

BUT never freely observed –coupling is too strong for perturbative tools ? The field may never have got started....

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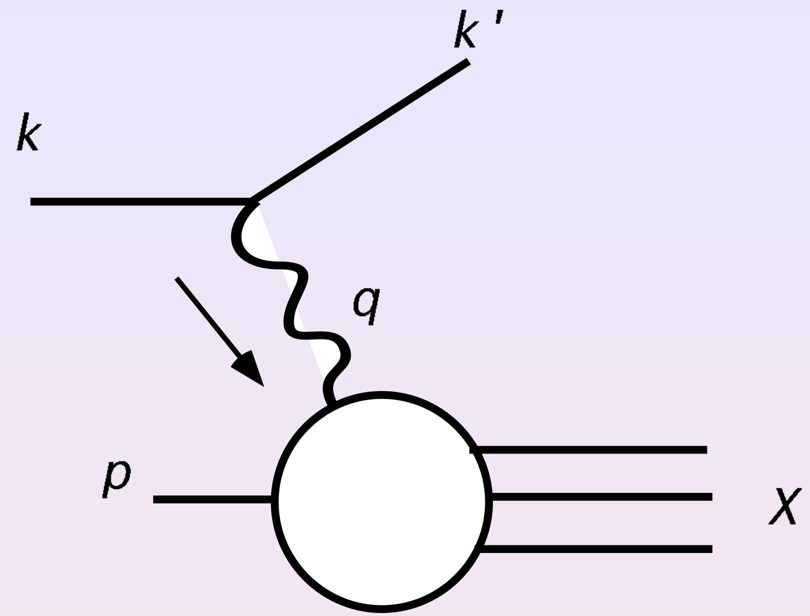
A hint from SLAC

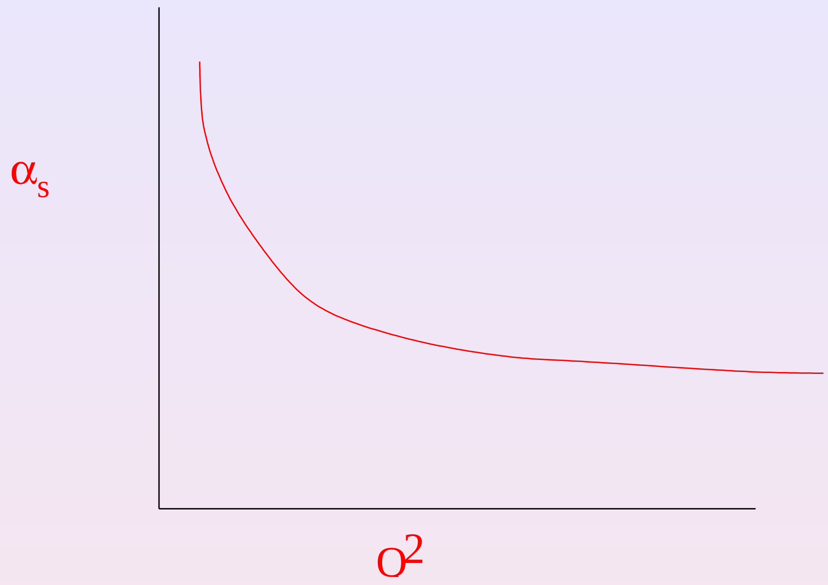


The SLAC DIS experiments confirmed presence of quarks and showed a remarkable scaling behaviour.

$$\sigma_{eP}(x, Q^2) \to \sigma_{eq}(x, Q^2) F(x)$$

The key message was : the strong coupling is asymptotically zero! Gross, Wilczek, Politzer –2004 nobel prize

Running coupling



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

This gave PT calculations a chance. Must try to work in a region where there is a hard scattering which dominates the physics. Is this sufficient ?

Scales and observables

Hard processes include e^+e^- annihilation at large centre-of–mass energies (e.g LEP) and high energy pp collisions (Tevatron and LHC). But partons always hadronise ! Observables that do not care about details of hadronic final state should be the best ones.

Examples include inclusive cross-sections in say eP or e^+e^-.

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Inclusive observables

Take DIS $eN \rightarrow eX$ cross-section. Can generally be written as

$$\sum_X |\langle X|J_\mu(0)|p_N\rangle|^2 \; \delta^4(p_X - p_N - q) =$$

$$\int \frac{d^4y}{(2\pi)^4}\, \mathrm{e}^{-iq\cdot y} \langle p_N\,|\,J^\mu(y)\,J_\mu(0)\,|p_N\rangle\,.$$

This can be expanded in powers of $p_N.y$ (light-cone expansion)

$$\left(y^2\right)^{-2} \sum_n c_n(\alpha_s(1/y^2))\,(p_N \cdot y)^n$$

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Inclusive observables (contd.)

We know from first principles where to put the NP physics and minimise sensitivity to it

$$\sigma_{\mathrm{DIS}} = q(x, Q^2) + \frac{\Lambda^2}{Q^2(1-x)} + \cdots$$

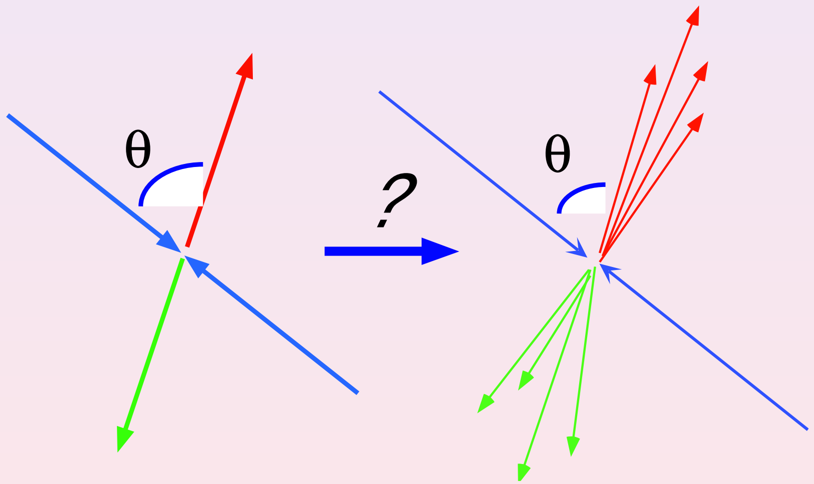
PDF with PT predictible Q^2 dependence.

$$\sigma_{ee} = \sum C_n \alpha_s^n + \frac{\Lambda^4}{Q^4} + \cdots$$

NP condensates provide negligible corrections. Less inclusive quantities have no such theorems/expansions. What can we learn here ?

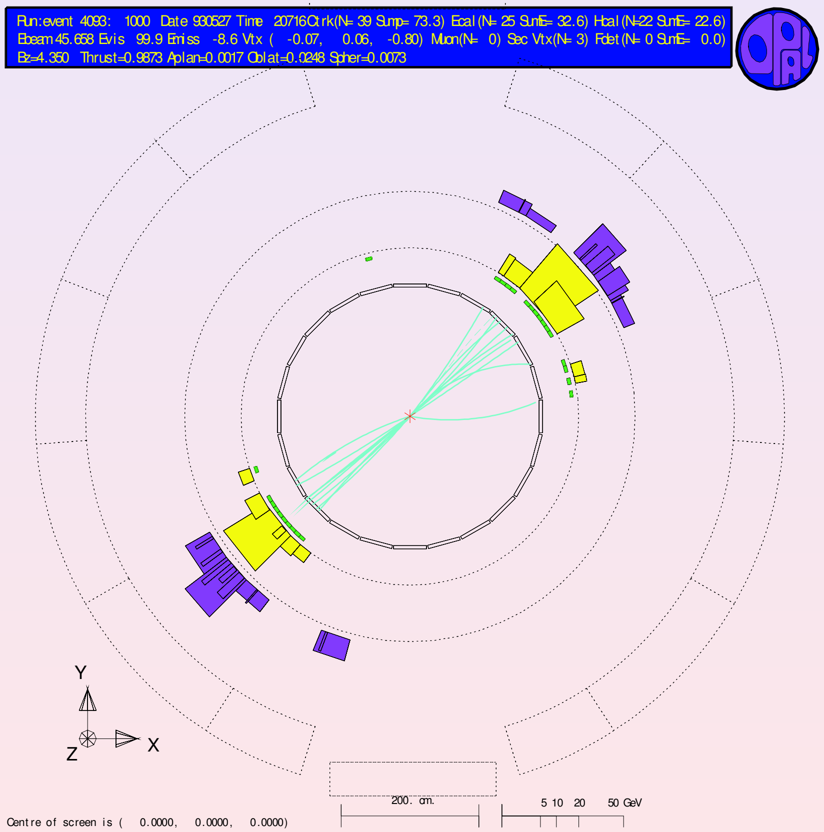
Birth of jet physics – hint from cosmic ray events

Quarks and gluons not seen directly. But they might give rise to jets of hadrons ? These may be as close as we can get to partons. Jets first seen in energetic cosmic ray collisions. Term used for a stream of particles with large (several GeV) longitudinal momenta and relatively small transverse momenta (fraction of a GeV).



Parton model gives angular distribution of jets.

SLAC GeV range e^+e^- collider designed to test this idea. At around 7 GeV jet structure started to emerge. At current energies jet structure very well defined



IRC safety and jet structure

Parton model has nothing to say on this and we turn to QCD. Not clear if QCD could say anything either since no complete sum over states as before.

Sterman and Weinberg realised existence of a concept (IRC safety) that rescues perturbation theory from divergences – no need to sum over all states.

G. Sterman, S. Weinberg 1977 Take inspiration from QED observables that show soft divergences at one-loop :

$$\sigma_1 = \sigma_0 \alpha_{\mathrm{EM}} C(Q/m_e) \ln \frac{\lambda}{m}$$

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IRC safety (contd.)

But practically we cannot resolve photons above some resolution ΔE. Hence at most we need to worry about

$$\alpha_{\mathrm{EM}} C(Q/m_e) \ln \frac{\Delta E}{m}$$

Sum over states below ΔE. α_{EM} is small so no need to worry about these terms !

F. Bloch , A. Nordsieck 1937

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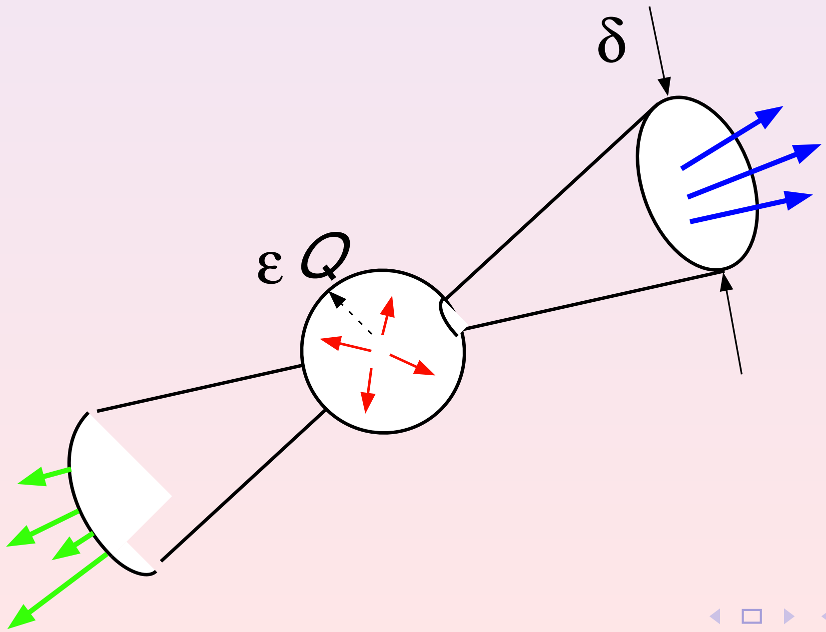
QCD resolution criteria

The minimum energy idea is inherited from QED. However there is another divergence to handle. Coefficients $C(Q/m_q)$ diverge logarithmically as $m_q \to 0$. High energy calculations in QCD face this problem.
Divergence in zero mass limit is collinear divergence. Introduce angular cut δ. Now we sum over states inside angular regions around hard partons –jets enter the scene with PT finite cross sections.



Jet cross-sections

Now one can define a two jet event : at most some fraction ϵ of energy is allowed outside cones of size δ. Otherwise three or higher jet event. Jet rates look like :

$$f_2 = 1 - 8C_F \frac{\alpha_s}{2\pi} \left(\ln \frac{1}{\delta} \left[\ln \left(\frac{1}{2\epsilon} - 1 \right) - \frac{3}{4} + 3\epsilon \right] + \frac{\pi^2}{12} - \frac{7}{16} - \epsilon + \frac{3}{2}\epsilon^2 + \mathcal{O}\left(\delta^2 \ln \epsilon\right) \right)$$

$$f_3 = 1 - f_2$$

Probability of three jets is $\mathcal{O}(\alpha_s)$ as we expect. Above algorithm not practically useful. Use other resolution criteria e.g $k_t \geq y$ etc. Main algorithms are k_t , cone, Cambridge algorithms.

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Calculational tools

- Fixed order calculations - Feynman graphs. Status is moving from NLO to NNLO.
- All order resummation to handle logarithmic enhancements (c.f $\alpha_s \ln \frac{1}{\delta} \ln \frac{1}{\epsilon}$).
- Monte Carlo tools. Talk by G. Marchesini

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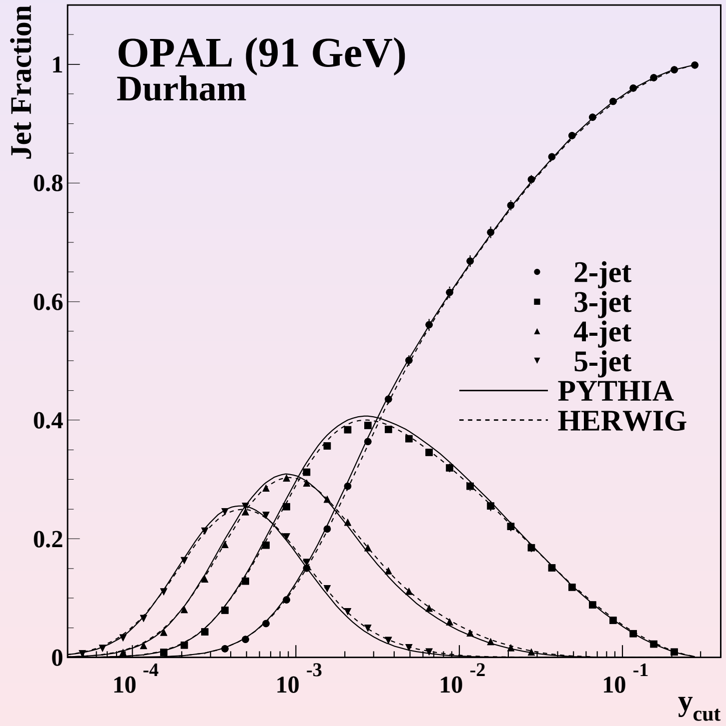
Jet rates

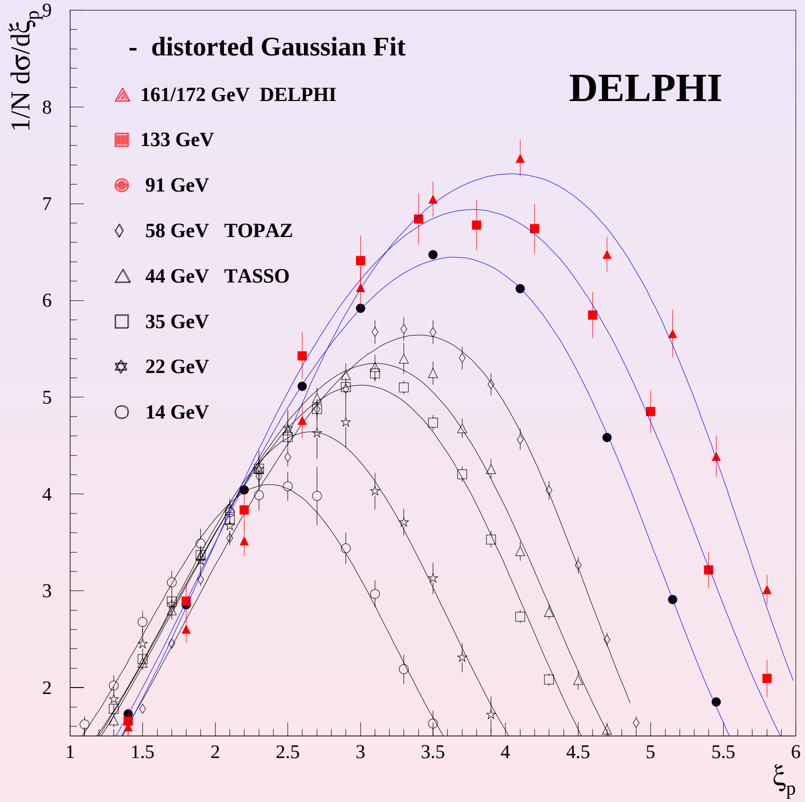
Jet rates have been used to extract α_s values. Both comparions to QCD Monte Carlo and analytical fixed-order+resummed calculations have been carried out.



Now we can be even more demanding.....

Inside jets

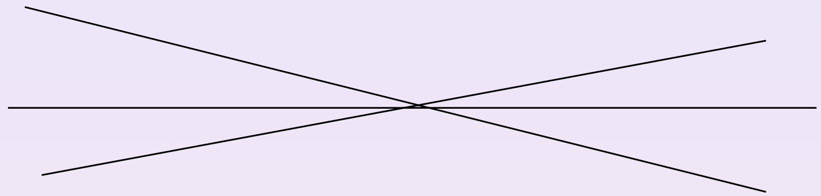
Can look for instance at the energy distribution of hadrons inside jets. A remarkable confirmation of soft gluon coherence effects.



$x\,D(x,s) \propto \exp\left[-\frac{1}{2\sigma^2}\left(\xi - \xi_p\right)^2\right]$

Dokshitzer, Khoze Troyan, 1989 Fong and Webber, 1992.

The shape of jets



IRC safe jet shape variables are invaluable for learning about QCD. Tell us about appearance of jets in detectors i.e how collimated/broad they are. Consider the thrust variable in e^+e^-.

$$T = \max_n \frac{\sum_i |P_i.n|}{\sum_i |P_i|}$$

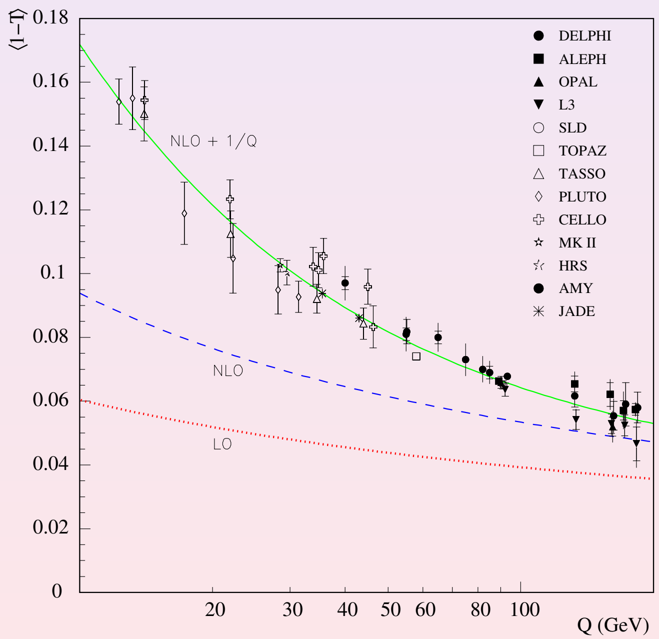
Narrow two-jet event gives $T \sim 1$.

Power corrections

Consider mean value of thrust $\langle 1-T\rangle$. IRC safe observable predictable in PT.

$$\langle 1-T\rangle = c_1\alpha_s(Q) + c_2\alpha_s^2(Q) + \cdots$$

Now compare to data



Jet physics as a window on NP dynamics

Need a $1/Q$ non-perturbative component –NP power corrections are significant. Same story for other jet shape variables.

Were accounted for by MC hadronisation – several adjustable parameters. Over the last decade great progress in understanding the origin and size of power corrections. Shown to be linked to $n!$ renormalon divergence of perturbation expansion.

For many common event shapes the renormalon effects can be shown to be of the form

$$\delta\langle V\rangle = C_V \frac{A}{Q}$$

where A is a universal quantity and C_V is perturbatively calculated ! Ratio of power corrections to different event shapes is calculable analytically.

Universal IR finite coupling ?

A link was made between the power correction and the notion of a universal IR finite coupling. If one introduces this model then

$$A \equiv \frac{4C_F}{\pi^2}\mathcal{M}\mu_I\left\{\alpha_0(\mu_I)-\alpha_s(\mu_R)-\beta_0\frac{\alpha_s^2}{2\pi}\left(\ln\frac{\mu_R}{\mu_I}+\frac{K}{\beta_0}+1\right)\right\},$$

$$\alpha_0(\mu_I)=\frac{1}{\mu_I}\int_0^{\mu_I}\alpha_s(k_t)dk_t$$

α_0 is average value of universal IR coupling.

Dokshitzer, Marchesini, Webber 1995

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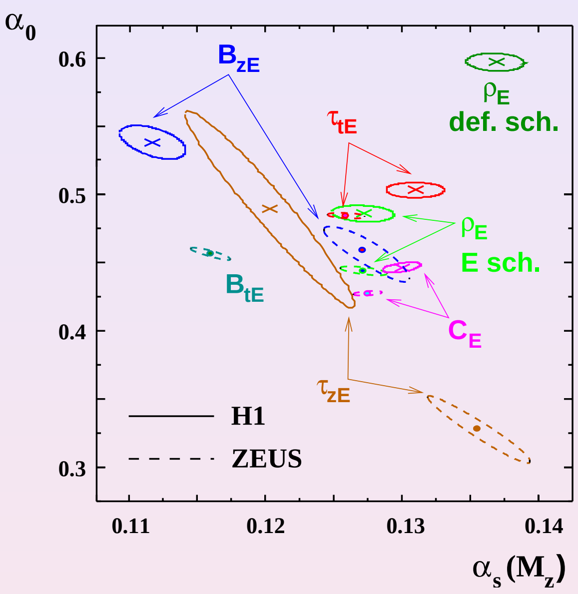
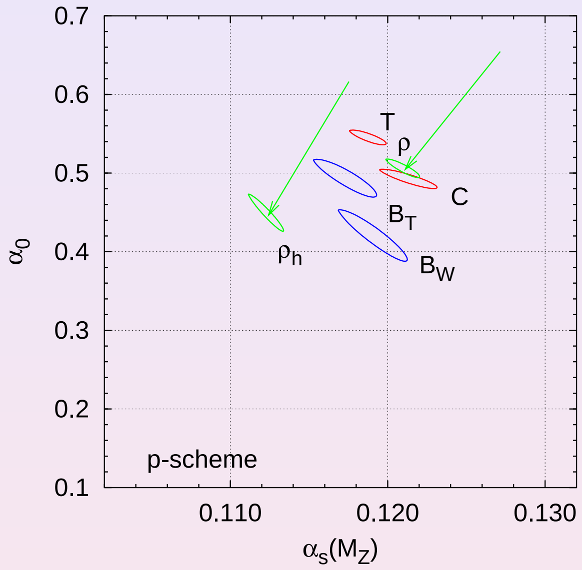
Universal IR coupling from LEP and HERA





Universality hypothesis supported by collider experiments within expected limit. $\alpha_0 \sim 0.5$

Event shape distributions

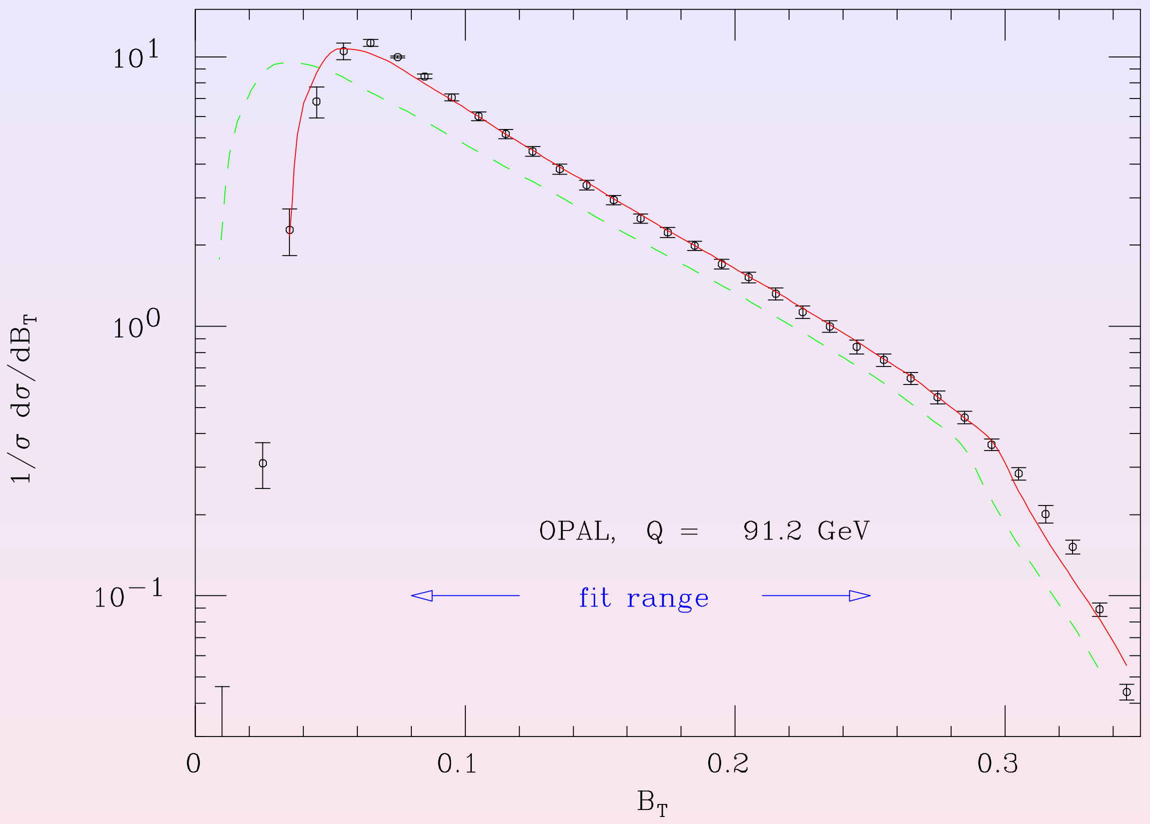
A more stringent test still ! Test at once understanding of QCD from short to long distance scales. Large logarithms need to be resummed for sensible description.

$$\frac{1}{\sigma}\frac{d\sigma}{dV} \sim \sum_n \frac{1}{V}\alpha_s^n \ln^{2n-1}\frac{1}{V}$$

Observable is sensitive to evolution from short to long distances. Our understanding of this reflected by ability to resum large logarithms to all orders.

$$\frac{1}{\sigma}\frac{d\sigma}{dV} \sim \frac{d}{dV}\exp\left(-c\alpha_s \ln^2\frac{1}{V}\right)$$

Event shape distributions (contd.)



Entire distribution fitted with just two parameters α_s and α_0 !

Dokshitzer, Lucenti, Marchesini and Salam 1997,1998

Inspite of the triumphs...

It is vital to learn more in the LHC era. Increasing precision in QCD not merely a question of calculation. Will always be limited by understanding of dynamics of partons and their transition to hadrons.

Call for NNLO calculations in jet physics at hadron colliders – should be tempered by realisation that at this level hadronisation effects will compete. Better understanding of these is just beginning. Other intriguing questions regarding factorisation and coherence. Collins,Qiu Forshaw,Kyreileis Seymour 2006 Many more issues.....

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