Selected QCD Results from DELPHI

(A Short Overview in 4 Lessons)

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Content

- QCD and the Standard Model
- The Physics Environment
- Momentum Spectra
- Quarks and Gluons: 3–jet Multiplicities
- Power Corrections, Scale Dependence and the Determination of α_{strong}

QCD: the most beautiful part of the Standard Model

$$\textbf{SM}= U(1) \otimes SU(2) \otimes SU(3)_{colour}$$

The 18+? parameters of the Standard Model

- 3 coupling constants $\rightarrow \alpha_s$
- 4 parameters of the CKM matrix
- Higgs mass and VEV
- 12 fermion masses
- leptonic mixing sector ???

The complete dynamics of QCD can directly be derived from the gauge–group structure (e.g. Colour Factors)

QCD: the most ugly part of the Standard Model

SM= $U(1) \bigotimes SU(2) \bigotimes$ **JETSET**

The 18+? parameters of hadronization models

- model dependence: ARIADNE, HERWIG, PHYTHIA/JETSET
- cut–off in parton shower
- heavy quark suppression
- fragmentation functions
- particle decays

QCD is the theory of quarks and gluons, while we only observe hadrons!

Hadronization is a non–perturbative process, which is not understood from first principles!

Hadronization effects can only be estimated from phenomenological models (generators, power corrections)

1. Lesson

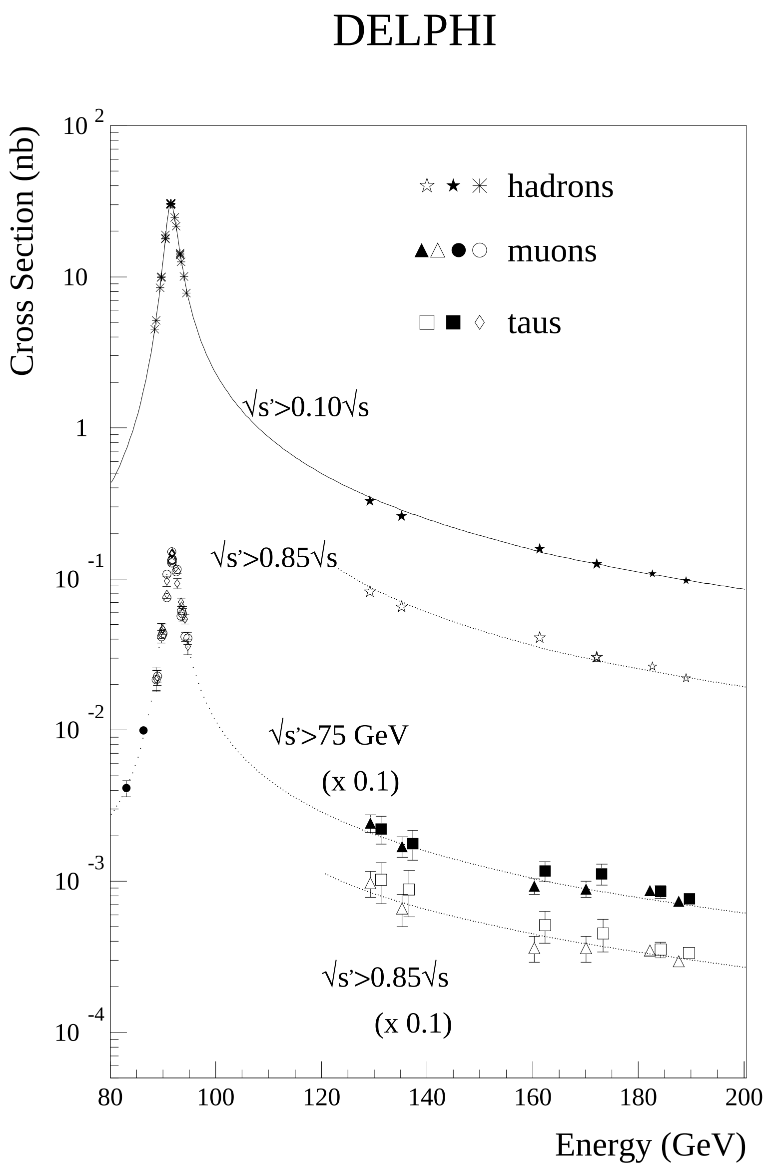
Due to hadronization, experimental tests of pQCD are more complicated than one would expect from the mere gauge–group structure

The Physics Environment I

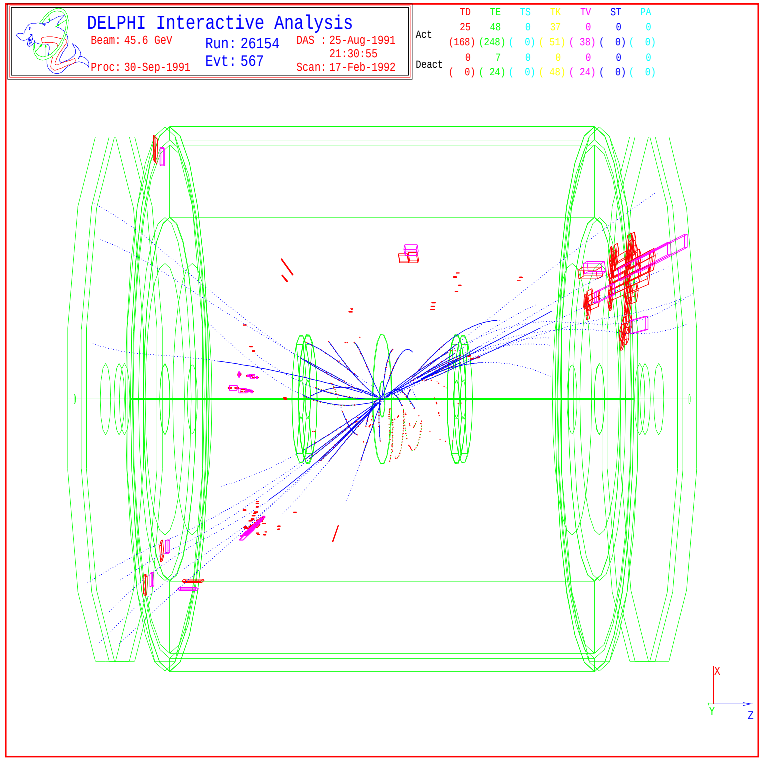
$e^+e^- \to q\overline{q} \to$ **hadrons**

$\approx$ 1 million hadronic events at LEP1 ($E_{CM} = 91.2$GeV)

$\approx$ 10.000 hadronic events at LEP2 ($E_{CM} = 130 - 208$ GeV)



The Physics Environment II



$e^+e^- \to q\bar{q}g \to$ **hadrons**

$N_{ch} \approx 25$

Momentum Spectra: Theory

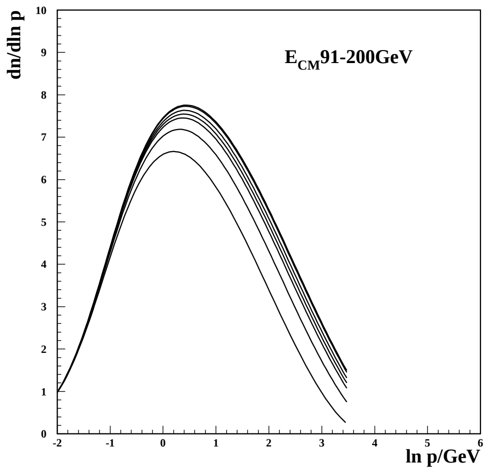
The momentum spectra can not be calculated directly in perturbative QCD since it is not infrared safe!

$$\frac{1}{N_{evt}}\frac{dn}{dp}$$

One needs to introduce an additional cut-off (Q_0)

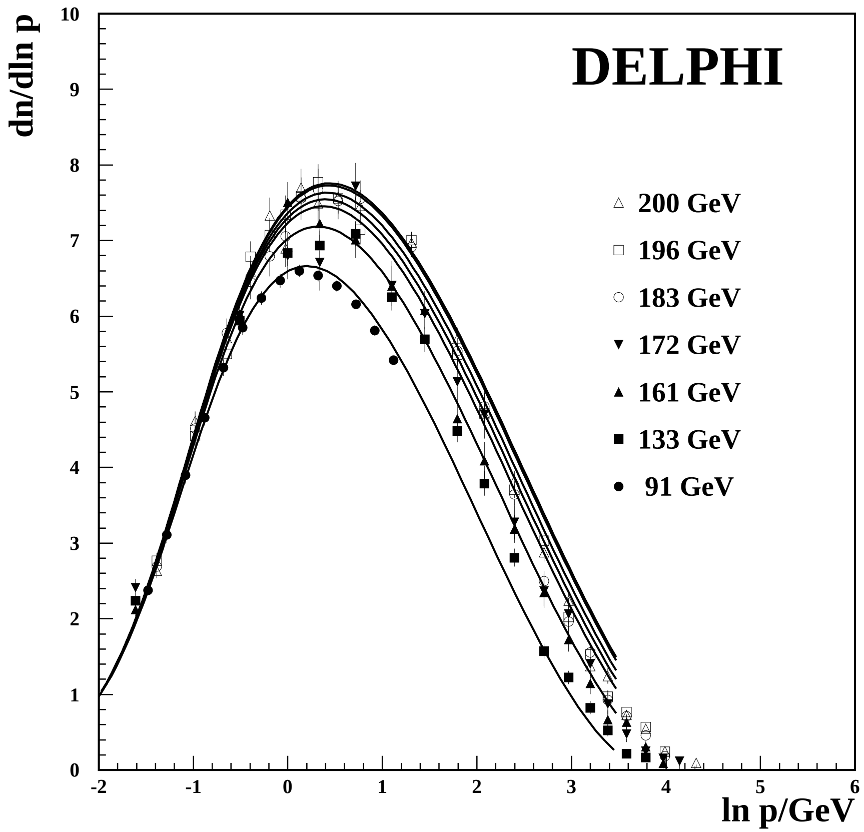
Local Parton Hadron Duality (LPHD) states:

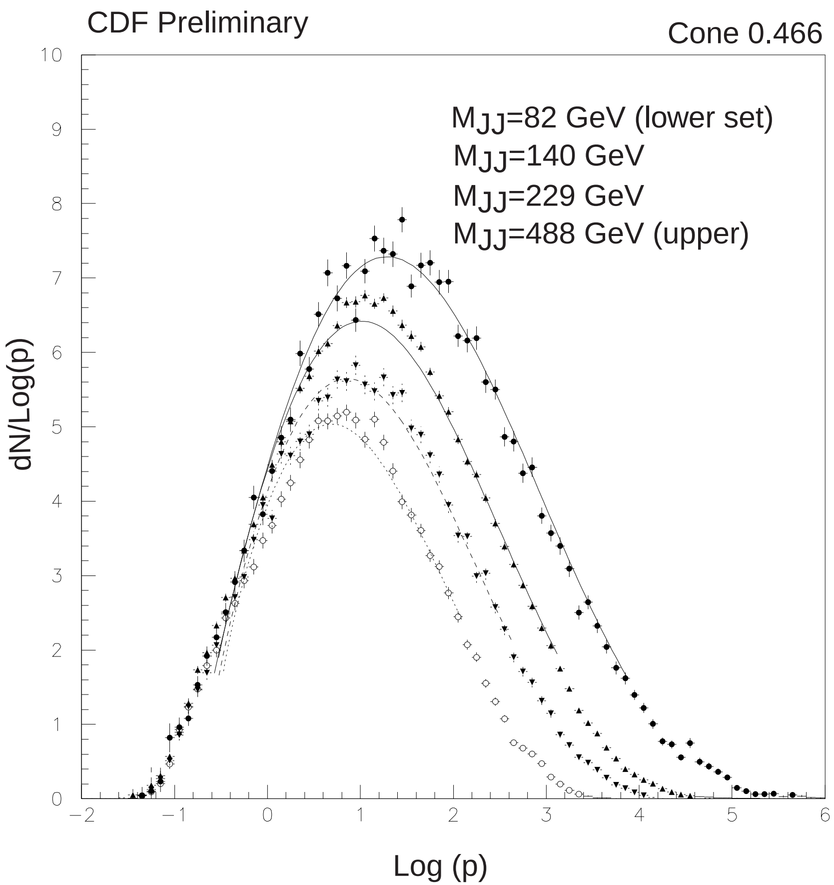
hadronic spectra $\propto$ partonic spectra with $Q_0 \approx m_{\rm hadron}$



This partonic momentum spectra exhibits universal behavior at low momentum due to coherent emission of soft gluons!

Momentum Spectra: Experiment





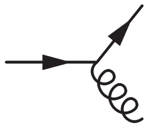
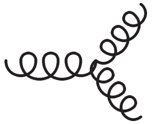
The universal behavior at low momenta shows up in both, e^+e^- and $p\bar{p}$ collisions!

2. Lesson

coherence matters !

Why study quark and gluon jets?

- Probability of radiation/splitting is governed by colour factors:

$C_F \propto \left| \right.$  $\left. \right|^2$ $\quad C_A \propto \left| \right.$  $\left. \right|^2$

- Colour factors are the Casimir operators of the underlying symmetry group.

- Difference between quark and gluon jets:

$$\frac{C_A}{C_F} = \frac{3}{4/3} = 2.25$$

Ratio of gluon and quark **jet**–mutliplicities

Some measurements of the gluon– quark jet multiplicity ratio r_n:

Cleo	$E_{\mathrm{Jet}} < 3.5\mathrm{GeV}$	$r_n = 1.04 \pm 0.02 \pm 0.05$
HRS	$E_{\mathrm{Jet}} = 9.7\mathrm{GeV}$	$r_n = 1.29 \pm 0.2(\mathrm{stat.})^{+0.21}_{-0.20}(\mathrm{syst.})$
Tasso	$E_{\mathrm{Jet}} = 11\mathrm{GeV}$	$r_n \simeq 1.$
Opal	$E_{\mathrm{Jet}} = 24.5\mathrm{GeV}$	$r_n = 1.02 \pm 0.04^{+0.06}_{-0.00}$
Opal	$E_{\mathrm{Jet}} = 24\mathrm{GeV}$	$r_n = 1.25 \pm 0.02 \pm 0.03$
Aleph	$E_{\mathrm{Jet}} = 24\mathrm{GeV}$	$r_n = 1.249 \pm 0.084 \pm 0.022$
Delphi	$\overline{E_{\mathrm{Jet}}} = 24\mathrm{GeV}$	$r_n = 1.241 \pm 0.015 \pm 0.025$
Opal	$E_{\mathrm{Jet}} = 39\mathrm{GeV}$	$r_n = 1.552 \pm 0.041 \pm 0.061$

- what about soft tracks?
- what sets the scale?

Event-Multiplicity: Prediction by Eden et al.(1)

- Prediction by P.Eden, G.Gustafson & V.Khoze for gluon-gluon-events:

$$\boxed{\frac{dN_{gg}(L')}{dL'} \propto \frac{C_A}{C_F}\frac{dN_{q\bar{q}}(L)}{dL}}$$

$$with \quad L = \log\frac{s}{\Lambda^2} \quad and \quad L' = L + 11/6 - 3/2$$

- Constant of integration left free
  → Constant of integration can be determined from measurement of N_{gg}
  → Here: CLEO-measurement of N_{gg} in the decay $\chi_b'(J=2) \rightarrow gg$ at $E_{cm} = 9.9132\mathrm{GeV}$
- $N_{q\bar{q}}$ taken from several measurements of different experiments at various $\sqrt{s}$

Event-Multiplicity: Prediction by Eden et al.(2)

- Multiplicity of three-jet-events:

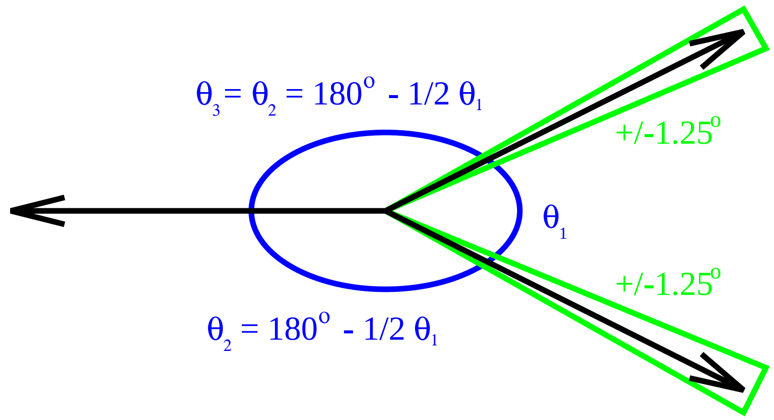
$$N_{q\bar{q}g} = N_{\bar{q}q}(L_{q\bar{q}}, \kappa_{Lu}) + \frac{1}{2} N_{gg}(\kappa_{Le})$$

with $L_{q\bar{q}} = \ln\left(\frac{s_{q\bar{q}}}{\Lambda^2}\right)$, $\kappa_{Lu} = \ln\left(\frac{p^2_{-\mathrm{Lu}}}{\Lambda^2}\right)$, $\kappa_{Le} = \ln\left(\frac{p^2_{-\mathrm{Le}}}{\Lambda^2}\right)$

and $p^2_{-\mathrm{Lu}} = \frac{s_{qg} s_{\bar{q}g}}{s}$, $p^2_{-\mathrm{Le}} = \frac{s_{qg} s_{\bar{q}g}}{s_{q\bar{q}}}$.

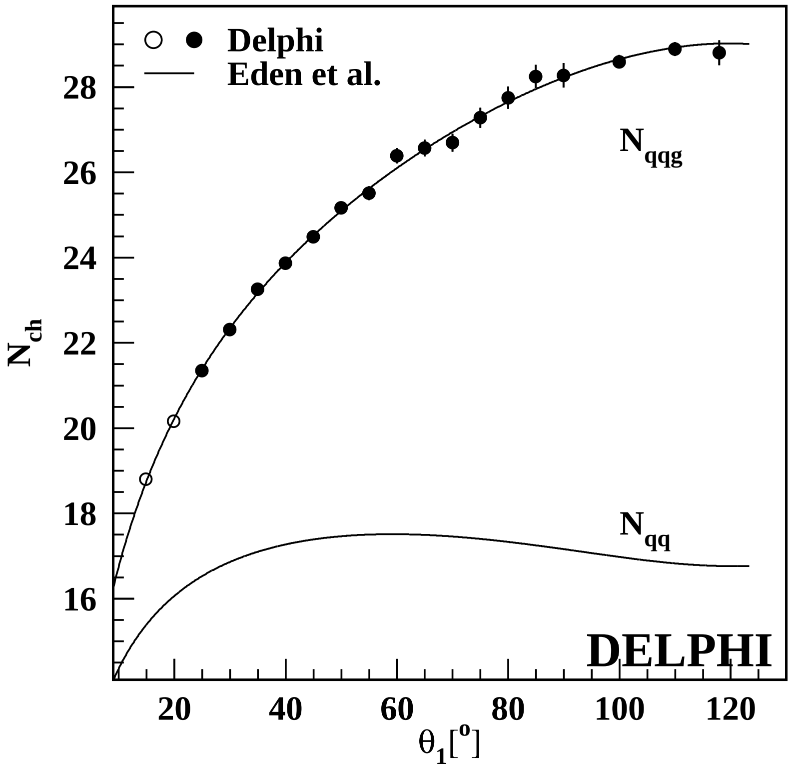
- Coherence effects are taken into account by the choice of scale variables

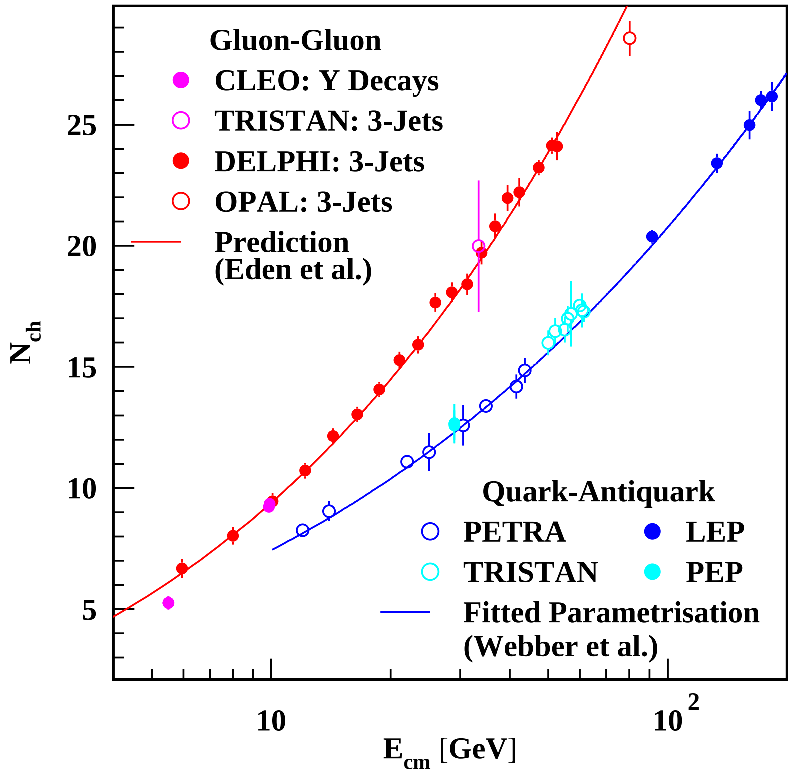
Analysis of whole Three-Jet-Events



- All events are clustered into three jets (no y_{cut})
- Selection of symmetric events
- $\Rightarrow$ **one angle characterizes the whole event**
- e.g. $p_T^2 = \frac{s_{qg}s_{\bar{q}g}}{s_{q\bar{q}}} = s\frac{\sin^2\theta/2}{(1+\cos\theta/2)^2}$
- essentially **no gluon identification** necessary!

3–jet multiplicities and C_A/C_F





Observable: **total** multiplicity of three jet events as a function of the opening angle θ.

$$\frac{C_A}{C_F} = 2.262 \pm 0.032$$

3. Lesson

coherence really matters !

Determination of α_s with event shapes

Finite perturbative calculations can be obtained for collinear and infrared (CIS) save quantities, like

$$\text{Thrust} = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum |\vec{p}_i|} \right) = \frac{\sum_i |\vec{p}_i \cdot \vec{n}_{thrust}|}{\sum_i |\vec{p}_i|}$$

fixed order calculation:

$$\langle 1 - T \rangle = \left(\frac{\alpha_s(\mu)}{2\pi} \right) A + \left(\frac{\alpha_s(\mu)}{2\pi} \right)^2 \left[B + A \cdot 2\pi \cdot b_0 \cdot \log(\mu^2/Q^2) \right] + \mathcal{O}(\text{unknown})$$

also NLLA and matched calculations available for many observables!

The Renormalization Scale Problem

The renormalization scale is an unphysical parameter. It enters in the renormalization of the theory, and does not drop out because the expansion in α_s is truncated.
μ may be chosen according to one of the following recipes:

- $\mu = Q$: "physical scale"
- $B + A \cdot 2\pi \cdot b_0 \cdot \log(\mu^2/Q^2) = 0$: effective charge (ECH, RSI) $\frac{\mu^2}{Q^2} = \exp -\frac{B}{2A\pi b_0}$
- treat μ as an free parameter for each observable: experimentally optimized scale
- $\frac{\partial \mathcal{O}}{\partial \mu} = 0$: principle of minimal sensitivity (PMS)

Theoretically no scale–choice is preferred, since only changes of $\mathcal{O}(\alpha_s^3)$ are introduced by this change. In NLO calculations a scale–change is equivalent to a renormalization–scheme–change.

The Hadronization Problem

As mentioned above: QCD applies directly only to quarks and gluons. Two ways of hadronization corrections

- **Monte Carlo Method:** Inside the generator a parton shower develops according to pQCD, before turned into hadrons.

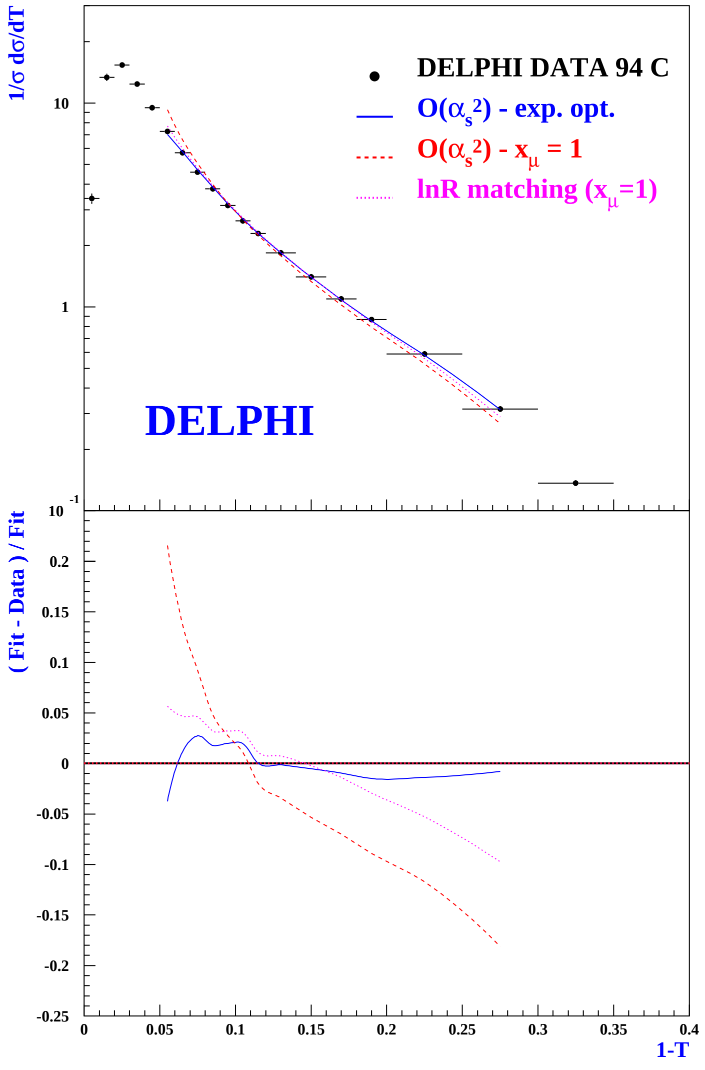
$$DATA_{\text{hadron level}} \cdot \frac{MC_{\text{parton level}}}{MC_{\text{hadron level}}} = DATA_{\text{parton level}}$$

- **Power Corrections:** IR renormalon ambiguity in pQCD should be canceled by non–perturbative effects. This allows for a QCD inspired parameterization (α_0) of hadronization effect.

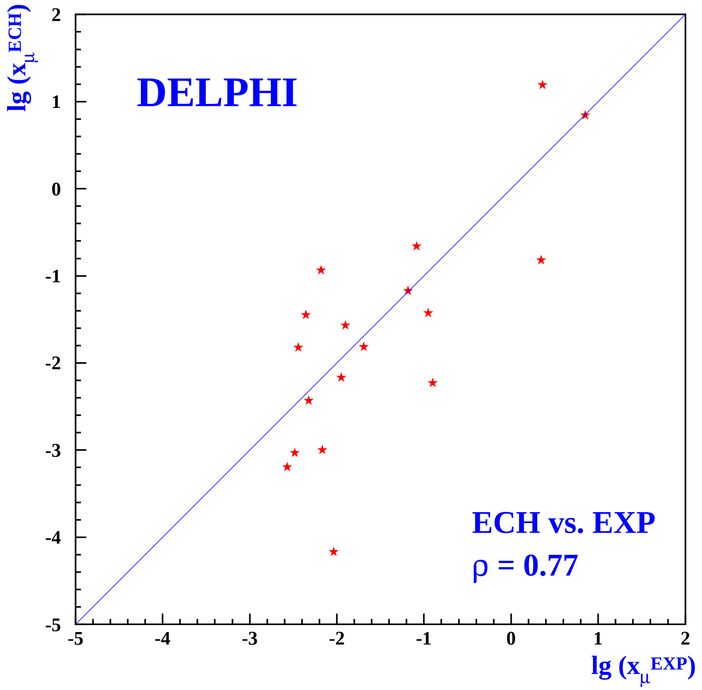
$$\langle y_{had} \rangle = \langle y_{pert} \rangle + \frac{something}{Q}$$

$$\frac{1}{\sigma}\frac{d\sigma}{dy} = F_{pert}(y - \frac{st}{Q})$$

Event shape distributions and optimized scales

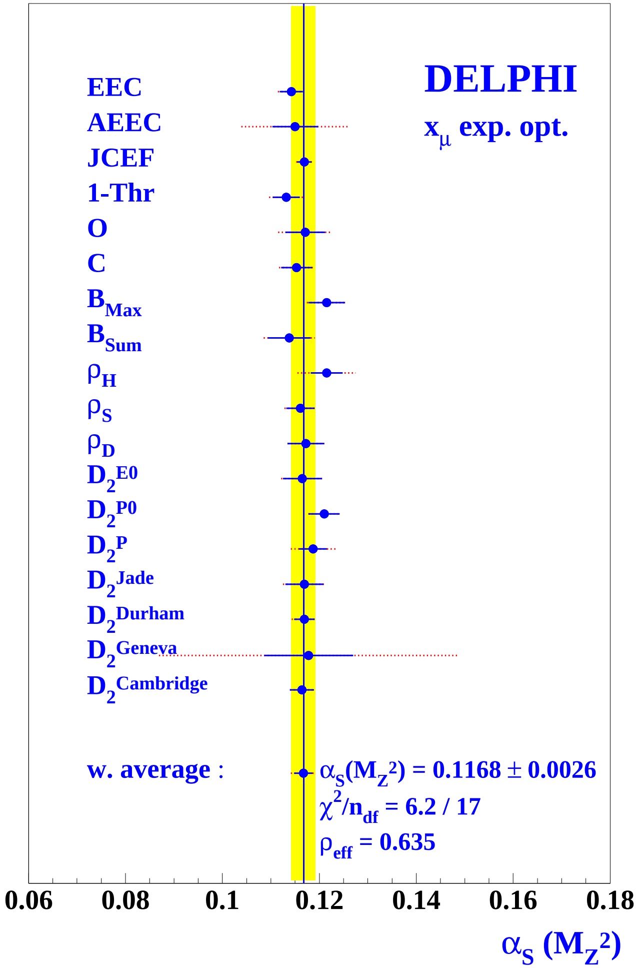


Second Order fits with experimentally optimized scales to **distributions** describe the data over the whole fit range ($\mu_{\mathrm{exp.opt.}}$: 5 GeV – 240 GeV)



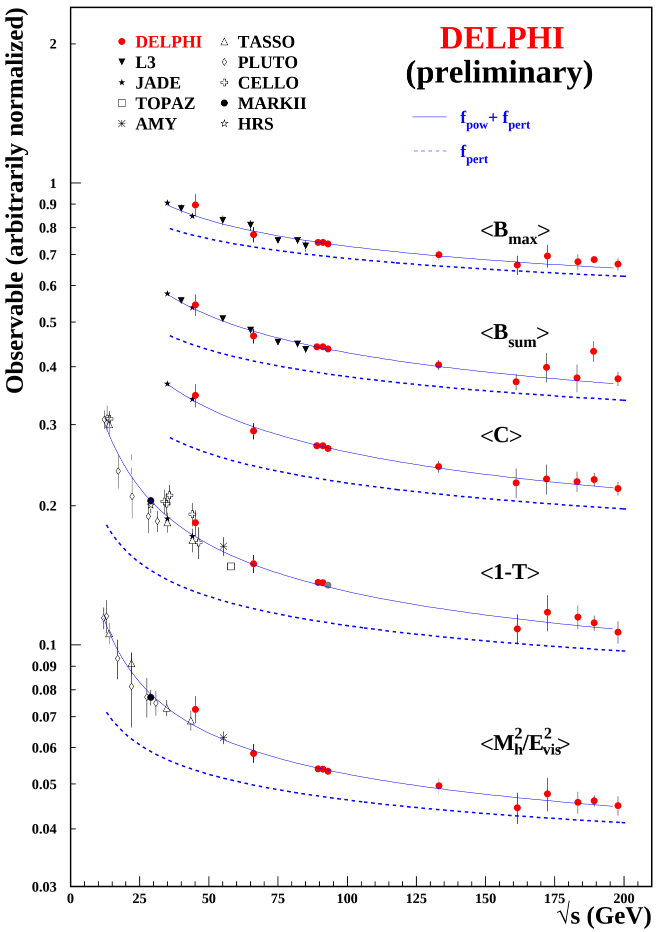
Event shape distributions and optimized scales

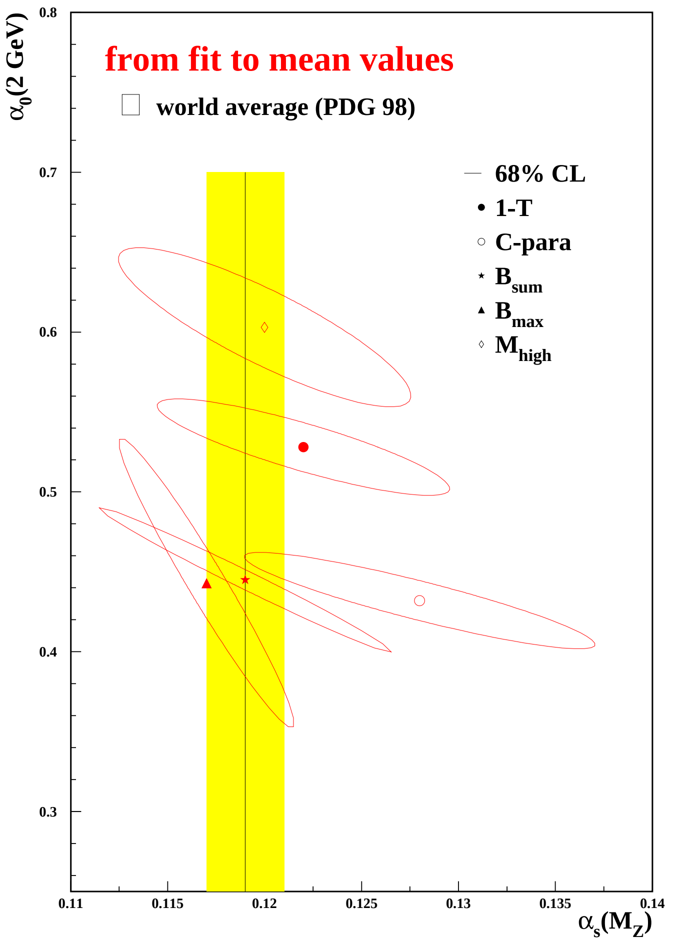
Second Order fits with experimentally optimized scales to **distributions** allow a consistent determination of α_s!



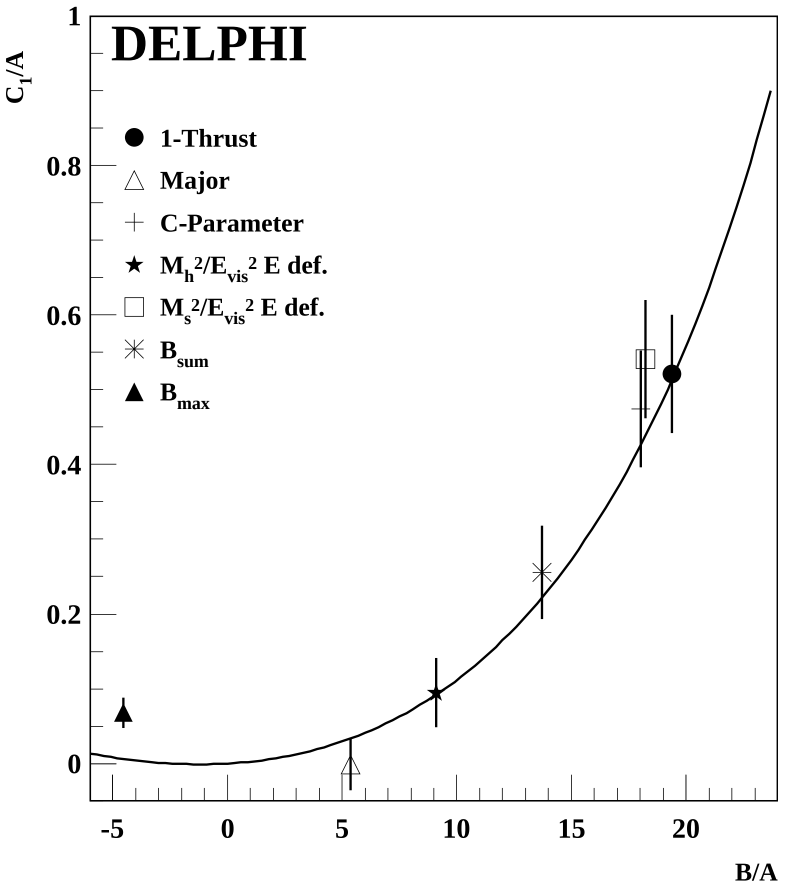
power corrections to mean values

Energy dependence of event shape means can be described by pQCD ($\mu = Q$) and power corrections.





Are power corrections purely non–perturbative?

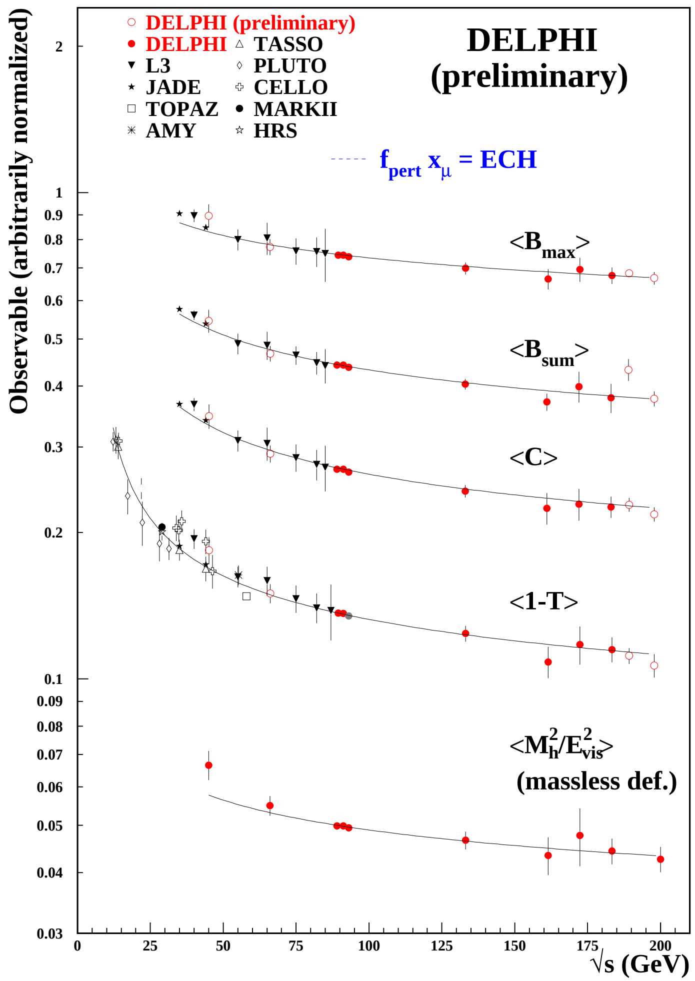


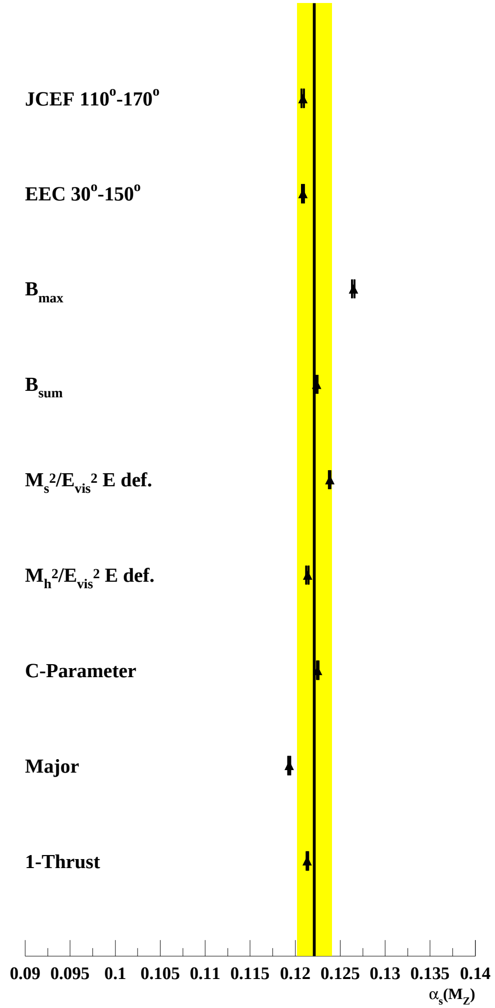
there is a correlation between the relative size of the second order contribution (B/A) and the size of power corrections ($\sim C/Q$)

$\Rightarrow$ power corrections can not be purely non–perturbative

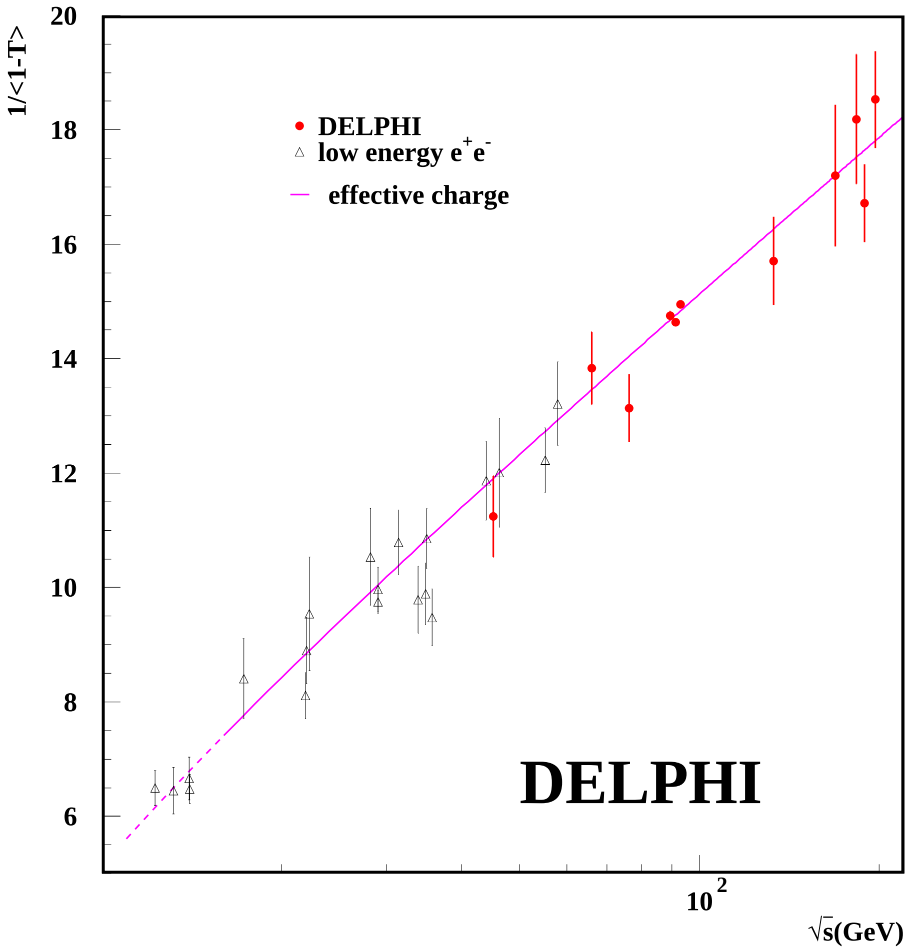
mean values with effective charge scale

Energy dependence of event shape means can also be described by pQCD alone with a proper scale choice. $\Rightarrow$ For this **inclusive observable** hadronization effects seem to be rather small !





The "Running" of $\langle 1-T \rangle$



This allows a consistent description of the $\langle 1-T \rangle$ energy dependence from 10 to 200 GeV.

BUT: in effective charge scheme:
Observable $\propto \alpha_s$
$\Rightarrow$ Test of RGE:

$$\frac{d\alpha_s^{-1}}{d\log\sqrt{s}} = 2b_0(1 + b_1\alpha_s + \cdots)$$

with $b_0 = \frac{33-2n_f}{12\pi}$ and $b_1 = \frac{153-19n_f}{2\pi(33-2n_f)}$

4. Lesson

A clever scheme choice helps to get more benefit from the perturbative calculations

The 4 lessons we have learned

1. Due to hadronization experimental tests of pQCD are more complicated than one would expect from the mere gauge–group structure

2. coherence matters: soft particles are coherently emitted from the whole colour charge

3. coherence really matters: 3–jet multiplicities can be described by a p_{-}–like scale (C_A/C_F measurement)

4. α_s :A clever scheme choice helps to get more benefit from the perturbative calculations