

QCD and TsLep

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$$\mathcal{L}_0 = \sum_{a=1}^3 \sum_f \bar{\Psi}_f^a(x) (\not{\partial} - m_f) \Psi_f^b(x)$$

$a=1,2,3$ colour

$f = \begin{matrix} u & c & b \\ d & s & t \end{matrix}$ flavour

Interaction via "local gauge promotion" $\Rightarrow \mathcal{L}_{QCD}$

$U(1)$ -symmetry \Rightarrow Interaction with photons $A_\mu(x)$

$SU(3)$ -colour symmetry \Rightarrow Inter. with gluons $G_\mu^\alpha(x)$
" among "

$$\not{\partial} \delta_{ab} \Rightarrow \not{\partial} \delta_{ab} + e A \delta_{ab} + g_s \sum_{\alpha=1}^8 \not{G}_\alpha \lambda_{ab}^\alpha$$

\uparrow
electric charge $\alpha = 4\pi e^2$

\uparrow strong coupling charge $\alpha_s = 4\pi g_s^2$

Construction of bridge between

2

L_{QCD} and PDB
quark-gluons \leftrightarrow hadrons

Analytical technique essentially only PT

Main obstacle for bridge: asymptotic freedom

$$\alpha_s(Q) \approx \frac{4\pi}{\beta_0 T} \left(1 - \frac{2\beta_1}{\beta_0^2} \frac{\ln T}{T} + \frac{4\beta_1^2}{\beta_0^4 T^2} \ln^2 T \right) \dots; T = \ln \frac{Q^2}{\Lambda^2}$$

Confinement of quark-gluons: PT not reliable

Hard physics: PT possible (?)

- No hope for the bridge yet
- At least a link

Strategy left: • Compute in PT parton distrib
in hard regions

• hope that partons \approx hadrons

Warning: a school of fish \approx a whale

July 1996
**PARTICLE
PHYSICS**

BOOKLET

From the *Review of Particle Physics* (next edition: July 1998)
R.M. Barnett et al., *Physical Review D* 54, 1 (1996)

Particle Listings and complete reviews plus a directory of online
HEP information are available at <http://pdg.lbl.gov/>

Particle Data Group

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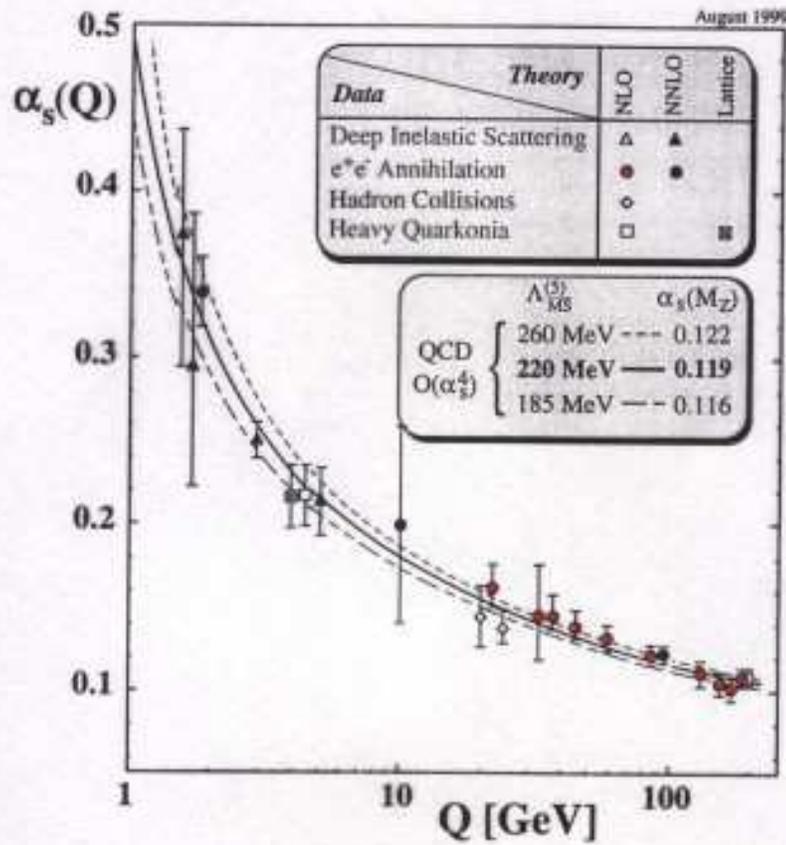
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AIP

AMERICAN INSTITUTE OF PHYSICS
Available from LBNL and CERN

World Summary of $\alpha_s(Q)$

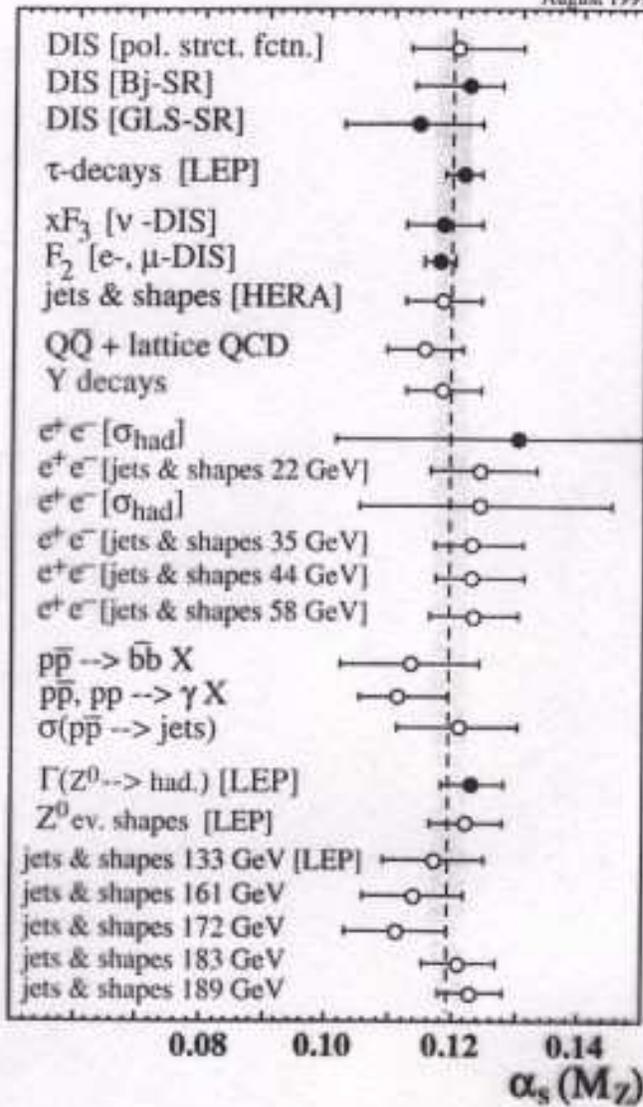


S. Bethke

$$\alpha_s(M_Z) = 0.119 \pm 0.003 \leftrightarrow \begin{cases} \Lambda_{\overline{MS}}^{(5)} = 220 \pm_{35}^{40} \text{ MeV} \\ \Lambda_{\overline{MS}}^{(4)} = 305 \pm_{45}^{50} \text{ MeV} \end{cases}$$

Figure 35.

August 1999



$$\alpha_s(M_Z) = 0.119 \pm 0.003$$

Figure 36.

Parton distributions in hard regions $\alpha_s(Q) \ll 1$

but $\alpha_s(Q) \times \ln \frac{Q}{\mu} \times \ln \frac{Q}{Q_0}$ $\mu = \text{Collinear}$
 $Q_0 = \text{IR}$

1. $\alpha_s^M(Q) \ln^{2M} Q \sim \ln^M Q$ Coll + IR sing
 2. $\alpha_s^M(Q) \ln^M Q \sim 1$ Coll sing
 3. $\alpha_s^M(Q) \ln^{M-1} Q \ll 1$ //
 4. $\alpha_s^M(Q) \ll 1$ Collinear + IR finite
4. $\alpha_s(Q), \alpha_s^2(Q) (\alpha_s^3(Q))$ finite orders

1+2 resummed to all orders

\Rightarrow Collin. singul. factorization

\Rightarrow coherent parton branching \Rightarrow $\left\{ \begin{array}{l} \text{Analytical-} \\ \text{MC-resummation} \end{array} \right.$

\Rightarrow preconfinement of colour \Rightarrow LHP duality

\Rightarrow MC simulation

l^+l^-

IPROC	Process
100	$l^+l^- \rightarrow q\bar{q}(g)$ (all q flavours)
100+IQ	$l^+l^- \rightarrow q\bar{q}(g)$ (IQ = 1, 2, 3, 4, 5, 6 for $q = d, u, s, c, b, t$)
107	$l^+l^- \rightarrow gg(g)$ (fictitious process)
110	$l^+l^- \rightarrow q\bar{q}g$ (all flavours)
110+IQ	$l^+l^- \rightarrow q\bar{q}g$ (IQ as above)
120	$l^+l^- \rightarrow q\bar{q}$ (all flavours, no hard gluon correction)
120+IQ	$l^+l^- \rightarrow q\bar{q}$ (IQ as above, no hard gluon correction)
127	$l^+l^- \rightarrow gg$ (fictitious process, no hard gluon correction)
150+IL	$l^+l^- \rightarrow \ell'\ell''$ (IL = 1, 2, 3 for $\ell = e, \mu, \tau$, N.B. $\ell \neq \ell'$)
200	$l^+l^- \rightarrow W^+W^-$ (see Sect. 4.3.2 on control of W/Z decays)
250	$l^+l^- \rightarrow Z^0Z^0$ (see Sect. 4.3.2 on control of W/Z decays)
300	$l^+l^- \rightarrow Z^0H \rightarrow Z^0q\bar{q}$ (all flavours)
300+IQ	$l^+l^- \rightarrow Z^0H \rightarrow Z^0q\bar{q}$ (IQ as above)
306+IL	$l^+l^- \rightarrow Z^0H \rightarrow Z^0\ell\bar{\ell}$ (IL as above)
310, 311	$l^+l^- \rightarrow Z^0H \rightarrow Z^0W^+W^-, Z^0Z^0Z^0$
312	$l^+l^- \rightarrow Z^0H \rightarrow Z^0\gamma\gamma$
399	$l^+l^- \rightarrow Z^0H \rightarrow Z^0$ anything
400+ID	$l^+l^- \rightarrow \nu\bar{\nu}H + l^+l^-H$ (ID as in IPROC = 300 + ID)
500+ID	$l^+l^- \rightarrow l^+l^-\gamma\gamma \rightarrow l^+l^-q\bar{q}/\ell\bar{\ell}/W^+W^-$ (ID=0-10 as in IPROC = 300 + ID)
550+ID	$l^+l^- \rightarrow l\nu_\ell\gamma W \rightarrow l\nu_\ell q\bar{q}'/\ell\bar{\ell}'$ (ID=0-9 as in IPROC = 300 + ID))
1300	$q\bar{q} \rightarrow Z^0/\gamma \rightarrow q'\bar{q}'$ (all flavours)
1300+IQ	$q\bar{q} \rightarrow Z^0/\gamma \rightarrow q'\bar{q}'$ (IQ as above)
1350	$q\bar{q} \rightarrow Z^0/\gamma \rightarrow \ell\bar{\ell}$ (all lepton species)
1350+IL	$q\bar{q} \rightarrow Z^0/\gamma \rightarrow \ell\bar{\ell}$ (IL = 1 - 6 for $\ell = e, \nu_e, \mu, \nu_\mu$, etc.)
1399	$q\bar{q} \rightarrow Z^0/\gamma \rightarrow$ anything
1400	$q\bar{q} \rightarrow W^\pm \rightarrow q'\bar{q}''$ (all flavours)
1400+IQ	$q\bar{q} \rightarrow W^\pm \rightarrow q'\bar{q}''$ (q' or q'' as above)
1450	$q\bar{q} \rightarrow W^\pm \rightarrow l\nu_\ell$ (all lepton species)
1450+IL	$q\bar{q} \rightarrow W^\pm \rightarrow l\nu_\ell$ (IL = 1, 2, 3 for $\ell = e, \mu, \tau$)
1499	$q\bar{q} \rightarrow W^\pm \rightarrow$ anything
1500	QCD 2 \rightarrow 2 hard parton scattering After generation, IHPROC is subprocess (see Sect. 4.4.2)
1600+ID	$gg/q\bar{q} \rightarrow H$ (ID as in IPROC = 300 + ID)
1700+IQ	QCD heavy quark production (IQ as above) After generation, IHPROC is subprocess (see Sect. 4.4.2)
1800	QCD direct photon + jet production After generation, IHPROC is subprocess (see Sect. 4.4.5)
1900+ID	$q\bar{q} \rightarrow q'\bar{q}'W^+W^- \rightarrow q'\bar{q}'H$ (ID as in IPROC = 300 + ID)
2000	t production via W^\pm exchange (sum of 2001-2008)
2001-4	$\bar{u}b \rightarrow \bar{d}t, \bar{d}b \rightarrow \bar{u}t, \bar{d}\bar{b} \rightarrow \bar{u}\bar{t}, ub \rightarrow dt$
2005-8	$\bar{c}b \rightarrow \bar{s}t, \bar{s}b \rightarrow \bar{c}t, sb \rightarrow ct, cb \rightarrow st$
2100	$W^\pm +$ jet production
2110	$W^\pm +$ jet production (Compton only: $gq \rightarrow Wq$)
2120	$W^\pm +$ jet production (annihilation only: $q\bar{q} \rightarrow Wg$)
2150	$Z^0 +$ jet production
2160	$Z^0 +$ jet production (Compton only: $gq \rightarrow Zq$)
2170	$Z^0 +$ jet production (annihilation only: $q\bar{q} \rightarrow Zg$)

IPROC	Process
2200	QCD direct photon pair production After generation, IHPRD is subprocess (see Sect. 4.4.5)
2300	QCD Higgs + jet production in the SM After generation, IHPRD is subprocess (see Sect. 4.4.9)
2400	Mueller-Tang colour singlet exchange
2450	Quark scattering via photon exchange
2500+IQ	$gg/q\bar{q} \rightarrow Q\bar{Q}H$ (all q flavours, IQ as above for Q flavour)
2510+IQ	$gg \rightarrow Q\bar{Q}H$
2520+IQ	$q\bar{q} \rightarrow Q\bar{Q}H$ (s -channel b only)
2600	$q\bar{q}' \rightarrow W^\pm H$ (all q, q' flavours)
2650	$q\bar{q} \rightarrow Z^0 H$ (all q flavours)
3000-999	Minimal supersymmetric standard model (MSSM) processes
3000	2-parton \rightarrow 2-sparticle processes (sum of those below)
3010	2-parton \rightarrow 2-sparton processes
3020	2-parton \rightarrow 2-gaugino processes
3030	2-parton \rightarrow 2-slepton processes
3300-3350	$q\bar{q} \rightarrow W^+ H^-, W^- H^+, H^+ H^-$
3400	$b\bar{g} \rightarrow t H^- + \text{ch. conj.}$
3500	$b(\bar{b})q \rightarrow b(\bar{b})q' H^\pm + \text{ch. conj.}$
3610+ID	$q\bar{q}/gg \rightarrow H^0$, (heavy scalar Higgs, ID as in IPROC = 300 + ID)
3620+ID	$q\bar{q}/gg \rightarrow h^0$, (light scalar Higgs, ")
3630+ID	$q\bar{q}/gg \rightarrow A^0$, (pseudoscalar Higgs, ")
3710+ID	$q\bar{q} \rightarrow q'\bar{q}' H^0$, (ID as in IPROC = 300 + ID)
3720+ID	$q\bar{q} \rightarrow q'\bar{q}' h^0$, (")
3810+IQ	$gg + q\bar{q} \rightarrow Q\bar{Q}H^0$ (all q flavours, s -channel, IQ as above)
3820+IQ	$gg + q\bar{q} \rightarrow Q\bar{Q}h^0$ (")
3830+IQ	$gg + q\bar{q} \rightarrow Q\bar{Q}A^0$ (")
3840+IQ	$gg \rightarrow Q\bar{Q}H^0$ (IQ as above)
3850+IQ	$gg \rightarrow Q\bar{Q}h^0$ (")
3860+IQ	$gg \rightarrow Q\bar{Q}A^0$ (")
3870+IQ	$q\bar{q} \rightarrow Q\bar{Q}H^0$ (all q flavours, s -channel, IQ as above)
3880+IQ	$q\bar{q} \rightarrow Q\bar{Q}h^0$ (")
3890+IQ	$q\bar{q} \rightarrow Q\bar{Q}A^0$ (")
3910	$q\bar{q}' \rightarrow W^\pm H^0$ (all q, q' flavours)
3920	$q\bar{q}' \rightarrow W^\pm h^0$ (")
3960	$q\bar{q} \rightarrow Z^0 H^0$ (all q flavours)
3970	$q\bar{q} \rightarrow Z^0 h^0$ (")
4000-199	R -parity violating supersymmetric processes
5000	Pointlike photon-hadron jet production (all flavours)
5100+IQ	Pointlike photon heavy flavour pair production (IQ as above)
5200+IQ	Pointlike photon heavy flavour single excitation (IQ as above) After generation, IHPRD is subprocess (see Sect. 4.4.5)
5300	Quark-photon Compton scattering
5500	Pointlike photon production of light (u, d, s) $L=0$ mesons
5510,20	$S=0$ mesons only, $S=1$ mesons only After generation, IHPRD is subprocess (see Sect. 4.4.5)
5900	$\gamma\gamma \rightarrow q\bar{q}$

DIS

IPROC	Process
7000 - 7999	Baryon-number violating and other multi- W^\pm processes generated by HERBVI package
8000	Minimum bias soft hadron-hadron event
9000	Deep inelastic lepton scattering (all neutral current)
9000+IQ	Deep inelastic lepton scattering (NC on flavour IQ)
9010	Deep inelastic lepton scattering (all charged current)
9010+IQ	Deep inelastic lepton scattering (CC on flavour IQ)
9100	Boson-gluon fusion in neutral current DIS (all flavours)
9100+IQ	Boson-gluon fusion in neutral current DIS (IQ as above)
9107	J/ψ + gluon production by boson-gluon fusion
9110	QCD Compton process in neutral current DIS (all flavours)
9110+IP	QCD Compton process in NC DIS (IP=1-12 for $d-t, \bar{d}-\bar{t}$)
9130	All $\mathcal{O}(\alpha_s)$ NC processes (i.e. 9100+9110)
9140+IP	Heavy quark production by charged-current boson-gluon fusion IP: 1 = $s\bar{c}$, 2 = $b\bar{c}$, 3 = $s\bar{t}$, 4 = $b\bar{t}$ (+ ch. conj.)
9500+ID	$W^+W^- \rightarrow H$ in DIS (ID as in IPROC = 300 + ID)
10000+IP	as IPROC = IP but with soft underlying event (soft remnant fragmentation in lepton-hadron) suppressed

MC parameters

Name	Description	Default
QCDLAM	Λ_{QCD} (see below)	0.18
RMASS(1)	Down quark mass	0.32
RMASS(2)	Up quark mass	0.32
RMASS(3)	Strange quark mass	0.50
RMASS(4)	Charmed quark mass	1.55
RMASS(5)	Bottom quark mass	4.95
RMASS(6)	Top quark mass	170.
RMASS(13)	Gluon effective mass	0.75
VQCUT	Quark virtuality cutoff (added to quark masses in parton showers)	0.48
VGCUT	Gluon virtuality cutoff (added to effective mass in parton showers)	0.10
VPCUT	Photon virtuality cutoff	0.40
CLMAX	Maximum cluster mass parameter	3.35
CLPOW	Power in maximum cluster mass	2.00
PSPLT	Split cluster spectrum parameter	1.00
QDIQK	Maximum scale for gluon \rightarrow diquarks	0.00
PDIQK	Gluon \rightarrow diquarks rate parameter	5.00
QSPAC	Cutoff for spacelike evolution	2.50
PTRMS	Intrinsic p_T in incoming hadrons	0.00

Notes on parameters:

- QCDLAM can be identified at high momentum fractions (x or z) with the fundamental 5-flavour QCD scale $\Lambda_{\overline{MS}}^{(5)}$. However, this relation does not necessarily hold in other regions of phase space, since higher order corrections are not treated precisely enough to remove renormalization scheme ambiguities [14].
- RMASS(1, 2, 3, 13) are effective light quark and gluon masses used in the hadronization phase of the program. They can be set to zero provided the parton shower cutoffs VQCUT and VGCUT are large enough to prevent divergences (see below).
- For cluster hadronization, it must be possible to split gluons into $q\bar{q}$, ie. RMASS(13) must be at least twice the lightest quark mass. Similarly it may be impossible for heavy-flavoured clusters to decay if RMASS(4, 5) are too low.
- VQCUT and VGCUT are needed if the quark and gluon effective masses become small. The condition to avoid divergences in parton showers is

$$1/Q_i + 1/Q_j < 1/QCDL3 \quad (5.3)$$

for either i or j or both gluons, where $Q_i = \text{RMASS}(i) + \text{VQCUT}$ for quarks, $\text{RMASS}(13) + \text{VGCUT}$ for gluons, and QCDL3 is the equivalent $\Lambda^{(3)}$ computed from QCDLAM. In the notation of Ref. [14] and Sect. 2, QCDL3 is the 3-flavour equivalent of QCDL5 where

The basis of MC simulations

1) Collinear singularity factorization

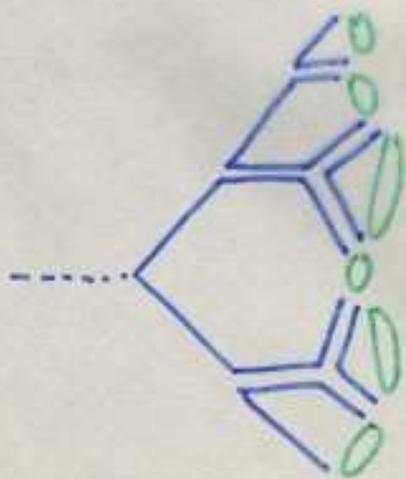
⇒ Universality of hard collisions l^+l^- , lh , hh

Lep, Hera, LHC, Tevatron

2) Coherence of emission

- Colour connection and angular ordering
- gluon multiplication ⇒ Multiplicity
- hump-backed plateau
- Jet algorithms
- Heavy quark emission

3) Colour preconfinement ⇒ LHPD



$$\langle M^2 \rangle \sim Q^2$$

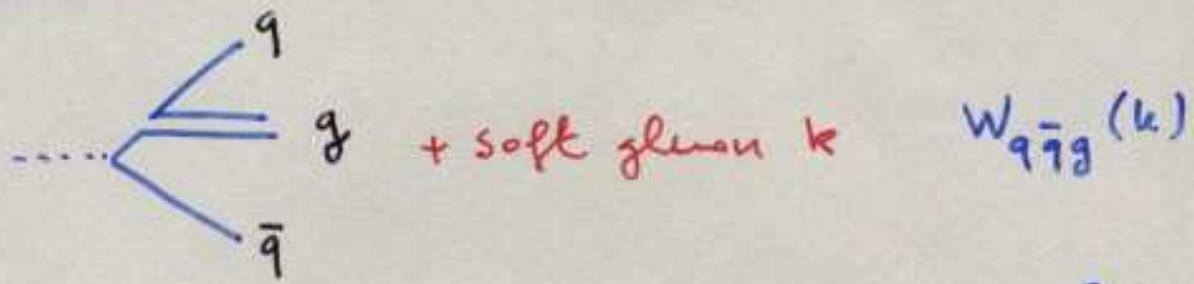
$$\langle M^2 \rangle \sim Q_0^2 \quad \text{IR cutoff}$$

partons \simeq hadrons

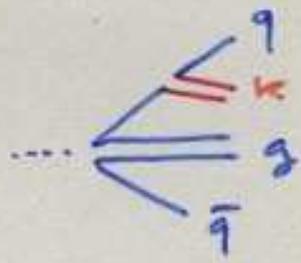
locally in ph. sp.

Colour connection and angular ordering

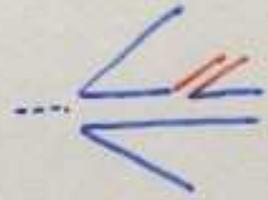
Example 1. Emission in 3-Jet events



$$W_{q\bar{q}g}(k) \approx \frac{2C_F}{1-\cos\theta_{qk}} \theta(\theta_{qg} - \theta_{qk})$$

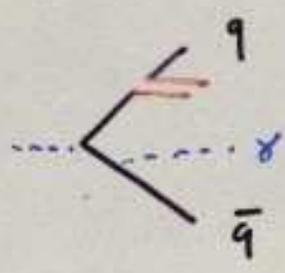


$$+ \frac{C_A}{1-\cos\theta_g} \theta(\theta_{qg} - \theta_g)$$

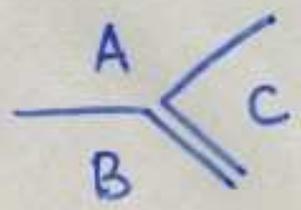


$$+ q \leftrightarrow \bar{q}$$

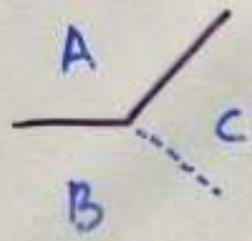
$$W_{q\bar{q}g}(k) \approx \frac{2C_F}{1-\cos\theta_{qk}} \theta(\theta_{q\bar{q}} - \theta_{qk}) + q \leftrightarrow \bar{q}$$



Laboratory frame



$$A \ll B, C$$



$$A \gg B, C$$

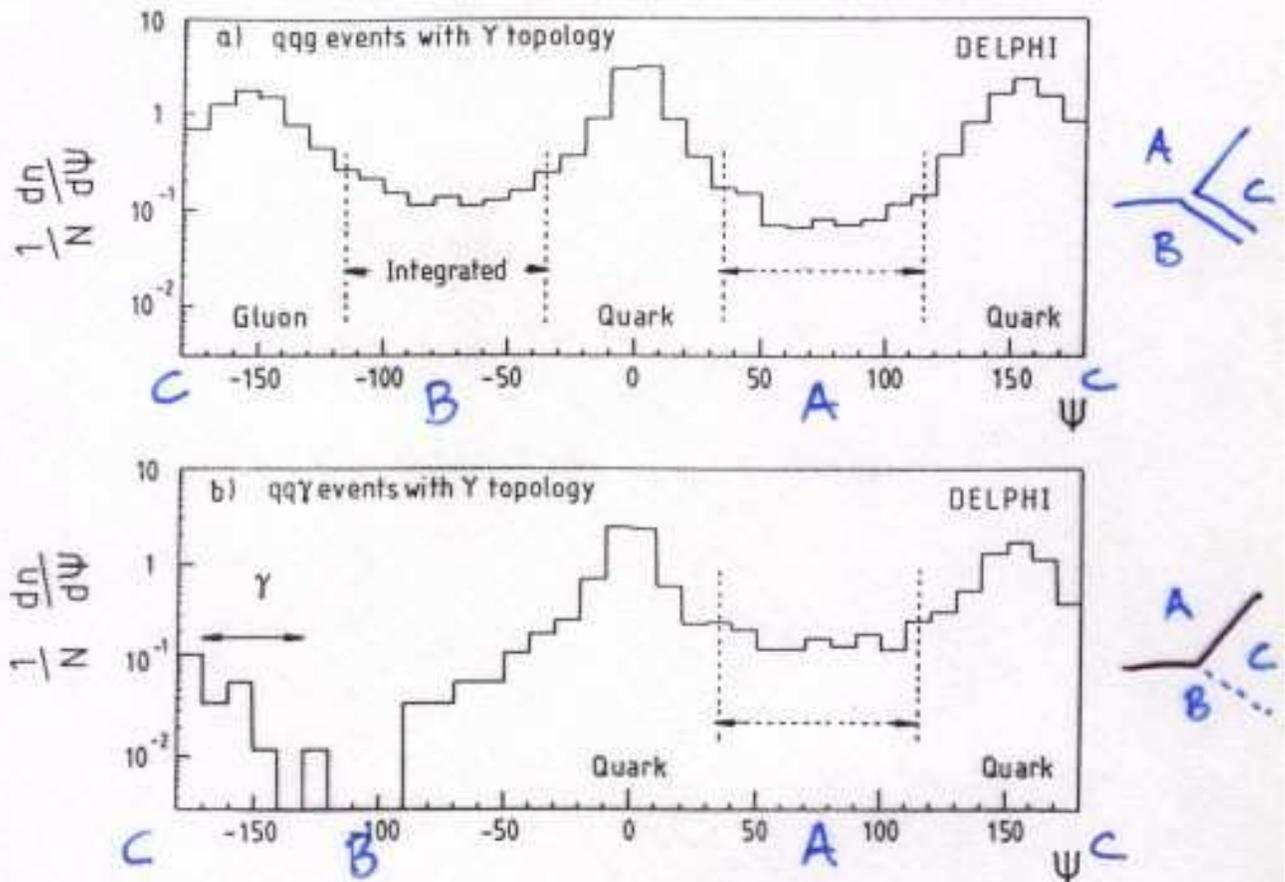


Figure 7.3: Charged particle flow in $q\bar{q}g$ and $q\bar{q}\gamma$ events [144]. The dotted lines indicate the intervals of angular integration $\pm[35^\circ, 115^\circ]$.

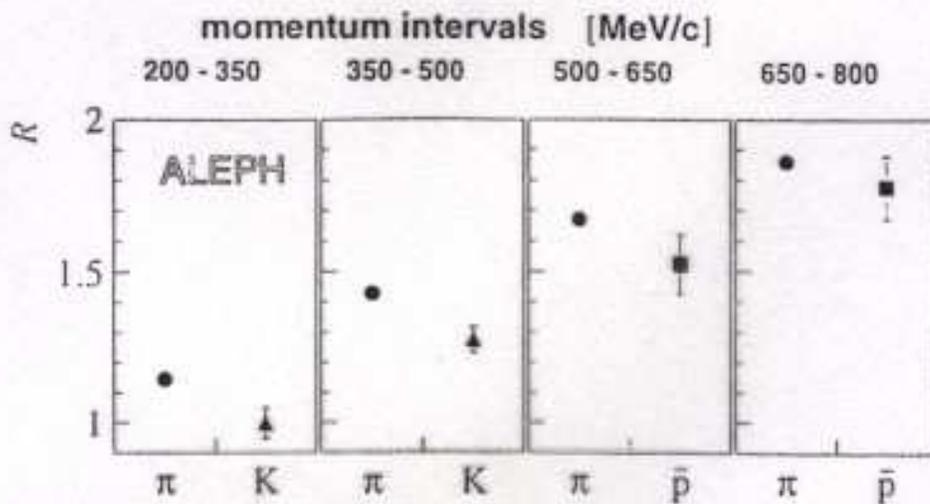


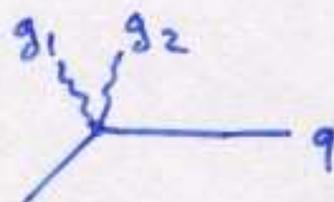
Figure 7.4: The inter-jet particle flow ratio $R(qg/q\bar{q})$ as function of particle type in momentum intervals, as measured by ALEPH Collaboration [254].

Colour connection and angular ordering ^{4.2}

Example 2. EMM correlation

(how to learn from data)

Expected dominant contrib



• Energy weighting select q ($E_q > E_g$)

• Multiplicity " " g ($N_g > N_q$)

$$C(\varphi) = \frac{C_{EMM}(\varphi)}{(C_{EM})^2}$$

leading contrib $C^{(0)}(\varphi) = 1 + \frac{C_A}{2C_F} \cdot \frac{\cos \varphi}{\text{ch}(\eta_1 - \eta_2) - \cos \varphi}$

100% disagreement with data (and MC)

Next to leading contrib. needed

• correction of order $\sqrt{\alpha_s}$

• near singularity



$$\frac{\text{Next-to-leading}}{\text{Leading}} = \sqrt{2C_A \frac{\alpha_s(Q)}{\pi}} \frac{C_F}{C_A} \left(2 - \frac{4}{3} \cos \varphi \right) = O(1)$$

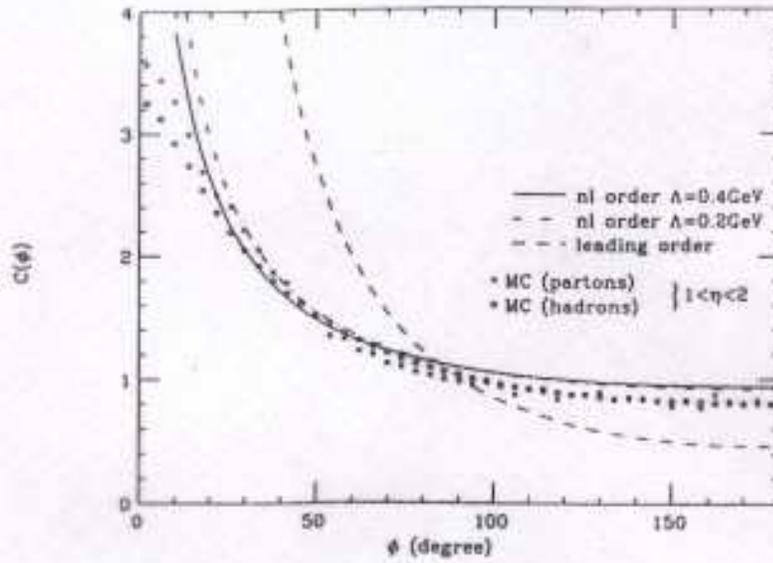


Figure 5.4: Azimuthal correlations $C(\varphi)$ of partons in a jet, at leading order and next-to-leading order for different values of Λ and comparison to the Monte Carlo (HERWIG) [32] result [199].

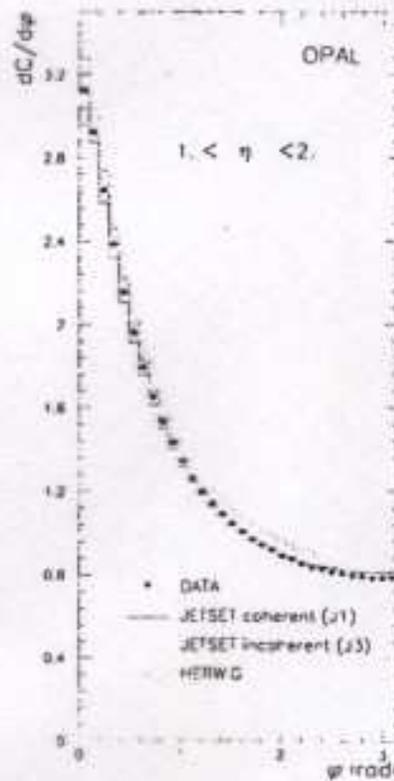


Figure 5.5: Azimuthal correlations of hadrons in a jet as measured by the OPAL Collaboration in comparison with model calculations [200].

Multiplicity

$$\ln N_g(Q) = \frac{1}{\beta_0} \sqrt{\frac{96\pi}{\alpha_s(Q)}} + \left(\frac{1}{4} + \frac{10}{27} n_f \beta_0 \right) \ln \alpha_s(Q) + O(1)$$

$N_g(Q)$ gluon multiplicity $\left(\begin{array}{l} \text{coherent in} \\ \text{essential} \end{array} \right)$

LHPD \Rightarrow $N_{\text{hadrons}}(Q) = C_{\text{hadr.}} N_g(Q)$

Multiplicity in quark
gluon jets $\begin{array}{l} N_{\text{hadr}}^{(q)} \\ N_{\text{hadrons}}^{(g)} \end{array}$

$$N_h^{(q)}(Q) = \frac{C_A}{C_F} N_n^{(q)}(Q)$$

crucial the comparison at the same Q .

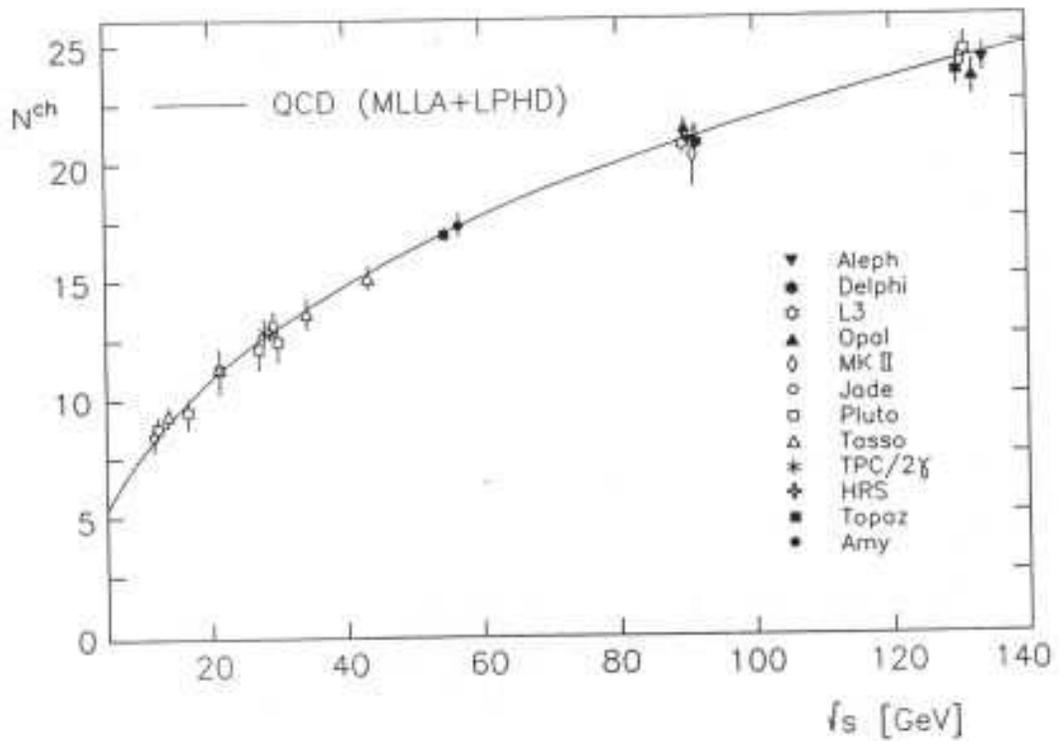


Figure 3.7: Energy dependence of the mean charged particle multiplicity N^{ch} together with the MLLA-LPHD prediction (from Refs. [5,123–126]).

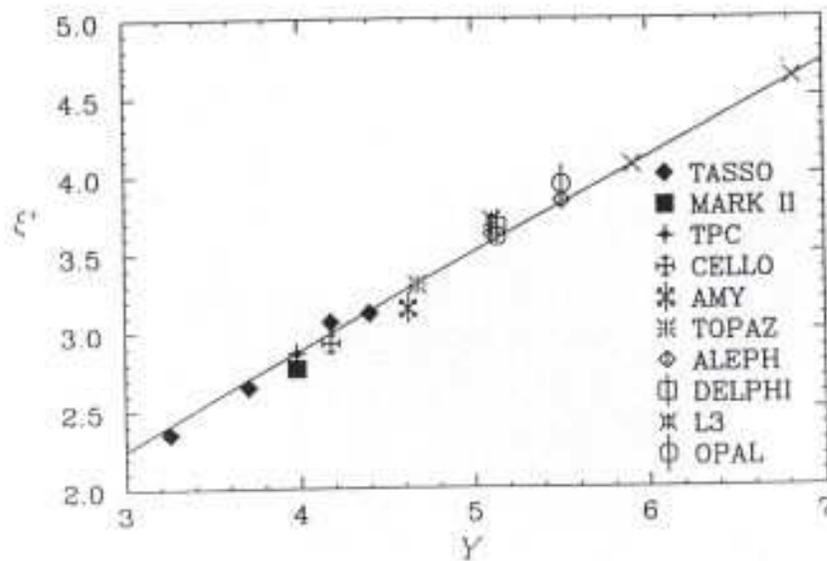


Figure 3.8: Peak position ξ^* of the inclusive ξ -spectra of all charged particles, as a function of $Y = \log(\sqrt{s}/2\Lambda_{QCD})$. Comparison between experimental data collected in [5] and LEP-1.5 data [124–126] and theoretical predictions numerically extracted [76] from the shape of the limiting spectrum (solid line); the crosses correspond to $\sqrt{s} = 200$ GeV and 500 GeV.

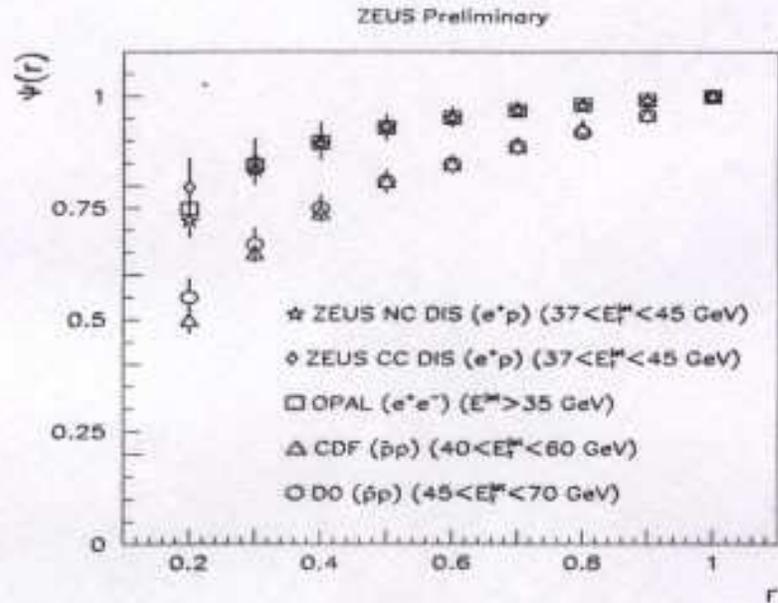


Figure 1. "Energy profile" of HERA quark jets. CDF/D0 (gluon) jets are broader.

Given the perfect identification of jets achieved by e^+e^- experiments, the C_A/C_F ratio was recently extracted from a comparative study of the scaling violation pattern in the fragmentation of quark and gluon jets. It can also be read out directly from the rate of growth of particle multiplicities with jet hardness, as shown in Fig. 2.

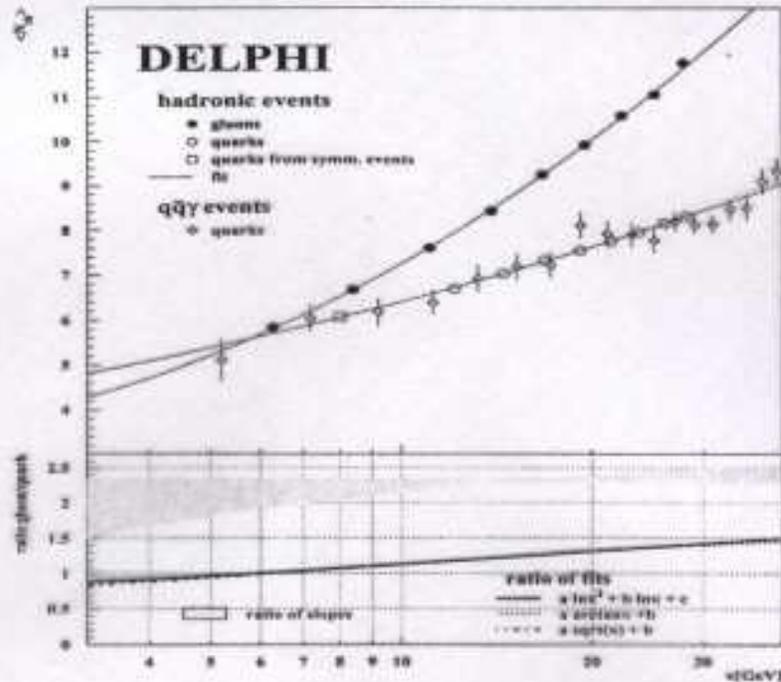


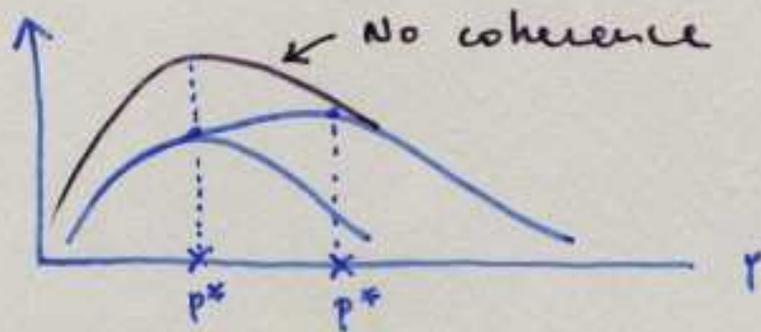
Figure 2. Charged hadron multiplicity from quark and gluon jets.

Hump-backed plateau

4.4

Single parton (hadron) inclusive distrib.

$$D(p) = \frac{p d\sigma}{\sigma dp}$$



No coherence p^* independent of Q

Coherence
$$p_n^* = C_n \sqrt{Q\Lambda} \exp\left\{-\left(11 + \frac{2}{27} n_f\right) \frac{1}{\beta_0} \frac{1}{\sqrt{\alpha_s}}\right\}$$

$$D_n(p) = \frac{N_n(Q)}{\sqrt{2\pi} \sigma(Q)} e^{-\phi(p, Q)}$$

$$Q = 5 \text{ GeV} \quad p_n^* \approx 0.5 \text{ GeV}$$

$$Q = M_{Z_0} \quad p_n^* \approx 1 \text{ GeV}$$

LHPD hadrons \approx partons $\lesssim 1 \text{ GeV}$

$$\frac{d\sigma}{\sigma d\xi_p}$$

$$\xi_p = \ln\left(\frac{Q}{2p}\right)$$

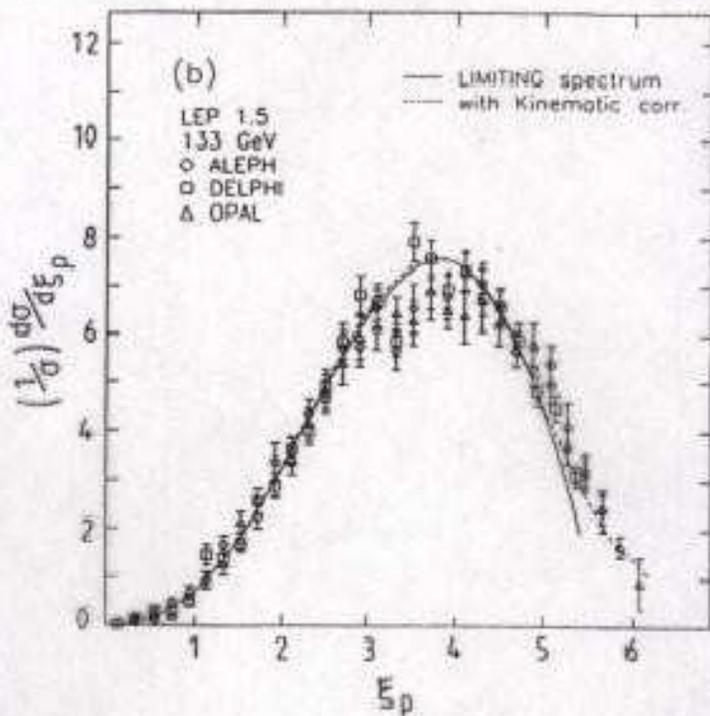
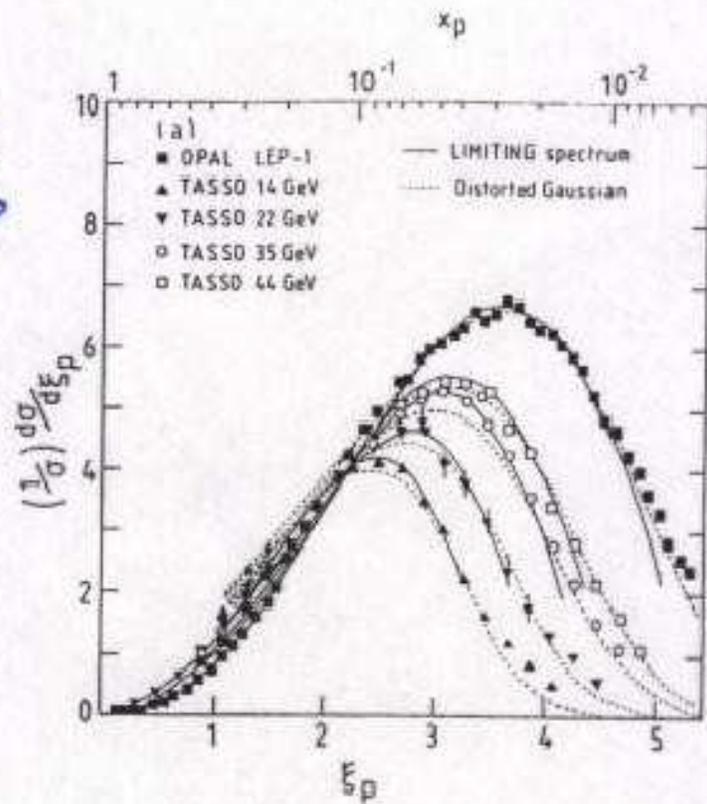


Figure 3.6: (a) Plots of ξ_p distribution of charged particles [108] together with the prediction of (3.29) and (3.23) at $\Lambda_{cA} \simeq 250$ MeV; (b) ξ_p distribution of charged particles at LEP-1.5 measured by the DELPHI [124], ALEPH [125] and OPAL [126] Collaborations in comparison with the prediction of the limiting spectrum (3.29) at $\Lambda_{cA} = 270$ MeV (solid line). The dashed line shows the prediction of the limiting spectrum after the correction for kinematical effects at low momenta, see Ref. [76].

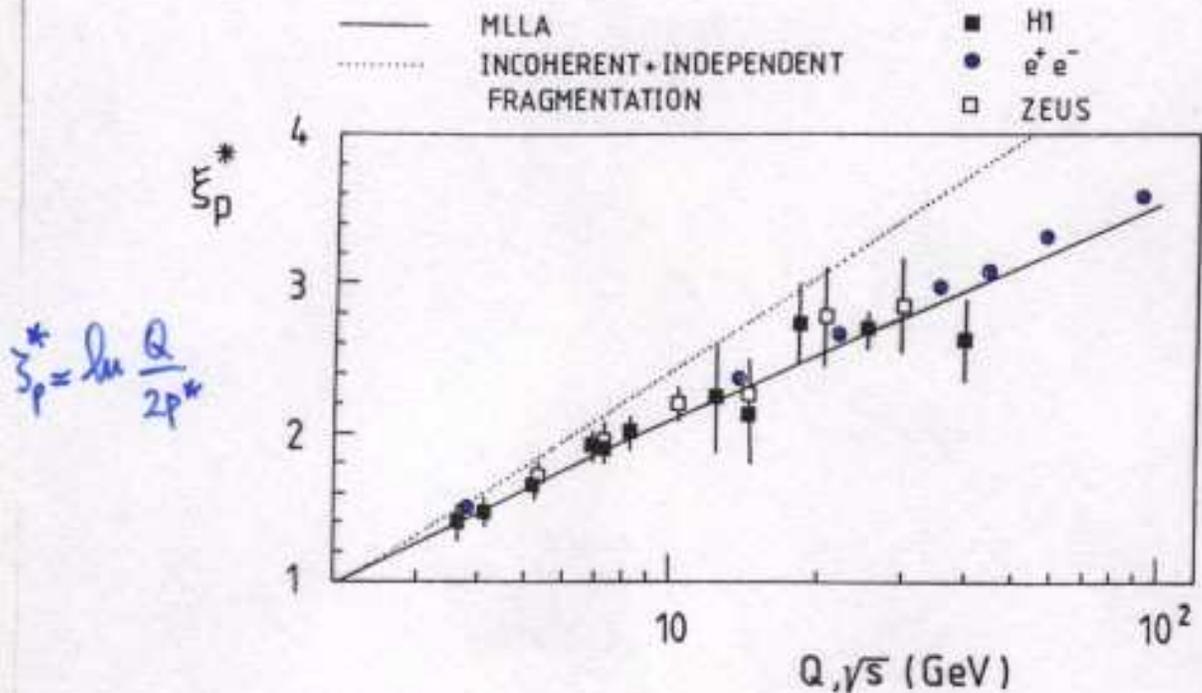


Figure 8.6: Evolution of the peak position compared with e^+e^- data [262]. The solid line is the MLLA-based fit to the H1 data.

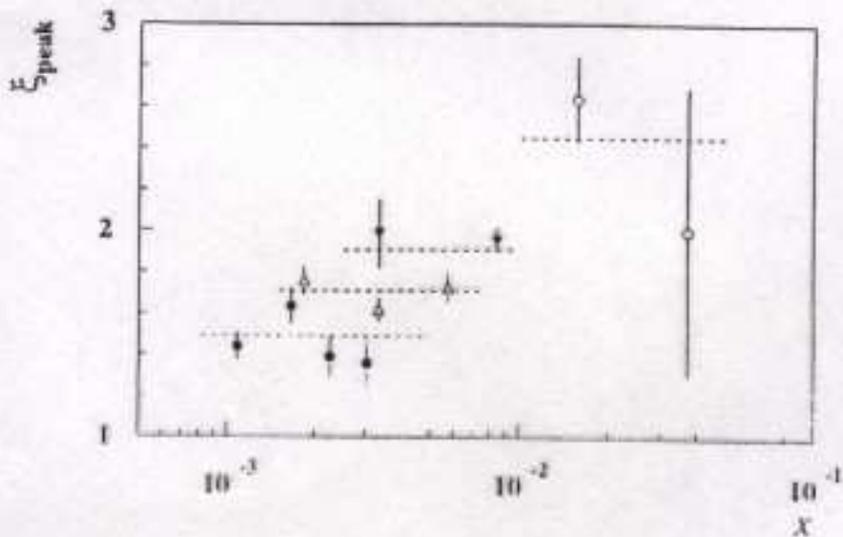


Figure 8.7: Peak position of ξ_p -distribution as a function of Bjorken x showing no significant x -dependence; for intervals $12 < Q^2 < 25 \text{ GeV}^2$ (solid circles), $25 < Q^2 < 45 \text{ GeV}^2$ (open triangles), $45 < Q^2 < 80 \text{ GeV}^2$ (solid triangles), and $200 < Q^2 < 500 \text{ GeV}^2$ (open circles). The dashed lines refer to the $\xi_{p\text{peak}}$ expected from the fit at the relevant mean Q^2 value.

Jet algorithms

Jade algorithm $M_{ij}^2 \approx E_i E_j \theta_{ij}^2$

k_{\perp} - algorithm $M_{ij}^2 \approx (E_m \theta_{ij})^2$

$$E_m = \min(E_i, E_j)$$

Theoretical motivation of k_{\perp} algorithm

$E_m \rightarrow$ IR singul

$\theta_{ij} \rightarrow$ coll singul.

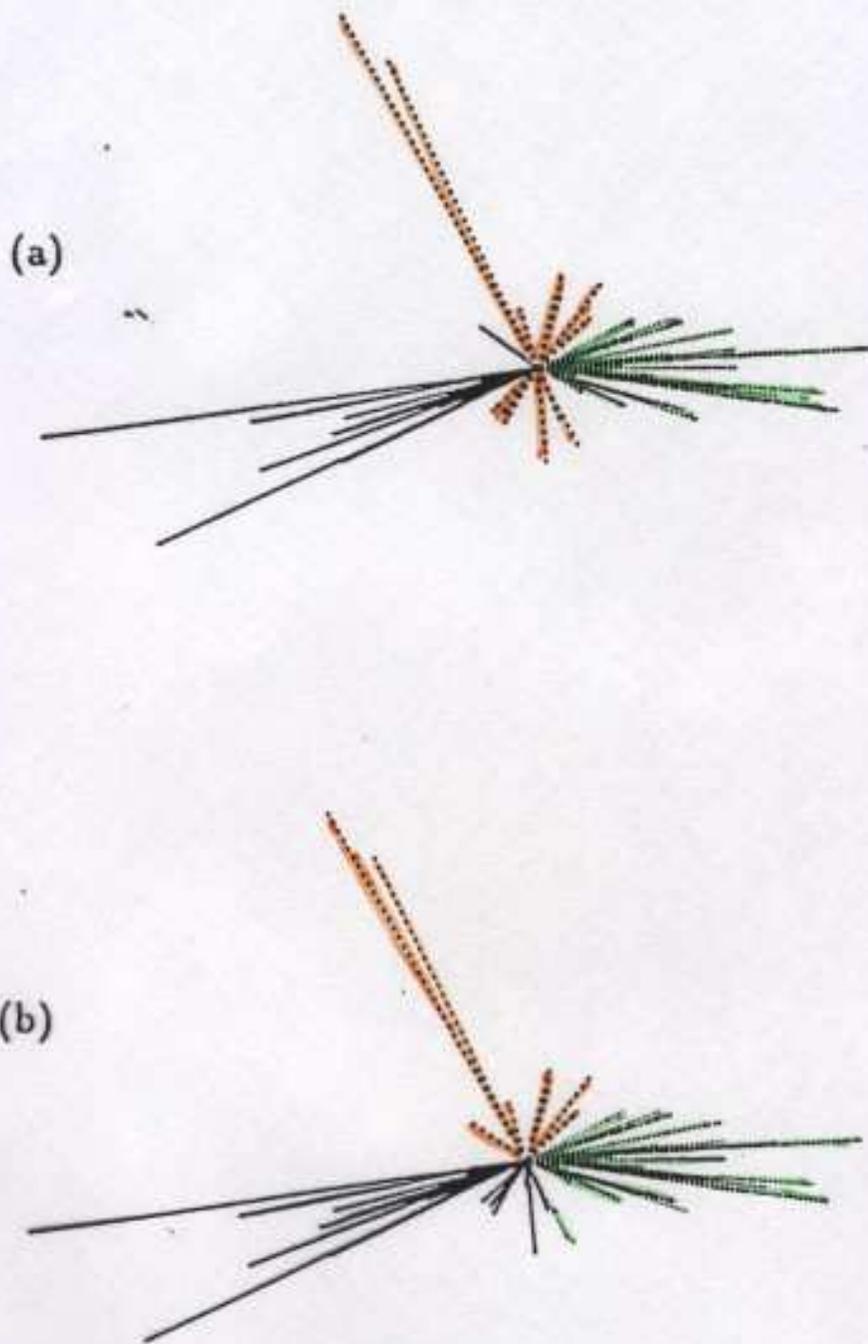


Fig. 6: A 3-jet event as 'seen' by (a) the JADE algorithm and (b) the k_{\perp} -algorithm.

Messages on LQCD and PDB links

- Colour field generated by hard partons
 \approx structure of flow of hadrons

No visible reshuffling LHPD

- Short distance $Q \gg \Lambda$

but sometime $p \lesssim 0.5 \text{ GeV}$

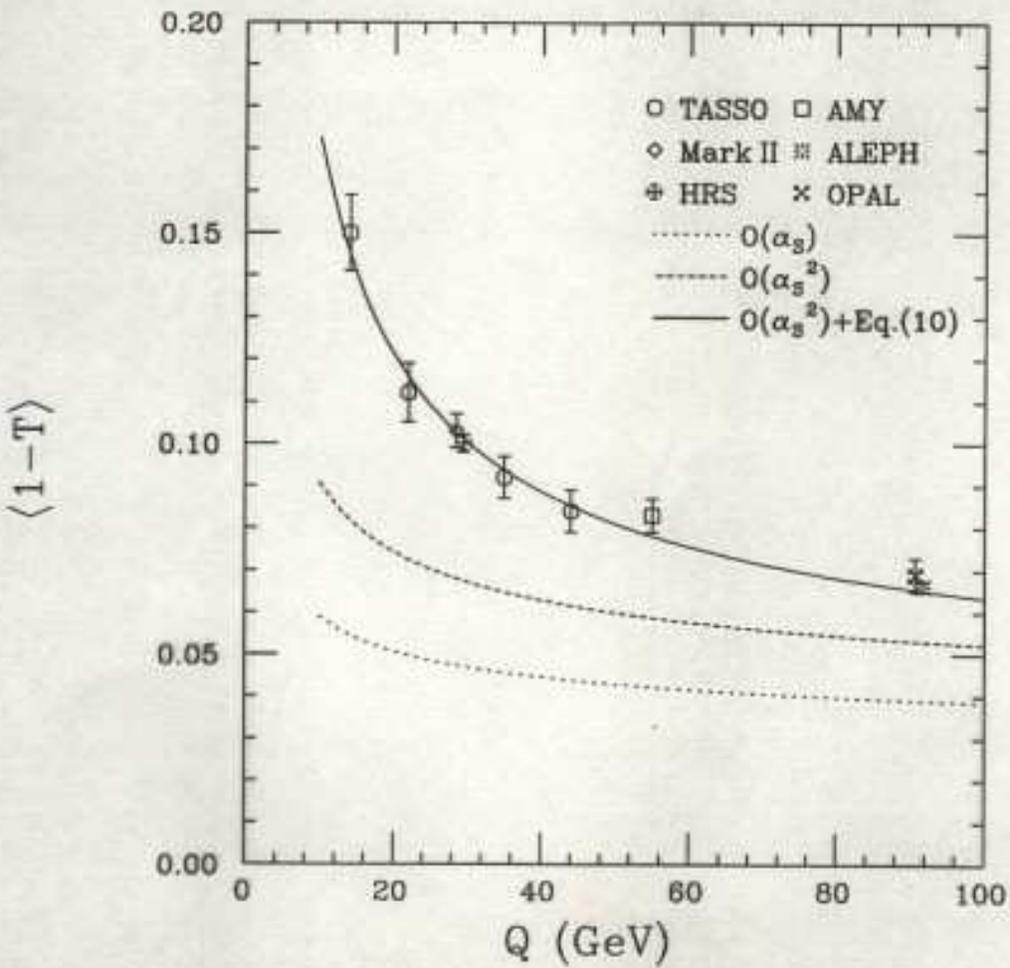
- \Rightarrow large amount of "predictions" (MC)
- but more difficult to explore
 partons \leftrightarrow hadrons

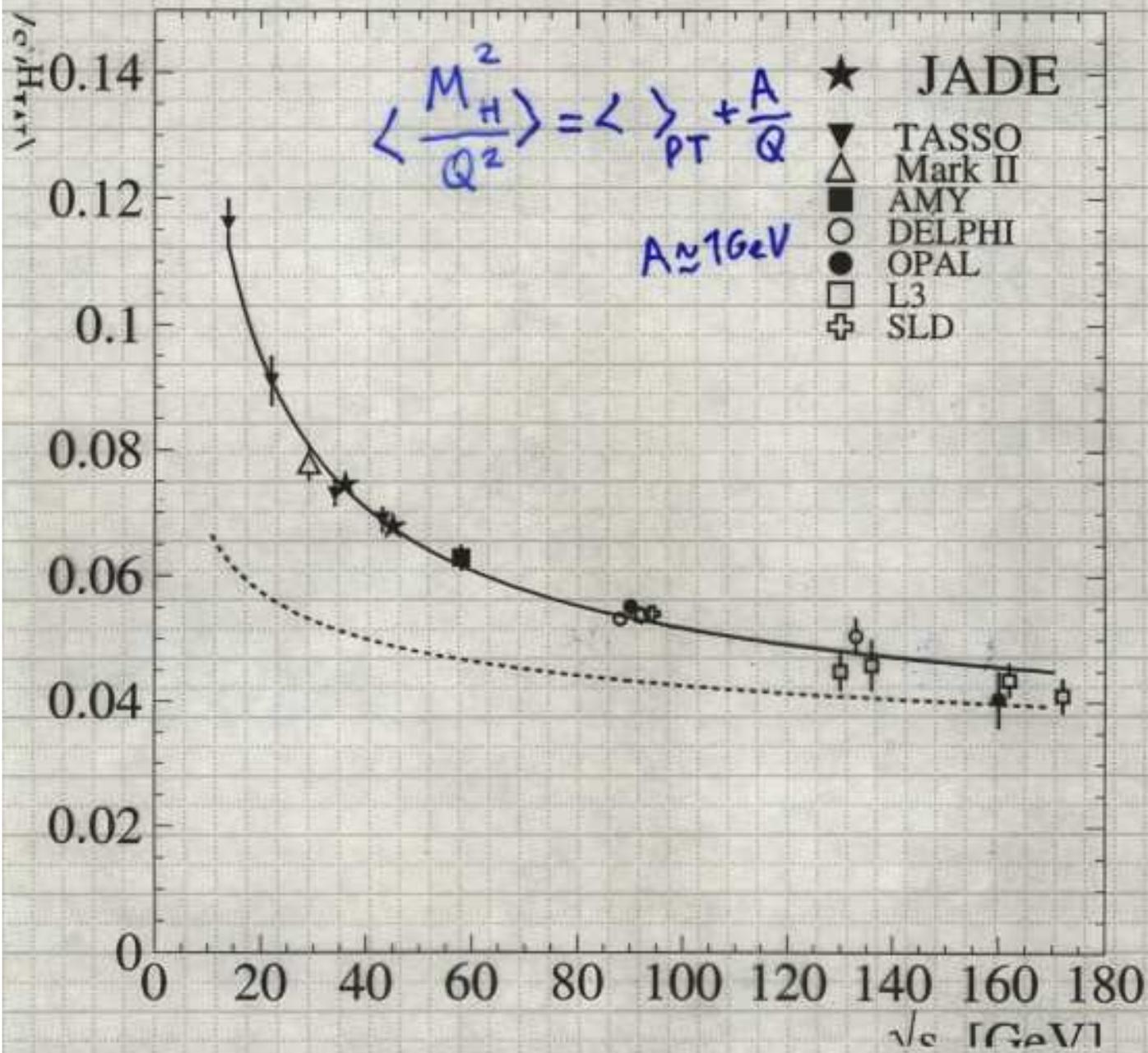
New field to explore partons \leftrightarrow hadrons

Large power corrections to PT results

- Shape variables (in e^+e^-)
- EE correlations "

$$\langle 1-T \rangle = \langle 1-T \rangle_{PT} + \frac{A}{Q} \quad A \approx 1 \text{ GeV}$$





Shope variables and power corrections

Examples

$$\begin{array}{l}
 \text{Thrust: } Q \cdot (1-T) = \sum k_{ti} e^{-|n_i|} \\
 \text{C-par: } Q \cdot C = \sum k_{ti} \frac{3}{\ln \eta_i} \\
 \text{Braatenij } Q \cdot 2B = \sum k_{ti}
 \end{array}
 \left. \vphantom{\begin{array}{l} \text{Thrust:} \\ \text{C-par:} \\ \text{Braatenij} \end{array}} \right\} V$$

$$\frac{V d\sigma}{\sigma dV} = F_V(v) \quad , \quad \bar{V}(Q) = \int dv F_V(v)$$

Collin-IR finite \Rightarrow PT expression depends on $\alpha_s(k_\perp)$ $0 < k_\perp < Q$

eg $t = 1-T$

$$t \frac{d\sigma}{\sigma dt} = C_1(t) \alpha_s(Q) + C_2(t) \alpha_s^2(Q) + \dots$$

$$C_1(t) = \frac{4}{3} \left(\frac{2}{1-t} (2-3t+3t^2) \ln \frac{1-2t}{t} - 3(1+t)(1+3t) \right)$$

$$\bar{t}_{PT}(Q) = C_1 \alpha_s(Q) + C_2 \alpha_s^2(Q) + \dots$$

$$\text{PDB} \Rightarrow \bar{t}(Q) = \bar{t}_{PT}(Q) + \frac{A}{Q} \quad , \quad A \approx 1 \text{ GeV}$$

• high statistics \Rightarrow detectable at lep1 lep2

• understanding of $\frac{A}{Q} \Rightarrow$ more info. on $L_{\text{had}} \leftrightarrow$ PDB

Origin of power corrections to PT distrib

AF: $k^2 \gg \Lambda_{QCD}^2$

$$\alpha_s(k^2) \simeq \frac{48}{\beta_0 \ln \frac{k^2}{\Lambda^2}} = \frac{\alpha_s(Q^2)}{1 - \frac{\beta_0 \alpha_s(Q^2)}{4\pi} \ln \frac{Q^2}{k^2}}$$

$$= \sum_{l=1}^{\infty} \alpha_s^l(Q^2) \left(\frac{\beta_0}{4\pi} \ln \frac{Q^2}{k^2} \right)^{l-1}$$

• Coll-IR "finite" observable in hard reg $Q^2 \gg \Lambda^2$ are functional of $\alpha_s(k_{\perp}^2)$ $0 < k_{\perp} < Q$

$$\bar{V}(Q) = \int_0^{Q^2} \frac{dk_{\perp}^2}{k_{\perp}^2} \alpha_s(k_{\perp}^2) \cdot v\left(\frac{k_{\perp}^2}{Q^2}\right) + \dots$$

$v\left(\frac{k_{\perp}^2}{Q^2}\right) \rightarrow 0$ $k_{\perp} \rightarrow 0$. shape obs. $v\left(\frac{k_{\perp}}{Q}\right) \rightarrow v_0 \cdot \frac{k_{\perp}}{Q}$

$$\bar{V}(Q) = \sum_{l=1}^{\infty} C_l \alpha_s^l(Q) \quad C_l \sim l! \cdot \left(\frac{2\beta_0}{4\pi}\right)^l \cdot v_0$$

\Rightarrow Resummation is mathematically ambiguous

$$\bar{V}(Q) = \bar{V}_{PT}(Q) + \frac{\Lambda}{Q}$$

• Suggestion Assume PT structure even $k_{\perp} \sim \Lambda$

hard gluons $k_{\perp} \gg \Lambda \Rightarrow$ gluon $k_{\perp} = O(\Lambda)$
 $\alpha_s(k_{\perp}) \ll 1 \quad \alpha_s(k_{\perp}) = O(1)$

Confinement and power effects

in Infrared-and-Collinear-Safe observables
(Pushing fwd Serman-Weinberg wisdom)

V Zakharov, B Webber, G Serman, E Stein, G Smye, M Seymour, A Schäfer, G Salam, P Nason, C Maxwell, G Marchesini, M Maul, L Mankiewicz, L Magnea, D Kosower, G Korchemsky, F Hautmann, G Grunberg, N Glover, W Giele, YuL D, M Dasgupta, V Braun, M Beneke, P Ball, R Akhoury

+ those concerned with Heavy Quark decays, (quasi)elastic scattering processes, hadron wave-functions, inter-quark potential, etc.

First steps are being made towards a joined technology for triggering and quantifying genuine *Non-Perturbative* effects in Euclid-translatable cross sections (vacuum condensates) and Minkowskian characteristics of hadronic final states.

Some recent theoretical references:

M Beneke, VM Braun, L Magnea, hep-ph/9701309; YuL Dokshitzer, BR Webber, hep-ph/9704298; BR Webber, hep-ph/9712236, 9805484; YuL Dokshitzer, A Lucenti, G Marchesini, GP Salam, hep-ph/9802381, 9812487; VI Zakharov, hep-ph/9802416, 9811294, 9812374; E Stein, M Maul, L Mankiewicz, A Schäfer, hep-ph/9803342; M Dasgupta, GE Smye, BR Webber, hep-ph/9803382; G Serman, hep-ph/9806533; GP Korchemsky, hep-ph/9806537; M Beneke, hep-ph/9807443; G Grunberg, hep-ph/9807494; GE Smye, hep-ph/9810292, 9812251

Extend "PT analysis" at $k_t = 0(k_{\perp})$

8

• Definition of running coupling (Differential method)

• gluon = gluon at $k_{\perp} = 0(\Lambda)$

- not a parton: does not branch

- interact strongly $\alpha_s(k_{\perp}) = 0(1)$

- $t_{form} \approx \frac{\omega}{k_{\perp}^2} \approx \omega R_n^2 = t_{life}$

• use PT techniques to compute gluon contrib

• Introduce NP parameter

$\left[\frac{d\omega}{\omega} \alpha_s(k_{\perp}) \right]$ scheme

$$\alpha_0 \equiv \int_0^{\mu_I} \frac{dk_{\perp}}{\mu_I} \alpha_s(\mu_I) = \alpha_0(\mu_I)$$

• Ren. group \Rightarrow result independent of μ_I

• Results depend on

$$\alpha_s(M_Z^2) \quad \alpha_0(\mu_I) \quad \text{eg. } \mu_I = 2\text{GeV}$$

only i.e. universal predictions

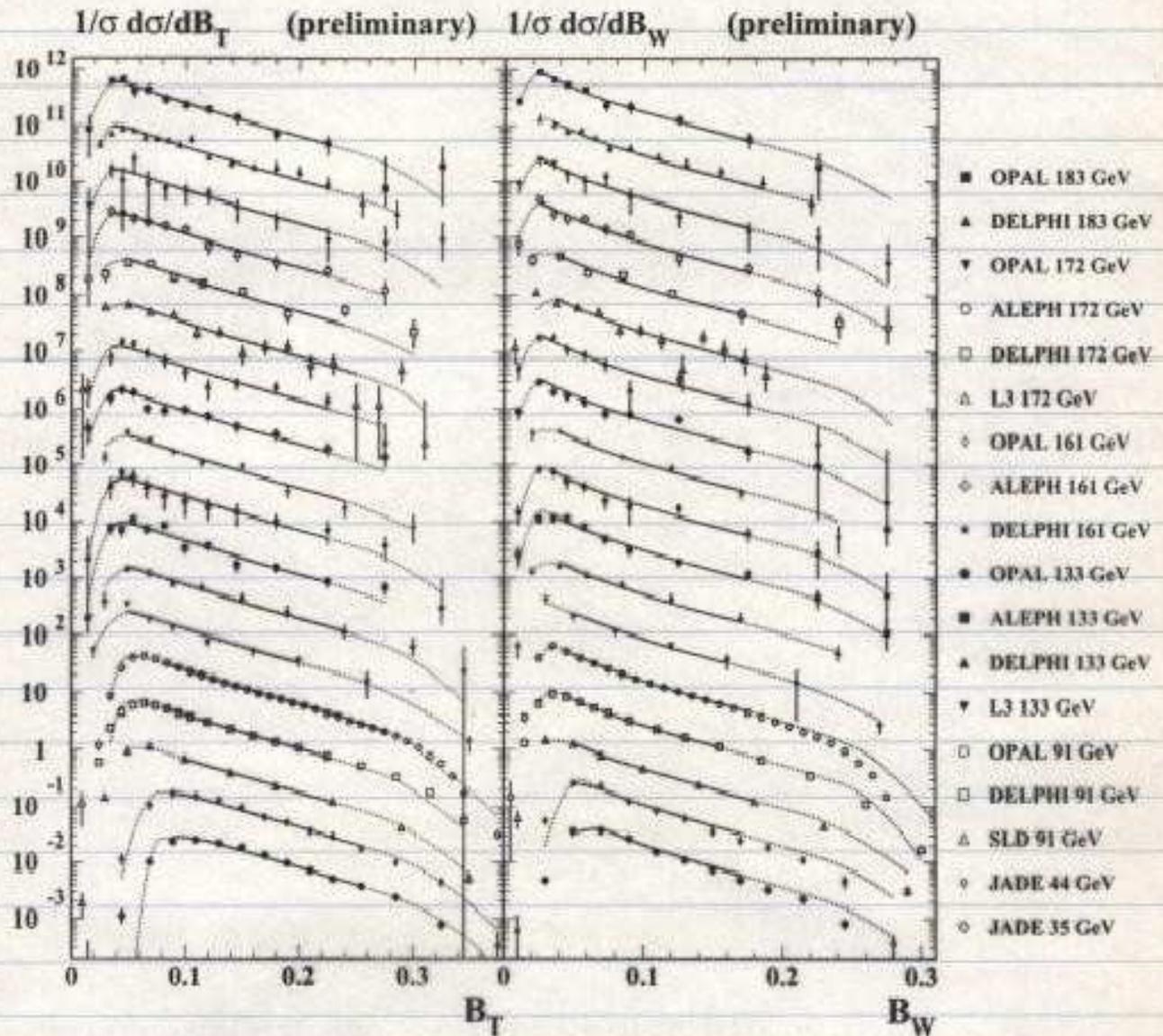


Figure 3: Scaled distributions for B_T (left) and B_W (right) measured by several experiments at $\sqrt{s} = 35$ to 183 GeV. The error bars indicate the statistical experimental errors of the data points. The curves are the result of the simultaneous global (α_s, α_0) -fit using resummed QCD predictions with the modified $\ln(R)$ -matching plus power corrections which include the revised power corrections to jet broadening observables [8]. The fit ranges which are indicated by the solid lines are chosen individually for each center-of-mass energy.

Figures

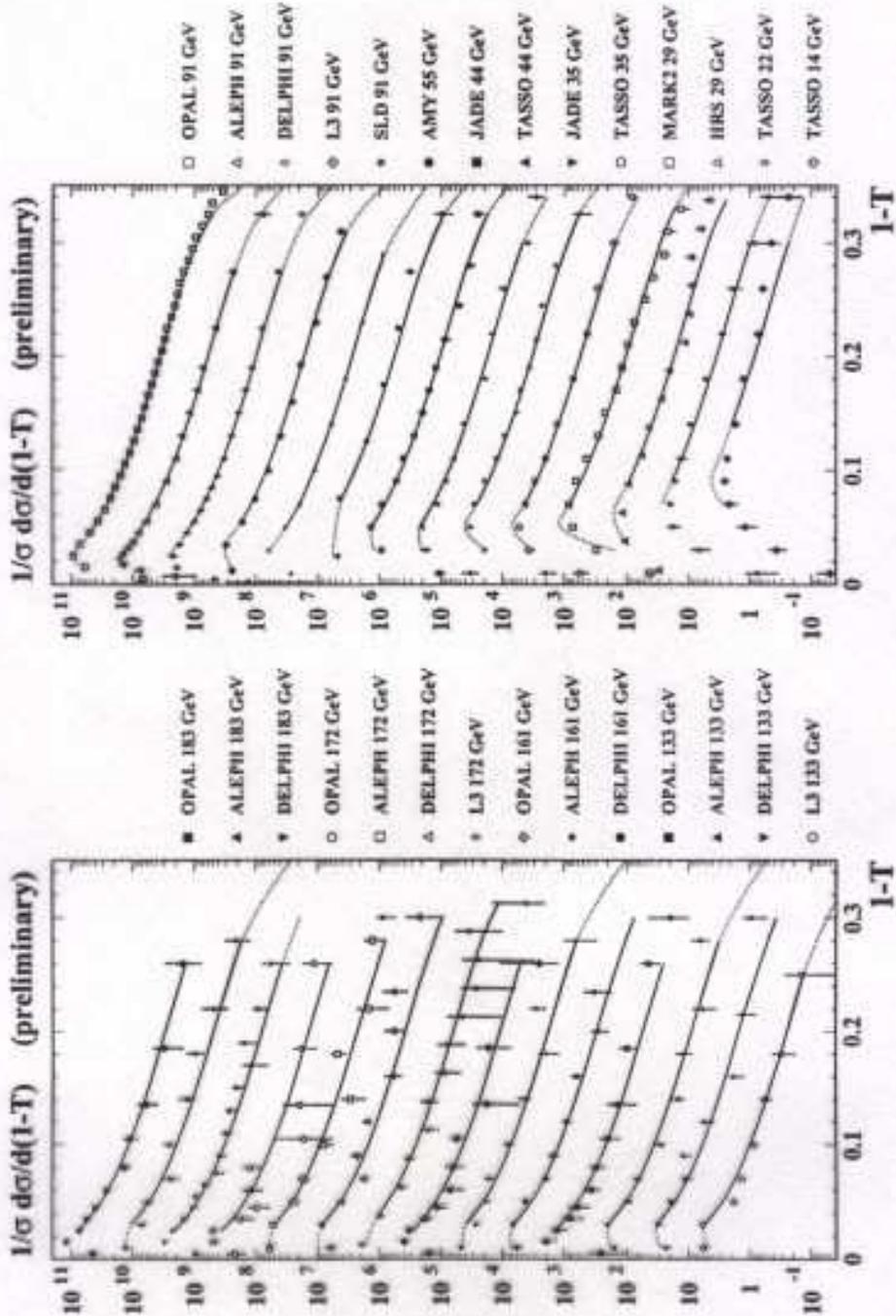
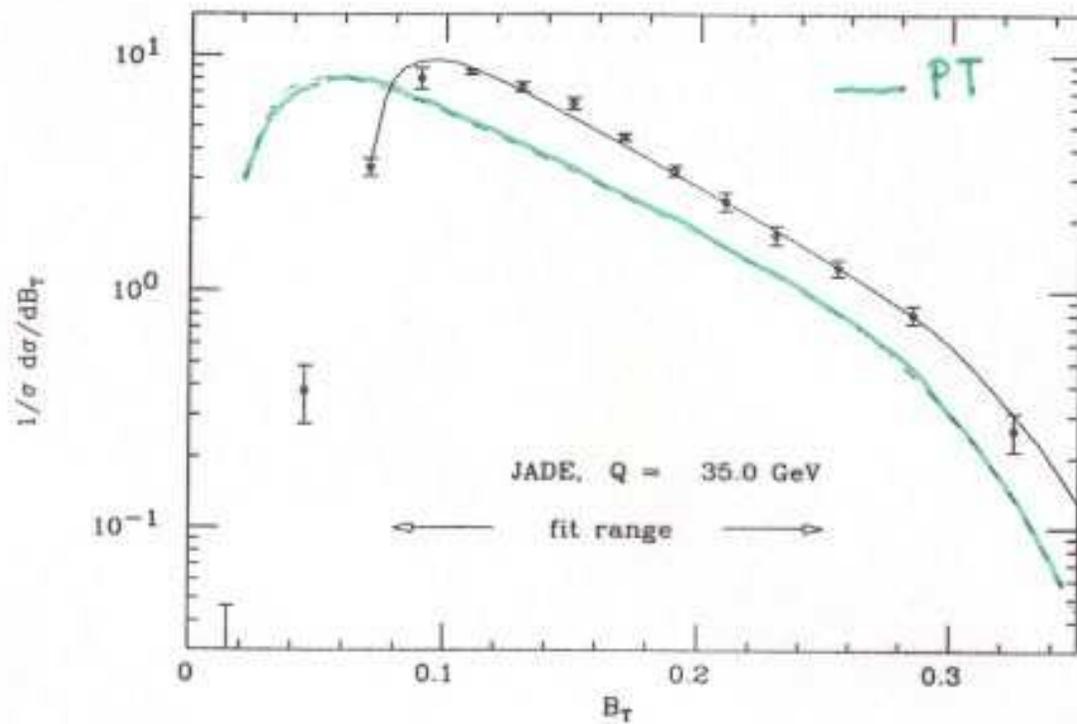


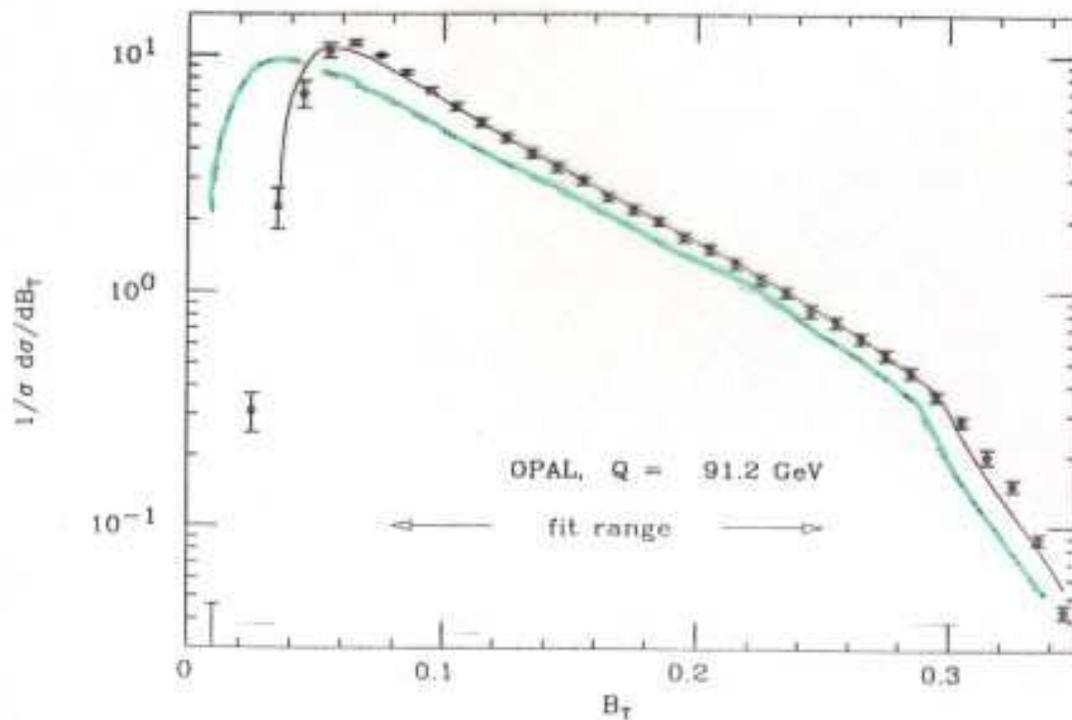
Figure 1: Scaled distributions for $1 - T$ measured by several experiments at $\sqrt{s} = 14$ to 183 GeV. The error bars indicate the statistical and experimental errors of the data points. The curves are the result of the simultaneous global (α_s, α_0) -fit using resummed QCD predictions with the modified $\ln(R)$ -matching plus power corrections. The fit ranges which are indicated by the solid lines are chosen individually for each center-of-mass energy.

$$\frac{1}{\sigma} \frac{d\sigma}{dB} \approx f_B^{\text{pt}} \left(B - \frac{D_B}{Q} \ln \frac{B_0}{B} \right) \quad \text{Shift} \checkmark \text{ and Squeeze} \checkmark$$

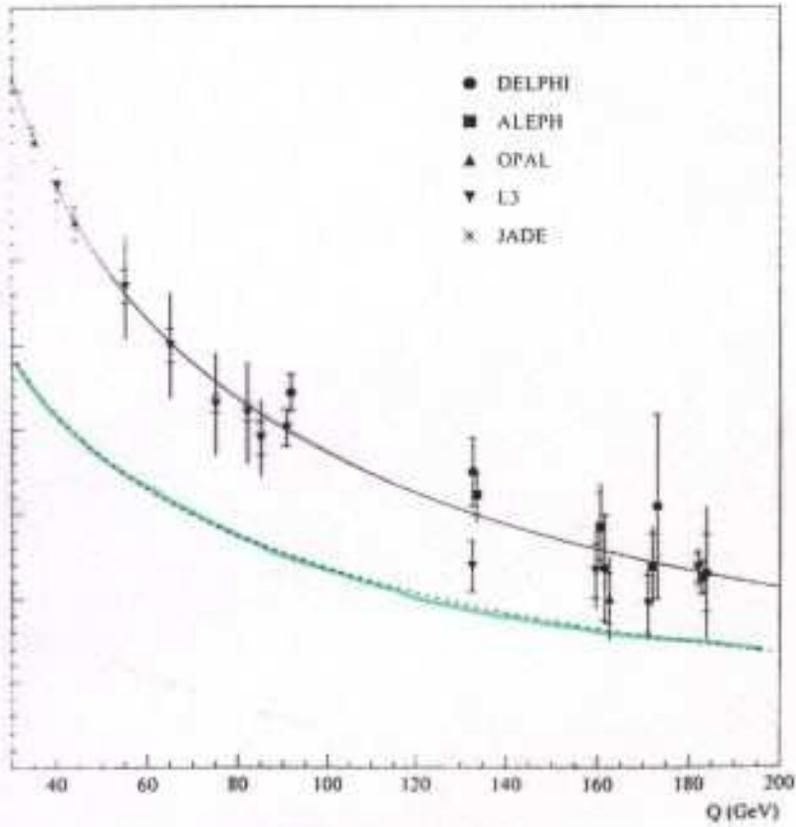
(with $D_B \simeq 0.5 \text{ GeV}$)



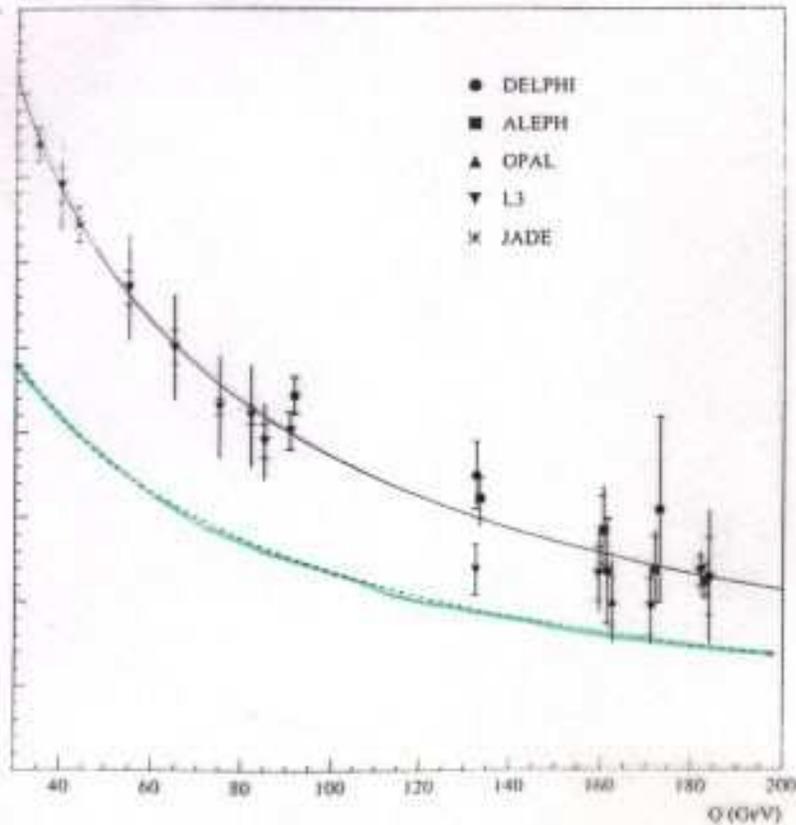
YuL D.
G Marchesini
& GP Salam,
hep-ph/
/9812487



Y. Dokshitzer G. Selzer GM
hep-ph/9812847



$\langle B_W \rangle$



$\langle B_T \rangle$

Parton-gluon calculation

$$F(V) = \frac{d\sigma}{\sigma dV}, \quad V = \sum_i v(k_i)$$

(e.g. thrust
 $1-T = \sum k_{i\perp} e^{-|k_{i\perp}|}$)

$$F(V) = \sum_n \int \frac{d\sigma_n}{\sigma} \delta(V - \sum_i v(k_i))$$

at parton level

$$= \int \frac{d\lambda}{2\pi i} e^{\lambda V} \underbrace{\sum_n \int \frac{d\sigma_n}{\sigma} \prod_i e^{-\lambda v(k_i)}}_{e^{-R(\lambda, Q)}}$$

Radiator

$$R(\lambda, Q) = R_{PT}(\lambda, Q) + \lambda \cdot \delta V$$

$$\delta V = a_V \cdot \frac{\mu_I}{Q} \alpha_0(\mu_I)$$

universal

↑
observable dept.

$$\frac{d\sigma}{\sigma dV} = F(V) = F_{PT}(V + \delta V)$$

$$\bar{V}(Q) = \int \frac{V d\sigma}{\sigma dV} = \bar{V}_{PT}(Q) + \langle \delta V \rangle$$

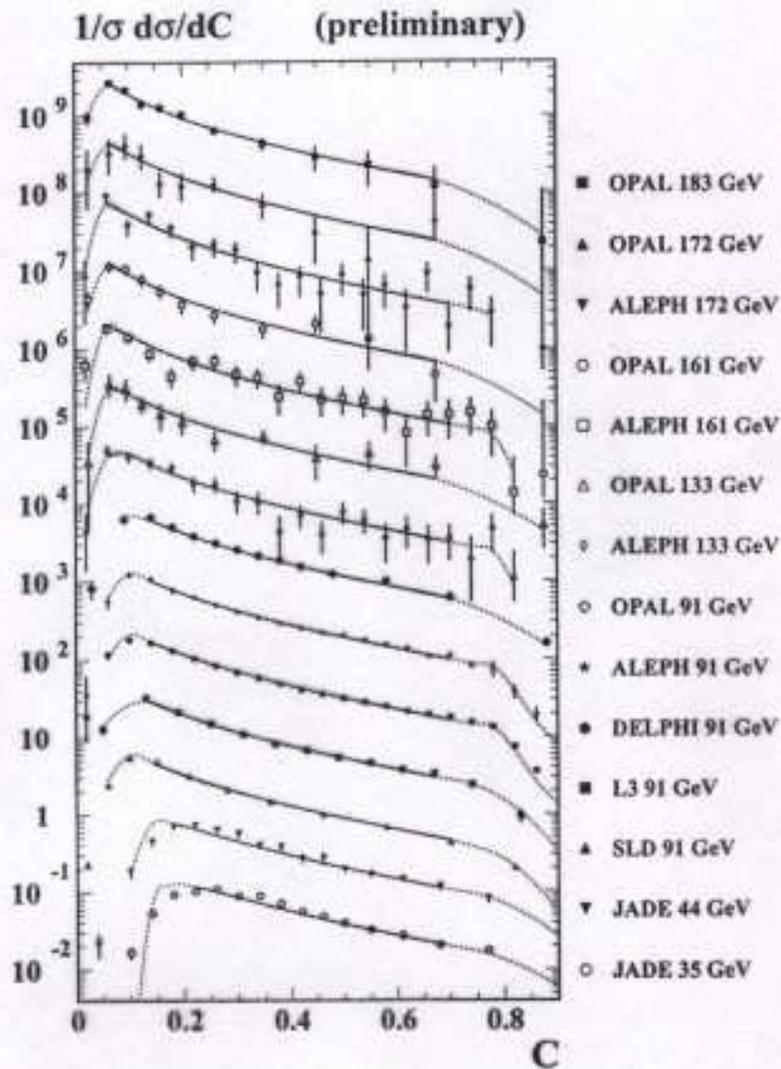


Figure 2: Scaled distributions for the C -parameter measured by several experiments at $\sqrt{s} = 35$ to 183 GeV. The error bars indicate the statistical and experimental errors of the data points. The curves are the result of the simultaneous global (α_s, α_0) -fit using resummed QCD predictions with the modified $\ln(R)$ -matching plus power corrections. The fit ranges which are indicated by the solid lines are chosen individually for each center-of-mass energy.

Movilla Fernández, D. Biebel, S. Bethke
 hep-ex/990633

✌ Infra-Red-finite effective QCD coupling?

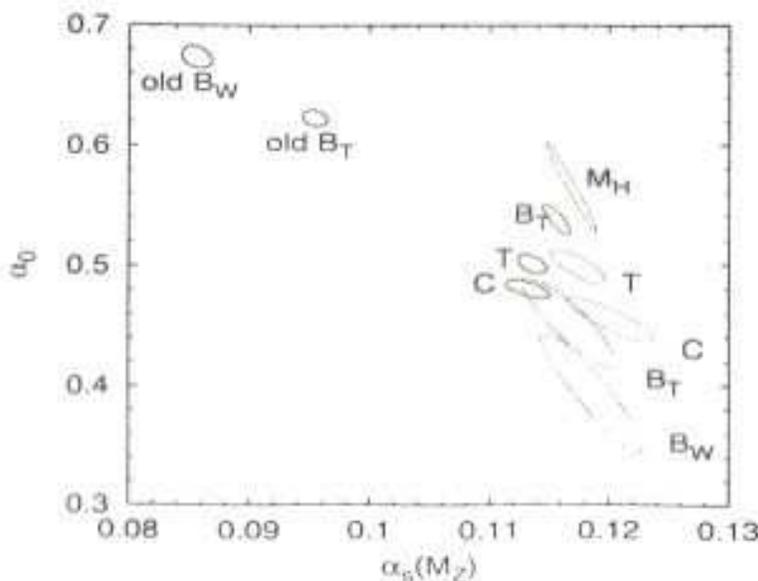
The coefficients a_F for the $1/Q$ corrections to event shapes have been computed to two-loop order:

F	$1-T$	C	M_T^2/Q^2	M_H^2/Q^2	B_T	B_W
a_F	$\frac{16}{3\pi}\mathcal{M}$	$8\mathcal{M}$	$\frac{16}{3\pi}\mathcal{M}$	$\frac{8}{3\pi}\mathcal{M}$	$\frac{8}{3\pi}\mathcal{M}$	$\frac{4}{3\pi}\mathcal{M}$
a_F	3.1	14.4	3.1	1.5	1.5	0.8

where $\mathcal{M} \simeq 1.8$ is the two-loop correction ("Milan") factor. Using these one can make fits to $\alpha_{\overline{MS}}$ and α_0 :

Variable	$\alpha_{\overline{MS}}$	α_0	$\chi^2/\text{d.o.f.}$
$1-T$	0.1177 ± 0.0013	0.498 ± 0.009	57.0/38
C	0.1206 ± 0.0021	0.453 ± 0.011	10.7/8
M_H^2/Q^2	0.1171 ± 0.0012	0.560 ± 0.022	15.2/25
B_T	0.1170 ± 0.0023	0.451 ± 0.023	14.9/21
B_W	0.1189 ± 0.0025	0.391 ± 0.031	12.8/20

Yu.L. D. G. Marchesini & G.P. Salam, hep-ph/9812487



To be compared with an ancient estimate from the analysis of mean heavy quark energy losses in e^+e^- annihilation,

$$\alpha_0 \equiv \frac{1}{2\text{GeV}} \int_0^{2\text{GeV}} dk \alpha_s(k^2) = 0.44 \pm 0.03 \pm 0.05$$

Yu.L. D. G. Marchesini & S. Trnani, 1999

Energy-Energy correlation



$$\chi = \pi - \theta_{12} \ll 1$$

The first NLO calculation

Coll-IR finite

- 79 Dehshetev Deakonov Tregua
- 79 Parisi Petrousis
- 83 Kolesova Trentadue
- 81 Collins Soper
- 81 Robert Willet

• Large power corrections (not rational)

$$\Sigma(\chi) = \int_0^{b_0} b db J_0(bQ\chi) e^{-R(bQ)} (1 - \lambda b\alpha_0)$$

$$R(bQ) = R_{PT}(bQ) + b^2 \cdot Q^2 \alpha_s(\mu_I)$$

Gaussian smearing

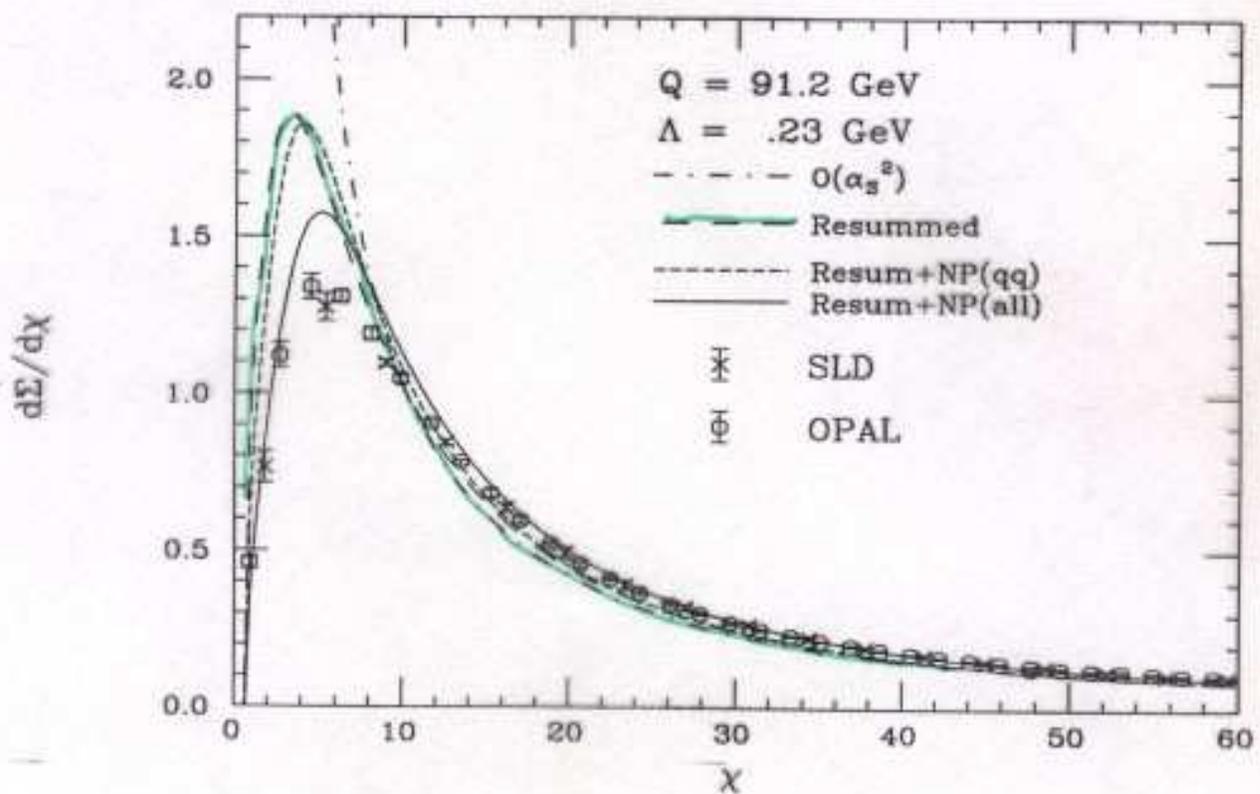
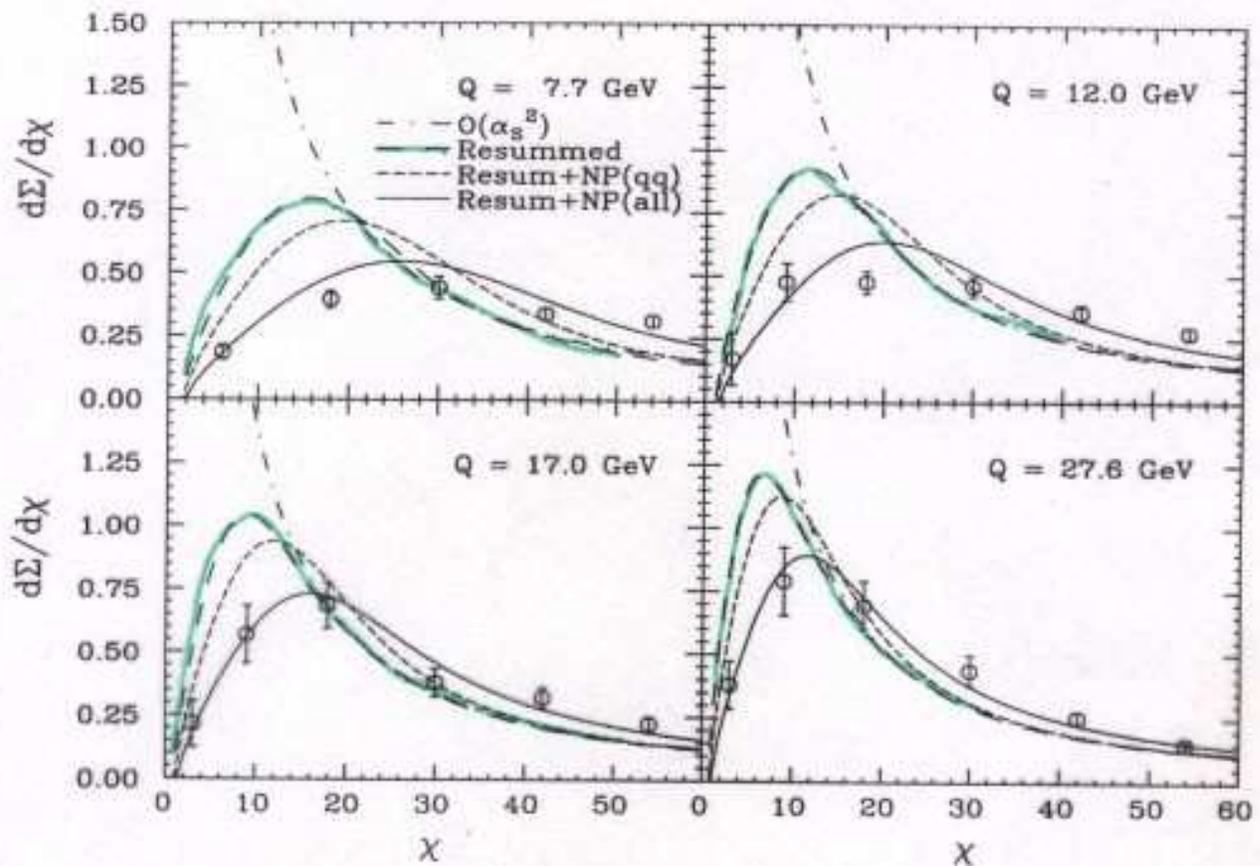
↑
q-gluon
correlation

$$\langle b \rangle_{PT} \sim \frac{1}{Q} \left(\frac{Q}{\Lambda} \right)^{1-\gamma}$$

$$\gamma \approx 0.3595$$

With Default Parameters

Dokshitzer Webber GM
JHEP 07 (99) 012



Conclusions

$$\mathcal{L}_{QCD} \leftrightarrow \text{PDB}$$

- Assume partons \simeq hadrons
- Possible PT calculations
 - very flexible \Rightarrow universal MC simulations
 - predictions works (almost too) well
- Hadronization effects very friendly
 - almost "invisible" e.g. $N_n(Q) = C_n \cdot N_g(Q)$
 - univ. power corrections $\alpha_s(k_t) \quad k_{\perp} = O(\Lambda)$

Questions

- 1) on the main assumption, a theory?
- 2) QCD infra-jets beyond MC simulations

QCD in danger

Movilla Fernández and Sigi Bethke 1998 on

analysis of α -dependence

Petra-Lep

Difficulties in retrieving Desy data

" the retrieval of data eleven years after shutdown curbersome and incomplete "

" missing data sets... "

" missing informations about luminosity... "

• Non compatible media.....

• Missing informations on storage organization.....

Lep in 5-10 years?

New avenue in QCD studies: Inter-jets

Near-to-planar 3-jet events

Andrea Banfi
talk

Out of plane $T \approx 0.5 - 0.8$

- Most of our knowledge (except string effect) in 2-jet events $1 - T \ll 1$
- Inter-jet radiation, no branching in-jet
- New technology for inter-jet studies beyond branching