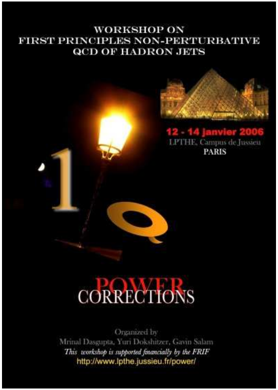

WORKSHOP ON
FIRST PRINCIPLES NON-PERTURBATIVE
QCD OF HADRON JETS

12 - 14 janvier 2006
LPTHE, Campus de Jussieu
PARIS

POWER
CORRECTIONS

Organized by
Mrinal Dasgupta, Yuri Dokshitzer, Gavin Salam
This workshop is supported financially by the FRIF
http://www.lpthe.jussieu.fr/power/

Overview of the FRIF workshop on first principles non-perturbative QCD of hadron jets

(`http://www.lpthe.jussieu.fr/power`)

Gavin P. Salam

LPTHE, Universities of Paris VI and VII and CNRS

LPT, Orsay
26 January 2006

Workshop brief

Analytical approaches to hadronisation have been extensively tested in the context of jet-physics, where *non-perturbative effects can be as large as the NLO perturbative corrections.* There exists a vast body of data from the LEP and HERA colliders and a variety of theoretical approaches, many yet to be fully explored.

The current situation is somewhat ambiguous: different analyses lead to different conclusions; in some cases the theory is probably incomplete; in others there may still be deficiencies in the experimental analyses.

This situation needs to be resolved rapidly, while the LEP and HERA experimenters still remain active in the subject. And it's about time to start addressing *similar issues at hadron colliders.*

The aim of this small workshop – about 30 experimenters and theorists – is to *help put together an overall picture of the situation* and to establish where further work could usefully be carried out, both experimentally and theoretically.

Review of current status	
George Sterman	Review of theoretical status
Stefan Kluth	Review of status in e+e-
Thomas Kluge	Review of status in DIS
Getting the most out of 2-jets	
Chris Maxwell	Effective charges in theory
Klaus Hamacher	Effective charges in practice
Christopher Lee	N-P effects from soft-collinear effective theory
Thomas Gehrmann	Status of NNLO jet calculations
Lorenzo Magnea	Angularities
Beyond 2 jets	
Andrea Banfi	Why multi-jet studies?
Hasko Stenzel	e+e- multi-jet studies
Justin Frantz	Hard scattering results from RHIC
Giulia Zanderighi	Hadron-hadron event shapes
Lester Pinera	Progress on measuring hadron-hadron event shapes
Joey Huston	Underlying events in hadron-hadron collisions
Extending the field	
Georges Grunberg	Beyond leading powers
Mrinal Dasgupta	Anomalous dimensions in powers
Einan Gardi	Power corrections in B decays
Nikolai Uraltsev	Nonperturbative radiation in jets and the OPE
Matteo Cacciari	Power-suppressed effects in fragmentation functions
Conclusions	
Alfred Mueller	Concluding talk

+ numerous other active participants!

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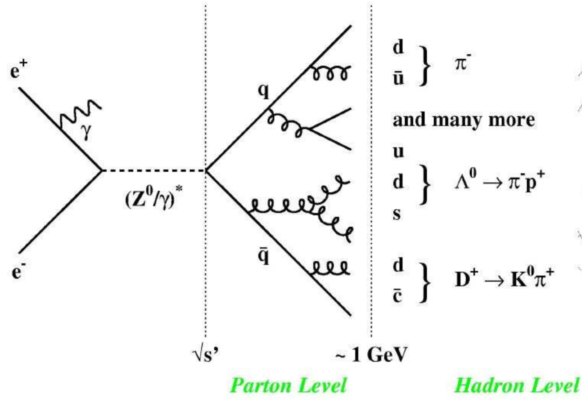
1 QCD Event



Electro-weak Production **Parton Shower** **Hadronisation**

e^+

γ

e^-

$(Z^0/\gamma)^*$

q

$\bar{q}$

d
$\bar{u}$ } π^-

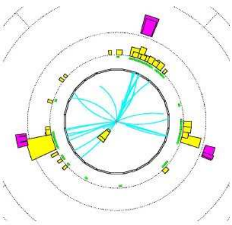
and many more

u
d } $\Lambda^0 \rightarrow \pi^- p^+$
s

d
$\bar{c}$ } $D^+ \rightarrow K^0 \pi^+$

$\sqrt{s'}$ ~ 1 GeV

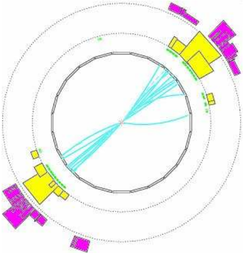
Parton Level *Hadron Level*



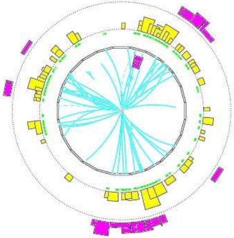
Simple ‘laboratory’: event shapes

Continuous measures of shape of an event. Most famous example is Thrust:

$$T = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_i.\vec{n}_T|}{\sum_i |\vec{p}_i|} ,$$



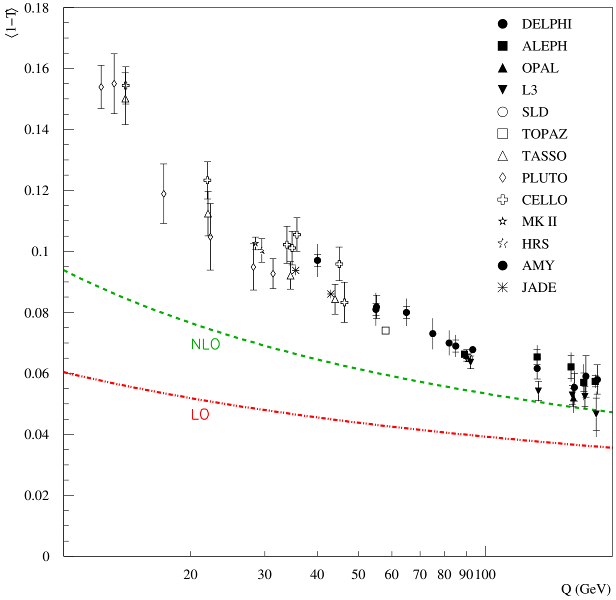
2-jet event: $T \simeq 1$



3-jet event: $T \simeq 2/3$

There exist many other measures of aspects of the shape in e^+e^- and DIS: Thrust-Major, C-parameter, broadening, heavy-jet mass, jet-resolution parameters,. . .

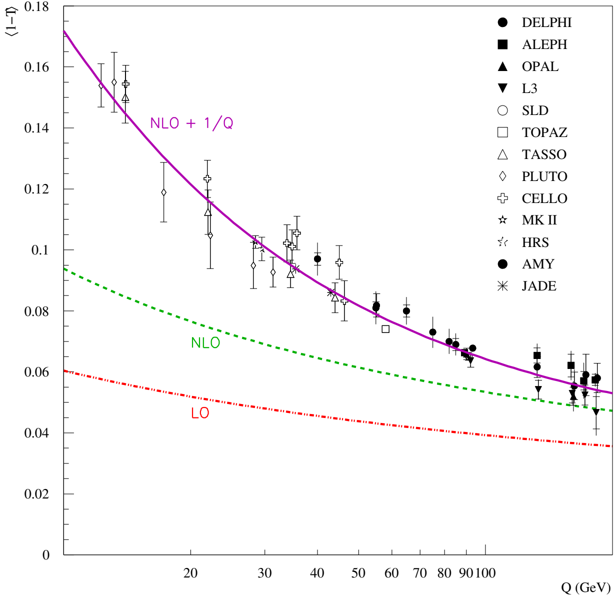
Observable class #1: mean values (v. Q)



Means are simplest quantities to discuss.

Basic hypothesis, observation: hadronisation just adds Q-dependent correction to mean value.

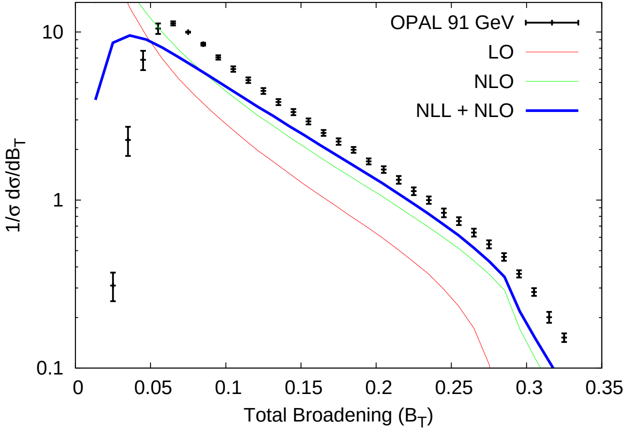
Observable class #1: mean values (v. Q)



Means are simplest quantities to discuss.

Basic hypothesis, observation: hadronisation just adds Q-dependent correction to mean value.

Observable class #2: distributions

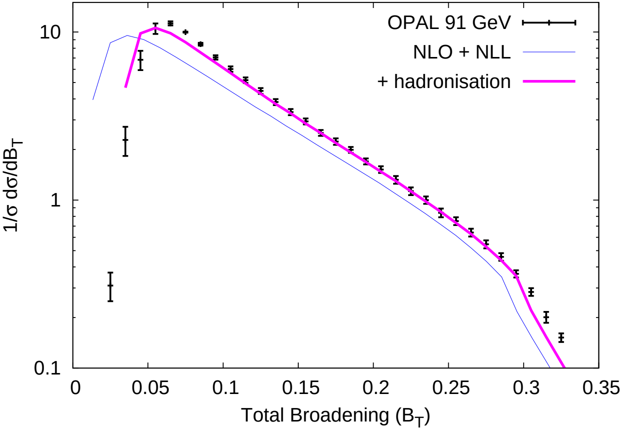


Distributions contain vastly more information.

They are also more difficult to predict.

Basic hypothesis, observation: hadronisation shifts, squeezes, smears, etc.

Observable class #2: distributions



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Basic hypothesis, observation: hadronisation shifts, squeezes, smears, etc.

Ambitions

In order of increasing ambitiousness:

- Can one predict Q-dependence of corrections?
- Can one predict relations between corrections for different observables?
- Can one relate the corrections to some operator that can be measured on the lattice?

Real progress started on first two points in mid-90's, much based on renormalon-inspired arguments

Akhoury & Zakharov
Beneke & Braun
Dokshitzer & Webber + Marchesini
Korchemsky & Sterman

Standard approaches

Dokshitzer-Webber approach

$$\langle V\rangle = \langle V\rangle_{PT} + c_V\mathcal{P} \qquad \mathcal{P} = \mathcal{M}\frac{\mu_I}{Q}\cdot(\alpha_0(\mu_I) - \text{PT double count.})$$

$$\frac{d\sigma}{dV}(v) = \frac{d\sigma}{dV}_{PT}(v - c_V\mathcal{P})$$

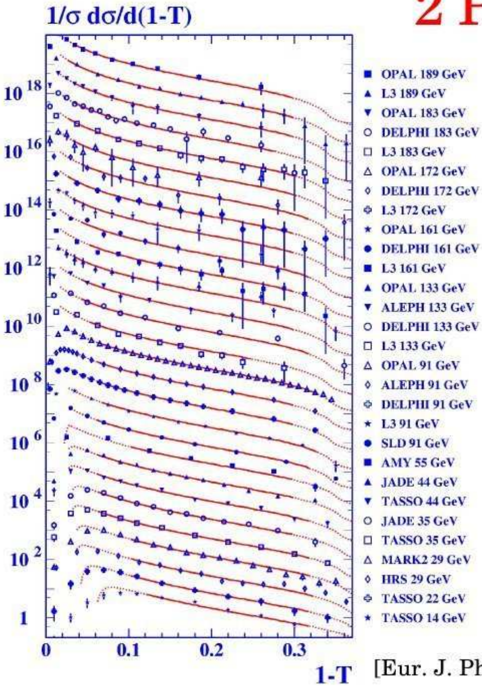
α_0 is fundamentally non-perturbative but universal, c_V is can be predicted perturbatively. *The most widely used approach.*

Korchemsky-Sterman shape-function approach

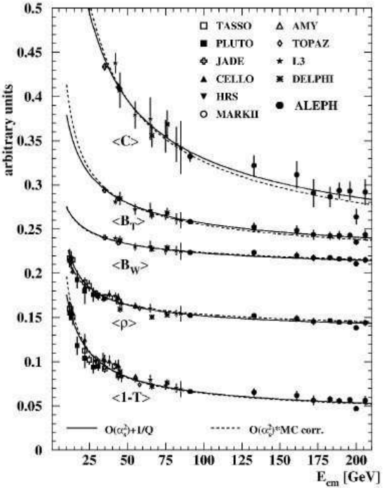
$$\frac{d\sigma}{dV}(v) = \int dx \frac{d\sigma}{dV}_{PT}(v - x/Q)\, f_V(x)$$

$f_V(x)$ is a an observable-specific shape-function, which should be independent of Q. *More flexible, but less predictive.*

2 Power Correction Fits



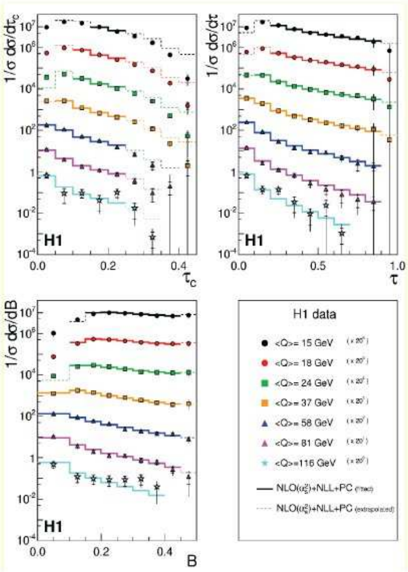
[Eur. J. Phys. C22 (2001) 1]

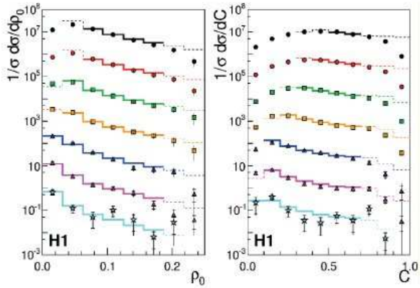


[Eur. J. Phys. C35 (2004) 457]

Kluth (e+e-)

Distributions

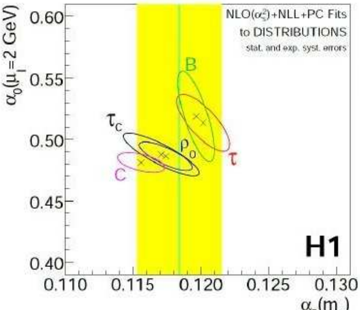


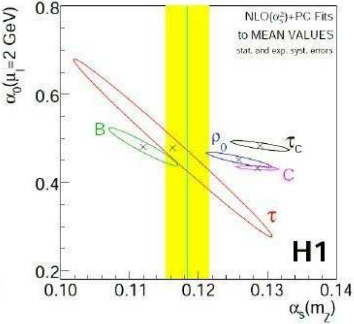


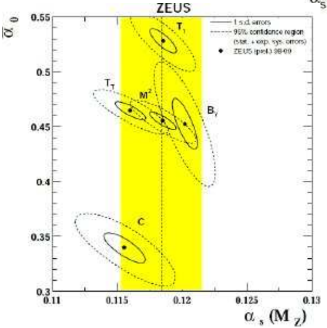
- good description over large range!
- down to <Q>=15GeV

Kluge (DIS data)

True test: universality of α_0



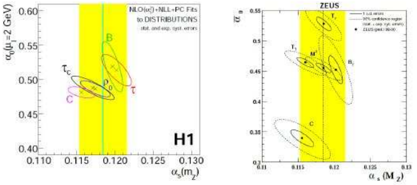




Universality: α_0 should be the same for all observables (as should α_s...)

- Reasonably true, $\alpha_0 \simeq 0.5$
- Some problems (*e.g.* α_s large in H1 means)
- Different experiments measure same things, sometime get different fit results.

Comparison of H1/ZEUS Results



DISAGREE

- ZEUS:
  - C-par: α_0 low
  - overall α_0 lower, except T_γ
  - χ^2/dof large for T_t,ρ_0,C

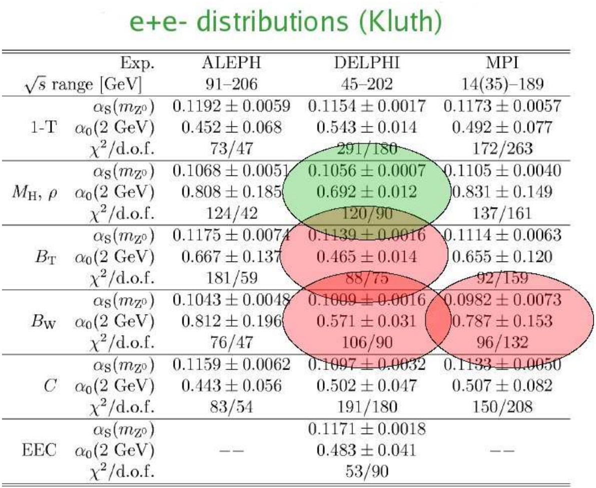
AGREE

- α_s compatible with world mean
- α_s shape-by-shape
- neg. correlation between (α_s,α_0)
- C prefers lowest (α_s,α_0) values
- χ^2/dof best for γ-axis variables

DIFFERENCES

- correlations: H1 uses Bayes unfolding, syst. correlations
- matching scheme:
  H1: mod logR, ZEUS: mod M^2
- bins used for fitting different

Universality of α_0 in e^+e^-



e+e- distributions (Kluth)

	Exp.	ALEPH	DELPHI	MPI
	$\sqrt{s}$ range [GeV]	91–206	45–202	14(35)–189
1-T	$\alpha_S(m_{Z^0})$	0.1192 ± 0.0059	0.1154 ± 0.0017	0.1173 ± 0.0057
	α_0(2 GeV)	0.452 ± 0.068	0.543 ± 0.014	0.492 ± 0.077
	χ^2/d.o.f.	73/47	291/180	172/263
M_H, ρ	$\alpha_S(m_{Z^0})$	0.1068 ± 0.0051	0.1056 ± 0.0007	0.1105 ± 0.0040
	α_0(2 GeV)	0.808 ± 0.185	0.692 ± 0.012	0.831 ± 0.149
	χ^2/d.o.f.	124/42	120/90	137/161
B_T	$\alpha_S(m_{Z^0})$	0.1175 ± 0.0074	0.1139 ± 0.0016	0.1114 ± 0.0063
	α_0(2 GeV)	0.667 ± 0.137	0.465 ± 0.014	0.655 ± 0.120
	χ^2/d.o.f.	181/59	88/75	92/159
B_W	$\alpha_S(m_{Z^0})$	0.1043 ± 0.0048	0.1009 ± 0.0016	0.0982 ± 0.0073
	α_0(2 GeV)	0.812 ± 0.196	0.571 ± 0.031	0.787 ± 0.153
	χ^2/d.o.f.	76/47	106/90	96/132
C	$\alpha_S(m_{Z^0})$	0.1159 ± 0.0062	0.1097 ± 0.0032	0.1133 ± 0.0050
	α_0(2 GeV)	0.443 ± 0.056	0.502 ± 0.047	0.507 ± 0.082
	χ^2/d.o.f.	83/54	191/180	150/208
EEC	$\alpha_S(m_{Z^0})$		0.1171 ± 0.0018	
	α_0(2 GeV)	– –	0.483 ± 0.041	– –
	χ^2/d.o.f.		53/90	

From distributions:

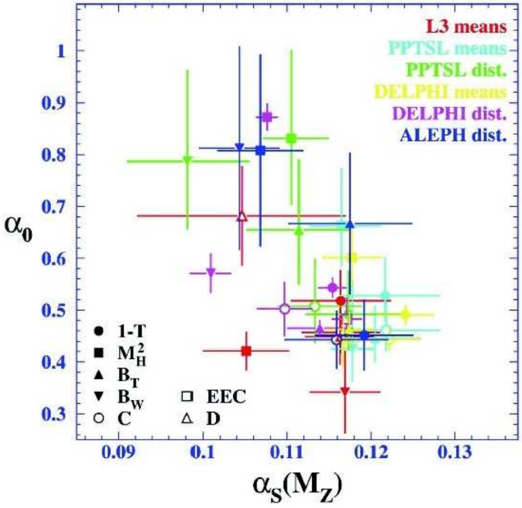
- T, C consistent
- B_T maybe has problem
- B_W, ρ_H probably have problem

From means consistency is better for all observables

NB: $1/Q$ shift predictive near 2-jet limit, but also applied elsewhere

$\exists$ signs this might be a cause of the problems for B_W, ρ_H

2 Power Correction Summary



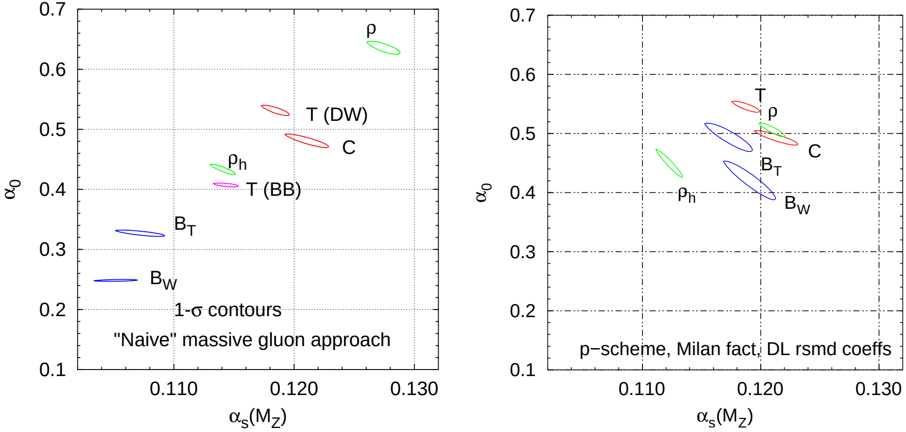
Results for α_0 consistent at 20-30% level, but errors partially much smaller

Expect ca. 20% uncertainty from Milan factor? Really consistent?

Correlations:
  ~ -90% (fit)
  ~ -40 – 0 % (total)

Kluth

Progress since 1995? (For e^+e^- means)



Modern data with old (left) v. new theory (right).

Many effects: Milan factor (all), double-logarithmic resummations (ρ_h, B_X), hadron mass effects (ρ, ρ_h)

Good overall consistency, but some problems persist

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+ numerous other active participants!

Alternative to hadronisation

Are we sure (data − NLO) is due to hadronisation? What about higher orders?

cf. Sterman's Lemma: $1/Q \sim 7\alpha_s^3$

Alternative: renormalisation group improved PT (effective charges)

Grunberg '84

- Treat event shape as an effective charge $\mathcal{R}$
- Write β-function for this effective charge and fit $\langle V \rangle$ at many scales
- This resums a certain class of higher-order effects
- Afterwards, convert into $\alpha_s(M_Z)$ in $\overline{\mathrm{MS}}$ scheme

Actual fit uses

$$\langle V \rangle = \mathcal{R} + \frac{K_0}{Q}$$

where K_0 allows for hadronisation effects

RGI & Means Need no Significant Power Terms

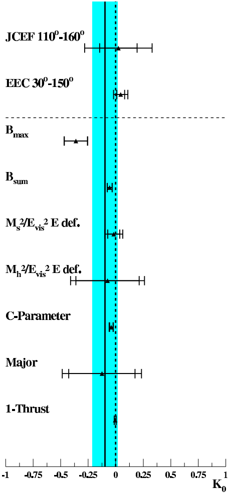
Fitting RGI with power–terms to many observable means yields:

K_0 compatible with 0 ⇔ No P.C.!

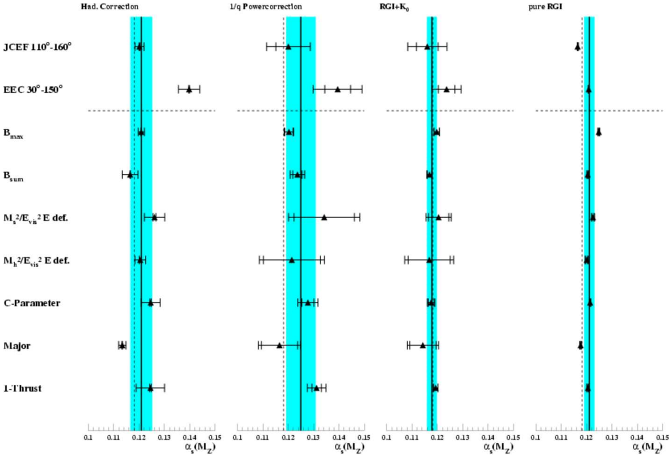
Virtue of both:
RGI and inclusiveness of mean values.

Presence of genuine
power terms for means unclear !

Possible contribution:
$\mathcal{O}(\sim 2\%)$ (rel.) at the Z.

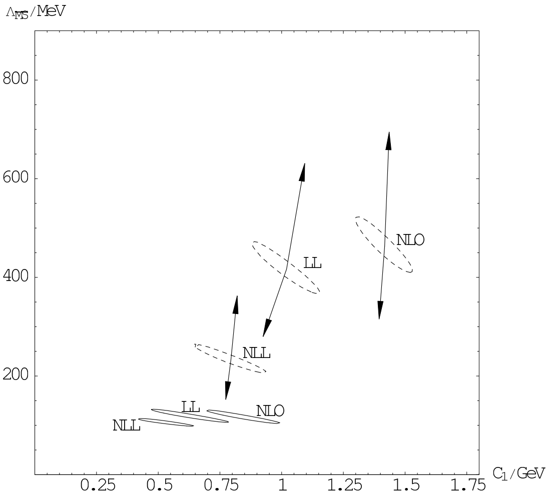


Cmp. α_s from Means Obtained with Various Methods



RGI yields smallest scatter; $\langle\alpha_s(M_Z)\rangle = 0.121 \pm 0.002$

RGI and distributions



Maxwell & Dinsdale

Fits to 1-thrust for $\Lambda_{\overline{MS}}$ and C_1. Solid 2σ error ellipses are for ECH, dashed are $\overline{MS}$PS.

RGI extended to distributions and resummations.

Unlike situation for means, *hadronisation corrections are needed* (but smaller than 'standard' picture).

What are significance of

- Amazing uniformity of α_s values for means
- absence of $1/Q$ there
- need for it in distributions

NNLO may provide further clues

Summary

Main features of antenna subtraction at NNLO

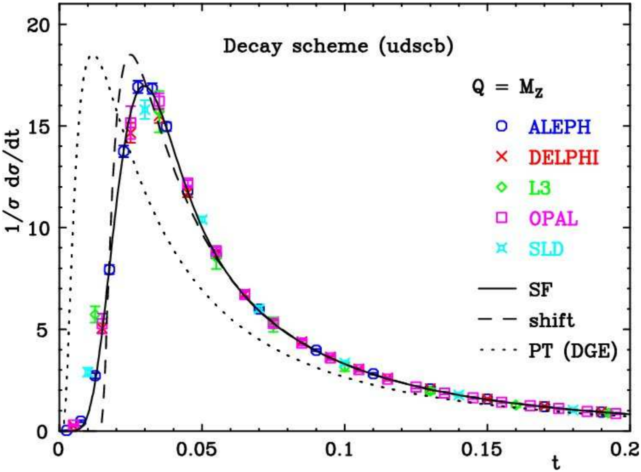
- building blocks of subtraction terms: 3 and 4 parton antenna functions
- antenna functions are derived from physical $|\mathcal{M}|^2$
  - quark-antiquark: $\gamma^* \to q\bar{q} + X$
  - quark-gluon: $\tilde{\chi} \to \tilde{g}g + X$
  - gluon-gluon: $H \to gg + X$
- subtraction terms:
  - approximate correctly the full $|\mathcal{M}|^2$ (double real, one-loop/real)
  - do not oversubtract
  - can be integrated analytically
- for $e^+e^- \to 3$ jets $(1/N^2)$ constructed the 3, 4 and 5 parton contributions
- showed $\mathcal{P}oles(\text{three-parton}) = 0$
- in progress: all colour factors in 3-jet rate
- possible extensions: lepton-hadron, hadron-hadron; same antenna functions, but different phase space

Shape functions

More rather than less hadronisation. . .

Enable the best quality fits to data

Sometimes with Gardi-Rathsman Dressed-Gluon-Exponentiation



NB: watch out for small value of $\alpha_s \simeq 0.110$

Angularities

Major drawback of shape functions: only first moment has a predictable relation between observables. This is reason why little experimental study

Interesting development: *angularities,* a class of observables with related shape functions Berger Kucs & Sterman '03
Berger & Magnea '04

$$\tau_a = \sum_i \frac{E_i}{Q} (\sin\theta_i)^a (1 - |\cos\theta_i|)^a = \sum_i \frac{p_{T,i}}{Q} e^{-(1-a)|\eta_i|}$$

NB: a = 0 is thrust, a = 1 is broadening

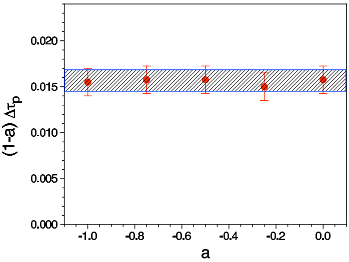
Take ν^{th} moment of shape function for τ_a, $f_{a,\nu}$, then

$$f_{a,\nu} = [f_{0,\nu}]^{\frac{1}{1-a}}$$

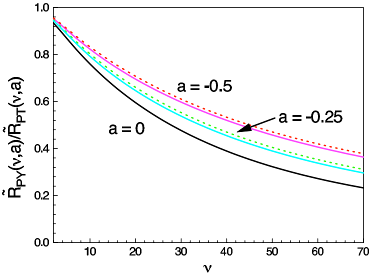
assuming hadronisation is (a) rapidity independent and (b) decorrelated between different rapidities Berger & Sterman '03

Testing the scaling rule

The scaling rule is a *prediction* waiting for data *analysis* … in the meantime, it can be compared with PYTHIA output (Berger).



Shift in the position of the peak of τ_a distribution, between NLL result and PYTHIA, after rescaling by $1 - a$, vs. shift for $a = 0$ computed from data.



The leading shape function for different a, PYTHIA output (solid) vs. scaled result (dashed).

Angularities (cont.)

- Angularities *deserve to be measured*
- Could provide unique insight beyond the Dokshitzer-Webber "shift" approach
- Being investigated in various theoretical contexts

DGE: Berger & Magnea
SCET: Lee

- NB: other related class of observables, fractional EEC moments

$$FC_a \equiv \sum_{i \neq j} \frac{E_i E_j |\sin\theta_{ij}|^a (1 - |\cos\theta_{ij}|)^{1-a}}{(\sum_i E_i)^2} \Theta\left[(\vec{q}_i \cdot \vec{n}_T)(\vec{q}_j \cdot \vec{n}_T)\right] ,$$

with similar NP properties but better (linear) $a \geq 1$ limit.

Banfi, GPS & Zanderighi

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Universality ↔ rapidity-independence?

- Most event-shape hadronisation corrections come from large-angle emission
- At large angles, basic event is two colour charges moving fast in opposite directions — looks boost invariant

➥ (NP part of) hadron-emission pattern is rapidity-independent:

$$\frac{dn_h}{dk_t\,d\eta} = \Phi_h(k_t)$$

Feynman tube model

- Observable factorises: $V(k) \simeq f_V(\eta) \cdot \frac{k_t}{Q}$

$$\langle V \rangle_{NP} \simeq \underbrace{\int d\eta\, f_V(\eta)}_{c_V} \cdot \underbrace{\int dk_t \frac{k_t}{Q} \Phi_h(k_t)}_{\langle k_t \rangle / Q \to \alpha_0 \mu_I / Q}$$

- But what happens in multi-jet events, where boost invariance broken?

Soft radiation and confinement

- Soft dressed gluon emission from a $q\bar{q}$ dipole

$$\frac{dw}{d\ln k_t d\eta} = 2A_q[\alpha_s^{\overline{\rm MS}}(k_t)] = 2C_F\frac{\alpha_s^{\rm CMW}(k_t)}{\pi} \to \sum_h \Phi_h(k_t)$$

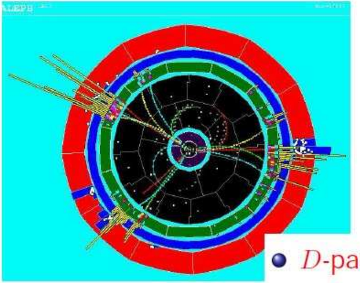
$$k_t^2 = \frac{(2pk)(2k\bar{p})}{2p\bar{p}} \qquad \eta = \frac{1}{2}\ln\frac{\bar{p}k}{pk}$$

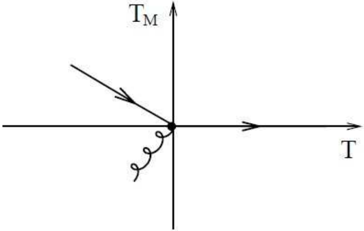
- Soft dressed gluon emission from more dipoles

$$dw = \sum_{i<j}(-2\vec{T}_i\cdot\vec{T}_j)\frac{d\kappa_{ij}}{\kappa_{ij}}d\eta_{ij}\frac{\alpha_s^{\rm CMW}(\kappa_{ij})}{\pi} \to \sum_{i<j}\frac{d\kappa_{ij}}{\kappa_{ij}}d\eta_{ij}\sum_h \Phi_h^{(ij)}(\kappa_{ij})?$$

$$\kappa_{ij}^2 = \frac{(2p_ik)(2kp_j)}{2p_ip_j} \qquad \eta_{ij} = \frac{1}{2}\ln\frac{p_jk}{p_ik}$$

Three-jet events





- *D*-parameter: determinant of the momentum tensor $\theta_{\alpha\beta}$

$$\theta_{\alpha\beta}\, Q \equiv \sum_h \frac{p_h^\alpha p_h^\beta}{|\vec{p}_h|} \qquad D \equiv 27 \det \theta$$

$$c_D = C_F\ g_q(T, T_M) + C_F\ g_{\bar{q}}(T, T_M) + C_A\ g_g(T, T_M)$$

- Thrust-minor: sum of the momenta out of the event plane

$$K_{\rm out} \equiv \sum_h |p_h^{\rm out}| \quad \delta K_{\rm out} \simeq \sum_i \kappa_i |\sin \phi_i|$$

uniform in rapidity

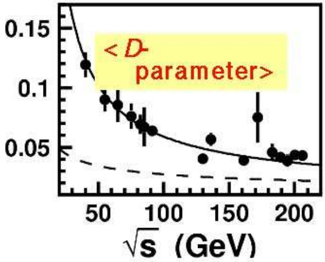
non- perturbative analysis of 4- jet observables

L3 analysis of mean value of *D*- parameter

$$\langle D \rangle = \langle D_{pert} \rangle + \langle D_{pow} \rangle$$

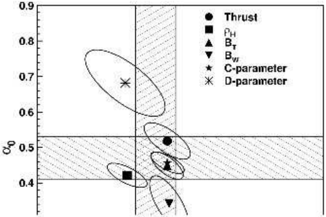
$$\langle D_{pert} \rangle = B_D \cdot \left(\frac{\alpha_s}{2\pi} \right)^2 + D_D \cdot \left(\frac{\alpha_s}{2\pi} \right)^3$$

$$\langle D_{pow} \rangle = 195 \frac{\alpha_s}{2\pi} P$$



Results:

L3	$\alpha_s(M_z)$	α_0(2 GeV)
D- parameter	0.1046 ± 0.0078 ± 0.0096	0.682 ± 0.094 ± 0.018
all combined	0.1126 ± 0.0045 ± 0.0039	0.478 ± 0.054 ± 0.024

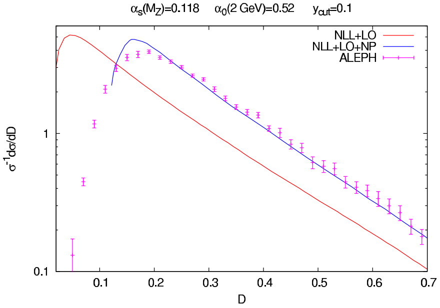


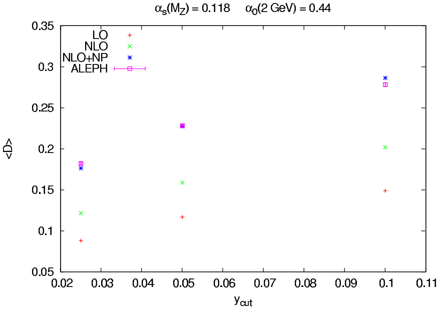
Given the mildly discrepant values of α_0 and these problems with the fits to the second moments, one can conclude that the power correction ansatz gives a good qualitative description, but that additional terms will be needed to achieve a good quantitative description.

Stenzel

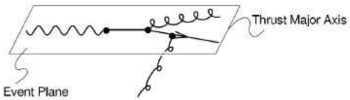
D-parameter: theory vs data

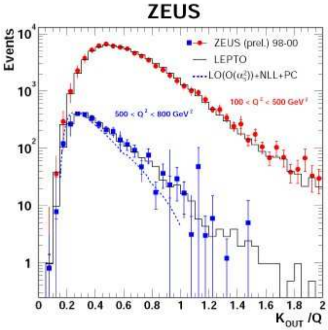
- Select 3-jet events with $y_3 > y_{\mathrm{cut}}$
- D-parameter distribution with LO matching
- D-parameter means for different values of y_{cut}





3-jet Distributions





- K_{out}: momentum out of event plane
- sensitive to large angle emissions, in between hard jets
- extend from current hemisphere ($\eta<0$) to $\eta<3$
- not so inclusive as 2-jet variables: require $0.1<y_2<2.5$
- rather well description by LO+NLL+PC at higher Q, but some shift
- also prel. H1 data available Q: 15...81 GeV

Multijet summary

Some (preliminary) data are available:

- Aleph, H1, ZEUS

Some calculations exist

- Manual resummations Banfi, Dokshitzer, Marchesini, Mueller
- Automated CAESAR
- Fixed-order NLOJET

Assembly of all elements still missing Banfi & Zanderighi, in progress

Motivations for hadron-hadron event-shapes

At hadron colliders

- two jets are present in the initial state, therefore all studies of *final states* lead beyond the well-tested two-jet regime [multi-jet events not suppressed by powers of α_s]
  - sensitivity to underlying jet-production channel
  - studies of hadronization corrections in multi-jet events
  - dijet production allows studies of quantum evolution of colour

    $\Rightarrow$ colour evolution that arises in 4-jet events has never been investigated
- resummation effects become important earlier

$$e^+e^- \to q\bar{q} \leadsto \enclose{circle}{2C_F}\,\alpha_s L^2/\pi \qquad \Longleftrightarrow \qquad gg \to gg \leadsto \enclose{circle}{4C_A}\,\alpha_s L^2/\pi$$

- rich source of gluon jets [again no α_s suppression]
- event shapes defined as ratios $\Rightarrow$ many uncertainties cancel
- studies of underlying event

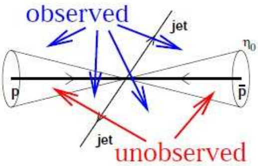
  $\Rightarrow$ the forward sensitivity (to beam-fragmentation) can be tuned [see later]

Observables in hadronic dijet production

Theoretical predictions limited to global observables [At least if one aims at NLL accuracy]

$\Longleftrightarrow$

Experiments have only detectors in a limited rapidity range [Usually modelled by a rapidity cut $|\eta| < \eta_0$ along the beam]



⚠ *Mismatch between 'ideal' theoretical definition and what can be measured in practice? NO!*

There are different classes of observables designed to solve this conflict!

Hadron-collider observables

Event-shape	Impact of $\eta_{\max}$	Resummation breakdown	Underlying Event	Jet hadronisation
$\tau_{\perp,g}$	tolerable	none	$\sim \eta_{\max}/Q$	$\sim 1/Q$
$T_{m,g}$	tolerable	none	$\sim \eta_{\max}/Q$	$\sim 1/(\sqrt{\alpha_s}Q)$
y_{23}	tolerable	none	$\sim \sqrt{y_{23}}/Q$	$\sim \sqrt{y_{23}}/Q$
$\tau_{\perp,\mathcal{E}}$, $\rho_{X,\mathcal{E}}$	negligible	none	$\sim 1/Q$	$\sim 1/Q$
$B_{X,\mathcal{E}}$	negligible	none	$\sim 1/Q$	$\sim 1/(\sqrt{\alpha_s}Q)$
$T_{m,\mathcal{E}}$	negligible	serious	$\sim 1/Q$	$\sim 1/(\sqrt{\alpha_s}Q)$
$y_{23,\mathcal{E}}$	negligible	none	$\sim 1/Q$	$\sim \sqrt{y_{23}}/Q$
$\tau_{\perp,\mathcal{R}}$, $\rho_{X,\mathcal{R}}$	none	serious	$\sim 1/Q$	$\sim 1/Q$
$T_{m,\mathcal{R}}$, $B_{X,\mathcal{R}}$	none	tolerable	$\sim 1/Q$	$\sim 1/(\sqrt{\alpha_s}Q)$
$y_{23,\mathcal{R}}$	none	intermediate	$\sim \sqrt{y_{23}}/Q$	$\sim \sqrt{y_{23}}/Q$

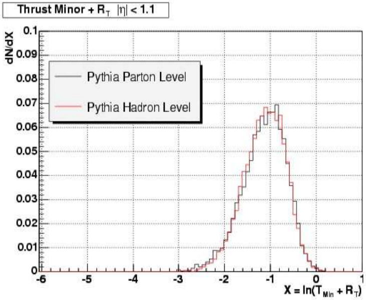
Banfi, Zanderighi & GPS

NB: there may be surprises after more detailed study, *e.g.* matching to NLO...

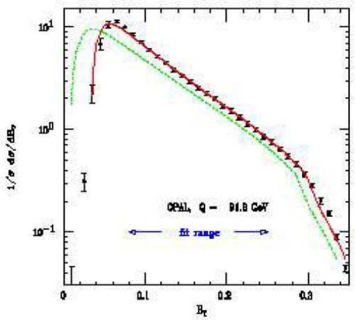
Grey entries are definitely subject to uncertainty

Note complementarity between observables

Hadronization Effects?



?

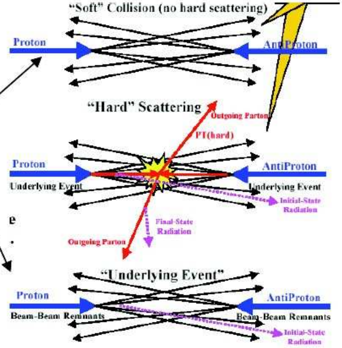


Does Pythia not know about these?

Importance of underlying event

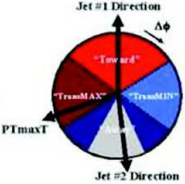
- Have to subtract underlying event from hard scatter in order to compare jet cross sections to parton-level calculations

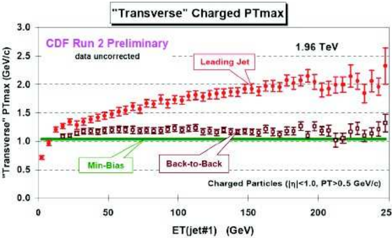
how similar are these two?



Σp_T in max region increases as jet E_T increases

Σp_T in min region stays flat, at level similar to min bias





need inclusive jet production in MCatNLO

currently underway, but slowly

Jet Event Shapes @ RHIC

- Good things @ RHIC
  - Not just *A+A: p+p, p+A*, polarized *p+p* (& lots!)
  - Dectectors optimized for soft physics (Good *E,p* resolution/ PID above 50 MeV...) in addition to hard
- Bad things
  - As *h+h*, central rapidity restriction
  - Ambiguity of $Q/\sqrt{s_{12}}$
  - In Au+Au...well... e.g. no jet finding (jets modified!)...etc...
- From your standpoint
  - For *p+p*, best source of low Q? (mid-η *x* ranges like Tevatron/LHC, but lower *s*)
  - *Au+Au* Interesting modification to hadronization – could Power Correction frameworks say anything sensible? How about in *d+Au ?*
- From HI experimentalist standpoint
  - Want to use jets to probe medium: event shapes are a natural goal

Underlying event ↔ small-x saturation

Point highlighted by Mueller:

> *hadron-collider event shapes, since they are sensitive to the 'underlying event' may also provide a way of getting information on high-energy saturation, which is expected to lead to a non-negligible (*$\sim 1-2$ GeV*) new kind of 'semi-perturbative' effect in hadron-hadron collisions*

Review of current status	
George Sterman	Review of theoretical status
Stefan Kluth	Review of status in e+e-
Thomas Kluge	Review of status in DIS
Getting the most out of 2-jets	
Chris Maxwell	Effective charges in theory
Klaus Hamacher	Effective charges in practice
Christopher Lee	N-P effects from soft-collinear effective theory
Thomas Gehrmann	Status of NNLO jet calculations
Lorenzo Magnea	Angularities
Beyond 2 jets	
Andrea Banfi	Why multi-jet studies?
Hasko Stenzel	e+e- multi-jet studies
Justin Frantz	Hard scattering results from RHIC
Giulia Zanderighi	Hadron-hadron event shapes
Lester Pinera	Progress on measuring hadron-hadron event shapes
Joey Huston	Underlying events in hadron-hadron collisions
Extending the field	
Georges Grunberg	Beyond leading powers
Mrinal Dasgupta	Anomalous dimensions in powers
Einan Gardi	Power corrections in B decays
Nikolai Uraltsev	Nonperturbative radiation in jets and the OPE
Matteo Cacciari	Power-suppressed effects in fragmentation functions
Conclusions	
Alfred Mueller	Concluding talk

+ numerous other active participants!

Where the miracle hides?

Calculate the M_X^2-spectrum itself :

$$\frac{\mathrm{d}\Gamma^{\rm pert}}{\mathrm{d}M_X^2}=C_F\int\frac{\mathrm{d}\omega}{\omega}\,\vartheta(\omega-\mu)\int\frac{\mathrm{d}\lambda^2}{\lambda^2}\,\rho(\lambda^2)\int\frac{\mathrm{d}k_\perp^2}{k_\perp^2+\lambda^2}\,\delta(M_X^2-(k_\perp^2+\lambda^2)\tfrac{m_b}{2\omega})$$

$$=\frac{C_F}{M_X^2}\int\frac{\mathrm{d}\omega}{\omega}\,\vartheta(\omega-\mu)\int\frac{\mathrm{d}\lambda^2}{\lambda^2}\,\rho(\lambda^2)\;\vartheta(M_X^2-\tfrac{m_b}{2\omega}\lambda^2)$$

The radiation is driven by a different effective coupling $\tilde{\alpha}_s(k_\perp^2)$:

$$\delta\tilde{\alpha}_s(Q^2)=\pi\int_0^{Q^2}\frac{\mathrm{d}\lambda^2}{\lambda^2}\,\rho(\lambda^2)\quad \text{vs.}\quad \delta\alpha_s^{\epsilon}(Q^2)=\pi\int_0^{\infty}\frac{\mathrm{d}\lambda^2}{\lambda^2+Q^2}\,\rho(\lambda^2)$$

the kinematic constraint to have definite M_X^2 (rather than definite $k_\perp$) changes the dispersion integral

$\tilde{\alpha}_s$ and α_s^ϵ coincide 'with the $\log$ accuracy', yet not in powers

Integer moments of $\delta\tilde{\alpha}_s(Q^2)$ all vanish, while those of $\delta\alpha_s^\epsilon(Q^2)$ are 'positive'

Uraltsev

Theoretical question of ambiguity in couplings came up twice:

- discussion of power accuracy of the coupling Uraltsev
- question of infrared-finite coupling in Sudakov exponent and freedom in defining it Grunberg

Where the miracle hides?

Calculate the M_X^2-spectrum itself :

$$\frac{\mathrm{d}\Gamma^{\rm pert}}{\mathrm{d}M_X^2} = C_F \int \frac{\mathrm{d}\omega}{\omega}\,\vartheta(\omega-\mu)\int\frac{\mathrm{d}\lambda^2}{\lambda^2}\,\rho(\lambda^2)\int\frac{\mathrm{d}k_\perp^2}{k_\perp^2+\lambda^2}\,\delta\!\left(M_X^2-(k_\perp^2+\lambda^2)\tfrac{m_b}{2\omega}\right)$$

$$= \frac{C_F}{M_X^2}\int\frac{\mathrm{d}\omega}{\omega}\,\vartheta(\omega-\mu)\int\frac{\mathrm{d}\lambda^2}{\lambda^2}\,\rho(\lambda^2)\;\vartheta\!\left(M_X^2-\tfrac{m_b}{2\omega}\lambda^2\right)$$

The radiation is driven by a different effective coupling $\tilde{\alpha}_s(k_\perp^2)$:

$$\delta\tilde{\alpha}_s(Q^2) = \pi\int_0^{Q^2}\frac{\mathrm{d}\lambda^2}{\lambda^2}\,\rho(\lambda^2) \quad \text{vs.} \quad \delta\alpha_s^{\epsilon}(Q^2) = \pi\int_0^{\infty}\frac{\mathrm{d}\lambda^2}{\lambda^2+Q^2}\,\rho(\lambda^2)$$

the kinematic constraint to have definite M_X^2 (rather than definite $k_\perp$) changes the dispersion integral

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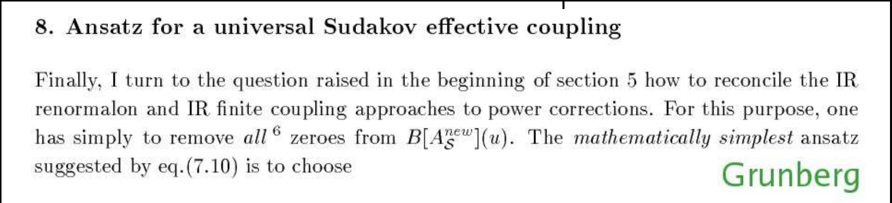


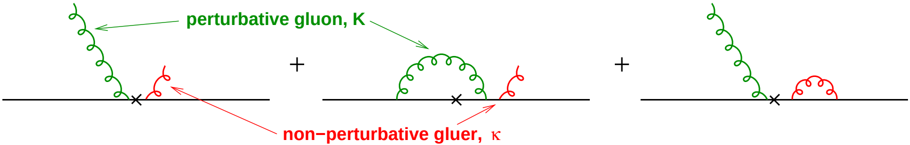
8. Ansatz for a universal Sudakov effective coupling

Finally, I turn to the question raised in the beginning of section 5 how to reconcile the IR renormalon and IR finite coupling approaches to power corrections. For this purpose, one has simply to remove *all* [6] zeroes from $B[A_{\mathcal{S}}^{new}](u)$. The *mathematically simplest* ansatz suggested by eq.(7.10) is to choose

Grunberg

Anomalous dimensions

Try to calculate $\mathcal{O}\left(\alpha_s\alpha_0/Q\right)$ contribution:



$$\int \frac{dK_t}{dK_t} C_F\alpha_s(K_t) \int \frac{d\kappa_t}{d\kappa_t} \text{“}(C_F + C_A)\text{”}\, \delta\alpha_s(\kappa_t) \cdot V(K,\kappa)$$
$$- \int \frac{dK_t}{dK_t} C_F\alpha_s(K_t) \int \frac{d\kappa_t}{d\kappa_t}\, C_F\, \delta\alpha_s(\kappa_t) \cdot V(\kappa)$$
$$- \int \frac{dK_t}{dK_t} C_F\alpha_s(K_t) \int \frac{d\kappa_t}{d\kappa_t} \text{“}(C_F + C_A)\text{”}\, \delta\alpha_s(\kappa_t) \cdot V(K)$$

Not too clear how to calculate this in practice, but seems likely there is a residual logarithmic contribution:

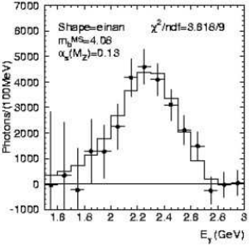
$$\frac{\alpha_0}{Q} \cdot \alpha_s \ln \frac{Q}{\lambda}$$

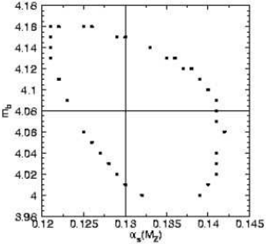
i.e. power correction has anomalous dimension [Dasgupta, GPS, Trocsanyi]

DGE applied to B-meson decay spectra

Resummed perturbation theory can be directly used as an approximation to inclusive B meson decay spectra, **without** a leading power **non-perturbative** function!

- Application to $\bar{B} \longrightarrow X_s\gamma$:
  Predictions for moments in the experimentally–accessible range $E_\gamma > E_0$ agree well with data.
  Potential measurement of m_b.

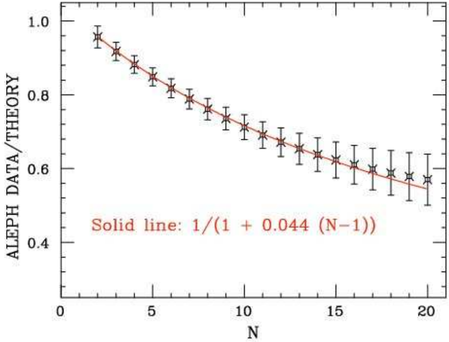




- Application to charmless semileptonic decay*:
  The event fraction for an invariant mass cut $P^+P^- < (1.7\,\mathrm{GeV})^2$ has $\pm 10\%$ accuracy.
  Consistent values for $|V_{ub}|$ are obtained from two different cuts.

*The program can be found at: `www.hep.phy.cam.ac.uk/∼andersen/BDK/B2U`

ALEPH vs CLEO/BELLE



Gap with theoretical prediction increasing at large N.

0.044 corresponds to

$$\frac{5\ \mathrm{GeV}^2}{M_\Upsilon^2}$$

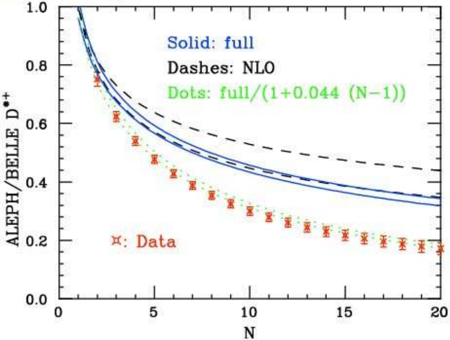
$$\frac{0.52\ \mathrm{GeV}}{M_\Upsilon}$$

Fragmentation functions (Cacciari)

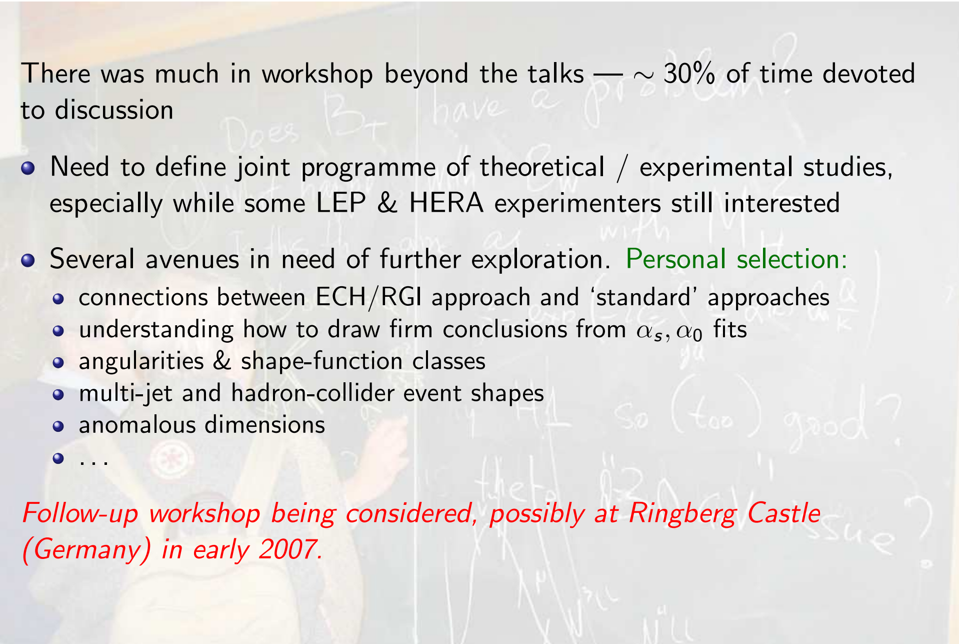
Not a perturbative uncertainty issue: difference is larger than uncertainty band for perturbative evolution

NB. heavy quark mass scale effects cancel in this ratio

$$\frac{\sigma_q(N, M_Z^2, m^2)}{\sigma_Q(N, M_\Upsilon^2, m^2)} = \frac{\bar{a}_q(N, M_Z^2, \mu_Z^2)}{1 + \alpha_s(\mu_Z^2)/\pi}\, E(N, \mu_Z^2, \mu_\Upsilon^2)\, \frac{1 + \alpha_s(\mu_\Upsilon^2)/\pi}{a_q(N, M_\Upsilon^2, \mu_\Upsilon^2)}$$



Outlook



There was much in workshop beyond the talks — $\sim$ 30% of time devoted to discussion

- Need to define joint programme of theoretical / experimental studies, especially while some LEP & HERA experimenters still interested
- Several avenues in need of further exploration. Personal selection:
    - connections between ECH/RGI approach and 'standard' approaches
    - understanding how to draw firm conclusions from α_s, α_0 fits
    - angularities & shape-function classes
    - multi-jet and hadron-collider event shapes
    - anomalous dimensions
    - ...

Follow-up workshop being considered, possibly at Ringberg Castle (Germany) in early 2007.