The Lund Models

and their Monte Carlo implementations

in commemoration of

BO ANDERSSON

and his legacy

Michael H. Seymour

University of Manchester

(Lund postdoc 1993/4)

- The Lund string model
- The dipole cascade model
- The linked dipole chain model
- The importance of energy conservation
- Latest news
- The future

The Lund Model

BO ANDERSSON
Lund University

This book is dedicated to the memory of my teacher, Gunnar Källén, who died much too young. He was the greatest teacher any man could have had. Those of us who enjoyed the vision of physics according to the way he described it, as a great adventure, have often asked what he would have said about the greatest adventure my generation will ever have, i.e. the confined field theory of QCD (which is so different from what we talked about in Lund in the 1960s!).

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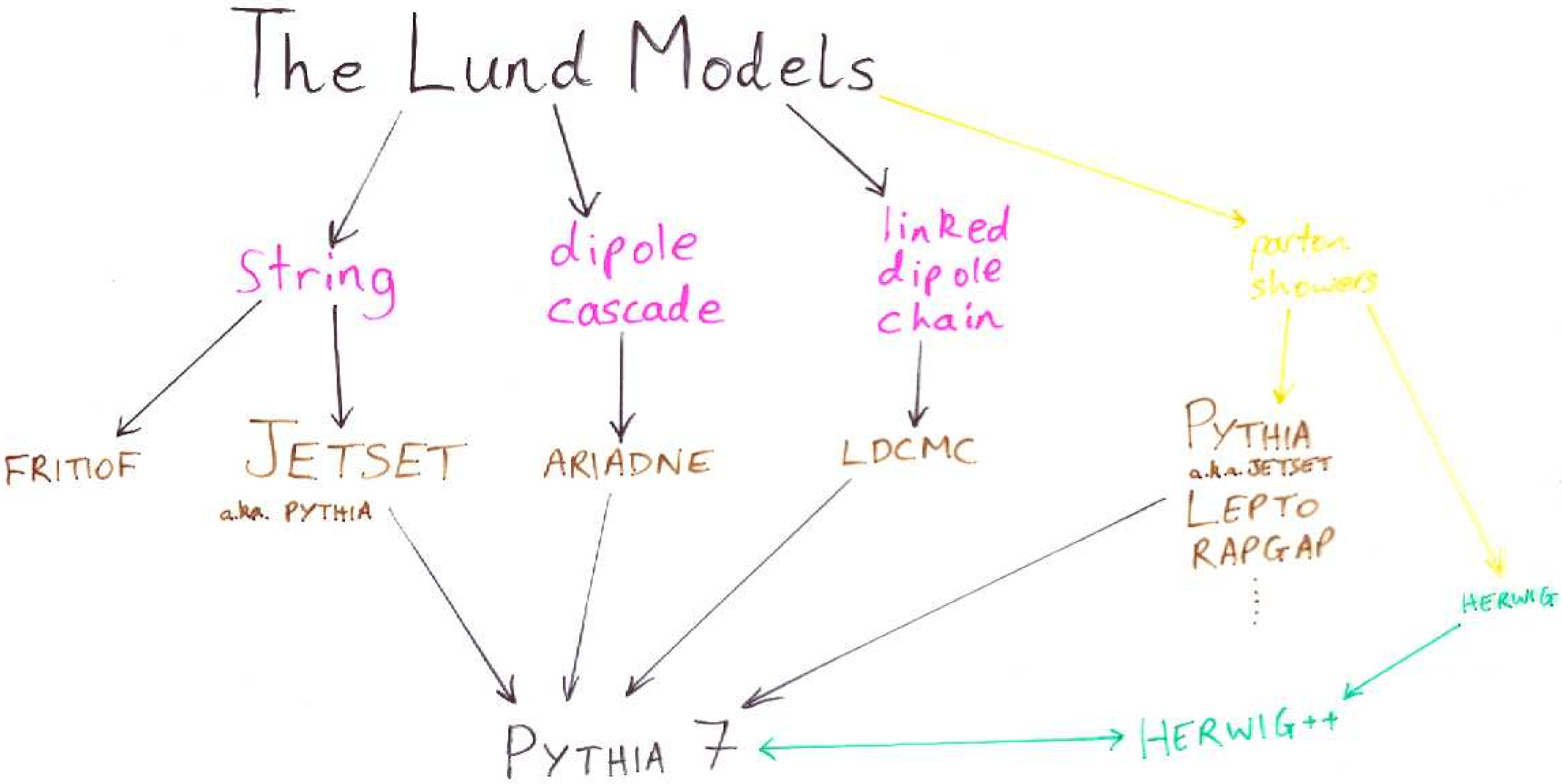
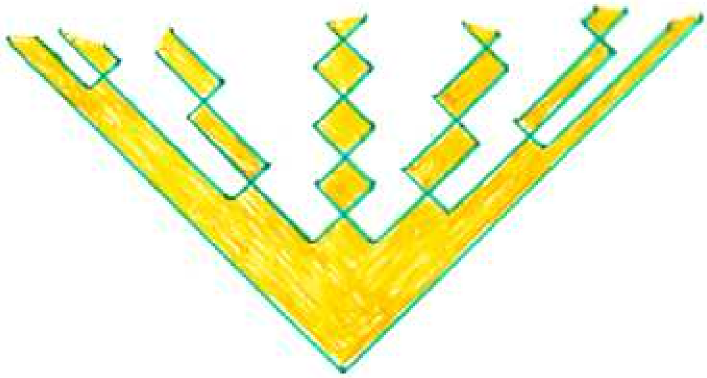

The Lund Models
String
dipole cascade
linked dipole chain
parton showers
FRITIOF
JETSET
a.k.a. PYTHIA
ARIADNE
LDCMC
PYTHIA
a.k.a. JETSET
LEPTO
RAPGAP
HERWIG
PYTHIA 7
HERWIG++

The Lund string model of hadronization

QCD field lines at long distance:

F ~ constant ⇒ STRING

extra $q\bar{q}$ pairs tunnel out → string breaks



is a model of confinement (cf E-cons discussio

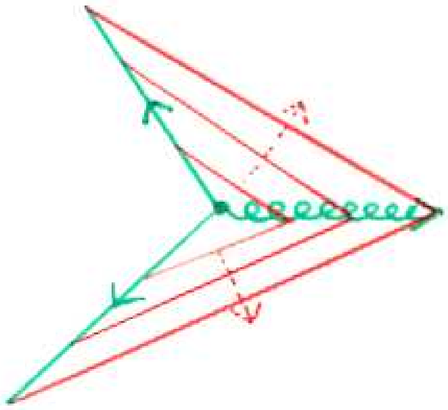
Fits ~ all data ~ perfectly (with many parameters...)

	JETSET 7.3 PS	JETSET 7.4 PS	ARIADNE 4.06	JETSET 7.4 ME	HERWIG 5.8 C	LEP[41],[46],[47],[49]	
Charged Particles							
$< N_{ch} >$	20.87	20.51	20.80	20.86	20.94	20.98	± 0.21
Pseudoscalar Mesons							
$\pi^\pm$	17.19	17.09	17.13	17.38	17.66	17.1	± 0.4
π^0	9.55	9.83	9.52	10.03	9.81	9.9	± 0.08
$K^\pm$	2.20	2.23	2.19	2.15	2.11	2.42	± 0.13
K^0	2.13	2.17	2.12	2.10	2.08	2.12	± 0.06
η	1.07	1.10	1.09	1.16	1.02	0.73	± 0.07
$\eta'(958)$	0.10	0.09	0.10	0.10	0.14	0.17	± 0.05
$D^\pm$	0.19	0.20	0.20	0.20	0.24	0.20	± 0.03
D^0	0.46	0.49	0.48	0.49	0.53	0.40	± 0.06
$B^\pm, B^0$	0.36	0.36	0.36	0.38	0.36	0.34	± 0.06
Scalar Mesons							
$f_0(980)$	0.17	0.16	0.17	0.18		0.14	± 0.06
Vector Mesons							
$\rho^0(770)$	1.29	1.27	1.26	1.29	1.43	1.40	± 0.1
$K^{*\pm}(892)$	0.78	0.77	0.79	0.77	0.74	0.78	± 0.08
$K^{*0}(892)$	0.80	0.77	0.81	0.78	0.74	0.77	± 0.09
$\phi(1020)$	0.109	0.107	0.107	0.102	0.099	0.086	± 0.018
$D^{*\pm}(2010)$	0.18	0.22	0.19	0.22	0.22	0.17	± 0.02
$D^{*0}(2007)$	0.20	0.22	0.20	0.22	0.23		
Tensor Mesons							
$f_2(1270)$	0.29	0.29	0.29	0.30	0.28	0.31	± 0.12
Baryons							
p	0.97	0.97	0.96	0.90	0.78	0.92	± 0.11
Λ^0	0.361	0.349	0.365	0.300	0.368	0.348	± 0.013
Ξ^-	0.0288	0.0300	0.0300	0.0256	0.0493	0.0238	± 0.0024
$\Delta^{++}(1232)$	0.158	0.160	0.138	0.158	0.154	0.077	± 0.018
$\Sigma^\pm(1385)$	0.037	0.036	0.032	0.033	0.065	0.0380	± 0.0062
$\Xi^0(1530)$	0.0073	0.0069	0.0063	0.0060	0.0249	0.0063	± 0.0014
Ω^-	0.0013	0.0019	0.0021	0.0010	0.0077	0.0051	± 0.0013
Λ_c^0	0.032	0.033	0.032	0.029	0.007	0.031	± 0.016

Hamacher & Weierstall hep-ex/9511011

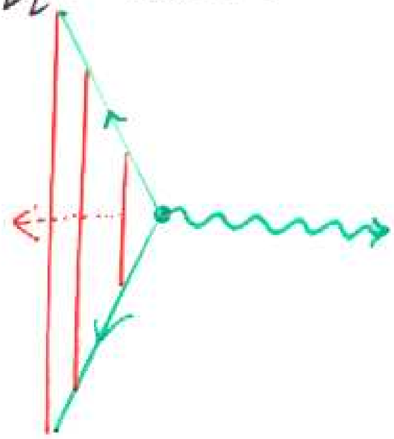
The string effect I - three jet events (inc

gluon is just a kink on the string



⇒ no new free parameters

cf $q\bar{q}\gamma$ event:



OPAL collab. →
Z. Phys. C68 (1995) 531

Also predicted by colour coherence of gluon radiation

Need **both** colour coherence **and** string-like hadronization to fit data!

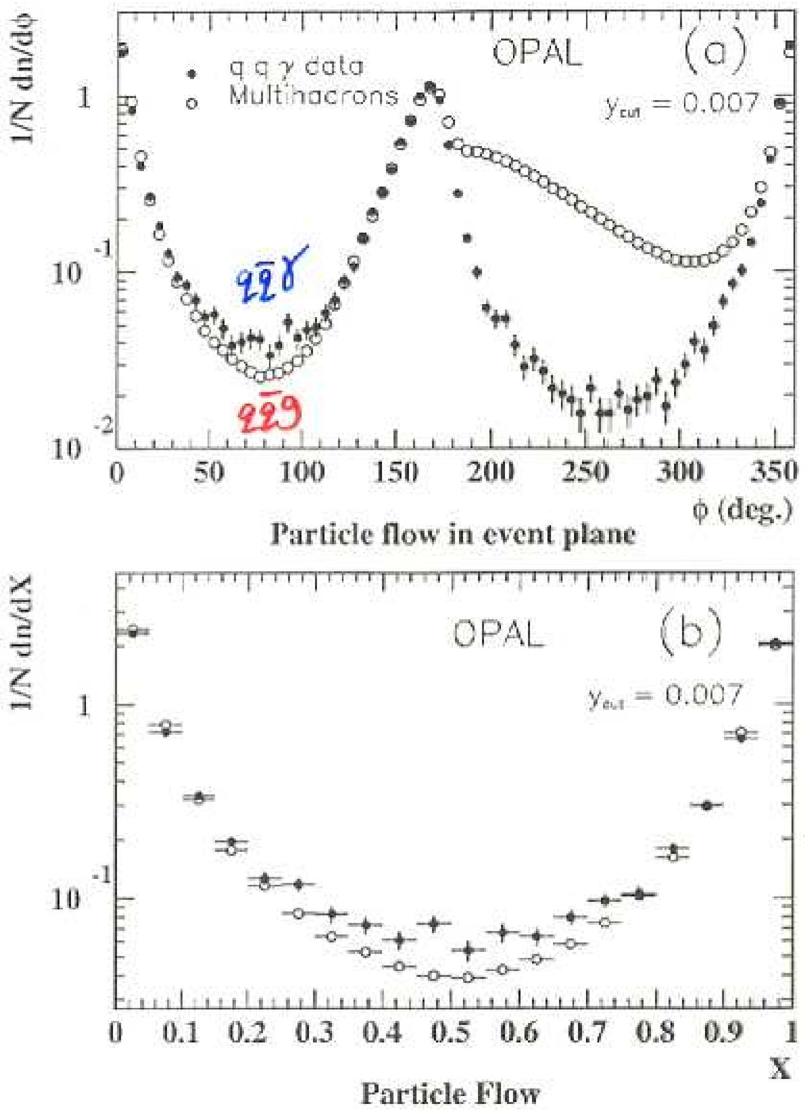
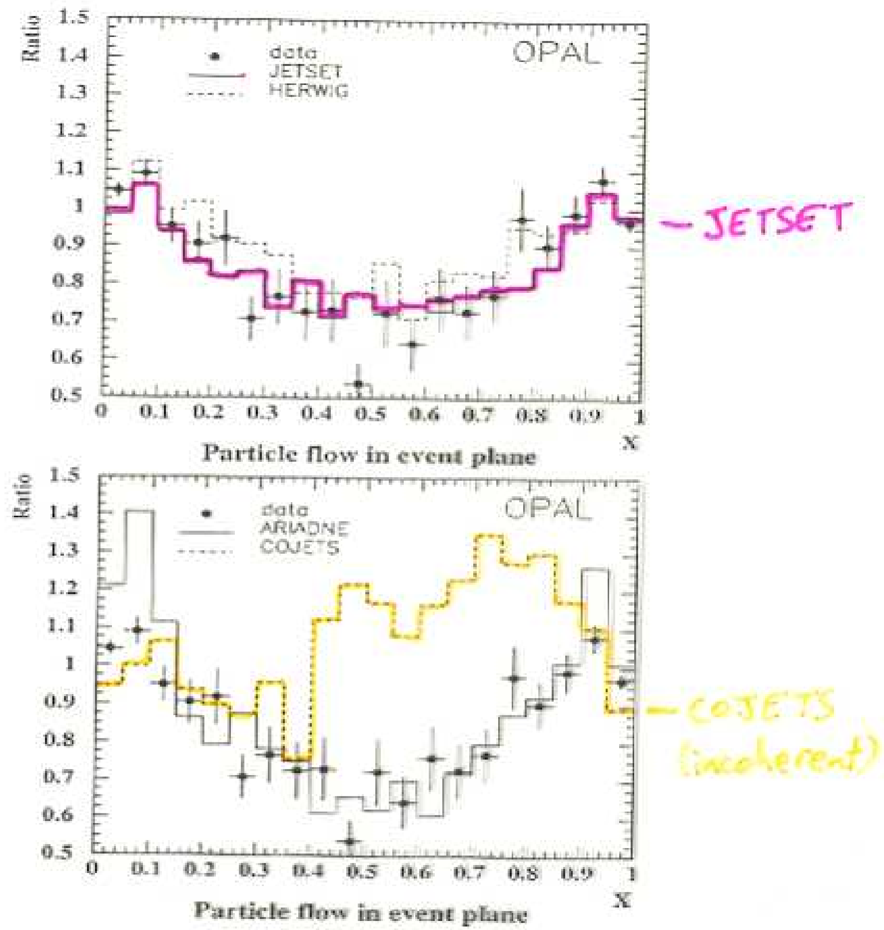
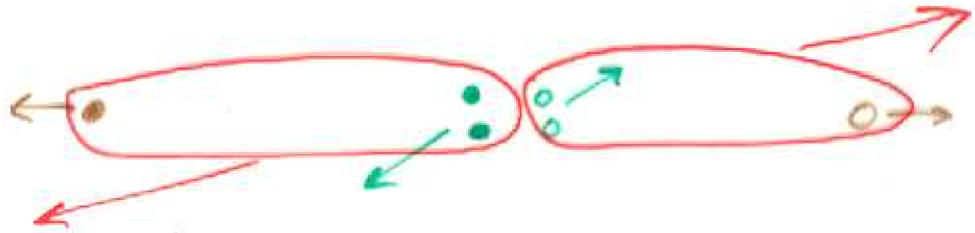


Figure 1: (a) Charged particle flow in the event plane for two-jet radiative events, and three-jet multihadronic events. Error bars for the $q\bar{q}g$ sample are smaller than the dots. (b) Charged particle flow with respect to the reduced angle X.

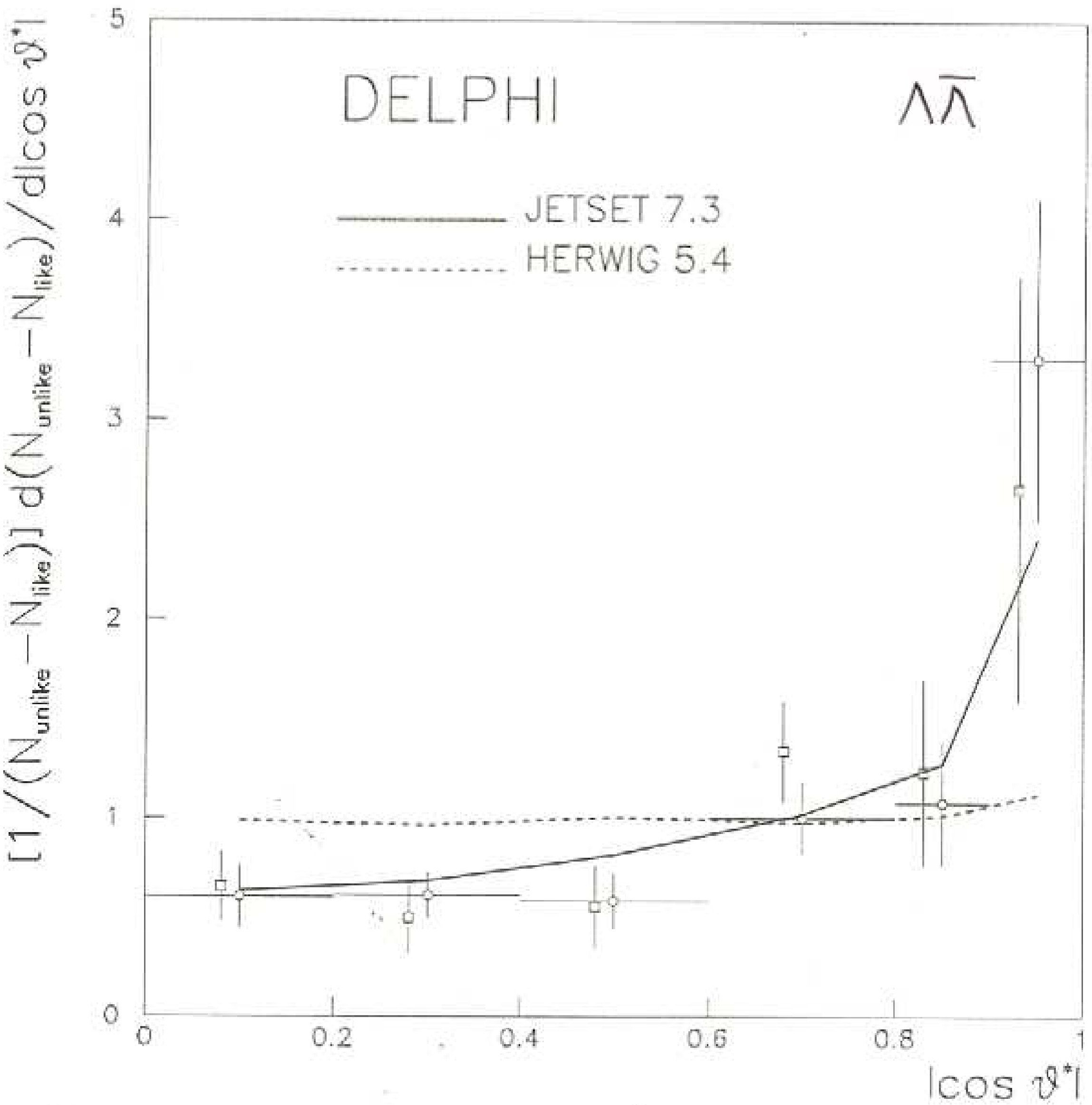


igure 6: Ratio of charged particle flows in three-jet and two-jet radiative events with spect to the reduced angle X for various Monte Carlo models: JETSET coherent parton ower with string fragmentation, HERWIG, ARIADNE and COJETS.

The string effect II - baryon-antibaryon correlation



baryons predominantly primary : remember string direction



Phys. Lett. B318 (1993) 249

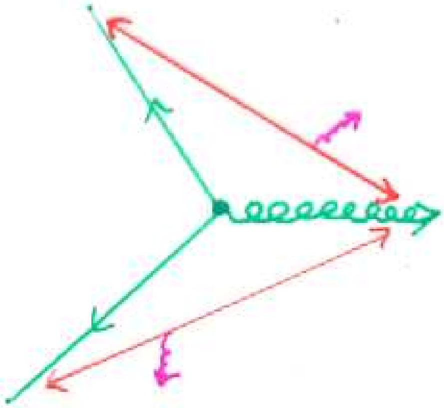
Pushed by data, HERWIG cluster model has had to become more stringlike : ~50% of hadrons come from cluster fission

The Dipole Cascade Model

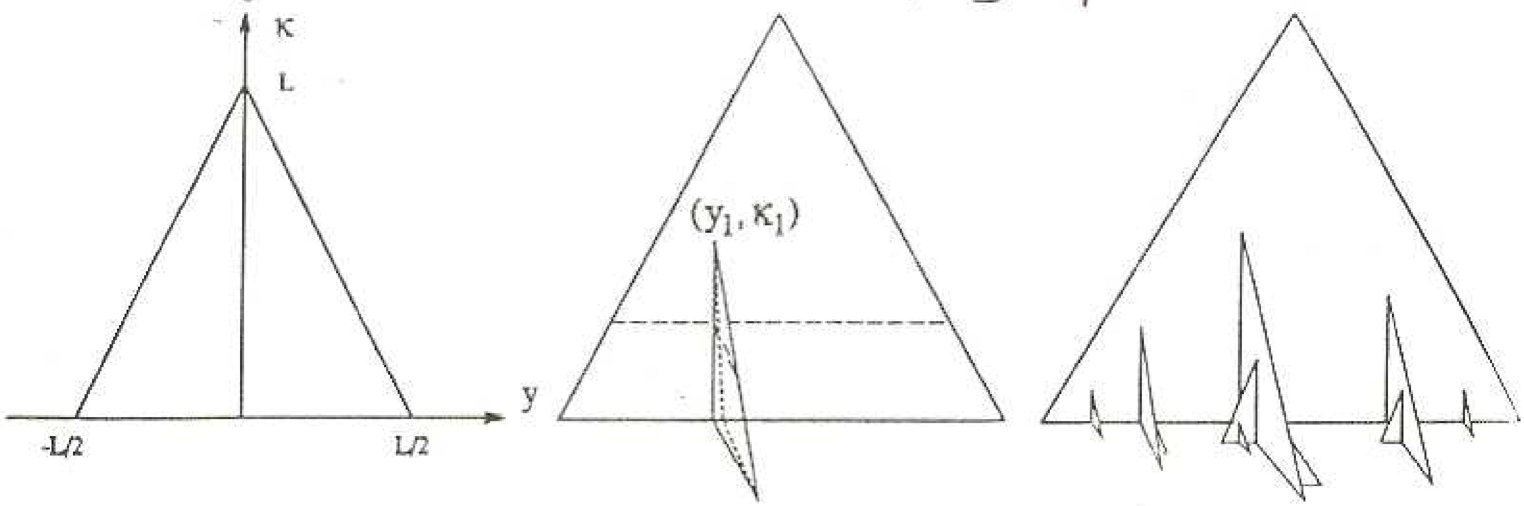
a.k.a. the colour dipole model

soft radiation from colour-anticolour dipole universal (and semiclassical)

each dipole radiates independently apart from kinematic recoil effects



with ~ uniform density in triangular phase space in log(transverse momentum) vs rapidity space



Sufficient for analytical calculations, but for Monte Carlo implementation, need recoil strategy

ARIADNE gives best description of $e^+e^- \to 4$ jets ⟶

⇒ good choice of recoil strategy

Hamacher & Weierstall hep-ex/9511011

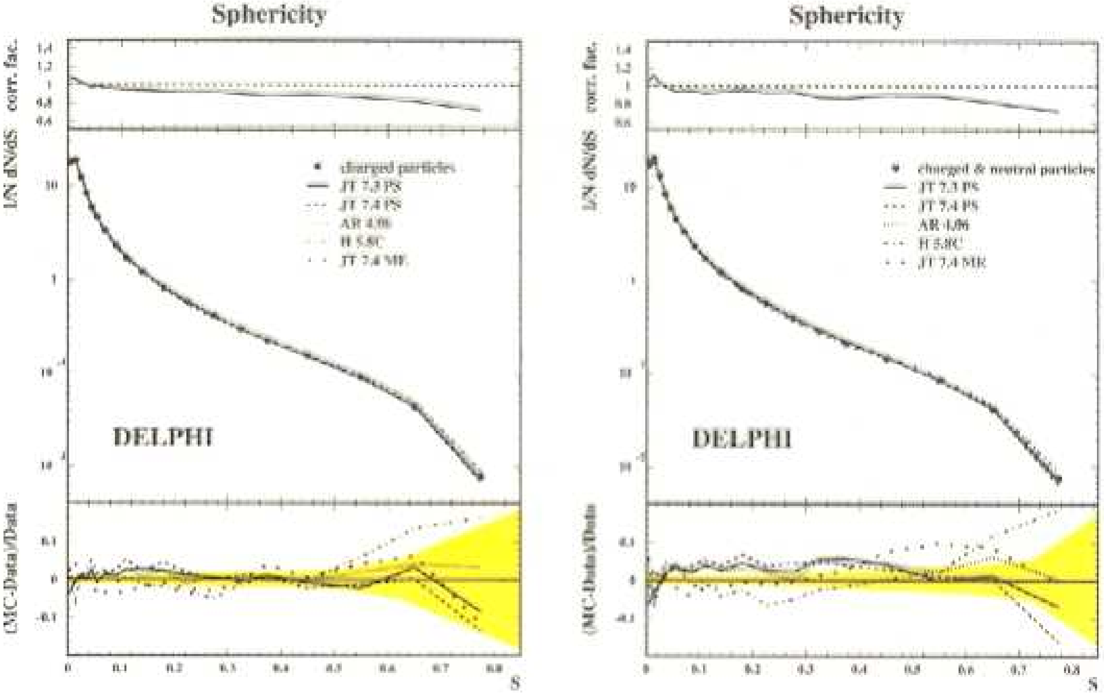


Figure 19: Distribution of the Sphericity

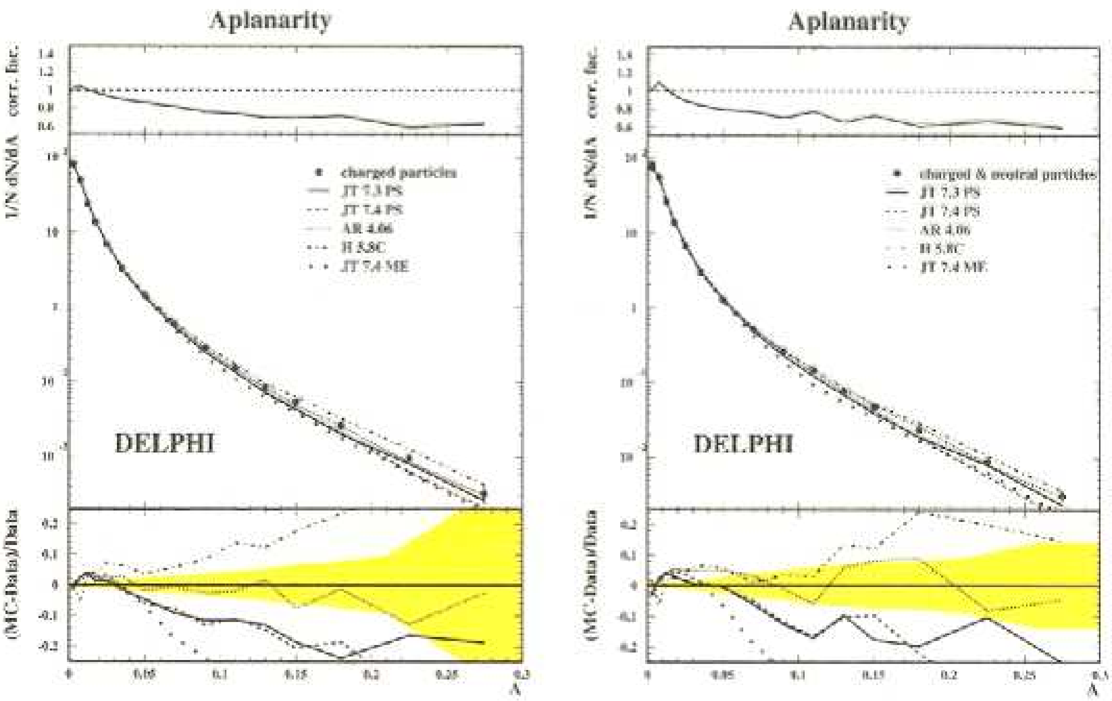
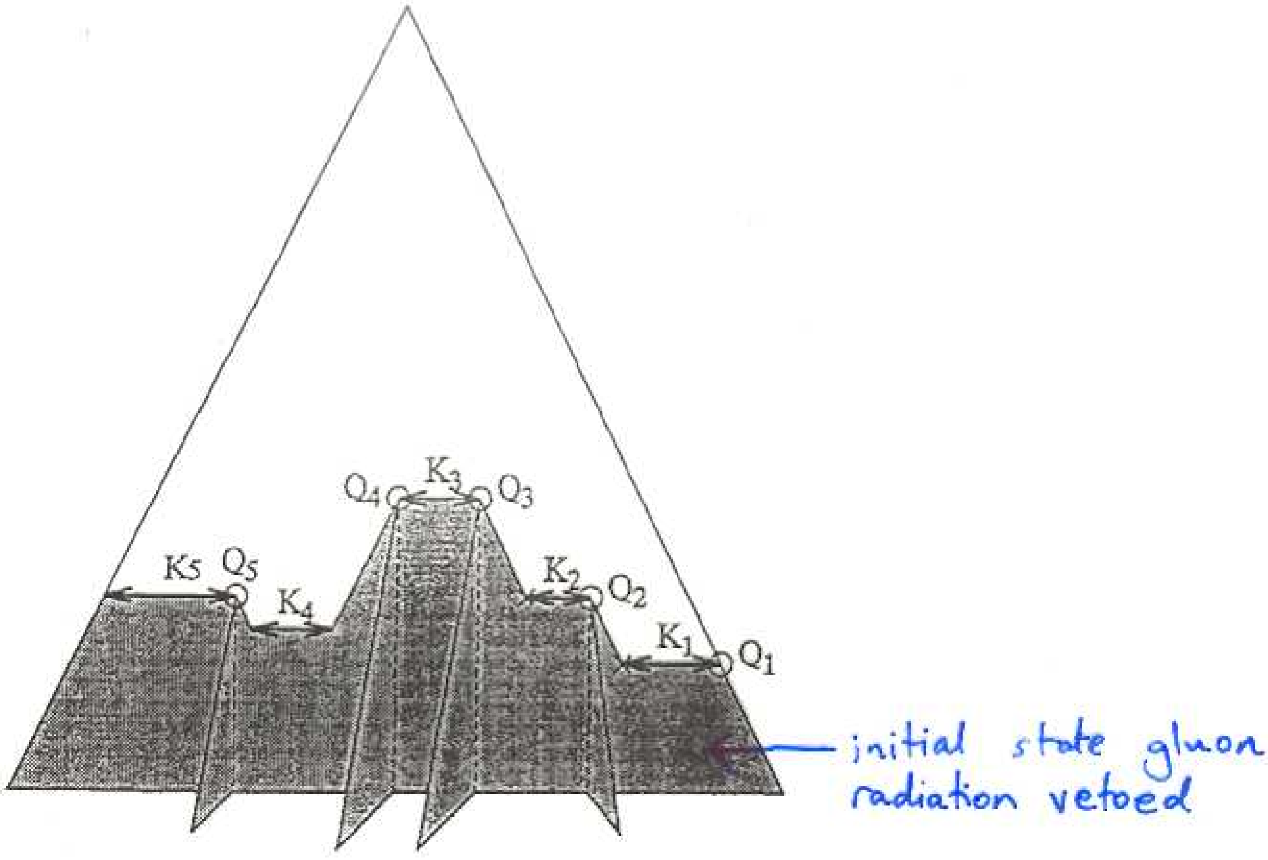


Figure 20: Distribution of the Aplanarity

The Linked Dipole Chain Model for small x cascades

Critical study of CCFM equation (Catani, Ciafaloni, Fiorani & Marchesini) showed that its "non-Sudakov" logs can be made Sudakov-like by a suitable division of phase space into initial state and final state



Linked dipole chain then acts as starting point for conventional dipole cascade: final state radiation

- left-right symmetric
- 2→2 scattering at highest p_t.

LDCMC Allows inclusion of subleading effects
- energy conservation
- full splitting functions

-huge effects ?

⇒ huge uncertainties !

The Importance of Energy Conservation was always stressed by Bo

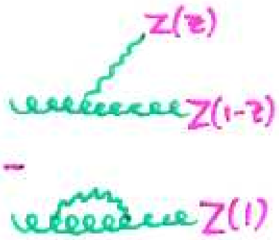
- energy conservation is a next-to-next-to-leading log effect in jet evolution

⇒ negligible? NO!

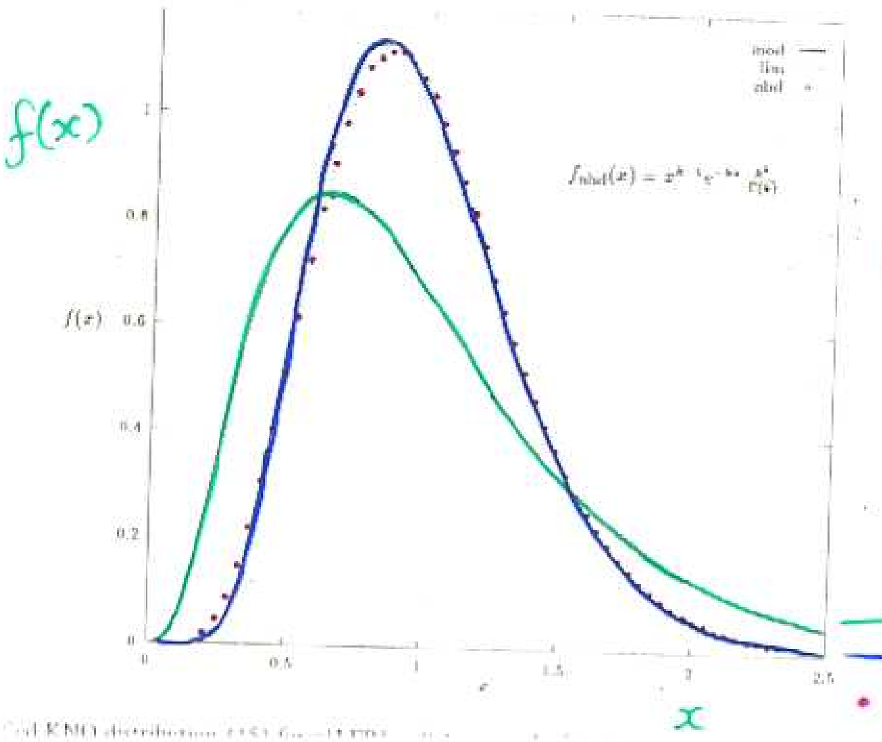
1) "Improved QCD treatment of the KNO phenomenon"
Yuri Dokshitzer: Lund preprint LUTP-93-03
Phys. Lett. B305 (1993) 295

MLLA evolution equation for generating functional:

$$\frac{dZ(Q)}{d\ln Q} = \int_0^1 dx\, P(x) \left[Z(xQ)\, Z((1-x)Q) - Z(Q) \right]$$



recoil effect: $(1-x)Q \to Q$ with NLL accuracy
retain ⇒ profound effect on KNO function

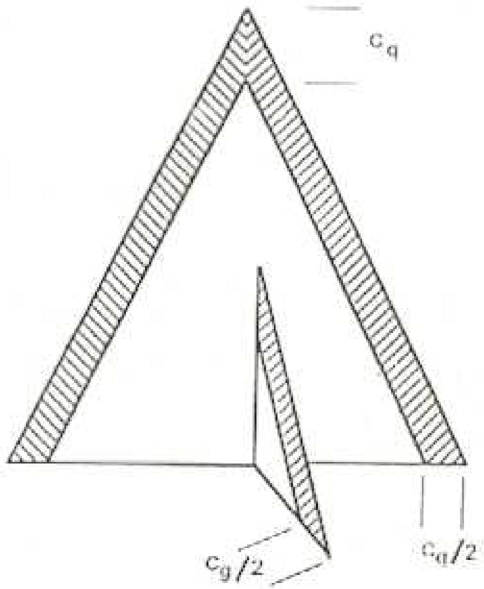


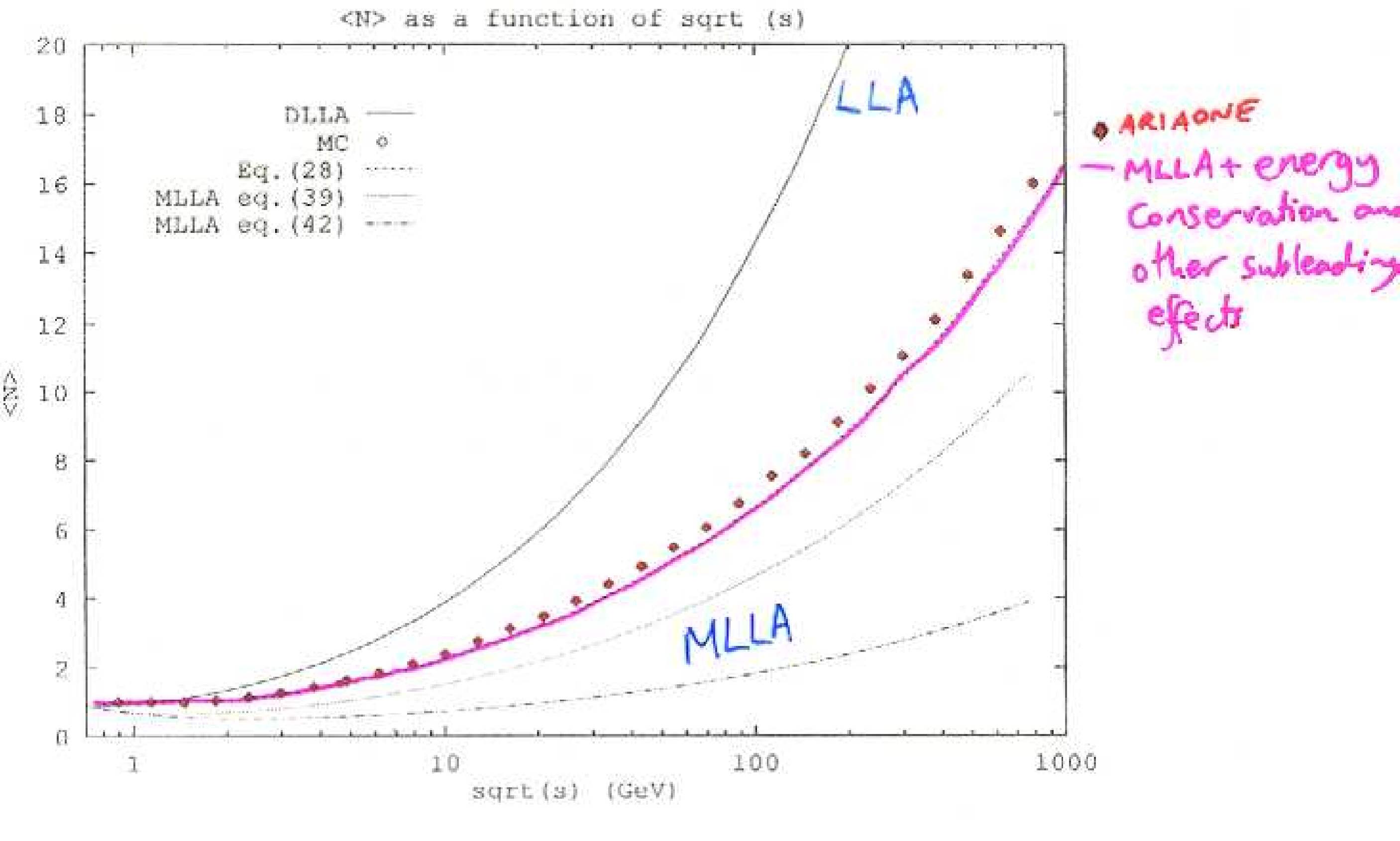
$$P_n \simeq \frac{1}{\bar{n}} f\left(\frac{n}{\bar{n}}\right)$$

– energy conservation as a NNLL effect

2) "Hadron and jet multiplicities in QCD cascades"
M. Olsson & Gösta Gustafson: Lund preprint LUTP-93-01
Nucl. Phys. B406 (1993) 293

snipping ends off DCM triangle to implement energy conservation and other subleading effects





– energy conservation as a NNLL effect

3) "Soft isolated photon production as a probe of the parton shower mechanism"
Mike Seymour: Lund preprint LUTP-94-06
Z. Phys. C64 (1994) 445

Large angle low energy photons (~3 – 10 GeV)
sensitive to competition for phase space with gluons

ARIADNE: photon low $k_\perp \Rightarrow$ emitted last
HERWIG: photon large angle $\Rightarrow$ emitted first
JETSET: half way in between

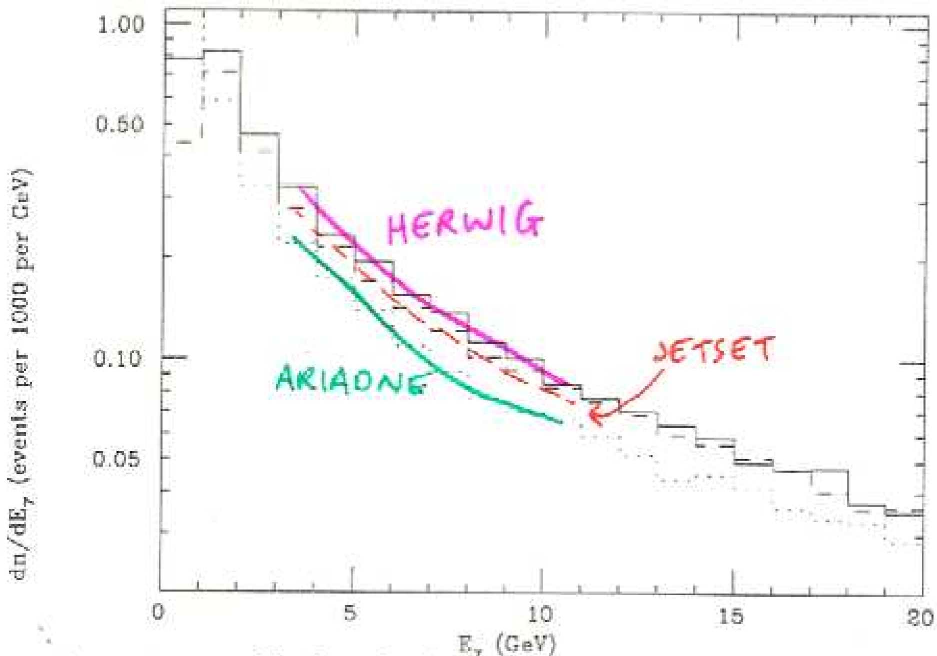


Figure 3: Energy spectrum of isolated photons that are more than 60° from the thrust axis, from HERWIG (solid), ARIADNE (dashed) and JETSET (dotted).

→ only known difference in measurable predictions of perturbative parts of the models

..... a recent example: energy conservation in BFKL

J.R. Andersen, V. Del Duca, S. Frixione, C.R. Schmidt and W.J. Stirling, "Mueller–Navelet Jets at Hadron Colliders" JHEP 0102 (2001) 007

Mueller–Navelet jets supposed to be smoking gun for BFKL evolution....

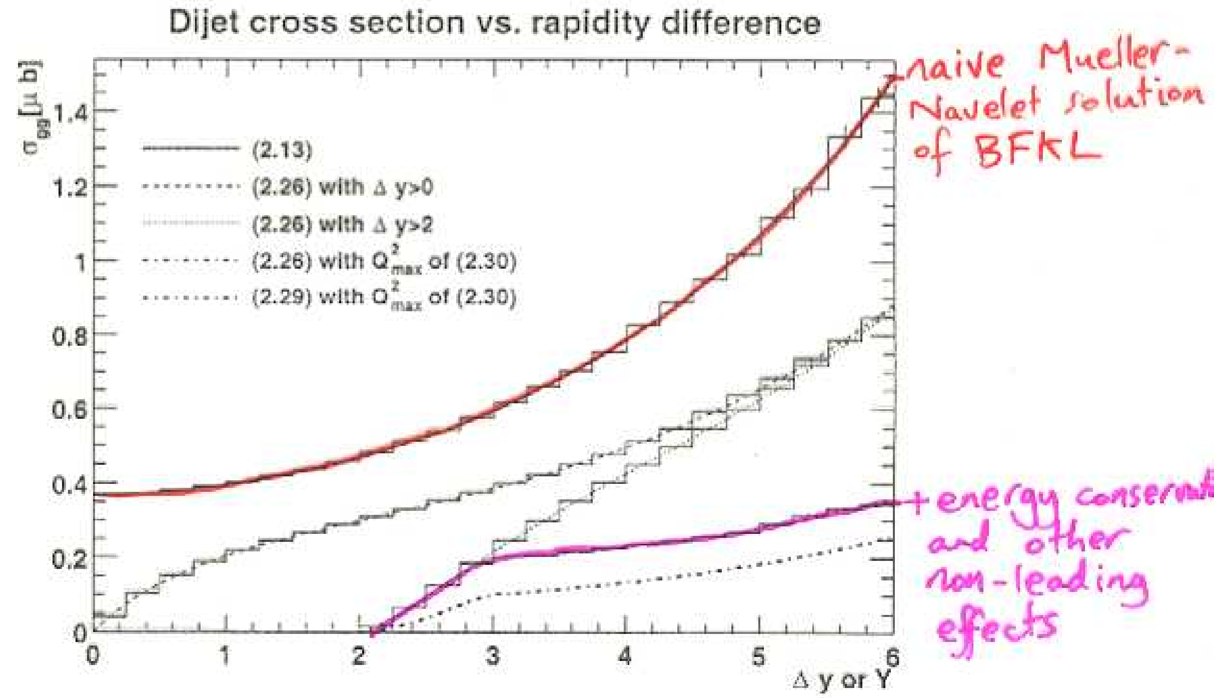


Figure 2: *The dependence of the LL BFKL gluon-gluon cross section on Δy in the standard Mueller-Navelet calculation (Eq. (2.13)) (upper solid line) and on Y for the D0 setup (Eq. (2.26)). Four curves are shown for the definition of x's applied in the D0 analysis: Dashed line for the requirement $\Delta y > 0$, dotted line for $\Delta y > 2$, dash-dotted for $Q^2_{\max}$ of Eq. (2.30) and finally the lower, fat dash-dotted line for the asymptotic behaviour (Eq. (2.29)) using $Q^2_{\max}$ of Eq. (2.30). The histograms are filled using the MC.*

Latest news – constant progress & updates

- one example: matrix element/parton shower matching
  - parton shower/dipole cascade reliable for soft or collinear emission and high multiplicities
  - fixed order matrix elements reliable for hard well-separated emission and fixed multiplicity
  - can we combine advantages of both?

- T. Sjöstrand and G. Miu, Phys. Lett. B449 (1999) 313
  - consistent treatment of parton shower kinematics with hard process
    → non-logarithmic effect but very important
  - match with tree-level next-order M.E. at high p_t
    → eg p_t distribution of Higgs at LHC ⟶

- L. Lönnblad, JHEP 0205 (2002) 046
  - match DCM with all orders of tree level matrix element (in e^+e^-)
    → even better description of 4-jet events

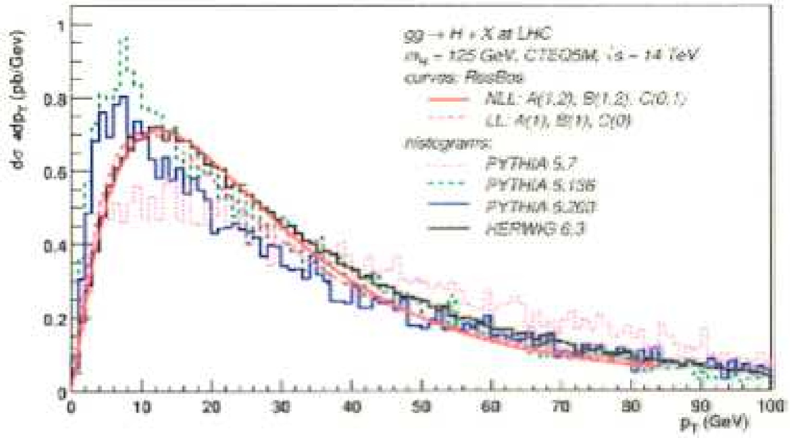
- G. Corcella and M.H. Seymour, Nucl. Phys. B565 (2000) 227

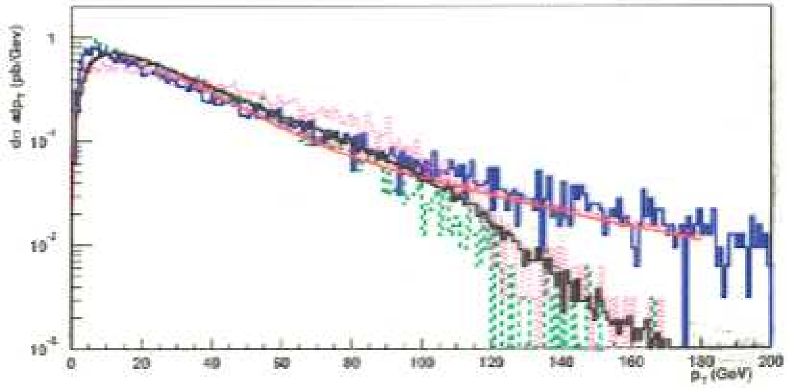
⋮

A Final Example

- Light Higgs production at the LHC
  - Kinematics identical to Z production at Tevatron
  - Gluon–gluon fusion at smallish x: a lot more initial state radiation
  - $\Rightarrow$ parton showers and matrix element corrections more important

- Detection efficiency depends crucially on Higgs p_t. . .





The Future – PYTHIA 7

- PYTHIA and HERWIG are approaching 20 years old! and have grown uncontroledly

⇒ need major rewrites: PYTHIA7 and HERWIG++ with shared structure and interface

Switch to object oriented design and open architecture → easier to accept new external contributions while protecting integrity of 'core'

(at least) five year project.....

Current status:
- conceptual design exists
- most administration code exists (Lönnblad, Sjöstrand + Bertini, Ribon)
- string model implemented (Bertini)
- cluster model implemented (Ribon)
- HERWIG-like parton showers in progress (Ribon, Gieseke)
- secondary hadron decays almost complete (Stephens)

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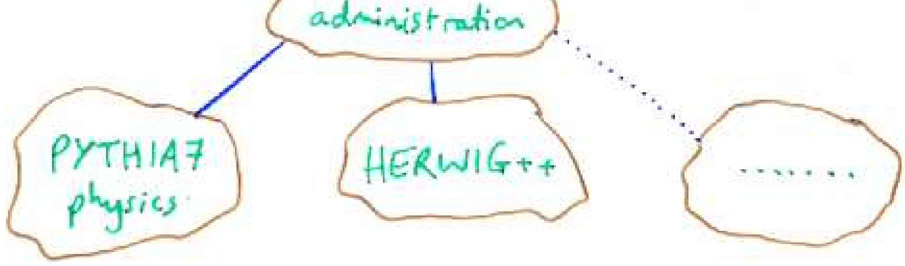
Current goal:
- fully working programs with all of current funcionality by ~2004

Structure:



Summary

– Bo Andersson's legacy is strong and healthy and will continue to have a profound influence on our field for many years to come

He impressed on us all the importance of:

- practical implementations of physical models
- physical insight and intuition
- making physical approximations rather than mathematical

⋮

- getting excited about physics