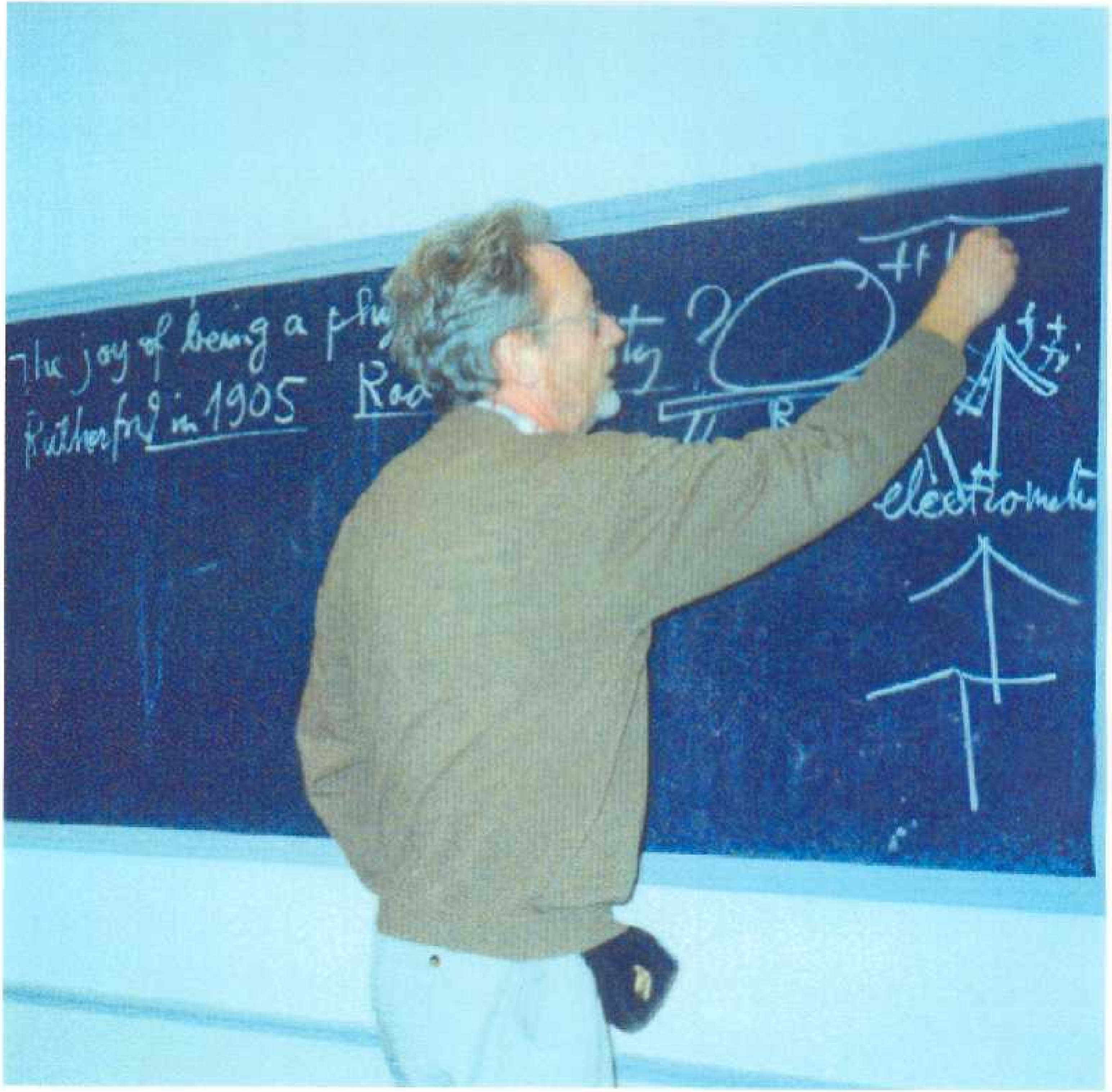

Bo Andersson

8/6 1937 - 4/3 2002

LUND MODEL

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Patrik Edén, Markus Ringnér, Christer Friberg,
Emanuel Norrbin

I. String fragmentation model

Infrared stability

II. Parton cascade models. Dipole model

colour coherence

III. MC programs

Applications to all kinds of high energy collisions

JETSET version 1 (1978)

Appendix

Listings of the program components.

```
      SUBROUTINE JETGEN(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /PAR/ PUD, PS1, SIGMA, CX2, EBEG, WFIN, IFLBEG
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      IFLSGN=(10-IFLBEG)/5
      W=2.*EBEG
      I=0
      IPD=0
C 1 FLAVOUR AND PT FOR FIRST QUARK
      IFL1=IABS(IFLBEG)
      PT1=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI1=6.2832*RANF(0)
      PX1=PT1*COS(PHI1)
      PY1=PT1*SIN(PHI1)
  100 I=I+1
C 2 FLAVOUR AND PT FOR NEXT ANTIQUARK
      IFL2=1+INT(RANF(0)/PUD)
      PT2=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI2=6.2832*RANF(0)
      PX2=PT2*COS(PHI2)
      PY2=PT2*SIN(PHI2)
C 3 MESON FORMED, SPIN ADDED AND FLAVOUR MIXED
      K(I,1)=MESO(3*(IFL1-1)+IFL2,IFLSGN)
      ISPIN=INT(PS1+RANF(0))
      K(I,2)=1+9*ISPIN+K(I,1)
      IF(K(I,1).LE.6) GOTO 110
      TMIX=RANF(0)
      KM=K(I,1)-6+3*ISPIN
      K(I,2)=8+9*ISPIN+INT(TMIX+CMIX(KM,1))+INT(TMIX+CMIX(KM,2))
C 4 MESON MASS FROM TABLE, PT FROM CONSTITUENTS
  110 P(I,5)=PMAS(K(I,2))
      P(I,1)=PX1+PX2
      P(I,2)=PY1+PY2
      PMTS=P(I,1)**2+P(I,2)**2+P(I,5)**2
    RANDOM CHOICE OF X=(E+PZ)MESON/(E+PZ)AVAILABLE GIVES E AND PZ
      X=RANF(0)
      IF(RANF(0).LT.CX2) X=1.-X**(1./3.)
      P(I,3)=(X*W-PMTS/(X*W))/2.
      P(I,4)=(X*W+PMTS/(X*W))/2.
C 6 IF UNSTABLE, DECAY CHAIN INTO STABLE PARTICLES
  120 IPD=IPD+1
      IF(K(IPD,2).GE.8) CALL DECAY(IPD,I)
      IF(IPD.LT.I.AND.I.LE.96) GOTO 120
C 7 FLAVOUR AND PT OF QUARK FORMED IN PAIR WITH ANTIQUARK ABOVE
      IFL1=IFL2
      PX1=-PX2
      PY1=-PY2
C 8 IF ENOUGH E+PZ LEFT, GO TO 2
      W=(1.-X)*W
      IF(W.GT.WFIN.AND.I.LE.95) GOTO 100
      N=I
      RETURN
      END
```

```
      SUBROUTINE EDIT(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /EDPAR/ ITHROW, PZMIN, PMIN, THETA, PHI, BETA(3)
      REAL ROT(3,3), PR(3)
C 1 THROW AWAY NEUTRALS OR UNSTABLE OR WITH TOO LOW PZ OR P
      I1=0
      DO 110 I=1,N
      IF(ITHROW.GE.1.AND.K(I,2).GE.8) GOTO 110
      IF(ITHROW.GE.2.AND.K(I,2).GE.6) GOTO 110
      IF(ITHROW.GE.3.AND.K(I,2).EQ.1) GOTO 110
      IF(P(I,3).LT.PZMIN.OR.P(I,4)**2-P(I,5)**2.LT.PMIN**2) GOTO 110
      I1=I1+1
      K(I1,1)=IDIM(K(I,1),0)
      K(I1,2)=K(I,2)
      DO 100 J=1,5
  100 P(I1,J)=P(I,J)
  110 CONTINUE
      N=I1
    ROTATE TO GIVE JET PRODUCED IN DIRECTION THETA, PHI
      IF(THETA.LT.1E-4) GOTO 140
      ROT(1,1)=COS(THETA)*COS(PHI)
      ROT(1,2)=-SIN(PHI)
      ROT(1,3)=SIN(THETA)*COS(PHI)
      ROT(2,1)=COS(THETA)*SIN(PHI)
      ROT(2,2)=COS(PHI)
      ROT(2,3)=SIN(THETA)*SIN(PHI)
      ROT(3,1)=-SIN(THETA)
      ROT(3,2)=0.
      ROT(3,3)=COS(THETA)
      DO 130 I=1,N
      DO 120 J=1,3
  120 PR(J)=P(I,J)
      DO 130 J=1,3
  130 P(I,J)=ROT(J,1)*PR(1)+ROT(J,2)*PR(2)+ROT(J,3)*PR(3)
C 3 OVERALL LORENTZ BOOST GIVEN BY BETA VECTOR
  140 IF(BETA(1)**2+BETA(2)**2+BETA(3)**2.LT.1E-8) RETURN
      GA=1./SQRT(1.-BETA(1)**2-BETA(2)**2-BETA(3)**2)
      DO 160 I=1,N
      BEP=BETA(1)*P(I,1)+BETA(2)*P(I,2)+BETA(3)*P(I,3)
      DO 150 J=1,3
  150 P(I,J)=P(I,J)+GA*(GA/(1.+GA)*BEP+P(I,4))*BETA(J)
  160 P(I,4)=GA*(P(I,4)+BEP)
      RETURN
      END
```

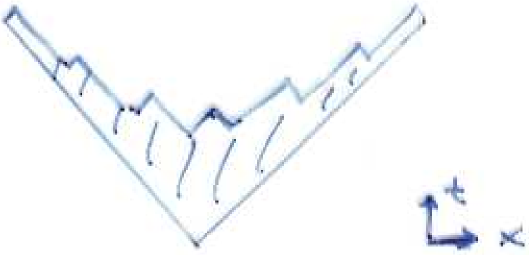
```
      SUBROUTINE DECAY(IPD,I)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      COMMON /DATA2/ IDCO(12), CBR(29), KDP(29,3)
      DIMENSION U(3), BE(3)
C 1 DECAY CHANNEL CHOICE, GIVES DECAY PRODUCTS
      TBR=RANF(0)
      IDC=IDCO(K(IPD,2)-7)
  100 IDC=IDC+1
      IF(TBR.GT.CBR(IDC)) GOTO 100
      ND=(59+KDP(IDC,3))/20
      DO 110 I1=I+1,I+ND
      K(I1,1)=-IPD
      K(I1,2)=KDP(IDC,I1-I)
  110 P(I1,5)=PMAS(K(I1,2))
C 2 IN THREE-PARTICLE DECAY CHOICE OF INVARIANT MASS OF PRODUCTS 2+3
      IF(ND.EQ.2) GOTO 130
      SA=(P(IPD,5)+P(I+1,5))**2
      SB=(P(IPD,5)-P(I+1,5))**2
      SC=(P(I+2,5)+P(I+3,5))**2
      SD=(P(I+2,5)-P(I+3,5))**2
      TOU=(SA-SD)*(SB-SC)/(4.*SQRT(SB*SC))
      IF(K(IPD,2).GE.11) TOU=SQRT(SB*SC)*TOU**3
  120 SX=SC+(SB-SC)*RANF(0)
      TOF=SQRT((SX-SA)*(SX-SB)*(SX-SC)*(SX-SD))/SX
      IF(K(IPD,2).GE.11) TOF=SX*TOF**3
      IF(RANF(0)*TOU.GT.TOF) GOTO 120
      P(100,5)=SQRT(SX)
C 3 TWO-PARTICLE DECAY IN CM, TWICE TO SIMULATE THREE-PARTICLE DECAY
  130 DO 160 IL=1,ND-1
      IO=(IL-1)*100-(IL-2)*IPD
      I1=I+IL
      I2=(ND-IL-1)*100-(ND-IL-2)*(I+IL+1)
      PA=SQRT((P(IO,5)**2-(P(I1,5)+P(I2,5))**2)*
     &(P(IO,5)**2-(P(I1,5)-P(I2,5))**2))/(2.*P(IO,5))
  140 U(3)=2.*RANF(0)-1.
      PHI=6.2832*RANF(0)
      U(1)=SQRT(1.-U(3)**2)*COS(PHI)
      U(2)=SQRT(1.-U(3)**2)*SIN(PHI)
      TDA=1.-(U(1)*P(IO,1)+U(2)*P(IO,2)+U(3)*P(IO,3))**2/
     &(P(IO,1)**2+P(IO,2)**2+P(IO,3)**2)
      IF(K(IPD,2).GE.11.AND.IL.EQ.2.AND.RANF(0).GT.TDA) GOTO 140
      DO 150 J=1,3
      P(I1,J)=PA*U(J)
  150 P(I2,J)=-PA*U(J)
      P(I1,4)=SQRT(PA**2+P(I1,5)**2)
  160 P(I2,4)=SQRT(PA**2+P(I2,5)**2)
C 4 DECAY PRODUCTS LORENTZ TRANSFORMED TO LAB SYSTEM
      DO 190 IL=ND-1,1,-1
      IO=(IL-1)*100-(IL-2)*IPD
      DO 170 J=1,3
  170 BE(J)=P(IO,J)/P(IO,4)
      GA=P(IO,4)/P(IO,5)
      DO 190 I1=I+IL,I+ND
      BEP=BE(1)*P(I1,1)+BE(2)*P(I1,2)+BE(3)*P(I1,3)
      DO 180 J=1,3
  180 P(I1,J)=P(I1,J)+GA*(GA/(1.+GA)*BEP+P(I1,4))*BE(J)
  190 P(I1,4)=GA*(P(I1,4)+BEP)
      I=I+ND
      RETURN
      END
```

```
      SUBROUTINE LIST(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /DATA3/ CHA1(9), CHA2(19), CHA3(2)
      WRITE(6,110)
      DO 100 I=1,N
      IF(K(I,1).GT.0) C1=CHA1(K(I,1))
      IF(K(I,1).LE.0) IC1=-K(I,1)
      C2=CHA2(K(I,2))
      C3=CHA3((47-K(I,2))/20)
      IF(K(I,1).GT.0) WRITE(6,120) I, C1, C2, C3, (P(I,J), J=1,5)
  100 IF(K(I,1).LE.0) WRITE(6,130) I, IC1, C2, C3, (P(I,J), J=1,5)
      RETURN
  110 FORMAT(////T11,'I',T17,'ORI',T24,'PART',T32,'STAB',
     &T44,'PX',T56,'PY',T68,'PZ',T80,'E',T92,'M'/)
  120 FORMAT(10X,I3,4X,A2,1X,2(4X,A4),5(4X,F8.1))
  130 FORMAT(10X,I3,4X,1X,I2,2(4X,A4),5(4X,F8.1))
      END
```

```
      BLOCK DATA
      COMMON /PAR/ PUD, PS1, SIGMA, CX2, EBEG, WFIN, IFLBEG
      COMMON /EDPAR/ ITHROW, PZMIN, PMIN, THETA, PHI, BETA(3)
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      COMMON /DATA2/ IDCO(12), CBR(29), KDP(29,3)
      COMMON /DATA3/ CHA1(9), CHA2(19), CHA3(2)
      DATA PUD/0.4/, PS1/0.5/, SIGMA/350./, CX2/0.77/,
     &EBEG/10000./, WFIN/100./, IFLBEG/1/
      DATA ITHROW/1/, PZMIN/0./, PMIN/0./, THETA,PHI,BETA/5*0./
      DATA MESO/7,1,3,2,8,5,4,6,9,7,2,4,1,3,6,3,5,9/
      DATA CMIX/2*0.5,1.,2*0.5,1.,2*0.25,0.5,2*0.,1./
      DATA PMAS/0.,2*139.6,2*493.7,2*497.7,135.,548.8,957.6,
     &2*765.9,2*892.2,2*896.3,770.2,782.5,1019.6/
      DATA IDCO/0,1,6,11,12,13,15,17,19,21,22,25/
      DATA CBR/1.,0.381,0.681,0.918,0.969,1.,0.426,0.663,0.957,
     &0.980,1.,1.,1.,0.667,1.,0.667,1.,0.667,1.,0.667,1.,1.,
     &0.899,0.987,1.,0.486,0.837,0.986,1./
      DATA KDP/1,1,8,2,1,1,2,8,1,1,1,2,3,6,4,7,5,4,6,5,7,2,2,
     &1,2,4,6,2,1,1,1,8,3,2,1,3,8,17,18,1,8,8,2,8,3,8,3,8,2,8,
     &3,3,8,3,5,7,3,9,0,0,8,8,3,8,9,9,14*0,8,4*0,8,0/
      DATA CHA1/'UD','DU','US','SU','DS','SD','UU','DD','SS'/
      DATA CHA2/'GAMM','PI+','PI-','K+','K-','K0','KB0','PI0','ETA',
     &'ETAP','RHO+','RHO-','K*+','K*-','K*0','KB*0','RHO0','OMEG','PHI
      DATA CHA3/'    ','STAB'/
      END
```

1977 First papers on hadron vs. quark fragm.
& quark fragm. model

1978 Semiclassical model in linear force field



First MC

1979 Gluon jets ; relativ. string
"string effect", infrared stability

1986 Fritiof model ; hh , AA

1987 Dipole model for parton cascades
Multifractal structure

1995 Linked Dipole Chain model
for initial state rad.

A. Hadronization model

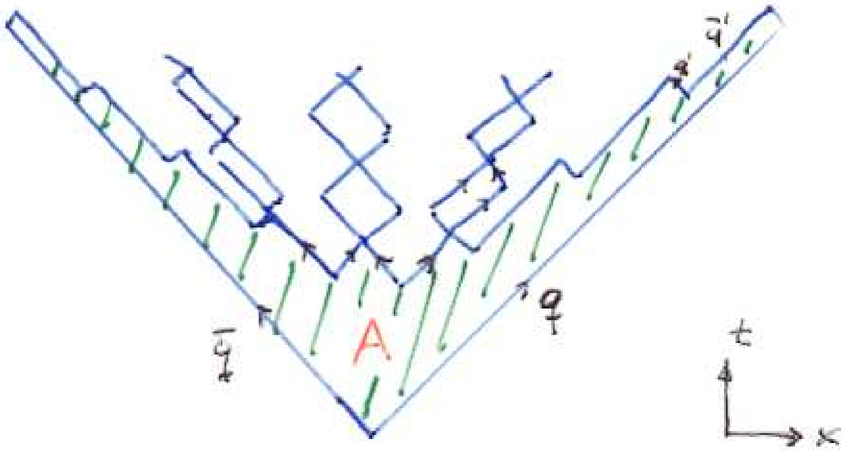
1+1 dim.

 Cascades: Lund, Feynman-Field

Outside-in formulation

Bjorken: QM → inside-out

Semiclassical model from constant force field



Left-right symmetry ⇒

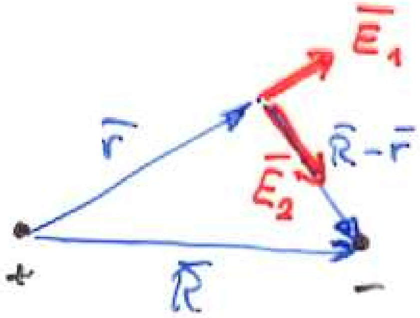
$$dProb \propto \underbrace{\prod_i N d^2 p_i \, \delta(p_i^2 - m_i^2)}_{\text{Phase space}} \cdot \exp(-bA)$$

Area law – Wilson loop

Dynamics: Inside-out; Calculations: Outside-in

B. Gluon Jet

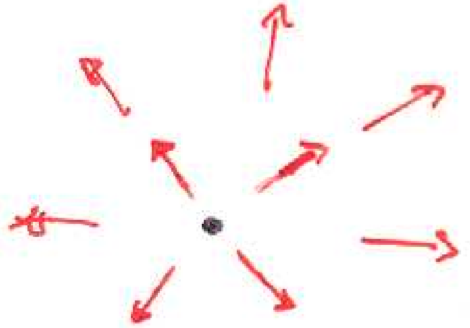
Cf. el.dyn.: Superposition of fields



Energy $\sim \frac{1}{2}\int(\bar{E}_1+\bar{E}_2)^2 dV =$

$$= \frac{1}{2}\int\bar{E}_1^2 dV + \frac{1}{2}\int\bar{E}_2^2 dV + \underbrace{\int\bar{E}_1\bar{E}_2 dV}_{V(\bar{R}) \sim \frac{q_1 q_2}{R}}$$

Colour electric field $\sim \bar{e}_r$?

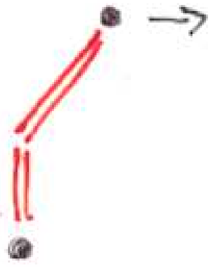


$\Rightarrow \int\bar{E}_1\bar{E}_2 dV \sim \int r^2 dr$

hopelessly divergent!

Superposition not possible for colour fields.

Force field compressed to a tube



Relativity ⇒ String = new degrees of freedom

State not specified only by colour charges

~ vacuum responce is a dynamical degree of freedom

Relativistic string: Pointlike "kinks" may carry energy.

Υ decay

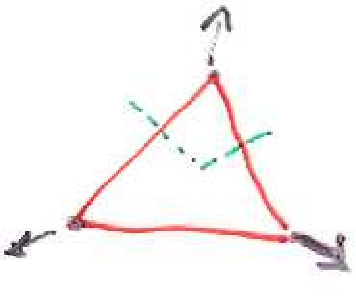
Early expectations:

$$n(g\text{ jet}) \sim 2 \times n(q\text{ jet})$$

$$\Rightarrow n(\Upsilon) \sim 3 \cdot n(\text{contin.})$$

Gluon = kink on a string $\Rightarrow$

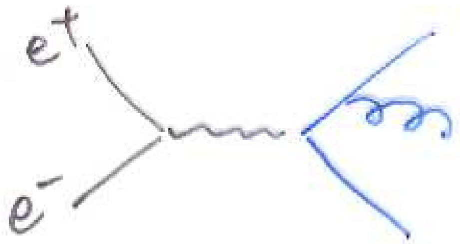
$$n_{q\bar{q}} \sim \ln\left(s/1\,\text{GeV}^2\right)$$

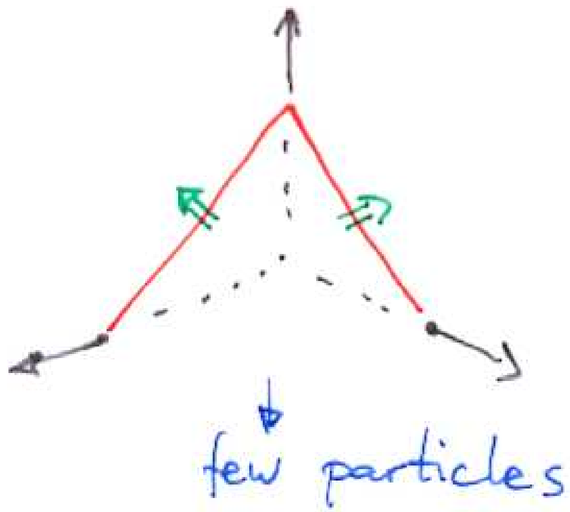


$$n_{\Upsilon} \sim 3 \ln\left(\frac{s}{3 \cdot 1\,\text{GeV}^2}\right)$$

$$\sim 2\, n_{q\bar{q}}$$

"String effect"





fig

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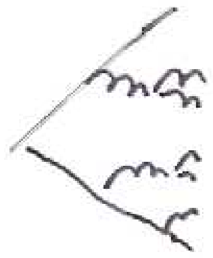
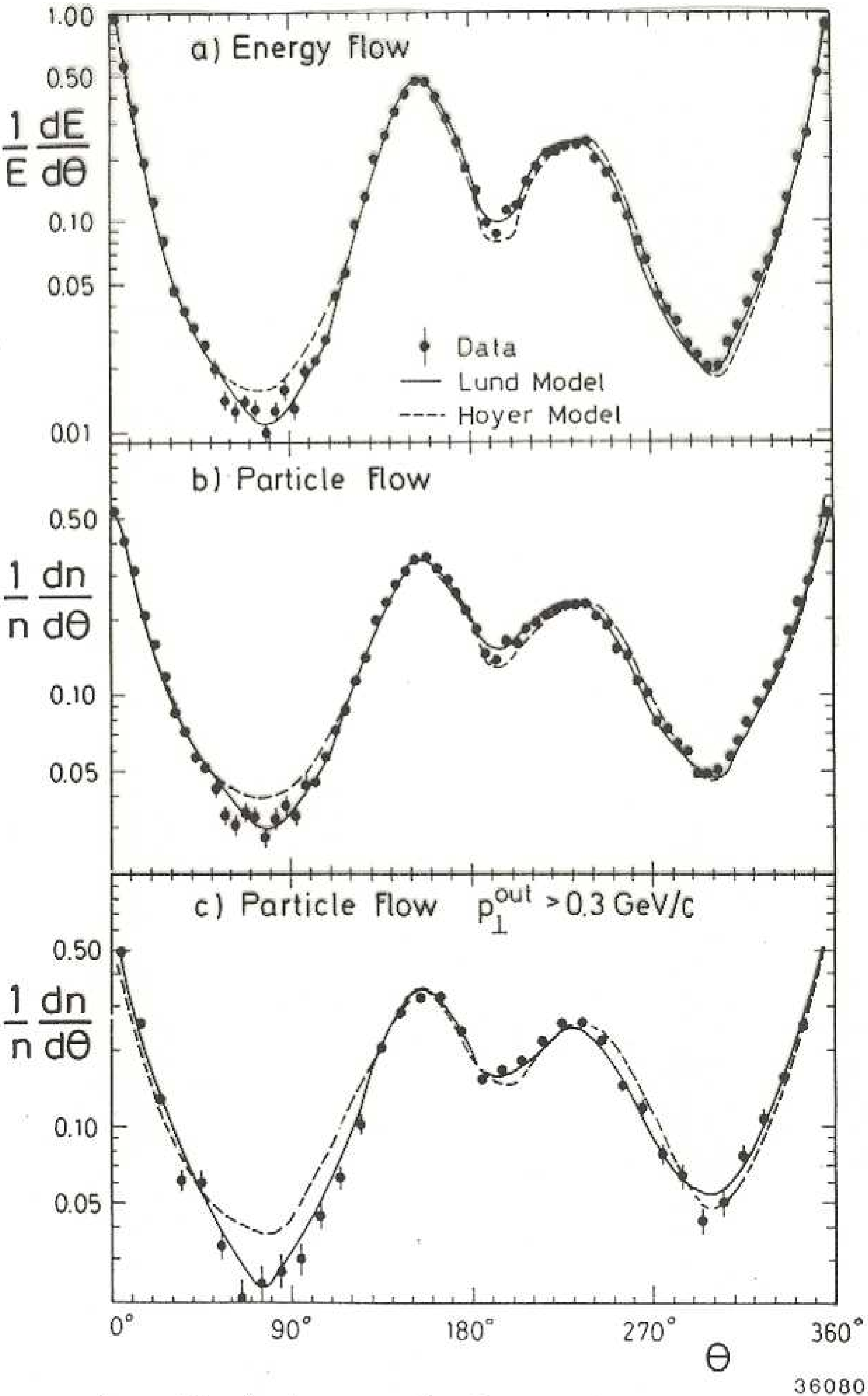
Infrared stability



Soft or collinear gluon: Ampl. → ∞

effect → 0

JADE (1981, 1983)



note: effect bigger if gluon always
could be identified correctly

C. hh-collisions, AA coll.

Hadron fragm. ~ quark fragm.

$\pi^{+} \to h \sim$

$\sim \frac{1}{2}(u \to h + \bar{d} \to h)$

Fragmentation model

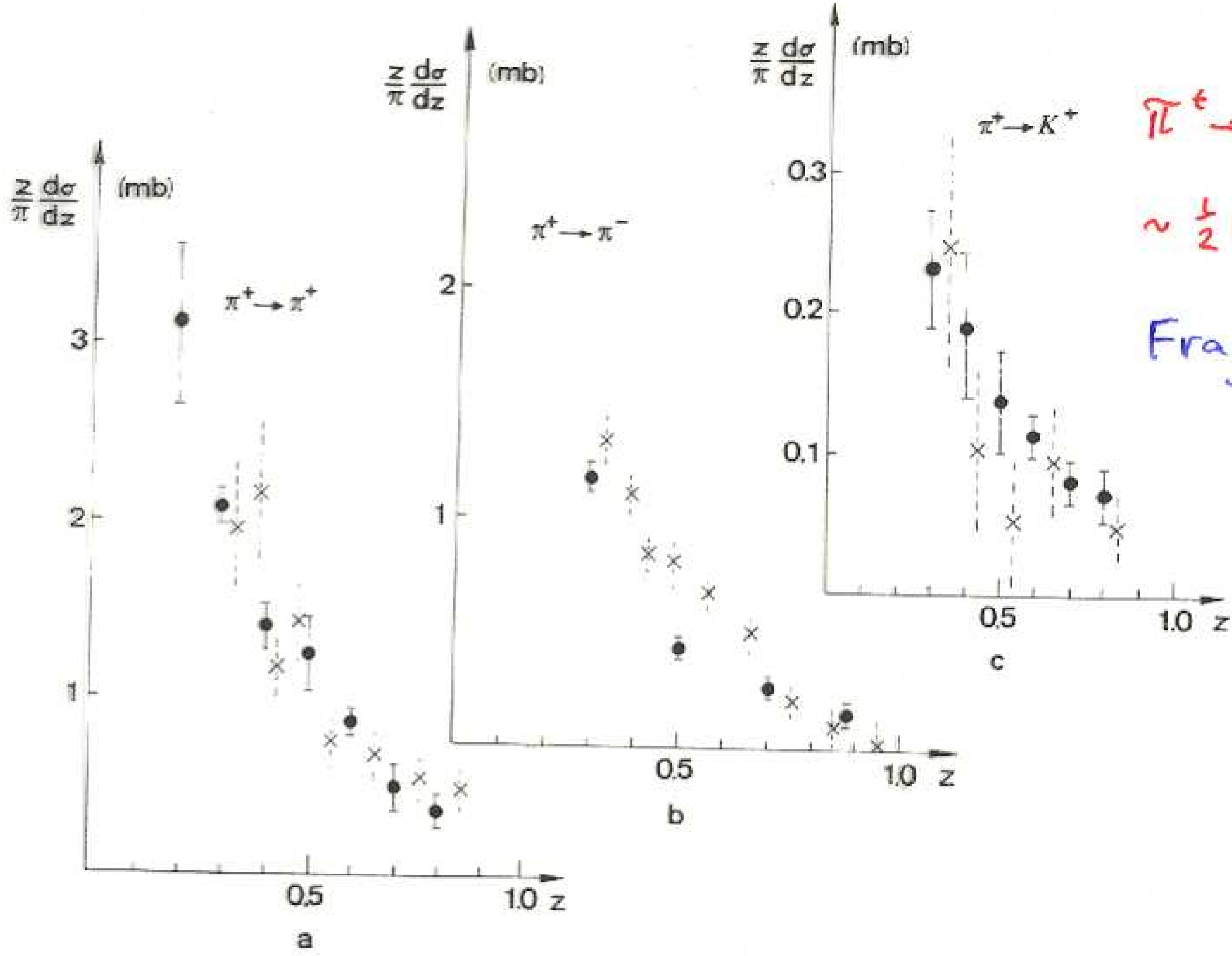
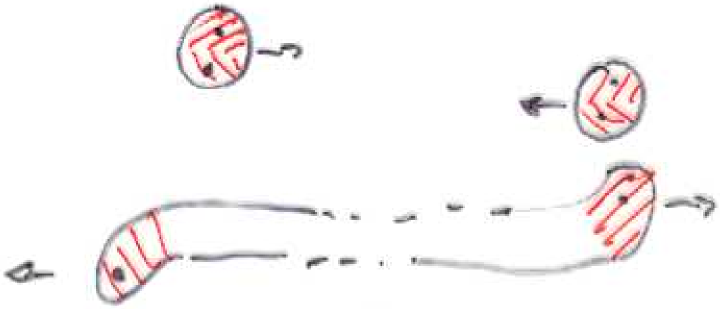


Fig. 5.1. The distributions $(z/\pi)\,d\sigma/dz$ for $\pi^+ \to \pi^+$, π^- and K^-. ●: data for $\pi^+ p \to hX$ from ref. [82], for $\pi^+ \to \pi^+$, the diffractive peak is subtracted. ×: predictions according to eq. (5.1) with quark fragmentation functions from refs. [14, 83] and $\sigma = 18.0$ mb.

Interpretation



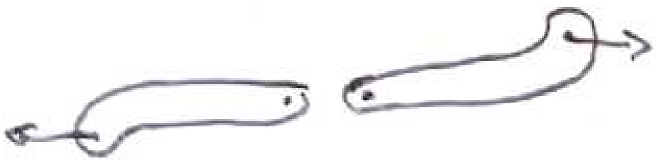
Bags fuse?

Particle distrib. ~ single string

Worked very well for inclusive distrib.

But too small multiplicity fluctuations

Fritiof



Two strings

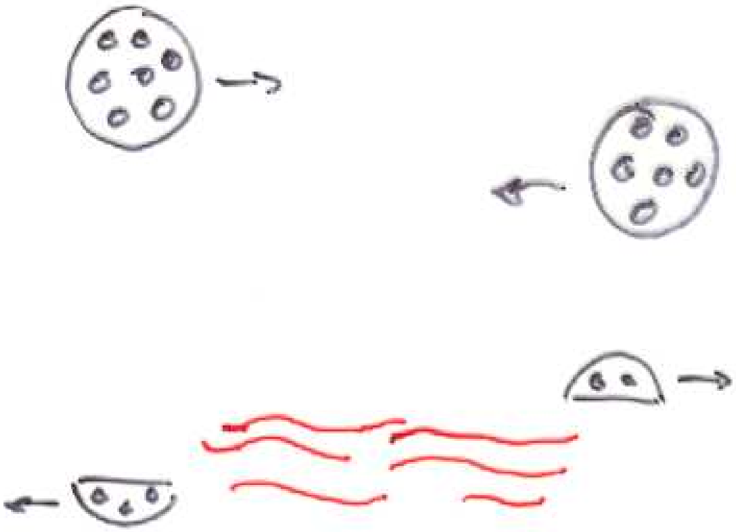
Sometimes overlap

– " – gap

Worked very well for energies up to ISR

Higher energies: Hard subcoll. and multiple scattering import.

Nucleus - nucleus coll.

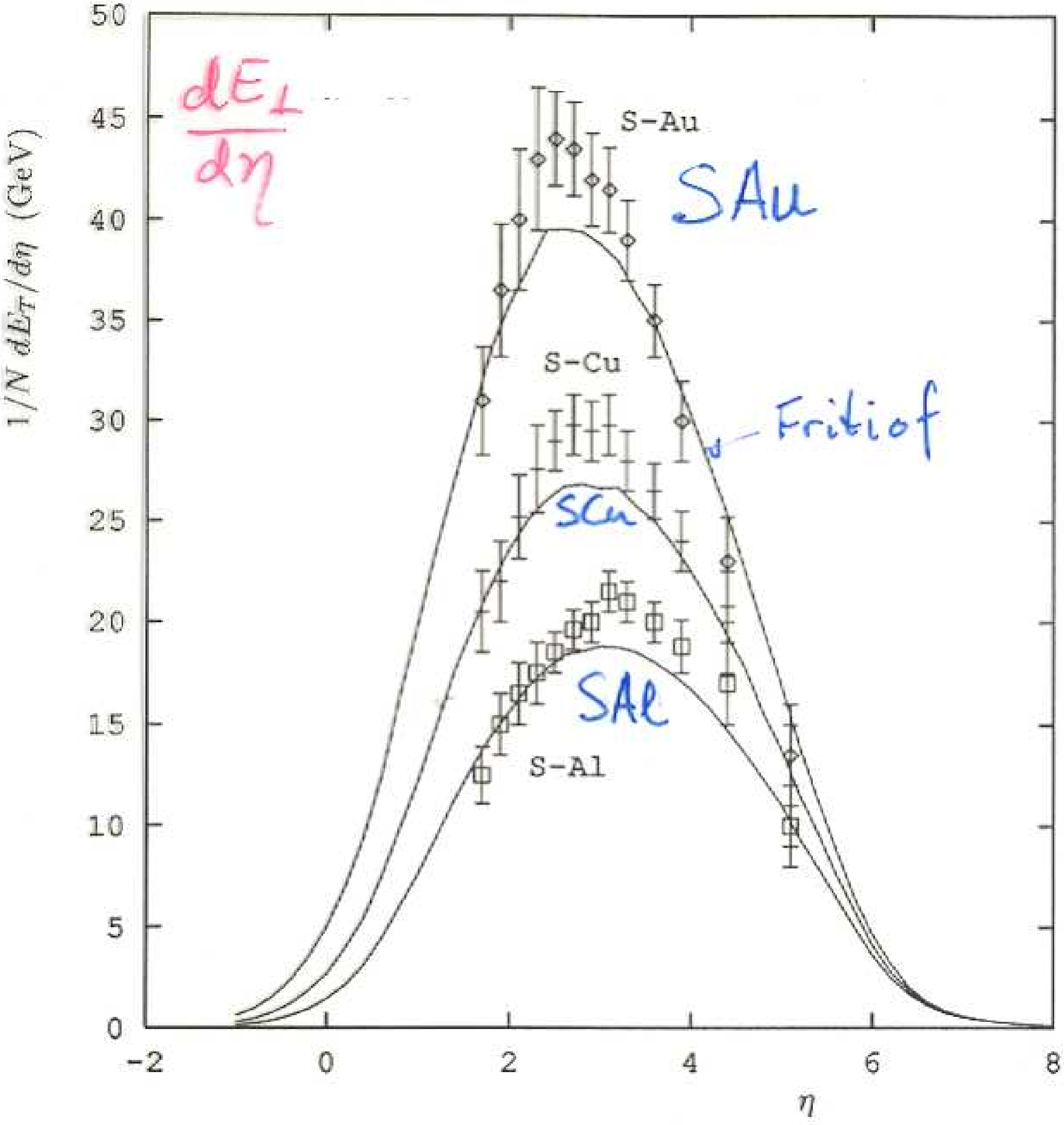


Collab. with KOSUFY (Evert Stenlund.
Ingvar Otterlund)

Aim: Deviations from data indicate plasma formation

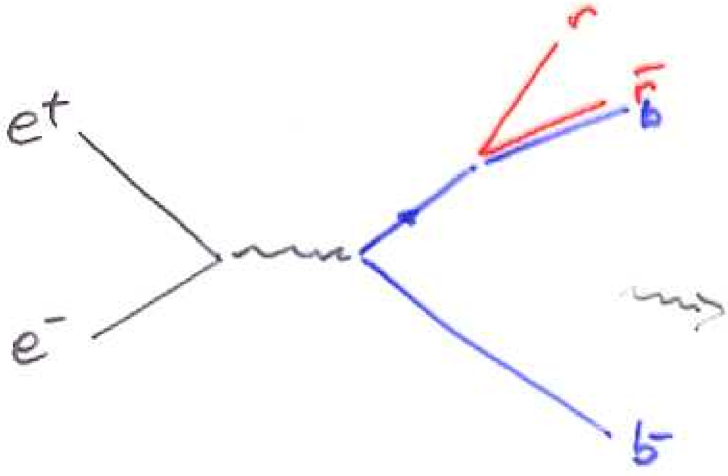
Worked too well!!

WA 80 200A GeV/c



D. Gluon cascades

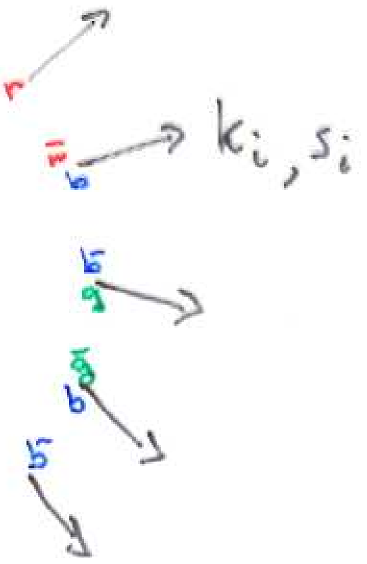
Colour coherence

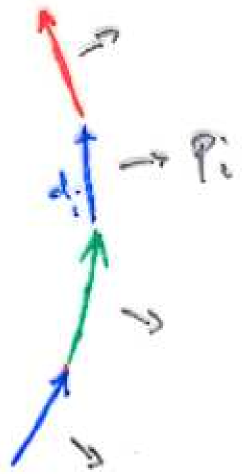


Radiates softer gluons
Like 2 colour dipoles

In this direction
$r + \bar{r}$ emission interferes destructively
Only $b\bar{b}$ emission

Dual description of a parton state

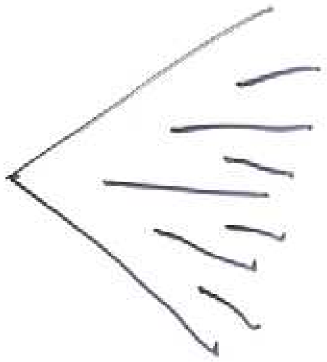




momenta k_i } for gluons
spins s_i }

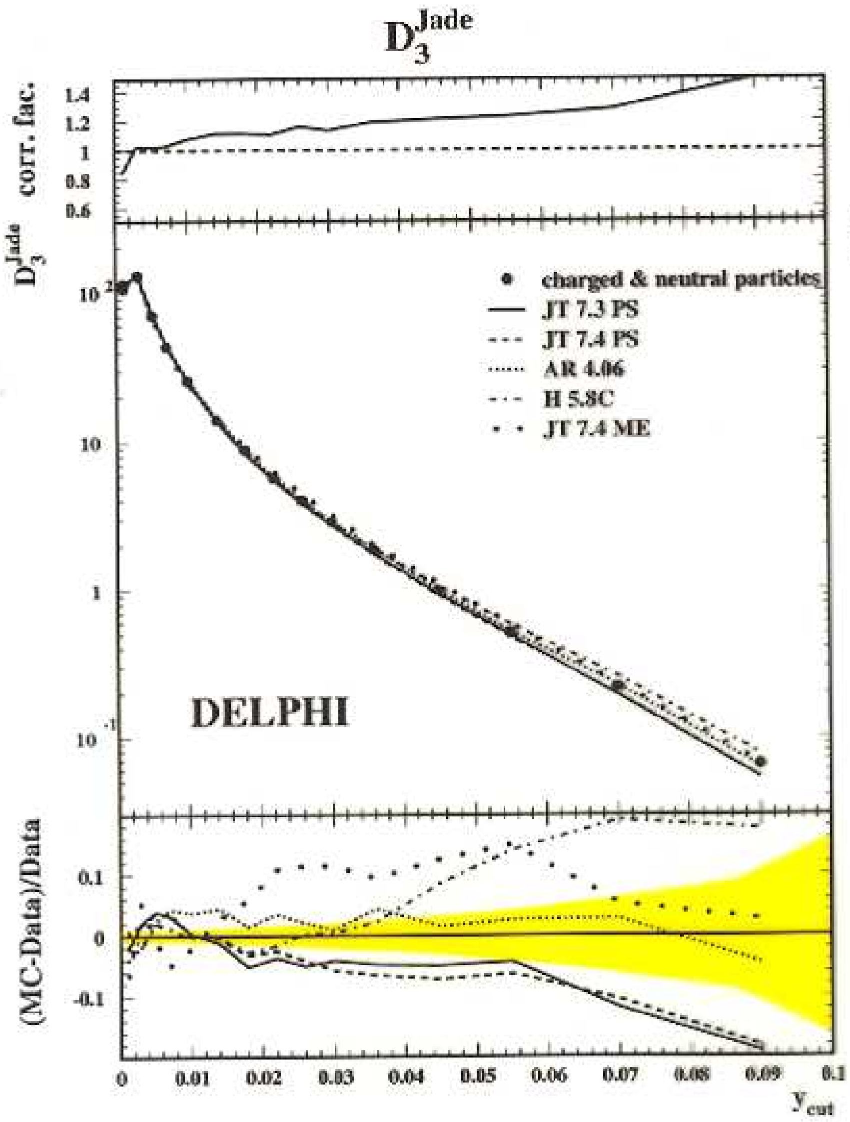
momenta p_i } for dipoles
direction d_i }

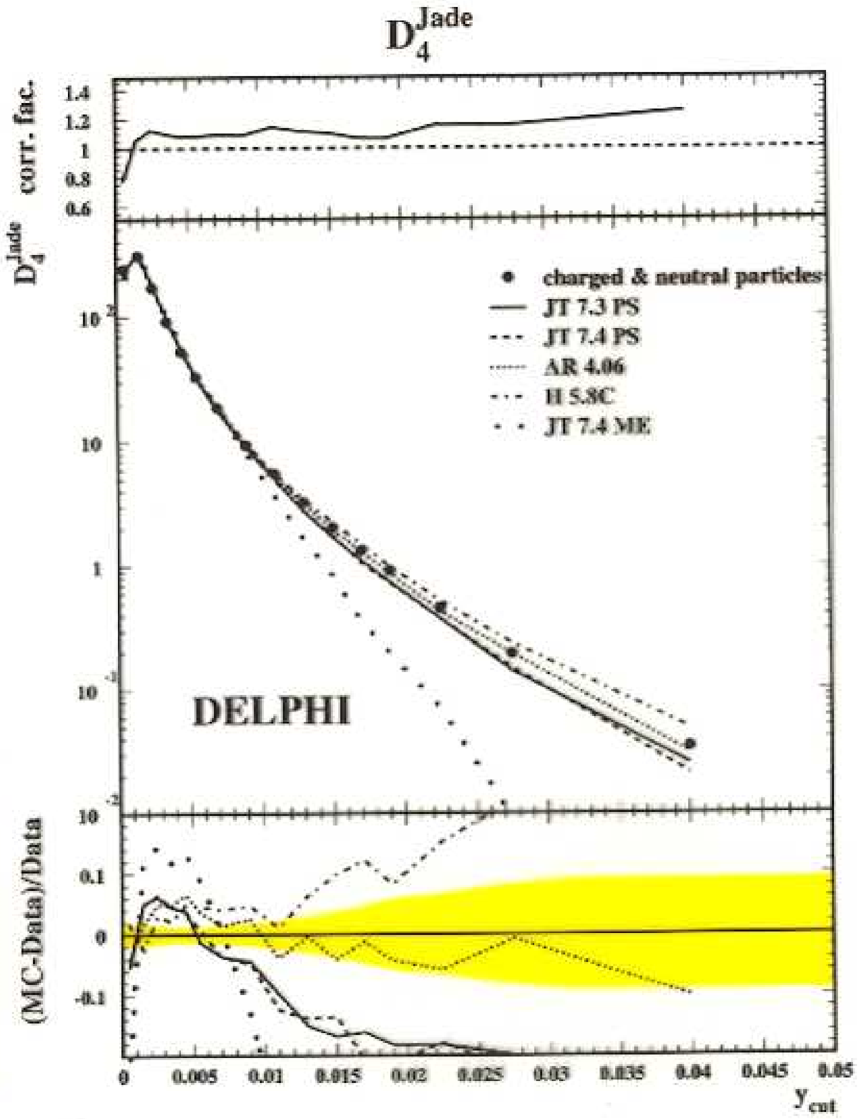
Gluon emission: 1 dipole → 2 dipoles



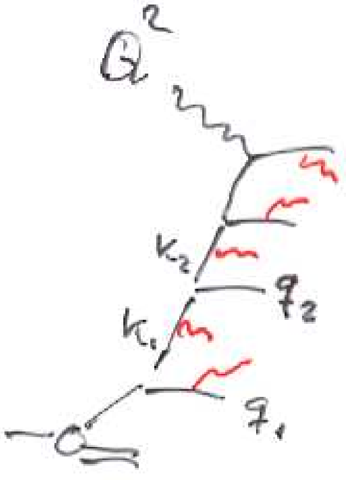
Basis for ARIADNE MC

and for analytic studies


D_3^{Jade}
D_3^{Jade} corr. fac.
1.4
1.2
1
0.8
0.6
D_3^{Jade}
10^2
10
1
10^{-1}
charged & neutral particles
JT 7.3 PS
JT 7.4 PS
AR 4.06
H 5.8C
JT 7.4 ME
DELPHI
(MC-Data)/Data
0.1
0
-0.1
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
y_{cut}


D_4^{Jade}
D_4^{Jade} corr. fac.
1.4
1.2
1
0.8
0.6
D_4^{Jade}
10^2
10
1
10^{-1}
10^{-2}
charged & neutral particles
JT 7.3 PS
JT 7.4 PS
AR 4.06
H 5.8C
JT 7.4 ME
DELPHI
(MC-Data)/Data
10
0.1
0
-0.1
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
y_{cut}

E. DIS Spacelike cascades



small x: $k_\perp$-nonordered chains

un-integrated parton distr.

Define separation

initial state rad. – final state rad.

suitably

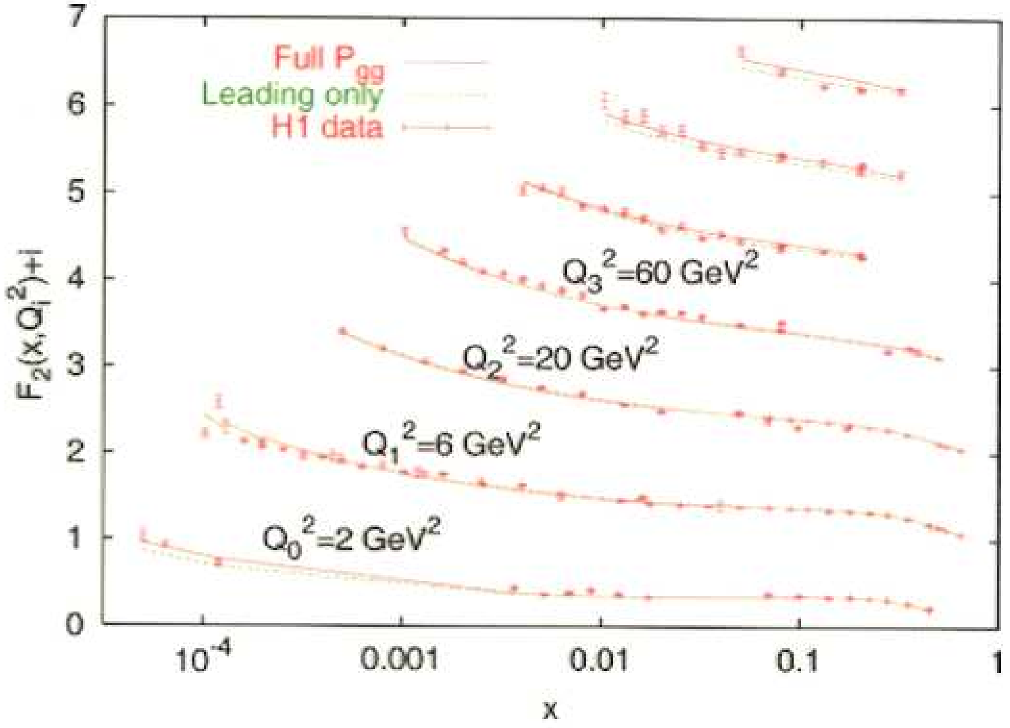
$$\Rightarrow d\sigma \sim \prod_i \frac{3\alpha_s}{\pi} \frac{dq_{\perp i}^2}{q_{\perp i}^2} \frac{dz_i}{z_i}$$

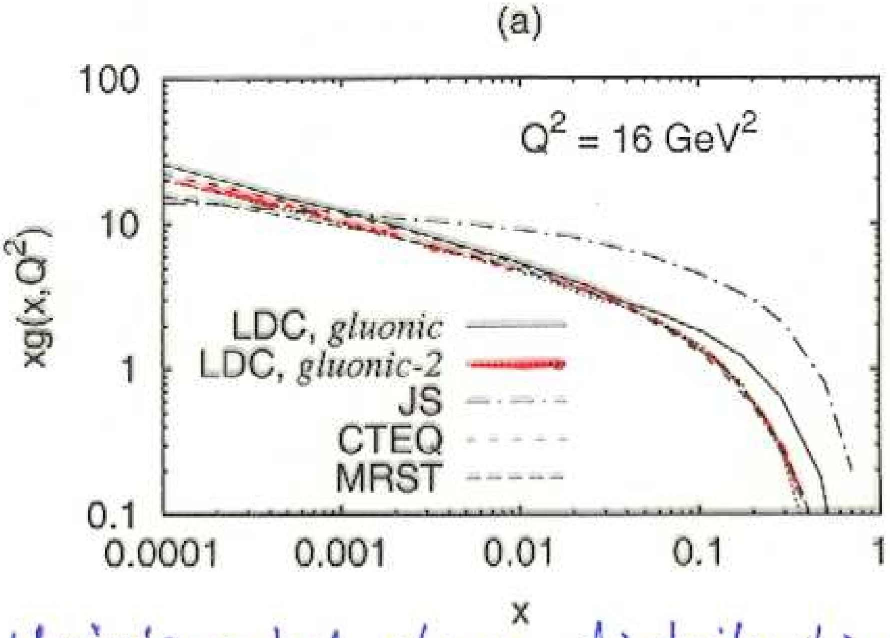
not only in DGLAP region

Linked Dipole Chain model

Fits $F_2(x, Q^2)$, $g(x, Q^2)$

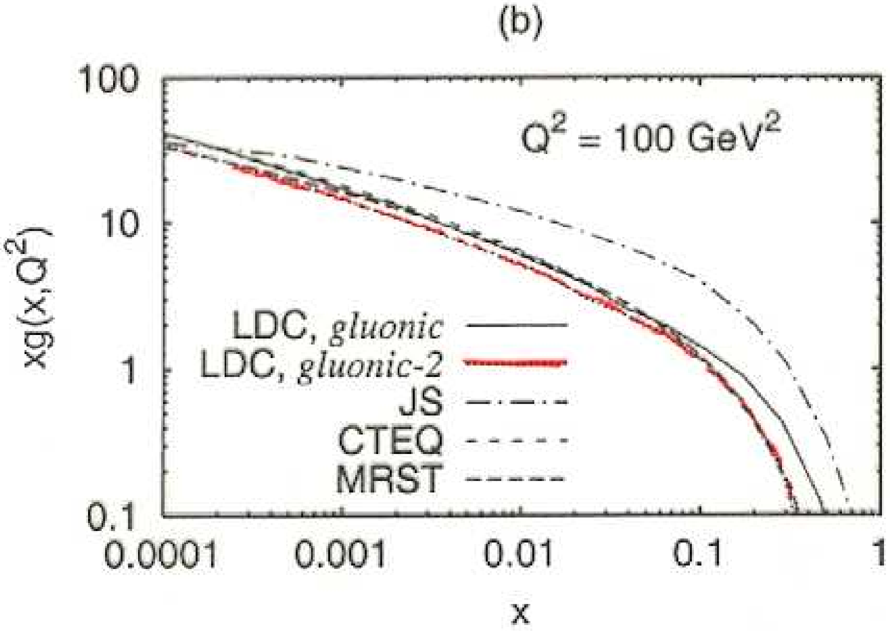
F_2 Linked Dipole Chain MC





Unintegrated gluon distributions

(a)



(b)

Figure 3: *The LDC integrated gluon distribution function (full curve is gluonic, dotted curve is gluonic-2), compared to the corresponding results of JS (dash-dotted curve), CTEQ (short-dashed curve) and MRST (long-dashed curve), for (a)* $Q^2 = 16$ *GeV*^{2} *and (b)* $Q^2 = 100$ *GeV*^{2}

Linked Dipole Chain model for hadronic coll.

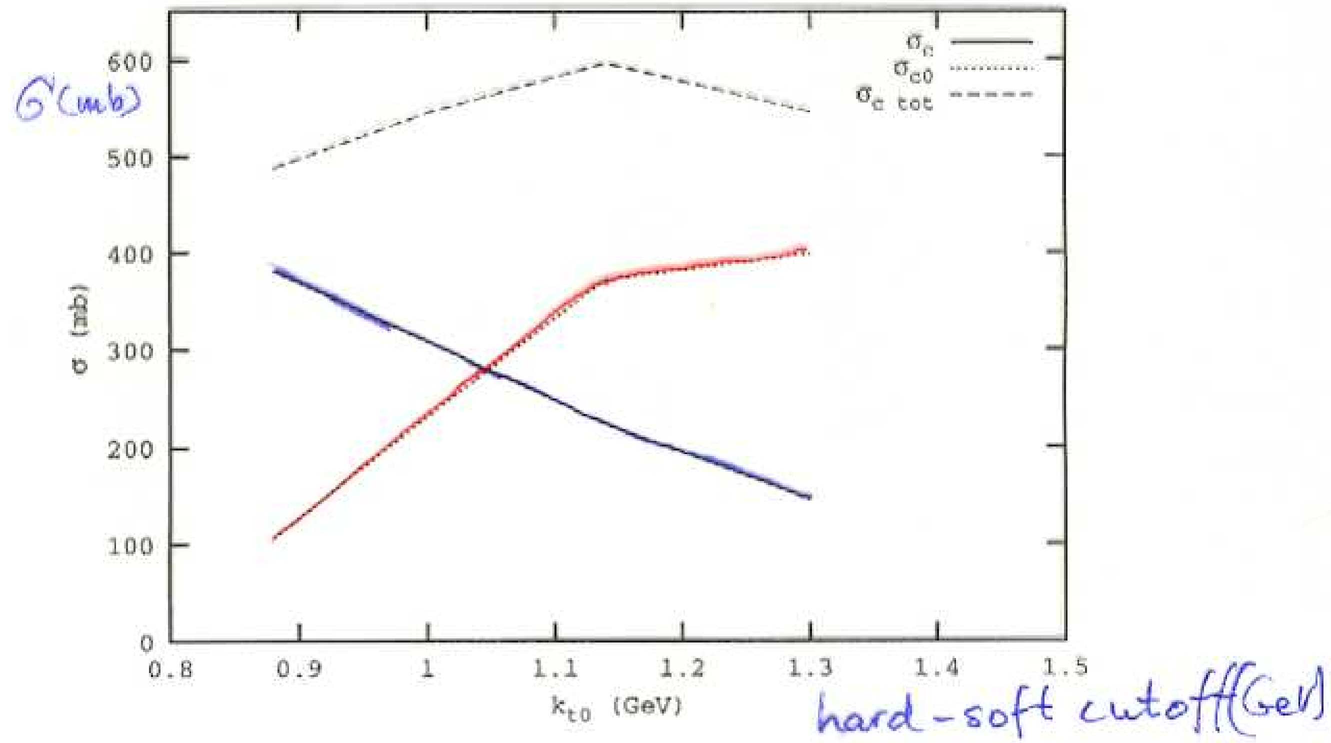


Figure 2: *The cross section per chain in the LDC model as a function of the cutoff, $k_{\perp 0}^2$. The full line is the cross section for chains with at least on emission above the cutoff, the dotted line is for chains without emissions above the cutoff, and the dashed line is the sum of the two. Note that the input parton densities have been refitted for each value of $k_{\perp 0}^2$.*

Cross section for hard scatt chain