Past, Present and Future of the PYTHIA Event Generator

Torbjörn Sjöstrand

Department of Astronomy and Theoretical Physics
Lund University
Sölvegatan 14A, SE-223 62 Lund, Sweden

Jyväskylä, 16 April 2021

1994: First ATLAS/CMS Technical Proposals

CMS Technical Proposal:

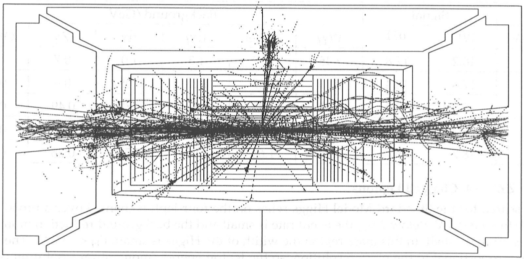


Fig. 12.9: Full GEANT simulation of H(150 GeV) $\rightarrow ZZ^* \rightarrow 2e^+ 2e^-$.

ATLAS T. P.:

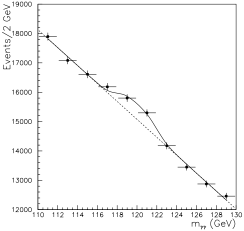


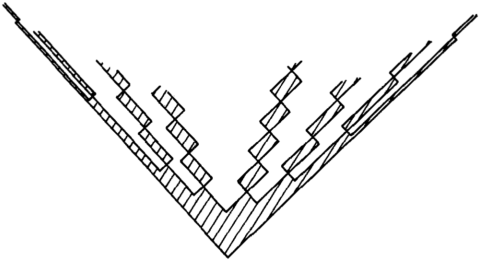
Figure 11.6: Expected $H \rightarrow \gamma\gamma$ signal for $m_H = 120$ GeV, combined with the prompt $\gamma\gamma$ background, assuming an integrated luminosity of 10^5 pb^{-1}.

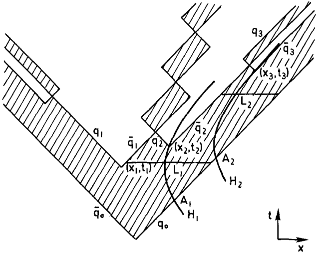
For ATLAS/CMS/LHCb detector design studies in the 1990'ies, PYTHIA was providing input for most GEANT 3 simulations!

How did that come about? What has happened since?

Many of the basic ideas came early, and are "easy" to present. Later additions are very important, but less transparent.

1977: Lund studies of hadronization begin





B.Andersson, G. Gustafson, C. Peterson, Z. Physik C1 (1979) 105 (begun 1977, preprint 1978, published 1979):

- constant string tension $\kappa \approx 1$ GeV/fm
- particle production (approximately) along hyperbola
- lightcone kinematics ($\mathrm{p}^{\pm} = E \pm p_z$)
- analytic, recursive procedure from one end
- no complete systems
- $f(z) = 1$ not left–right symmetric

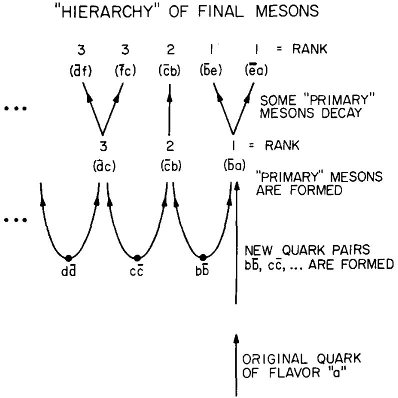
1978: The beginning of jet Monte Carlo

R.D. Field and R.P. Feynman,
A Parametrization of the Properties of Quark Jets,
Nucl. Phys. B136 (1978) 1

- recursive procedure, with
- **Monte Carlo implementation**
- only one jet
- no space–time picture

starting point for e^+e^- generators:

- Hoyer et al.
- Ali et al.



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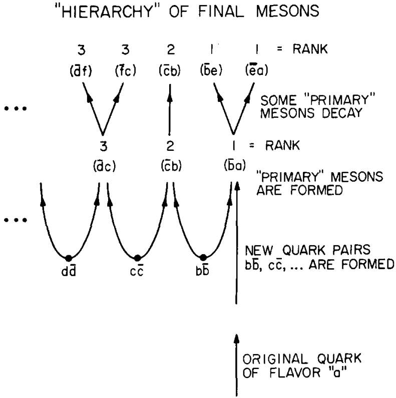


Lund: Bengt E.Y. Svensson suggests Monte Carlo implementation of current Lund analytic equations in Field–Feynman spirit, carried out by TS and B. Söderberg

1978: JETSET version 1

```
      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
C 5 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 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,I2,4X,A2,1X,2(4X,A4),5(4X,F8.1))
  130 FORMAT(10X,I2,4X,1X,I2,2(4X,A4),5(4X,F8.1))
      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
      TDU=(SA-SD)*(SB-SC)/(4.*SQRT(SB*SC))
      IF(K(IPD,2).GE.11) TDU=SQRT(SB*SC)*TDU**3
  120 SX=SC+(SB-SC)*RANF(0)
      TDF=SQRT((SX-SA)*(SX-SB)*(SX-SC)*(SX-SD))/SX
      IF(K(IPD,2).GE.11) TDF=SX*TDF**3
      IF(RANF(0)*TDU.GT.TDF) 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
```

≈ 200 punched cards
Fortran code

```
      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
C 2 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
```

```
      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/7,1,3,2,8,5,4,6,9,7,2,4,1,8,6,3,5,9/
      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*896.3,770.2,782.6,1019.6/
      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.,0.426,0.662,0.959,
     &0.980,1.,1.,1.,0.667,1.,0.667,1.,0.667,1.,0.667,1.,1.,
     &0.899,0.987,1.,0.486,0.837,0.984,1./
      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
```

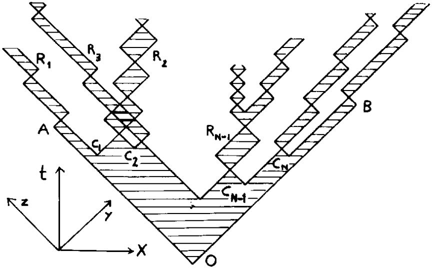
1973: The forgotten Artru–Mennessier model

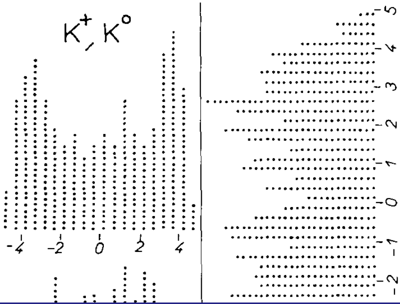
X. Artru and G. Mennessier,
String Model
and Multiproduction
Nucl. Phys.B70 (1974) 93

- exponential decay in area
- complete two-jet system
- Monte Carlo code
- off-shell hadrons
- no transverse d.o.f.
- **not salesmen**

1982: Lund symmetric
fragmentation function

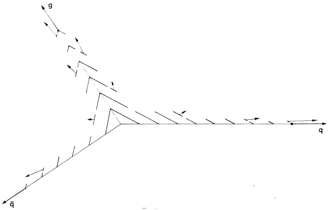
$$f(z) = \frac{(1-z)^a}{z} \exp\left(-\frac{bm_\perp^2}{z}\right)$$

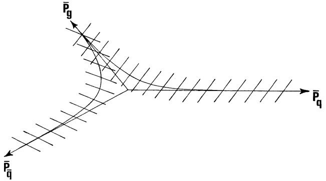




1980: The string effect

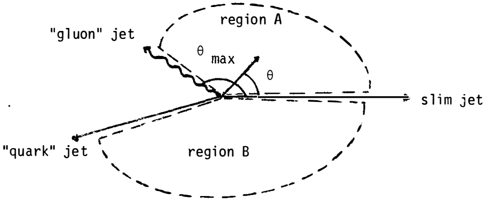
Lund December 1979

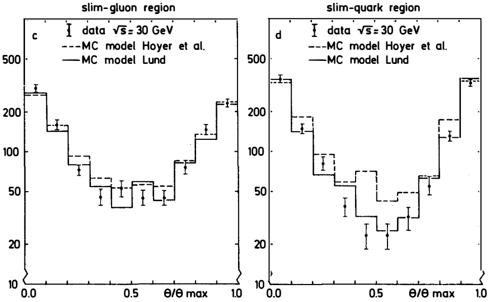




$\Rightarrow$ JADE,
Moriond, March 1980

. . . but not by TASSO





1982: The strong coupling

CELLO: The influence of Fragmentation Models in the Determination of the Strong Coupling Constant in e^+e^- Annihilation into Hadrons

Value of α_s obtained at $\sqrt{s}$ = 34 GeV with the Lund model (LM) and the Hoyer model (HM). (first order in QCD)

Method	Lund model	Hoyer model	$\frac{\alpha_s(\text{LM})}{\alpha_s(\text{HM})}$
$S \geqslant 0.25$ $A \leqslant 0.1$	0.280 ± 0.045	0.190 ± 0.030	1.47
$O \geqslant 0.20$	0.260 ± 0.040	0.190 ± 0.020	1.37
$O \geqslant 0.30$	0.255 ± 0.050	0.200 ± 0.035	1.28
# of 3-clusters	0.235 ± 0.025	0.145 ± 0.020	1.62
Cluster Thrust	0.235 ± 0.025	0.155 ± 0.015	1.52
EWAC*	0.250 ± 0.040	0.150 ± 0.020	1.67

The error in the determination of α_s using the 3-jet fraction (see text) is statistical only (including statistical Monte Carlo error).
*Energy-weighted angular correlation.

String fragmentation increases α_s by $\sim$ 50%!

JETSET 3: $\sim$ 1000 lines

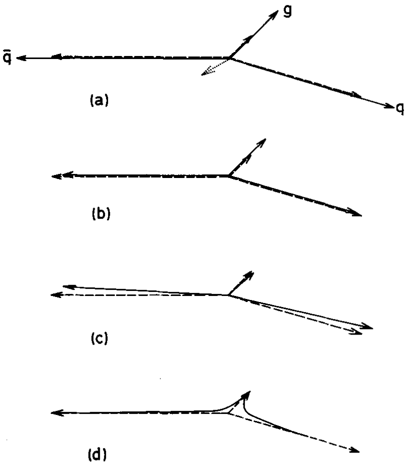
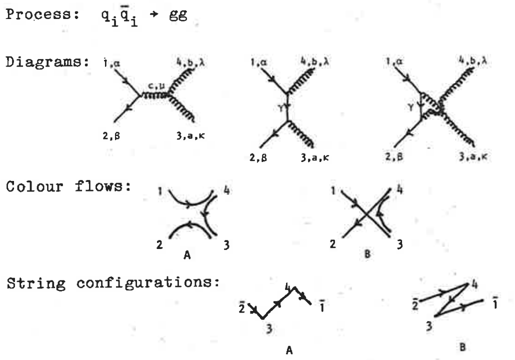
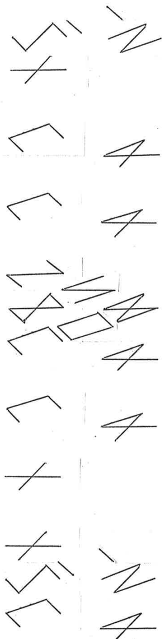


Fig. 2a–d. A slightly exaggerated picture of momentum conservation effects. In **a** the momenta of initial partons are full arrows and of jets after fragmentation dashed, with dotted indicating final momentum imbalance: In **b–d** the momenta before conservation are dashed (as in **a**), after full. Hoyer rescaling in **b**, Ali boost in **c**, Lund strings (along which particles are sitting) in **d**

1982: The beginning of PYTHIA

LEPTO: colour flow in ep DIS (G. Ingelman & TS)
Compton + High-$p_\perp$: colour flow in pp
(Hans-Uno Bengtsson)





$N_C \rightarrow \infty$ classifies colour topologies

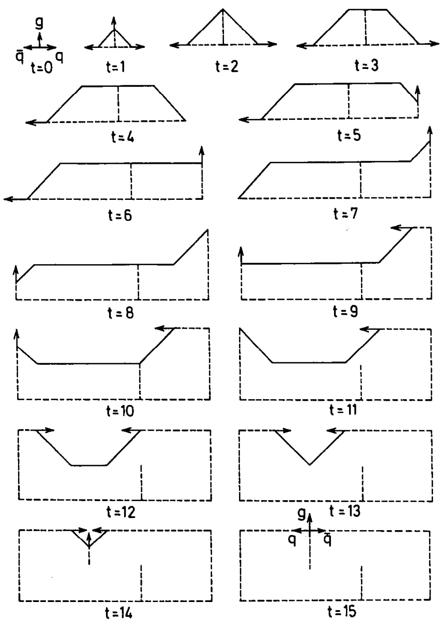
$\Rightarrow$ ~~Cassandra~~ $\Rightarrow$ **PYTHIA**

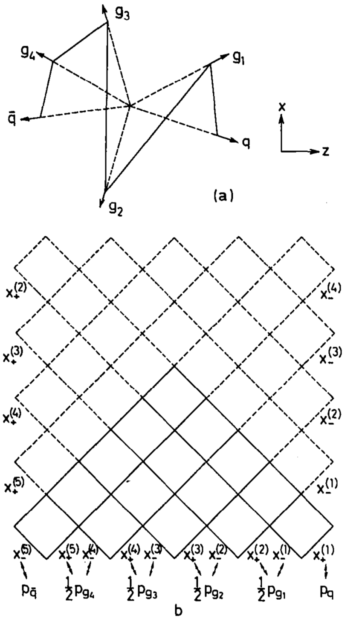
Delphi and Pythia

Delphi: 120 km west of Athens, on the slopes of Mount Parnassus.
Python: giant snake killed by Apollon.
The Oracle of Delphi: ca. 1000 B.C. – 390 A.D.
Pythia: local prophetess/priestess.
Key role in myths and history, notably in
"The Histories" by Herodotus of Halicarnassus ($\sim$482 – 420 B.C.)

1983: Complicated string topologies





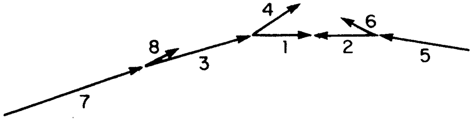
1984: Backwards evolution of ISR

Final-state radiation (FSR) intensely studied, two coded up:

- Kajantie–Pieterinen (incoherent) and
- Marchesini–Webber (coherent)

Initial-state radiation (ISR) big hurdle

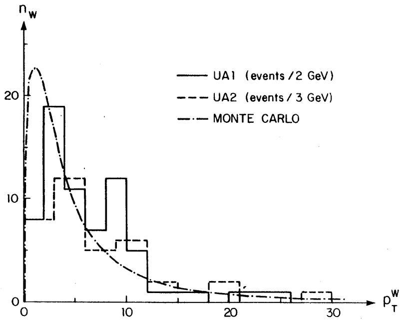
- forward evolution in time and Q^2 may not "hit right"
- backwards evolution reverses order



$$dP_b = \frac{df_b(x,t)}{f_b(x,t)} = |dt| \frac{\alpha_s(t)}{2\pi} \sum_a \int \frac{dx'}{x'} \frac{f_a(x',t)}{f_b(x,t)} P_{a\to bc}\left(\frac{x}{x'}\right) \qquad (2)$$

This probability exponentiates, so that one may define a form factor

$$S_b(x,t_1;t) = \exp\left\{-\int_t^{t_1} dt' \frac{\alpha_s(t')}{2\pi} \sum_a \int \frac{dx'}{x'} \frac{f_a(x',t')}{f_b(x,t')} P_{a\to bc}\left(\frac{x}{x'}\right)\right\} \qquad (3)$$



1985: Multiparton interactions

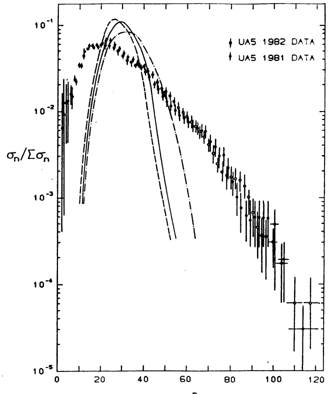
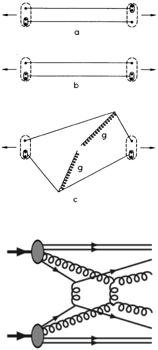


FIG.2



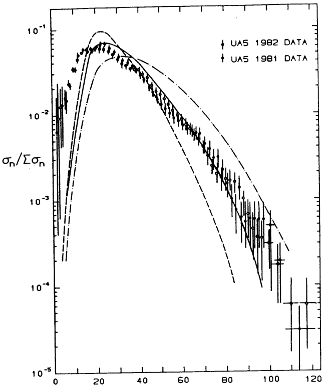
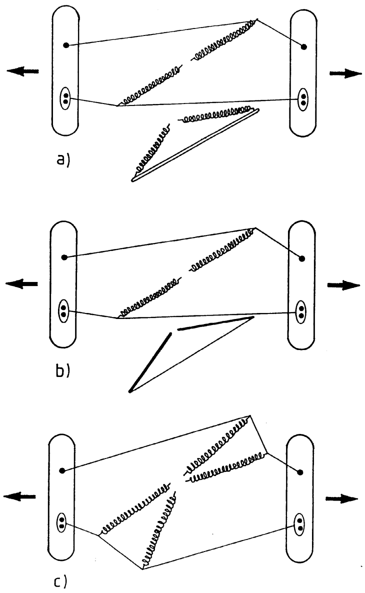


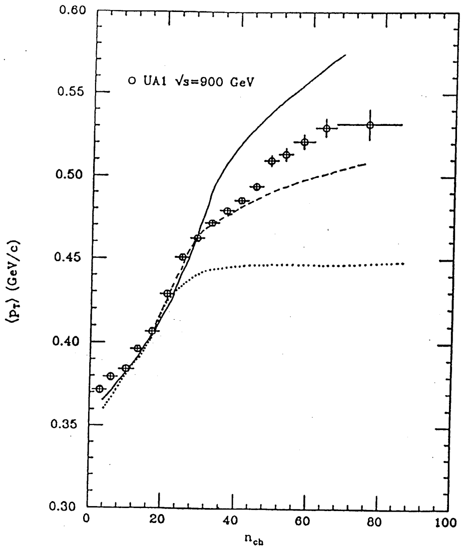
FIG.4

without MPI: low-$p_\perp$
+ QCD $p_{\perp\mathrm{min}} = 1.6$ GeV
+ ISR+FSR

with MPI,
$p_{\perp\mathrm{min}} = 2.0, 1.6, 1.2$ GeV

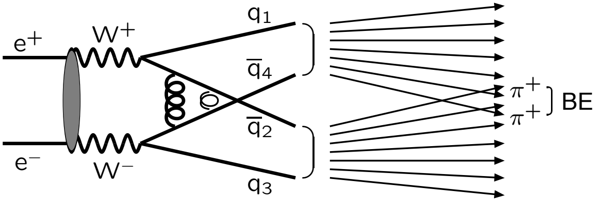
1986: Colour reconnection





extremes all or no colour reconnection

1996: Colour reconnection in e^+e^- annihilation



At LEP 2 search for effects in $\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^- \to \mathrm{q}_1\overline{\mathrm{q}}_2\,\mathrm{q}_3\overline{\mathrm{q}}_4$:

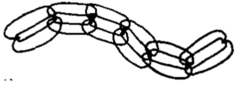
- perturbative $\langle \delta M_\mathrm{W} \rangle \lesssim 5$ MeV : negligible!
- nonperturbative $\langle \delta M_\mathrm{W} \rangle \sim 40$ MeV :

  favoured; no-effect option ruled out at 99.5% CL.

  Best description for reconnection in $\approx 50\%$ of the events.
- Bose-Einstein $\langle \delta M_\mathrm{W} \rangle \lesssim 100$ MeV : full effect ruled out (while models with ~ 20 MeV barely acceptable).

1986: Dipole showers

Gösta Gustafson: dual description of partonic state:
partons connected by dipoles ⇔ dipoles stretched between partons
parton branching ⇔ dipole splitting



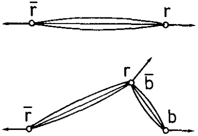


Fig. 3

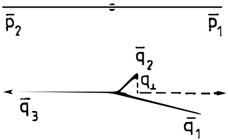


Fig. 4

$p_\perp$-ordered dipole emissions ⇒ **coherence** (cf. angular ordering)

- Originally implemented in ARIADNE
- Now basis for three different implementations in PYTHIA: old simple, VINCIA and DIRE
- plus showers in HERWIG, SHERPA, . . .

Huge enterprise with many people over many years, aiming for increased precision, NLO+NLL and beyond

1986: Matrix element corrections

Consider $\mathrm{e^+e^-} \to \gamma^*/\mathrm{Z}^0 \to \mathrm{q\overline{q}} \to \mathrm{q\overline{q}g}$
with $\mathrm{d}\mathcal{P}_{\mathrm{ME}} = \mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{q\overline{q}g}} / \sigma^{\mathrm{LO}}_{\mathrm{q\overline{q}}}$

$$\begin{aligned} \mathrm{d}\sigma_{\mathrm{q\overline{q}g}} &= \sigma^{\mathrm{NLO}}_{\mathrm{q\overline{q}}} \, \mathrm{d}\mathcal{P}_{\mathrm{PS}} \exp\left(- \int_{Q^2}^{Q^2_{\mathrm{max}}} \mathrm{d}\mathcal{P}_{\mathrm{PS}} \right) \\ &\quad \times \frac{\mathrm{d}\mathcal{P}_{\mathrm{ME}}}{\mathrm{d}\mathcal{P}_{\mathrm{PS}}} \exp\left(- \int_{Q^2}^{Q^2_{\mathrm{max}}} (\mathrm{d}\mathcal{P}_{\mathrm{ME}} - \mathrm{d}\mathcal{P}_{\mathrm{PS}}) \right) \\ &= \sigma^{\mathrm{NLO}}_{\mathrm{q\overline{q}}} \, \mathrm{d}\mathcal{P}_{\mathrm{ME}} \exp\left(- \int_{Q^2}^{Q^2_{\mathrm{max}}} \mathrm{d}\mathcal{P}_{\mathrm{ME}} \right) \end{aligned}$$

using the veto algorithm, assuming $\mathrm{d}\mathcal{P}_{\mathrm{PS}} > \mathrm{d}\mathcal{P}_{\mathrm{ME}}$ everywhere.

Later extended to (almost) all resonance decays $a \to b\,c \to b\,c\,\mathrm{g}$
and some ISR like $\mathrm{q\overline{q}} \to \gamma^*/\mathrm{Z}^0/\mathrm{W}^{\pm}/\ldots$.

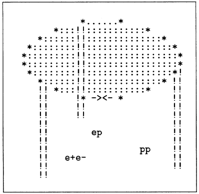
Rediscovered as the POWHEG method,
now commonly used for NLO processes.

1992: Unified full-length manual

CERN-TH.6488/92
W5035/W5044

PYTHIA 5.6 and JETSET 7.3
Physics and Manual

Torbjörn Sjöstrand
Theory Division, CERN
CH-1211 Geneva 23
Switzerland



CERN-TH.6488/92
May 1992

- good documentation
  key to early success
- 12 published manuals
- from 1992: steadily updated
  big manual (280 pp)
- PYTHIA 6.4 in JHEP 2006,
  (480 pp $\to$) 580 pp
  $> 11,500$ citations
- in total $> 35,000$ citations

- now bulk of documentation
  as xml/html manual
- but big new publication
  in preparation

does not stop a HUGE
amount of mail/questions

1996: SPYTHIA

No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour:	
(also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi \gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi \gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$

No.	Subprocess
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g \gamma^*_T \to f_i \bar{f}_i$
136	$g \gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$

No.	Subprocess
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
Heavy SM Higgs:	
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$
BSM Neutral Higgs:	
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$

No.	Subprocess
Higgs pairs:	
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$

No.	Subprocess
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
Left–right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$
SUSY:	
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$

No.	Subprocess
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell{}^*$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$

No.	Subprocess
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{j}{}_L$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{j}{}_R$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{j}{}_R +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{j}{}_L$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{j}{}_R$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{i}{}_L$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{i}{}_R$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{i}{}_L$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{i}{}_R$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{i}{}_R +$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
289	$gg \to \tilde{b}_1 \tilde{b}^*_1$
290	$gg \to \tilde{b}_2 \tilde{b}^*_2$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$

(Snowmass 1984, 1986; Aachen 1990; . . .)

1996: Parton-level interfaces

- originally: each generator is an island, with hard-coding only feasible for $2 \to 2$ and a few $2 \to 3$
- 1988: PDG particle codes ($1 = \mathrm{d}$, $2 = \mathrm{u}$, $11 = \mathrm{e}^-$, $21 = \mathrm{g}$, ...)
- 1989: HEPEVT commonblock for final (LEP) events
- 1996: LEP2 4-fermion generator parton input to JETSET
- (1989 $\to$) ~1998: CompHEP
- (1994 $\to$) ~2000: MadGraph
- 2001: Les Houches Accord, transfer of event information using Fortran commonblocks

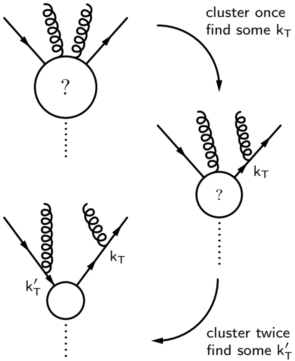
```
 INTEGER MAXPUP
 PARAMETER (MAXPUP=100)
 INTEGER IDBMUP,PDFGUP,PDFSUP,IDWTUP,NPRUP,LPRUP
 DOUBLE PRECISION EBMUP,XSECUP,XERRUP,XMAXUP
 COMMON/HEPRUP/IDBMUP(2),EBMUP(2),PDFGUP(2),PDFSUP(2),
&IDWTUP,NPRUP,XSECUP(MAXPUP),XERRUP(MAXPUP),
&XMAXUP(MAXPUP),LPRUP(MAXPUP)
```

```
 INTEGER MAXNUP
 PARAMETER (MAXNUP=500)
 INTEGER NUP,IDPRUP,IDUP,ISTUP,MOTHUP,ICOLUP
 DOUBLE PRECISION XWGTUP,SCALUP,AQEDUP,AQCDUP,PUP,VTIMUP,
&SPINUP
 COMMON/HEPEUP/NUP,IDPRUP,XWGTUP,SCALUP,AQEDUP,AQCDUP,
&IDUP(MAXNUP),ISTUP(MAXNUP),MOTHUP(2,MAXNUP),
&ICOLUP(2,MAXNUP),PUP(5,MAXNUP),VTIMUP(MAXNUP),
&SPINUP(MAXNUP)
```

- 2006: Les Houches Event Files 1.0, ditto, using file format
- several other standards: SLHA, LHAPDF, HepMC, ...

2000: Match and Merge

- Match: transition from (one) ME at high Q to PS at low
- Merge: combine several ME topologies: $X, X+1, X+2, \ldots$
- Use shower Sudakovs to provide missing virtual corrections
- Increasingly technical sophistication over 20 years!
- Main research topic of larger event generator community



many methods, several from Lund (Leif Lönnblad, Stefan Prestel)

- Match: MC@NLO, POWHEG
- Merge: CKKW, CKKW-L, MLM, FxFx
- M&M: UMEPS, NL^3, UNLOPS

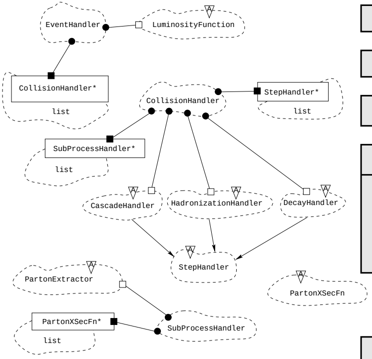
$\sim$ 10 alternatives in PYTHIA, all rely on LHEF input

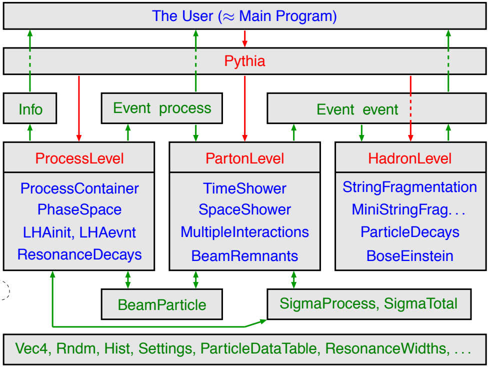
2004: PYTHIA 8

All early codes written in Fortran 77

1998: PYTHIA 7 in C++, sophisticated platform → ThePEG

2004: PYTHIA 8 in C++, simpler approach but physics focus



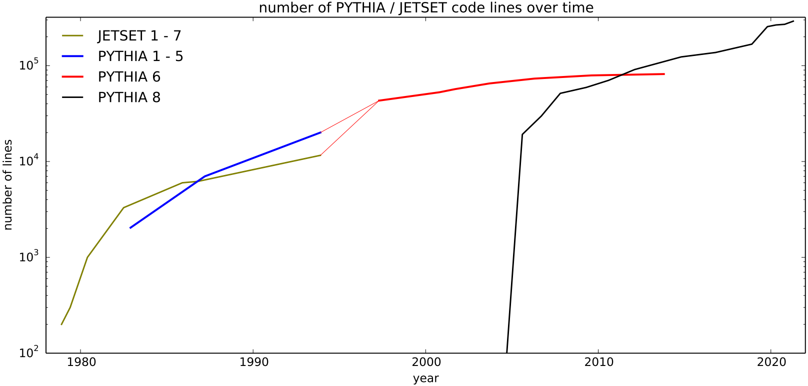


2007: 8.1 first public release

2014: 8.2 some systematization ⇒ minor incompatibility

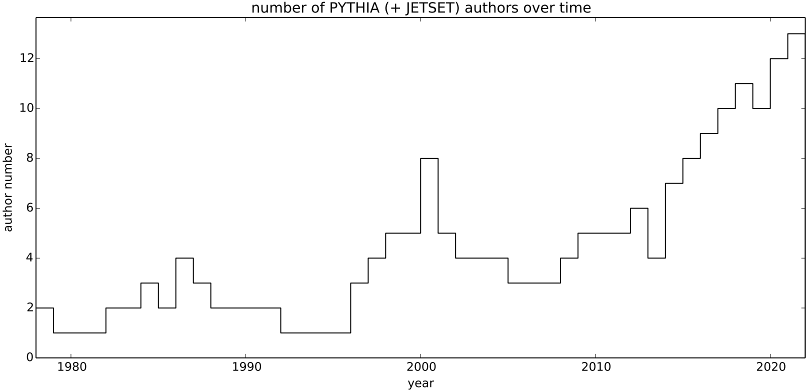
2019: 8.3 C++98 → C++11, significant internal changes

Code size expansion



- 1997: JETSET fused into PYTHIA
- size includes comment lines and blank lines
- for C++: source, headers, example main programs, but not data (PDF, LHEF), xml/html manual, ME libraries, . . .
- currently $\sim 300,000$ lines

Group size expansion



Does not include:

- non-coding collaborators, like Bo Andersson and Gösta Gustafson
- authors of other "Lund" programs built on top, like LEPTO, ARIADNE, FRITIOF, LDC, DIPSY, POMPYT, ...
- many authors of other non-Lund programs built on top

Administrative structure

Current authors:

Christian Bierlich
Nishita Desai
Leif Gellersen
Ilkka Helenius
Philip Ilten
Leif Lönnblad
Stephen Mrenna
Stefan Prestel
Christian Preuss
Torbjörn Sjöstrand
Peter Skands
Marius Utheim
Rob Verheyen

Exploding collaboration size new problem;
still finding our way.

Main tasks crystallized in recent years,
notably Philip Ilten as codemaster.

Future organization discussed this week,
resulting in triumvirate:

- spokesperson: Peter Skands
  (deputy: Ilkka Helenius)
- code master: Philip Ilten
  (deputy: Stephen Mrenna)
- web master: Christian Bierlich

Physics studies based on personal interest,
so far little to no central planning,
but now begun discussion of common projects.

Showers and matching&merging

Strive towards NLO + NLL by improved showers,
combined with higher-order matrix elements

VINCIA – VIrtual Numerical Collider
with Interleaved Antennae
Skands, Preuss, Verheyen

- antenna-dipole: $2 \to 3$ splittings with both recoiling
- sector shower: unique path to given final state
- full electroweak cascade module

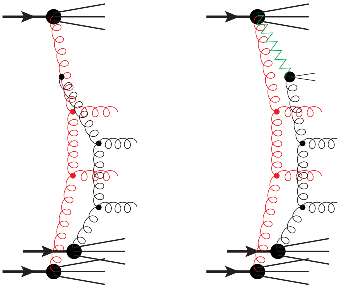
DIRE – DIpole REsummation
Prestel, Gellersen

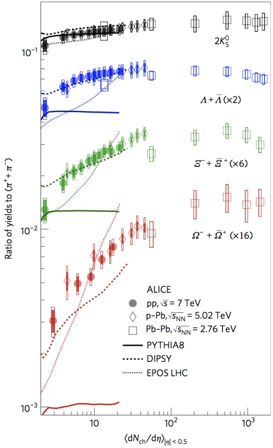
- developed jointly with SHERPA
- NLO splitting kernels (negative weights!)
- scale and scheme variations in merging
- Dark Matter emission in shower

Heavy-ion collisions

Bierlich, Lönnblad (+ Gösta Gustafson, students, postdocs)

- 1984: FRITIOF, successful at low energies, but not for higher
- 2016: ANGANTYR for complete pA and AA collisions
  - full nuclear geometry
  - subdivide collisions into binary ones
  - ropes with higher string tension
  - shove between strings gives flow





Hadronic rescattering and applications

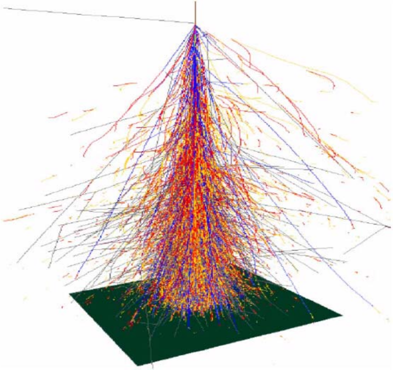
Utheim, TS (Bierlich, Ilten)

- space–time picture of hadronization
- low-energy hadron–hadron collisions
- hadronic rescattering in pp, pA, AA

Future (?):

- formation of pentaquarks etc.
- Bose-Einstein
- extend to arbitrary energies
- component of cosmic ray cascades

(PYTHIA already heavily used
for cosmic ray production,
e.g. by Dark Matter annihilation)



high-energy cosmic ray
in atmosphere,
not with PYTHIA

. . . and much more

- $\gamma\mathrm{p}, \gamma\gamma$, notably in AA collisions;
  UPC = UltraPeripheral Collisions (Helenius)
- DIS and photoproduction transition e.g. at EIC
  (Helenius, Prestel, Bierlich)
- BSM physics, e.g. Dark Matter (Desai, Prestel, Skands, . . .)
- bottom/charm/τ physics (Ilten)
- FCC and other future accelerators (all)
- Rivet and other common tools (Bierlich, . . .)
- code development (all), e.g. parallelization (Utheim, . . .)

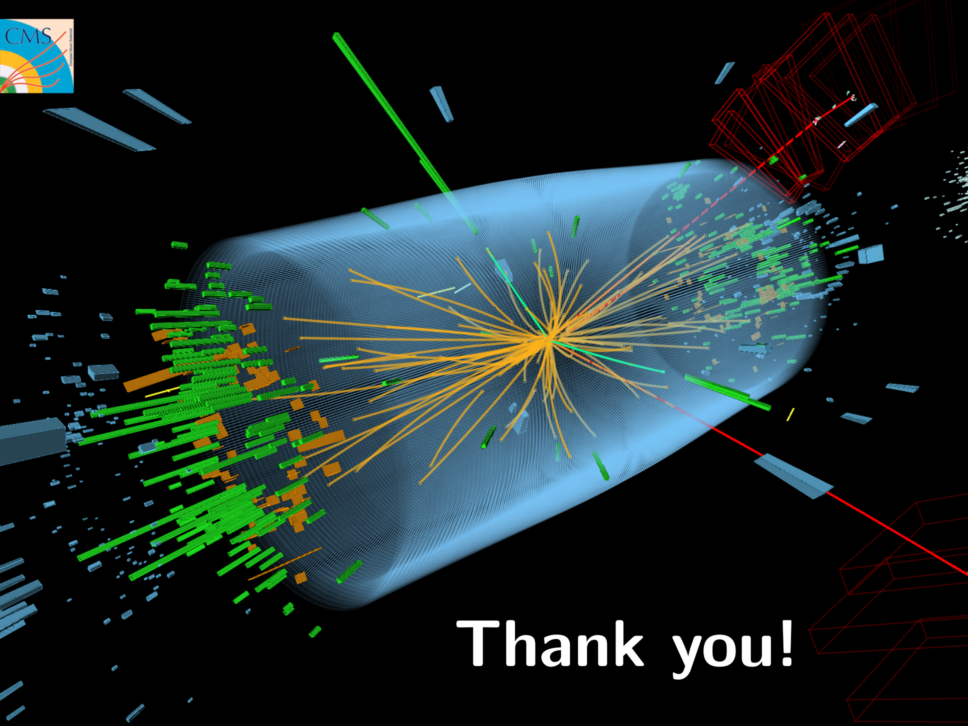
New topics tend to come along when least you expect it.
No lack of work to be done!

Five-year plan?

- Dark showers
- DM annihilation spectra
- New BSM models
- BSM in hadron decay
- EW evolution
- Precision physics
- Become NNLO generator
- Heavy Ions
- Photon-ion collisions
- Smooth DIS transition
- Nonperturbative models
- B physics
- QED at hadronic scales
- Cosmic rays

- Improved code structure
- Better interfaces
- New tunes
- Machine learned ME generation
- Native code rather than external links, like PHOTOS
- Parallel processing
- GPU's and other new computing

- Interact with numerous experimental collaborations, old and new



Thank you!