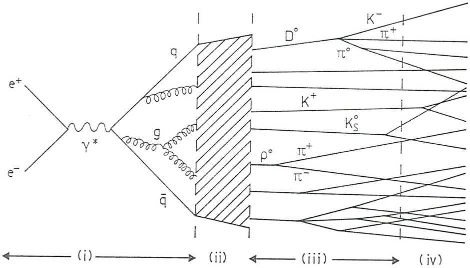
Origins of Pythia

Modern event generators were born at DESY (Hamburg), for the PETRA e^+e^- collider! (1978 − 86, 13 − 46 GeV)

- Combine perturbative picture of hard processes, involving electroweak and strong interactions, with nonperturbative picture of hadronization.
- Provide "complete" events, with parameters to be tuned to data, and used to study and understand different kinds of physics.



JETSET version 1 (November 1978)

```
      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
      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
```

RANF

```
      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
```

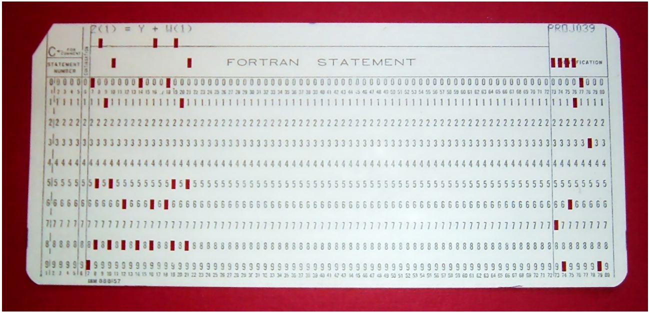
≈ 200 punched cards

Fortran code

(Sjostrand/Soderberg)

```
      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
```




*

*https://en.wikipedia.org/wiki/Punched_card

The Lund String Model

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**

by self-interactions among soft gluons in the “vacuum”.

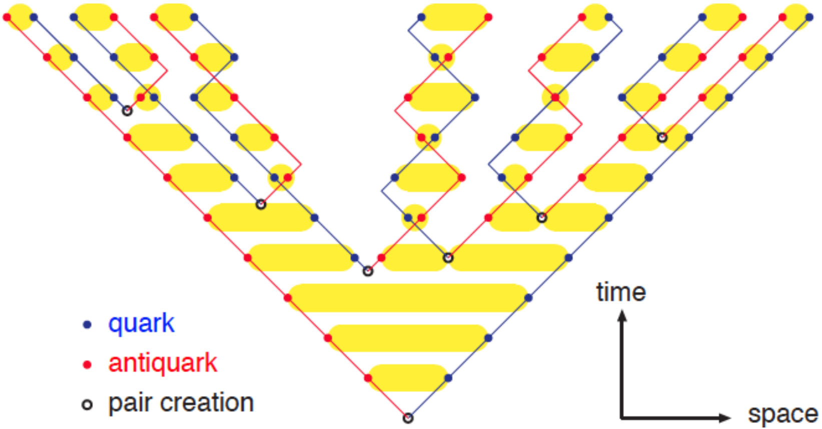
Gives linear confinement with string tension:

$$F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

String breaks into hadrons along its length,
with roughly uniform probability in rapidity,
by formation of new $\mathrm{q\overline{q}}$ pairs that screen endpoint colors.

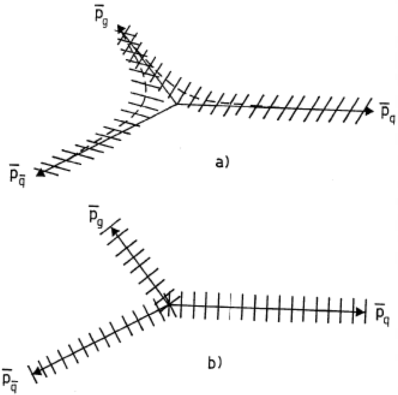
Lund String Model: 2 jets

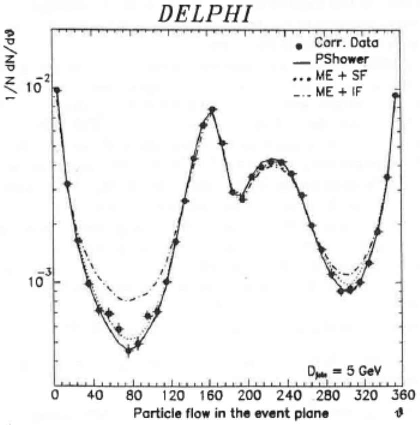
$e^+e^- \to q\bar{q}$



Consistent description of 2 jet topologies

Lund String Model: 3 jets





(a) String vs (b) Independent (Feynman-Field) fragmentation

No new parameters introduced for gluon jets!

Multiparton interactions modeling

Regularise cross section with $p_{\perp 0}$ as free parameter

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

with energy dependence

$$p_{\perp 0}(E_{\mathrm{CM}}) = p_{\perp 0}^{\mathrm{ref}} \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}}\right)^{\epsilon}$$

Matter profile in impact-parameter space gives time-integrated overlap which determines level of activity:

Many colored partons produced close in space–time
$\Rightarrow$ color rearrangement; reduction of total string length
$\Rightarrow$ steeper $\langle p_{\mathrm{T}} \rangle (n_{\mathrm{ch}})$

Full Disclosure

A large number of parameters need to be fit (tuned) to data to make predictions

Anonymous reviewer:

> *It is well-known in scientific computing that with enough parameters, all discrepancies between simulation and data can be eliminated. However if the underlying algorithms or model in the simulation are flawed, the resulting over-parameterized, data-fit code still cannot predict new results ...*

Actual parameters $<$ # Apparent parameters

Some parameters are just necessary choices (cutoffs, PDF, *etc*)

Sensitive parameters $<$ # Actual parameters

Amount of information in differential data $\gg$ # Sensitive parameters

Perturbative, inclusive QCD calculations also have inputs: α_s, μ_R, μ_F, PDFs and is limited in predictions

Minimal # parameters $\sim 15 - 20$

Parameter Tuning

A Challenging Problem!

Divide and Conquer

- Start with data from electron-positron colliders
- Removes complication of the beams
- Know collision energy
- $\cdots$ but limited range
- Most data @ $M_Z \sim 91\ \mathrm{GeV}$

Monash 2013 Tune Parameters

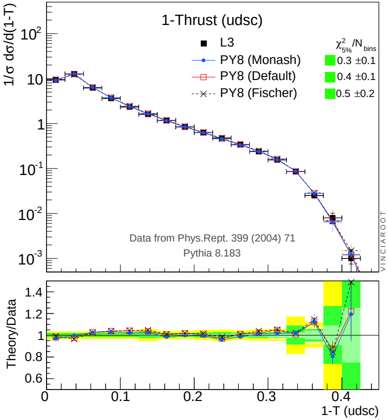
Final-state radiation (FSR) parameters.

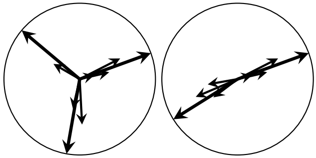
FSR Parameters	Monash 13	(Default)	Comment
TimeShower:alphaSvalue	= 0.1365	= 0.1383	! Effective alphaS(mZ) value
TimeShower:alphaSorder	= 1	= 1	! Running order
TimeShower:alphaSuseCMW	= off	= off	! Translation from $\overline{\text{MS}}$ to CMW
TimeShower:pTmin	= 0.50	= 0.40	! Cutoff for QCD radiation
TimeShower:pTminChgQ	= 0.50	= 0.40	! Cutoff for QED radiation
TimeShower:phiPolAsym	= on	= on	! Asymmetric azimuth distributions

$$\text{FSR:} \quad \mu_R^2 = p_{\perp\text{evol}}^2 = z(1-z)Q^2 \ ,$$

with $Q^2 = p^2 - m_0^2$ the offshellness of the emitting parton (with on-shell mass m_0), and z the energy fraction appearing in the DGLAP splitting kernels, $P(z)$.

pTmin :: avoid Landau pole





$$\alpha_s(M_Z) = 0.1365 \neq 0.13$$

$$\text{CMW} \neq \overline{\text{MS}}$$

$$\Lambda_{\text{CMW}} = 1.6\Lambda_{\overline{\text{MS}}}$$

Hadronic Z decays at $\sqrt{s} = 91.2\,\text{GeV}$. The Thrust distribution in light-flavor tagged events, compared with L3 data

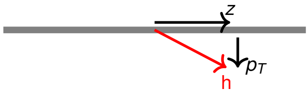
Choice of cutoff, hadronization parameters also impact prediction

String-breaking parameters.

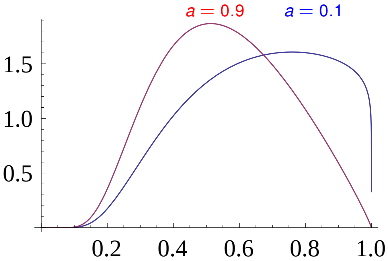
HAD Parameters	Monash 13	(Default)	Comment
# String breaks: pT and z distributions			
StringPT:sigma	= 0.335	= 0.304	! Soft pT in string breaks (in GeV)
StringPT:enhancedFraction	= 0.01	= 0.01	! Fraction of breakups with enhanced pT
StringPT:enhancedWidth	= 2.0	= 2.0	! Enhancement factor
StringZ:aLund	= 0.68	= 0.3	! Lund FF a (hard fragmentation supp)
StringZ:bLund	= 0.98	= 0.8	! Lund FF b (soft fragmentation supp)
StringZ:aExtraSquark	= 0.0	= 0.0	! Extra a when picking up an s quark
StringZ:aExtraDiquark	= 0.97	= 0.50	! Extra a when picking up a diquark
StringZ:rFactC	= 1.32	= 1.00	! Lund-Bowler c-quark parameter
StringZ:rFactB	= 0.855	= 0.67	! Lund-Bowler b-quark parameter
# Flavour composition: mesons			
StringFlav:ProbStoUD	= 0.217	= 0.19	! Strangeness-to-UD ratio
StringFlav:mesonUDvector	= 0.5	= 0.62	! Light-flavour vector suppression
StringFlav:mesonSvector	= 0.55	= 0.725	! Strange vector suppression
StringFlav:mesonCvector	= 0.88	= 1.06	! Charm vector suppression
StringFlav:mesonBvector	= 2.2	= 3.0	! Bottom vector suppression
StringFlav:etaSup	= 0.60	= 0.63	! Suppression of eta mesons
StringFlav:etaPrimeSup	= 0.12	= 0.12	! Suppression of eta' mesons
# Flavour composition: baryons			
StringFlav:probQQtoQ	= 0.081	= 0.09	! Diquark rate (for baryon production)
StringFlav:probSQtoQQ	= 0.915	= 1.000	! Strange-diquark suppression
StringFlav:probQQ1toQQ0	= 0.0275	= 0.027	! Vector diquark suppression
StringFlav:decupletSup	= 1.0	= 1.0	! Spin-3/2 baryon suppression
StringFlav:suppressLeadingB	= off	= off	! Optional leading-baryon suppression
StringFlav:popcornSpair	= 0.9	= 0.5	!
StringFlav:popcornSmeson	= 0.5	= 0.5	!

Lund symmetric fragmentation function:

$$f(z) \propto \frac{z^{(a_i - a_j)}(1-z)^{a_j}}{z} \exp\left(\frac{-bm_\perp^2}{z}\right)$$

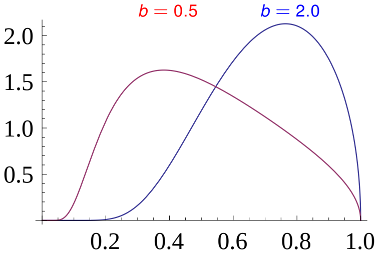


The *a* parameter

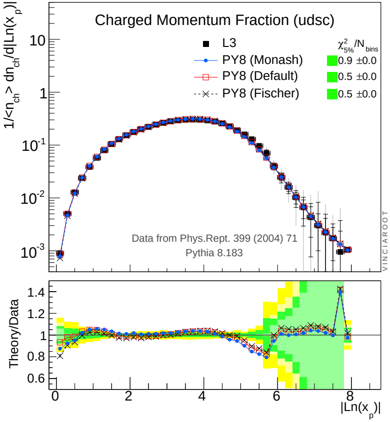


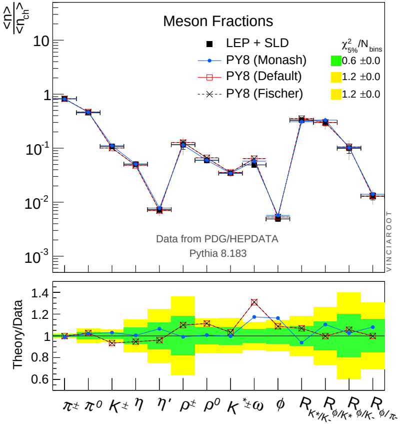
$b = 1\,\text{GeV}^{-2}$, $m_\perp = 1\,\text{GeV}$

The *b* parameter



$a = 0.5$, $m_\perp = 1\,\text{GeV}$





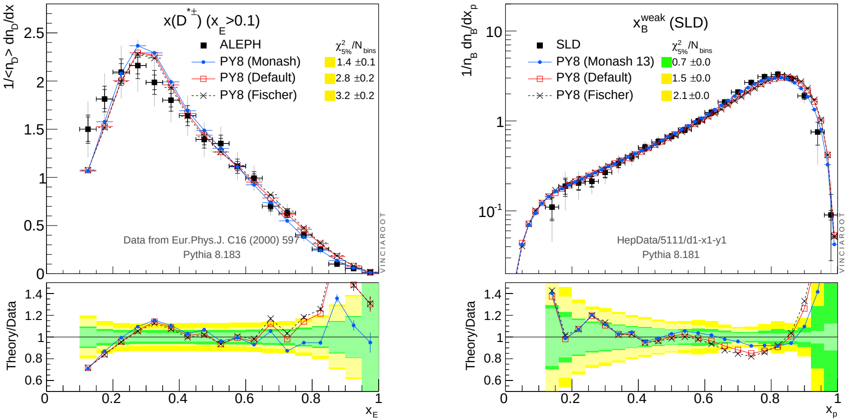

```
StringZ:aLund          =  0.68
StringZ:bLund          =  0.98

StringZ:aExtraDiquark =  0.97
StringZ:aExtraSquark  =  0.00
```

```
StringFlav:ProbStoUD      = 0.217
StringFlav:mesonUDvector = 0.5
StringFlav:mesonSvector  = 0.55
StringFlav:etaSup         = 0.60
StringFlav:etaPrimeSup    = 0.12
```

Heavy Flavor Tuning

$$f_{\text{massive}}(z, m_Q) \propto \frac{f(z)}{z^{b r_Q m_Q^2}} \qquad g \to c\bar{c}, b\bar{b}$$



`StringZ:rFactC = 1.32`   `StringZ:rFactB = 0.855`

Universality Assumption

Final state effects (FSR, hadronization) are tuned in the relatively clean e^+e^- environment

- Somewhat problematic, because kinematics is limited, e.g. not much $g \to Q\overline{Q}$ splitting

Any differences in hadron collisions come from environment

- Color flow from initial to final state
- High density of colored partons

Must/should test this!

Initial-state radiation (ISR) and primordial-k_T parameters.

ISR Parameters	**Monash 13**	**(Default)**	**Comment**
SpaceShower:alphaSvalue	= 0.1365	= 0.137	! Effective alphaS(mZ) value
SpaceShower:alphaSorder	= 1	= 1	! Running order
SpaceShower:alphaSuseCMW	= off	= off	! Translation from $\overline{\text{MS}}$ to CMW
SpaceShower:samePTasMPI	= off	= off	! ISR cutoff type
SpaceShower:pT0Ref	= 2.0	= 2.0	! ISR pT0 cutoff
SpaceShower:ecmRef	= 7000.0	= 1800.0	! ISR pT0 reference ECM scale
SpaceShower:ecmPow	= 0.0	= 0.0	! ISR pT0 scaling power
SpaceShower:rapidityOrder	= on	= on	! Approx coherence via y-ordering
SpaceShower:phiPolAsym	= on	= on	! Azimuth asymmetries from gluon pol
SpaceShower:phiIntAsym	= on	= on	! Azimuth asymmetries from interference
TimeShower:dampenBeamRecoil	= on	= on	! Recoil dampening in final-initial dipoles
BeamRemnants:primordialKTsoft	= 0.9	= 0.5	! Primordial kT for soft procs
BeamRemnants:primordialKThard	= 1.8	= 2.0	! Primordial kT for hard procs
BeamRemnants:halfScaleForKT	= 1.5	= 1.0	! Primordial kT soft/hard boundary
BeamRemnants:halfMassForKT	= 1.0	= 1.0	! Primordial kT soft/hard mass boundary

Parton Distribution Functions

Parton-distribution (PDF) and Matrix-Element (ME) parameters.

PDF and ME Parameters	Monash 13	(Default)	Comment
PDF:pSet	= 13	= 8	! PDF set for the proton
SigmaProcess:alphaSvalue	= 0.130	0.135	! alphaS(MZ) for matrix elements
MultiPartonInteractions:alphaSvalue	= 0.130	0.135	! alphaS(MZ) for MPI

Need to choose one:

- several independent groups/methodologies

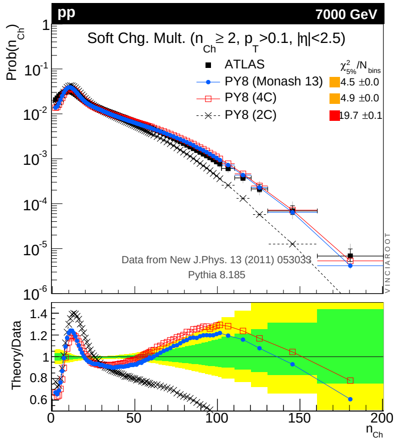
Impacts physics in several places:

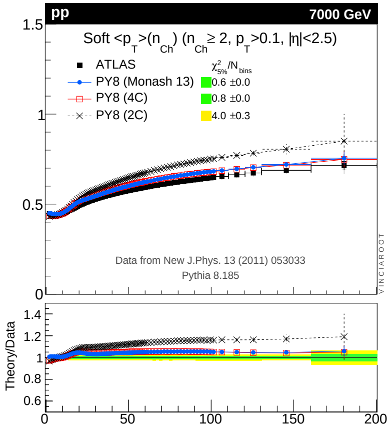
- parton shower
- multi-parton interactions
- kinematics of hard process
- used at high AND low Q^2

Multi-Parton-Interaction (MPI), Color-Reconnection (CR), and Diffractive parameters.

MPI Parameters	Monash 13	(Default)	Comment
MultipartonInteractions:pT0Ref	= 2.28	= 2.085	! MPI pT0 IR regularization scale
MultipartonInteractions:ecmRef	= 7000.0	= 1800.0	! MPI pT0 reference ECM scale
MultipartonInteractions:ecmPow	= 0.215	= 0.19	! MPI pT0 scaling power
MultipartonInteractions:bProfile	= 3	= 3	! Transverse matter overlap profile
MultipartonInteractions:expPow	= 1.85	= 2.0	! Shape parameter
BeamRemnants:reconnectRange	= 1.8	= 1.5	! Color Reconnections
SigmaTotal:zeroAXB	= on	= on	! Carried over from 4C
SigmaDiffractive:dampen	= on	= on	! Carried over from 4C
SigmaDiffractive:maxXB	= 65.0	= 65.0	! Carried over from 4C
SigmaDiffractive:maxAX	= 65.0	= 65.0	! Carried over from 4C
SigmaDiffractive:maxXX	= 65.0	= 65.0	! Carried over from 4C
Diffraction:largeMassSuppress	= 4.0	= 2.0	! High-mass diffraction suppression power

Good description of Hard and Soft Physics



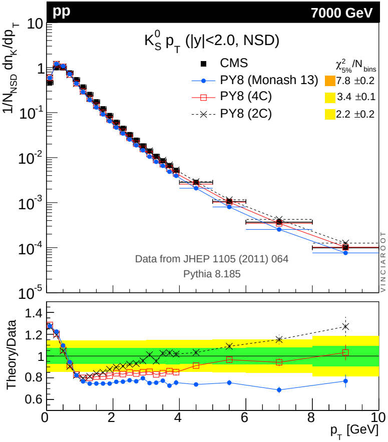


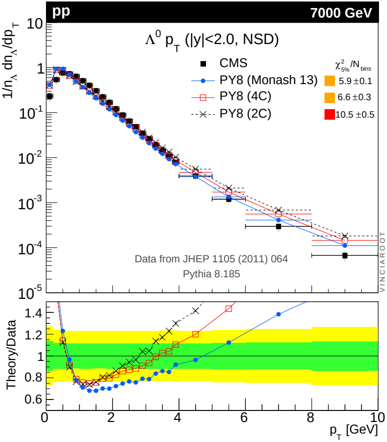
pT0Ref :: number of interactions, naive number of strings

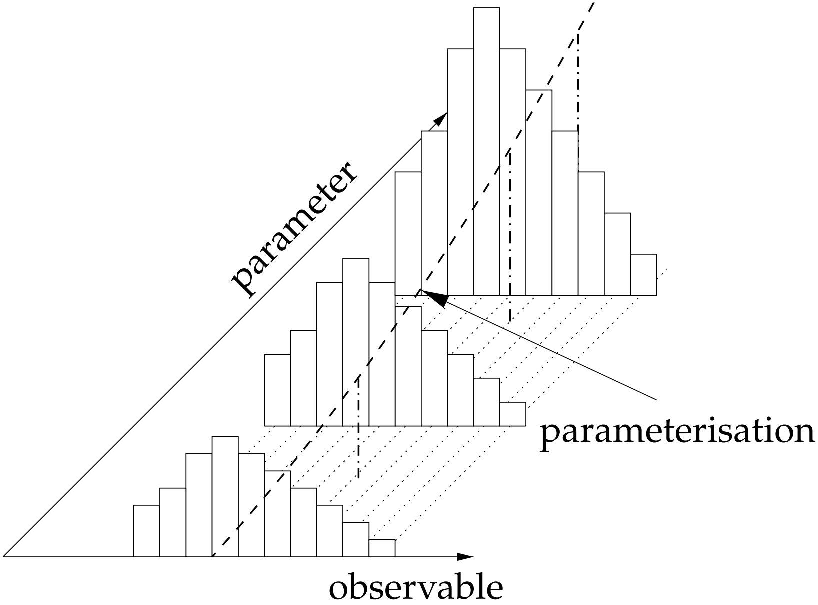
range :: color reconnections that alter string lengths, p_T of hadrons

Problems with flavor

Production of strange-flavored mesons and baryons






parameter
parameterisation
observable

The Eternal Struggle

Started out with intent to use simple principles.

Spent rest of life making increasingly complex models/codes.

You spend 10% of the effort and code to get to 90% of the physics, and then the going gets tough.

Particle physics is more complex than we would wish, but simpler than it could have been.

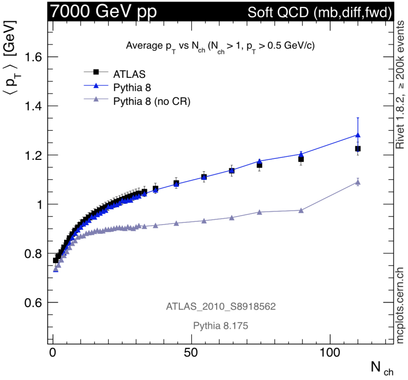
Why stick with event generators?

Our objective is to understand physics, not to write code.

But often code offers a unique way to gain insight.

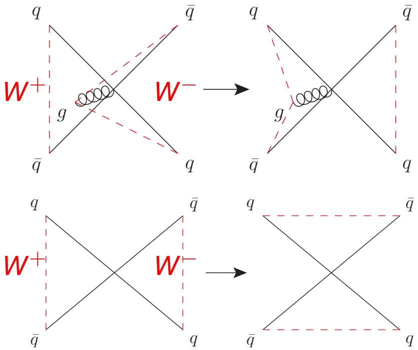
Phenomenology of Color Reconnections

Needed to explain hadronic activity



Most sensitive distribution to tune

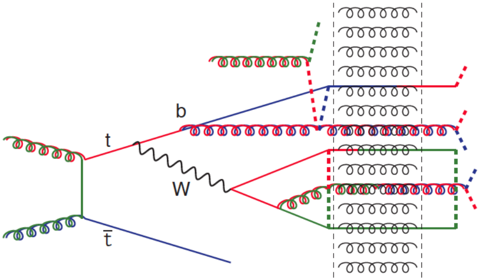
Only extreme CRs ruled out at LEP



Limited M_W extraction to $\ell\nu jj$

The top mass uncertainty from CR

$$\Gamma_t \approx 1.5 \text{ GeV}$$
$$\Gamma_W \approx 2 \text{ GeV}$$
$$\Gamma_Z \approx 2.5 \text{ GeV}$$
$$\Rightarrow$$
$$c\tau \approx 0.1 \text{ fm}$$

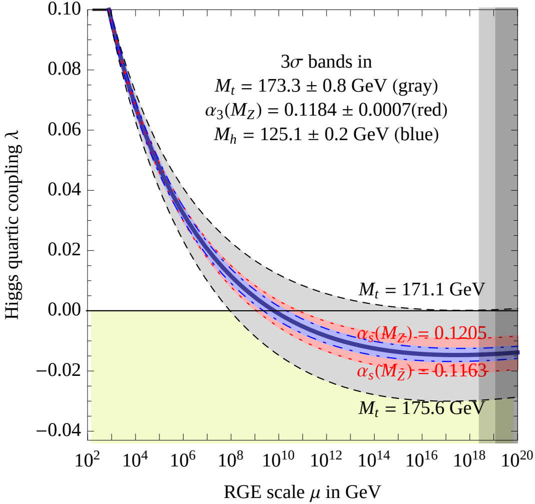


Decays occur when p "pancakes" have passed, after MPI/ISR/FSR with $p_\perp \geq 2$ GeV, but inside hadronization colour fields.

Experimentalists achieve impressive m_t precision,
e.g. CMS $m_t = 172.35 \pm 0.16 \pm 0.48$ GeV (PRD93 (2016) 072004),
whereof CR ± 0.10 GeV
from PYTHIA 6.4 Perugia 2011 |CR - noCR|
Is this realistic?

Is this small enough to answer: Stable or Meta-stable?

Is there a lower minimum for our vacuum?



RG evolution of λ varying M_t, $\alpha_3(M_Z)$, M_h by $\pm 3\sigma$.

What is the Future?

Current success of the Standard Model is surprising

Accumulating more and more data @ LHC – experimental uncertainties pushing the theory calculations

Development of the parton shower and matching to matrix elements is far from done (needed also for full $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$

Systematic appraisal of event generator uncertainties still needed

Full treatment of EW physics at high energy is needed

Better treatment of photon radiation (ala YFS?)

Forays into $\nu\mathrm{A}$ interactions

$\ldots$

Last Thoughts

Who will be writing event generators 20 years from now?

Who are we training?[†]

What are we training them to do?

Event generator physics is not just about having ideas and writing some code. I think that part of the reason the PYTHIA manual has been one the most-highly-cited physics papers since 2012 is our dedication to the needs of the community.

[†] I have no students. For Törbjörn, banking jobs pay more. Peter has a good start at Monash.

Here is an example of what an event generator author has to do (in just one random week):

> *GENSER at CERN reports an issue with* PYTHIA6[‡] *when compiled with the new gfortran-4.9 with respect to gfortran-4.8. This occurs with "-O" but not "-g". It has never occurred in a previous version of gfortran. Fortunately, this is a problem I can reproduce. I print out event listings, and run code in a debugger, and eventually find a line where the two calculations diverge. It looks like a compiler problem! My Computing Division colleagues look at it and say the line violates the Fortran 66 standard.*[§] *Indeed, it is a 20 year old bug in the code, unnoticed until this point. The code is rewritten, and we prepare a new release.*

[‡] We are not even officially supporting the FORTRAN version, but it was still used by CMS and ATLAS and that is part of service work.

[§] I was alive, but barely.

https://press3.mcs.anl.gov/hepfce/opportunities/

ACM SIGHPC/INTEL COMPUTATIONAL & DATA SCIENCE GRADUATE FELLOWSHIPS

APRIL 3, 2017 JCHILDERS

ACM SIGHPC and Intel have launched an international graduate fellowship program aimed at increasing the diversity of students pursuing degrees in data science and computational science. This program will support students pursuing degrees at institutions anywhere in the world. Interested faculty advisors and students can find more information at http://www.sighpc.org/fellowships. Nominations close April 30, 2017. Contact fellowships@sighpc.org with any questions.

HEP-CCE ANNOUNCES: GRADUATE STUDENT SUMMER INTERNSHIP PROGRAM

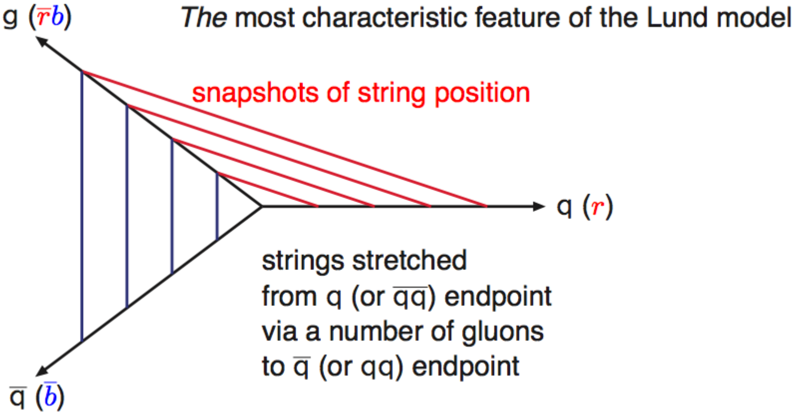
MARCH 8, 2017 JCHILDERS

The HEP-CCE announces a summer internship program for graduate students in the US who would like to work at Argonne National Laboratory, Fermilab National Accelerator Laboratory, and Lawrence Berkeley National Laboratory. The program covers the three high energy physics frontier areas (Cosmic, Energy, and Intensity) and is aimed at computationally-oriented graduate students interested in new educational, training, and research opportunities. A strong computing/computational background is highly desirable. Continue reading →

ME: mrenna@fnal.gov

BACKUP

The Lund Gluon Picture



Gluon = kink on string

Force ratio gluon/ quark = 2,
cf. QCD $N_C / C_F = 9/4, \rightarrow 2$ for $N_C \rightarrow \infty$

No new parameters introduced for gluon jets!

Interleaved evolution

- Transverse-momentum-ordered parton showers for ISR/FSR
- MPI also ordered in p_{T}

⇒ Allows interleaved evolution for ISR, FSR and MPI:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_{\mathrm{T}}} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_{\mathrm{T}}} \right) \times \exp\left(- \int_{p_{\mathrm{T}}}^{p_{\perp\mathrm{max}}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_{\mathrm{T}}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_{\mathrm{T}}} \right) \mathrm{d}p'_{\mathrm{T}} \right)$$

Ordered in decreasing p_{T} using “Sudakov” trick.
Corresponds to increasing “resolution”:
smaller p_{T} fill in details of basic picture set at larger p_{T}.

- Start from fixed hard interaction ⇒ underlying event
- No separate hard interaction ⇒ minbias events
- Possible to choose two hard interactions, e.g. $\mathrm{W}^-\mathrm{W}^-$

Systematic tuning (vs Brute Force vs Expert)

RIVET: collection of experimental data, together with matching analysis routines. Can be applied to generator events for comparison with data.

PROFESSOR: parameter tuning in multidimensional parameter space.

- Generate large event samples at $\mathcal{O}(n^2)$ *random* points in (reasonable) parameter space. Slow!
- Analyze events and fill relevant histograms.
- For each bin of each histogram parametrize

$$X_{MC} = A_0 + \sum_{i=1}^{n} B_i p_i + \sum_{i=1}^{n} C_i p_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} D_{ij} p_i p_j$$

- Do minimization of χ^2 on parametrized results. Fast!

MCPLOTS

Repository of comparisons between various tunes and data,
mainly based on RIVET for data analysis,
see `http://mcplots.cern.ch/`.
Part of the LHC@home 2.0 platform for home computer participation.

Generator	Version
alpgenherwigjimmy	
alpgenpythia6	
herwig++	
herwig++powheg	
pythia6	
pythia8	
sherpa	
vincia