LUND UNIVERSITY

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Status and Developments of Event Generators

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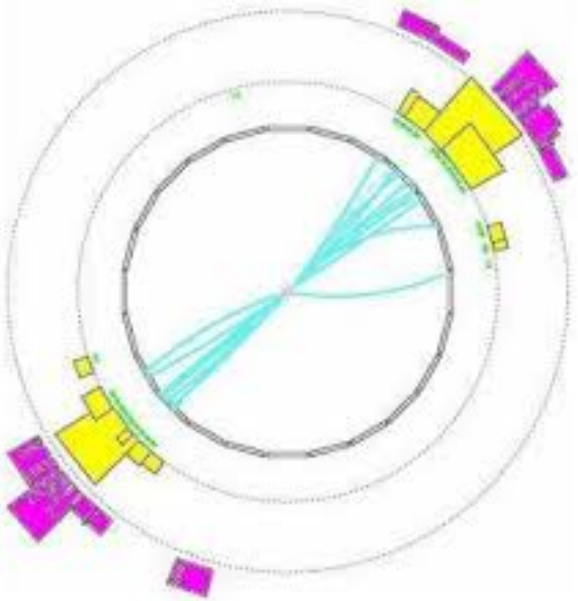
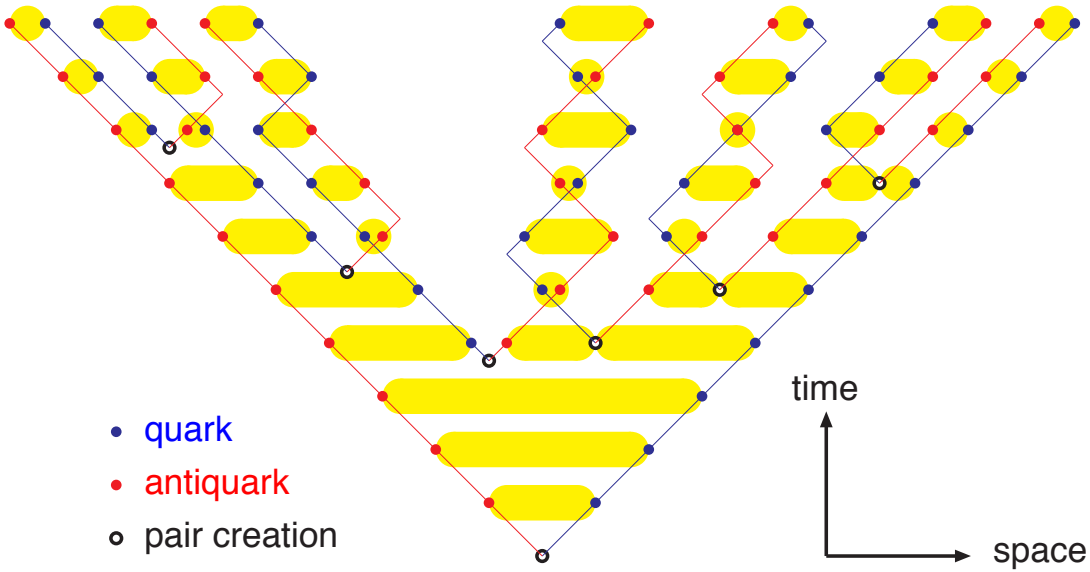
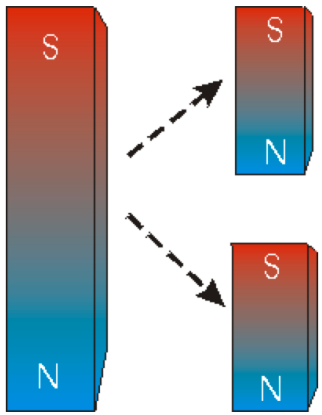
Further talks by Gavin Salam, Rikkert Frederix, Tomas Jezo, Marek Schönherr, Frank Tackmann, ... and several of the experimental presentations (?)

1976: Lund QCD Phenomenology group

Created by Bo Andersson and Gösta Gustafson







Lund string model: $\sim$ like rubber band that is pulled apart and breaks into pieces, or like a magnet broken into smaller pieces.

Complete, consistent description of 2-jet events — but not necessarily perfect.

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

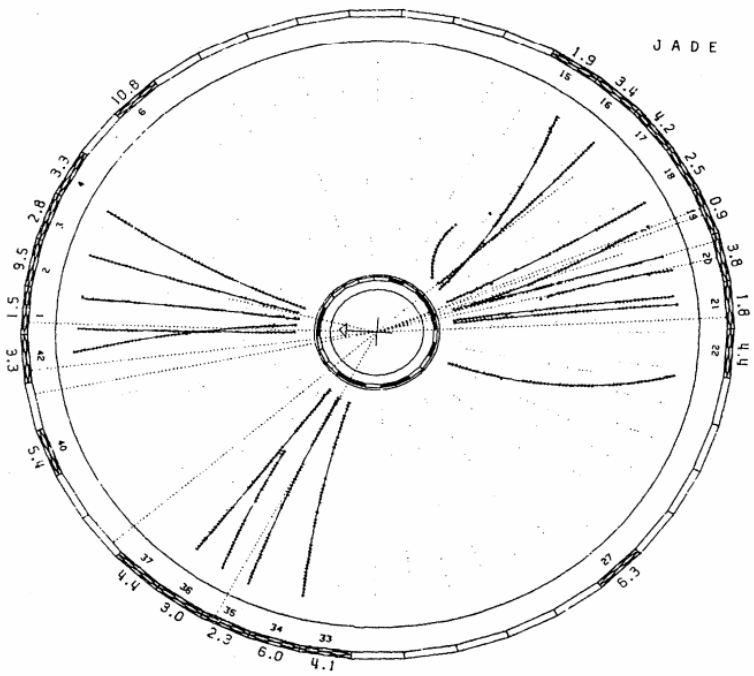
Fortran code

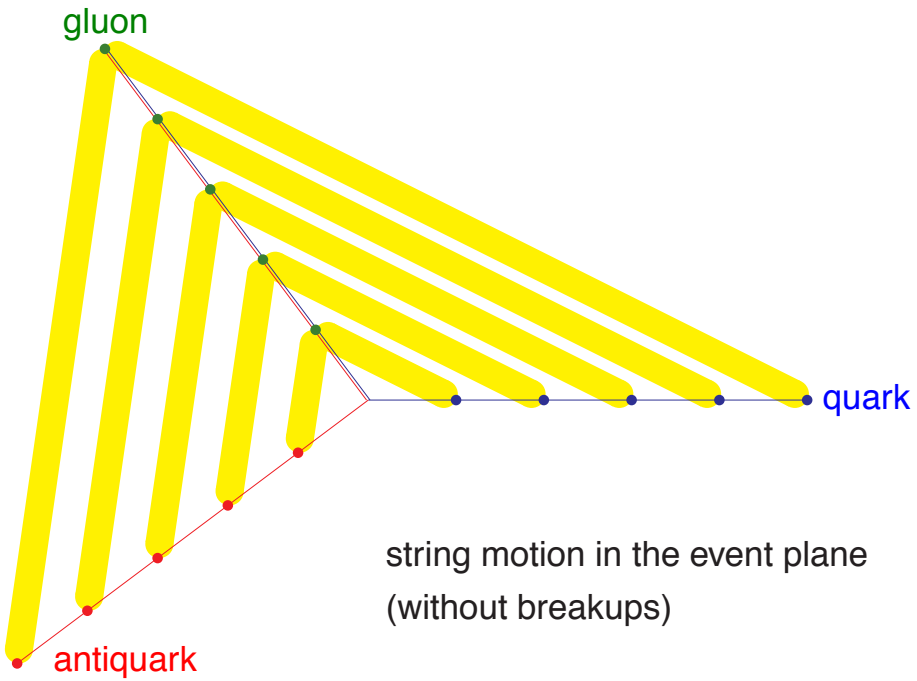
```
      SUBROUTINE EDIT(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /EDPAR/ ITHROW, PZMIN, PMIN, THETA, PHI, BETA(3)
      REAL ROT(3,3), PR(3)
C 1 THROW AWAY NEUTRALS OR UNSTABLE OR WITH TOO LOW PZ OR P
      I1=0
      DO 110 I=1,N
      IF(ITHROW.GE.1.AND.K(I,2).GE.8) GOTO 110
      IF(ITHROW.GE.2.AND.K(I,2).GE.6) 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.,0.426,0.662,0.957,
     &0.980,1.,1.,1.,0.667,1.,0.667,1.,0.667,1.,0.667,1.,1.,
     &0.899,0.987,1.,0.486,0.837,0.984,1./
      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-','KO','KBO','PIO','ETA',
     &'ETAP','RHO+','RHO-','K*+','K*-','K*O','KB*O','RHOO','OMEG','PHI'/
      DATA CHA3/'    ','STAB'/
      END
```

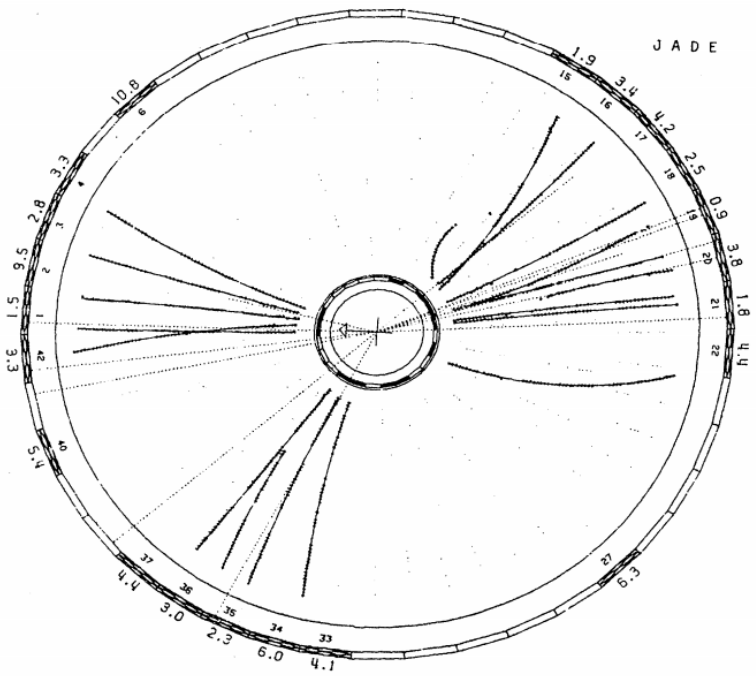
1980: string (colour coherence) effect

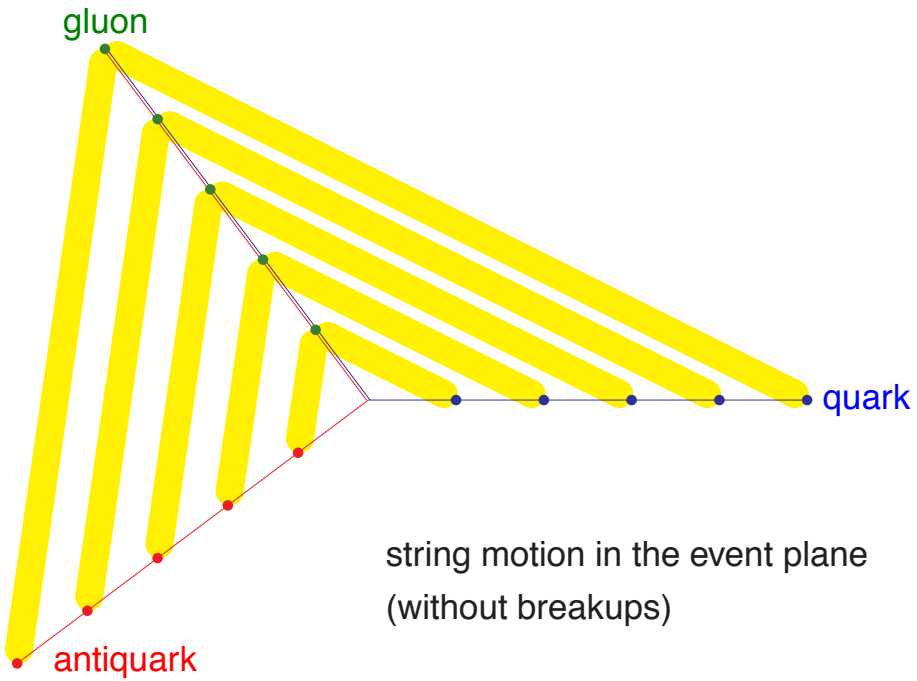




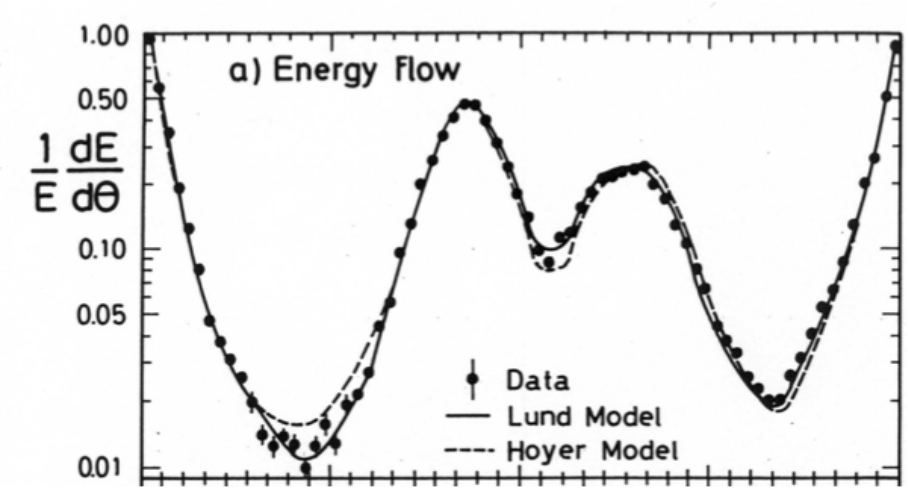
string motion in the event plane
(without breakups)

1980: string (colour coherence) effect





string motion in the event plane
(without breakups)



Predicted unique event structure;
inside & between jets.
Confirmed first by JADE 1980.

Generator crucial to sell physics!

(today: PS, M&M, MPI, . . .)

Lund contributions

Physics:

- string fragmentation (& colour coherence)
- dipole showers
- backwards evolution (for ISR)
- multiparton interactions (MPI)
- colour reconnection (CR)
- matching (POWHEG style) & merging (CKKW-L, ...)
- small-x evolution (CCFM, ...)
- interleaved evolution
- heavy-ion collisions
- QCD effects for BSM

Generators:

JETSET
PYTHIA
Fritiof
Ariadne
LDC
DIPSY

Lepto
VINCIA
DIRE

RapGap
HIJING
...
GEANT

The workhorses

Herwig, PYTHIA and Sherpa offer convenient frameworks
for LHC physics studies, covering all aspects above,
but with slightly different history/emphasis:

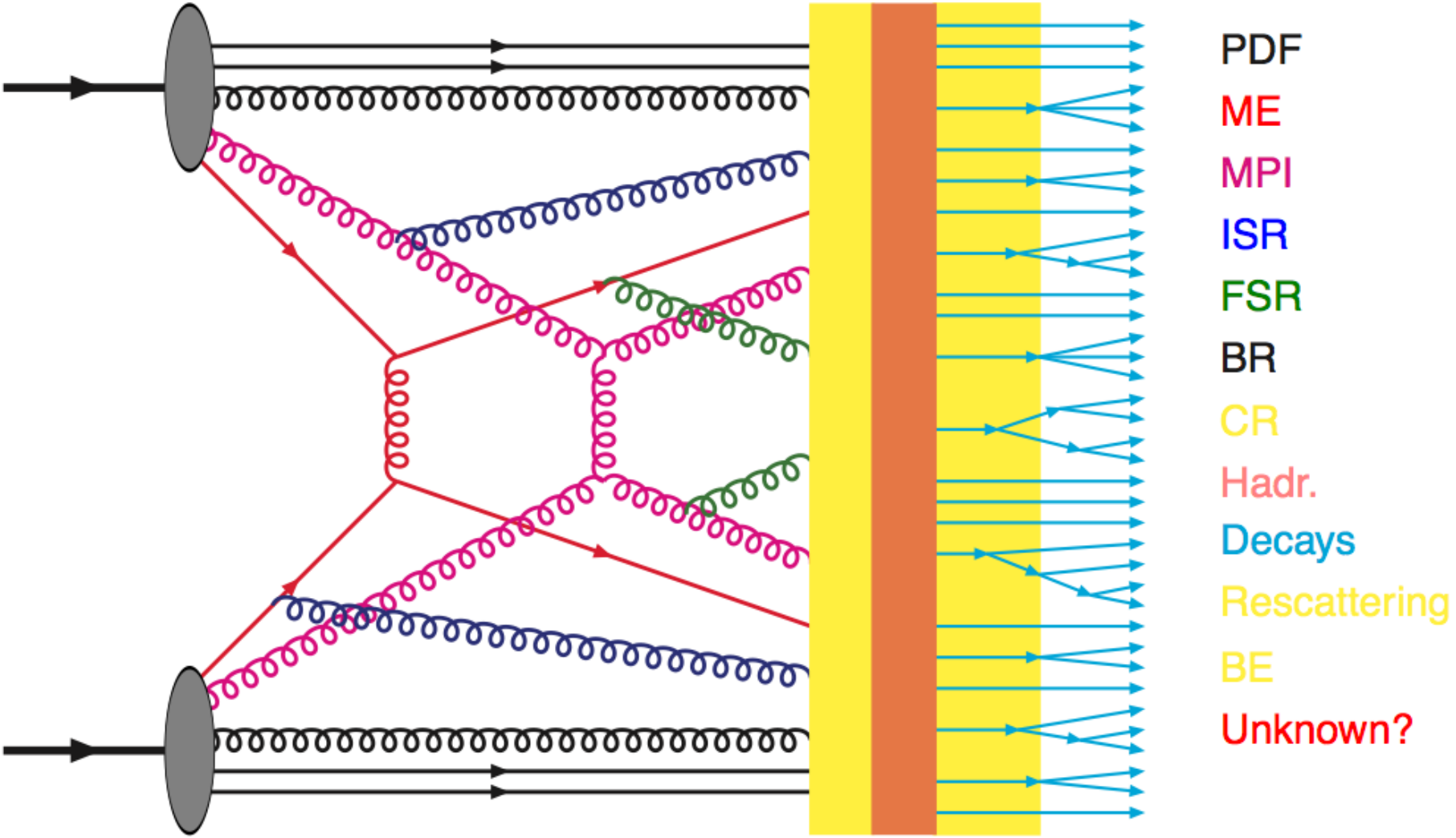
PYTHIA (successor to JETSET, begun in 1978):
originated in hadronization studies,
still special interest in soft physics.

Herwig (successor to EARWIG, begun in 1984):
originated in coherent showers (angular ordering),
cluster hadronization as simple complement.

Sherpa (APACIC++/AMEGIC++, begun in 2000):
had own matrix-element calculator/generator
originated with matching & merging issues.

The structure of an event

All full-fledged generators need to address many issues:



MCnet

Herwig
PYTHIA
Sherpa
MadGraph

Plugin:
Ariadne
DIPSY
HEJ

CEDAR:
Rivet
Professor
HepForge
LHAPDF
HepMC

- EU-funded 2007–10, 2013–16, **2017–20**
- Generator development
- Services to community
- PhD student training
- Common activities

Nodes:
Manchester
CERN
Durham
Glasgow
Göttingen
Heidelberg
Karlsruhe
UC London
Louvain
Lund

Monash (Au)
SLAC (US)

MCnet

Herwig
PYTHIA
Sherpa
MadGraph

Plugin:
Ariadne
DIPSY
HEJ

CEDAR:
Rivet
Professor
HepForge
LHAPDF
HepMC

- EU-funded 2007–10, 2013–16, **2017–20**
- Generator development
- Services to community
- PhD student training
- Common activities
- Short-term studentships (3 - 6 months). Experimentalists welcome!
- Summer schools
  2016: DESY (w. CTEQ)
  2017: Lund, 3 - 7 July

Send your students!

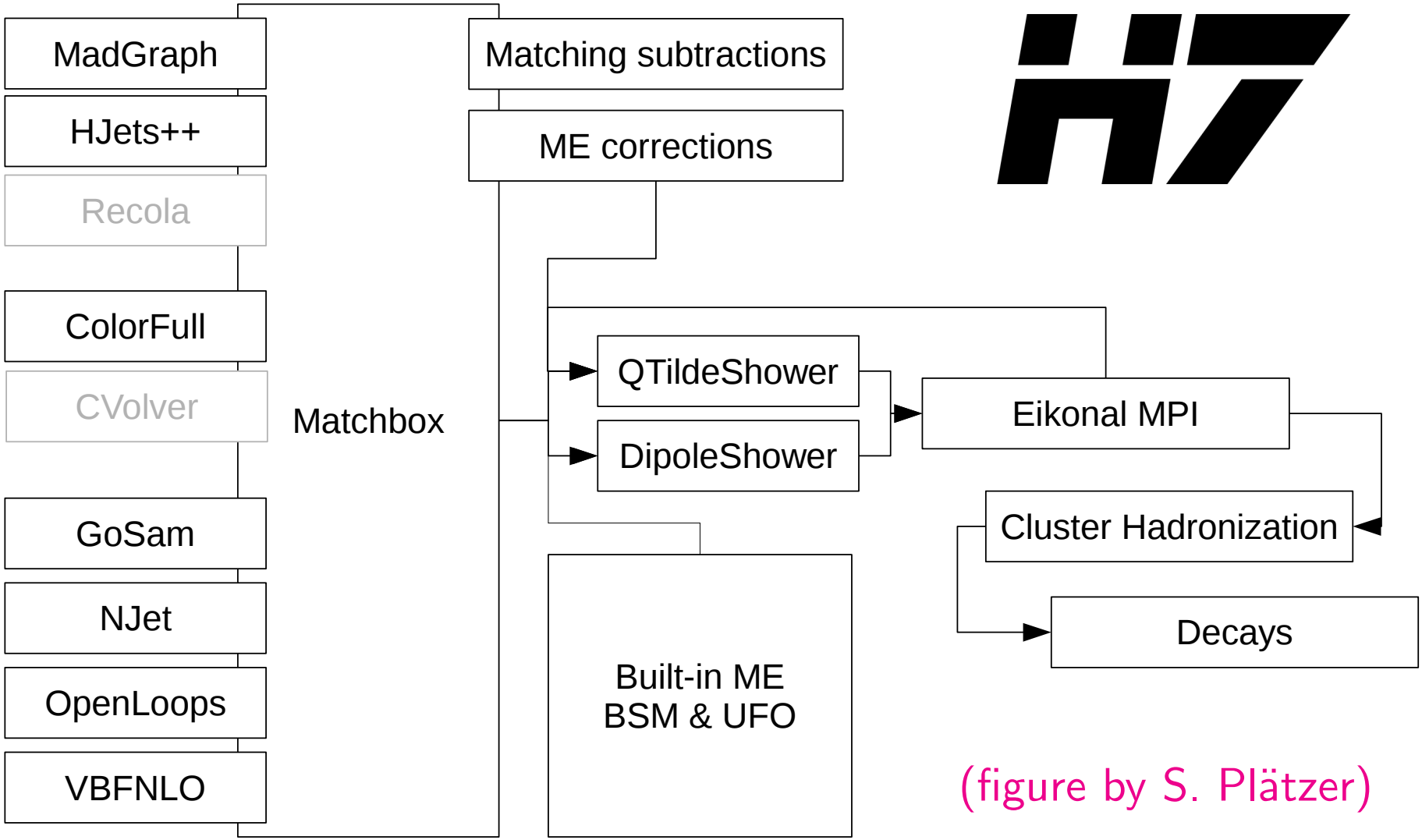
Nodes:
Manchester
CERN
Durham
Glasgow
Göttingen
Heidelberg
Karlsruhe
UC London
Louvain
Lund

Monash (Au)
SLAC (US)

Herwig 7.0 news

- Herwig++ 3.0 $\Rightarrow$ **Herwig 7.0** (December 2015).
  Concludes 16 years effort to replace Fortran Herwig 6.
- **NLO** matched to parton showers **default** for hard process.
  - Fully **automated**: no external codes to run,
    no intermediate event files.
  - Choice of **subtractive** (MC@NLO type)
    or **multiplicative** (PowHeg type) matching.

Matchbox in Herwig 7



(figure by S. Plätzer)

script downloads & sets up external libraries (above + more)

Herwig 7.0 news

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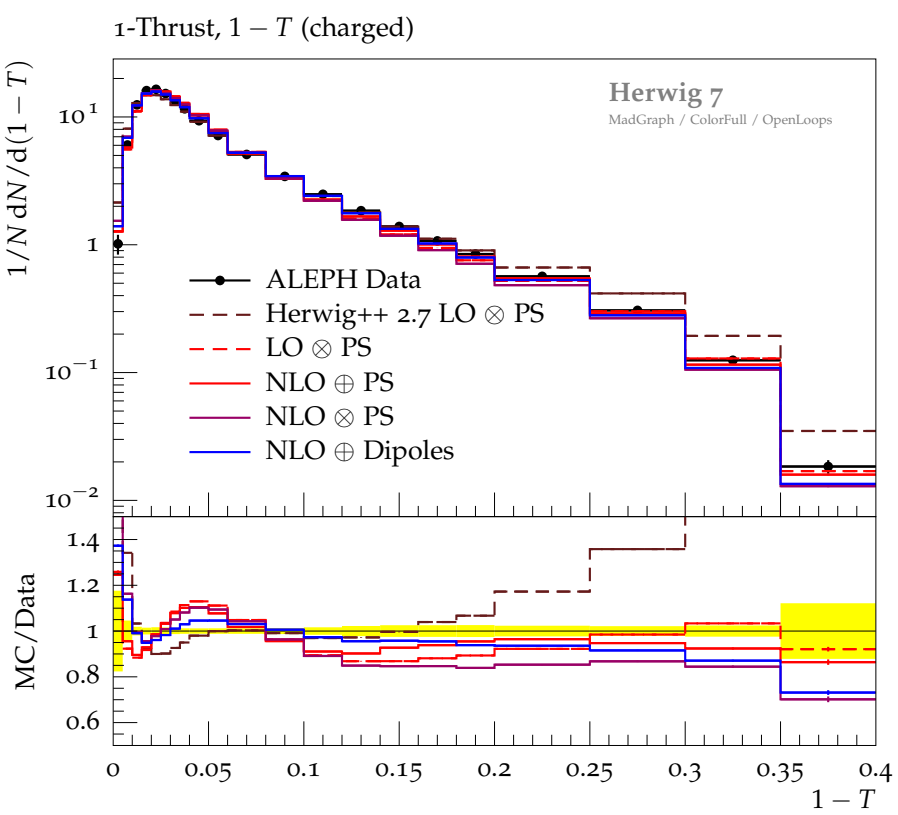
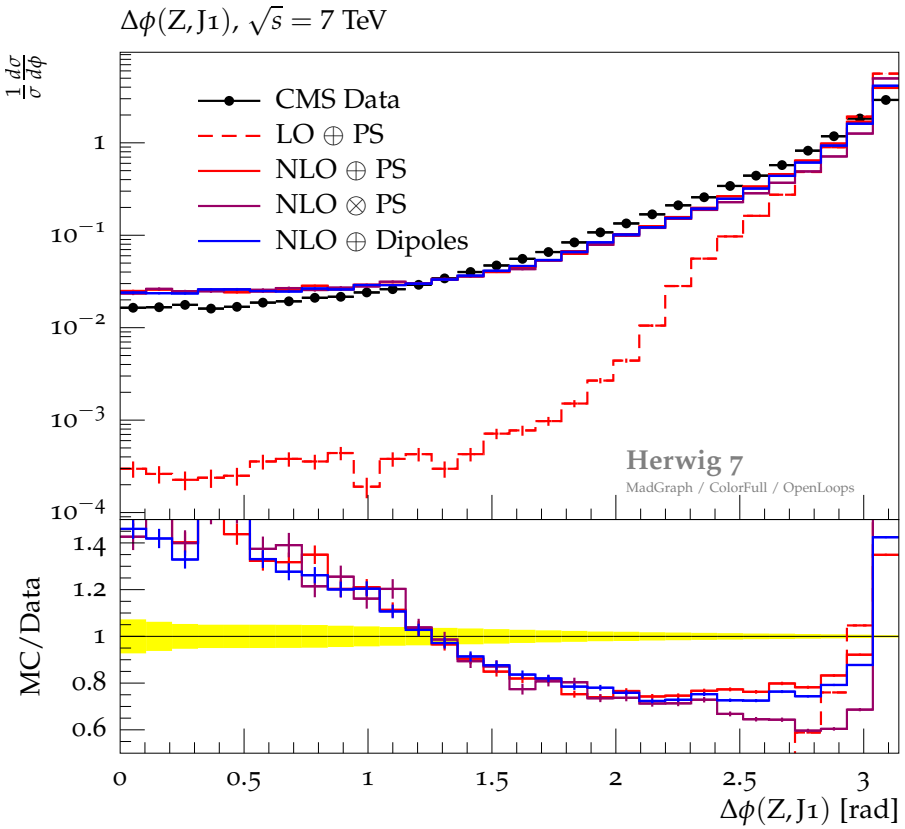
  Concludes 16 years effort to replace Fortran Herwig 6.
- **NLO** matched to parton showers **default** for hard process.
  - Fully **automated**: no external codes to run,
    no intermediate event files.
  - Choice of **subtractive** (MC@NLO type)
    or **multiplicative** (PowHeg type) matching.
- Two showers: angular ordered or **dipole**.
  Spin correlations and QED radiation in the former.
- Facilities for parton-shower uncertainties.
- New tunes, including MB/UE.
- Vastly improved documentation, usage and installation.
- Several parallelization options.

Herwig 7 examples





LO $\rightarrow$ NLO $\Rightarrow$ major improvements in e^+e^- and pp alike.

Subtractive or multiplicative matching less important.

Ditto angular-ordered or dipole shower.

Future of Herwig 7

Herwig 7.1 later this year:

- **NLO multijet merging** (unitarized merging ideas).
- Loop-induced processes.
- Extended UFO-model support.
- Extended reweighting: weight vectors in HepMC files.
- Improved top decay in dipole shower.
- Interface to HEJ.
- Soft interactions and diffraction.

In the longer run:

- Code now 500k lines $\Rightarrow$ need for significant restructuring.
- Amplitude-based parton showers.

Sherpa 2.2 news and activities

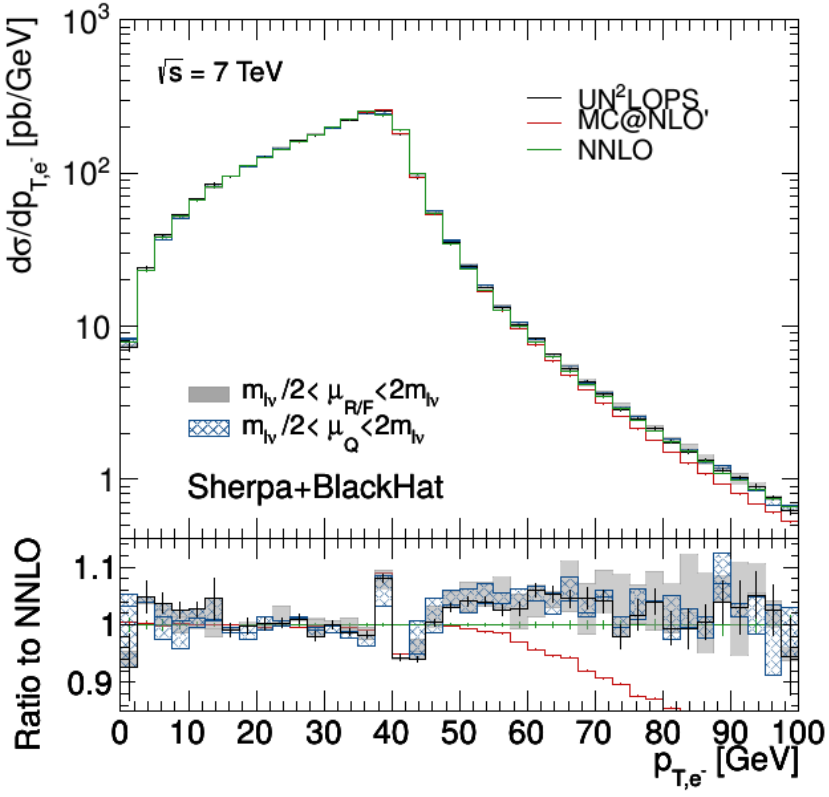
Recent news:

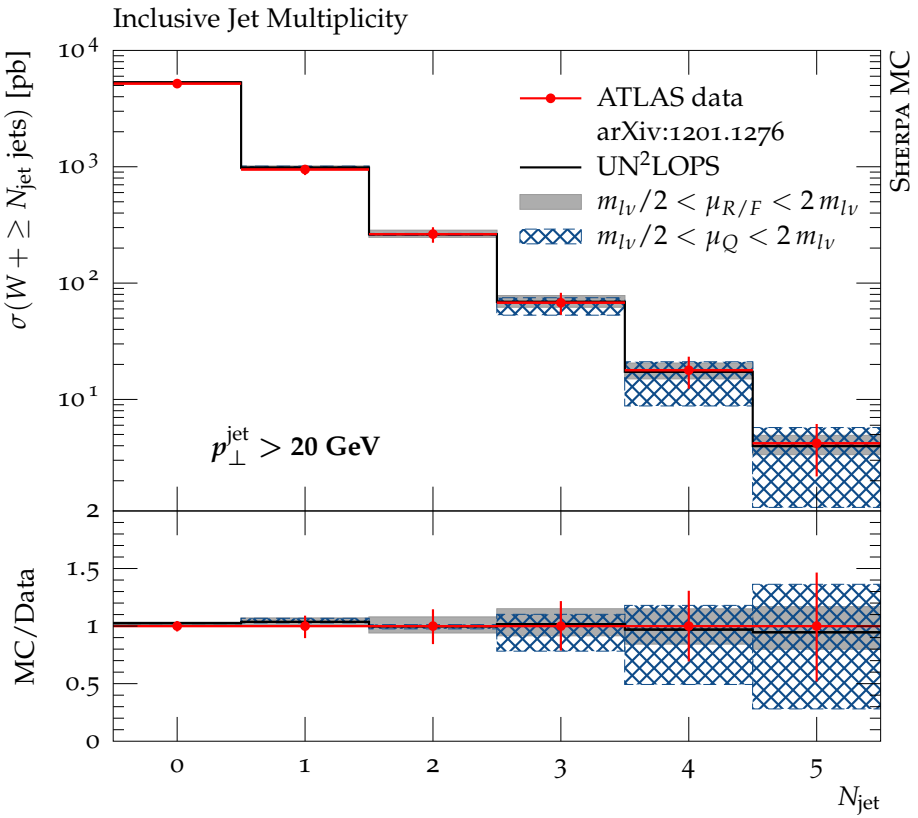
- DIRE shower (see below).
- UNNLOPS - first results on NNLO merging.

Sherpa NNLO QCD with parton showers

W production @ NNLO+PS with SHERPA +BLACKHAT

[Höche et al. arXiv:1507.05325]





↪ fully differential hadron-level NNLO+PS simulation

- inclusive (born-like) distribution NNLO accurate
- 0-jet bin NNLO, 1-jet bin NLO, 2-jet bin LO, $\geq$ 3-jets shower accuracy

↪ small corrections away from Born kinematics

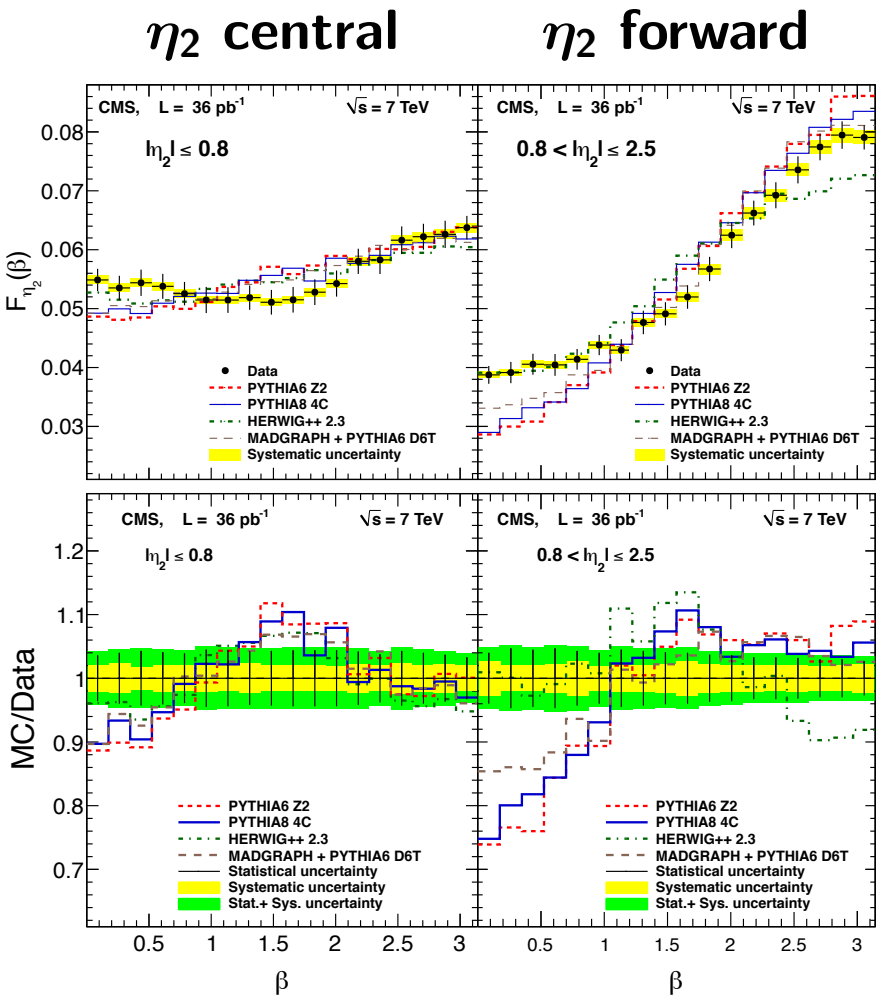
Sherpa 2.2 news and activities

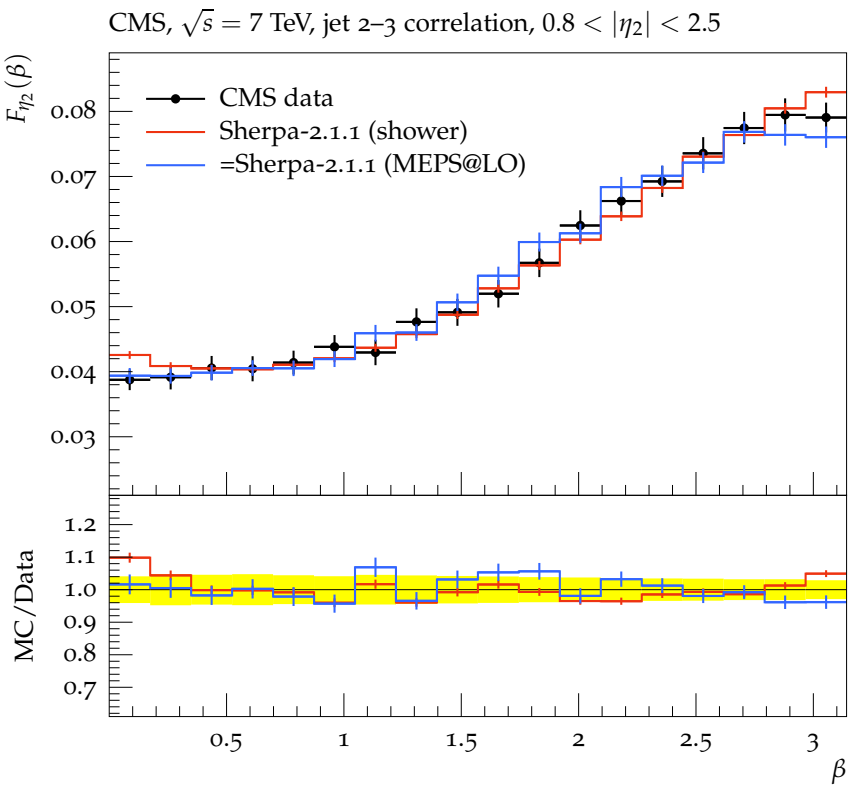
Recent news:

- DIRE shower (see below).
- UNNLOPS - first results on NNLO merging.
- On-the-fly scale variations of NLO ME + PS.
  ME observables through interpolating grids
  (ApplGrid, FastNLO, MCgrid, ...).
- Electroweak NLO corrections, together with OpenLoops.
- Merging for loop-induced processes.

Sherpa QCD coherence test

Study events with two hard and one further softer third jets.
Angular distribution of third around second probes colour coherence:





PYTHIA/Herwig does not quite describe data, whereas Sherpa fares much better.

Sherpa 2.2 news and activities

Recent news:

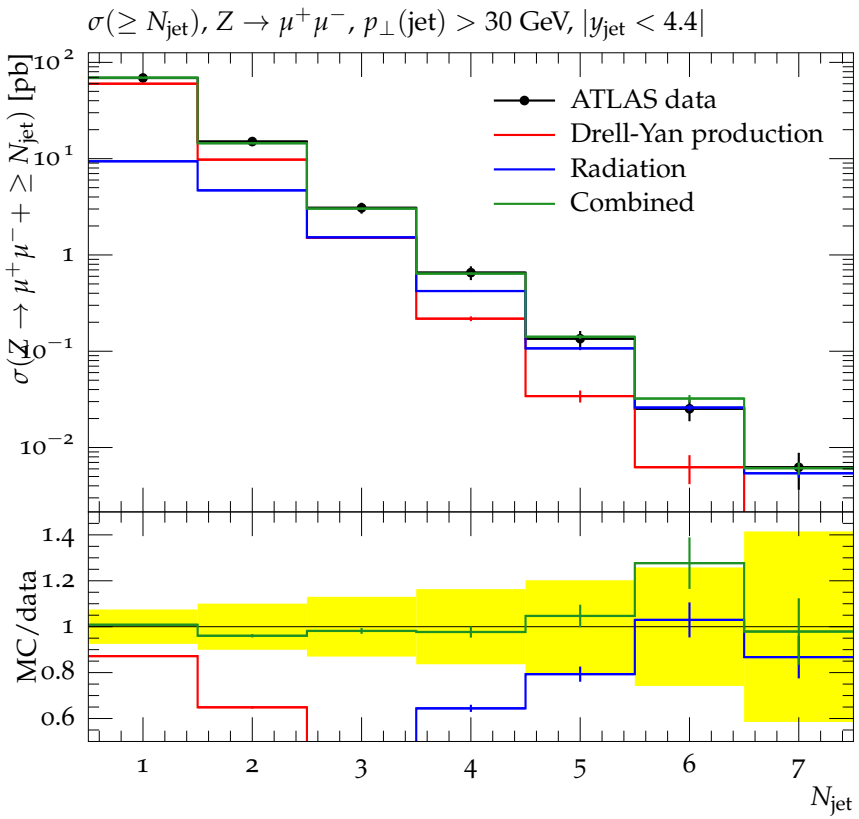
- DIRE shower (see below).
- UNNLOPS - first results on NNLO merging.
- On-the-fly scale variations of NLO ME + PS.
  ME observables through interpolating grids
  (ApplGrid, FastNLO, MCgrid, ...).
- Electroweak NLO corrections, together with OpenLoops.
- Merging for loop-induced processes.

Ongoing work and plans:

- Full NNLO QCD + NLO EW (for $2 \to 1$, $2 \to 2$).
- Higher-order shower
  (one-loop splitting functions, sub-leading colour).
- Automated N-jettiness slicing.

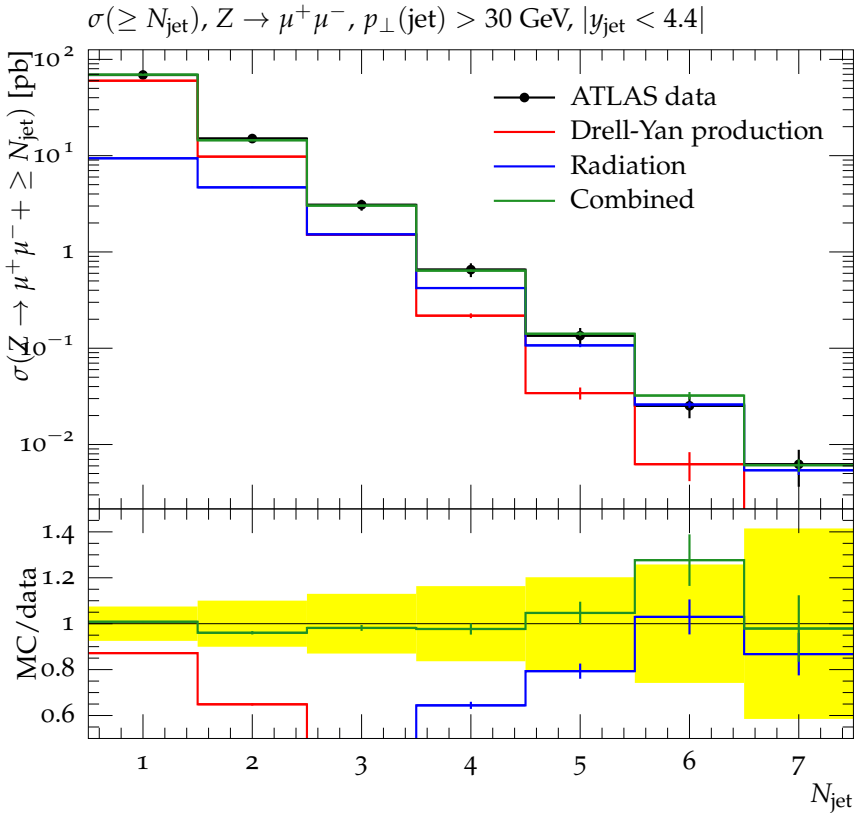
PYTHIA 8.2 news

- New match&merge schemes (now 8) and options.
- Weak showers: $q \to qZ^0$, $q \to q'W^{\pm}$ (also merged).

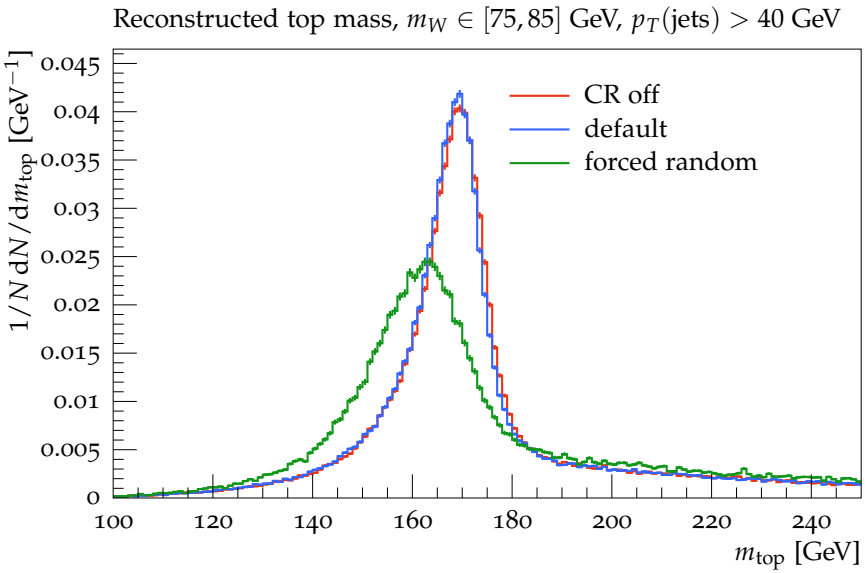


PYTHIA 8.2 news

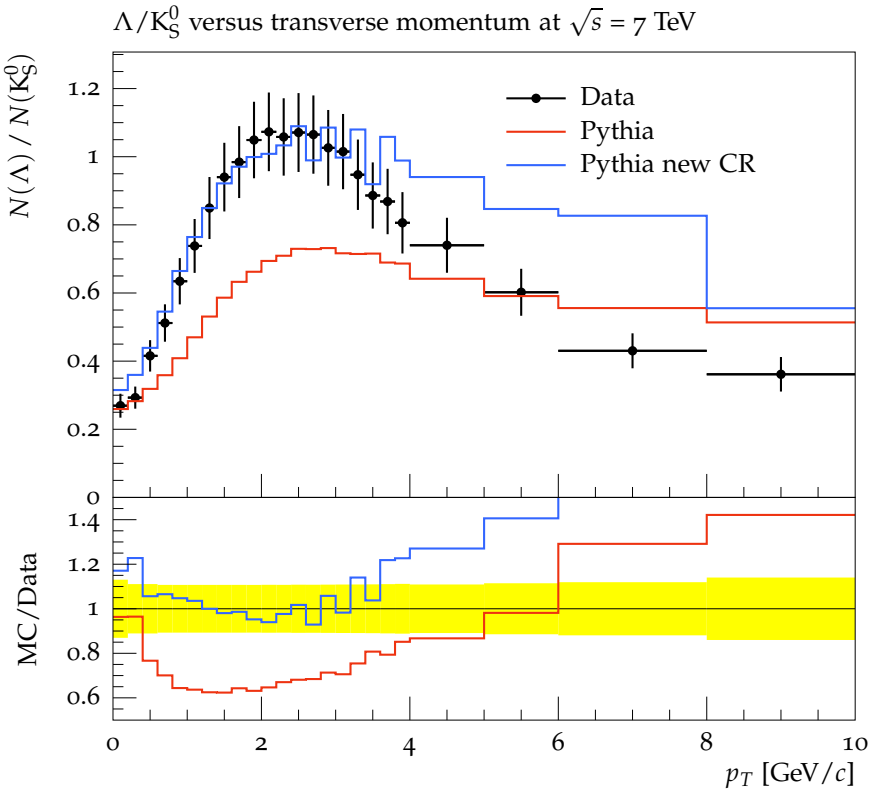
- New match&merge schemes (now 8) and options.
- Weak showers: $q \to qZ^0$, $q \to q'W^{\pm}$ (also merged).
- Allow reweighting of rare shower branchings.
- Automated parton-shower uncertainty bands.
- Extended interface for external shower plugins.
- Complete LHEF v3 support.
- Can run Madgraph5_aMC@NLO and POWHEG BOX from within PYTHIA.
- Complete Python interface.



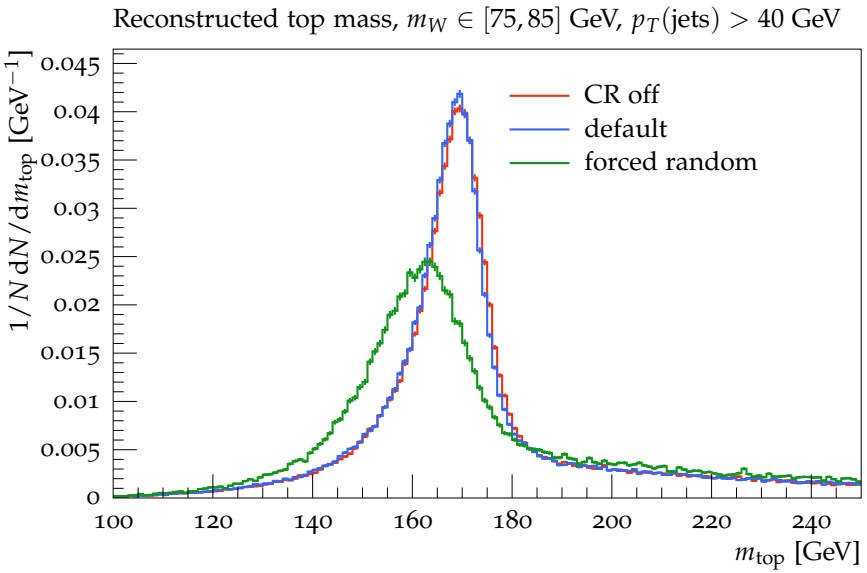
PYTHIA 8.2 news

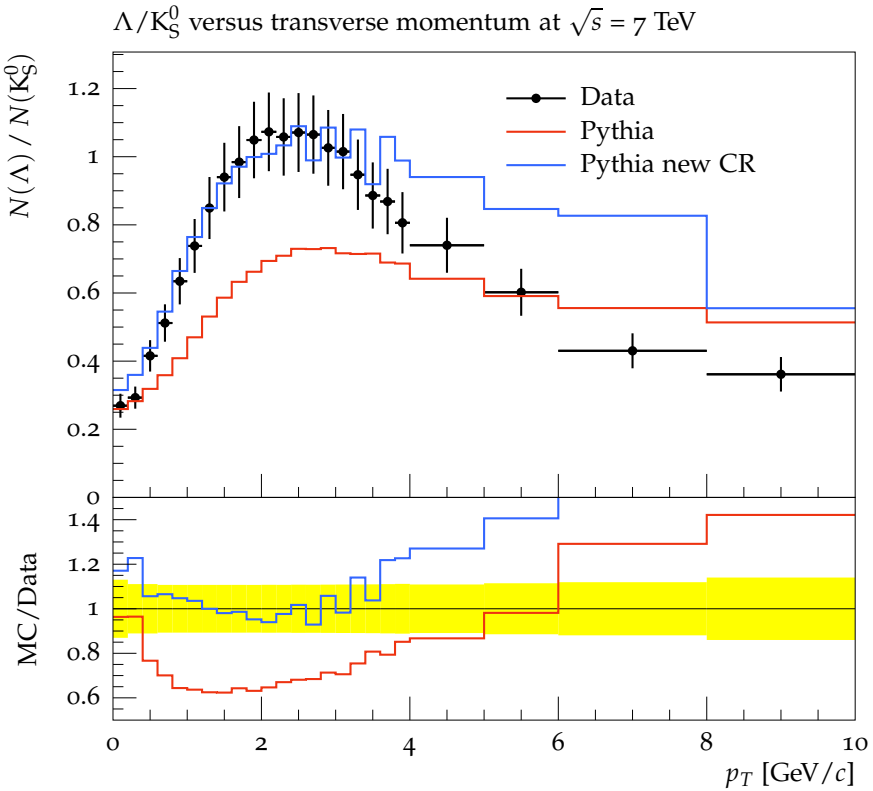


- Many new colour reconnection models.



PYTHIA 8.2 news





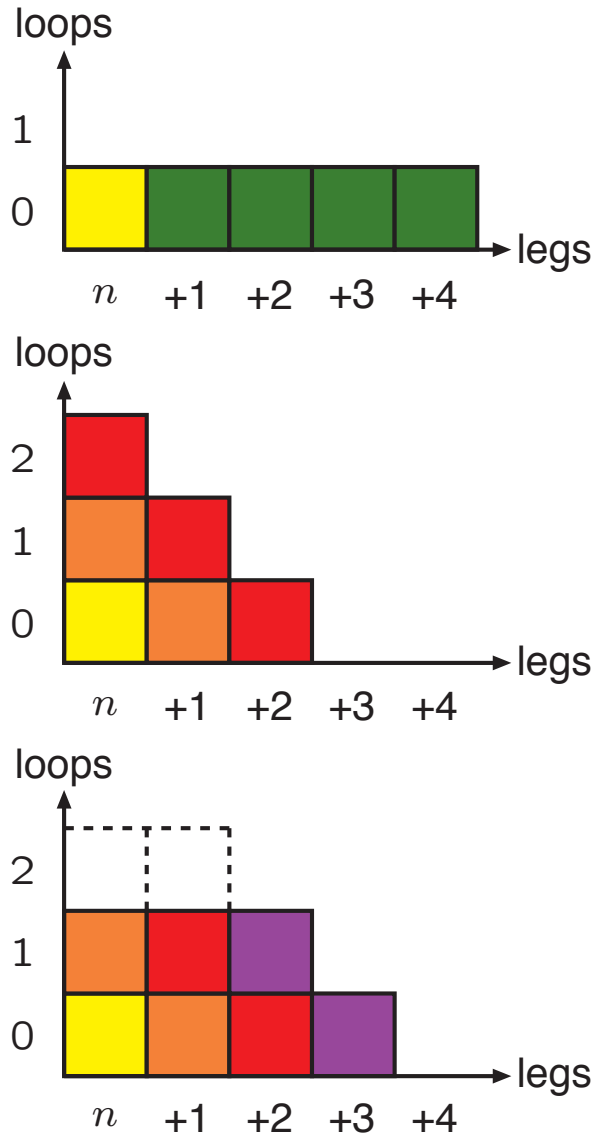
- Many new colour reconnection models.
- Double onium production.
- New model for hard diffraction.
- Several new tunes; Monash new default.

Ongoing work and plans:

- $\gamma\gamma$, $\gamma\mathrm{p}$ and ep.
- Total, elastic and diffractive cross sections.
- Improved showers and hadronization.

Match and merge strategies

Input from:
Madgraph5_aMC@NLO
POWHEG BOX
ALPGEN
COMIX/Sherpa
NLOJET++
JETRAD
HJETS++
BlackHat
GoSam
Helac
OpenLoops
VBFNLO
CalpHEP/CompHEP
...



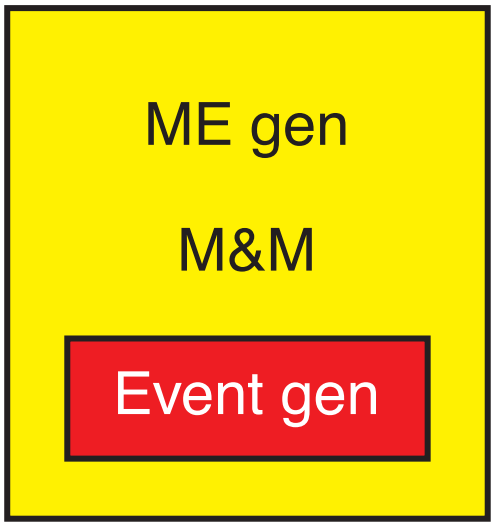
CKKW
CKKW-L
MLM
UMEPS
MC@NLO
POWHEG
MENLOPS
MEPS@NLO
NL^3
UNLOPS
FxFx
NNLOPS
MiNLO
UN^2LOPS
MIN^2LOPS

Intense activity, no "final word".

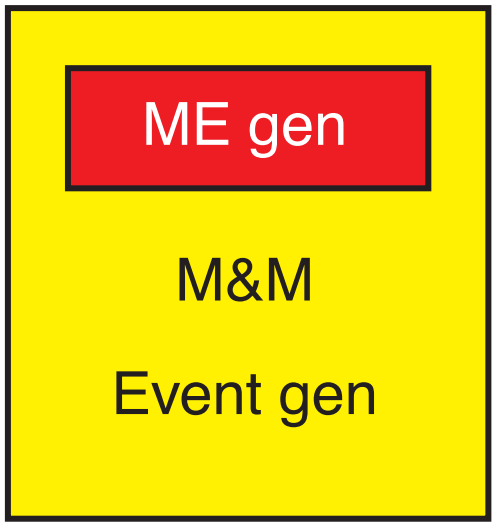
Combination strategies

Big flexibility, but different baseline "world view":

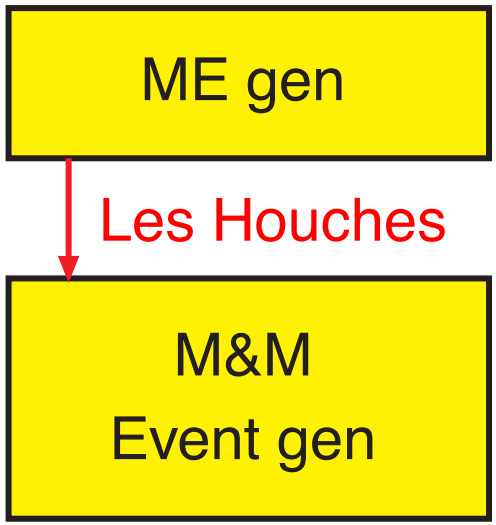
MadGraph:



Herwig, Sherpa:



Pythia:



Event gen = ISR + FSR + MPI + BBR + CR + hadronization + ...
$\neq$ "hadronizer"

ME and Event Generators both indispensable

VINCIA: an Interleaved Antennae shower

Markovian process: no memory of path to reach current state.

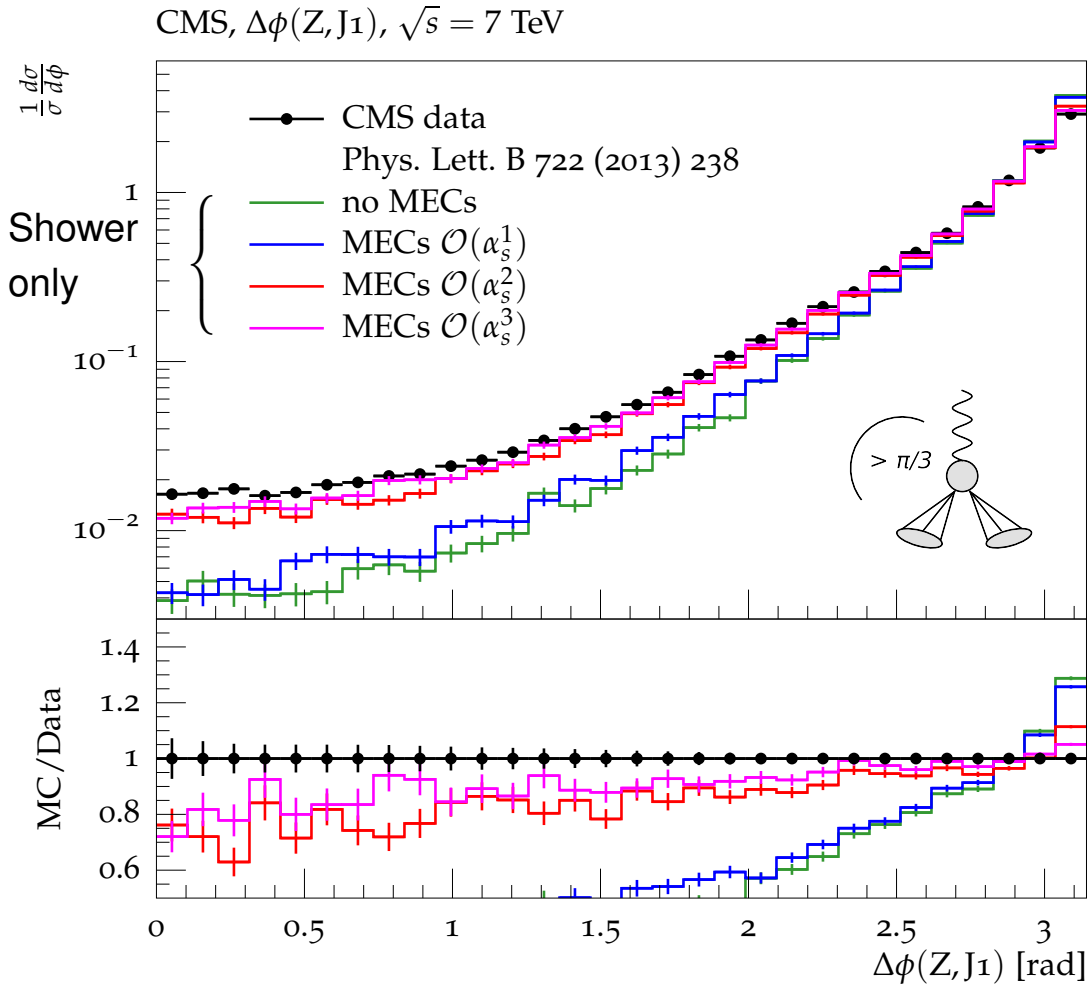
Based on antenna factorization of amplitudes and phase space.

Smooth ordering fills whole phase space.

Step-by-step reweighting to new matrix elements: $Z \to Zj \to Zjj \to Zjjj$ (also Sudakov), e.g.

$$W = \frac{|\mathcal{M}_{Zj}|^2}{\sum_i a_i |\mathcal{M}_Z|_i^2}$$

Replaces PYTHIA normal showers; recent release.



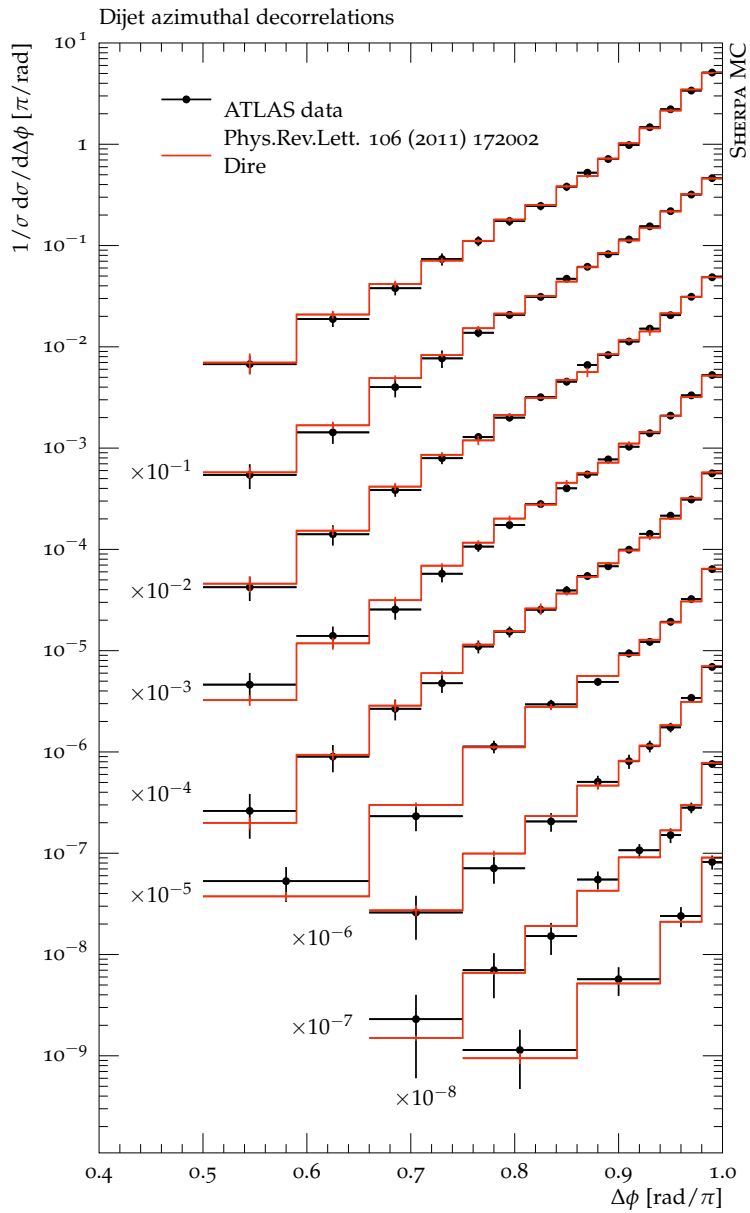
DIRE: a Dipole Resummation shower

Joint Sherpa/PYTHIA development, but separate implementations, means technically well tested.

"Midpoint between dipole and parton shower",
dipole with emitter & spectator,
but not quite CS ones:
unified initial–initial, initial–final, final–initial, final–final.

Soft term of kernels in all dipole types is less singular

$$\frac{1}{1-z} \to \frac{1-z}{(1-z)^2 + p_\perp^2/M^2}$$



Apologies: will not cover

- High Energy Jets (HEJ): BFKL-inspired description of well-separated multijets, with approximate matrix elements and virtual corrections.
- Deductor: improved handling of colour, partitioned dipoles, all final partons share recoil, q^2/E evolution variable.
- Geneva: Soft Collinear Effective Theory resummed (exclusive) n-jet rates as starting point for showers.
- Ariadne: first dipole parton shower program.
- DIPSY: evolution and collision of dipoles in transverse space.
- revived Fritiof: overlayed modified pp collisions to model pA.
- EPOS: pp/pA/AA, MPI + strings, saturation, thermalized core separate from corona, hydrodynamical evolution.
- DPMJET, QGSJET, SIBYLL: other pp/pA/AA/cosmic ray.
- ...

Summary and Outlook

- Increased ME calculational capability: legs and loops.
- Match and merge approaches still steadily developing.
  Generators typically offer several options.
  Spread between approaches one measure of uncertainty.
- Continued/increased interest in parton shower development, with each generator offering several options.
- Automated uncertainty bands for scale choices etc.
- Many challenges remaining in soft physics, pA, AA: diffraction, colour reconnection, collective effects, ...
- **Generators have gone from fringe activity for a few to a mainstream part of phenomenology research.**


Thank You!