Status of the PYTHIA8 Event Generator

PYTHIA

Stephen Mrenna
Fermilab

April 13, 2017

Why do we have event generators?

Aristotle's approach to "Why" questions: the 4 causes

- formal cause
- material cause
- essential cause
- final cause

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Why do we have event generators?

Aristotle’s approach to “Why” questions: the 4 causes

- formal cause What is it?
- material cause What is it made of?
- essential cause Where does it come from?
- final cause What is it good for?

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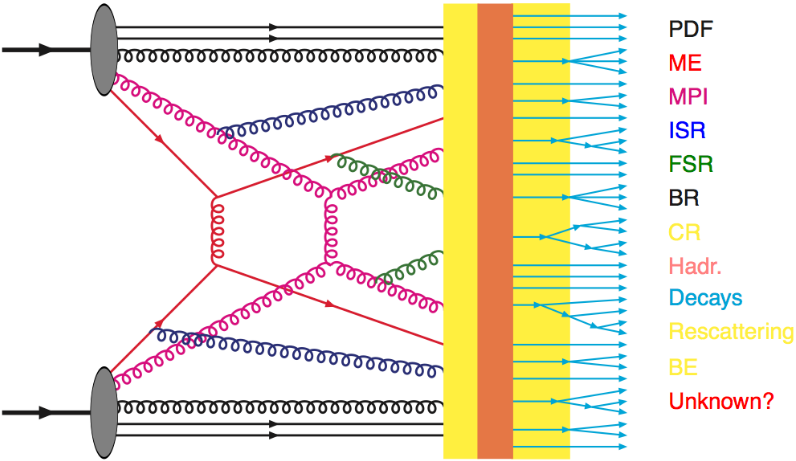
What is Pythia8?

Simulation of “elementary” particle interactions using all the Standard Model physics we know



What is it made of?

$>$ 100,000 lines of code (C++)

$\sim$ 1000 physics "rules"

$\sim$ 1000 parameters (booleans, integers, real numbers)

$>$ 40,000 lines of documentation

$\sim$ 1000 files

9 authors: Lund (4), Heidelberg, Boston, Chicago, Melbourne

PYTHIA

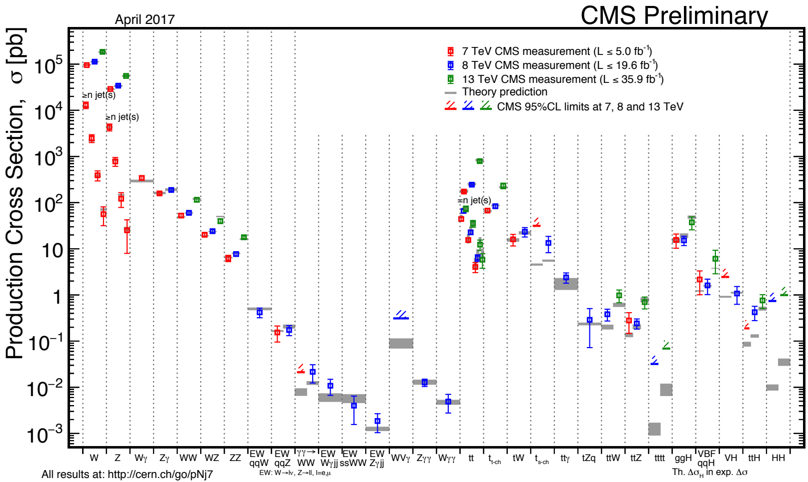
- thousands of users worldwide
- 20,000$+$ citations to PYTHIA/JETSET manuals

Where does it come from?

+Peter Skands @ Monash, Australia; Phil Ilten @ MIT

What is it good for?

Theory vs. Data for the Standard Model



Pythia8 is a component of most of these predictions

The Pythia8 Collaboration

```
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```

Modern particle physics depends on computer models/simulations

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#8 - 17: Daya Bay Collaboration - New measurements suggest 'antineutrino anomaly' fueled by modeling error

4 April 2017 - Daya Bay Collaboration

Analysis indicates missing particles problem may stem from uranium isotope

Results from a new scientific study may shed light on a mismatch between predictions and recent measurements of ghostly particles streaming from nuclear reactors—the so-called "reactor antineutrino anomaly," which has puzzled physicists since 2011.

The anomaly refers to the fact that scientists tracking the production of antineutrinos—emitted as a byproduct of the nuclear reactions that generate electric power—have routinely detected fewer antineutrinos than they expected. One theory is that some neutrinos are morphing into an undetectable form known as "sterile" neutrinos.

But the latest results from the Daya Bay reactor neutrino experiment, located at a nuclear power complex in China, suggest a simpler explanation—a miscalculation in the predicted rate of antineutrino production for one particular component of nuclear reactor fuel.

Antineutrinos carry away about 5 percent of the energy released as the uranium and plutonium atoms that fuel the reactor split, or "fission." The composition of the fuel changes as the reactor operates, with the decays of different forms of uranium and plutonium (called "isotopes") producing different numbers of antineutrinos with different energy ranges over time, even as the reactor steadily produces electrical power.

DATE ISSUED:

April 4th, 2017

SOURCE:

Daya Bay Collaboration

CONTENT:

Press Release

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Event Generator Reasons

- Structure of LHC events impossible to “solve” from first principles.
- Several competing mechanisms contribute, both perturbative and nonperturbative.
- Even if calculable somehow, need 1000-body expressions and phase space sampling.
- Immense variability, with “typical events” and “rare corners”.

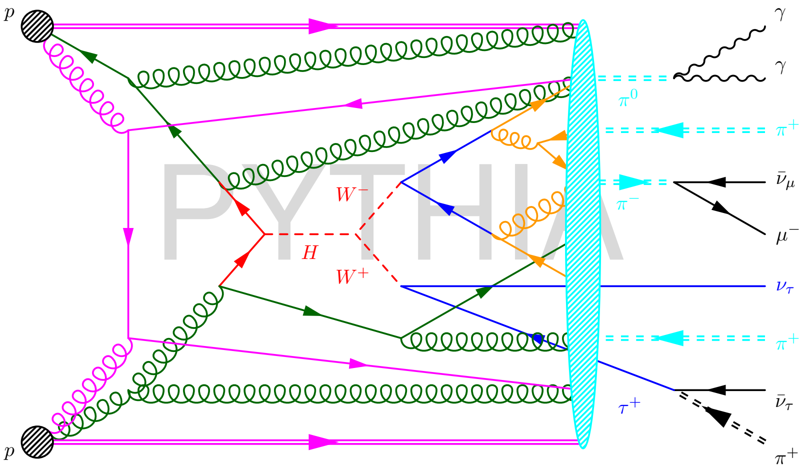
PYTHIA

An event generator is intended to simulate various event kinds, with random numbers providing quantum mechanical variability.

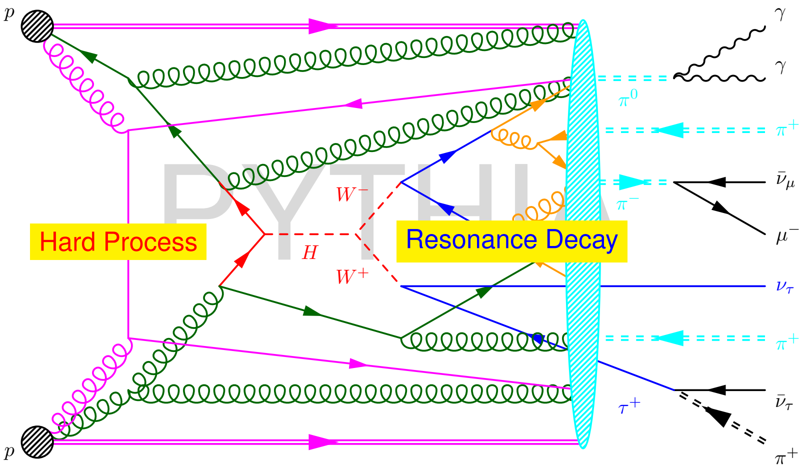
It can be used to

- predict event rates and topologies $\Rightarrow$ estimate feasibility
- simulate possible backgrounds $\Rightarrow$ devise analysis strategies
- study detector requirements $\Rightarrow$ optimize design and trigger
- study detector imperfections $\Rightarrow$ evaluate acceptance

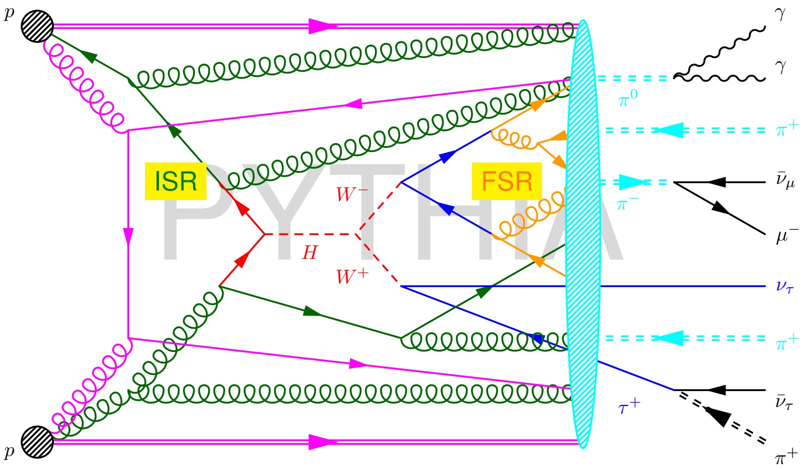
Cartoon of a proton-proton collision



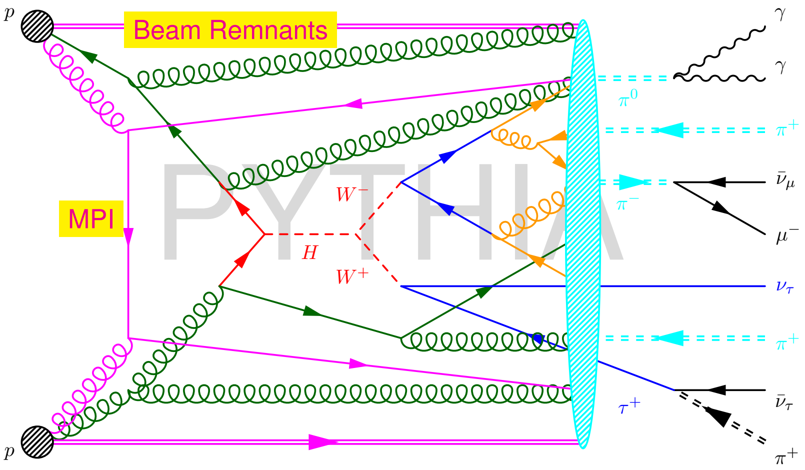
Cartoon of a proton-proton collision



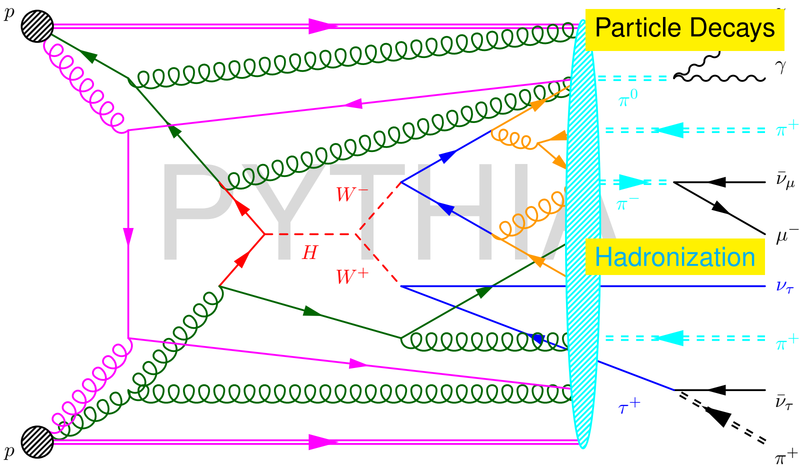
Cartoon of a proton-proton collision



Cartoon of a proton-proton collision



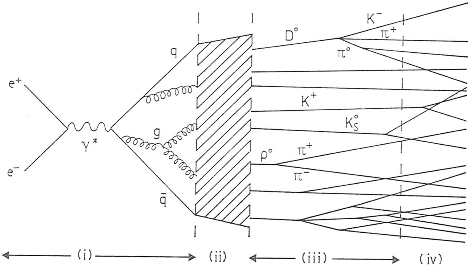
Cartoon of a proton-proton collision



Introduction

Modern event generators were born at DESY,
for the PETRA $\mathrm{e}^+\mathrm{e}^-$ 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.



PYTHIA

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
```

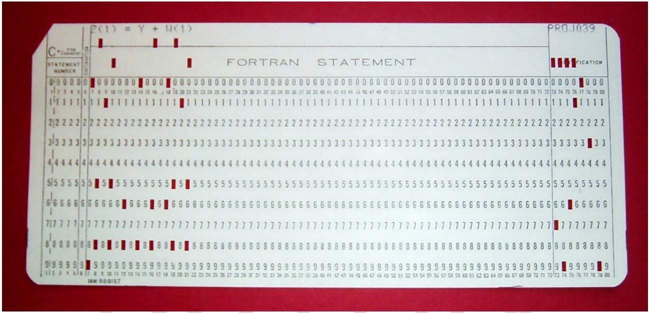
```
      SUBROUTINE EDIT(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /EDPAR/ ITHROW, PZMIN, PMIN, THETA, PHI, BETA(3)
      REAL ROT(3,3), PR(3)
C 1 THROW AWAY NEUTRALS OR UNSTABLE OR WITH TOO LOW PZ OR P
      I1=0
      DO 110 I=1,N
      IF(ITHROW.GE.1.AND.K(I,2).GE.8) GOTO 110
      IF(ITHROW.GE.2.AND.K(I,2).GE.6) 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
```

≈ 200 punched cards

Fortran code

(Sjostrand/Soderberg)



*

*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".

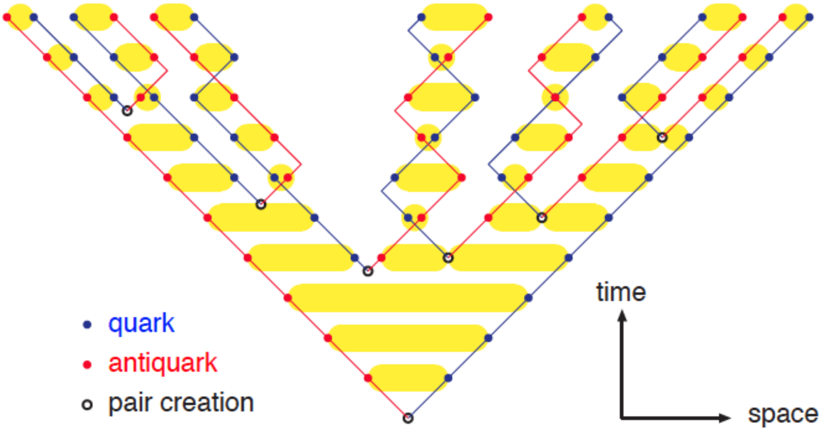
Gives linear confinement with string tension:

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

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

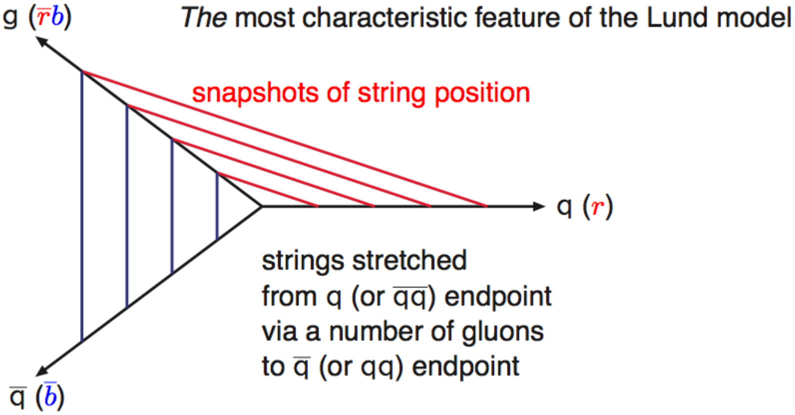
Lund String Model: 2 jets

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



Consistent description of 2 jet topologies

The Lund Gluon Picture



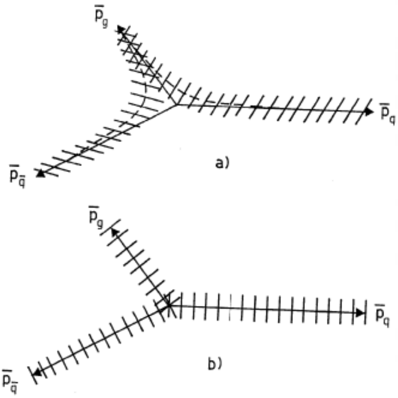
Gluon = kink on string

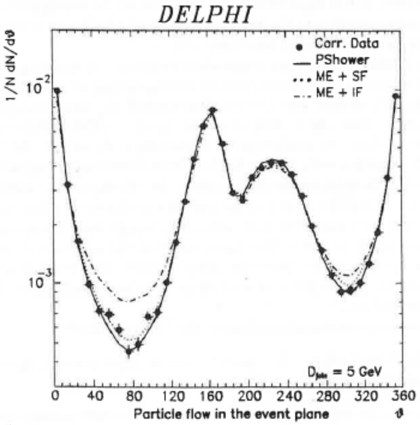
Force ratio gluon/ quark = 2,

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

No new parameters introduced for gluon jets!

Lund String Model: 3 jets





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

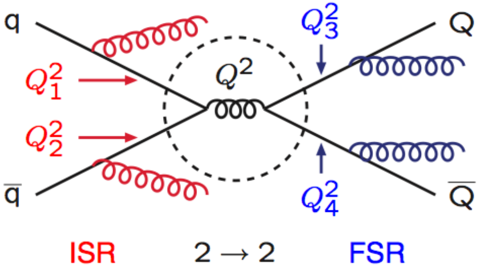
Outline for the Rest of the Talk

- Main features/physics/phenomena
- Thorny (corner) problems of modeling QCD
- BSM and QCD
- Developments
- Future

PYTHIA

MAIN PHENOMENA

$$2 \to n \quad = \quad (2 \to 2) \oplus \mathrm{ISR} \oplus \mathrm{FSR}$$



Iterative structure of gluon emissions in Parton Shower (PS) approximation starting from exact Matrix Element (ME) predictions

FSR = Final-State Radiation = timelike shower
$Q_i^2 \sim m^2 > 0$ decreasing

ISR = Initial-State Radiation = spacelike showers
$Q_i^2 \sim -m^2 > 0$ increasing

Showers are unitary: do not (explicitly) change cross sections;
emission probabilities do not exceed unity — Sudakov factor.

Matrix Elements and Parton Showers

Complementary strengths:

- ME's good for well separated jets
- PS's good for structure inside jets

Marriage desirable! But how?

Very active field of research; requires a lecture of its own

- Reweight first PS emission by ratio ME/PS (simple POWHEG)
- Combine several LO MEs, using showers for Sudakov weights
  - CKKW: analytic Sudakov – not used any longer
  - CKKW-L: trial showers gives sophisticated Sudakovs
  - MLM: match of final partonic jets to original ones
- Match to NLO precision of basic process
  - MCatNLO: additive $\Rightarrow$ LO normalization at high p_{T}
  - POWHEG: multiplicative $\Rightarrow$ NLO normalization at high p_{T}
- Combine several orders, as many as possible at NLO

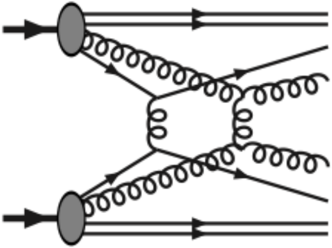
PYTHIA

Matching/merging with PYTHIA

- Built-in NLO+PS for many resonance decays
  ($\gamma^*/\mathrm{Z}^0, \mathrm{W}^\pm, \mathrm{t}, \mathrm{H}^0$, SUSY, …)
- Some few built-in $+1$ matching ($\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm + 1$ jet)
- Default max scale gives fairly good QCD jet rates,
  also for gauge boson pairs, top pairs (with damping), SUSY
- Accepts just about any valid Les Houches Event input
  (but matching at an ill–defined "scale")
- POWHEG interface extends on "scale" matching to showers
- MCatNLO interface under development by Frixione et al
- MLM matching code for ALPGEN and MadGraph5
- CKKW-L LO matching (tested for MadGraph5 input)
- UNLOPS NLO matching coming
- VINCIA: alternative antenna shower package, with ME matching
  on the way

PYTHIA

Multiparton interactions (MPI's)



Many parton-parton interactions per pp event: MPI.

Most have small p_{T}, $\sim$ 2 GeV
$\Rightarrow$ not visible as separate jets, but contribute to event activity.

Solid evidence that MPIs play central role for event structure.

Problem:

$$\sigma_{\mathrm{int}} = \iiint \mathrm{d}x_1 \, \mathrm{d}x_2 \, \mathrm{d}p_{\mathrm{T}}^2 \, f_1(x_1, p_{\mathrm{T}}^2) \, f_2(x_2, p_{\mathrm{T}}^2) \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_{\mathrm{T}}^2} = \infty$$

since $\int \mathrm{d}x \, f(x, p_{\mathrm{T}}^2) = \infty$ and $\mathrm{d}\hat{\sigma}/\mathrm{d}p_{\mathrm{T}}^2 \approx 1/p_{\mathrm{T}}^4 \to \infty$ for $p_{\mathrm{T}} \to 0$.

Requires empirical dampening at small p_{T},
owing to color screening (proton finite size).

Many aspects beyond pure theory $\Rightarrow$ model building.

PYTHIA

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

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

PYTHIA

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

ISR and MPI compete for beam momentum $\to$ PDF rescaling
$+$ flavor effects (valence, $\mathrm{q}\overline{\mathrm{q}}$ pair companions, ...)
$+$ correlated primordial $k_{\perp}$ and color in beam remnant

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

Interleaved evolution

- Transverse-momentum-ordered parton showers for ISR/FSR
- MPI also ordered in p_T

$\Rightarrow$ Allows interleaved evolution for ISR, FSR and MPI:

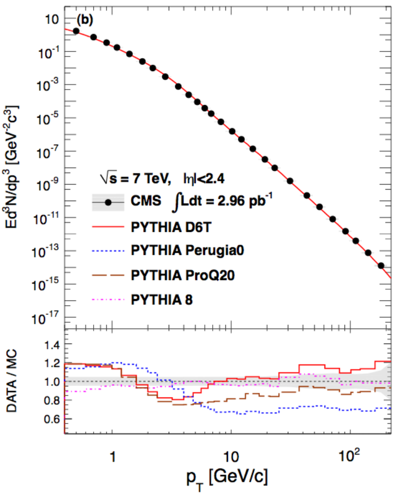
$$\begin{aligned}\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_T} &= \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_T}\right) \\ &\times \exp\left(-\int_{p_T}^{p_{\perp\max}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_T} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_T}\right) \mathrm{d}p'_T\right)\end{aligned}$$

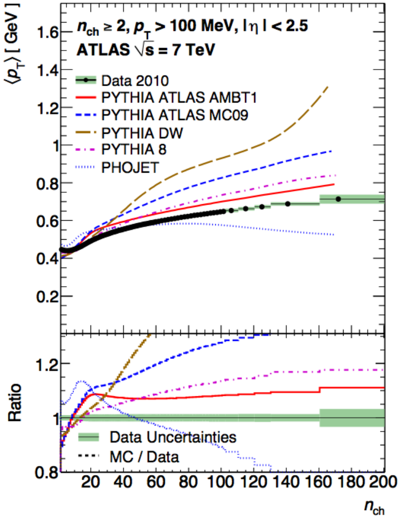
PYTHIA

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

Charged Transverse Momentum Distribution





$\langle p_\mathrm{T} \rangle$ sensitive to color correlations between MPIs!

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.

PYTHIA

- 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

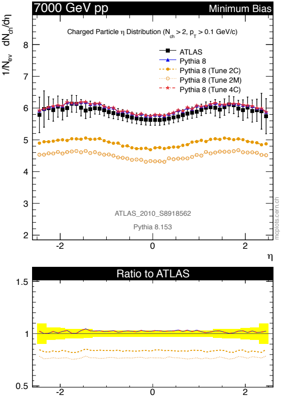
$$X_{MC} = A_0 + \sum_{i=1}^{n} B_i p_i \sum_{i=1}^{n} C_i p_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} D_{ij} p_i p_j$$

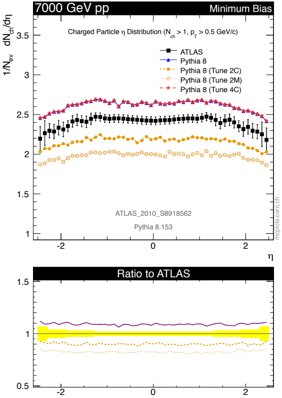
- Do minimization of χ^2 to parametrized results. Fast!

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	





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

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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

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	!

PYTHIA

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

PYTHIA

Multi-Parton-Interaction (MPI), Colour-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	! Colour 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

PYTHIA

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.

Colour Reconnection (CR)

CR needed to explain e.g. $\langle p_{\perp}\rangle(n_{\mathrm{ch}})$, 1987 and now:

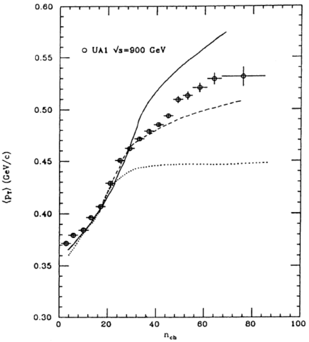
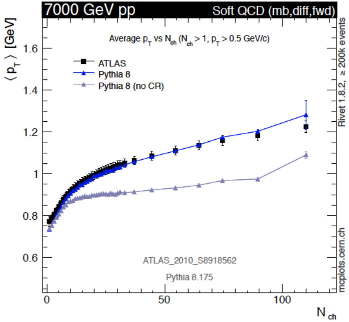


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, gg scatterings with "maximal" string length; solid line gg scatterings with "minimal" string length.

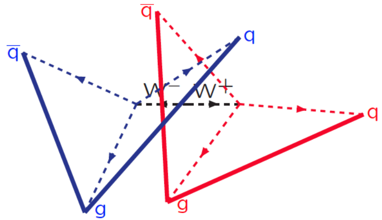


CR reduces total string length
$\Rightarrow$ reduces hadronic multiplicity

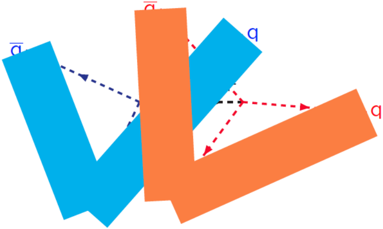
PYTHIA CR models for LEP 2

Colour reconnection studied in several models, e.g.

Scenario II: vortex lines.
Analogy: type II superconductor.
Strings can reconnect only if central cores cross.



Scenario I: elongated bags.
Analogy: type I superconductor.
Reconnection proportional to space–time overlap.

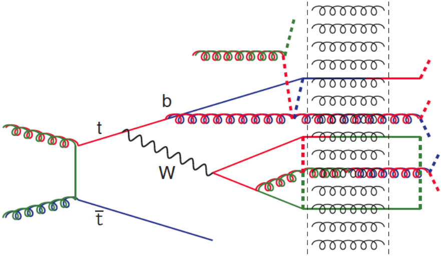


In both cases favour reconnections that reduce total string length.

(schematic only; nothing to scale)

The top mass uncertainty from CR

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

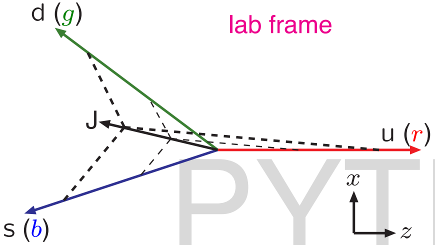


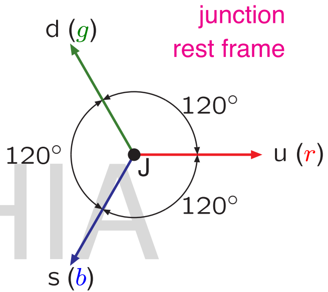
Decays occur when p "pancakes" have passed, after MPI/ISR/FSR with $p_\perp \geq 2$ GeV, but inside hadronization colour fields.

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?

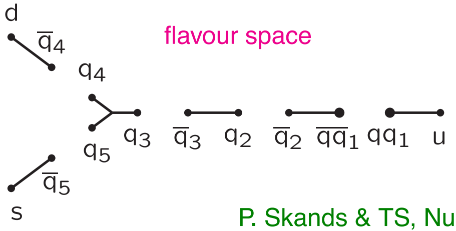
BSM physics 1: *R*-parity violation

Encountered in R-parity violating SUSY decays $\tilde{\chi}_1^0 \to \mathrm{uds}$,
or when 2 valence quarks kicked out of proton beam





PYTHIA



More complicated
(but ≈solved) with
gluon emission and
massive quarks

P. Skands & TS, Nucl. Phys. B659 (2003) 243

BSM physics 2: *R*-hadrons

What if coloured (SUSY) particle like $\tilde{\mathrm{g}}$ or $\tilde{\mathrm{t}}_1$ is long-lived?

⋆ Formation of R-hadrons

$\tilde{\mathrm{g}}\mathrm{q}\overline{\mathrm{q}}$	$\tilde{\mathrm{t}}_1\overline{\mathrm{q}}$	"mesons"
$\tilde{\mathrm{g}}\mathrm{qqq}$	$\tilde{\mathrm{t}}_1\mathrm{qq}$	"baryons"
$\tilde{\mathrm{g}}\mathrm{g}$		"glueballs"

⋆ Conversion between R-hadrons

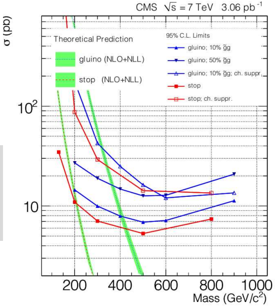
by "low-energy" interactions with matter:

$\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}} + \mathrm{p} \to \tilde{\mathrm{g}}\mathrm{uud} + \pi^+$ irreversible

⋆ Displaced vertices if finite lifetime, or else

⋆ punch-through: $\sigma \approx \sigma_{\mathrm{had}}$ but

$\Delta E \lesssim 1$ GeV $\ll E_{\mathrm{kin},R}$



A.C. Kraan, Eur. Phys. J. C37 (2004) 91;

M. Fairbairn et al., Phys. Rep. 438 (2007) 1

CMS, arXiv:1101.1645

Partly event generation, partly detector simulation.

Public add-on in PYTHIA 6, now integrated part of PYTHIA 8.

Can also be applied to non-SUSY long-lived "hadrons".

PYTHIA

BSM physics 3: Hidden Valley (Secluded Sector)

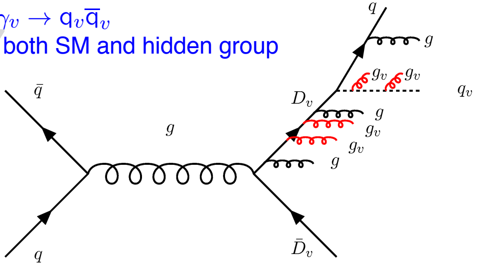
What if new gauge groups at low energy scales, hidden by potential barrier or weak couplings? (M. Strassler & K. Zurek, . . .)

Complete framework implemented in PYTHIA:

⋆ New gauge group either Abelian $U(1)$ or non-Abelian $SU(N)$

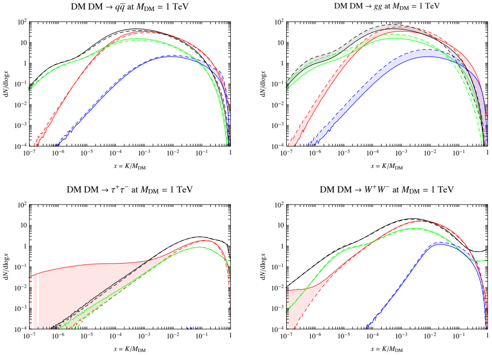
⋆ 3 alternative production mechanisms
1) massive Z': $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{Z}' \to \mathrm{q}_v\overline{\mathrm{q}}_v$
2) kinetic mixing: $\mathrm{q}\overline{\mathrm{q}} \to \gamma \to \gamma_v \to \mathrm{q}_v\overline{\mathrm{q}}_v$
3) massive F_v charged under both SM and hidden group

⋆ Interleaved shower in QCD, QED and HV sectors: add $\mathrm{q}_v \to \mathrm{q}_v\gamma_v$ (and F_v) or $\mathrm{q}_v \to \mathrm{q}_v\mathrm{g}_v$, $\mathrm{g}_v \to \mathrm{g}_v\mathrm{g}_v$, which gives recoil effects also in visible sector



L. Carloni & TS, JHEP 09 (2010) 105;
L. Carloni, J. Rathsman & TS, JHEP 04 (2011) 091

Common question: in my model DM particles annihilate pairwise.
Given the mass and the two-body branching ratios,
what is the spectrum of γ, $e^{\pm}$, $p/\overline{p}$, ν?



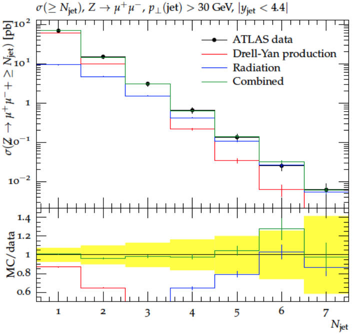
photons
$e^{\pm}$
$\overline{p}$
neutrinos

PYTHIA continuous
HERWIG dashed

M. Cirelli et al.,
JCAP 1103 (2011) 051,
JCAP 1210 (2012) E01

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.



VINCIA: an Interleaved Antennae shower

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

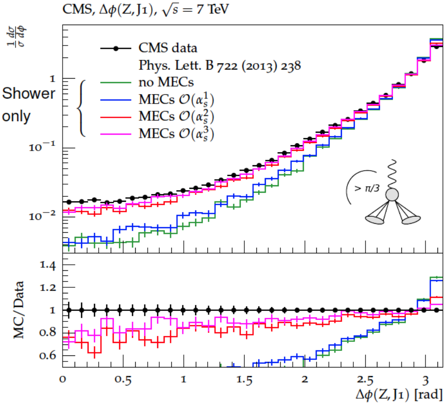
Based on antenna factorization of amplitudes and phase space.

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.



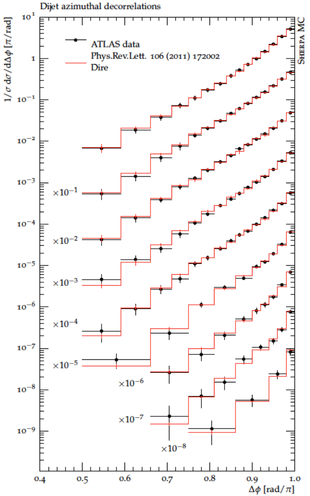
DIRE: a Dipole Resummation shower

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

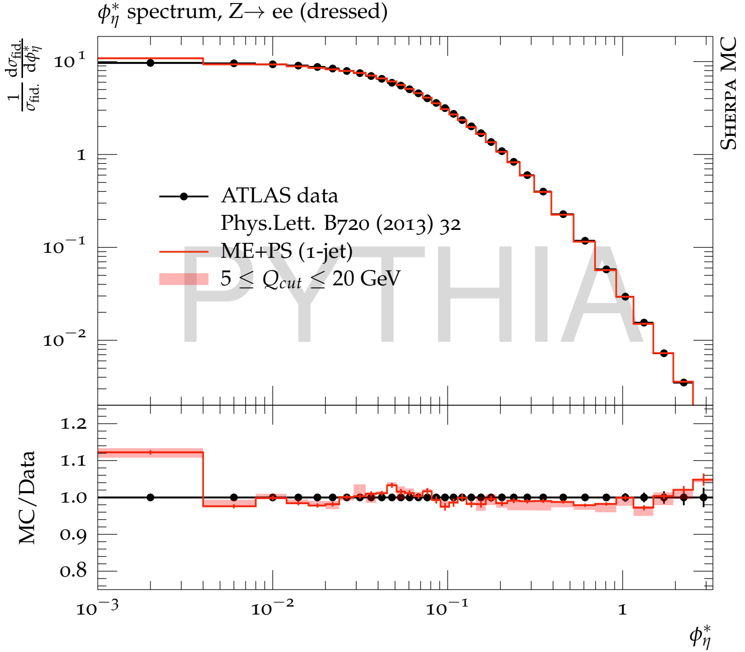
"Midpoint between dipole and parton shower",
dipole with emitter & spectator, but not quite CS ones:
unified initial–initial, initial–final, final–initial, final–final.

Soft term of kernels in all dipole types is less singular

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



LHC data comparisons (merged ME+DIRE showering)



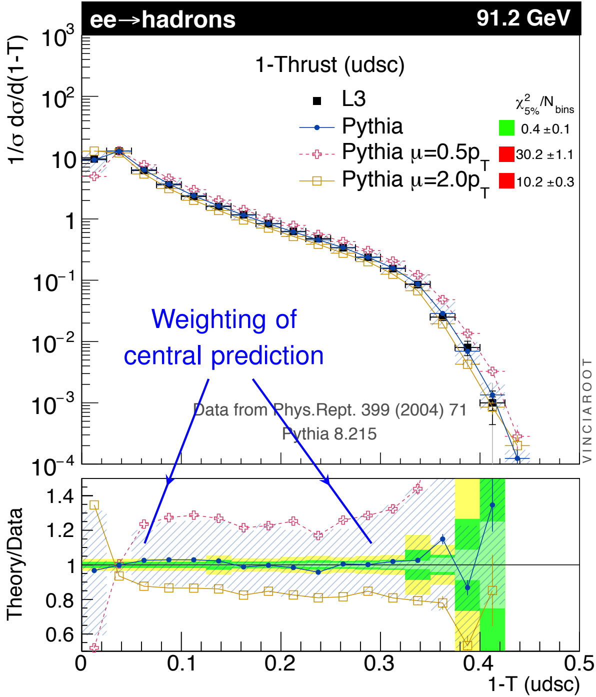
In Situ Shower Parameter Variation

- Includes renormalisation-scale and non-singular term variations
- Output = vector of alternative weights for each event
- quick estimate of uncertainties without needing separate runs
- a single sample to run through detector simulation etc.
- (hadronisation etc also only has to be carried out once).
- choose which variations you want, how large, correlated/uncorrelated

Note: simpler type of ME (hard parameter) weighting long available through `UserHooks`

Could be exploited in tuning

PYTHIA



ee→hadrons
91.2 GeV
1-Thrust (udsc)
L3
Pythia
Pythia μ=0.5p_T
Pythia μ=2.0p_T
χ²_5%/N_bins
0.4 ±0.1
30.2 ±1.1
10.2 ±0.3
1/σ dσ/d(1-T)
Weighting of
central prediction
Data from Phys.Rept. 399 (2004) 71
Pythia 8.215
VINCIAROOT
Theory/Data
1-T (udsc)

Selected Highlights from Pythia 8.224 (18 Jan 2017)

```
A new alternative "thermal hadronization" option is introduced,
wherein an exponential <ei>exp(-pT / T)</ei> hadronic transverse
momentum spectrum replaces the default Gaussian one, with a
"temperature" <ei>T</ei> as free parameter. Given this <ei>pT</ei>,
the next hadron (consistent with local flavour conservation) is picked
among the possibilities with an <ei>exp(-mT / T)</ei> weight.
This option is accessed with <code>StringPT:thermalModel = on</code>.

A new option <code>StringPT:closePacking = on</code> allows to
enhance the <ei>pT</ei> width in regions where there is a high
density of partly overlapping strings. This works both for the
default Gaussian and the alternative exponential (see above)
<ei>pT</ei> description; in the latter case it will also enhance the
rate of heavier-particle production.

New option with running coupling in Hidden Valley scenarios.
Some other small fixes in it.

Improved safety checks for the presence of LHE files.

New status codes 49 and 59 introduced for ISR and FSR partons,
respectively, to represent special states in the evolution where
<ei>E^2 - p^2 = m^2</ei> is not fulfilled.
```

PYTHIA

Bug fixes

Bug fix in the <code>TimeShower::findMEtype(...)</code> for a few rare cases.

Fix in the setup of tunes with <code>SpaceShower:rapidityOrder = off</code>.
The new (in 8.219) <code>SpaceShower:rapidityOrderMPI</code> then also ought to have been set off, but this was missed, giving small inconsistencies (around 2% reduction of the charged multiplicity).
Thanks to James Monk.

The handling of the <code>meMode</code> ranges 52 - 60 and 62 - 70 were incorrect, insofar as checks or not against duplication of existing channels go, and have now been set straight. Thanks to Christopher West.

Minor bug fix in the <code>TimeShower</code> machinery to optionally enhance the rate of some shower branchings.

Other minor bug fixes/updates.

PYTHIA

Future Developments (& Holy Grails)

- NLL parton showers
- Fully automated, efficient combination of Pythia and higher-order calculations
- pA collisions (like old Fritiof)
- String dynamics (DIPSY – ropes of strings)
- Forays into $\nu\mathrm{A}$ interactions
- $\ldots$

PYTHIA

Last Thoughts

Who will be doing the physics of event generation 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 is starting 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.*

PYTHIA

[‡] 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 →

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