Andrea Bianconi **Seattle 2014**

Simulation of Drell-Yan events with T-spins at low–to–intermediate energies (> Hades, << Tevatron), Q range 1.5–20 GeV

Case in study:
Reweighting / filtering / riorganizing Pythia events to introduce Transversity, Sivers and Boer-Mulders effects in the outputs of this code.

Acting on a pre-existing model and code (Lund / Pythia), one strategy is **not to modify this code at all,** but just print all the internal/final particles that Pythia has produced in an event and work on their data.

Define: "**Bare**" events: **as produced by Pythia**
"**Dressed**" events: **final generated events**

Problem 1: new terms in the cross section
Problem 2: new observable variables (hadron spin)
Problem 3: new unobservable variables (parton spin appearing in quantum sums)
Problem 4: **transition from inclusive to exclusive distributions**

Technical problems:

Analysis of the event output
Identification of key partons and key final particles
Pattern recognition

Proliferation of intermediate state and final particles: CPU forbids this method at large cm energy.

3 strategies: filter, change, divide events.

1) Filter bare events (with or without changing them).

1a) Take a bare event as it is or modify it. This is an attempt for a dressed event.
1b) Calculate the **reweight** ratio: **sigma_new / sigma_old**
1c) Use the reweight factor to **accept / reject** the event.
1d) If accepted it is a dressed event. If refused it is discarded and the procedure restarts from (1a) with **another bare event**.

2) Change bare events and filter changes.

2a) Take a bare event and somehow modify it. This is an attempt for a dressed event.
2b-c) As in the previous case
2d) If accepted it is a dressed event. If refused it is discarded but the procedure restarts from (2a) with **the same bare event**.

3) Introduce a new variable and divide bare events into subgroups.

3a) Introduce a new variable (= a spin). Randomly attribute a spin value to a bare event.
3b-c) Calculate the reweight etc and accept / reject the set "bare event + spin value".
3d) If accepted it is a dressed event (= an event with spin). If rejected, attribute a **new spin value** to **the same bare event** and restart from (3a).

The “divide into subgroup” method is based on the assumption:

Bare events contain the required phenomenology in inclusive way.

Example: non-polarized proton beam =
50 % spin up
\+ 50 % spin down

In principle I only need to **separate** events of the two kinds, not to modify them, to obtain polarized events.

In the following I stick myself to this principle, but it has two relevant limitations:

1) The assumption is not 100 % fulfilled.

2) Parton spins are unobservable and quantum: the “spin up + spin down” sum regards amplitudes not probabilities.

For efficiency, one would like to avoid discarding bare events. But some need to be discarded. Example:

1) Large Sivers function > 0

2) Pythia quarks have axial-symmetric k_T-distribution around the parent proton direction.

(1) and (2) may coexist if the initial proton state has average polarization zero.

Then I divide events into 2 subsets:

(a) proton spin up and rightward quark k_T
(b) proton spin down and leftward quark k_T

With a fully polarized spin-up proton state, (b) events must all be discarded.
An axial-symmetric k_T distribution would not be correct.

Summarizing: if partially polarized events are required, a fraction |Pol| / 2 of Pythia events must be discarded.

From inclusive to exclusive: two-point and three-point correlation distributions

3-point correlated statistical distribution: $F(\hat{S}, \hat{s}, \hat{k}_T)$

$$\hat{P} = (0, 0, \pm 1): \; direction\ of\ p\ or\ \bar{p}\ momentum$$

$$\hat{S}: \; p\ or\ \bar{p}\ spin\ with\ |S|^2 = 1$$

$$\hat{s}: \; q\ or\ \bar{q}\ spin\ with\ |s|^2 = 1$$

$$\hat{k}_T = \frac{1}{|k_T|}(k_{Tx}, k_{Ty}): \; direction\ of\ q\ or\ \bar{q}\ transverse\ momentum$$

Events characterized by all the 3 vectors are generated via a 3-point distribution.

$$Tr(\hat{S}, \hat{s}) \equiv \frac{h_1}{f_1} \hat{S} \cdot \hat{s}$$

$$Siv(\hat{S}, \hat{k}_T) \equiv \frac{f_{SIV}}{f_1} [\hat{P}, \hat{k}_T, \hat{S}]$$

$$BM(\hat{s}, \hat{k}_T) \equiv \frac{h_{BM}}{f_1} [\hat{P}, \hat{k}_T, \hat{s}]$$

$$1 + Tr(\hat{S}, \hat{s}) = \int d^2\hat{k}_T \, F(\hat{S}, \hat{s}, \hat{k}_T)$$

$$1 + Siv(\hat{S}, \hat{k}_T) = \sum_s F(\hat{S}, \hat{s}, \hat{k}_T)$$

$$1 + BM(\hat{s}, \hat{k}_T) = \sum_S F(\hat{S}, \hat{s}, \hat{k}_T)$$

There is no model-independent way to derive a 3-point correlation by combining 2-point ones.

Before one assumes the most obvious model to combine these correlations, a note:

Products of two-vector correlation terms are quadratic in proton spin or quark spin.

No model from fundamental matrix calculations could produce this.

Assuming that each two-vector correlation term is << 1 I may exploit this possibility:

$$(1+Tr)\cdot(1+Siv)\cdot(1+BM) \;\approx\; (1+Tr+Siv+BM)$$

The right-hand term is strictly linear in spins.
Assumption: the left-hand side is **almost** linear.

Any of the (1 + ...) terms may be used to split event sets into subsets corresponding to opposite values of some spin component.

Pythia bare events have no proton/quark spin but have parton transverse momentum.

A more practical form is

$$(1 + Tr) \cdot (1 + Siv) \cdot (1 + BM) \;\approx\; (1 + Siv)(1 + Tr + BM)$$

Rational sequence:

1) Given the average polarization → generate proton spin S

2) Given proton spin and quark K_T → select event subset (Sivers-compatible S-K_T correlation)

3) Given proton spin and quark K_T → split left events into quark spin subgroups (Transversity-compatible S-s correlation, BM-compatible s-K_T correlation)

State of the art in double polarized proton-antiproton Pythia events at cm energy 10 GeV:

(1) is OK,
(2) has been postponed,
(3) is half-OK (OK on double-spin Tr-Tr and BM-BM asymmetries, not on single spin Tr-Bm asymmetries)

Implementation of spins:

1) Observable spin: **±1** along a direction that is **specified by observation**

2) Parton spins: two possibilities:

2A) **±1** along a **randomly chosen** direction

2B) a **continuous-orientation** classical vector with $|\mathbf{s}|^2 = 1$.

The two are completely equivalent. I use the latter.

Full procedure

a) Read an ordinary Pythia event, without any polarization.

b) On the ground of the proton **average** polarization along an axis, a proton spin **±1** is generated along this axis.

c) The hadron-quark splitting is associated with a transverse quark spin.
This is weighted by the ratio $\mathbf{F(x, k_T, S, s) / F(x, k_T)}$.

$\mathbf{F(x, k_T, S, s)}$ includes Transversity and Boer-Mulders contributions, not (yet) Sivers.

d) The same is done for the antiproton and the antiquark.

e) The event is accepted / rejected on the ground of the hard-process probability

$$\mathbf{P_{hard}(spins) / P_{hard}(no\text{-}spins)},$$

where P_{hard}(spins) and P_{hard}(no-spins) are the **partons → leptons** cross sections calculated with / without specifying polarizations.

It may look simple, but the code doing this is 1226 lines long. 30 % is empty lines or extra stuff, but 7-800 of these lines are needed.

Details.

The hadron-quark splitting is reweighted in the Hadron CM frame (symmetric collider frame).

The parton-to-lepton reweighting is in a virtual photon CM frame (same z axis as the previous one: proton and antiproton aligned to z).

Azimuthal asymmetries are evalued in the same frame.

So, Pythia hadron / parton / lepton momenta must be boosted on and back.

At the present stage I have not distinguished uubar from ddbar events (the latter are 10 % of the total in the ppbar valence region).

In this test phase, the 3-vector distribution includes Transversity and BM effects via functions that do not depend on x and |$\mathbf{P}_T$|.

Transversity: Let TRV be a value of **S·s**, and **Prob(TRV)** a relative probability for this value:

For TRV > 0, Prob(TRV) = 1.
For TRV < 0, Prob(TRV) = 0.

Boer-Mulders term: Let BMV be a value of **P·(s Λ $\mathbf{k}_T$)** and **Prob(BMV)** a relative probability for this value:

For BMV > 0, Prob(BMV) = 1;
For BMV < 0, Prob(BMV) = 0

The quark spin is generated by the probability:

Prob(BMV) * Prob(TRV) * dɣ

where ɣ is the angle identifying the quark transverse spin in the (hadron) transverse plane.

This leads to Transversity and of BM-function of **approximate size 0.5 each**, that is the **largest possible** given the requirement of an **overall (spin-summed) $\mathbf{K}_T$-simmetric distribution**. A large Tr **and** a large BM are not 100 % compatible once $\mathbf{K}_T$ and the proton spin have been assigned.

(Anti)Quark-spin dependent hard process probability:

$$W_{s_T \bar{s}_T} = \frac{1}{4}\Big([1 + cos^2(\theta)](1 + s_z \bar{s}_z) - sin^2(\theta)(s_x \bar{s}_x + s_y \bar{s}_y) \Big)$$

Spin components along the **lepton** axis (they are not helicities)

Spin components orthogonal to the lepton axis.

Some specific results.

Protons 5 GeV vs antiprotons 5 GeV in collider configuration

$4 < Q < 9$ GeV

Any Q_T

Average polarization 0 or 1 along x axis

Asymmetries between pairs with positive or negative cos(...) or sin(....) in the dlepton frame.

$|\cos(\Theta)| < 0.5$ for all the reported events (asymmetries proportional to $\sin^2(\Theta) / 1 + \cos^2(\Theta)$)

"Zero hypothesis": TRV and BMV values are always accepted, zero polarizations.

cos(2 phi)	10171 10072	a difference of magnitude
cos(2 phi – phi1 – phi2)	10173 10070 →	300 events
sin(phi + phi1)	10263 9980	means no difference

Unpolarized events

cos(2 phi)	11097 9267 →	asymmetry 10 %
cos(2 phi – phi1 – phi2)	10269 10095	
sin(phi + phi1)	10311 10053	

Proton and antiprotopn polarization 100 %:

cos(2 phi)	11464 9203	(→ asymmetry 10 %)
cos(2 phi – phi1 – phi2)	11770 8897 →	asymmetry 14 %
sin(phi + phi1)	10437 10230	

100 % polarized proton   unpolarized antiproton

sin(phi + phi1)   10316 10070

The opposite

sin(phi + phi1)   10333 10097

Example of results