xdvmpGenerator

An Monte Carlo Generator for Exclusive Diffractive Vector Meson Production

Status of the implementation of the b-Sat/b-CGC Model for ep and eA

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January 21, 2010

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Motivation

Exclusive diffractive vector meson production is one of the most promising ways to study saturation in ep/eA

- Naive: $\sigma \sim G(x,Q^2)^2$

Issues:

- Experimentally difficult
  - rapidity gap, breakup, $\int L dt$ needed ?
  - reconstruction of t
  - detector requirements (resolution, acceptance)
  - sensitivity to physics (saturation)?
  - need to study in ep and eA

What's on the market?

RAPGAP

- only ep
- buggy ($t = (p-p')^2 \neq (p_{\gamma^*} - p_V)^2$, $p_z' > E'$, etc.)
- cannot run $J/\psi \Rightarrow$ need to add extra program
- hard to manipulate (see the code)
- in FORTRAN (cumbersome integration with ROOT and other tools)

Other ?

- None with the features we want

Requirements for a new generator

- Simple, i.e. easy to use, manipulate and modify
  - single purpose: e p → e' p' V
  - write only the necessary core
  - reuse what is available (and accessible)
- Based on a model that is known to describe data well
  - Dipole model (works well at Hera)
- Extendable to eA
  - Dipole model does that
- Modern
  - C++, integrates with ROOT and other tools
- Output should follow standards as much as possible
- Useful for detector/acceptance studies as well as physics studies (e.g., sensitivity to $G(x,Q^2)$ etc.)

Dipole Model (I)

Cross-section for production of final state VM:

$$\frac{\mathrm{d}\sigma^{\gamma^* p\to Ep}_{T,L}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\mathcal{A}^{\gamma^* p\to Ep}_{T,L}\right|^2 = \frac{1}{16\pi}\left|\int \mathrm{d}^2\boldsymbol{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\boldsymbol{b}\,(\Psi_E^*\Psi)_{T,L}\,\mathrm{e}^{-\mathrm{i}[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}\right|^2$$

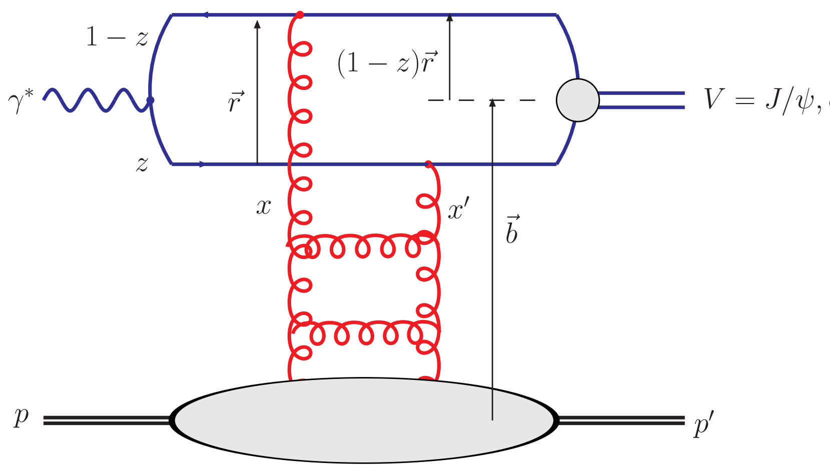
Amplitude

Overlap between photon and VM wave function

Dipole Cross-Section

Many dipole models on the market:

- Use : H. Kowalski, L. Motyka, G. Watt, Phys. Rev. D74, 074016
- Describes Hera data well
- has b-dependence
- Michael & TU have experience with it
- Henri is around to ask
- can be “easily” modified to do eA (via b-dependence)



Using it implies the generator has to be amplitude based (which is a bit problematic)

Dipole Model (II)

Cross-section for production of final state VM:

$$\frac{\mathrm{d}\sigma_{T,L}^{\gamma^* p \to Ep}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\mathcal{A}_{T,L}^{\gamma^* p\to Ep}\right|^2 = \frac{1}{16\pi}\left|\int \mathrm{d}^2\boldsymbol{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\boldsymbol{b}\,(\Psi_E^*\Psi)_{T,L}\,\mathrm{e}^{-\mathrm{i}[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}\right|^2$$

Overlap between photon and VM wave function

Dipole Cross-Section

Wave function:

- Boosted Gaussian
  - Forshaw, Sandapen, Shaw
- GausLC
  - Dosch, Gousset, Kulzinger, Pirner, Teaney, Kowalski
- Parameters tuned for HERA are available
- any improved wave function can be easily plugged in

Dipole Cross-Section:

- b-Sat
  - uses DGLAP evolution from initial G(x,Q)
  - can be adapted for A (b-dependence)
- b-CGC
- Parameters tuned for HERA are available

Photon Flux

Dipole models provide $\sigma_{L,T}$ (γ^* p $\rightarrow$ p' V)

For generator we need to consider σ (e p $\rightarrow$ e' p' V)

Need Photon Flux Γ_T , Γ_L

$\sigma^{e\,p \rightarrow e'\,p'\,V} = \Gamma_L\, \sigma_L^{\gamma^*\,p \rightarrow p'\,V} + \Gamma_T\, \sigma_T^{\gamma^*\,p \rightarrow p'\,V}$

The full formula is rather complex

What is used is a simplification (not always justified):

For $Q^2/(4E^2) = 0$ and $Q^2/\nu^2 = 0$, $m_e = 0$

Pick 2 independent variables best for MC: x, Q^2

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{\alpha}{2\pi}\frac{1}{xQ^2}\left(\left[1+(1-y)^2 - 2(1-y)\frac{Q^2_{min}}{Q^2}\right]\sigma_T + 2(1-y)\sigma_L\right)$$

where $Q^2_{min} = \dfrac{m_e^2 y^2}{1-y}$

Jacobian!

Full Shebang ...

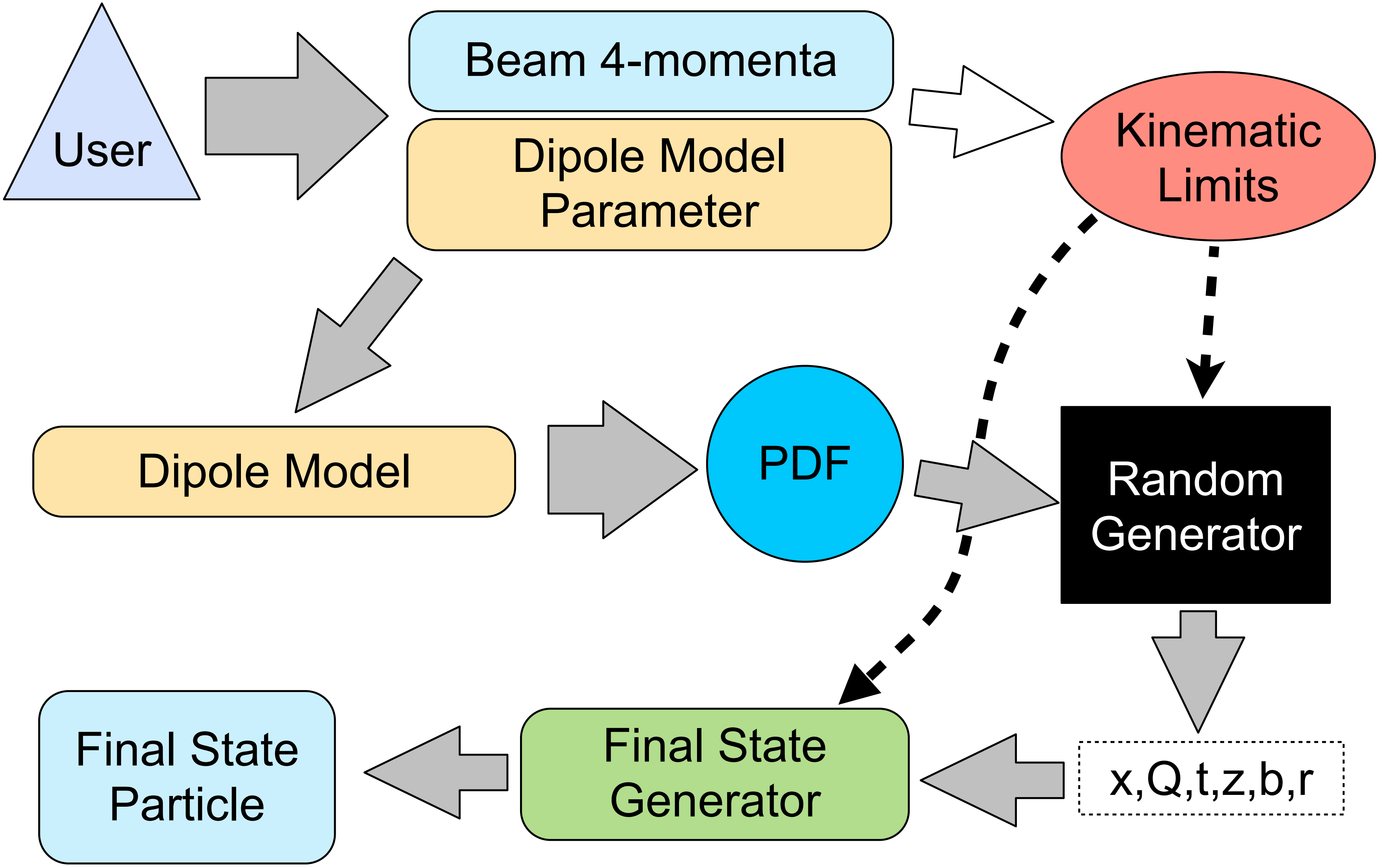
Dipole model calculations + flux give:

$$\frac{d^6\sigma}{dx\ dQ^2\ dt\ db\ dz\ dr}$$

- 6-dim Probability Distribution Function (PDF)
- all variables independent

- Given (input): beam energies **p**e, **p**p

Basic scheme behind *xdvmpGenerator*



Random Generator

Big Problem: generate random numbers according to a given distribution (here 6D PDF)

Techniques (good overview in Pythia6 manual chapter 4):

- Inverse transform method (invert cumulative PDF)
  - must integrate pdf and invert (note we have a DGLAP evolution in the PDF)
- Acceptance-rejection method (Von Neumann)
  - good if pdf is too complex
  - rather easy in 1-D, nightmare in N-D
- and many more
- General recommendation in all text books for N-dim: factorize
  - Problem is we cannot do that since the 6 parameters are heavily intertwined
- Largest fraction of code in most simulators is spent on this topic

UNURAN to the rescue (http://statmath.wu.ac.at/unuran/)

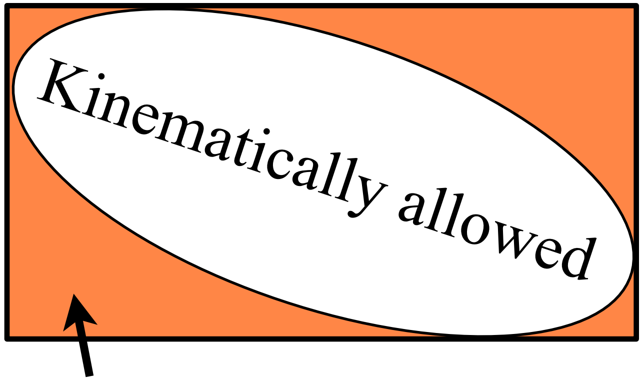
UNU.RAN Package

Universal Non-Uniform RANdom number generators
(Math Department University Vienna)

- provides tools to generate pretty much everything
- xdvmpGenerator:
  - Markov chain samplers for continuous multivariate distributions
  - HITRO: Hit-and-Run Sampler
- Bare minimum is implemented in Root/MathCore

Issues:

Requires uniform limits (domains)



Kinematically not allowed but generated
Need to discard after generation (tries > events)

Requires to pass mode of pdf to UNURAN

- pdf is max at $|t| = |t|_{min}$, $x=x_{min}$, $Q=Q_{min}$
- less obvious for b, z, r

Use MINUIT (TMinuit2)

Final State Particles

Given: $\mathbf{p}_e$, $\mathbf{p}_p$, s, t, x, Q^2, y

Need: $\mathbf{p}_{e'}$, $\mathbf{p}_{p'}$, $\mathbf{p}_{\gamma^*}$, $\mathbf{p}_{VM}$

Hannes Jung (DESY) gave me analytic solutions for all. After many checks: $\mathbf{p}_{e'}$, $\mathbf{p}_{\gamma^*}$ formulas are correct!

$\mathbf{p}_{p'}$ is not correct (possible source of problems in RAPGAP?)

New Ansatz:

- $t = (\mathbf{p}-\mathbf{p}')^2$, $m_{VM}^2 = (\mathbf{p}_{\gamma^*} + \mathbf{p}_p - \mathbf{p}_{p'})^2$, $|\mathbf{p}_{p'}| = m_p$
- allows to derive $\mathbf{p}_p$ numerically (root finder)
- use Hanne's analytic formula as first guess
  - fails at times since first guess is off by several GeV
- $\mathbf{p}_{VM}$ trough $\mathbf{p}_e + \mathbf{p}_p = \mathbf{p}_{e'} + \mathbf{p}_{p'} + \mathbf{p}_{VM}$
- solution obtained this way is fully consistent
  - $\mathbf{p}_{e'}$, $\mathbf{p}_{p'}$, $\mathbf{p}_{\gamma^*}$, $\mathbf{p}_{VM}$ $\Rightarrow$ s, t, x, Q^2, y

Kinematic Boundaries

Tricky since some formulas neglect masses others not (something to still work on)

$$s = \frac{Q^2}{xy} + m_p^2 + m_e^2$$

not just $Q^2 = s\,x\,y$

Currently implemented (but not sufficient):

$$0 < x < 1$$

$$0 < y < 1$$

$$\frac{m_e^2 y^2}{1-y} < Q^2 < s - m_e^2 - m_p^2$$

$$x_{IP} = \frac{m_V^2 + Q^2}{ys}$$

$$t < -\frac{x_{IP}^2 m_p^2}{1 - x_{IP}}$$

Implementation

Follow Pythia8 philosophy

- main program to be provided by user
- *xdvmpGenerator* is class with simple methods
  - init(), generateEvent(), printEventRecord(), ...
  - event record in plain structure (*xdvmpEvent*)
  - setup through runcard (txt file) or programmatically
- *xdvmpGenerator* uses many other classes and functions
  - class *xdvmpDipoleModel* (dipole model implementation)
    - alphaStrong.cpp (fcts to calculate α_s - adapted from MRST, rewritten in C++)
    - laguerre.c, dglap.c (for DGLAP from F. Gelis)
  - class *xdvmpFinalStateGenerator* (generate final state particles from *x*, Q^2, *s*, *t*)
  - class *xdvmpSettings* (handle parameter & runcard parsing)
- Total ~ 4200 lines of code only (requires only GSL, ROOT libs)

Example Main Program

```
#include "xdvmpGenerator.h"

int main(int argc, char *argv[])
{
    xdvmpGenerator generator;
    bool ok = generator.init(“xdvmpRuncard.txt”);
    xdvmpSettings settings = generator.runSettings(); // for convinience
    TFile *hfile = new TFile(settings.rootfile().c_str(),"RECREATE");
    TH1D *histo_r = new TH1D("histo_r", "r distribution", 200, 0., 2.);

    int nPrint = settings.numberOfEvents()/settings.timesToShow();
    unsigned long maxEvents = settings.numberOfEvents();

    generator.printEventHeader(cout);

    for (unsigned long iEvent = 0; iEvent < maxEvents; iEvent++) {
        xdvmpEvent event = generator.generateEvent();
        if (iEvent%nPrint == 0) {
            cout << "processed " << iEvent << " events" << endl;
        }
        histo_r->Fill(event.r);
        generator.printEventRecord(cout);
    }
    hfile->Write();
    generator.printStatistics();
    return 0;
}
```

Example Runcard

```
#==========================================================================
#   Comments start with a #
#   Name and value are separated by a "=":  name = value
#
#   The following settings are currently implemented:
#   eBeamEnergy:      electron beam energy (GeV)   (default = 10)
#   pBeamEnergy:      proton beam energy in (GeV)  (default = 250)
#   numberOfEvents:   number of events to generate (default = 10000)
#   vectorMeson:      rho | phi | jpsi  (default = rho)
#   waveFunction:     GausLC | BoostedGaussian (default = BoostedGaussian)
#   dipoleModel:      bSat | bCGC (default = bCGC)
#   timesToShow:      # of print-outs to tell how far we are (default=0)
#   rootfile:         name of root file for histos etc. (default ="")
#   xmin:             min x value (default = 1e-3)
#   Q2min:            min Q2 value (GeV^2)  (default = 1.)
#==========================================================================
eBeamEnergy = 10
pBeamEnergy = 250
vectorMeson = rho
dipoleModel = bSat
waveFunction = BoostedGaussian
numberOfEvents = 10000
timesToShow = 10;
rootfile = bla.root
Q2min = 1;
xmin = 1e-3;
```

Example Output (1)

```
#==================================================================
#
#   xdvmGenerator
#
#   An event generator for exclusive diffractive vector meson
#   production using the dipole model.
#
#   Code compiled on Jan 20 2010  16:50:46
#==================================================================
Run started at Wed Jan 20 23:22:34 2010
Runcard is 'xdvmpRuncard.txt'
mXmin = 0.001
Electron beam is: 0     0       -10     10      (0.000510999)
Proton beam is:   0     0       249.998 250     (0.93827)
sqrt(s) = 100.004
Initializing the xdvmp dipole model:
Vector meson to generate: rho
Dipole model used: bCGC
Wave function used: BoostedGaussian
```

Example Output (2)

```
Range of kinematic variables (domain) used in generator:
t = [-4, 0]
Q = [1, 100.004]
x = [0.001, 0.99]
b = [0, 2]
z = [1e-12, 1]
r = [0.001, 2]
Finding mode of pdf:
mode = (t=0, Q=1, x=0.001, b=0.453883, z=0.5, r=0.526119; value of
pdf = 107769)
Initializing the random generator:
Dimensions used: 6
pdf in log: no
Number of events to process: 10000
xdvmpGenerator is initialized.
```

For bCGC this takes < 1 s

For bSat ~ 1-2 min (due to DGLAP setup)

Example Event Record

```
xdvmpGen event file
============================================
iEvent, t, Q2, x, y, b, z, r, s
============================================
i, id, px, py, px, E, m, vx, vy, vz
============================================
processed 0 events
1       -0.171395       2.03611         0.00254752      0.0799258       0.525637        0.380722        0.344587        10000.8
============================================
1            11              0              0            -10             10    0.000510999             0              0              0
2          2212              0              0        249.998            250        0.93827              0              0              0
3            11    -0.00222092        1.36871       -9.14977        9.25157    0.000510999             0              0              0
4          2212       0.214882       0.352692        248.818         248.82        0.93827              0              0              0
5           113      -0.212661        -1.7214        0.33036        1.92867          0.776              0              0              0
============= End Event Record =============
2       -0.171395       2.03611         0.00254752      0.0799258       0.525637        0.380722        0.554715        10000.8
============================================
1            11              0              0            -10             10    0.000510999             0              0              0
2          2212              0              0        249.998            250        0.93827              0              0              0
3            11        1.34006      -0.278549       -9.14977        9.25157    0.000510999             0              0              0
4          2212       0.390437      -0.134496        248.769        248.771        0.93827              0              0              0
5           113        -1.7305       0.413045       0.379414        1.97772          0.776              0              0              0
============= End Event Record =============
```

- Note the VM does not decay (Geant can do this if needed)
- VM have zero width (should probably change that)
- The event record can be directly written into a ROOT Tree or any other format, the print-out shown here is optional
- Time to generate 1M events ~ 4 min on my 3y old MacBook Pro

To-Do List

- Improve kinematic limit checks
  - See still NaN in event record
- Calculate total cross-section within given limits
  - needed to normalize output and get “barns”
  - comes at a high price (6D integration takes time)
- Print-out format to follow that of other generators
- Test, test, test
- Add eA
  - how do kinematic limits change here

Could need volunteers that help to check, test, and improve ... anyone?