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From model to events using MadGraph/MadEvent 4

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Westcoast LHC Theory meeting, UC Irvine, May 4, 2007

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MadGraph: What is it ?

- By T. Stelzer and W.F. Long [Phys. Com. 81 (1994) 357-371]
- Given a process (specified in simple syntax), produces Feynman diagrams and a Fortran subroutine that computes the squared amplitudes by calls to the HELAS helicity amplitude library
- Reads particles.dat and interactions.dat files to know the particle content and interaction vertices of the model
- Produces info on the structure of Feynman diagrams to help phase-space integration
- Sums over particle labels such as protons (initial state), jets and leptons (final state)
- Manages processes with up to 7-8 final states particles

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MadEvent: What is it ?

- By F. Maltoni and T. Stelzer [JHEP 0302:027, 2003]
- Multi-purpose event generator
- Uses as input the process-dependent information (matrix elements and phase space mappings) produced by MadGraph
- The only event generator to exploit the powerful and general phase-space integration method named Single-Diagram-Enhanced multichannel integration:
  - ➔ Uses the squared diagrams as basis for multi-channel integration

    $$f_i = \frac{|A_{\rm tot}|^2}{\sum_i |A_i|^2} |A_i|^2$$
  - ➔ Interference terms cannot introduce new poles
- Trivially parallelizable technique makes cluster use efficient

Last time (at UC Davis):

- MG/ME software structure
- Process and event generation on the web
- Pythia (hadronization) and PGS (detector sim.) packages for complete event simulation on-line
- Three dedicated clusters (UIUC, UCL and Rome)
- New models: SUSY, 2HDM and Higgs EFT

This time:

- How to implement (parts of) your own model
- How to generate events with the new model
- How to go from Lagrangean to generation

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Existing models

- Standard Model (CKM diagonal)
- MSSM (CP and R-parity conserving)
  Hagiwara, Plehn, Rainwater, Stelzer + Alwall
- General 2HDM (including FCNC and CP violation)
  de Vissher, Herquet
- Higgs EFT (scalar couplings to gluons)
  Frederix
- UED (very soon to come)
  Alves

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Implementing a new model

Ways to implement your own model in MG/ME:

- Modify existing model (e.g. changing couplings)
- User model framework (e.g. subspace of larger models)
  - New particles
  - New interactions
  - Expressions for the new couplings
  - Perl script generates all files needed by MadEvent!
- MadRules
  - Directly from Lagrangean to implementation

Work in progress

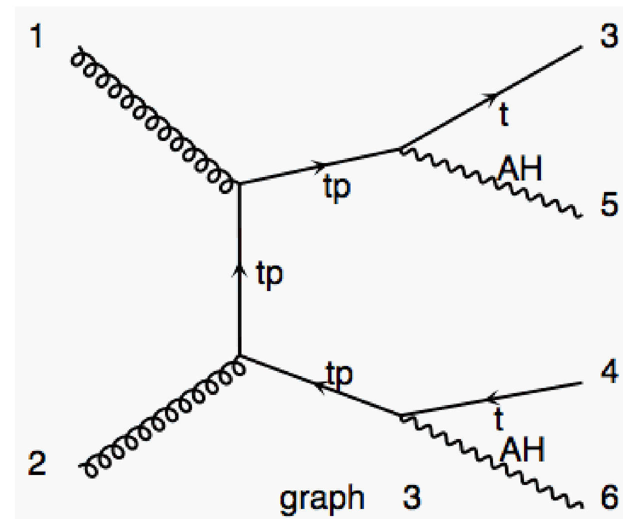
User model generation

de Vissher

Large-scale examples: UED (Alves)
Cornell Black Box (Meade, Reece)

Small-scale example:

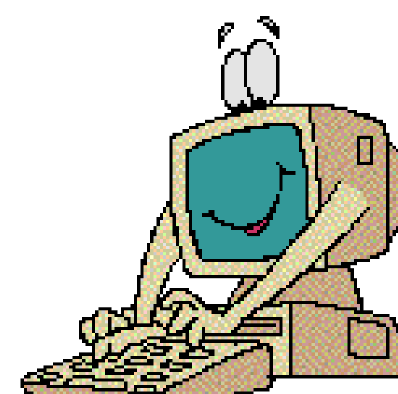
QCD T' pair production with T' → A_ht in Little Higgs model with T parity



$A_H^{\mu}\overline{t'}\_t$	$\frac{2ig'}{5}c_\lambda\gamma_\mu\left(c_\lambda\frac{v}{f}P_L + P_R\right)$

from Hubisz, Meade [hep-ph/0411264]

Let me show you how to do it!



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MadRules (under construction)

Duhr, Herquet

- Mathematica package
- Given particle content and Lagrangian, calculates all vertices and couplings
- Generates all MadGraph/MadEvent files needed
- Already tested with Standard model Lagrangean
- Next step – MSSM Lagrangean
- Perfect tool for implementation of complete theory, or major parts of a theory!

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MadRules example: SM gauge sector

Particles:

```
part1 = Particle[W, CV, S, -24, PartName -> "W-", AntiPartName -> "W+",
                 Mass → {MASSW, 80.1}, Width → {WIDTHW, 1}];
part2 = Particle[Z, RV, S, 23, Mass → {MASSZ, 80.1}, Width → {WIDTHZ, 1}];
part3 = Particle[A, RV, S, 22, Mass → ZERO, Width → ZERO];
part4 = Particle[H, RS, S, 25, Mass → {MASSH, 80.1}, Width → {WIDTHH, 1}];
part5 = Particle[G, RV, O, 21, Mass → ZERO, Width → ZERO];
```

Field strength tensors:

```
WW[1, mu_, nu_] := del[W1[mu], nu] - del[W1[nu], mu]
                    + gW (W2[mu] W3[nu] - W3[mu] W2[nu]);
WW[2, mu_, nu_] := del[W2[mu], nu] - del[W2[nu], mu]
                    + gW (-W1[mu] W3[nu] + W3[mu] W1[nu]);
WW[3, mu_, nu_] := del[W3[mu], nu] - del[W3[nu], mu]
                    + gW (W1[mu] W2[nu] - W2[mu] W1[nu]);
U1GaugeGroup["U1Y", Y, B]
NAGaugeGroup["SU3C", fSUN, TSUN, G, gs]
```

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MadRules example: SM gauge sector

Lagrangian:

```
Lgauge = -1 / 4 (Sum[WW[ii, mu, nu] WW[ii, mu, nu], {ii, 1, 3}] +
                 FS["U1Y", mu, nu] FS["U1Y", mu, nu]) -
                 1 / 4 FS["SU3C", mu, nu, a] FS["SU3C", mu, nu, a]
GetVerticesMG[Lgauge, "Gauge"]
```

Vertices:

```
VerticesMG["Gauge"]
```

VVV	{G, G, G}	GGG	G	(QCD 1)	R
VVVV	{G, G, G, G}	GGGG	G^2	(QCD 2)	R
VVV	{W−, W+, A}	WmWpA	gW sw	(QED 1)	R
VVVV	{W−, A, W+, A}	WmAWpA	$gW^2\ sw^2$	(QED 2)	R
VVV	{W−, W+, Z}	WmWpZ	cw gW	(QED 1)	R
VVVV	{W−, W−, W+, W+}	WmWmWpWp	gW^2	(QED 2)	R
VVVV	{W−, A, W+, Z}	WmAWpZ	$cw\ gW^2\ sw$	(QED 2)	R
VVVV	{W−, Z, W+, Z}	WmZWpZ	$cw^2\ gW^2$	(QED 2)	R

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MadRules example: SM gauge sector

Generated particles.dat:

```
#This file has been generated automatically by MadRules
W-     W+     V    W    MASSW     WIDTHW    S    W       -24
Z      Z      V    W    MASSZ     WIDTHZ    S    Z       23
A      A      V    W    ZERO      ZERO      S    A       22
H      H      S    D    MASSH     WIDTHH    S    H       25
G      G      V    W    ZERO      ZERO      O    G       21
```

Generated interactions.dat

```
# Interactions associated with Lagrangian Gauge
G    G    G GGG    QCD
G    G    G    G GGGG   DUM   QCD QCD
W-    W+    A WmWpA    QED
W-    A    W+    A WmAWpA   DUM   QED QED
W-    W+    Z WmWpZ    QED
W-    W-    W+    W+ WmWmWpWp   DUM   QED QED
W-    A    W+    Z WmAWpZ   DUM   QED QED
W-    Z    W+    Z WmZWpZ   DUM   QED QED
```

Generated couplings.f

```
c Interactions associated with Lagrangian Gauge
      GGG = G
      GGGG = G**2
      WmWpA = gW*sw
      WmAWpA = gW**2*sw**2
      WmWpZ = cw*gW
      WmWmWpWp = gW**2
      WmAWpZ = cw*gW**2*sw
      WmZWpZ = cw**2*gW**2
```

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Calculators

- Need consistent calculation of mass spectra / dependent parameters and decay widths
- Calculators (see web page/generation page) for
  - SM (EW parameters + decay widths)
  - MSSM (EW pars + decay widths from SLHA files)
  - 2HDM (Higgs boson spectrum + decay widths)
- For general model: BRIDGE Meade, Reece
  - Reads MG/ME user model files to calculate decay widths of all particles
  - Performs decay of final state particles in event file

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Six easy steps from model to events

1. Write your Lagrangean into Mathematica
2. Generate MG/ME files with MadRules
3. Set model parameters and calculate spectrum, calculate decay widths using BRIDGE
4. Define an interesting process and generate events with MadGraph/MadEvent
5. Decay undecayed final state particles to SM particles with BRIDGE
6. Run event file through Pythia for hadronization

(7. Give events or generator to experimentalist)

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MG/ME in Marmoset

(See also talk by Jesse Thaler)

- Possibility to use MG/ME instead of Pythia
- Define spin of particles
- For production processes – define t- or s-channel propagator or QCD
- Can use MG/ME also for decays
- Especially important for light t-channel, or large mass difference between coproduced particles
- Gives spin correlations in production and decay

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Summary

- MadGraph/MadEvent 4 – an integrated tool to generate any process, signal or background!
- Models: SM, MSSM, 2HDM, HEFT, UED (coming soon)
- Several ways to implement new models:
  - Modify existing model
  - User model framework
  - MadRules – Full model implementation from Lagrangean (coming soon)
- Fast – thanks to efficient and cluster-oriented generation
- Clusters found at:
  - UCL: http://madgraph.phys.ucl.ac.be/
  - Rome: http://madgraph.roma2.infn.it/
  - UIUC: http://madgraph.hep.uiuc.edu/

Try it out – we are grateful for any feedback!

Backup slides

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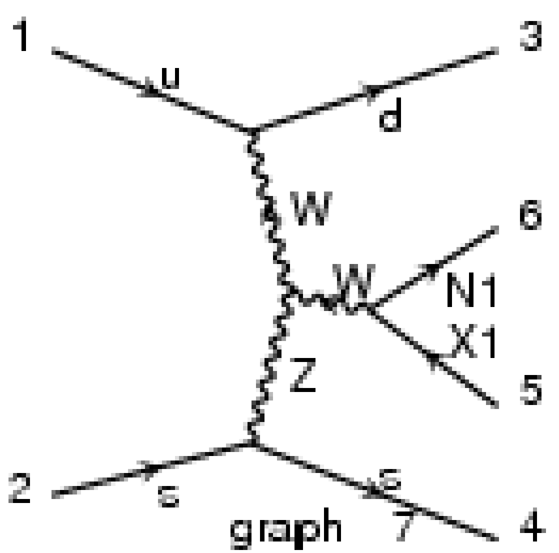
MSSM

Hagiwara, Plehn, Rainwater, Stelzer + Alwall

- CP and R-parity conserving MSSM
- Sfermion mixing and Yukawa couplings for 3rd gen.
- Uses SUSY Les Houches input files – independent of SUSY breaking scheme
- Detailed comparison of cross sections between SMadGraph, Omega and Amegic++ (hep-ph/0512260)
- Input files for the 10 SPS points available



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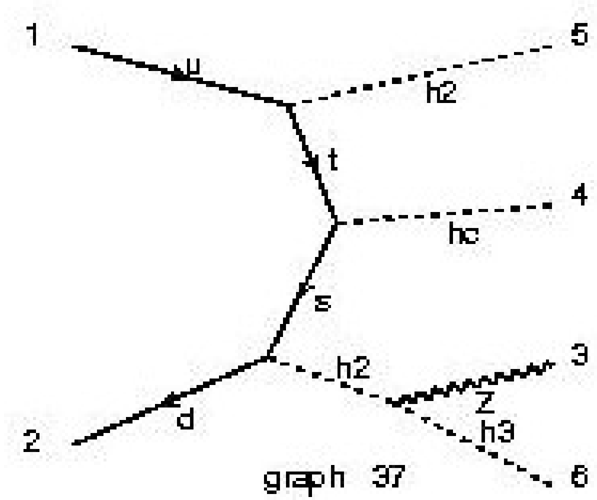
General 2HDM

de Vissher, Herquet

- Completely general 2HDM, with FCNC and CP violation
- New tree-level calculator (Herquet) with a web interface, TwoHiggsCalc, to generate the param_card for MadEvent
- Generic basis or Higgs basis, intensive use of recent basis invariance techniques (e.g. hep-ph/0504050)
- Tested in the SM & MSSM limits
- Sample files for various cases
- Simplified version without FCNC and off-diag. CKM elements



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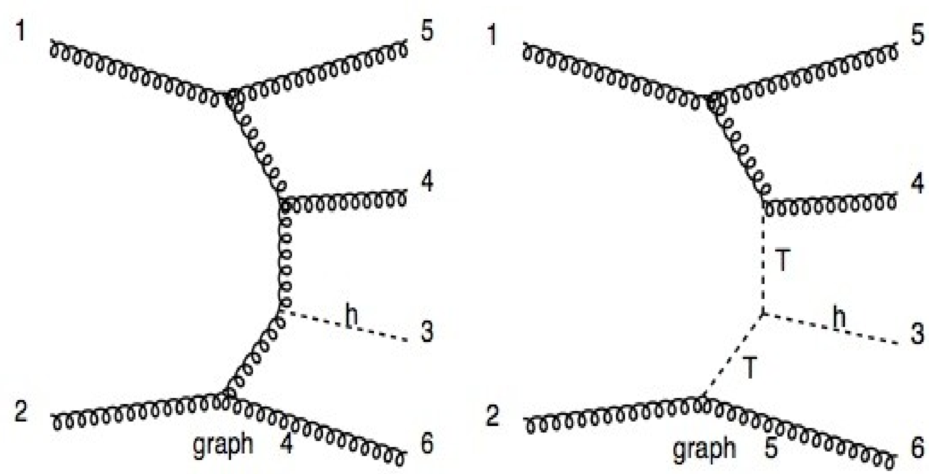
Higgs EFT

Frederix

- Effective couplings of Higgs to gluons
  - Effective non-propagating tensor particle to allow Higgs couplings to more than 3 gluons
  - Several new HELAS subroutines
  - Works for scalar and pseudo-scalar neutral Higgs bosons



User model generation

de Vissher

particles.dat

```
#Name anti_Name   Spin    Linetype Mass Width Color Label Model
#xxx   xxxx       SFV      WSDC     str  str  STO    str  PDG code

#MODEL EXTENSION
tp        tp~      F         S      TPMASS TPWID  T    TP    8
zp        zp       V         W      ZPMASS ZPWID  S    ZP   32
# END
```

interactions.dat

```
#   USRVertex
tp tp g  GG    QCD
tp t  zp GTPZP QED
t  tp zp GTPZP QED
```

couplings.f

```
c************************************
c UserMode couplings
c************************************

      GTPZP(1)=dcmplx(ee*param1,Zero)
      GTPZP(2)=dcmplx(ee*param1,Zero)
```

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Implemented vertices in MadGraph / HELAS

3-point:

- Fermion-fermion-scalar (dirac/majorana) (color: TTS, SSS,TOT, OTT, TST, STT)
- Fermion-fermion-vector (dirac/majorana) (color: TTO, TTS,SSS, OOO)
- vector-vector-scalar (color: SSS)
- 3-vector (color: SSS, OOO)
- 3-scalar (color: SSS, STT)
- vector-scalar-scalar (color: OTT, STT, SSS)

Implemented vertices in MadGraph / HELAS

4-point:

- vector-vector-scalar-scalar (color: OOTT, OSTT, SSTT, SSSS)
- 4-scalar (color: SSSS)
- 4-vector:
  - color octets: gggg-vertex (massless vectors)
  - color singlets: identical/anti-particles: WWWW
  - Color singlets (e.g. W+ a W- z vertex): W3W3

Implemented vertices in MadGraph / HELAS

Higgs effective theory:

- vector-vector-scalar, dimension-5 (massless vectors only) (color: SSS, OOS)
- vector-vector-vector-scalar dimension-5 (identical, massless vectors only) (color: SSSS, OOOS)
- vector-vector-tensor (massless vectors; non-propagating tensor) (color: SSS, OOO)
- vector-vector-vector-tensor (massless, identical vectors; non-propagating tensor) (color: OOOO, SSSS)
- tensor-tensor-scalar (non-propagating tensor) (color: SSS, OOS)

Some spin-2 graviton vertices (only ff~>G>ff~)

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Calculators

- SLHA-like model parameter input format (param_card)
- Can be used by other event generators (e.g. Pythia)
- Need to calculate dependent parameters (e.g. weak sector) and decay widths (to get branching ratios right)
- MSSM
  - Takes SLHA files from any SUSY spectrum generator
- 2HDM
  - Enter potential parameters and Yukawa couplings
  - Choice between Higgs basis and general basis
  - Calculates masses, mixings, couplings and decay widths

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2HDM Calculator

Higgs Basis (more info)

$$V = \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 - \left(\mu_3 H_1^\dagger H_2 + \text{h.c.}\right)$$
$$\lambda_1 \left(H_1^\dagger H_1\right)^2 + \lambda_2 \left(H_2^\dagger H_2\right)^2$$
$$+\lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right)$$
$$+\left[\left(\lambda_5 H_1^\dagger H_2 + \lambda_6 H_1^\dagger H_1 + \lambda_7 H_2^\dagger H_2\right)\left(H_1^\dagger H_2\right) + \text{h.c.}\right]$$

lambda1	1
lambda2	1
lambda3	1
lambda4	0
lambda5	0
Norm of lambda6	0
Norm of lambda7	0
Phase of lambda6	0
Phase of lambda7	0
Mass of Charged Higgs (GeV)	300

Generic Basis (more info)

$$V = \mu_1 \phi_1^\dagger \phi_1 + \mu_2 \phi_2^\dagger \phi_2 - \left(\mu_3 \phi_1^\dagger \phi_2 + \text{h.c.}\right)$$
$$+\frac{1}{2}\lambda_1 \left(\phi_1^\dagger \phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\phi_2^\dagger \phi_2\right)^2$$
$$+\lambda_3 \left(\phi_1^\dagger \phi_1\right)\left(\phi_2^\dagger \phi_2\right) + \lambda_4 \left(\phi_1^\dagger \phi_2\right)\left(\phi_2^\dagger \phi_1\right)$$
$$+\left[\left(\frac{1}{2}\lambda_5 \phi_1^\dagger \phi_2 + \lambda_6 \phi_1^\dagger \phi_1 + \lambda_7 \phi_2^\dagger \phi_2\right)\left(\phi_1^\dagger \phi_2\right) + \text{h.c.}\right]$$

Tan(beta)=v2/v1	1
Phase of v2	0
Norm of mu3	0
lambda1	1
lambda2	1
lambda3	1
lambda4	0
Norm of lambda5	0
Norm of lambda6	0
Norm of lambda7	0
Phase of lambda5	0
Phase of lambda6	0
Phase of lambda7	0

Yukawa parameters

Higgs basis (more info)

$$\mathcal{L}_Y = \frac{\bar{Q}_L\sqrt{2}}{v}\left[(M_d H_1 + Y_d H_2)d_R + (M_u \tilde{H}_1 + Y_u \tilde{H}_2)u_R\right] + \frac{\bar{E}_L\sqrt{2}}{v}\left[(M_e H_1 + Y_e H_2)e_R\right]$$

Generic Basis (more info)

$$\mathcal{L}_Y = \frac{\bar{Q}_L\sqrt{2}}{v}\left[(\Delta_d \phi_1 + \Gamma_d \phi_2)d_R + (\Delta_u \tilde{\phi}_1 + \Gamma_u \tilde{\phi}_2)u_R\right] + \frac{\bar{E}_L\sqrt{2}}{v}\left[(\Delta_e \phi_1 + \Gamma_e \phi_2)e_R\right]$$

Yukawa couplings to the second Higgs doublet of the down type quarks (norm and phase)

Y1D/G1D	0	0	Y1S/G1S	0	0	Y1B/G1B	0	0
Y2D/G2D	0	0	Y2S/G2S	0	0	Y2B/G2B	0	0
Y3D/G3D	0	0	Y3S/G3S	0	0	Y3B/G3B	0	0

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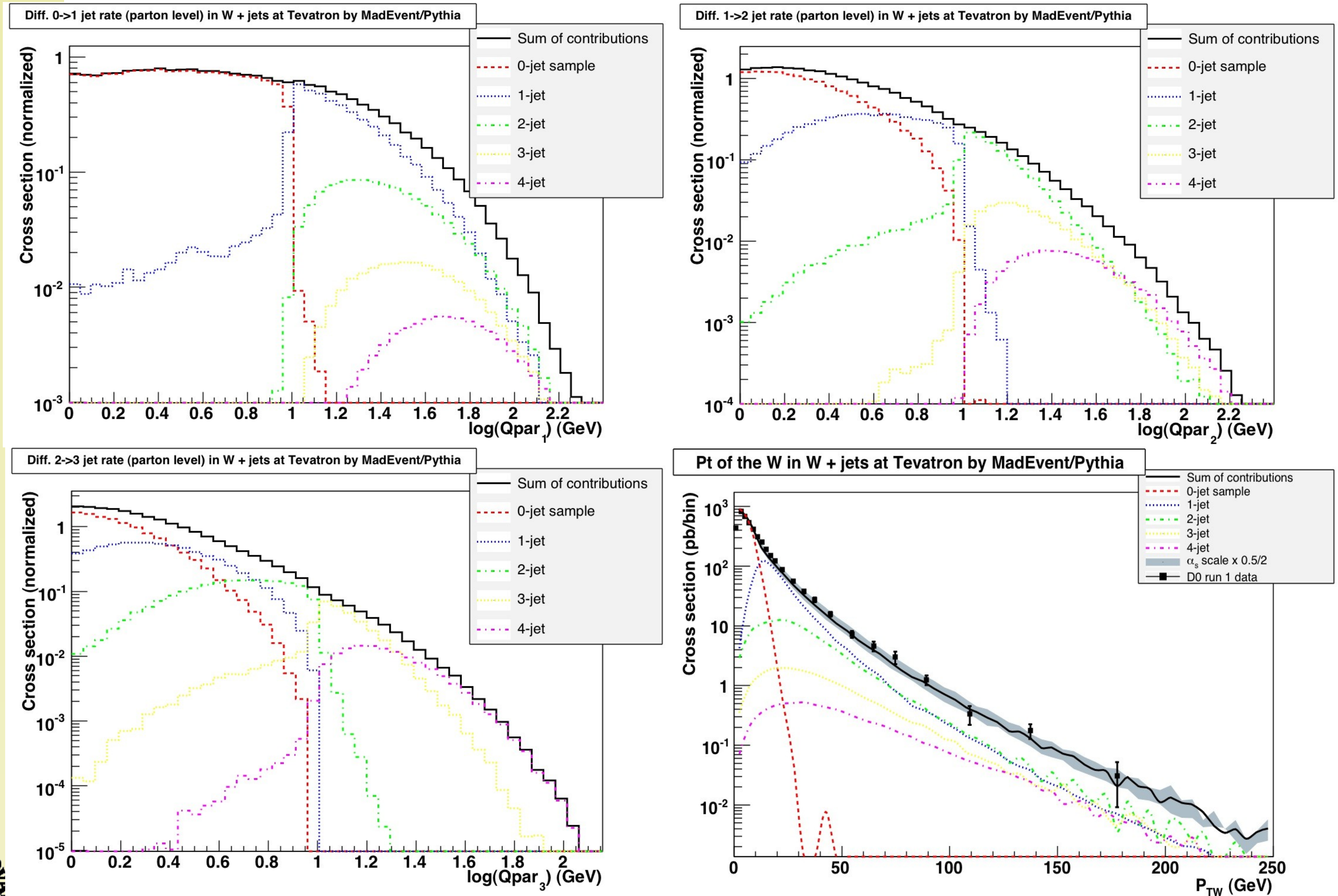
Matching of ME and PS



Differential jet rate for 0→1, 1→2, 2→3 jets and W pt in $p\bar{p}$→W+jets