MadGraph/MadEvent v4:

event simulation for SM and BSM physics

http://madgraph.hep.uiuc.edu

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JHEP09(2007)028

+ Pierre Artoisenet, Claude Duhr, Olivier Mattenlaer,...

Outline

- Matrix element generators
- The MadGraph/MadEvent approach
- Two simple examples at the ILC
- Conclusions

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Why tree-level?

- Most of the current collider pheno is done at tree-level both at the theoretical and (even more) at experimental level.
- Experiments need fully exclusive descriptions.
- MC at NLO are very recent (and impressive) achievements, but currently limited to a small set of key SM processes.

Why tree-level?

Always the fastest way,

very often the most accurate way,

sometimes the only way,

to bring ideas to life and
test them in the experiments!

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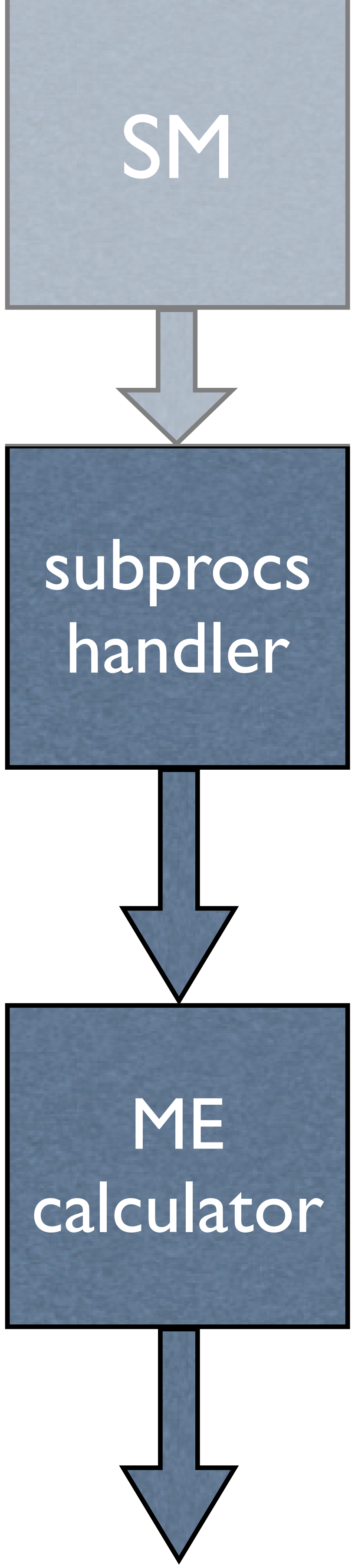
In other words,
“tree-level is nirvana”®!

®G. Passarino

General structure



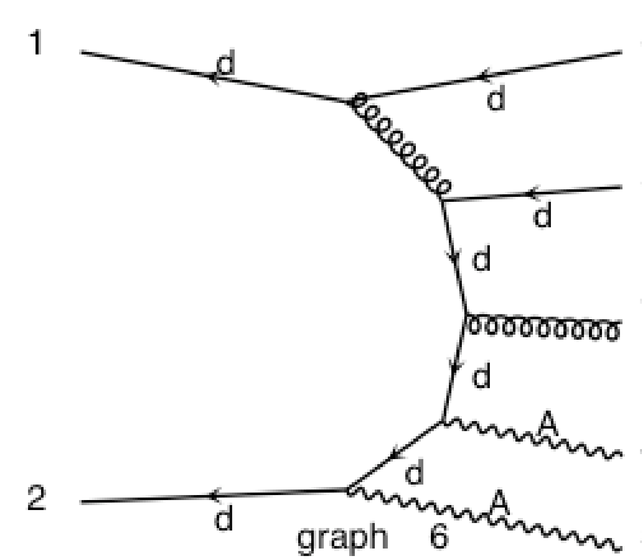
Includes all possible subprocess leading to a given multi-jet final state automatically or manually (done once for all)

d~ d -> a a u u~ g
d~ d -> a a c c~ g
s~ s -> a a u u~ g
s~ s -> a a c c~ g

"Automatically" generates a code to calculate |M|^2 for arbitrary processes with many partons in the final state.

Most use Feynman diagrams w/ tricks to reduce the factorial growth, others have recursive relations to reduce the complexity to exponential. ☺

$$\mathcal{A}(\{p\},\{h\},\{c\}) = \sum_i D_i$$



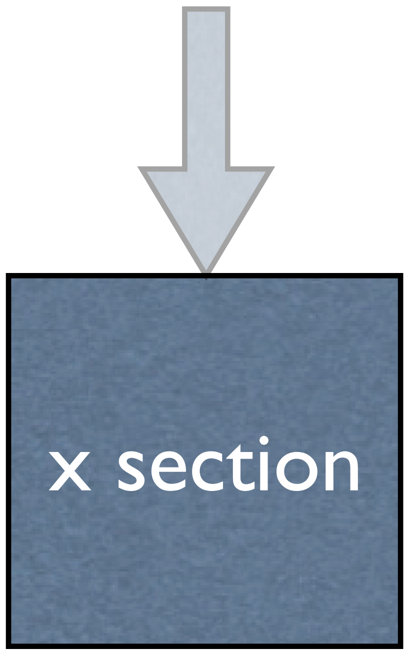
Beware of the factorial growth

gg→(n-2)g

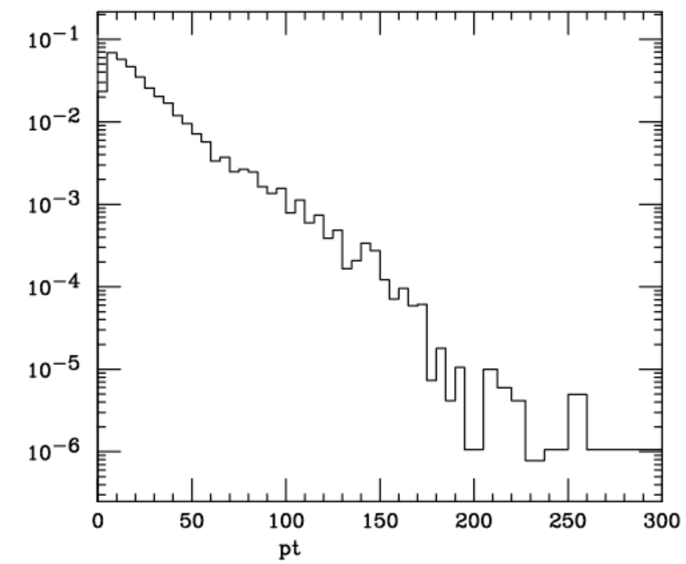
n	full Amp	partial Amp	BG
4	4	3	3
5	25	10	10
6	220	36	35
7	2485	133	70
8	34300	501	126
9	559405	1991	210
10	10525900	7335	330
11	224449225	28199	495
12	5348843500	108280	715
	$(2n)!$	3.8^n	n^4

- Complexity of plain vanilla Feynman calculations grows factorially
- "Old techniques" based on calculating simpler guauge invariant objects by a recursive techniques are much more powerful.
- In any case the calculation through partial amplitudes is not as efficient as the direct calculation of the full amplitude at fixed color through numerical recursive relations [ALPGEN, Moretti, Caravaglios, Mangano, Pittau, 1998; HELAC, Draggiotis, Kleiss, Papadopoulos, 1998], which has only an exponential growth.
- New twistor tree-level BCF or CSW recursive relations, without or with color, don't improve on the "old" Berends-Giele recursive relations. [Dinsdale, Wernick, Weinzierl, 2006; Duhr, Hoeche, FM, 2006].

General structure



Integrate the matrix element over the phase space using a multi-channel technique and using parton-level cuts.

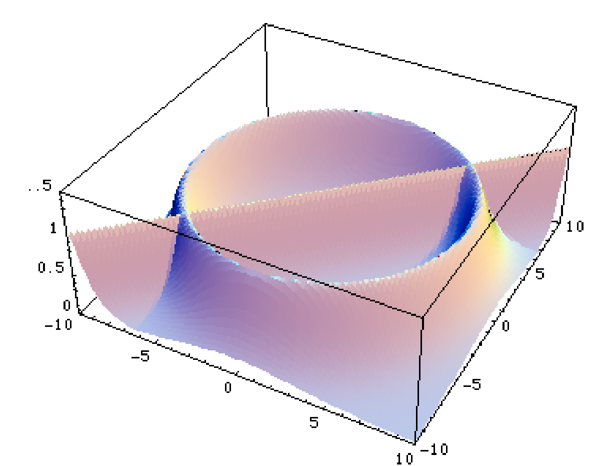


$$\hat{\sigma} = \frac{1}{2\hat{s}} \int d\Phi_p \sum_{h,c} |\mathcal{A}|^2$$

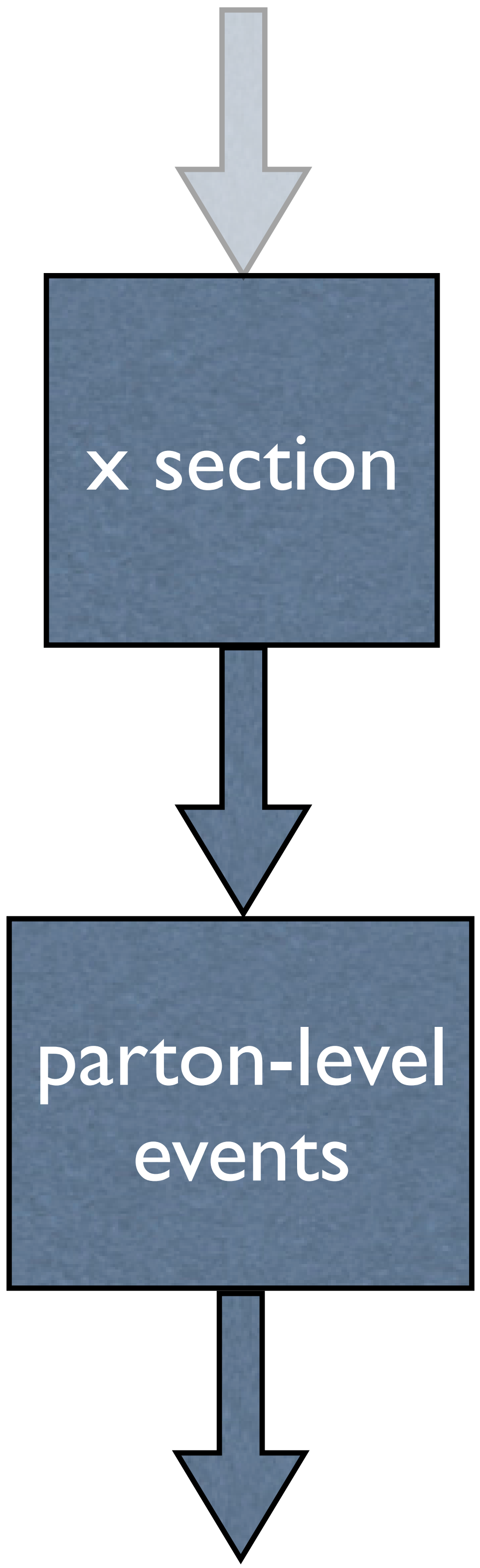
* Very difficult integration
* Efficient multi-channel techniques are neeeded

$$p(x) = \sum_{i=1}^{n} \alpha_i p_i(x)$$

$$I = \int f(x) dx = \sum_{i=1}^{n} \alpha_i \int \frac{f(x)}{p(x)} p_i(x) dx$$



General structure



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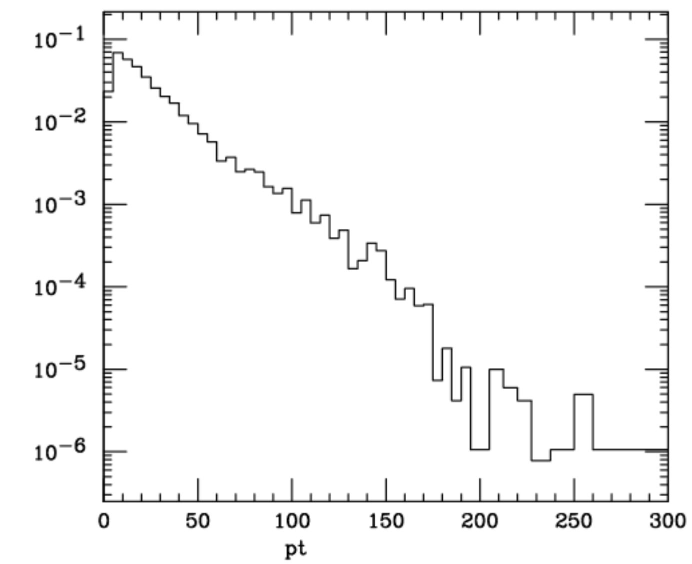
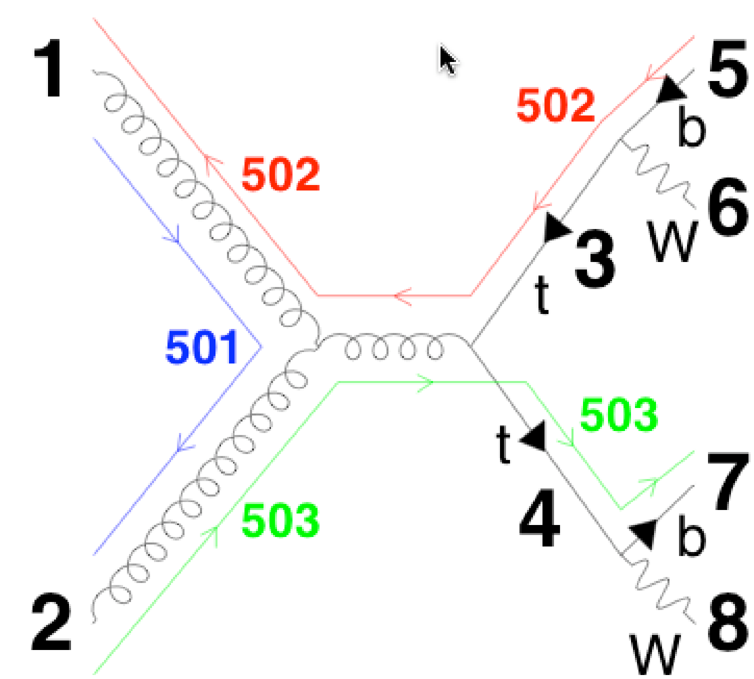


Events are obtained by unweighting. These are at the parton-level. Information on particle id, momenta, spin, color and mother-daugther is given in the Les Houches format.

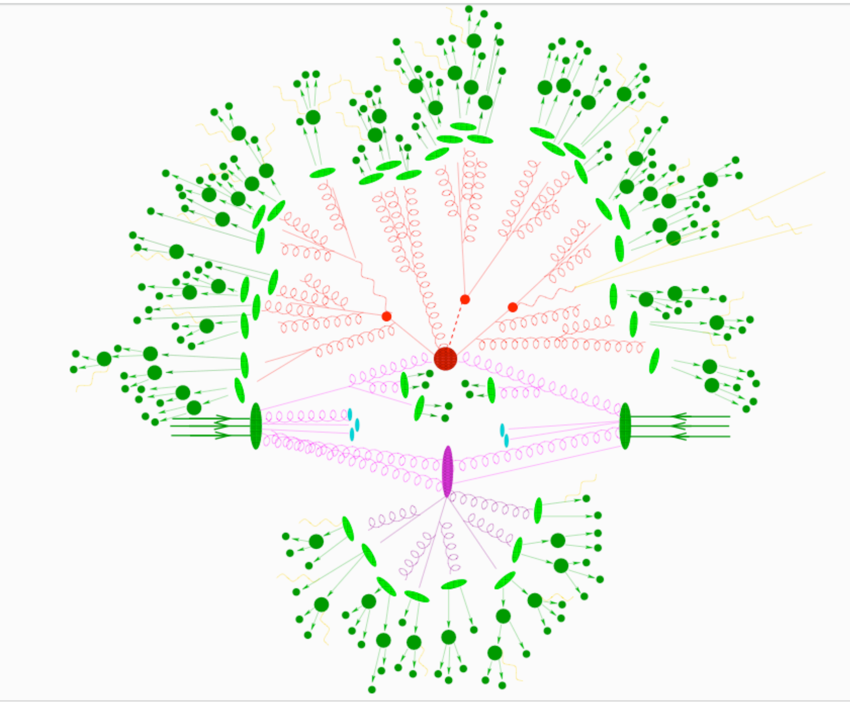


General structure

Shower & Hadro

Events in the LH format are passed to the showering and hadronization⇒

high multiplicity hadron-level events

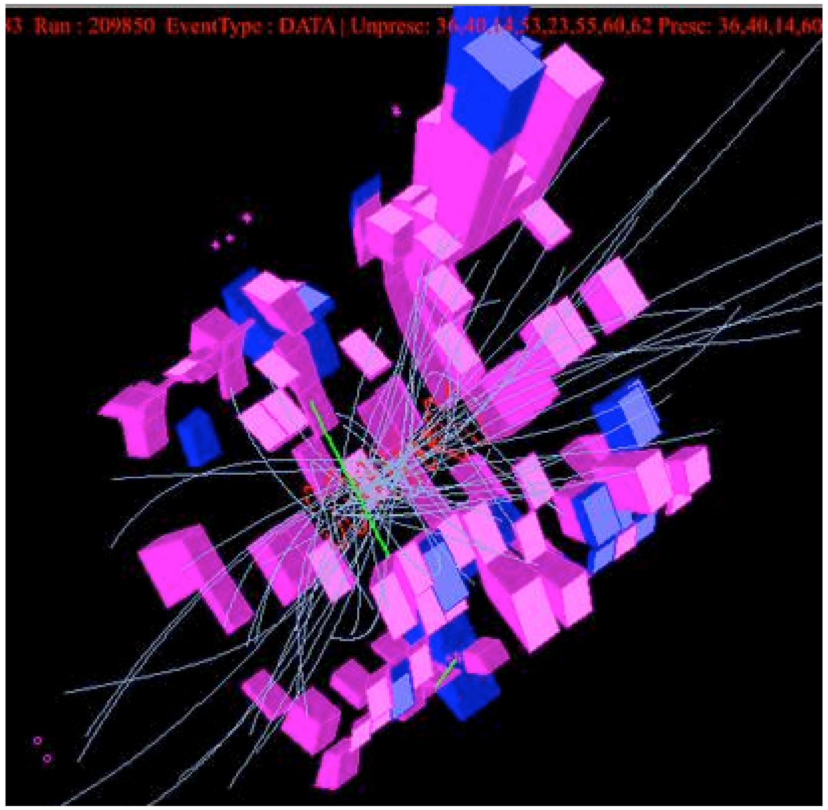


th

exp

Detector simulation & reco

Events in stdhep format are passed through fast or full simulation, and physical objects (leptons, photons, jet, b-jets, taus) are reconstructed.



Types of SM codes available

Several codes exist for the SM, built using different philosophies

TYPE	Characteristics	Examples
"One" Process	Highly dedicated, manual work, optimized, specific problems addressed	6 fermion codes: LUSIFER,SixPhact, Sixrad,... 6j ??
Library	Semi automatic, modular structure, author-driven efficient	
Multi-purpose	High automatization, user-driven, huge versatility	Grace Sherpa CompHep MadGraph Whizard

For new physics MC's the last option is the way to go

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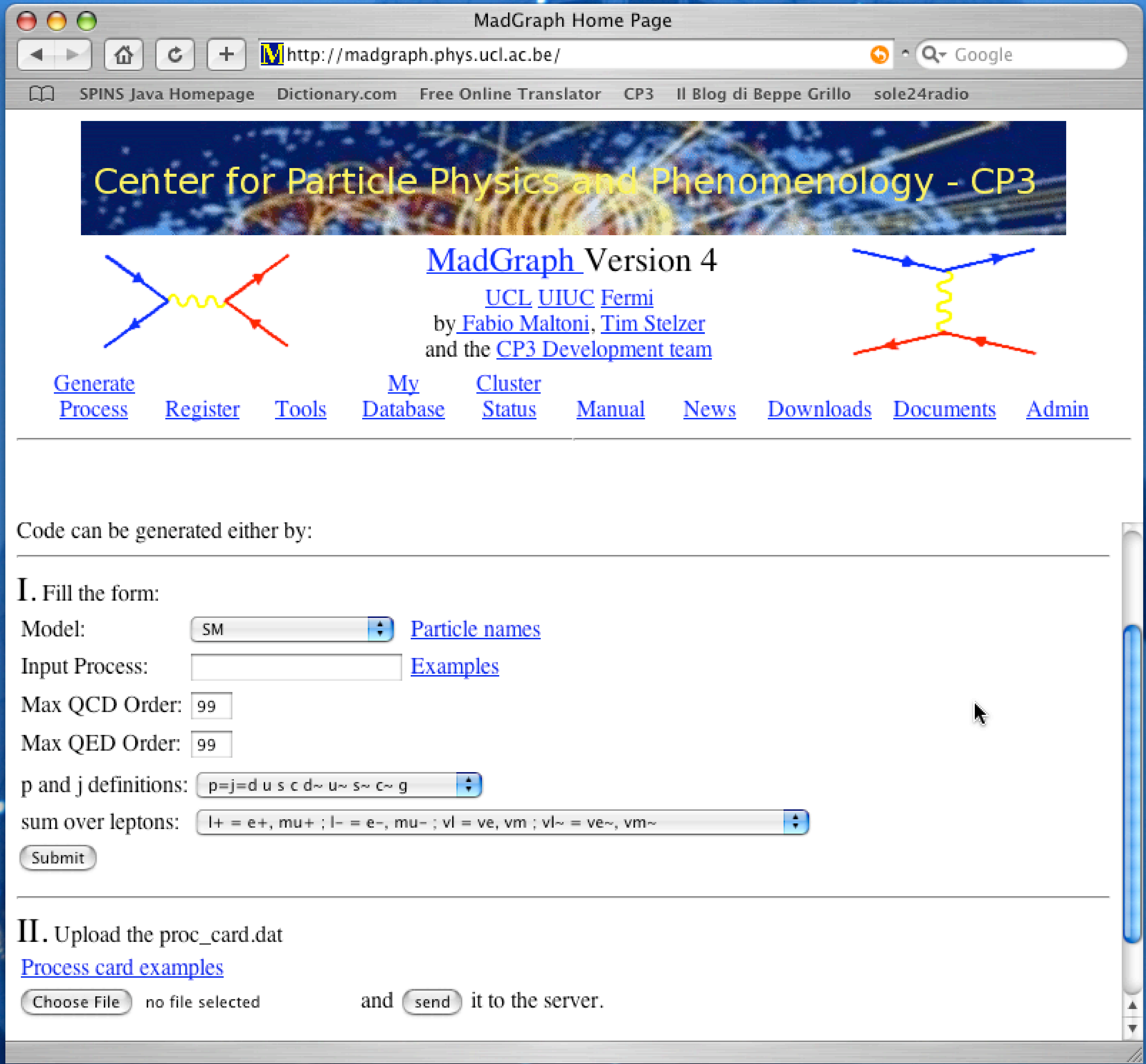
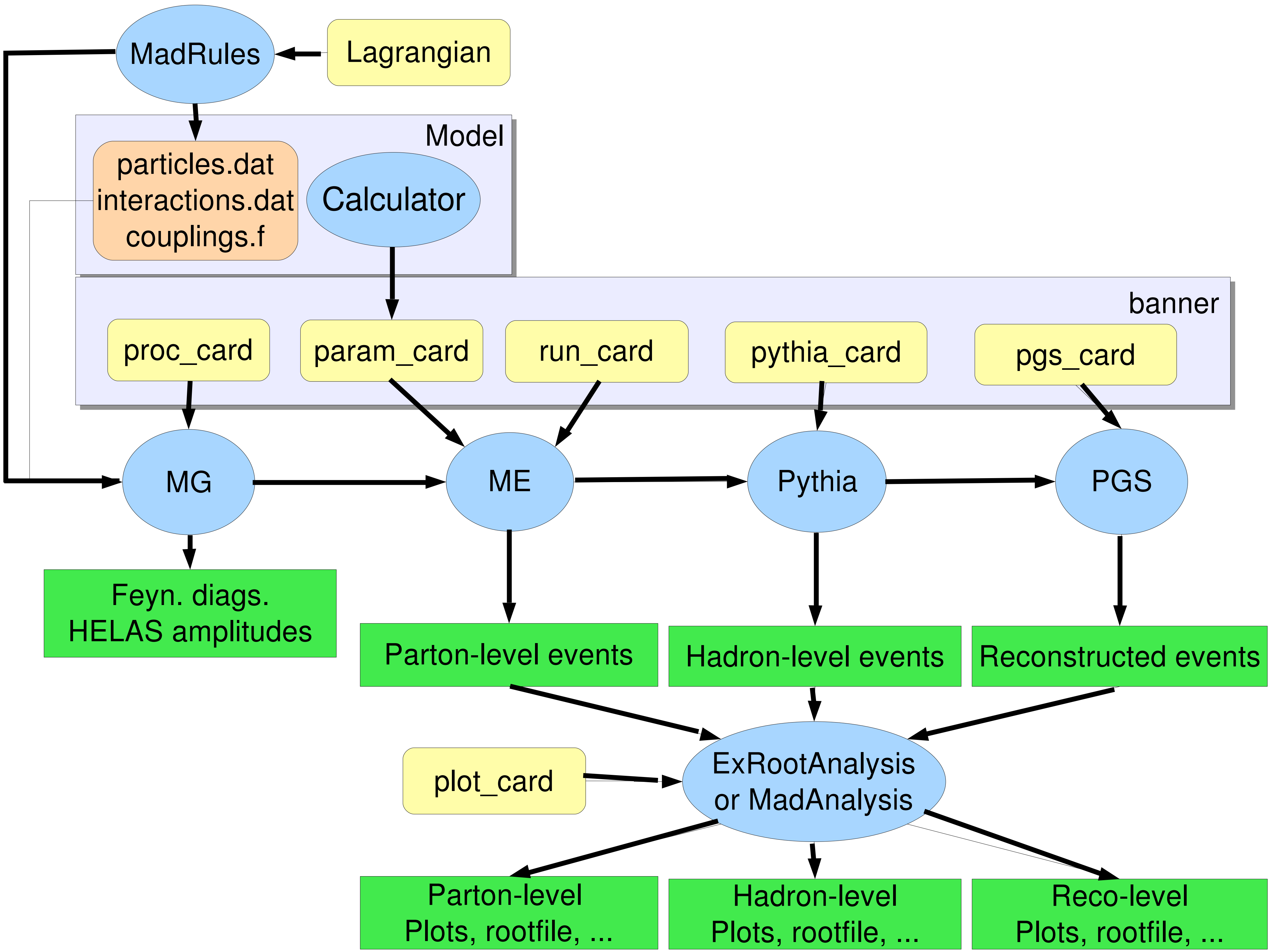

MadGraph Home Page
http://madgraph.phys.ucl.ac.be/
SPINS Java Homepage
Dictionary.com
Free Online Translator
CP3
Il Blog di Beppe Grillo
sole24radio
Center for Particle Physics and Phenomenology - CP3
MadGraph Version 4
UCL UIUC Fermi
by Fabio Maltoni, Tim Stelzer
and the CP3 Development team
Generate Process
Register
Tools
My Database
Cluster Status
Manual
News
Downloads
Documents
Admin
Code can be generated either by:
I. Fill the form:
Model: SM
Particle names
Input Process:
Examples
Max QCD Order: 99
Max QED Order: 99
p and j definitions: p=j=d u s c d~ u~ s~ c~ g
sum over leptons: l+ = e+, mu+ ; l- = e-, mu- ; vl = ve, vm ; vl~ = ve~, vm~
Submit
II. Upload the proc_card.dat
Process card examples
Choose File no file selected
and send it to the server.

Madgraph/MadEvent

- The new web generation:
  - User inputs model/parameters/cuts.
  - Code runs in parallel on modest farms.
  - Returns cross section, plots, parton-level events.
  - BSM physics (MSSM, 2HDM,...) + returns Pythia and PGS events!
- Advantages:
  - Reduces overhead to getting results
  - Events can easily be shared/stored
  - Quick response to user requests and to new ideas!

http://madgraph.phys.ucl.ac.be Belgian
http://madgraph.hep.uiuc.edu U.S.
http://madgraph.roma2.infn.it Italian

MadGraph/MadEvent Flow



MG/ME Features

- Helicity amplitudes, based on HELAS
- Parallel phase space integration
- Les Houches Accord standard (LHEF) for the parton-level event files
- Model development framework
- Les Houches Accord 2 for model parameters
- kt-MLM matching
- Interfaces for Pythia, Sherpa (and Herwig)
- Analysis platforms: ExRootAnalysis and MadAnalysis

Users

1. Web user: event generation from the browser. Personal database. On-line analysis tools.
2. Local user: advanced use for specific personal purposes (pheno/exp papers)
3. Addicted: professional use for adding new models (possibly public), new features, or group and physics oriented features, public tools development.

MadGraph standalone: a tool for theorists

- “Naked” Matrix elements can be also generated to be EXPORTED to any other ME MC or used in higher order computations.
- Matrix elements can be tested point-by-point in phase space AUTOMATICALLY for ANY process.
- Model and parameters are included in a small library (easy to compare different model implementations).

A word on integration:
The Single-Diagram-Enhanced technique

Imagine there were a basis of functions,

$$f = \sum_{i=1}^{n} f_i \qquad \text{with} \qquad f_i \geq 0\,, \qquad \forall\, i$$ such that:

1. we know how to integrate each one of them
2. they describe all possible peaks

Then the problem would be solved:

$$I = \int d\vec{\Phi} f(\vec{\Phi}) = \sum_{i=1}^{n} \int d\vec{\Phi}\, g_i(\vec{\Phi})\, \frac{f_i(\vec{\Phi})}{g_i(\vec{\Phi})} = \sum_{i=1}^{n} I_i$$

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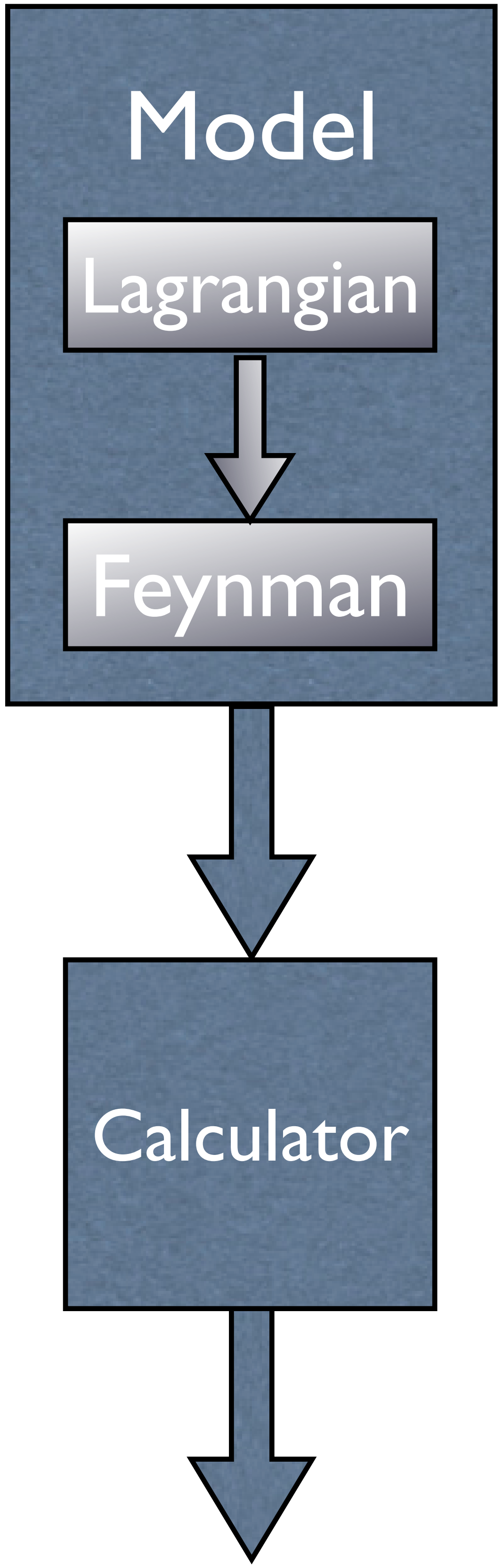
This basis exists:

$$f_i = \frac{|A_i|^2}{\sum_i |A_i|^2} |A_{\text{tot}}|^2$$

Add-on for BSM



Les Houches interface

Invent a model, renormalizable or not, with new physics. Write the Lagrangian and the Feyman Rules.

The particles content, the type of interactions and the analytic form of the couplings in the Feynman rules define the model at tree level.

SUSY, Little Higgs, Higgsless, GUT, Extra dimensions (flat, warped, universal,...)

Parameters Calculator.
Given the "primary" couplings, all relevant quantities are calculated: masses, widths and the values of the couplings in the Feynman rules.

Caution: tree-level relations have to be satisfied to avoid gauge violations and/or wrong branching ratios.

FeynHiggs, ISAJET, NMHDecay, SOFTSUSY, SPHENO, SUSPECT, SDECAY...

Models in MadGraph

Previously:

- Standard Model

Models in MadGraph

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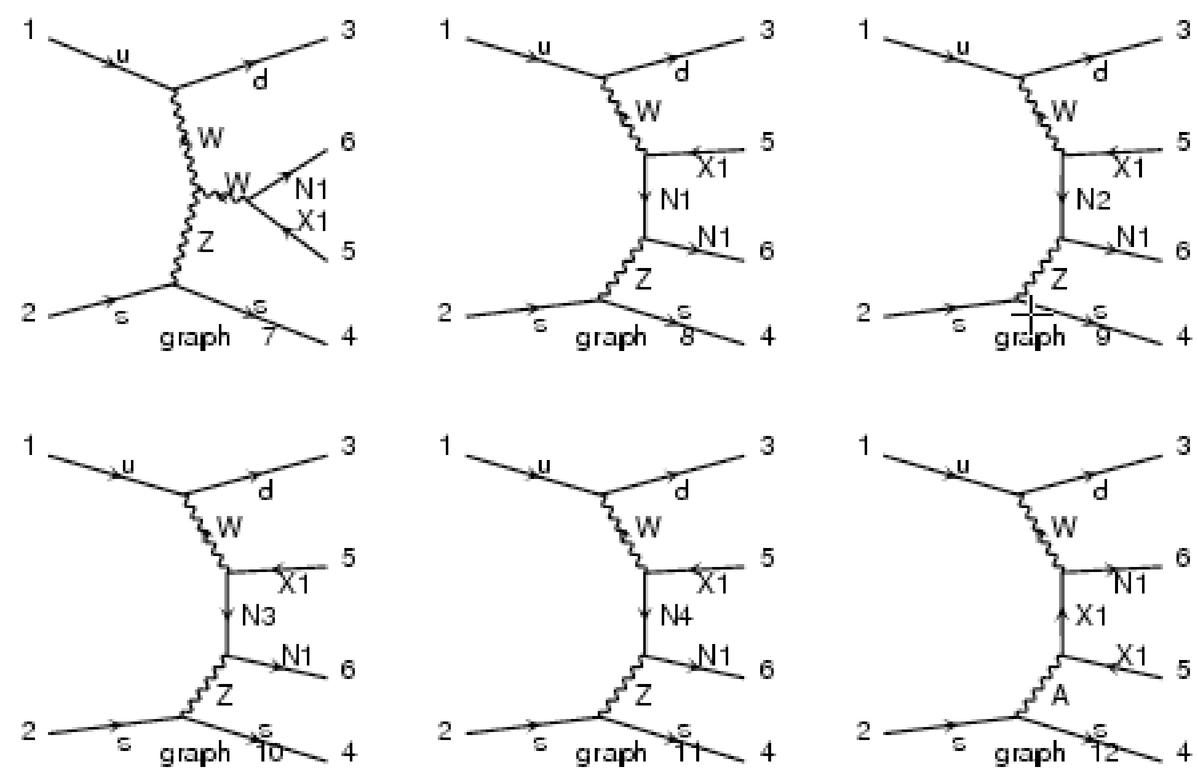
- Standard Model

New models:

- MSSM



Models in MadGraph

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New models:

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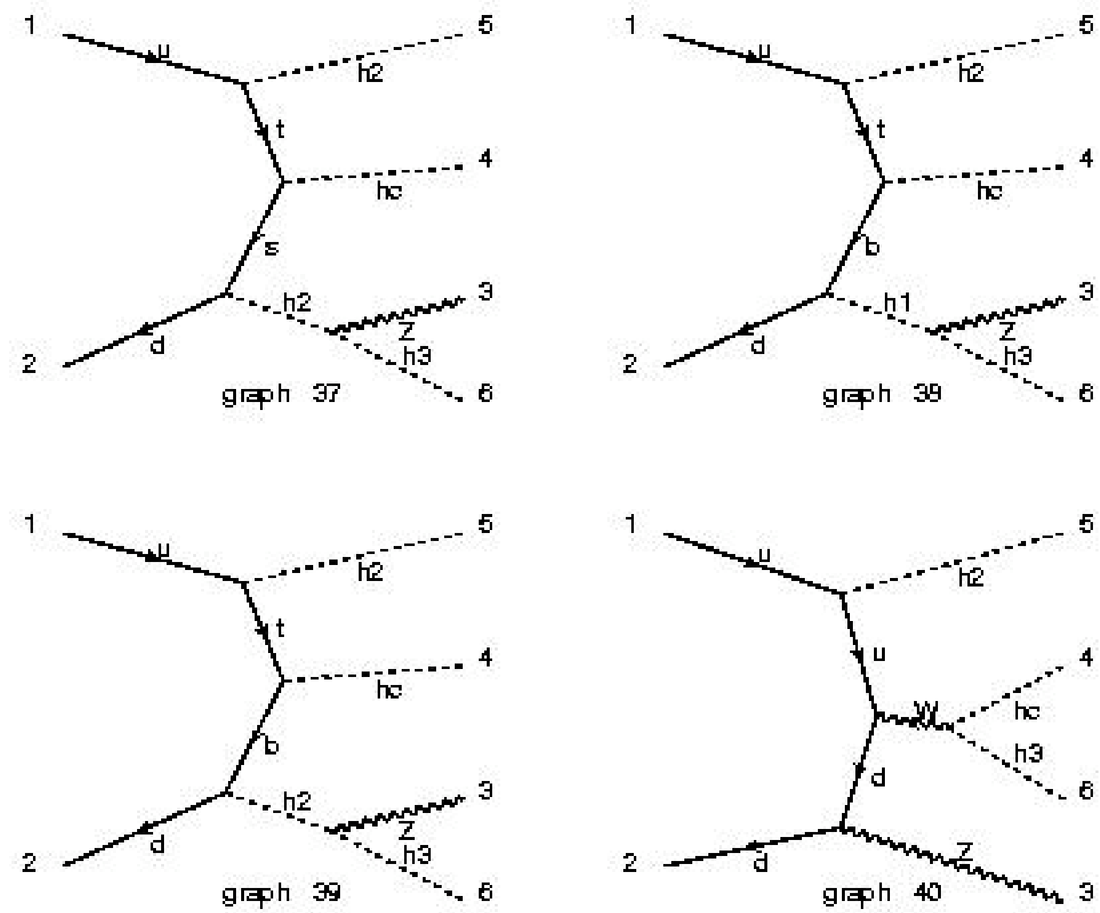
- General 2HDM:
  CPV, type I,II,...
  & Calculator



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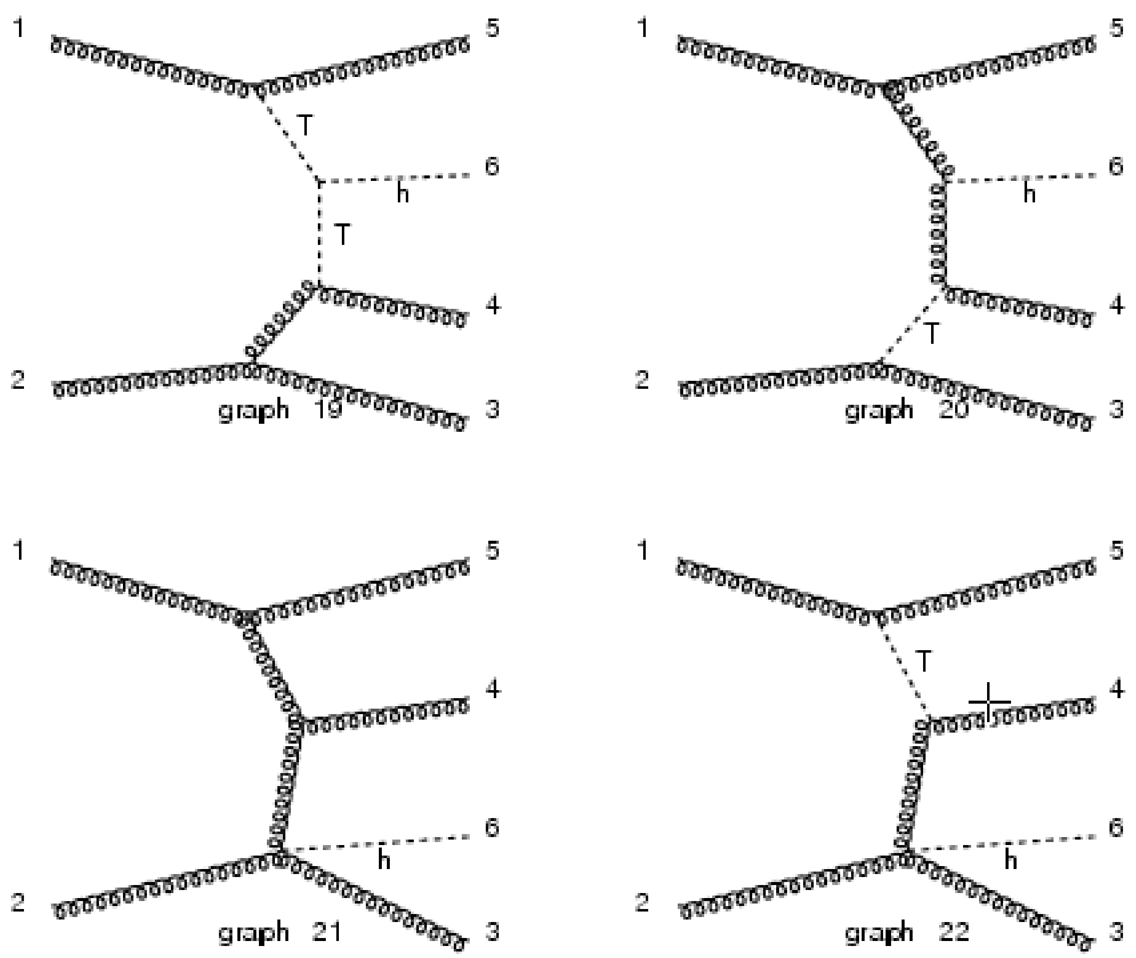
- Higgs EFT



Models in MadGraph

Previously:

- Standard Model

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

#
# Quarks
#

d        d~         F         S      ZERO   ZERO    T     d     1
u        u~         F         S      ZERO   ZERO    T     u     2
s        s~         F         S      ZERO   ZERO    T     s     3
c        c~         F         S      ZERO   ZERO    T     c     4
b        b~         F         S      BMASS  ZERO    T     b     5
t        t~         F         S      TMASS  TWIDTH  T     t     6
```

particles.dat

New models:

- MSSM
- General 2HDM: CPV, type I,II,... & Calculator
- Higgs EFT

```
#
# QCD interactions
#

d d g GG QCD
u u g GG QCD
s s g GG QCD
c c g GG QCD
b b g GG QCD
t t g GG QCD

g g g G  QCD
```

interactions.dat

- New: General framework for user-defined models

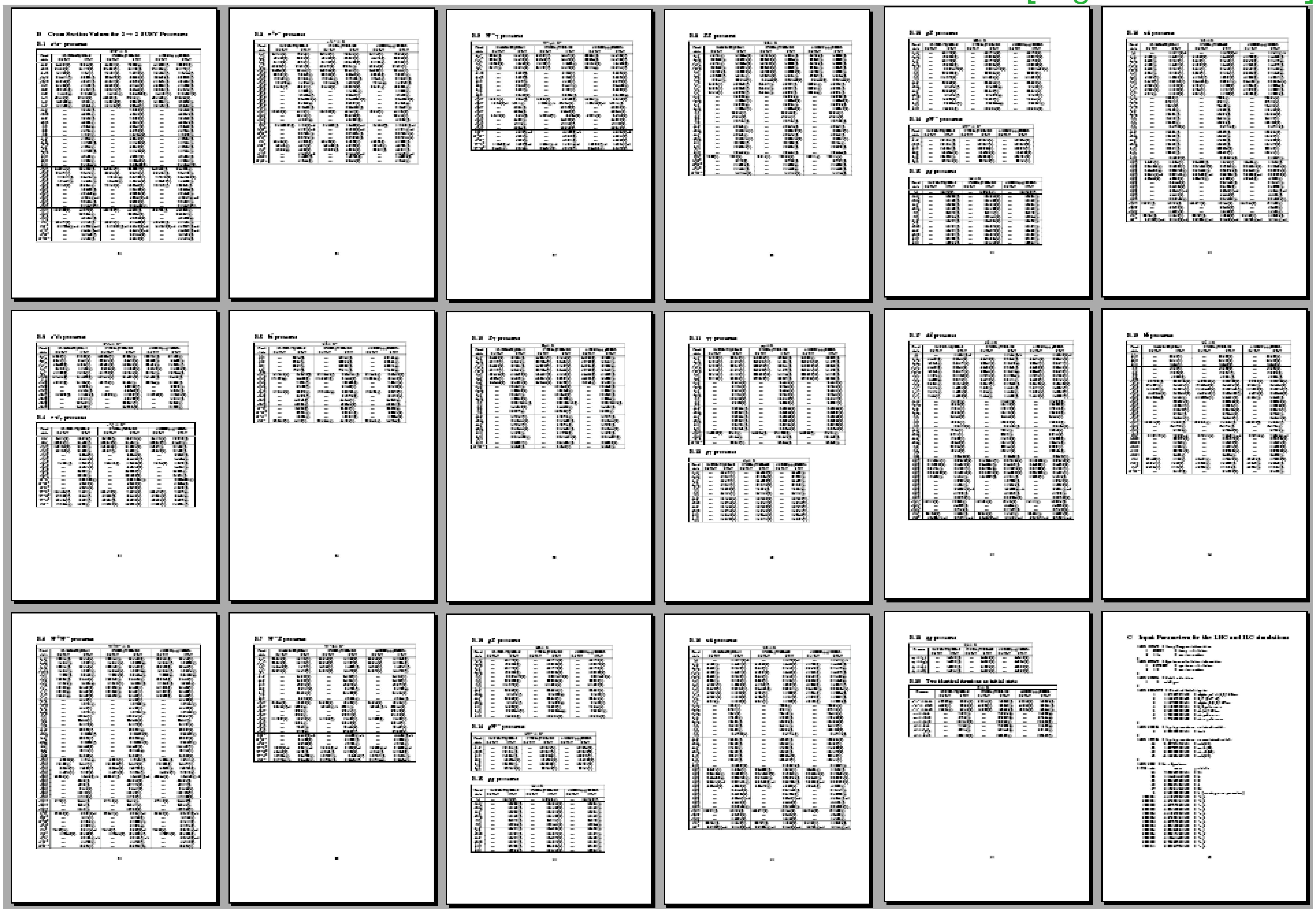
MSSM: SMadGraph

[Hagiwara,Plehn, Rainwater, Stelzer + Alwall]

- CP and R-parity conserving MSSM
- Detailed comparison of cross sections between SMadGraph, Omega and Amegic++ [hep-ph/0512260]
- Available on the Web version of MadEvent.

MadGraph/Sherpa/Whizard SUSY comparison

[Hagiwara et al. 2005]



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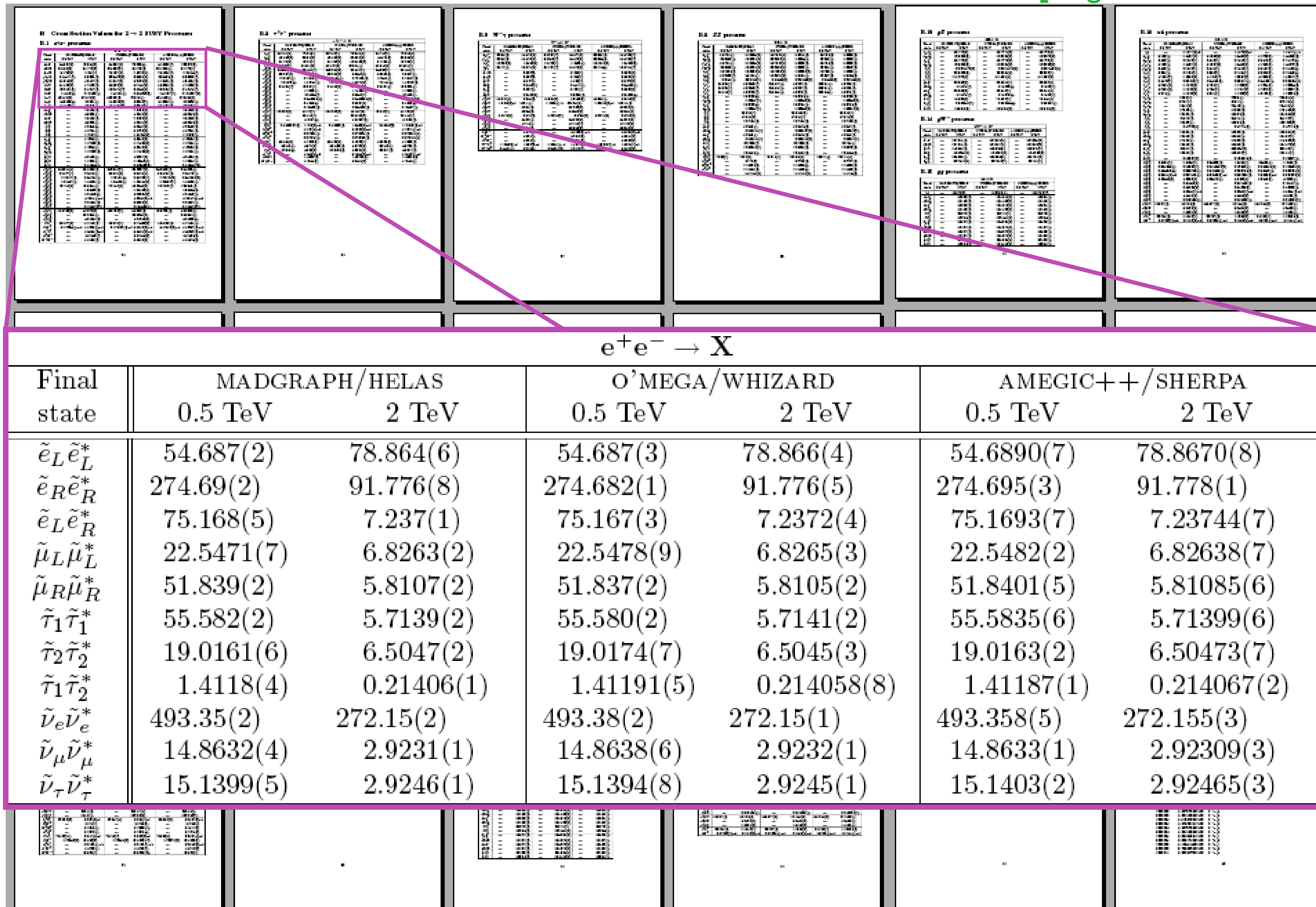
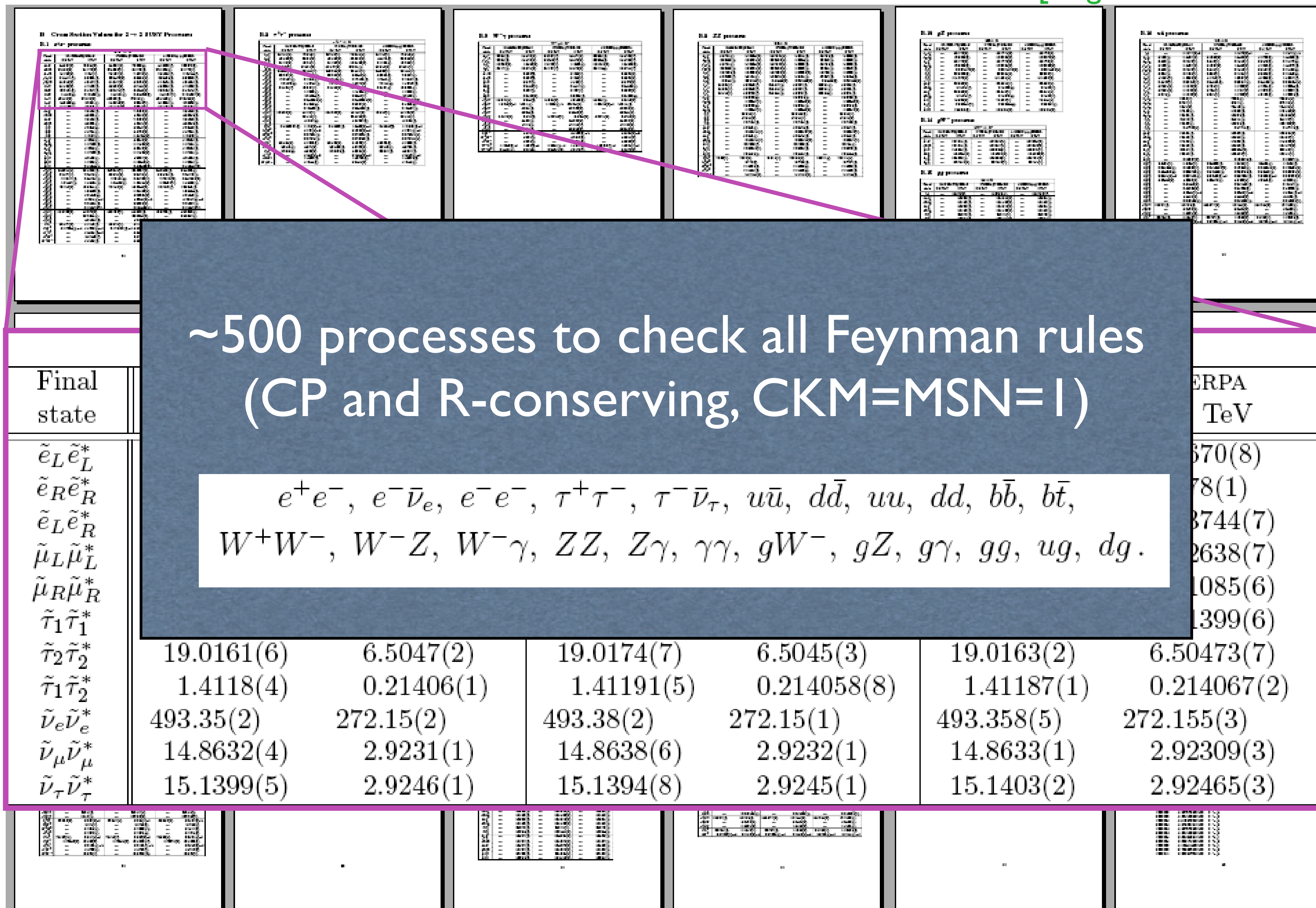


$e^+e^- \to X$						
Final state	MADGRAPH/HELAS 0.5 TeV	MADGRAPH/HELAS 2 TeV	O'MEGA/WHIZARD 0.5 TeV	O'MEGA/WHIZARD 2 TeV	AMEGIC++/SHERPA 0.5 TeV	AMEGIC++/SHERPA 2 TeV
$\tilde{e}_L\tilde{e}_L^*$	54.687(2)	78.864(6)	54.687(3)	78.866(4)	54.6890(7)	78.8670(8)
$\tilde{e}_R\tilde{e}_R^*$	274.69(2)	91.776(8)	274.682(1)	91.776(5)	274.695(3)	91.778(1)
$\tilde{e}_L\tilde{e}_R^*$	75.168(5)	7.237(1)	75.167(3)	7.2372(4)	75.1693(7)	7.23744(7)
$\tilde{\mu}_L\tilde{\mu}_L^*$	22.5471(7)	6.8263(2)	22.5478(9)	6.8265(3)	22.5482(2)	6.82638(7)
$\tilde{\mu}_R\tilde{\mu}_R^*$	51.839(2)	5.8107(2)	51.837(2)	5.8105(2)	51.8401(5)	5.81085(6)
$\tilde{\tau}_1\tilde{\tau}_1^*$	55.582(2)	5.7139(2)	55.580(2)	5.7141(2)	55.5835(6)	5.71399(6)
$\tilde{\tau}_2\tilde{\tau}_2^*$	19.0161(6)	6.5047(2)	19.0174(7)	6.5045(3)	19.0163(2)	6.50473(7)
$\tilde{\tau}_1\tilde{\tau}_2^*$	1.4118(4)	0.21406(1)	1.41191(5)	0.214058(8)	1.41187(1)	0.214067(2)
$\tilde{\nu}_e\tilde{\nu}_e^*$	493.35(2)	272.15(2)	493.38(2)	272.15(1)	493.358(5)	272.155(3)
$\tilde{\nu}_\mu\tilde{\nu}_\mu^*$	14.8632(4)	2.9231(1)	14.8638(6)	2.9232(1)	14.8633(1)	2.92309(3)
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$	15.1399(5)	2.9246(1)	15.1394(8)	2.9245(1)	15.1403(2)	2.92465(3)

MadGraph/Sherpa/Whizard SUSY comparison

[Hagiwara et al. 2005]



~500 processes to check all Feynman rules (CP and R-conserving, CKM=MSN=1)

$$e^+e^-,\ e^-\bar{\nu}_e,\ e^-e^-,\ \tau^+\tau^-,\ \tau^-\bar{\nu}_\tau,\ u\bar{u},\ d\bar{d},\ uu,\ dd,\ b\bar{b},\ b\bar{t},$$
$$W^+W^-,\ W^-Z,\ W^-\gamma,\ ZZ,\ Z\gamma,\ \gamma\gamma,\ gW^-,\ gZ,\ g\gamma,\ gg,\ ug,\ dg\,.$$

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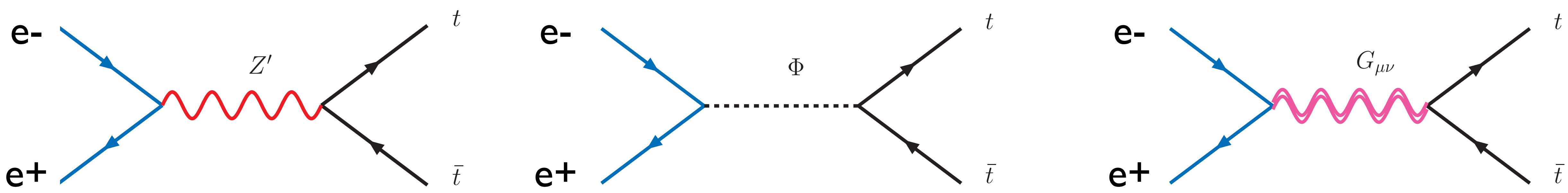
Example #2: New resonances

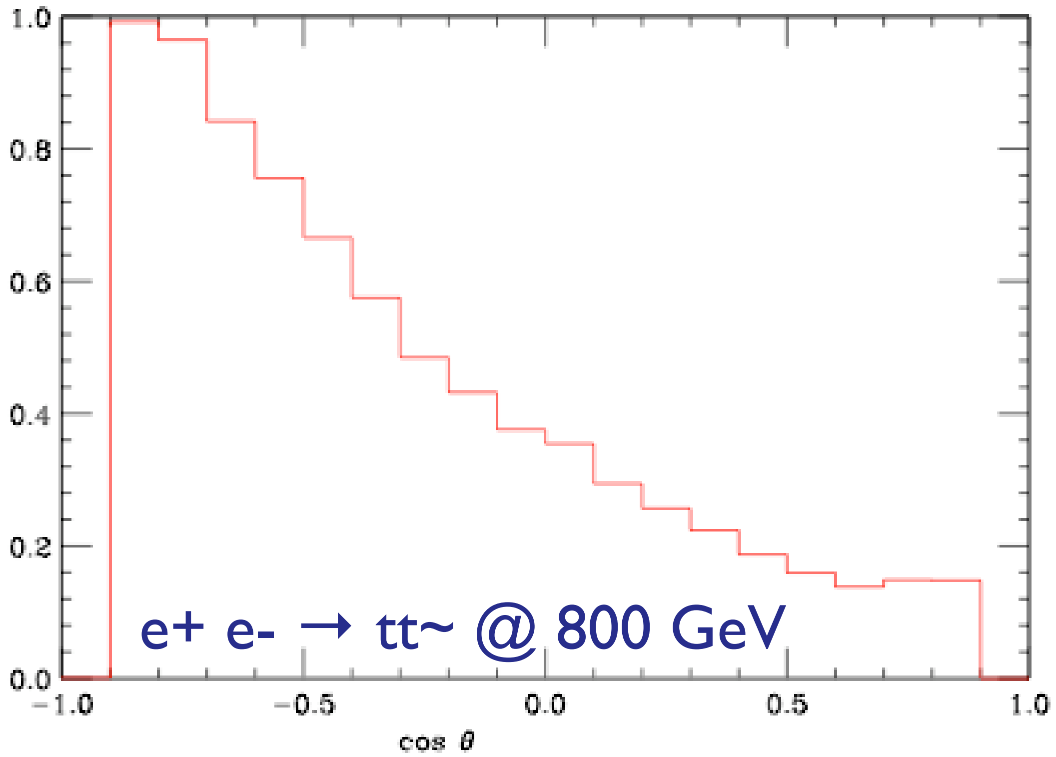
[R. Frederix, FM, LHC work in progress]

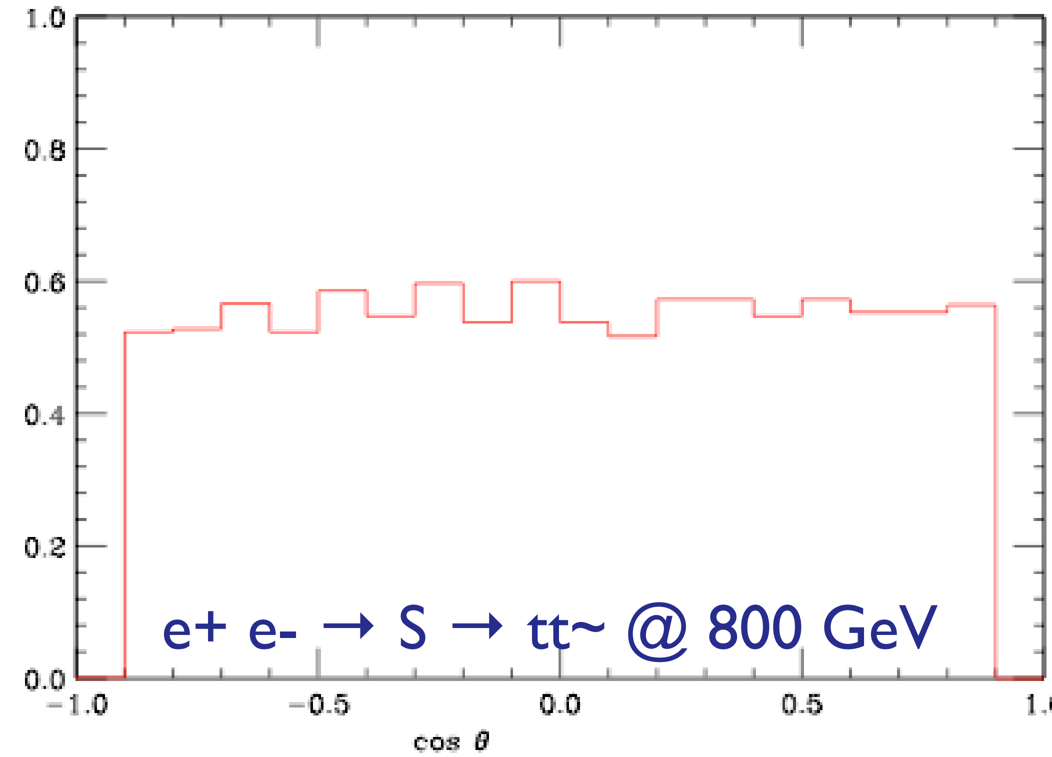


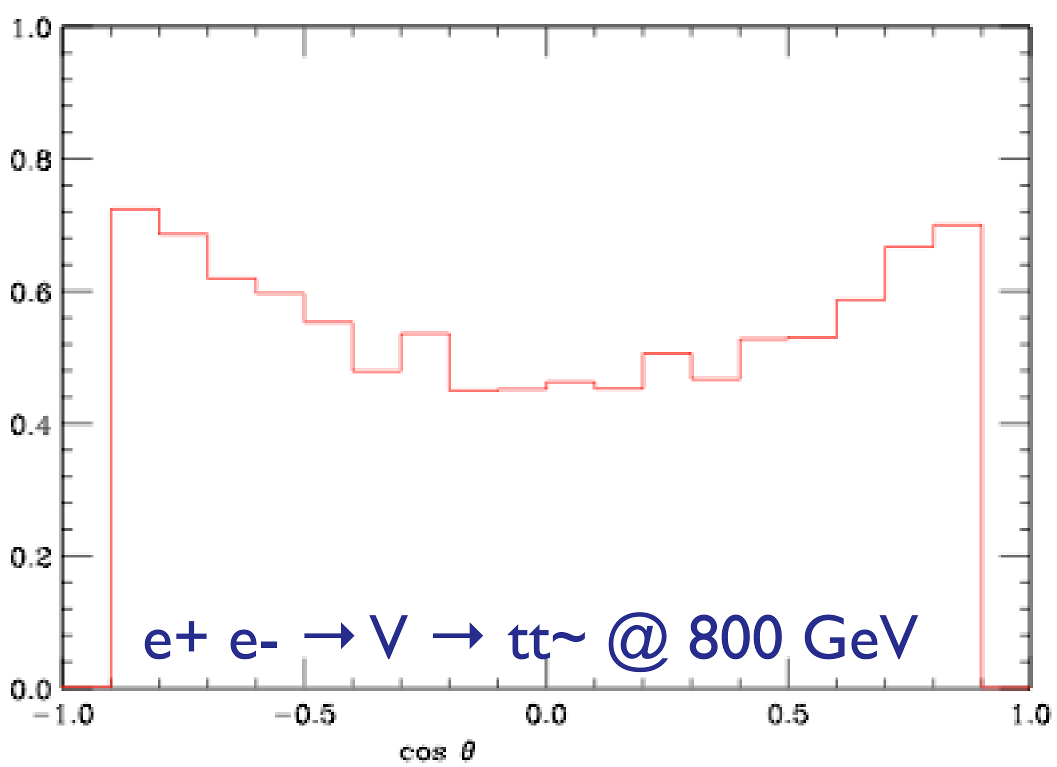
How to extract the spin information about the resonance?

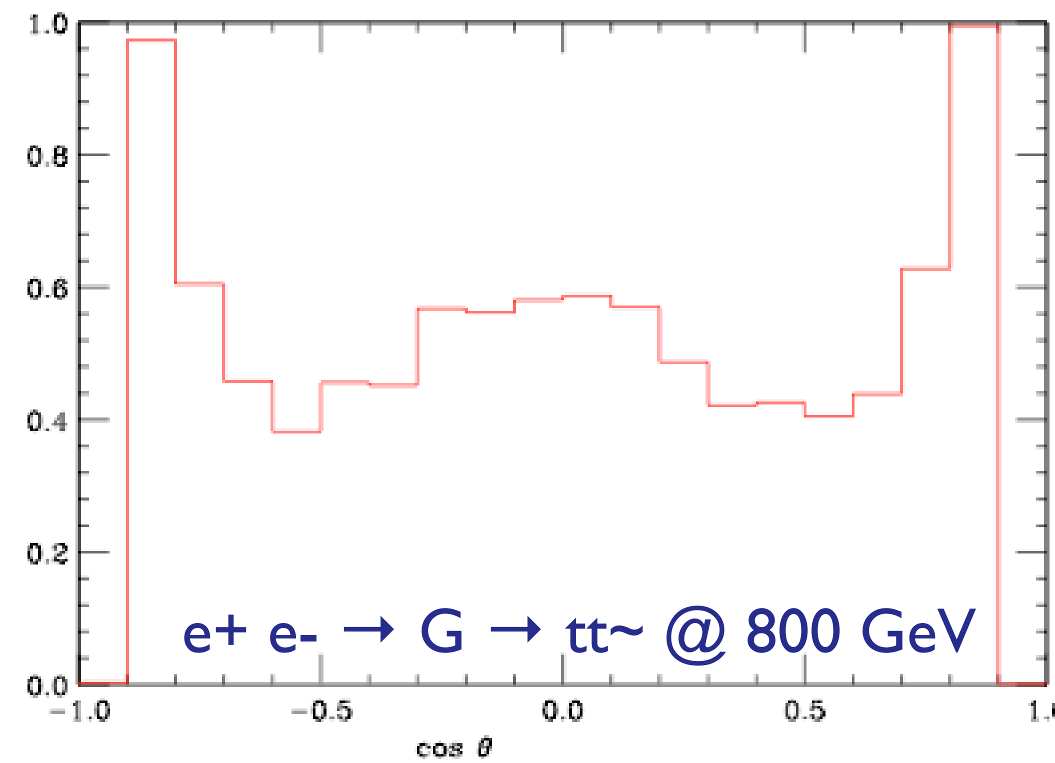
First look at the t tbar distributions!
(No need of sophisticated tools, both TH and EXP)

Example #2: New resonances









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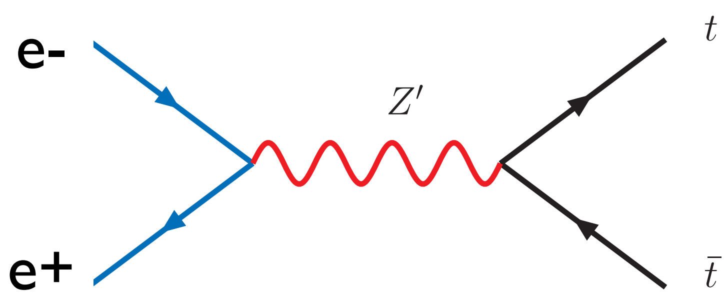
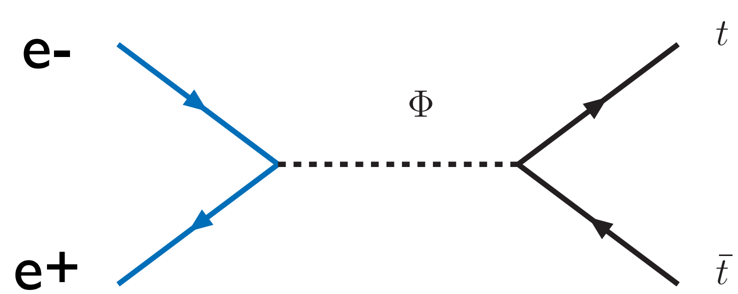
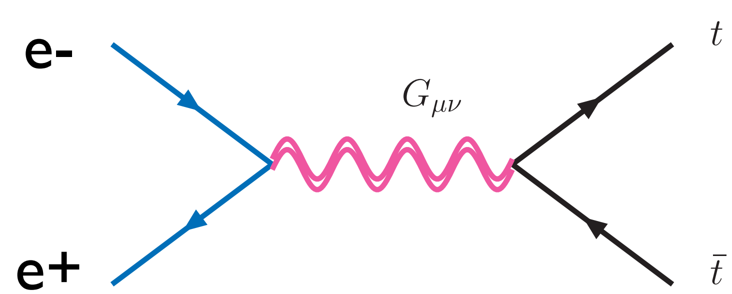
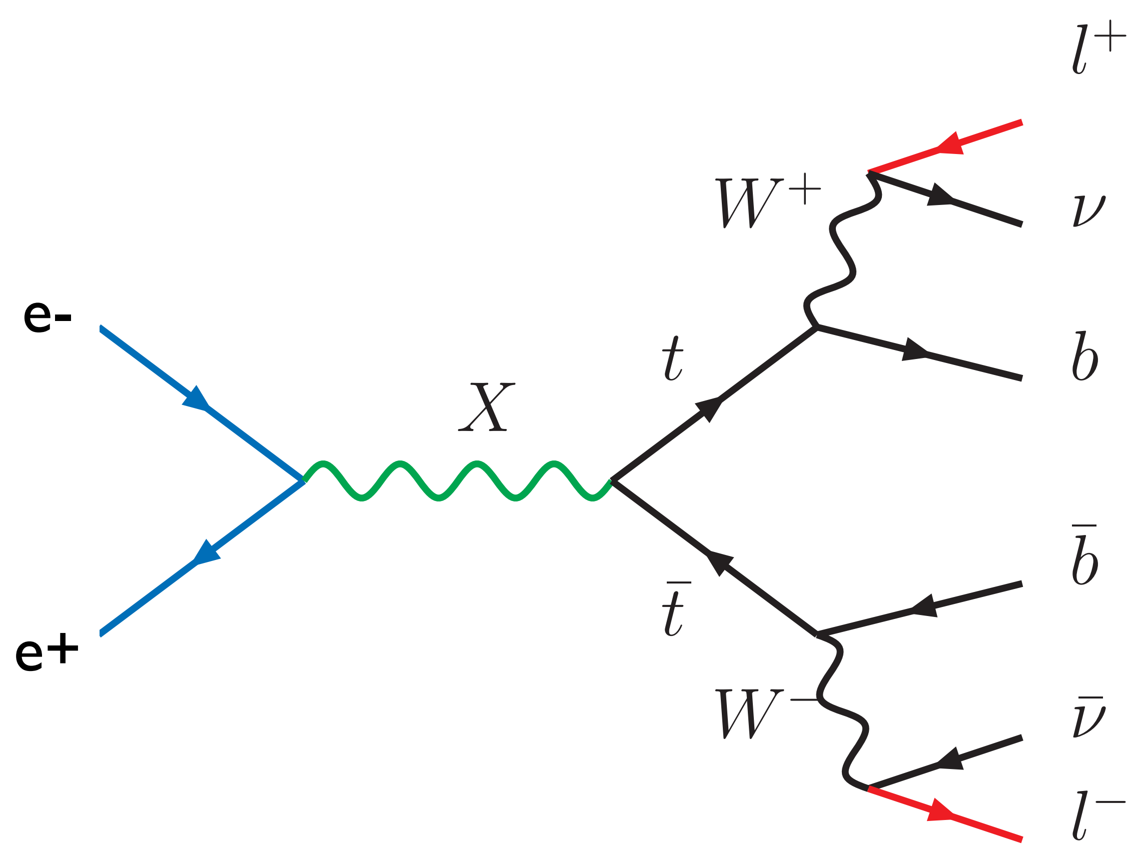


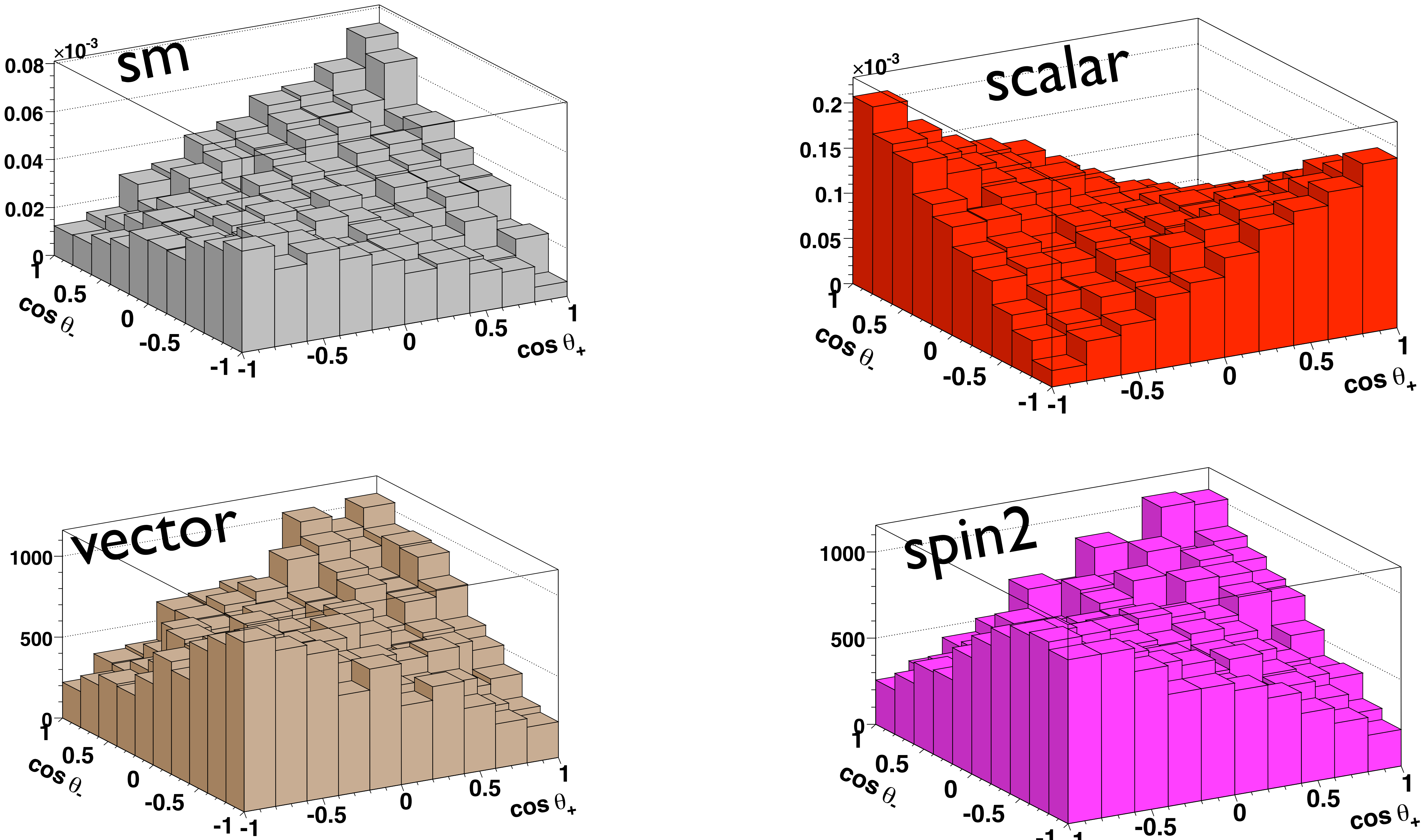




To gain information about the couplings structure use angular correlations between the leptons!



Example #2: Resonances



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + \kappa_t \kappa_{\bar{t}} D \cos\theta_- \cos\theta_+\right)$$

Example #2

Take a paper that looks interesting:

Determining the CP properties of the Higgs boson

P.S. Bhupal Dev,[1] A. Djouadi,[2] R.M. Godbole,[1] M.M. Mühlleitner,[3] and S.D. Rindani[4]

[1] *Center for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India.*
[2] *Laboratoire de Physique Théorique, U. Paris–Sud and CNRS, F–91405 Orsay, France.*
[3] *Theory Division, Department of Physics, CERN, CH-1211 Geneva 23, Switzerland.*
Laboratoire de Physique Théorique, LAPTH, F–74941 Annecy-le-Vieux, France.
[4] *Theoretical Physics Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India.*

The search and the probe of the fundamental properties of Higgs boson(s) and, in particular, the determination of their charge conjugation and parity (CP) quantum numbers, is one of the main tasks of future high-energy colliders. We demonstrate that the CP properties of a Standard Model-like Higgs particle can be unambiguously assessed by measuring just the total cross section and the top polarization in associated Higgs production with top quark pairs in e^+e^- collisions.

0707.2878 [hep-ph]

and check if it is interesting
for you (at the TH or EXP level)

Example #2

Implement and test the model:

$$g_{\Phi tt} = -i\frac{e}{s_W}\frac{m_t}{2M_W}(a + ib\gamma_5) \qquad (1)$$

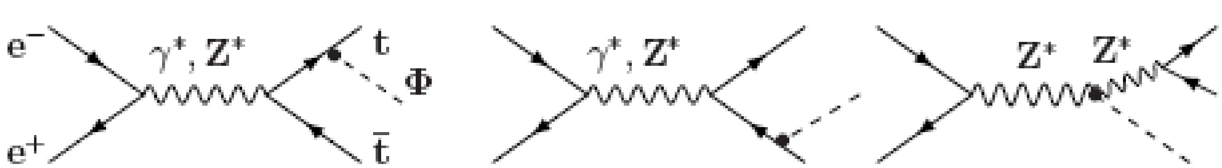
$$g^{\mu\nu}_{ZZ\Phi} = -ic(eM_Z/s_W c_W)g^{\mu\nu}$$

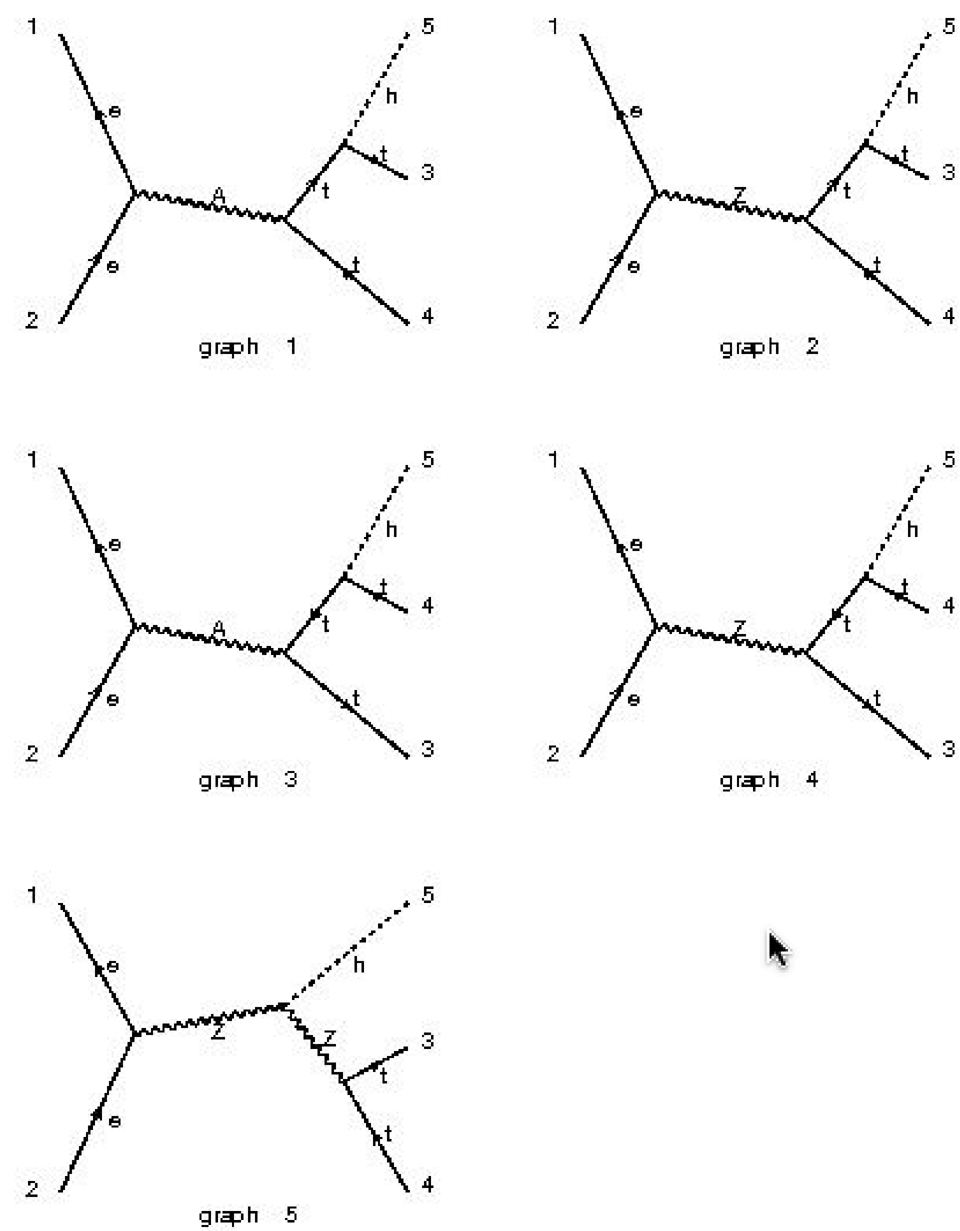
```
c***********************************
c UserMode couplings
c***********************************
c
c      change the couplings to the top
c
      a_cp=dsqrt(1d0-b_cp**2)
      c_cp=a_cp

         ghtop(1) = -mtMS/v*dcmplx(a_cp,-b_cp)
         ghtop(2) = -mtMS/v*dcmplx(a_cp, b_cp)
c
c     change the couplings to the Z
c
         gzzh  = c_cp*dcmplx( ee2/sc2*Half*v, Zero )
```

Notes: Perl scripts avoid fortran handling.
Full automatization from Lagrangian formulation (in Mathematica) being tested.

Example #2

Generate the process:
e+e- > tt~h
Check the Feynman diagrams:

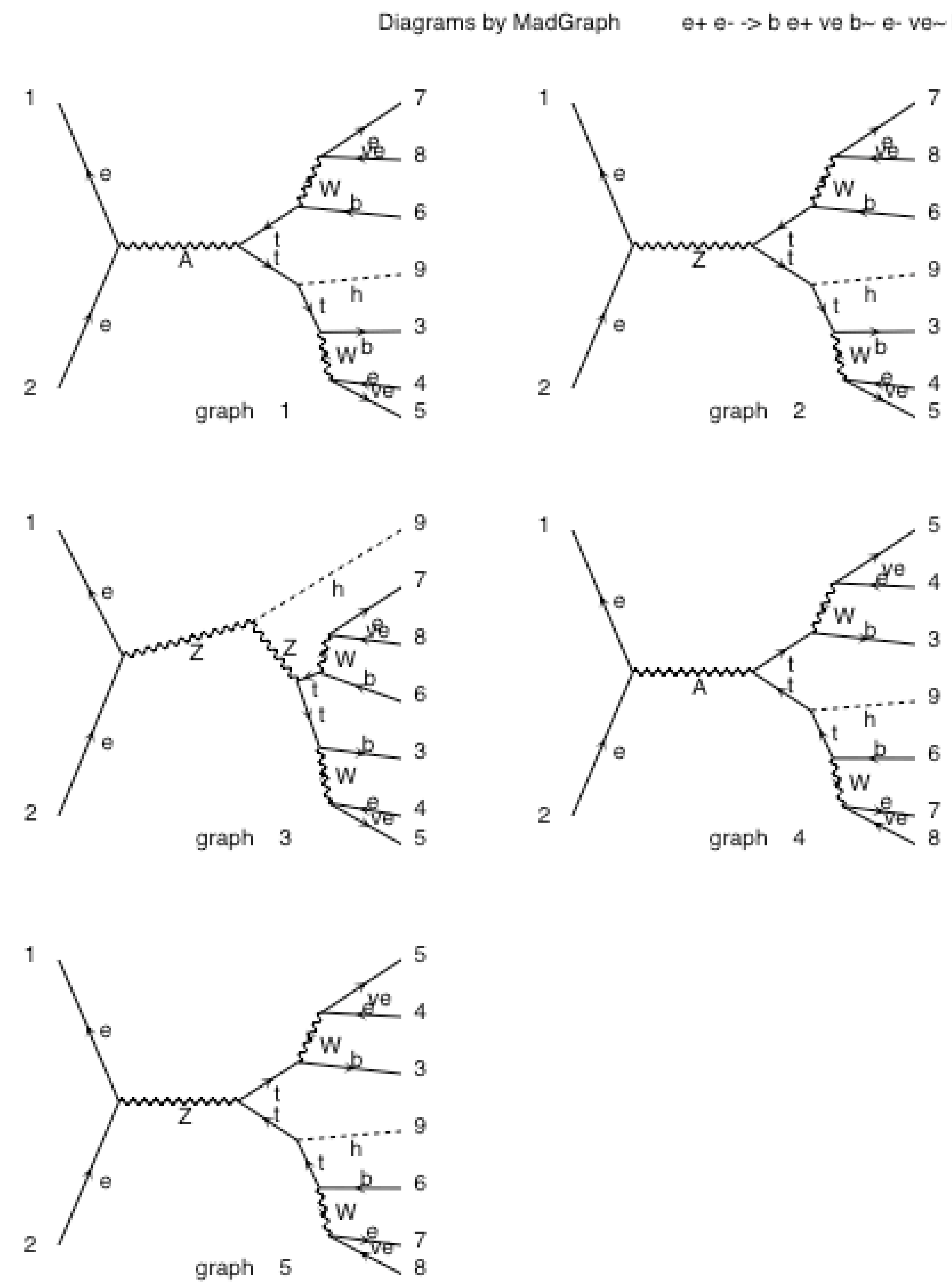




Example #2

Should we include the full matrix element with spin correlations?

We have calculated the cross section for the production of a mixed CP Higgs state in the process $e^+e^- \rightarrow t\bar{t}\Phi$, including the polarization dependence of the final state top quarks, using two independent methods: the helicity method in which the amplitudes are derived using the explicit form of the spinors and the Bouchiat–Michel method [21] in which the squared amplitudes are calculated with the trace technique. The lengthy results will be given elsewhere [22] and, for the unpolarized total cross section, they agree with those given in Ref. [18].



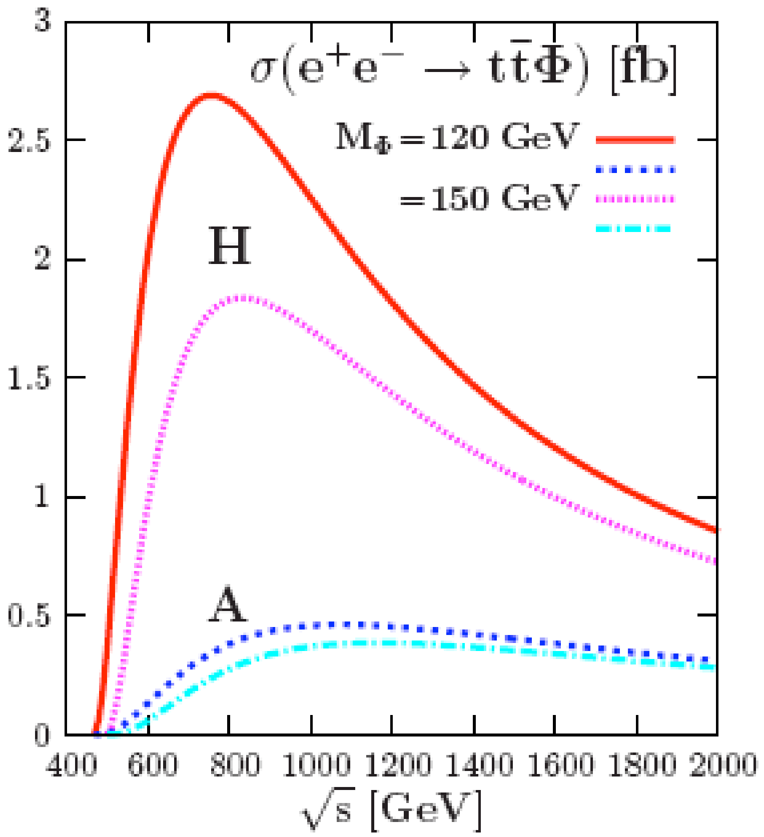
Let's include the decays but only the relevant diagrams (decay chains)

e+e- > (t>b e+ ve) (t~ > b~ e- ve~)h

Check the Feynman diagrams:

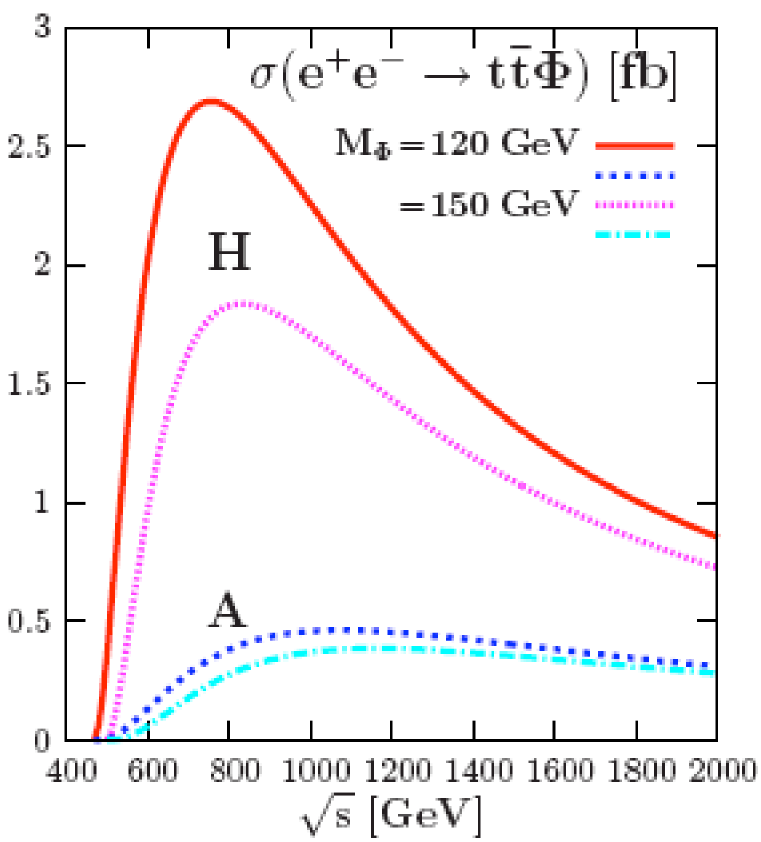
Example #2

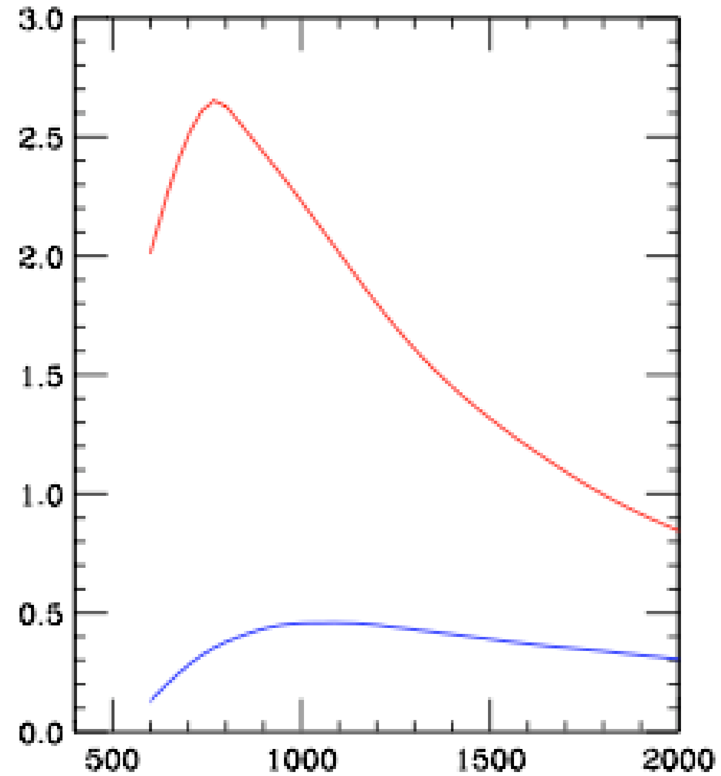
Run the code and reproduce the key plots:



Example #2

Run the code and reproduce the key plots:

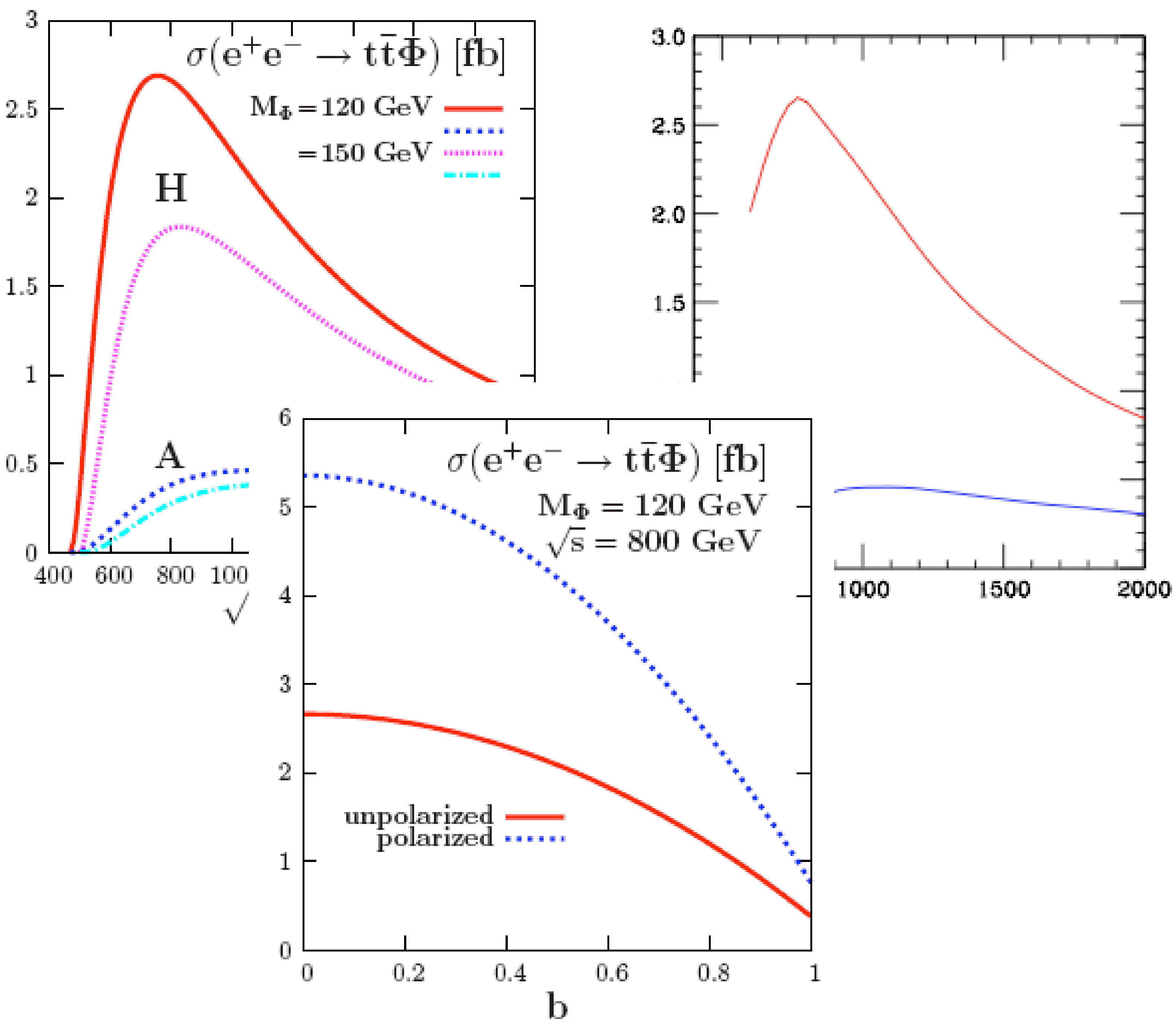




✓

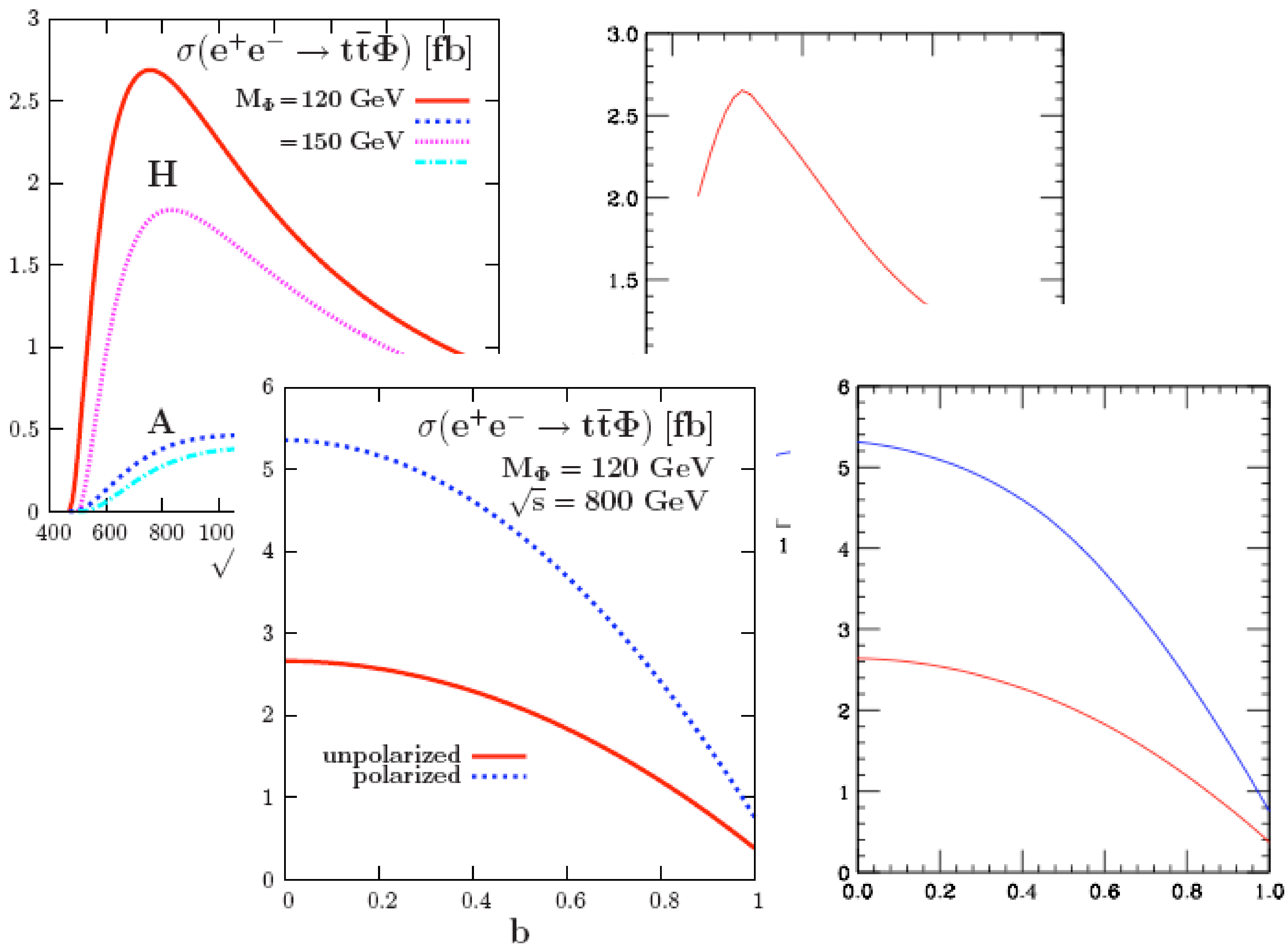
Example #2

Run the code and reproduce the key plots:



Example #2

Run the code and reproduce the key plots:

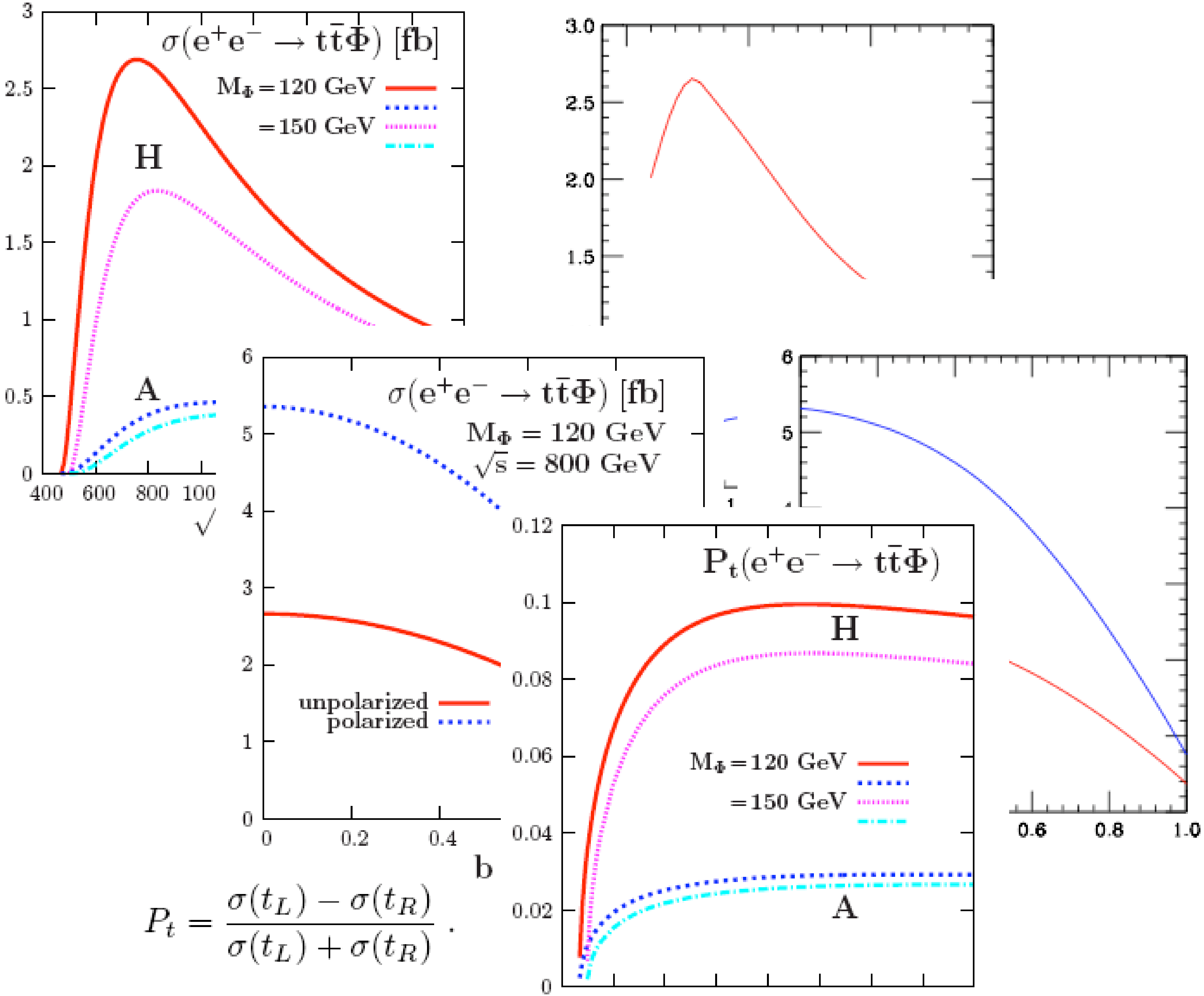


✓

New MG/ME feature: polarized beam option

Example #2

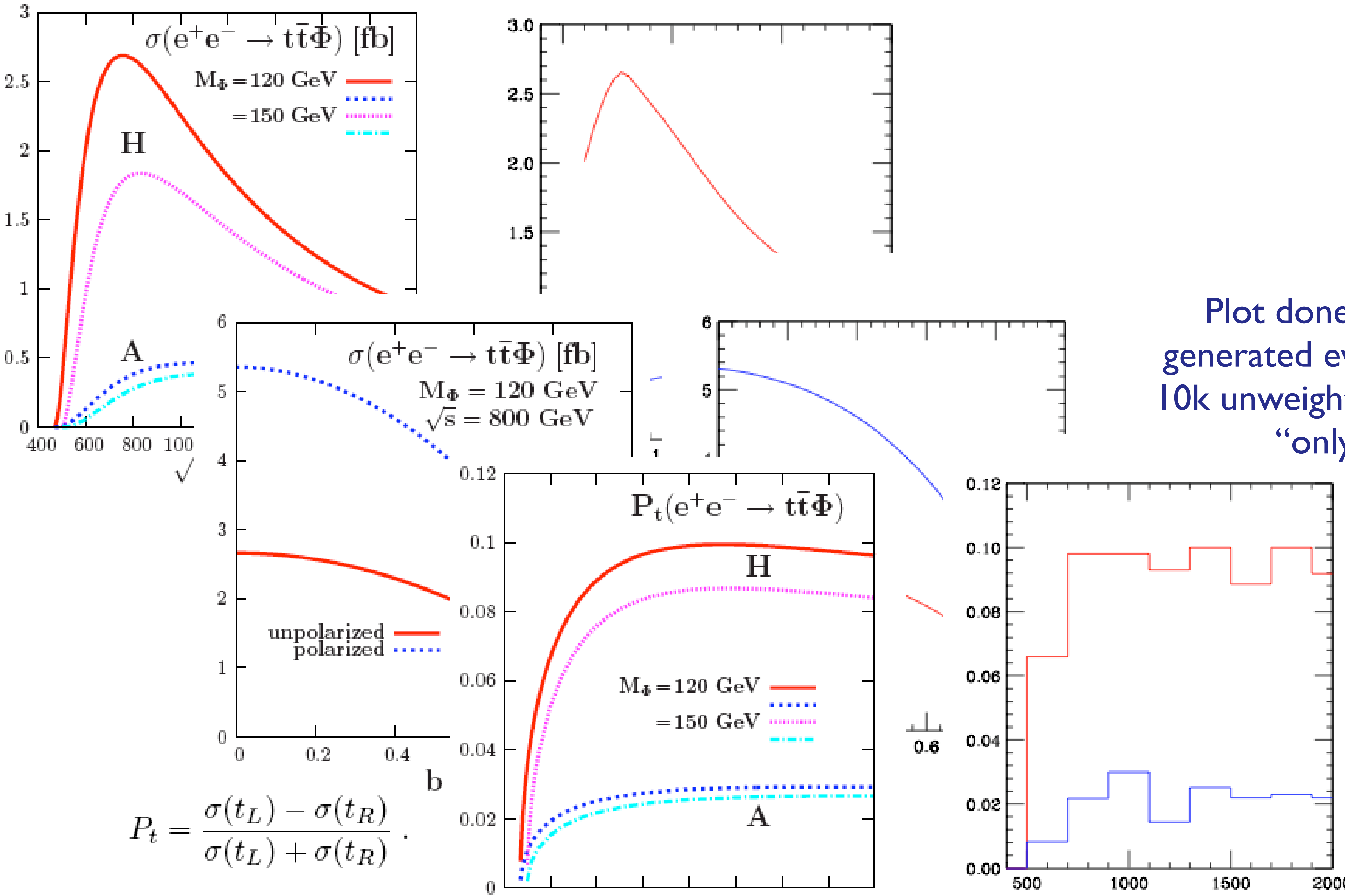
Run the code and reproduce the key plots:



$$P_t = \frac{\sigma(t_L) - \sigma(t_R)}{\sigma(t_L) + \sigma(t_R)} \, .$$

Example #2

Run the code and reproduce the key plots:



$$P_t = \frac{\sigma(t_L) - \sigma(t_R)}{\sigma(t_L) + \sigma(t_R)} .$$

Plot done at the generated event level: 10k unweighted events "only".

✓

Example #2

Let’s have a look at one of the 10k unweighted parton level events:

```
<event>
13 661  0.7523000E-09  0.9118800E+02  0.7818608E-02  0.1180000E+00
     -11    -1     0     0     0     0  0.00000000000E+00  0.00000000000E+00  0.40000000000E+03  0.40000000000E+03  0.00000000000E+00 0.   1.
      11    -1     0     0     0     0  0.00000000000E+00  0.00000000000E+00 -0.40000000000E+03  0.40000000000E+03  0.00000000000E+00 0.  -1.
      -6     2     1     2     0   501  0.21576819504E+02  0.11742807515E+03  0.17907989202E+03  0.27523353730E+03  0.17154876961E+03 0.   0.
       6     2     1     2   501     0  0.37313006430E+02 -0.17247266251E+03  0.50240395029E+02  0.25368398033E+03  0.17519242227E+03 0.   0.
     -24     2     3     3     0     0  0.23809114735E+02  0.19536706953E+00  0.10979342295E+03  0.13897369075E+03  0.81805738706E+02 0.   0.
      24     2     4     4     0     0 -0.41620642890E+02 -0.80858637691E+02 -0.16877548962E+01  0.12201081187E+03  0.81322767362E+02 0.   0.
       5     1     4     4   501     0  0.78933649321E+02 -0.91614024814E+02  0.51928149925E+02  0.13167316846E+03  0.42000000000E+01 0.  -1.
     -11     1     6     6     0     0  0.17720954129E+02 -0.42672282303E+02 -0.17992624359E+02  0.49585183508E+02  0.00000000000E+00 0.   1.
      12     1     6     6     0     0 -0.59341597020E+02 -0.38186355389E+02  0.16304869463E+02  0.72425628357E+02  0.00000000000E+00 0.  -1.
      -5     1     3     3     0   501 -0.22322952315E+01  0.11723270808E+03  0.69286469074E+02  0.13625984655E+03  0.42000000000E+01 0.   1.
      11     1     5     5     0     0  0.23715730964E+02 -0.70970007411E+01 -0.38882144588E+01  0.25058362403E+02  0.00000000000E+00 0.  -1.
     -12     1     5     5     0     0  0.93383771988E-01  0.72923678106E+01  0.11368163741E+03  0.11391532835E+03  0.00000000000E+00 0.   1.
      25     1     1     2     0     0 -0.58889825935E+02  0.55044587357E+02 -0.22932028705E+03  0.27108248237E+03  0.12000000000E+03 0.  -1.
</event>
```

* spin, color, 4-momenta, masses.

* correct mother-daughter information

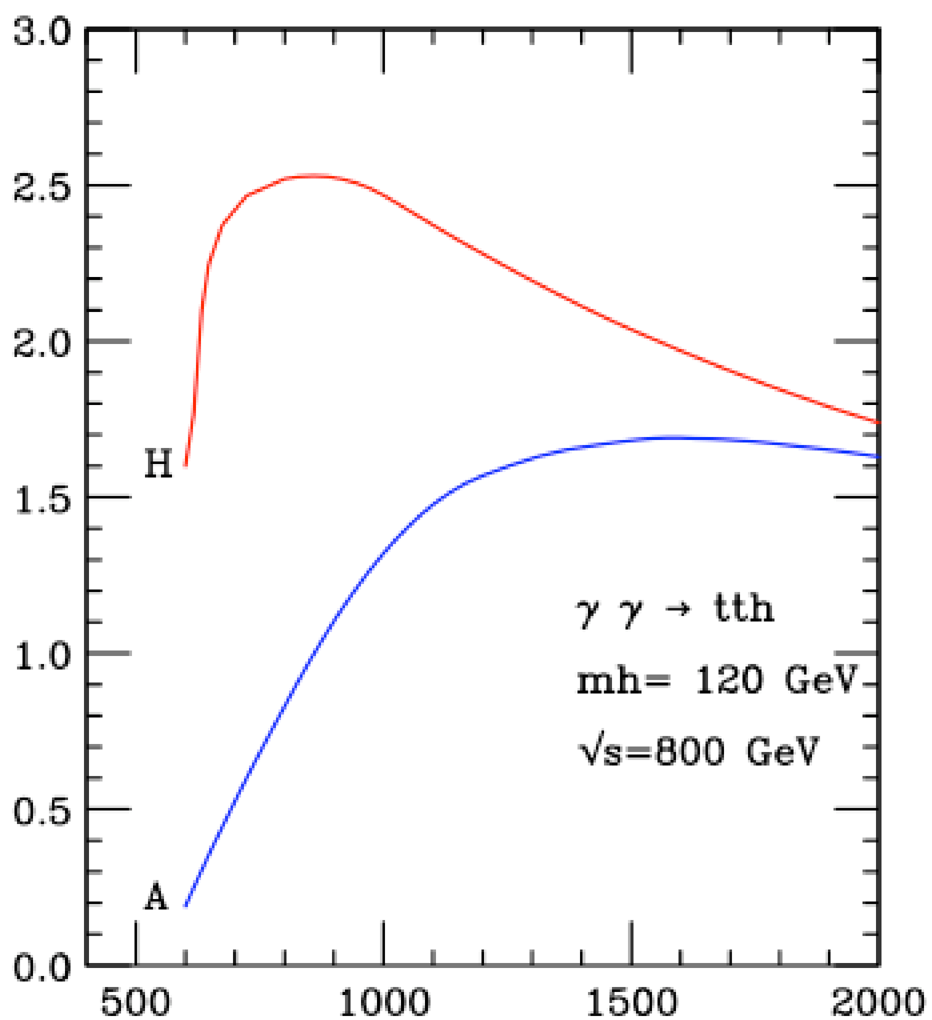
* ready to be passed to Pythia (automatic) or Herwig for decays, showering and hadronization.

* ready for further experimental analysis

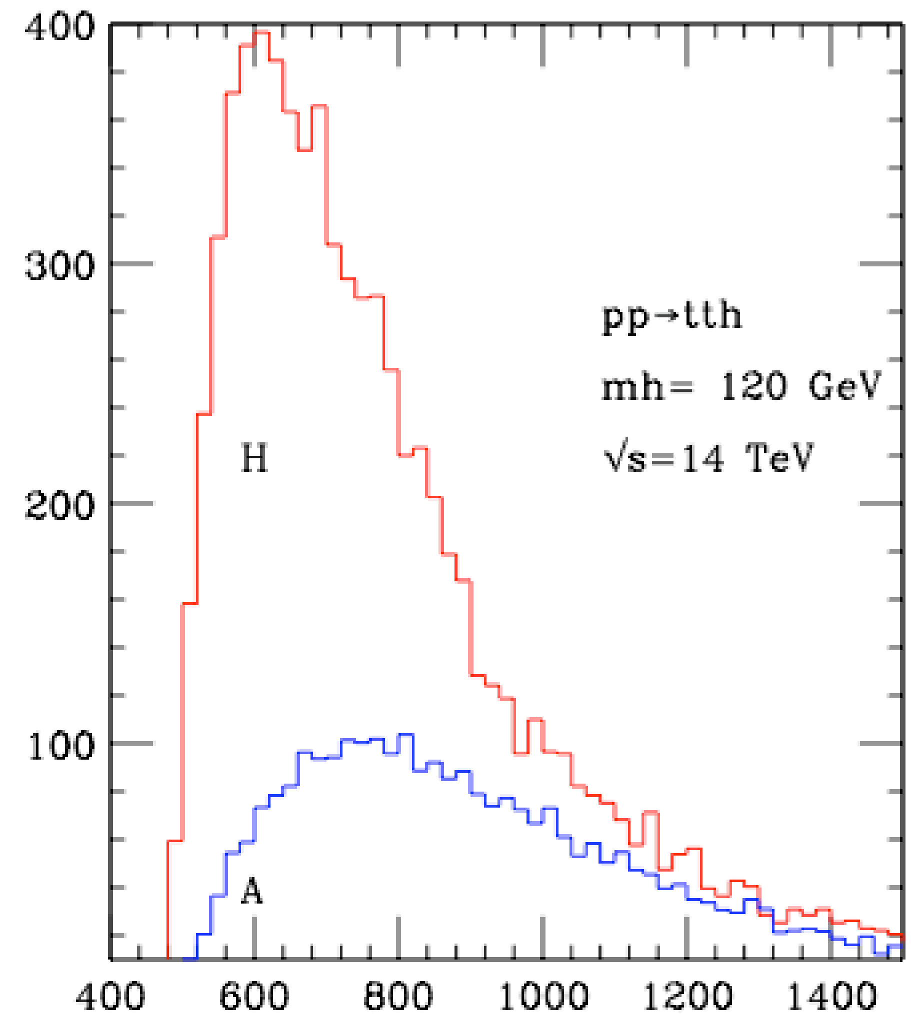
Example #2

Go beyond? new ideas?:

aa > tt~h



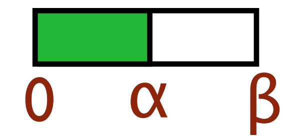
pp > tt~h



Total elapsed time: an afternoon (including coffee breaks)

Bottom line: quick path from ideas to results/exp analysis!

R&D



- ✦ Mathematica based program to extract Feynman rules and couplings directly from the Lagrangian (Compatible w/ FeynArts)[C. Duhr]
- ✦ Specify complete decay chain without computing all diagrams, especially useful for very rich multi-particle final states [J. Alwall & T. Stelzer]
- ✦ Matrix element techniques in analysis [P. Artoisenet & O. Mattelaer]
- ✦ Tools for e+e- : Polarization, energy smearing, energy scans, matching [J. Alwall]
- ✦ Grid version

Community contributions:

* BRIDGE, a program to calculate widths and decays unstable particles in any model [P. Meade & M. Reece] http://www.lns.cornell.edu/public/theory/BRIDGE/
* New models being developed on "daily" basis.

Conclusions

- MadGraph/MadEvent is:
  - Multi purpose: any new signal & backgrounds in one framework
  - Complete simulation chain: interfaces from model to detector simulation
  - User friendly: Mac's philosophy
  - Parallel: cluster (..grid!) oriented structure
  - Open: Source code always available, >1500 registered users and many contributors, help and feedback always welcome.

http://madgraph.hep.uiuc.edu