Recent developments in MadGraph/MadEvent

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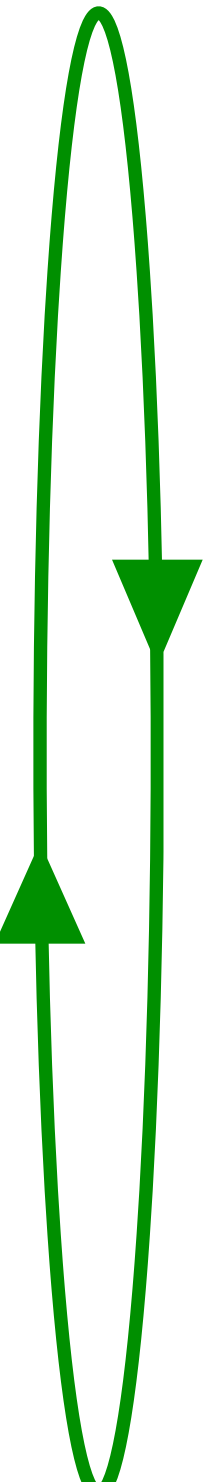
+ Steve Mrenna, Tilman Plehn, David L. Rainwater,
+ Pierre Artoisenet, Claude Duhr, Olivier Mattelaer, ...

+ OUR GOLDEN USERS!!

Motivation:
Minimal strategy for BSM physics



- Find excess(es) over SM background

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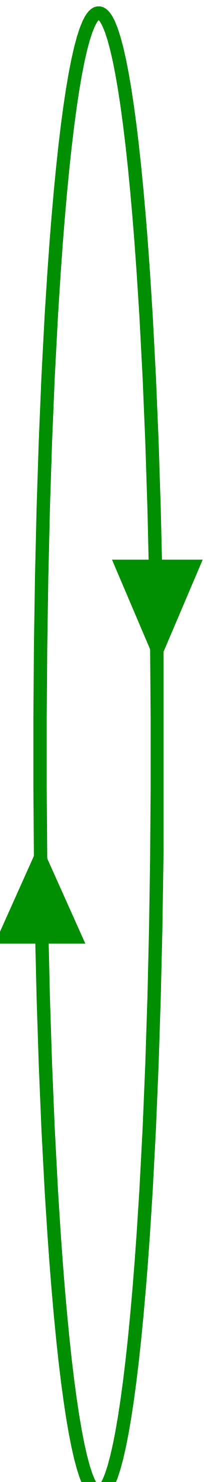

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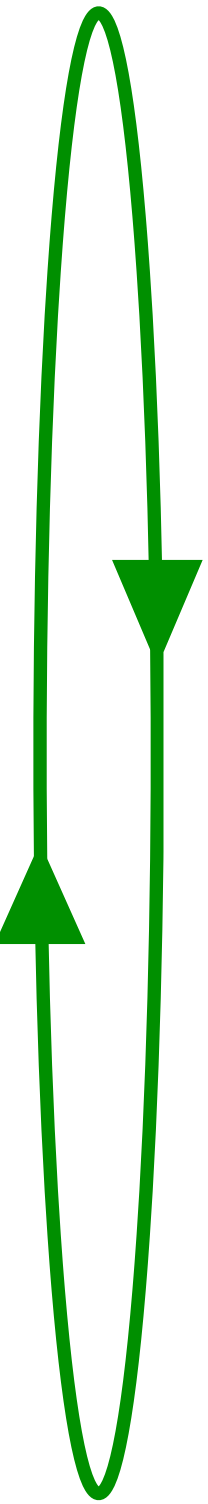

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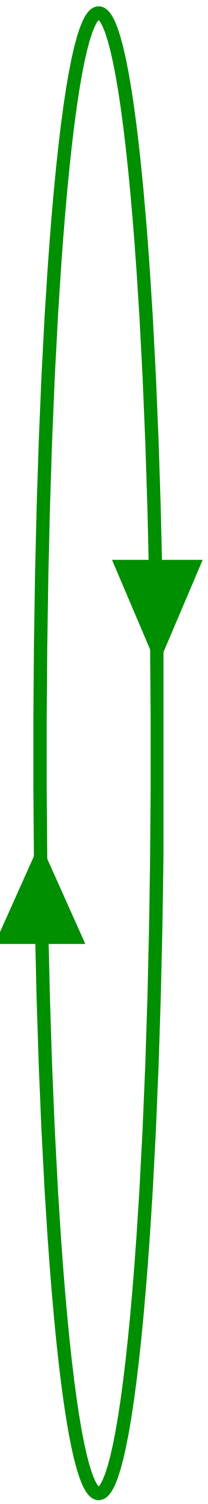

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MadGraph/MadEvent

What is MadGraph/MadEvent?

- MG/MEv4 is a user-driven, matrix element based, tree-level event generator
- Both for SM as well as BSM
- Web server interface from which the simulation itself can be done on-line or off-line
- With MG/ME and its tools/interfaces, the full simulation chain from hard scale physics to detector simulation is available within one framework

The MG/ME philosophy

- Fill the gap between theorists and experimentalists
  - Easy to implement new models
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  - Signal but also multi-particle backgrounds

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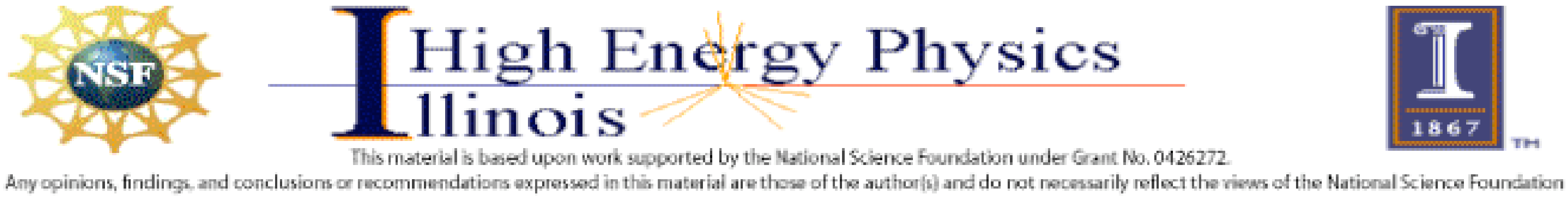
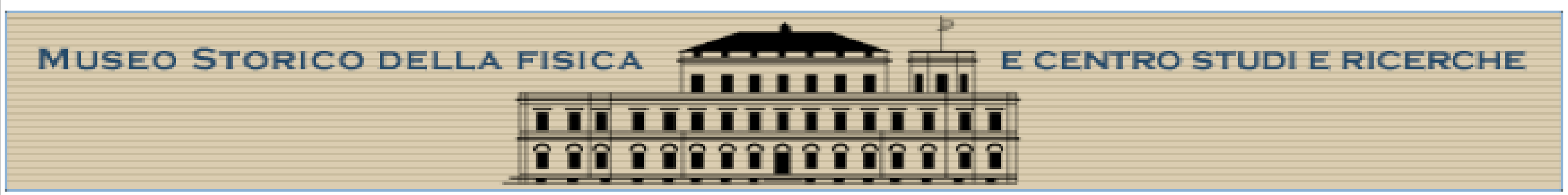
- Web based event generation
  - Code runs in parallel on our farms
  - Centralized maintenance
  - Personal process database for each user

MadGraph on the Web

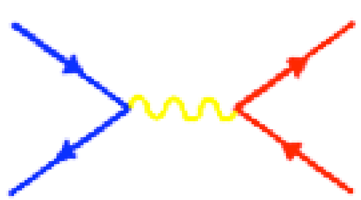


http://madgraph.hep.uiuc.edu/

http://madgraph.phys.ucl.ac.be/



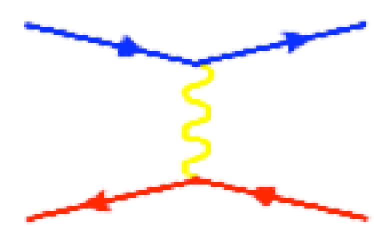
http://madgraph.roma2.infn.it/



MadGraph Version 4

UCL UIUC Fermi

by the MG/ME Development team

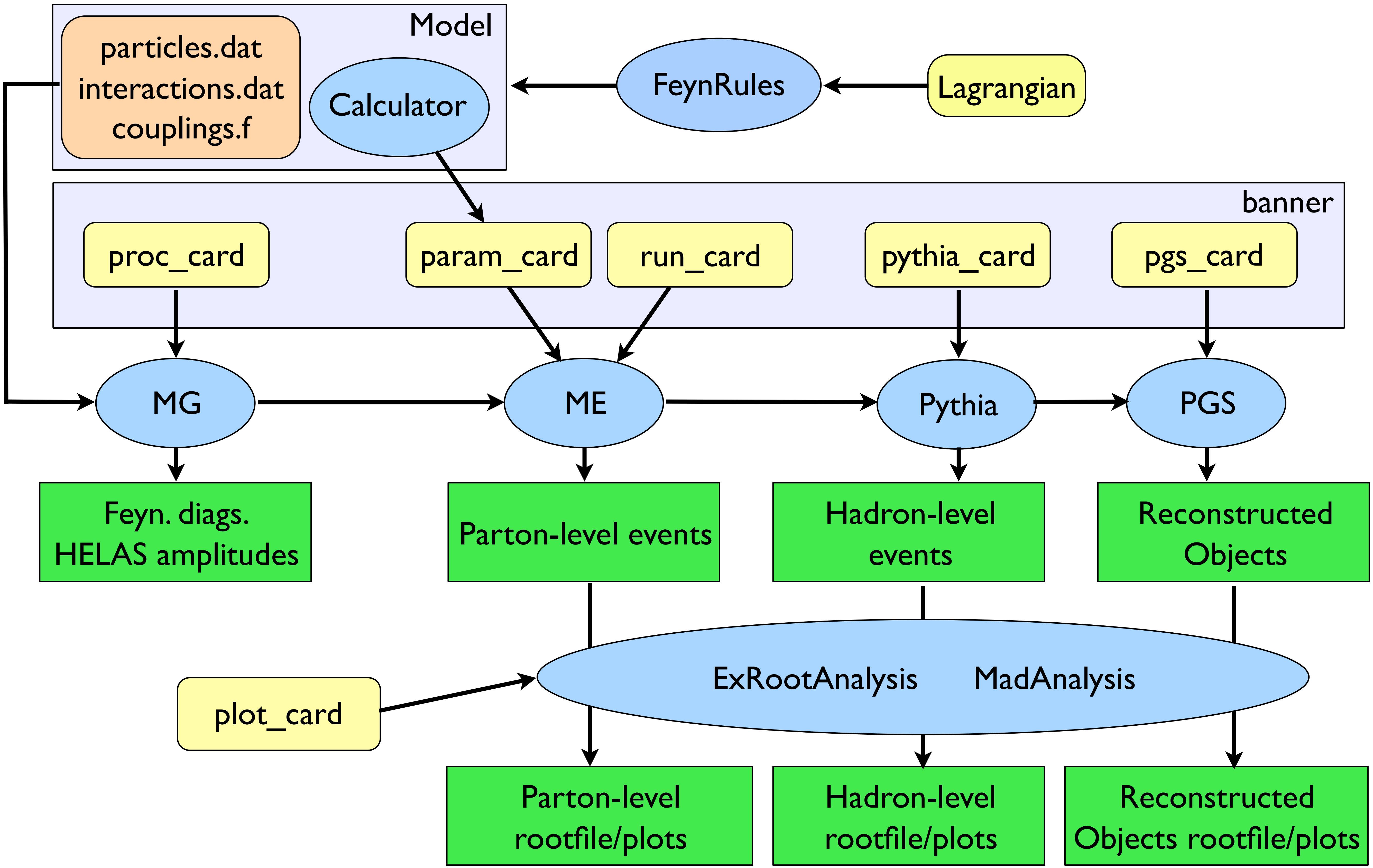


Generate Process | Register | Tools | My Database | Cluster Status | Downloads (needs registration) | Wiki/Docs | Admin

Three medium size clusters public access (+1 private cluster). ~1500 registered users.

Thanks to: D. Lesny, L. Nelson (UIUC), F. Chalier, T. Keutgen (UCL), R. Ammendola, N. Tantalo (RM2)

MG/ME flow chart



Features

- Complete web simulation: MadEvent → Pythia → PGS, with personal web databases
- Multi-processes in single code & generation
- Standalone version for theorists
- New complete models: SM, HEFT, MSSM, 2HDM, TopBSM
- Easy new model implementation: USRMOD & interface to FeynRules
- Les Houches Accord (LHEF) for parton-level event files & Les Houches Accord 2 for model parameters
- Merging w/ Parton Showers (k_T a la MLM) w/ Pythia
- Decay chains specifications
- Decay width calculator
- Analysis platforms: ExRootAnalysis, MadAnalysis and MatchChecker

Outline: recent developments

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Matching ME with PS & GRID use

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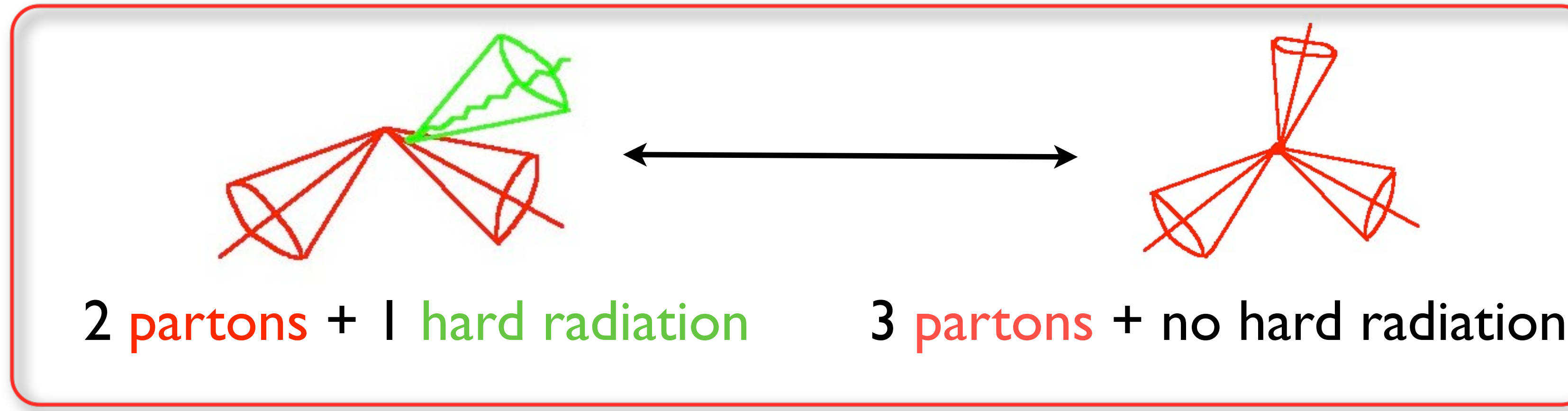
ME-PS complimentarity

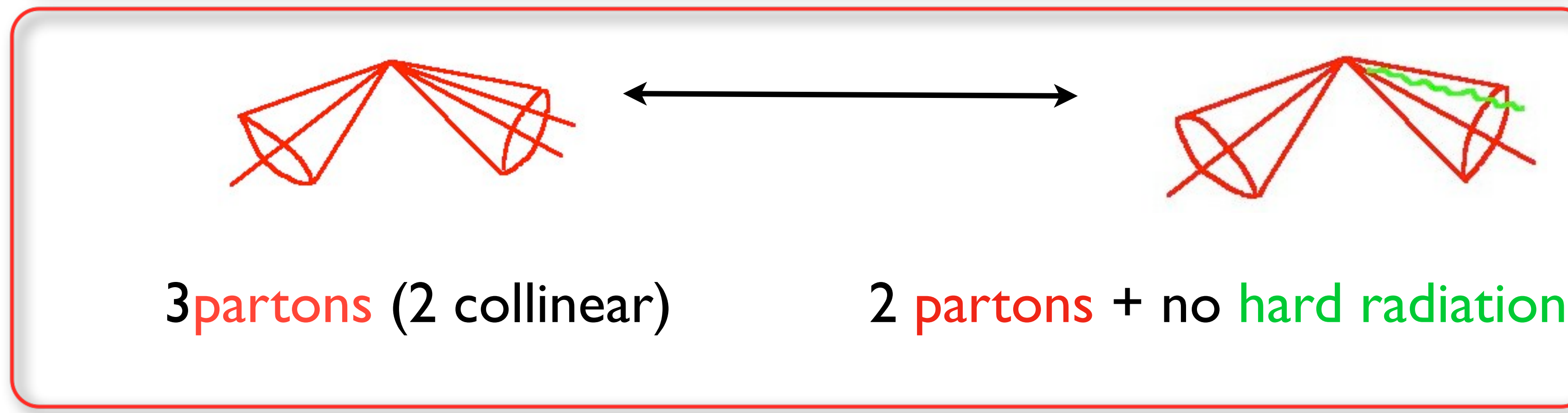
Matrix Elements	Parton Shower
Fixed order calculation	Resums large logarithms
Computationally expensive	Computationally cheap
Limited number of particles	No limit on # of particles
Valid when partons are well-separated	Valid when partons are collinear and/or soft
Quantum interference correct	Quantum interference through angular ordering
Needed for multi-jet description	Needed hadronization/ detector simulation

Complimentary, but we need to avoid double counting!

Solution to double counting

- To avoid overlap one parton has to give one jet (except for highest multiplicity)
- To classes of solutions available: CKKW and MLM.





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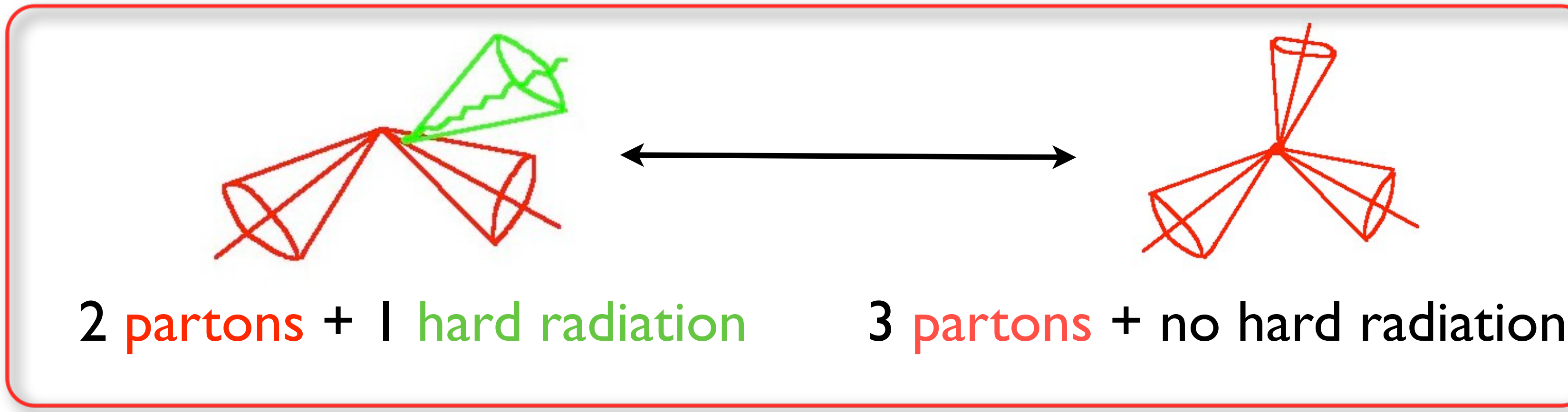
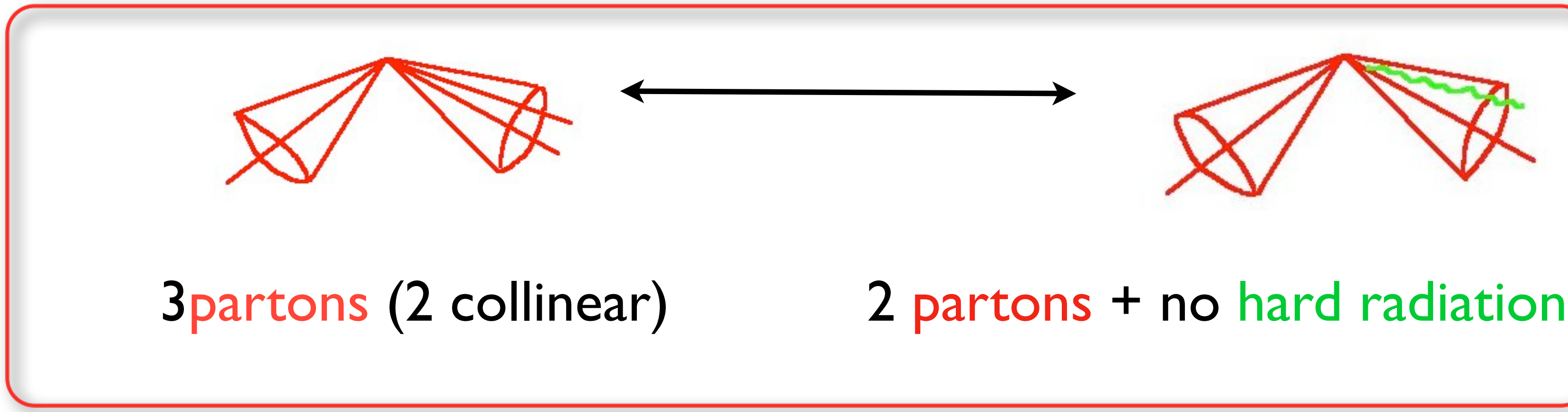




CKKW (reweighting method):

→Control the showers: veto additional resolvable radiation.

→reweight event by probability of having no resolvable emission (Sudakov form factor).

MLM (reject instead of reweight):

→ No control on the shower, but match jets (PS level) with partons (ME level).

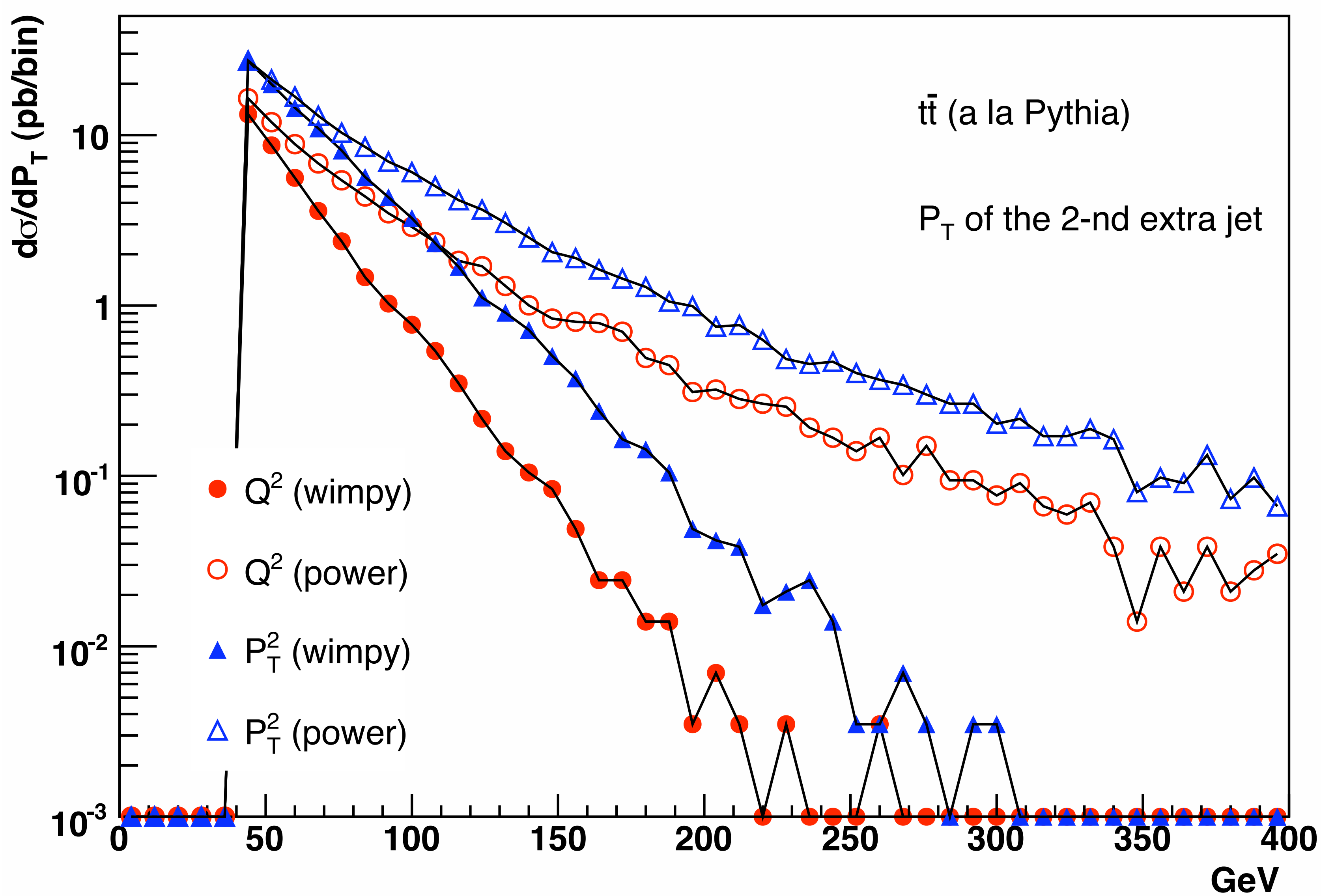
→ reject events that have more or less jets.

Matching ME and PS

- K_T MLM scheme implemented by J. Alwall.
- Interfaced to (fortran) Pythia, with Q^2 and pt^2 ordered showers.
- Extensively validated in V+jets (data and comparison [arXiv:0706.2569]) and now also in VV+jets, tt+jets, h+jets, inclusive jets, ...
- Merging in BSM Physics samples available (e.g. gluino/squark)
- Interfaces with Pythia8 and Herwig++ are through standard LHEF and not yet available with merging.

PS alone vs Matched Sample

- A parton shower like Pythia is by construction a highly tuneable tool. Consider for instance the pt distribution of the 2nd extra jet in ttbar events with different settings:



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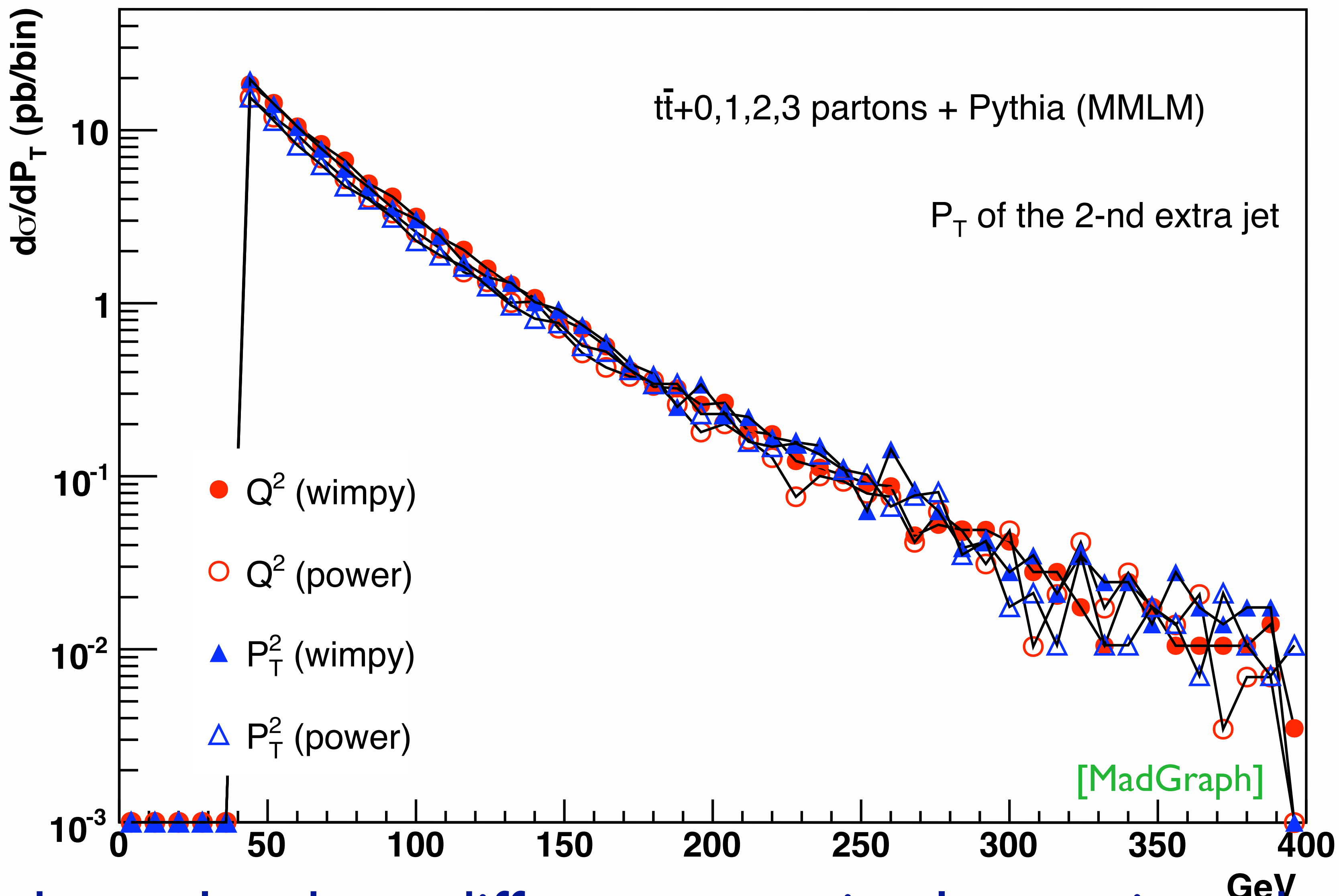
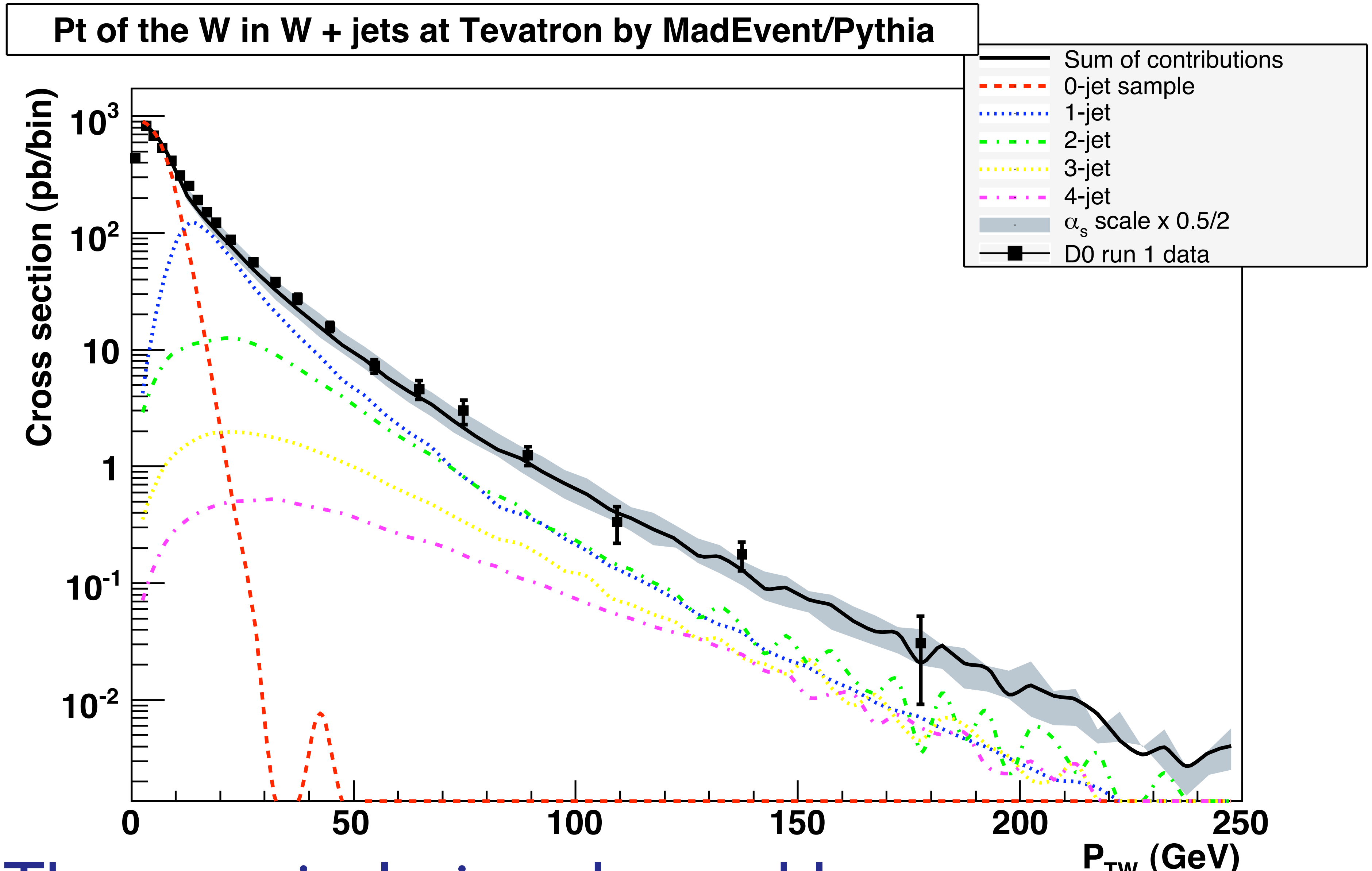


In matched samples these differences are irrelevant since the high pt behavior is described by the matrix element.

Uncertainties in the matching itself are not shown.

It's working!



- The most inclusive observable
- All parton multiplicities contribute
- Excellent agreement with TeV data (validation)

MG on the grid

[J. Alwall, S. de Visscher, P. Demin, RF, F. Maltoni, T. Stelzer]

- Usual MG code creation from the web.
- Usual selection of parameters by cards.
- Run in a special mode (on a single machine or over the web cluster) and obtain a gridpack.tar.gz.
- This is a ready-to-go package, "optimized" for the specific process and settings, to be run on a single machine, whose only inputs are:
  1. the random number seed
  2. the number of events requested

New physics implementation

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Bottom-up vs. Top-down

- For new physics associated, two approaches are possible:
  - top-down (e.g., model parameter scanning)
  - bottom-up (e.g., inverse problem, OSET)
- Different EXP strategies and different TH and MC tools:

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Well-defined models	Coarse structure
Extremely optimized (→non-portable) analysis	General searches
Dedicated MC tools	multi-purpose MC's

New models in MG/ME

1. Modify by hand the available models : SM, 2HDM, MSSM, HEFT, TopBSM, ...

☹ touch fortran

☺ start from any implemented model

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3. NEW: interface to FeynRules
   - ☺ !

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   - **bottom-up**
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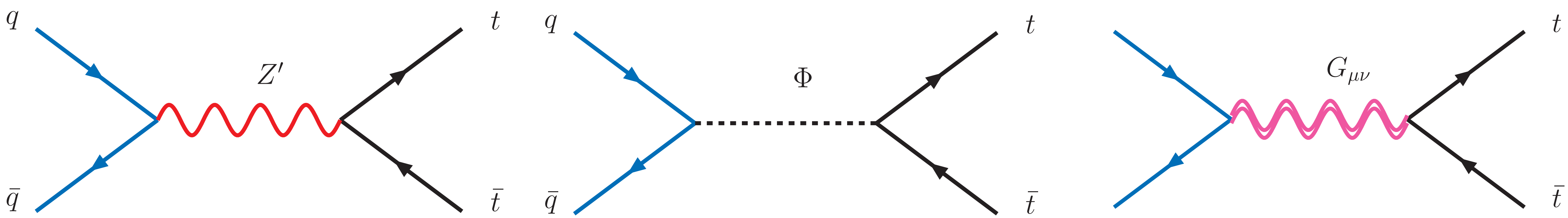
   - **top-down**

Bottom-up -- e.g. TopBSM

[RF, F. Maltoni] arXiv:0712.2355



- In the topBSM model general resonances are added to the SM that couple to top quarks.

  These resonances can describe a large variety of models: Two-Higgs doublet models to extra dimensions and many more, by tuning the couplings and the masses of the resonances.

- In this way general resonances in ttbar events can be analyzed

Bottom-up -- e.g. TopBSM

[RF, F. Maltoni]
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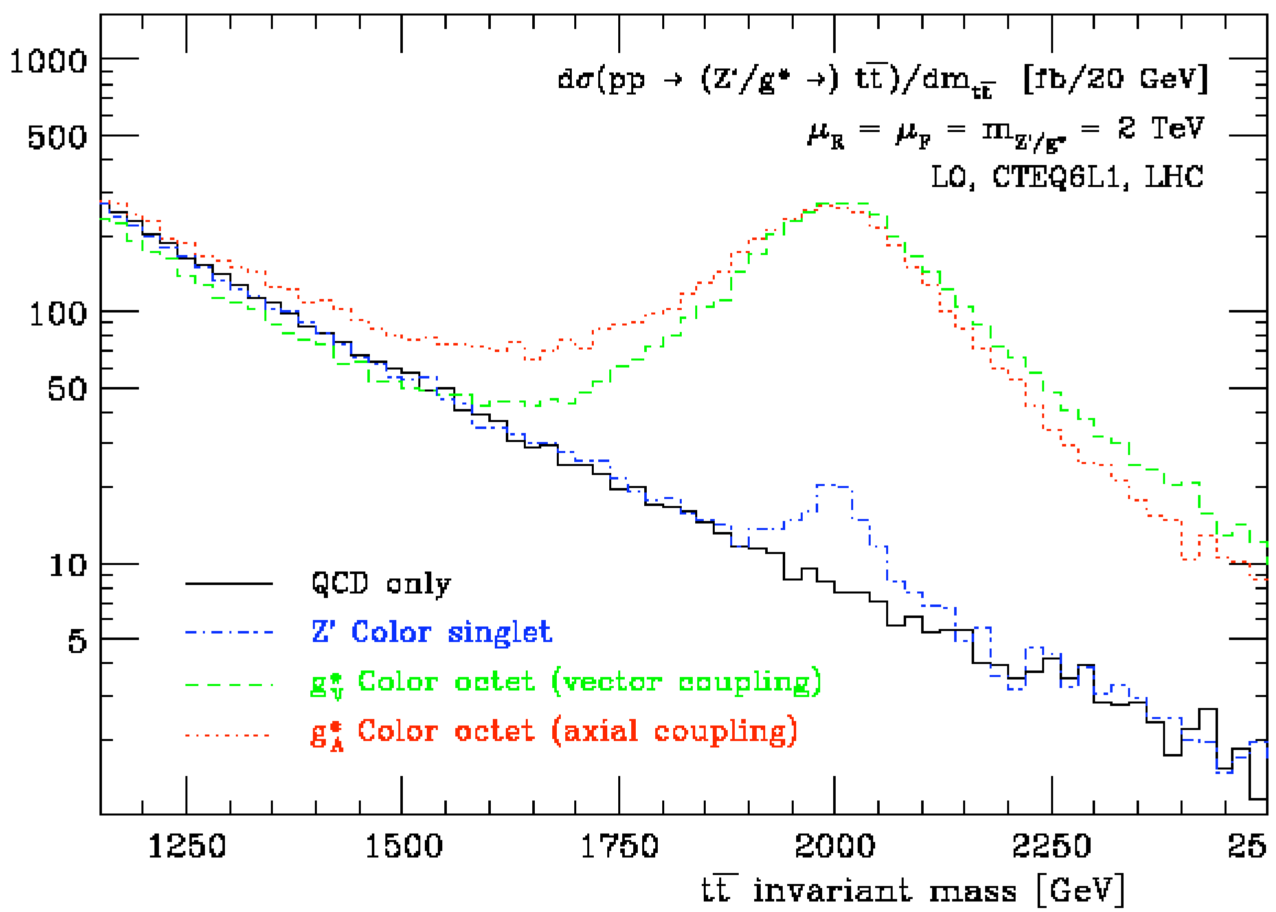
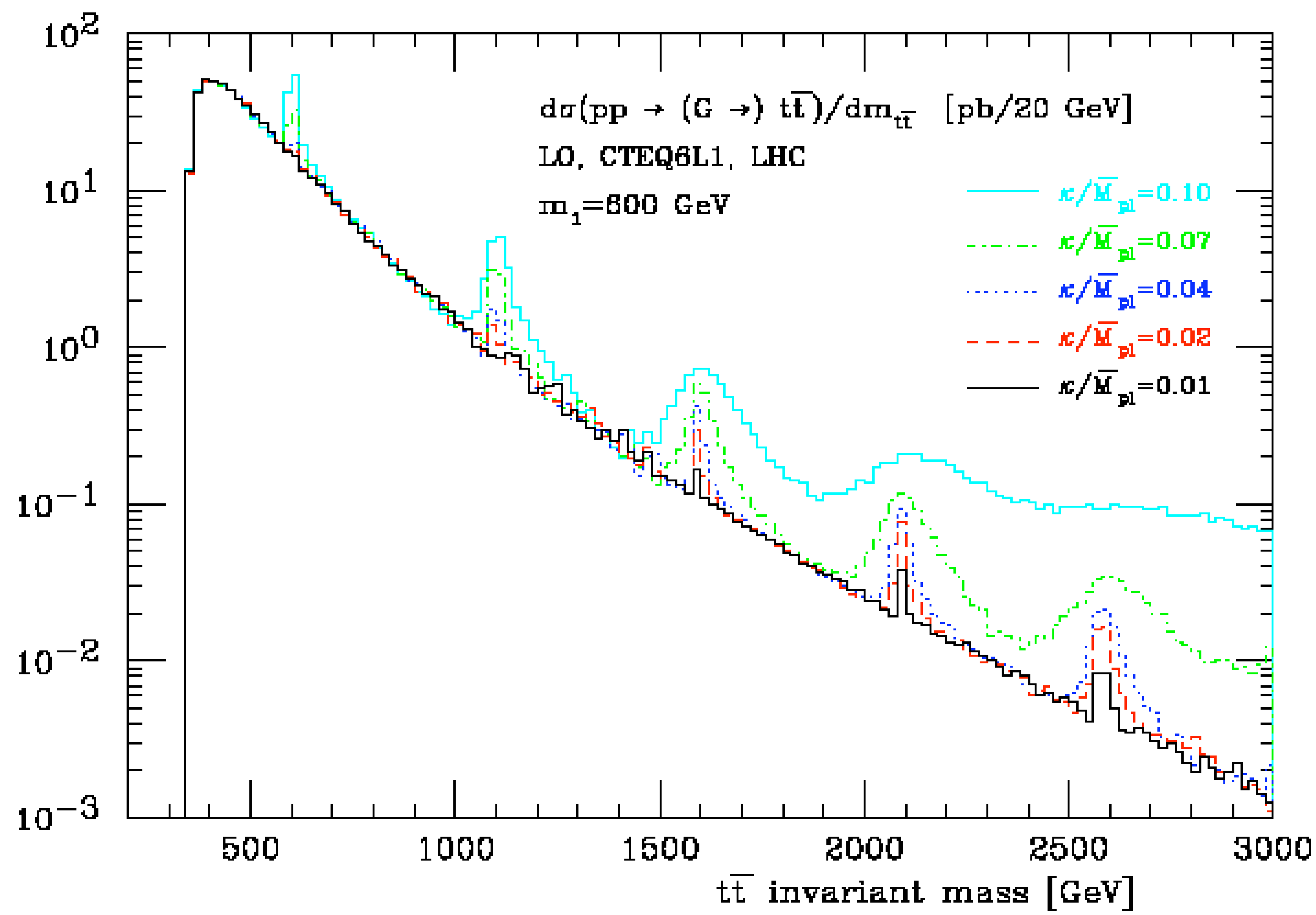


Spin-1



Spin-2

Top-down

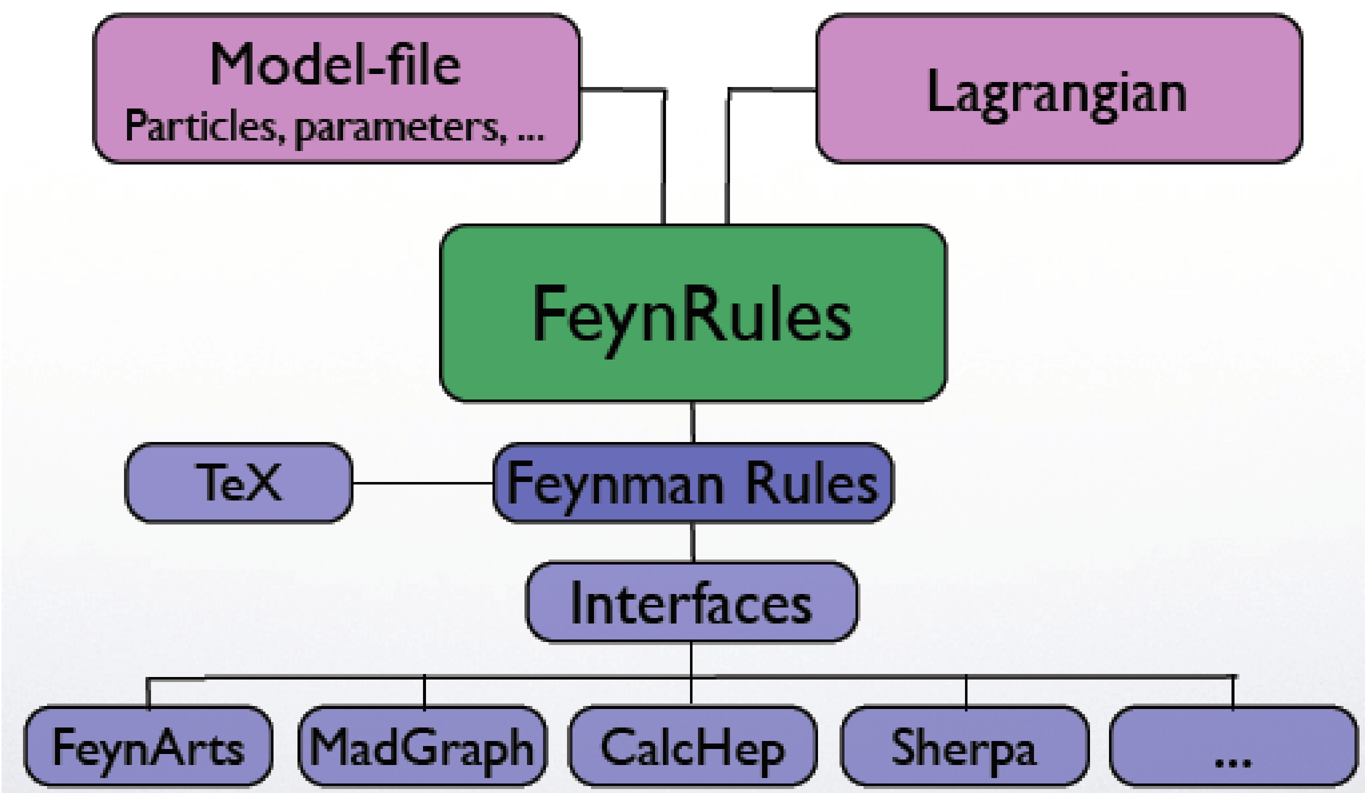
- For the top-down approach it is mandatory that the complete model is implemented, and that any final state can be studied to make use of all the information of the model to verify or exclude it.
- With the interface to “FeynRules” implementing a new model can be done directly from the Lagrangian.

FeynRules

[C. Duhr, N. Christensen + MC collaborators]

A new tool to extract Feynman rules and couplings directly from the Lagrangian and effortless implement in any MC.

Mathematica package where Lagrangians for new models can be developed and studied at the TH level and then passed to full fledged MC for the LHC.



- Get Feynman Rules for 'any' possible Lagrangian
- Only limited Mathematica knowledge required; interfaces take care of fortran/C++ code

wikipage at europa.fyma.ucl.ac.be/feynrules

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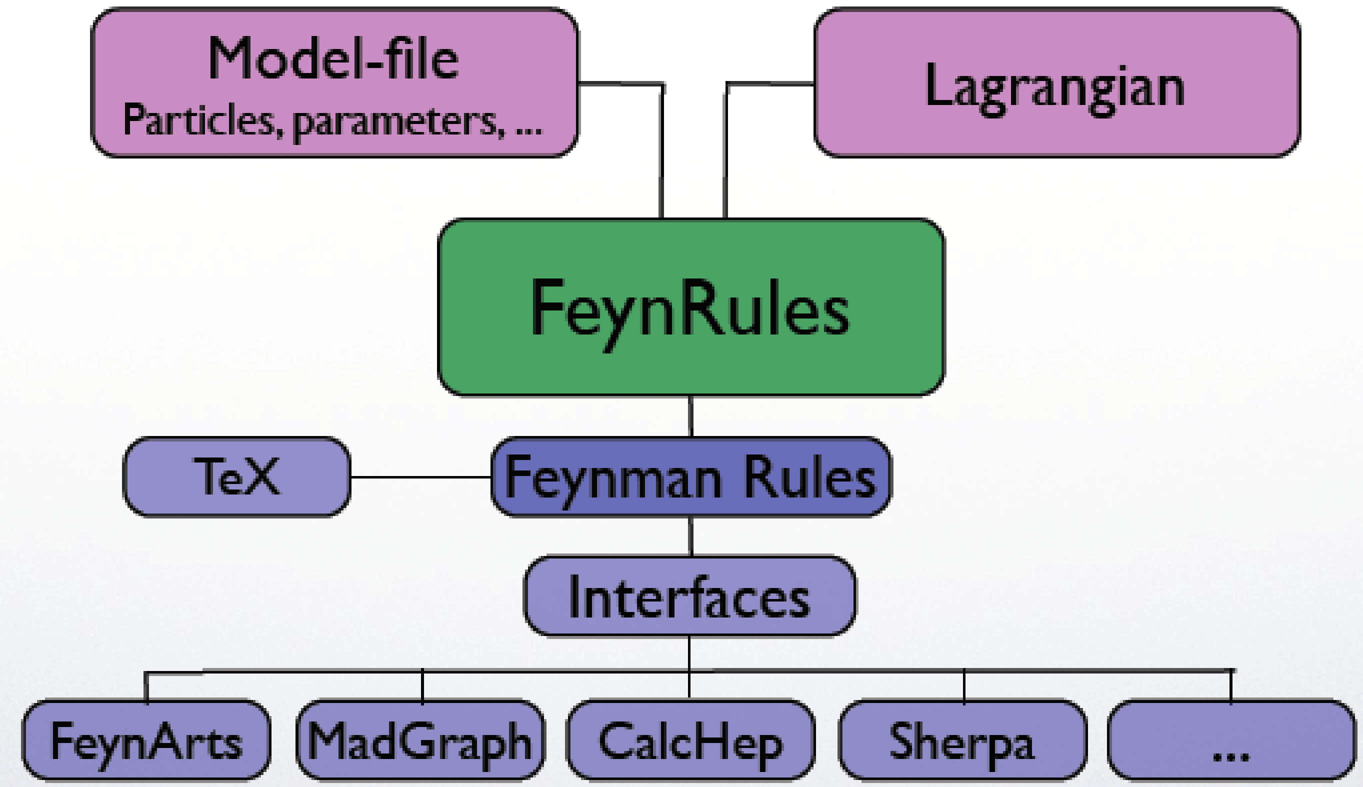

$$\kappa^{-1}\mathcal{L}_{\rm F}^{\vec n}(\kappa) = \frac{1}{2}\Big[(\tilde h^{\vec n}\eta^{\mu\nu} - \tilde h^{\mu\nu,\vec n})\overline{\psi} i\gamma_\mu D_\nu \psi - m_\psi \tilde h^{\vec n}\overline{\psi}\psi + \frac{1}{2}\overline{\psi} i\gamma^\mu(\partial_\mu \tilde h^{\vec n} - \partial^\nu \tilde h^{\vec n}_{\mu\nu})\psi\Big] + \frac{3\omega}{2}\tilde\phi^{\vec n}\overline{\psi} i\gamma^\mu D_\mu\psi - 2\omega m_\psi \tilde\phi^{\vec n}\overline{\psi}\psi + \frac{3\omega}{4}\partial_\mu \tilde\phi^{\vec n}\overline{\psi} i\gamma^\mu\psi$$

$$k\Big(-2\,\mathrm{mpsi}\,\mathrm{om}\,\phi\,\psi^\dagger.\psi + \frac{3}{4}\,i\,\mathrm{om}\,\partial_\mu(\phi)\,\psi^\dagger.\gamma^\mu.\psi + \frac{3}{2}\,\mathrm{om}\,\phi\,\big(i\,\psi^\dagger.\gamma^\mu.\partial_\mu(\psi) - g\,\psi^\dagger.\gamma^\mu.T^a.\psi\,G_{\mu,a}\big) + \frac{1}{2}\Big(\frac{1}{2}\,i\,(\partial_\mu(h_{\nu,\nu}) - \partial_\nu(h_{\mu,\nu}))\,\psi^\dagger.\gamma^\mu.\psi - \mathrm{mpsi}\,\psi^\dagger.\psi\,h_{\mu,\mu} + \big(i\,\psi^\dagger.\gamma^\mu.\partial_\nu(\psi) - g\,\psi^\dagger.\gamma^\mu.T^a.\psi\,G_{\nu,a}\big)\big(h_{\rho,\rho}\,\eta_{\mu,\nu} - h_{\mu,\nu}\big)\Big)\Big)$$

wikipage at europa.fyma.ucl.ac.be/feynrules

FeynRules

- (Example) models implemented:
  - Standard Model (+Higgs effective theory)
  - 3-site model
  - partial super-symmetric models
- Extensive testing between MG/ME and CalcHEP/CompHEP
- Full MSSM under testing and UED underway
- Trivial to add new sectors (e.g. NMSSM) which is highly non-trivial in stock version
- Future: write all MG/ME models in FeynRules format
  - Also extend the USRMOD to work with any model

Decay Chains

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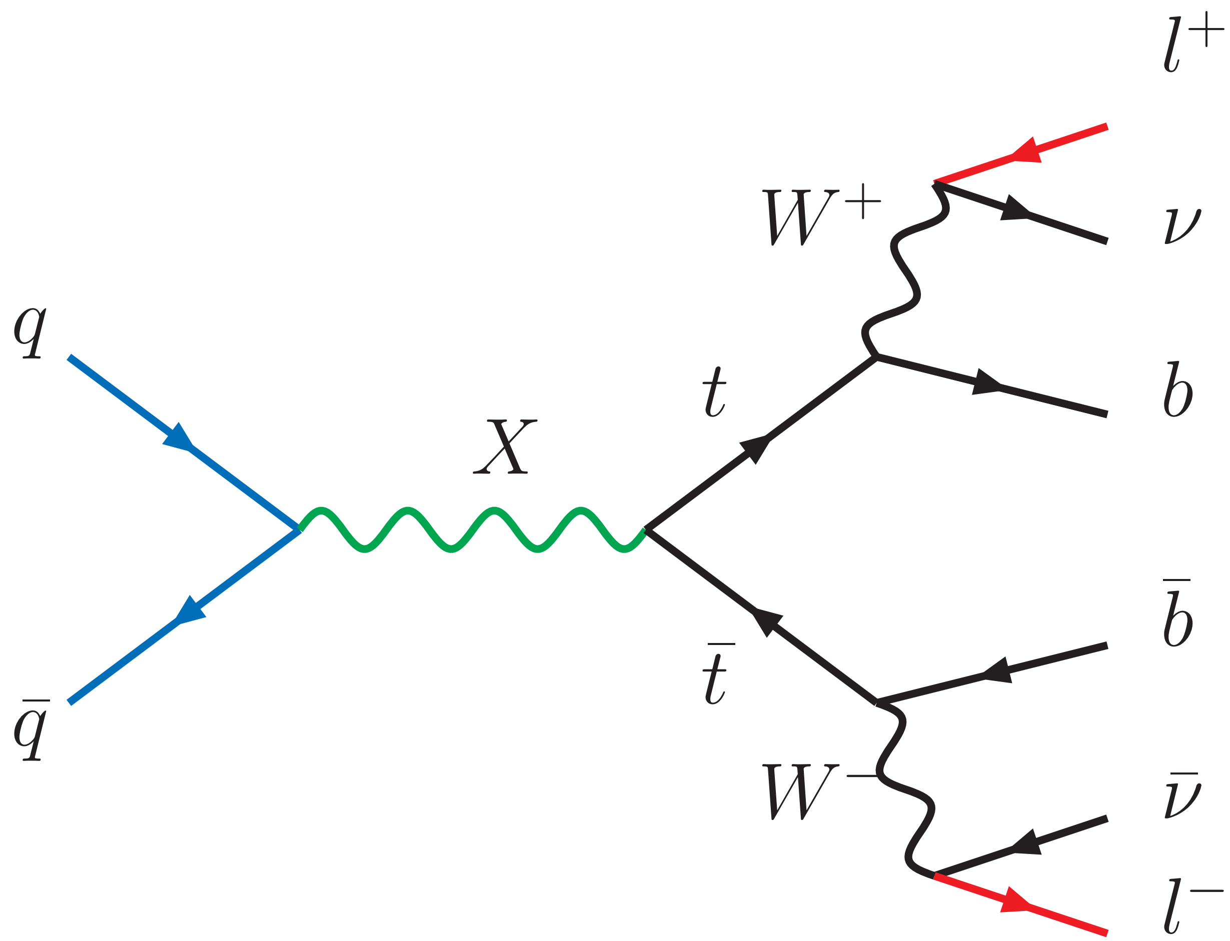
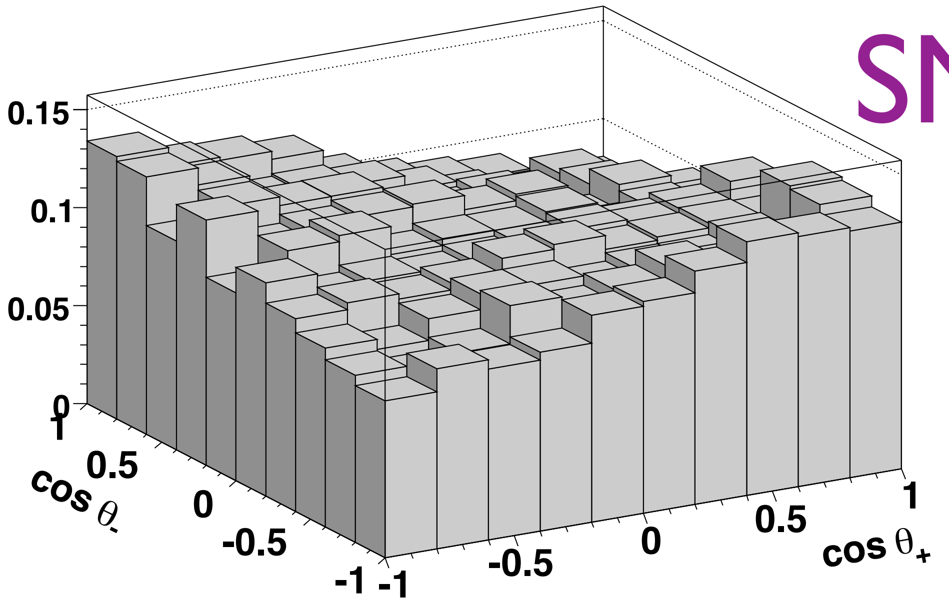
Spin correlations

- To access the properties (e.g. spin, CP or coupling structure) of resonances full matrix elements that describe the final state particles are needed.
- For example: to determine the coupling structure of a Spin-1 resonance in ttbar production the full 2→6 need to be generated.



Example: Spin correlations in ttbar production

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 - A\cos\theta_+\cos\theta_- + b_+\cos\theta_+ + b_-\cos\theta_-\right)$$



SM

Angle between l^+ in top rest-frame and top in top pair rest-frame

Angle between l^- in anti-top rest-frame and anti-top in top pair rest-frame

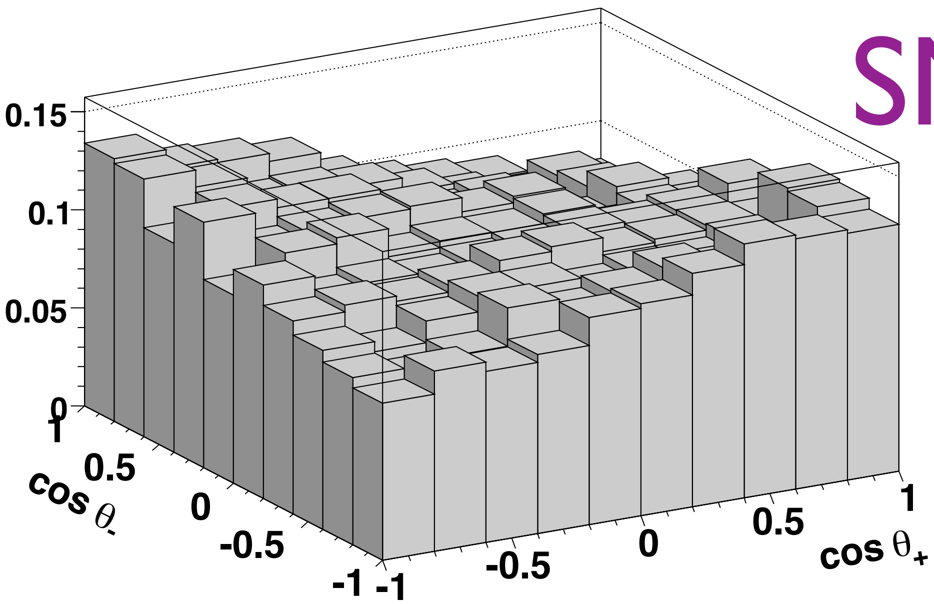
Example: Spin-1

Example: Spin correlations in ttbar production

[RF, F. Maltoni]
arXiv:0712.2355

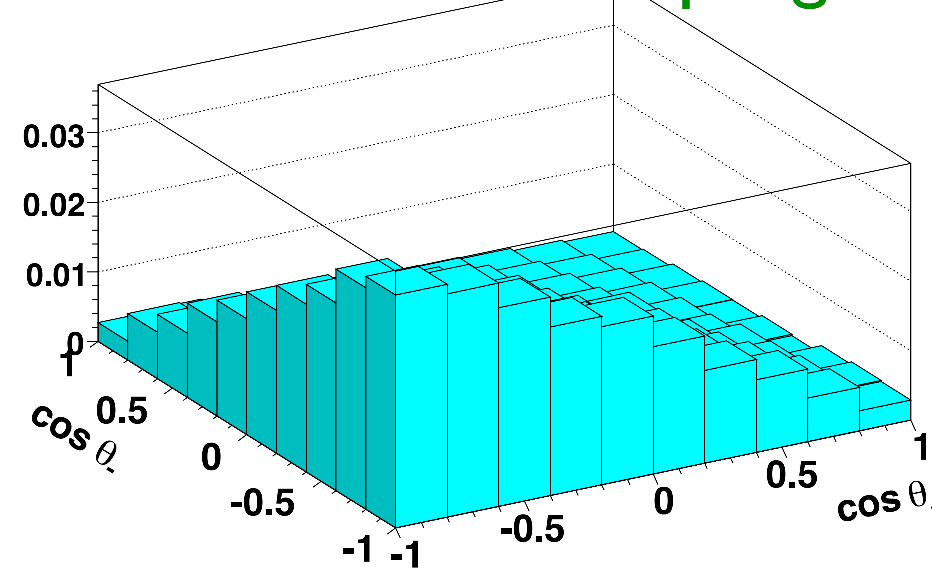
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\Big(1 - A\cos\theta_+\cos\theta_- + b_+\cos\theta_+ + b_-\cos\theta_-\Big)$$

SM

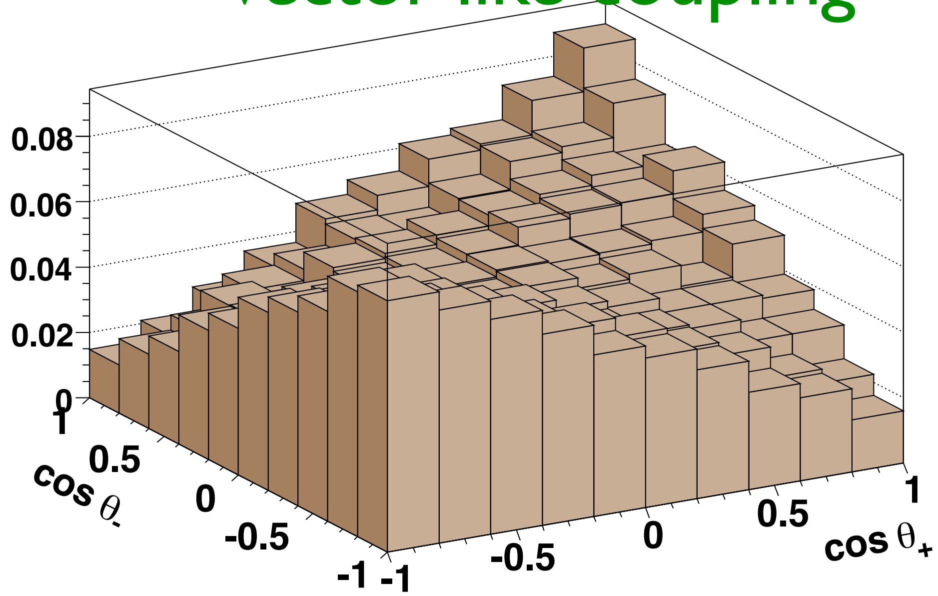


Spin-1

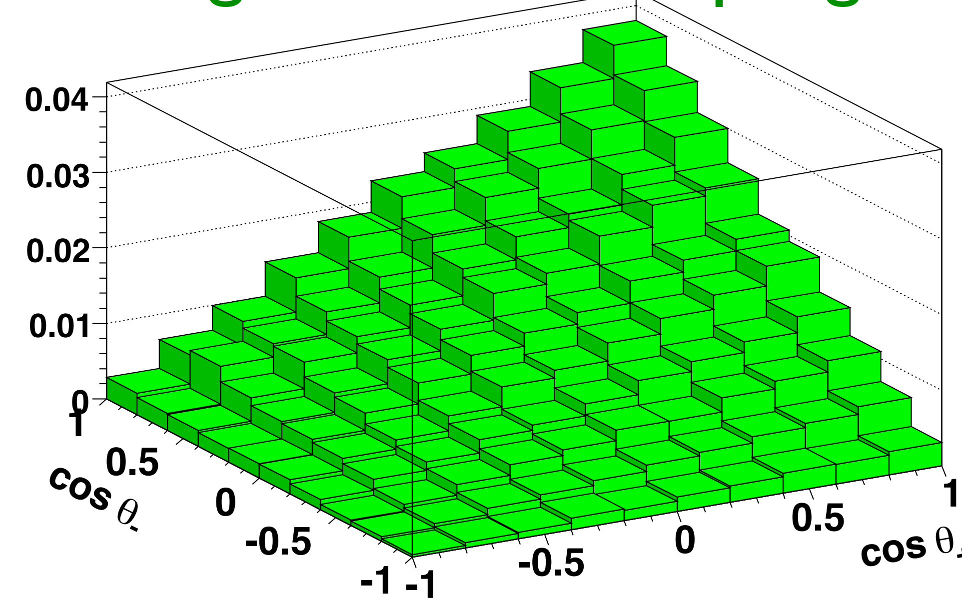
Left-handed coupling



Vector-like coupling

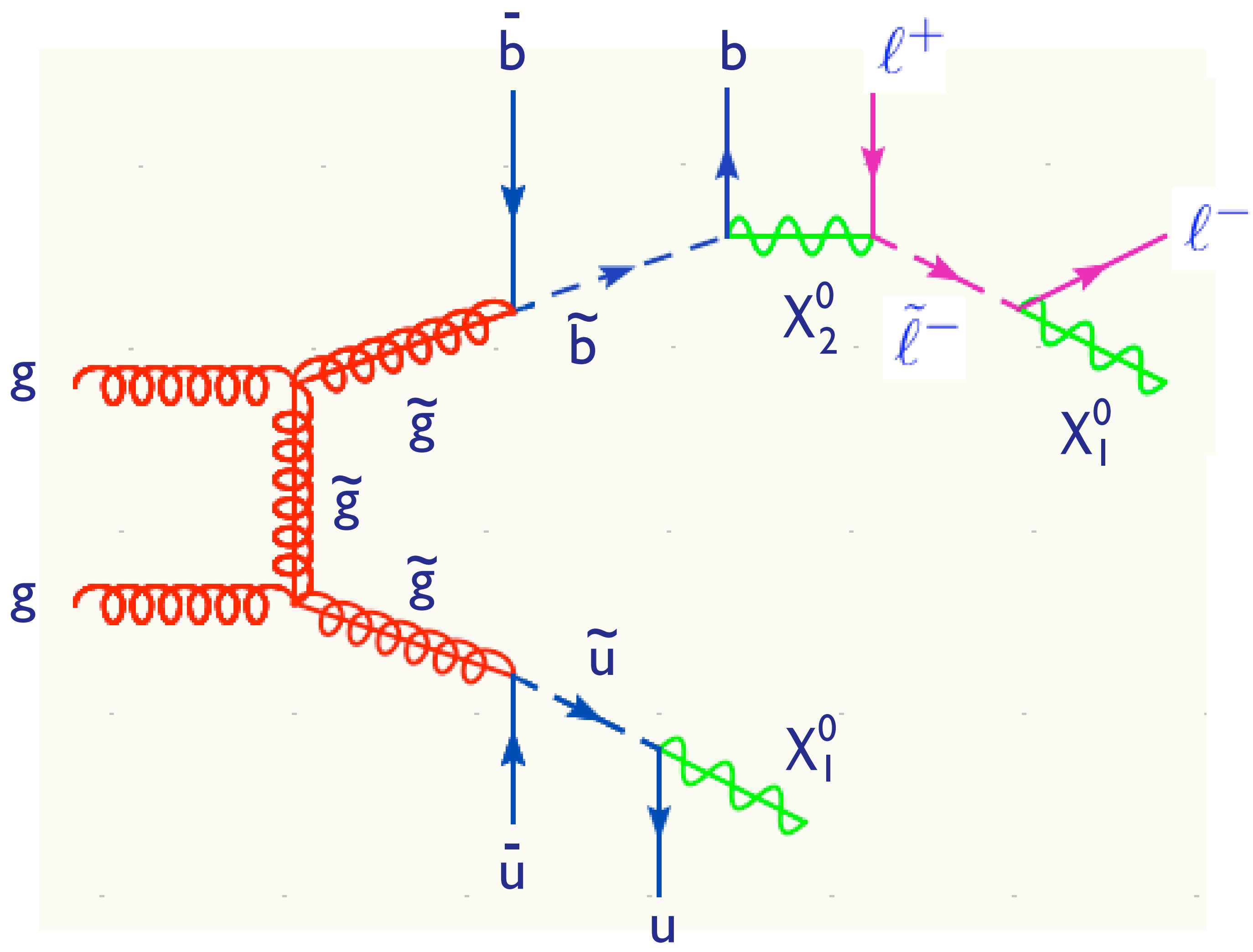


Right-handed coupling



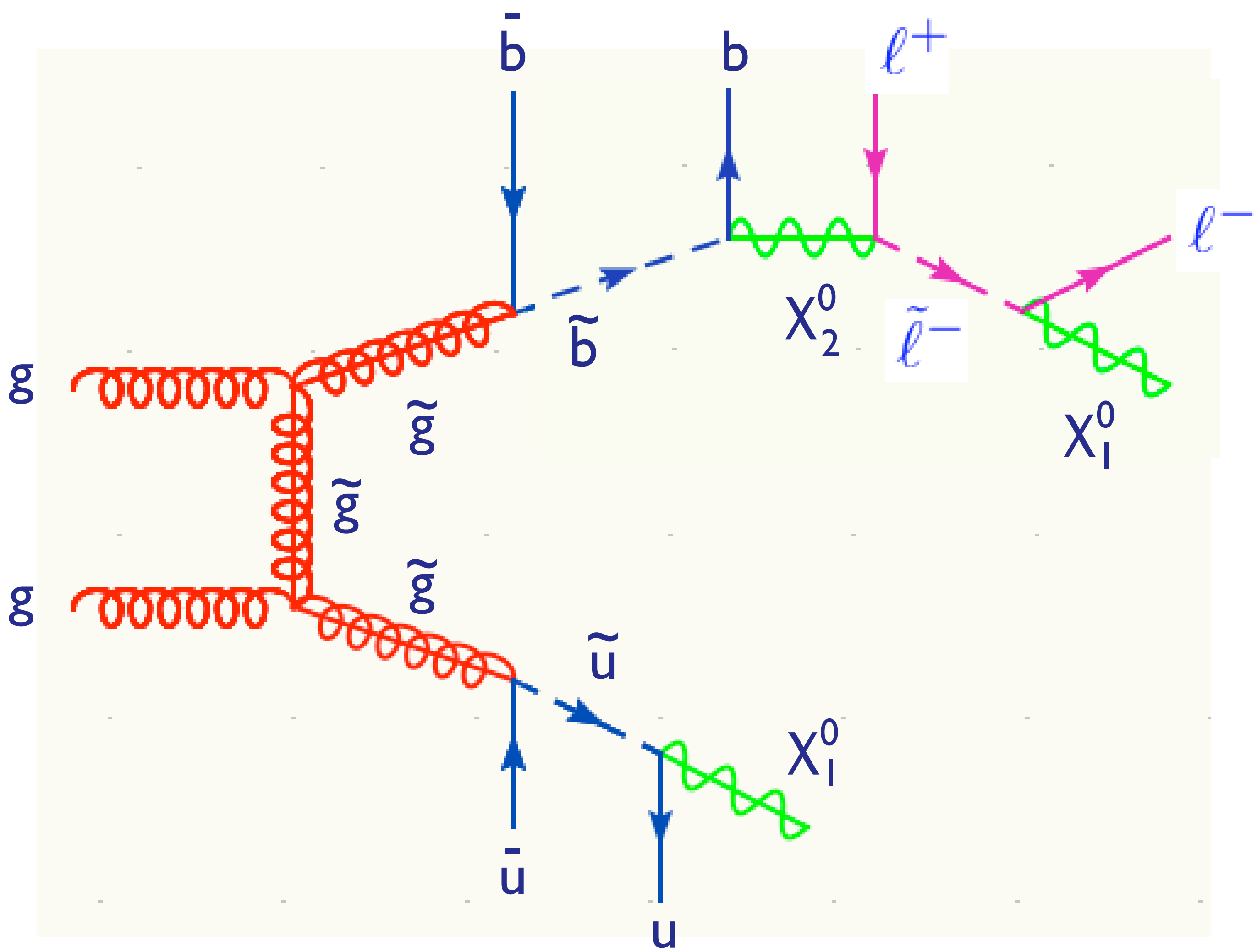
Decay Chains

- What to do for even more complicated structures like long decay chains in SUSY events?



Decay Chains

```
gg >(go>u~(ul > u n1 ))(go>b~(b1>(b(n2>mu+(mul- >mu- n1)))))
```



[J. Alwall, T. Stelzer]

In this case:

1. Full matrix element is obtained which includes correlations between production and decays.
2. Spin of the intermediate states is kept.
3. One can go beyond 1→2 decays.
4. Resonances have BW.
5. Non-resonant contributions can be systematically included only where relevant.

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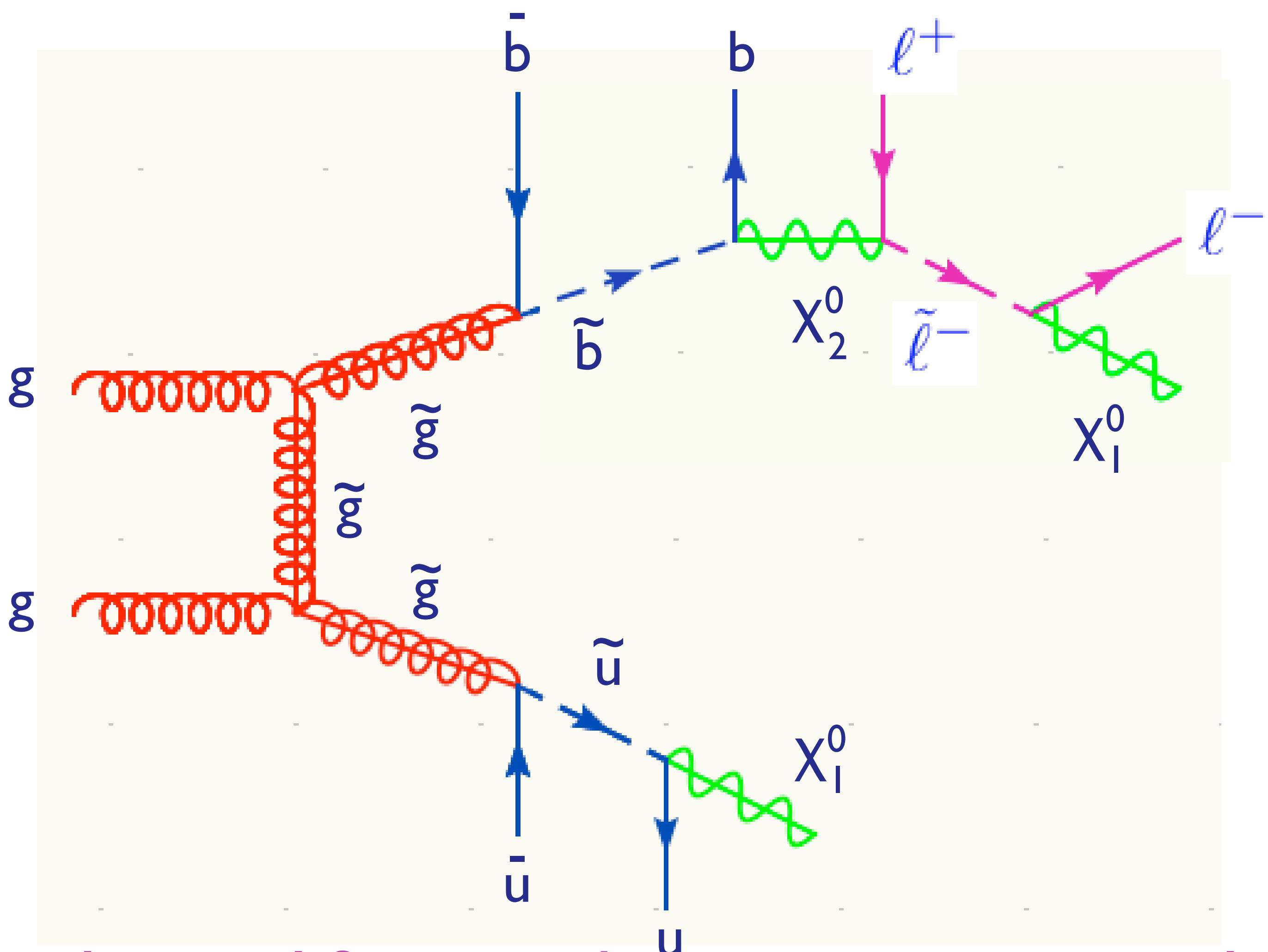
[J. Alwall, T. Stelzer]



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Example simplification: the process can exactly factorized in

```
gg >(go>u~ul)(go>b~b1)
```

where the squarks can be decayed at the event level, for example by BRIDGE

```
ul > u n1
b1 > b(n2>mu+(mul- >mu- n1))
```

[P. Meade, M. Reece] hep-ph/0703031

Matrix Element Methods

- Find excess(es) over SM background
  Fully exclusive description for rich and energetic SM final states (multi-jet+EW/QCD).
  Flexible MC to be validated and tuned.
  Accurate predictions (NLO, NNLO) for "standard candle" SM X-sections.
- Identify finite set of coarse models compatible with excess(es)
  "Bottom-up" approach, "inverse problem" tools, e.g. OSETs.
- Look for predicted excesses in other channels
  Simulation of any BSM signature: fast path from model to events
- Mass spectrum, quantum numbers, couplings
  Accurate ME-based description for final state distributions keeping all relevant information (e.g. decay chains with spin)
- Determine underlying model
  Accurate predictions for primary parameters (e.g. spectrum calculators)
- Refine
  Off-shell effects, Matrix Element methods, Global fits (e.g. Sfitter)

MadWeight

[P. Artoisenet, V. Lemaître, F. Maltoni, O. Mattelaer]

- Tool to find matrix element weight of experimental events for (almost) any process in any model.

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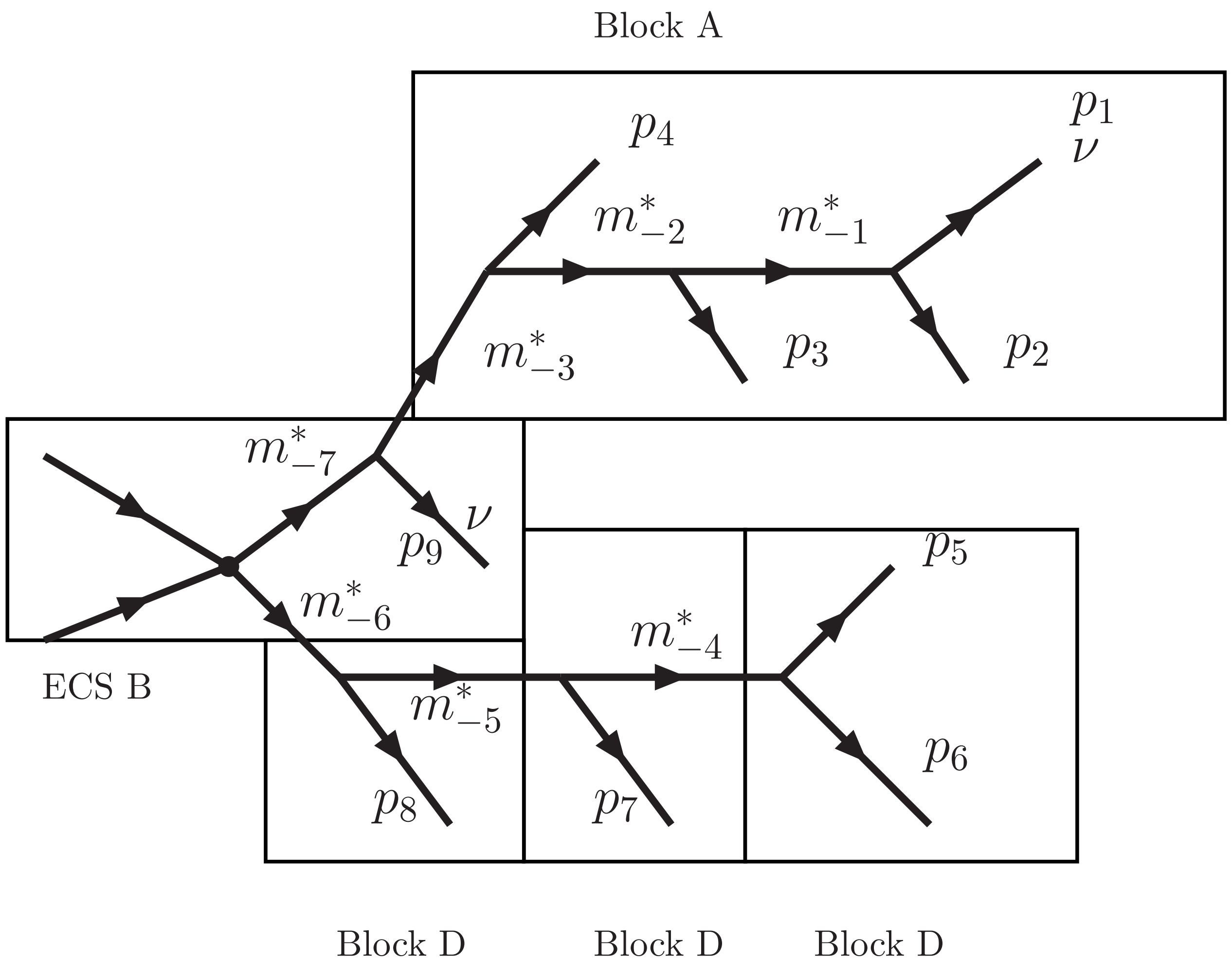

Phase space integration using automatic change of variables to align with peaks

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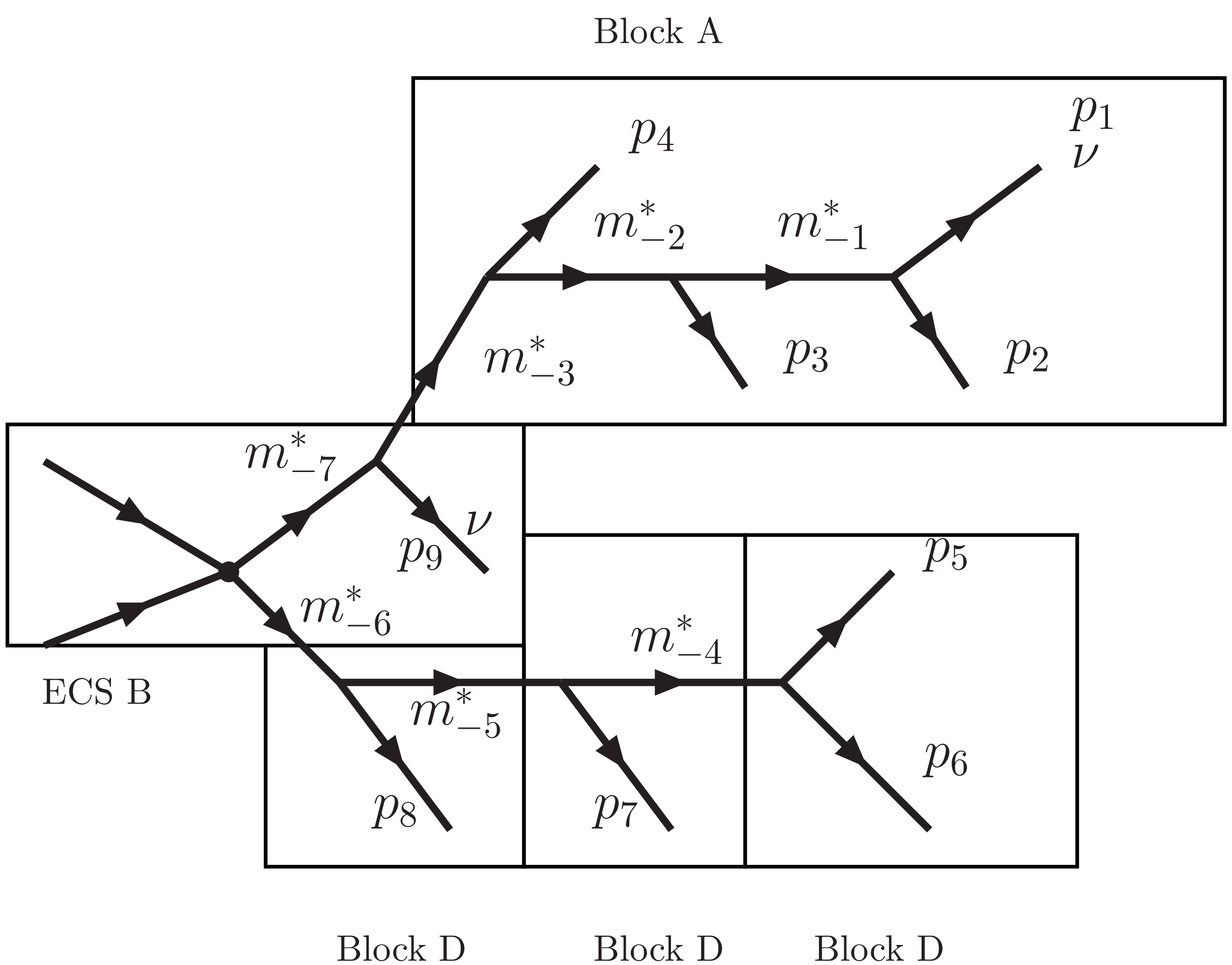

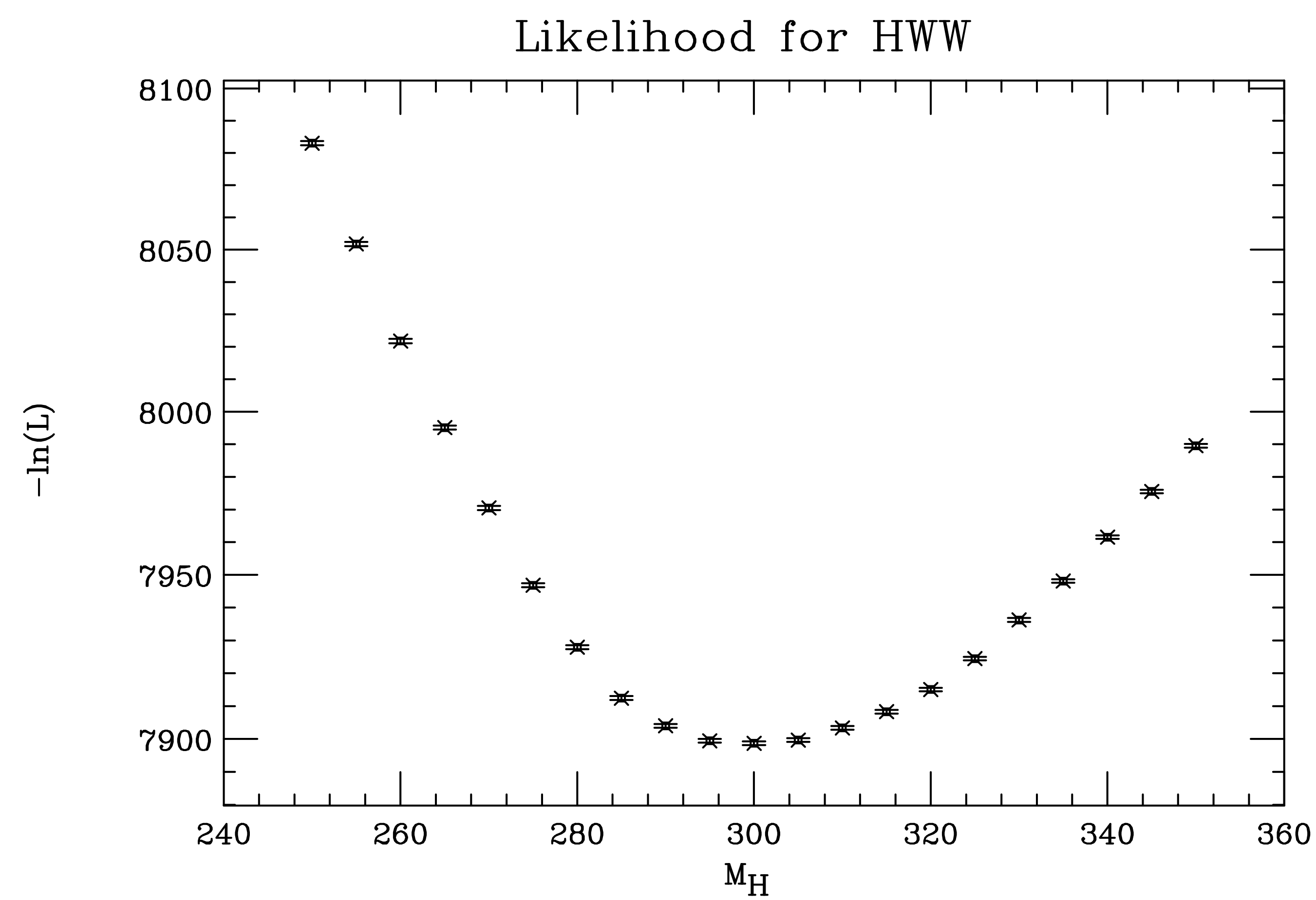

Phase space integration using automatic change of variables to align with peaks

Find likelihood for model parameters (here Higgs mass in $h \to WW$)

MadGraph for theorists

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- **Refine**
  Off-shell effects, Matrix Element methods, Global fits (e.g. Sfitter)

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).

Dipole subtraction

[RF, N. Greiner]

$$\sigma^{\rm NLO} = \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^A \right] + \int_m \left[\int_{\rm loop} d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^A \right]_{\epsilon=0}$$

- Goal: Automatic Dipole Subtraction for any NLO calculation
  - Catani-Seymour subtraction scheme
  - Reals & subtraction terms for the reals and virtuals
  - Both for SM and BSM
  - Compatible with MG StandAlone
- Beta version working!

Conclusions

- MadGraph/MadEvent is an event generator that is:
  - Multi purpose, new models are easy to implement
  - Complete, interfaces from model to detector simulation
  - User friendly, due to the web interface
  - Fast, thanks to the cluster oriented structure
  - Open, everybody can contribute!

See also the three operational cluster at
http://madgraph.phys.ucl.ac.be
http://madgraph.hep.uiuc.edu
http://madgraph.roma2.infn.it

Coming soon

- MadWeight: a General approach to Matrix Element techniques
  [P. Artoisenet, V. Lemaître, F. Maltoni, O. Mattelaer]
- Event generation for quarkonium
  [P. Artoisenet, F. Maltoni, T. Stelzer]
- Automated dipole subtraction
  [RF, N. Greiner]
- MG for the GRID
  [J. Alwall, S. de Visscher, P. Demin, RF, F. Maltoni, T. Stelzer]
- Spin-2 interactions
  [K. Hagiwara, J. Kanzaki, Q. Li, K. Mawatari]
- ...