New Developments in MadGraph/MadEvent

Johan Alwall, SLAC

With the MG/ME team

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F. Maltoni, T. Stelzer
+ P. Artoisenet, C. Duhr, O. Mattelaer
+ S. Mrenna, T. Plehn, D. L. Rainwater

SUSY08, Seoul, Korea, 17 June 2008

MadGraph/MadEvent

[Long, Stelzer, 1994; Maltoni, Stelzer, 2003]

- Event generation for any process – online or locally:
  - User requests a process (ex. pp>tt~jjj) and the corresponding code is generated on the fly.
  - User inputs model/collider-parameters/cuts, and code runs in parallel on modest farms.
  - Returns cross section, parton-level events, plots.
- Advantages:
  - Reduces overhead to getting results
  - Events can easily be shared/stored
  - Quick response to user requests and to new ideas!
- Limitations:
  - Optimization on single procs limited by generality
  - Tree-level amplitudes based on Feynman diagrams

MadGraph/MadEvent

[Long, Stelzer, 1994; Maltoni, Stelzer, 2003]

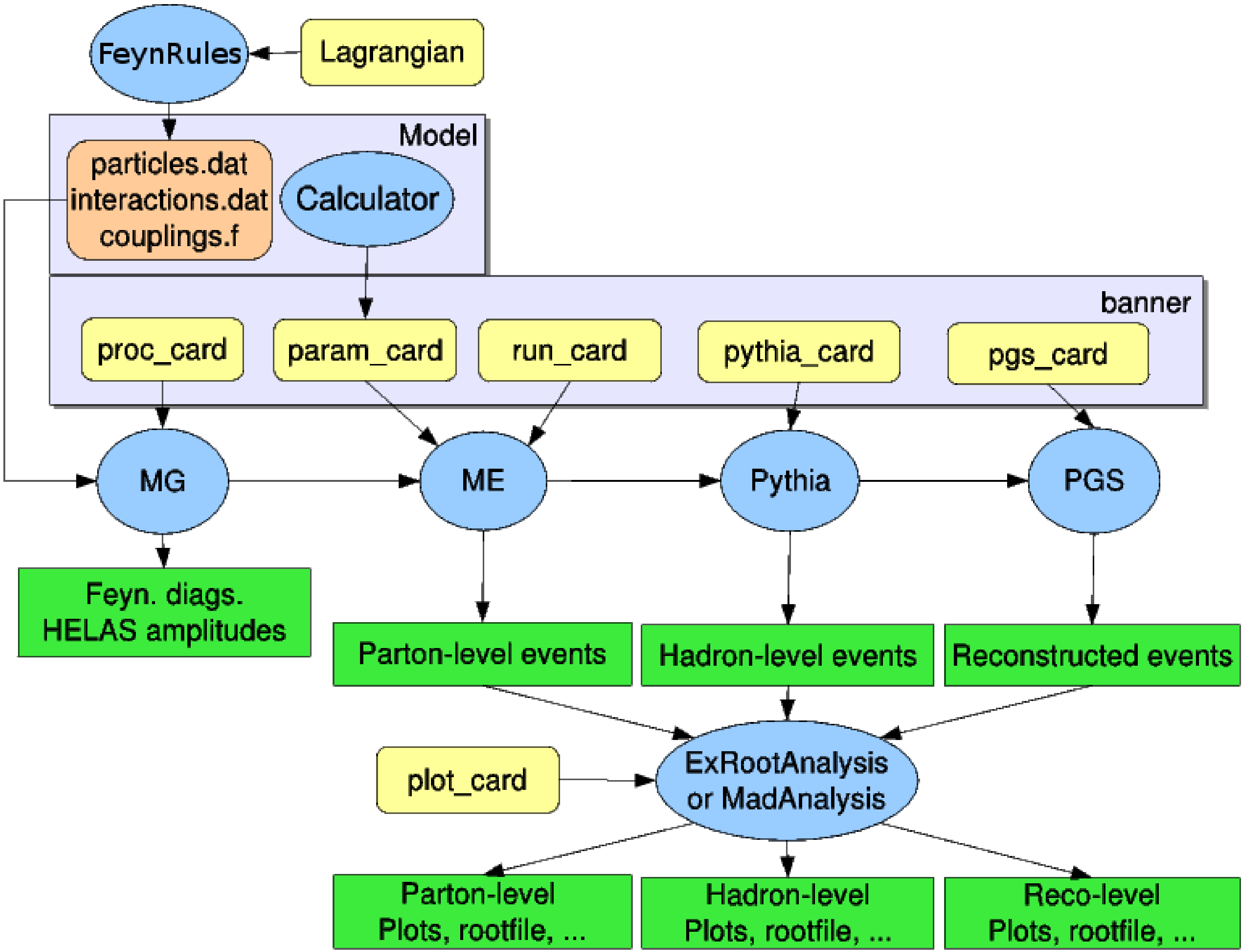
- Tree-level amplitudes based on Feynman diagrams

MadGraph/MadEvent 4

[JA et al., arXiv:0706.2334]

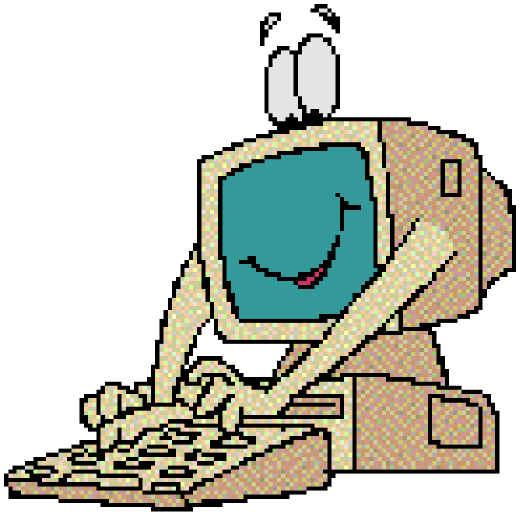
- Complete web simulation: MadEvent $\rightarrow$ Pythia $\rightarrow$ PGS
- Personal web databases
- Multiple processes in single code & generation
- Standalone MadGraph version for theorists
- New complete models: SM, HEFT, MSSM, 2HDM
- USRMOD: Easy New Model implementation
- Les Houches Accord (LHEF) for parton-level event files
- “SUSY Les Houches Accord” for model parameters
- Merging/matching w/ Pythia parton showers
- Analysis platforms: ExRootAnalysis and MadAnalysis

MG/ME workflow



How do I use MG/ME 4?

1. Open your browser
2. Google us and go to one of our sites
3. Create a process
4. Generate events



Recent and ongoing developments

- Matching for SM&BSM processes [JA] ✓
- Staged web simulation :
  LHEF $\rightarrow$ Pythia $\rightarrow$ PGS [JA et al.] ✓
- Decay chain specifications [JA, Stelzer] ✓
- Decay width calculation A>BC... [JA] ✓
- Grid Version [Mad Team] ✓
- LHC event repository [Mad Team]
- FeynRules [Christensen, Duhr] ✓
- MadWeight [Artoisenet, Mattelaer]
- Automatic dipole subtraction [Frederix, Greiner]

Jet matching/merging

Matrix elements

1. Fixed order calculation
2. Computationally expensive
3. Limited number of particles
4. Valid when partons are hard and well separated
5. Quantum interference correct
6. Needed for multi-jet description

Parton showers

1. Resums logs to all orders
2. Computationally cheap
3. No limit on particle multiplicity
4. Valid when partons are collinear and/or soft
5. Partial quantum interference through angular ordering
6. Needed for hadronization/ detector simulation

Complementary approximations

Need to combine without double counting

Matching schemes

The simple idea behind matching

- Use matrix element description for well separated jets, and parton showers for collinear jets
- Phase-space cutoff to separate regions

$\Longrightarrow$ No double-counting between jet multiplicities

Difficulties

- Get smooth transition between regions
- No/small dependence from precise cutoff
- No/small dependence from largest multiplicity sample

How to accomplish this

- CKKW scheme (Catani, Krauss, Kuhn, Webber)
- Lönnblad scheme
- MLM scheme

Matching in MG/ME+Pythia

[JA; JA, F. Maltoni, S. de Visscher; cf. Mrenna & Richardson 2004]

- k_T and cone jet MLM schemes
- New "shower k_T" scheme
- Both Q^2 and p_T-ordered Pythia showers
- Extensively validated in V+jets [arXiv:0706.2569], VV+jets, t pair+jets, H+jets and inclusive jets
- Matching in BSM processes (e.g. gluino/squark)

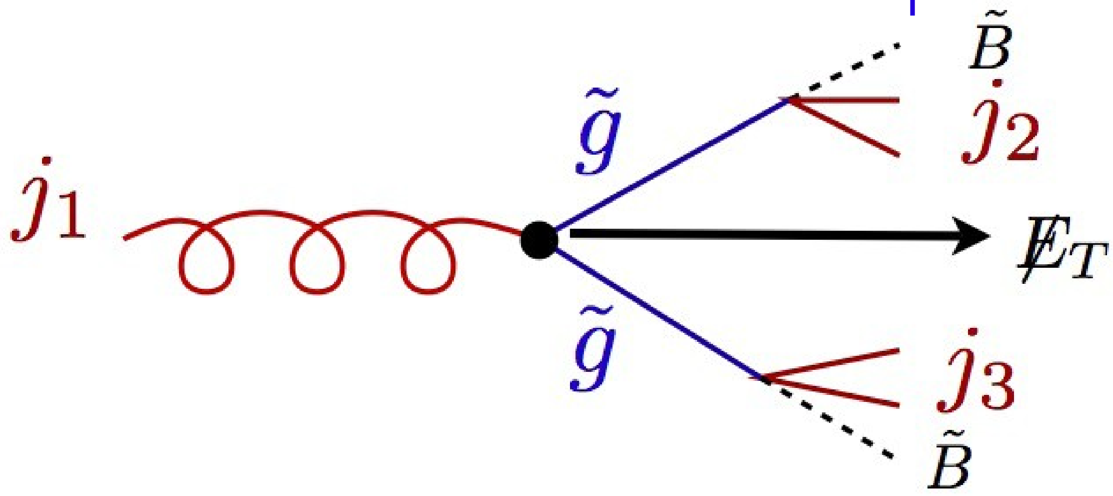
Light gluinos + jets

[JA, Le, Lisanti, Wacker, arXiv:0803.0019]

See talk by J. Wacker in PS 2

Special difficulty when decay products are soft (nearly degenerate masses):

- No (small) missing transverse energy in decay
- Need recoil agains jets to get $\not{E}_T$ signature



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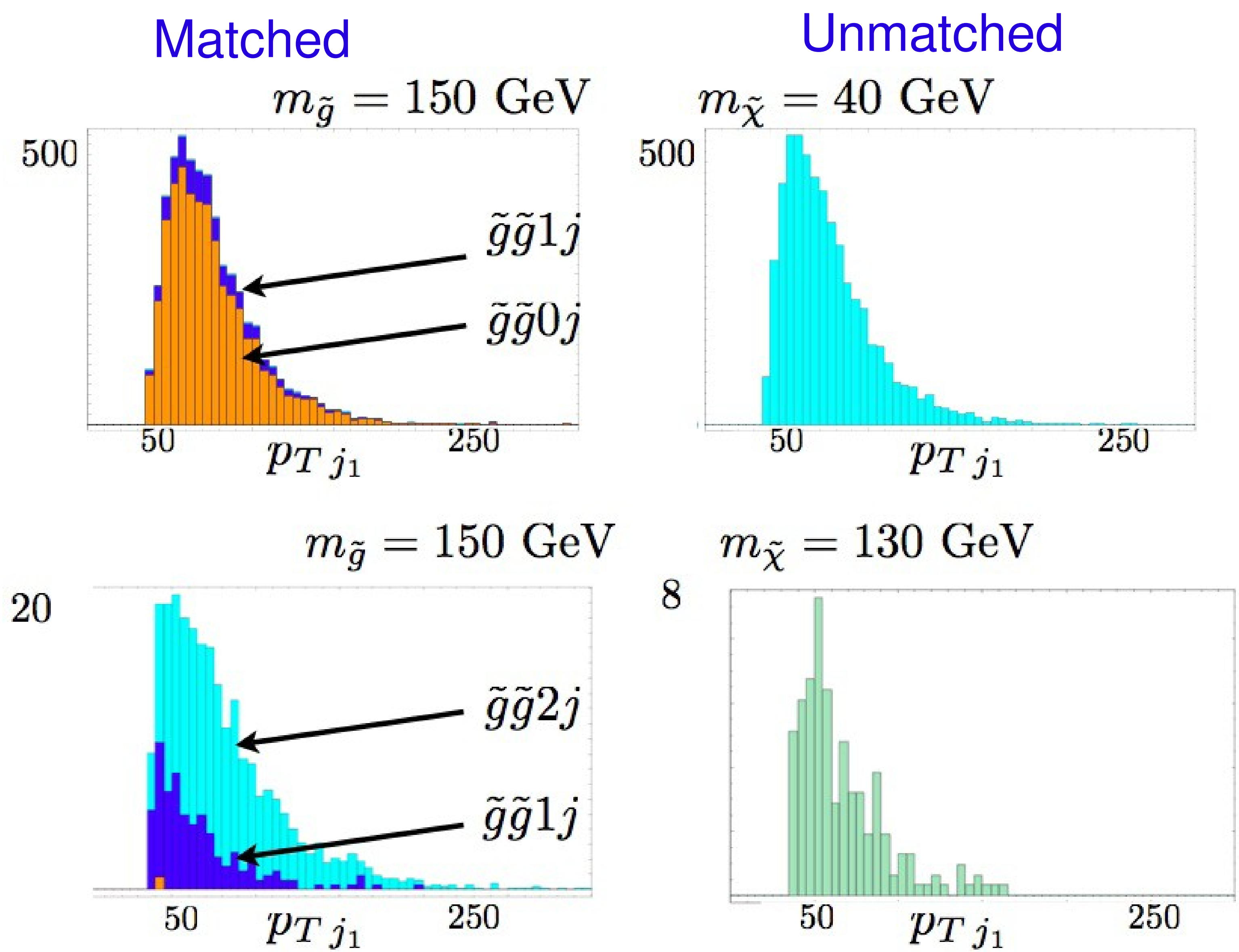


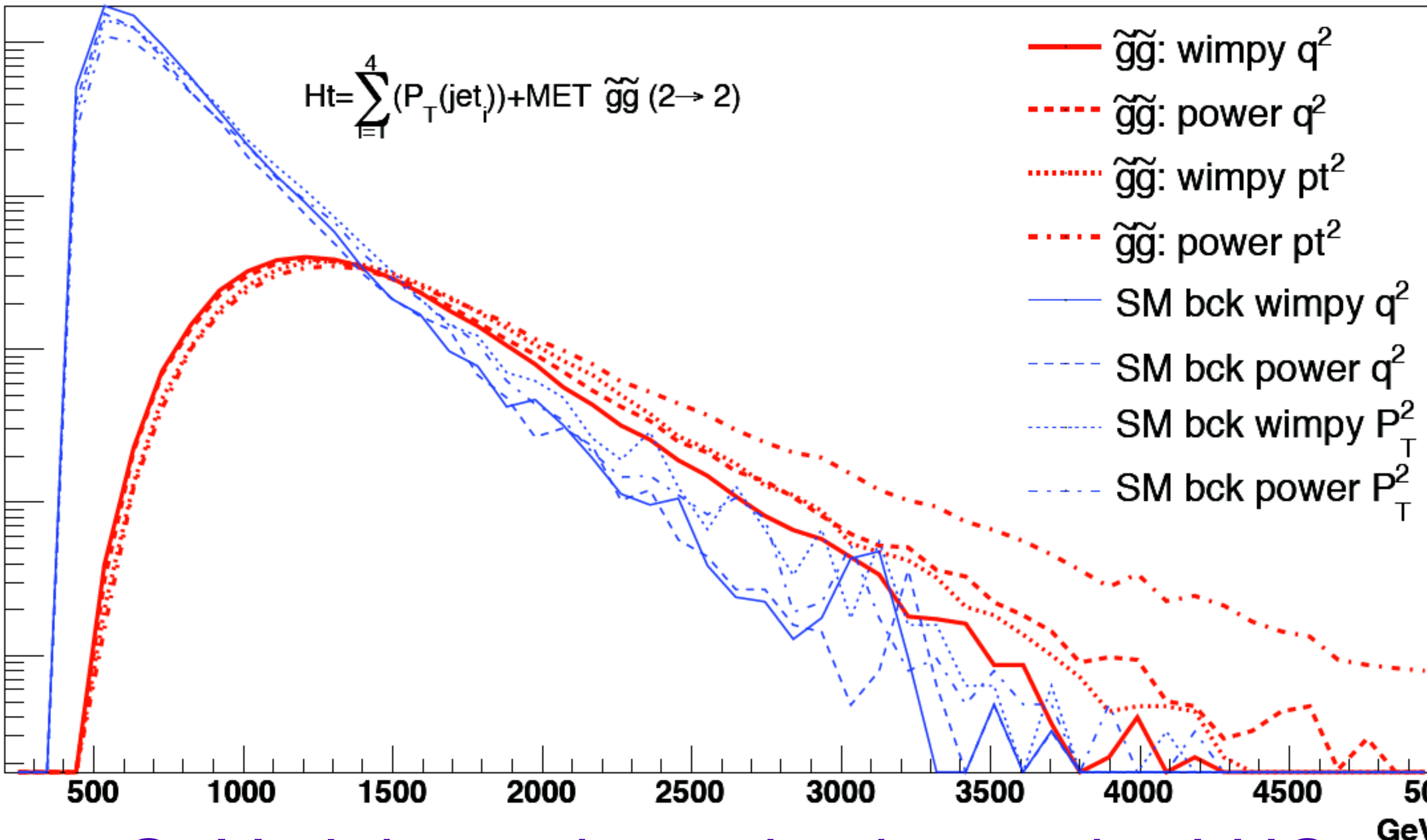
Tevatron, after 2-jet and missing E_T cuts

Matching for heavy gluinos/squarks

[JA, de Visscher, Maltoni, in progress]

See talk by S. de Visscher in PS 2

Impact after decay (4-jet H_T) - unmatched



600 GeV gluino pair production at the LHC

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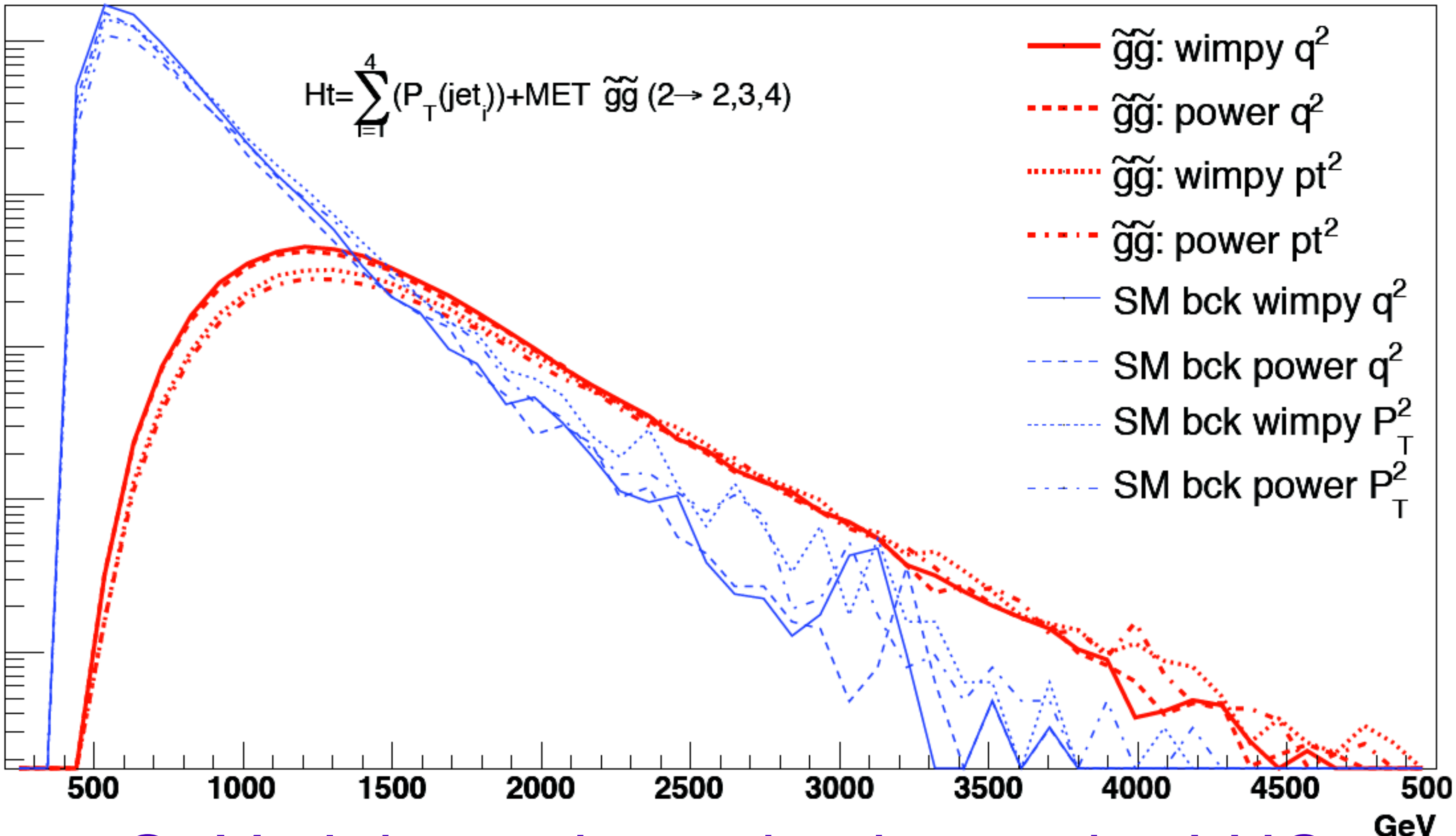
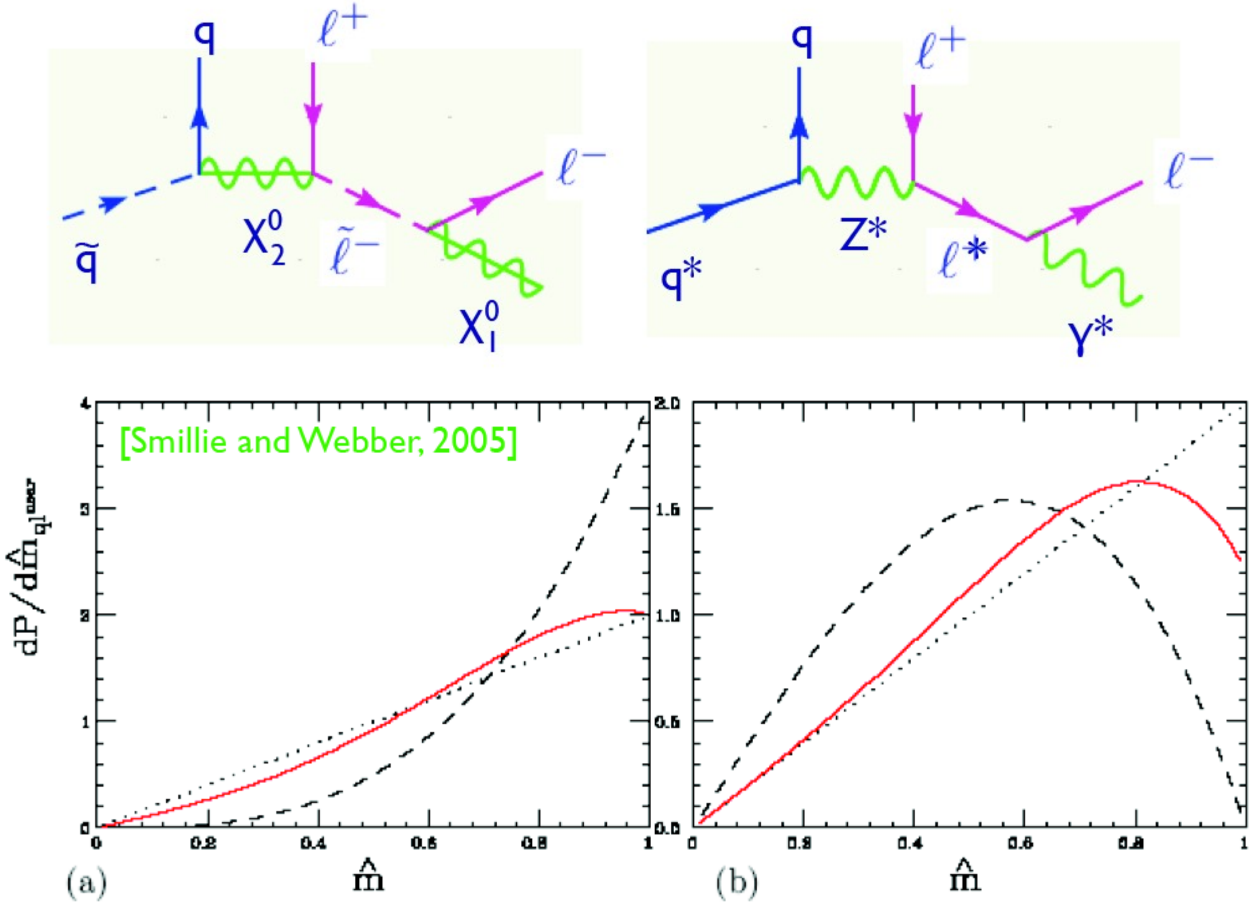


600 GeV gluino pair production at the LHC

SUSY vs. UED – spin effects

Long decay chains give information on intermediate particle masses and spins through edge and endpoint positions and shapes



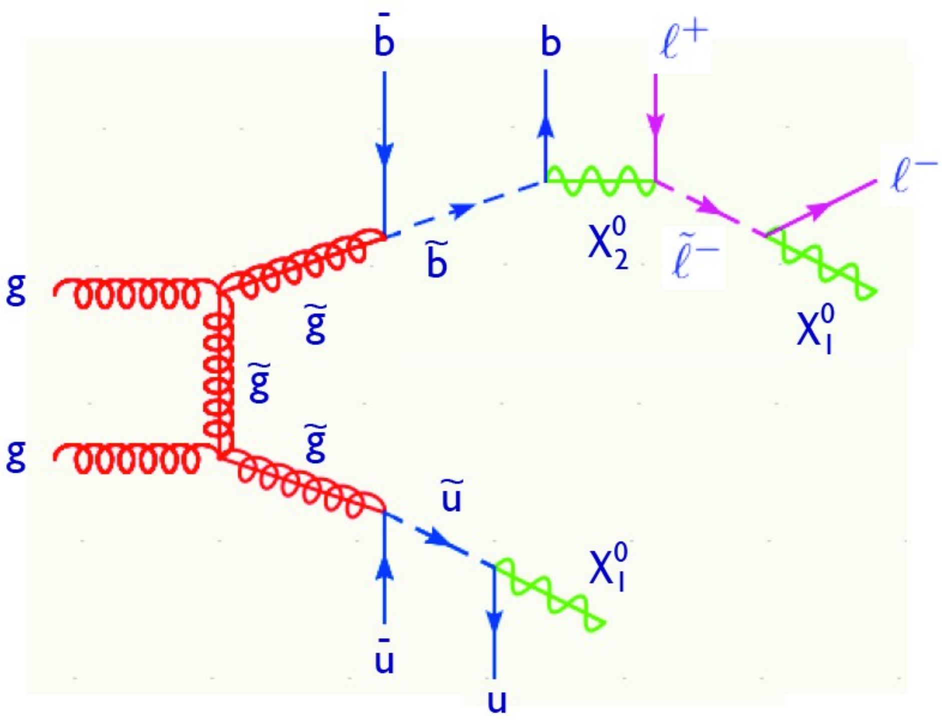
Beware of common simplifications:

1. Production and decay factorized
2. Spin ignored
3. Chains only through 1 → 2 decays.
4. Narrow width approximation employed.
5. Non-resonant diagrams ignored.

Decay chains

[JA, T. Stelzer]

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



1. Full matrix element with all correlations between production and decay
2. $1 \to N$ decays possible
3. BW for all resonances
4. Non-resonant contributions can be included only where relevant

Decay chains

[JA, T. Stelzer]

```
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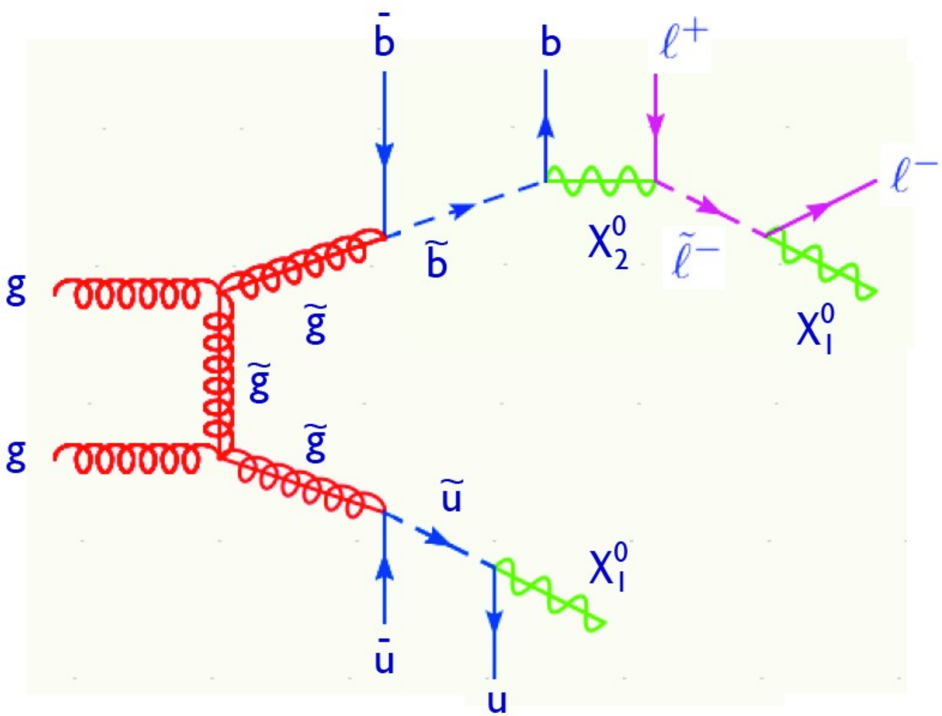


1. Full matrix element with all correlations between production and decay
2. 1 → N decays possible
3. BW for all resonances
4. Non-resonant contributions can be included only where relevant

Example safe simplification: factorize process at scalar decay

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

Decay scalars at event level with MG or BRIDGE

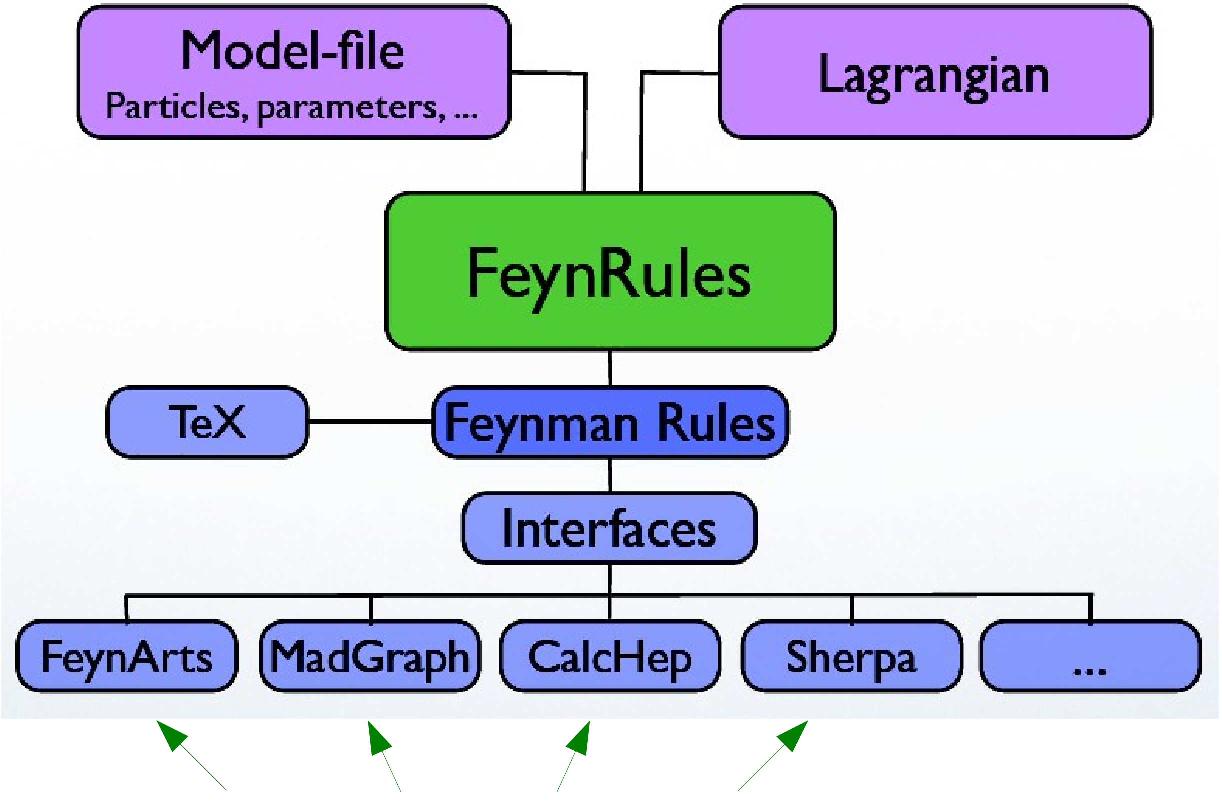
[P. Meade, M. Reece, 2007]

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

FeynRules

[Christensen, Duhr + MC collaborators]

New tool (Mathematica package) to extract Feynman rules and couplings directly from Lagrangian + Generation of MC files



Interfaces available

FeynRules

[C. Duhr + MC collaborators]

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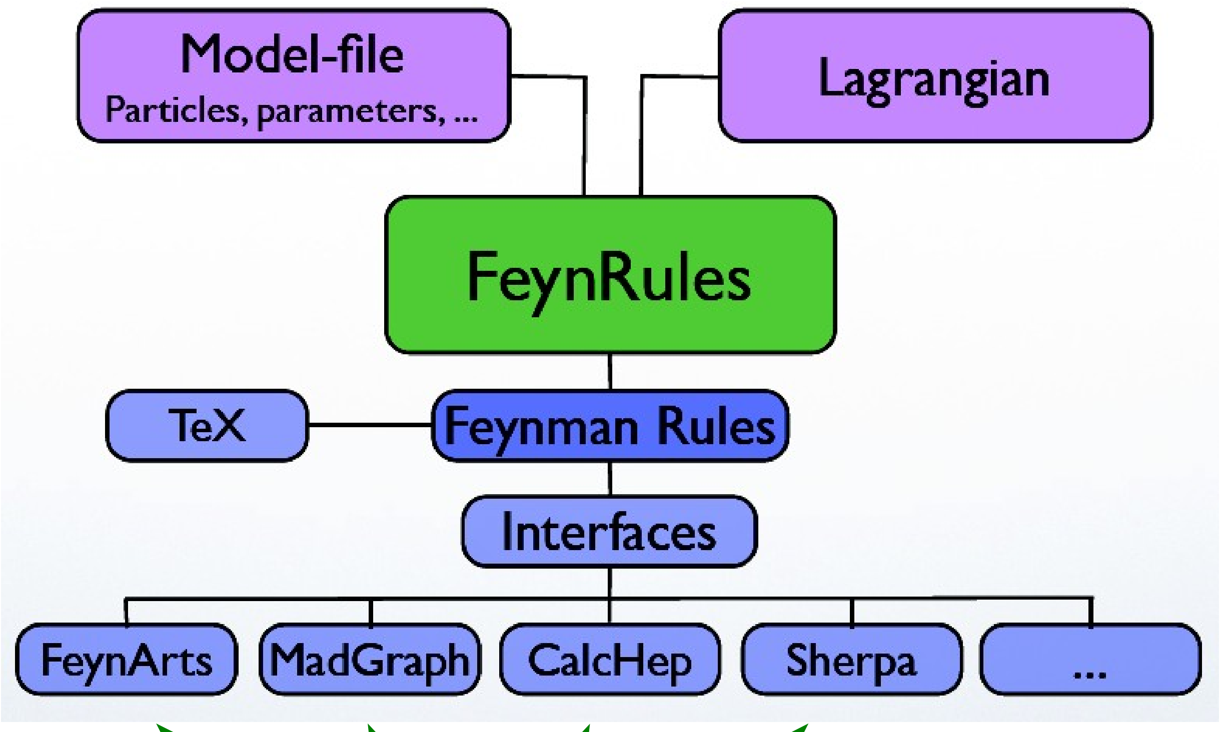

$$
\begin{aligned}
\kappa^{-1}\mathcal{L}_{\mathrm{F}}^{\vec{n}}(\kappa) \;=\; & \frac{1}{2}\Big[(\tilde{h}^{\vec{n}}\eta^{\mu\nu} - \tilde{h}^{\mu\nu,\vec{n}})\overline{\psi}i\gamma_\mu D_\nu\psi \\
& - m_\psi \tilde{h}^{\vec{n}}\overline{\psi}\psi + \frac{1}{2}\overline{\psi}i\gamma^\mu(\partial_\mu\tilde{h}^{\vec{n}}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

Interfaces available

...

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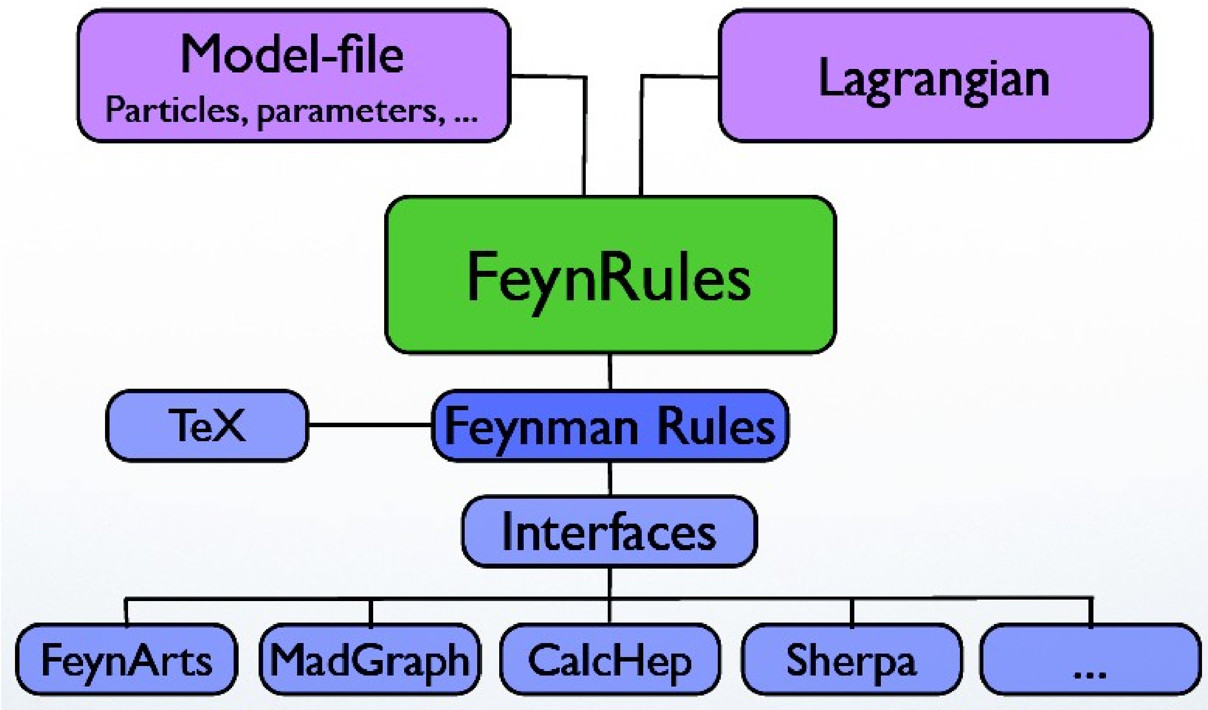
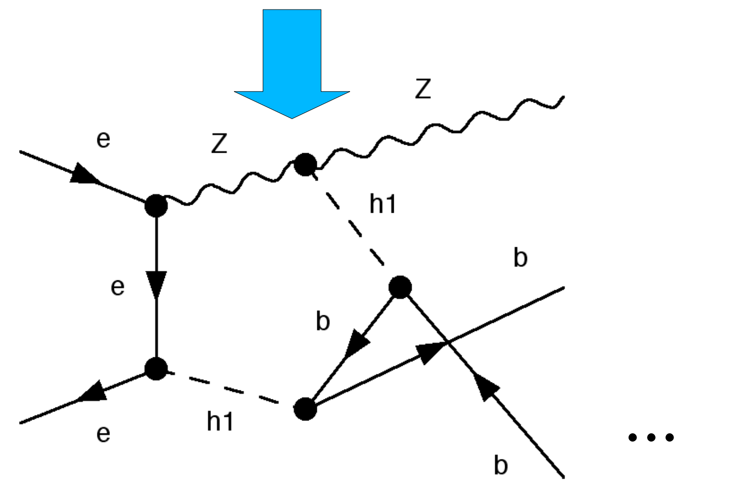


Interfaces available

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



...

FeynRules

[C. Duhr + MC collaborators]

- Example models implemented
  - Standard Model
  - 3-site Model
  - Higgs effective theory
  - Partial supersymmetric models
- Extensive testing between MG/ME and CalcHEP/CompHEP (FR outputs and stock versions)
- Full MSSM under testing and UED underway
- Trivial to make changes (e.g. NMSSM) which would be very work-intensive in stock versions!

Conclusions

- LHC poses new challenges to the MC community
- Continuous developments necessary
- MadGraph/MadEvent approach:
  - Building a community
    - Web based : public clusters with personal DB's, Twiki, open CVS repository.
    - Support to spin-offs, independent projects, and custom MC needs (Ex: BRIDGE, FeynRules, NLO, BSM implementations, ...)
  - Providing a fully-fledged platform for physics studies at colliders
    - Complete (staged) simulation chain via web + Grid version
    - SM and BSM : signal and backgrounds (including multi-jet samples with ME/PS merging)
    - TH and EXP tools : StandAlone, ExRootAnalysis, MatchChecker, MadWeight,...

Backup slides

Automatic dipole subtraction

[R. Frederix, N. Greiner]

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

- Goal: Automatic divergence subtraction for reals of any NLO calculation
  - Catani-Seymour subraction scheme
  - Both for SM and BSM
  - Compatible also with MG standalone
- Alpha version (FS dipoles) working
  - IS-FS and IS-IS dipoles in bugfix mode

MadWeight

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

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

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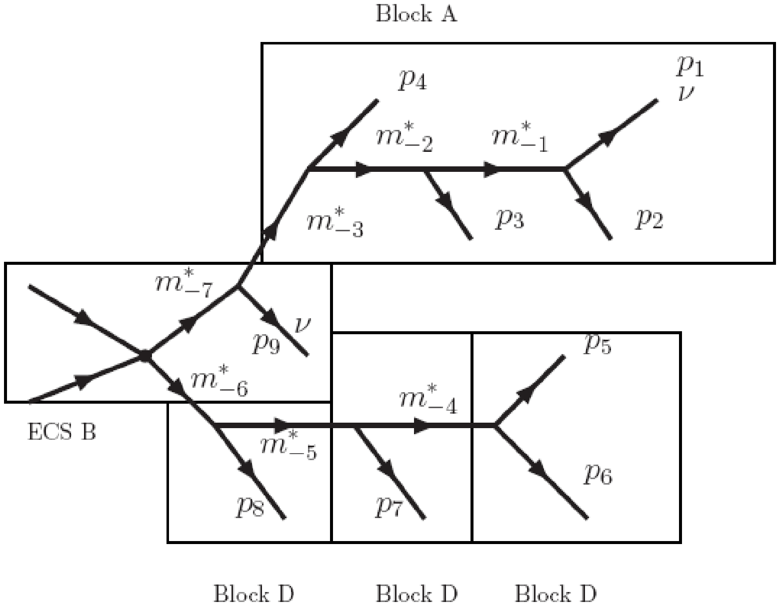

Phase space integration using automatic change to variables aligned with peaks

MadWeight

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

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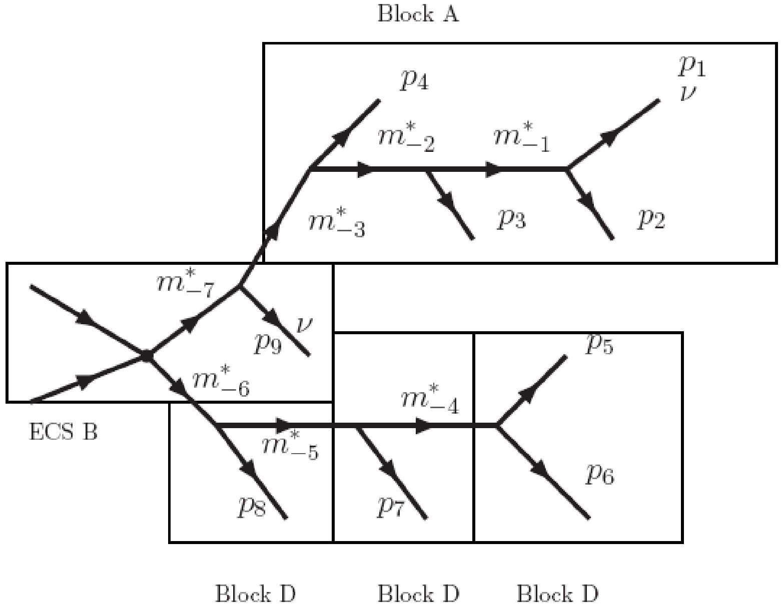

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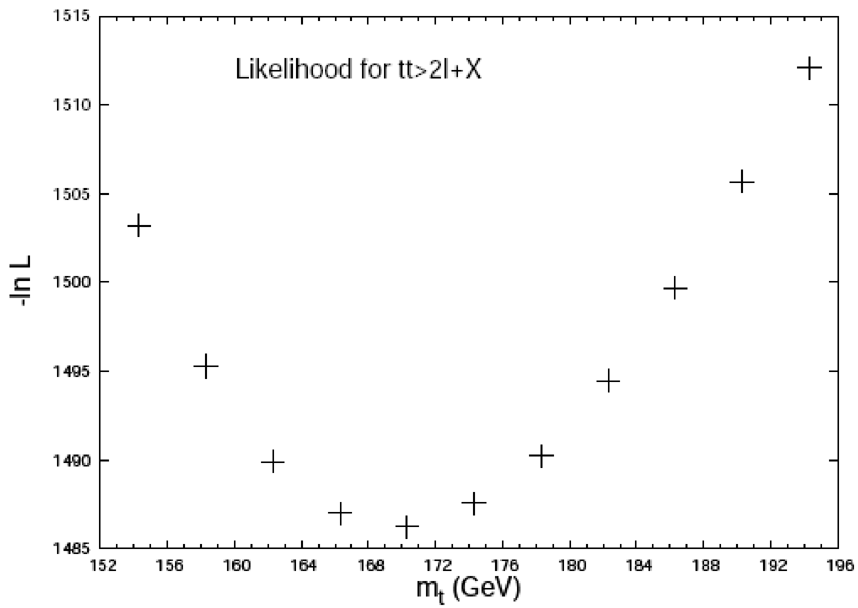


Find likelihood for model parameters (here top mass)

MG/ME on the Grid

[Mad team]

- Optimized/specialized code for given process
- MG code creation as usual
- Selection of parameters (cards) as usual
- Train grids + get relative subprocess cross sections once and for all in a “gridpack”
- Quick and efficient generation of few events on single machine – only run relevant channels
- Only input: random seed, number of events

LHC event samples

[Mad team, see MadGraph Wiki]

- Provide set of samples for key SM and BSM processes at LHC including Pythia+PGS simulations
- Started generation of matched LHC backgrounds
  - W/Z/a + jets; top pairs + jets; QCD, b pairs + jets; Higgs + jets; VVV, single top, VBF, ...
- Small-size (1M) event sample + Grid code
- Samples validated by MC authors
  - Used by experiments as reference
  - Used by theorists for semi-realistic proto-analyses

More about matching in MG

Shower kT scheme

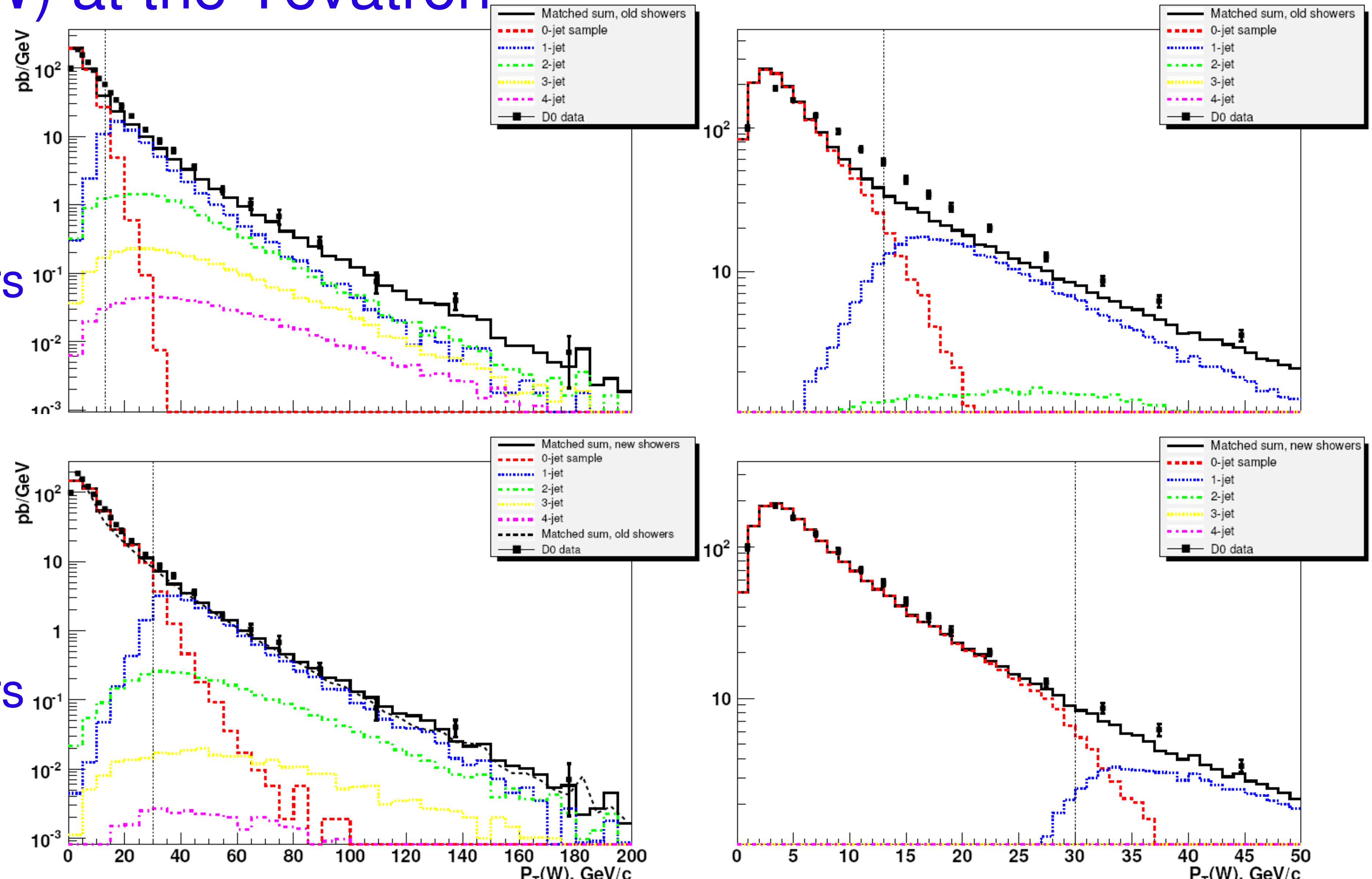
- Keep/reject event based on k_T of hardest shower emission (as reported by Pythia)
- Highest multiplicity treatment as in CKKW, use min dparton as cutoff
- No jet clustering
- No need of "fiducial region", can use $k_T^{match} = d_{cut}^{ME}$
- Need similar kT definitions in ME and PS (only "new", p_T-ordered showers at present)

Difference between Pythia showers

$p_T(W)$ at the Tevatron

“Old” Pythia showers

“New” Pythia showers

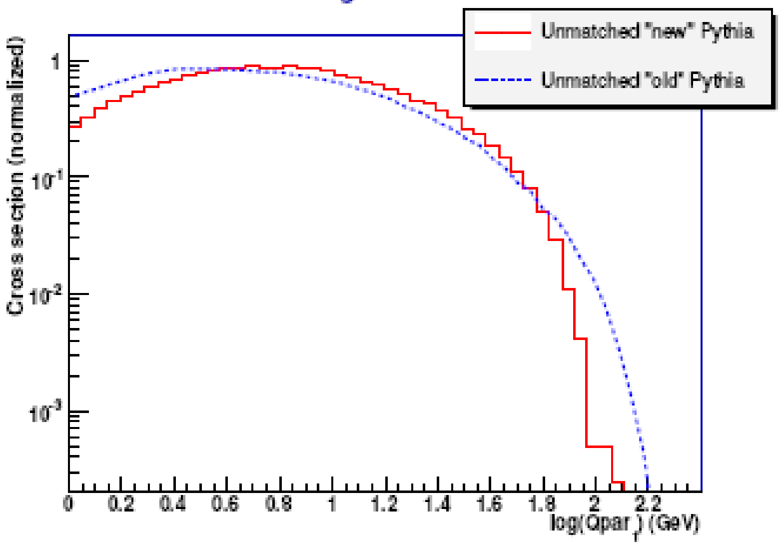


Tail well described by both (given by ME) but head quite different

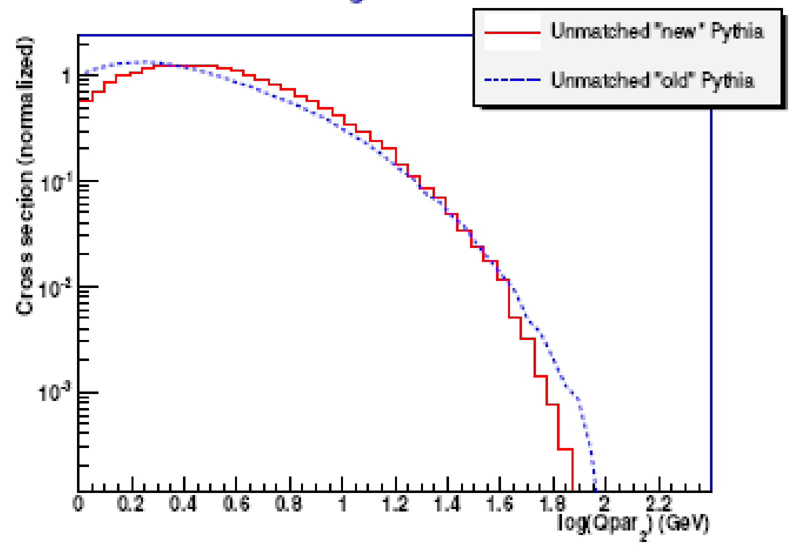
Comparisons between old and new Pythia showers

Differential jet rates in W production at the Tevatron

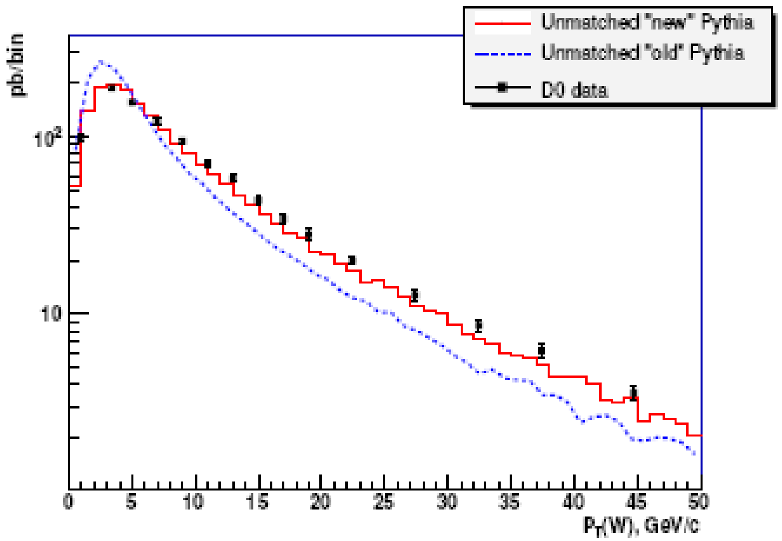
$0 \longrightarrow 1$ jet rate

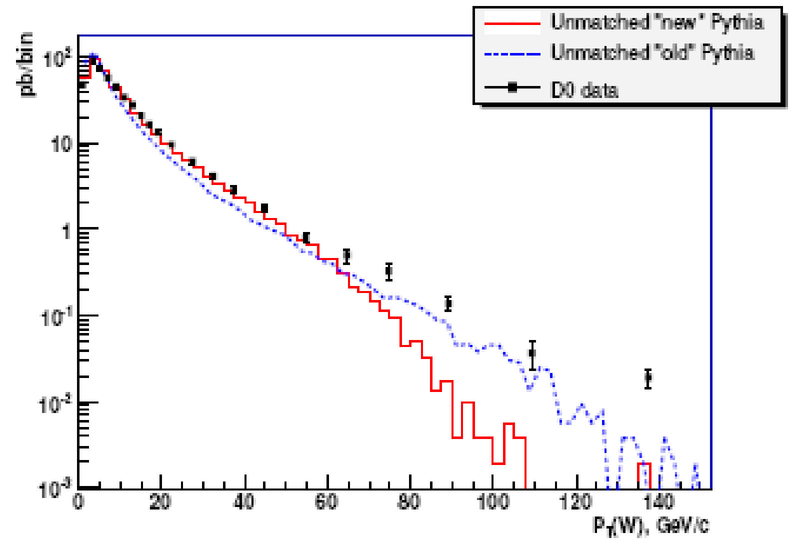


$1 \longrightarrow 2$ jet rate



$p_T(W)$ in W production at the Tevatron





Model building with FeynRules

- Step 1: Add all the parameters of the new sector to the model file:

```
f1 == {Value -> 600,
      InteractionOrder -> {QED, -1}},

l1 == {Value -> 0.25,
       InteractionOrder -> {QED, 2}},

ca == {Value -> 0.896242},
```

ca: Cosine of the mixing angle

$$L = -\frac{1}{2}(D_\mu\Phi)^\dagger(D_\mu\Phi) - \frac{\lambda_0}{8}(\Phi^\dagger\Phi - f_0^2)^2 - \frac{1}{2}(\partial_\mu H)^2 - \frac{\lambda_1}{8}(2f_1 H - \Phi^\dagger\Phi)^2$$

Slides from C. Duhr, MC4BSM 2008

Model building with FeynRules

- Step II: Add all the particles of the new sector to the model file:

Mass eigenstate

```
S[1] == {
  ClassName -> h1,
  SelfConjugate -> True,
  Mass -> {Mh1, 78.5}},

S[2] == {
  ClassName -> H,
  SelfConjugate -> True,
  Unphysical -> True,
  Definitions -> {H -> sa h1 +ca h2}}
```

Mixing

$$L = -\frac{1}{2}(D_\mu\Phi)^\dagger(D_\mu\Phi) - \frac{\lambda_0}{8}(\Phi^\dagger\Phi - f_0^2)^2 - \frac{1}{2}(\partial_\mu H)^2 - \frac{\lambda_1}{8}(2f_1 H - \Phi^\dagger\Phi)^2$$

Slides from C. Duhr, MC4BSM 2008

Model building with FeynRules

- Step III: The lagrangian describing the new sector (Unitary gauge)

```
Φ = {0, h + f0}

LHill = -1 / 2 del[H, mu] ^2 -
   l1 / 8 (2 f1 H - HC[Φ].Φ) ^2
```

$$-\frac{1}{2}\,\partial_{\mathrm{mu}}(H)^2 - \frac{1}{8}\,\mathrm{l1}\left(2\,\mathrm{f1}\,H - \Phi^{\dagger}.\Phi\right)^2$$

$$L = -\frac{1}{2}(D_\mu\Phi)^\dagger(D_\mu\Phi) - \frac{\lambda_0}{8}(\Phi^\dagger\Phi - f_0^2)^2 - \frac{1}{2}(\partial_\mu H)^2 - \frac{\lambda_1}{8}(2f_1 H - \Phi^\dagger\Phi)^2$$

Slides from C. Duhr, MC4BSM 2008

Phenomenology with FeynRules

- The results obtained by FeynRules can be easily exported to FeynArts:

```
WriteFeynArtsOutput["HillModel.mod",{LSM + LHill}, FlavorExpand → SU2W]
```

– – – FeynRules interface to FeynArts – – –

C. Duhr, 2007

- This produces a FeynArts model-file which can be read by FeynArts.

```
topo = CreateTopologies[1, 2 → 3,
   ExcludeTopologies → Internal];
Amp = InsertFields[topo,
        {F[2, {1}], -F[2, {1}]} → {V[2], F[4, {3}], -F[4, {3}]},
        Model → HillModel];
```

- The results obtained by FeynRules can be easily exported toMC generators:

```
WriteMGOutput[LSM + LHill]
```

– – – FeynRules interface to MadGraph – – –

C. Duhr, M. Herquet

- Etc.

Slides from C. Duhr, MC4BSM 2008