New Physics, QCD radiation and MadGraph/MadEvent

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for the MadGraph Team

CalTech, Pasadena, 11 May 2009

NATIONAL ACCELERATOR LABORATORY

Imagine a simulation program which can simulate **any process** in **any model** with good efficiency and minimal risk for errors?

Too good to be true?

Imagine a simulation program which can simulate **any process** in **any model** with good efficiency and minimal risk for errors?

Too good to be true?

It exists!

(or something very close)

(and is easy to use)

MadGraph/MadEvent

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

Matrix element event generation of any process:

- User requests a process (ex. pp>tt~jjj) and the corresponding code is generated on the fly
  (up to 10 external particles, max. 10K diagrams)
- User inputs model/collider-parameters/cuts, and code runs in parallel on our farms or locally
- Returns cross section, parton-level events, plots
- Limitations:
  - Optimization on single procs limited by generality
  - Tree-level amplitudes, based on Feynman diagrams

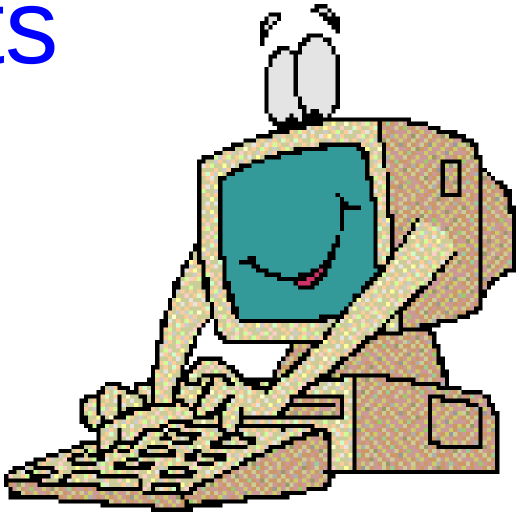
MadGraph/MadEvent v. 4

[JA et al., arXiv:0706.2334]

- Complete web simulation: MadEvent → Pythia → PGS
- Personal web databases
- Multiple processes in single 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
- Analysis platforms: ExRootAnalysis and MadAnalysis

How do I use MG/ME 4?

1. Open your browser
2. Go to one of our sites
3. Create a process
4. Generate events



Sounds easy? It is!

Let me show you!

Our ambition

TH

EXP

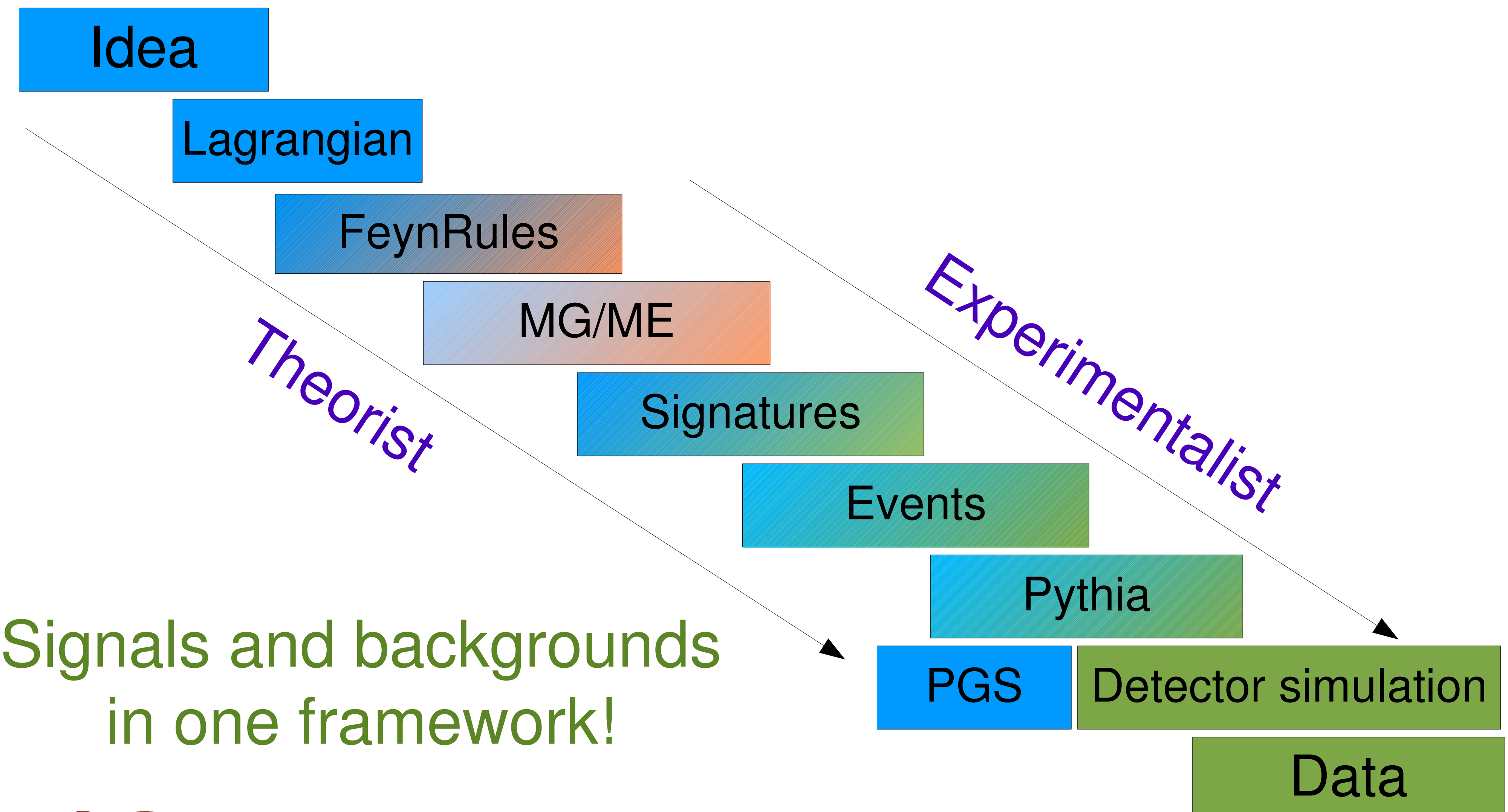
Idea

A framework to go from theoretical idea to data comparison

Data

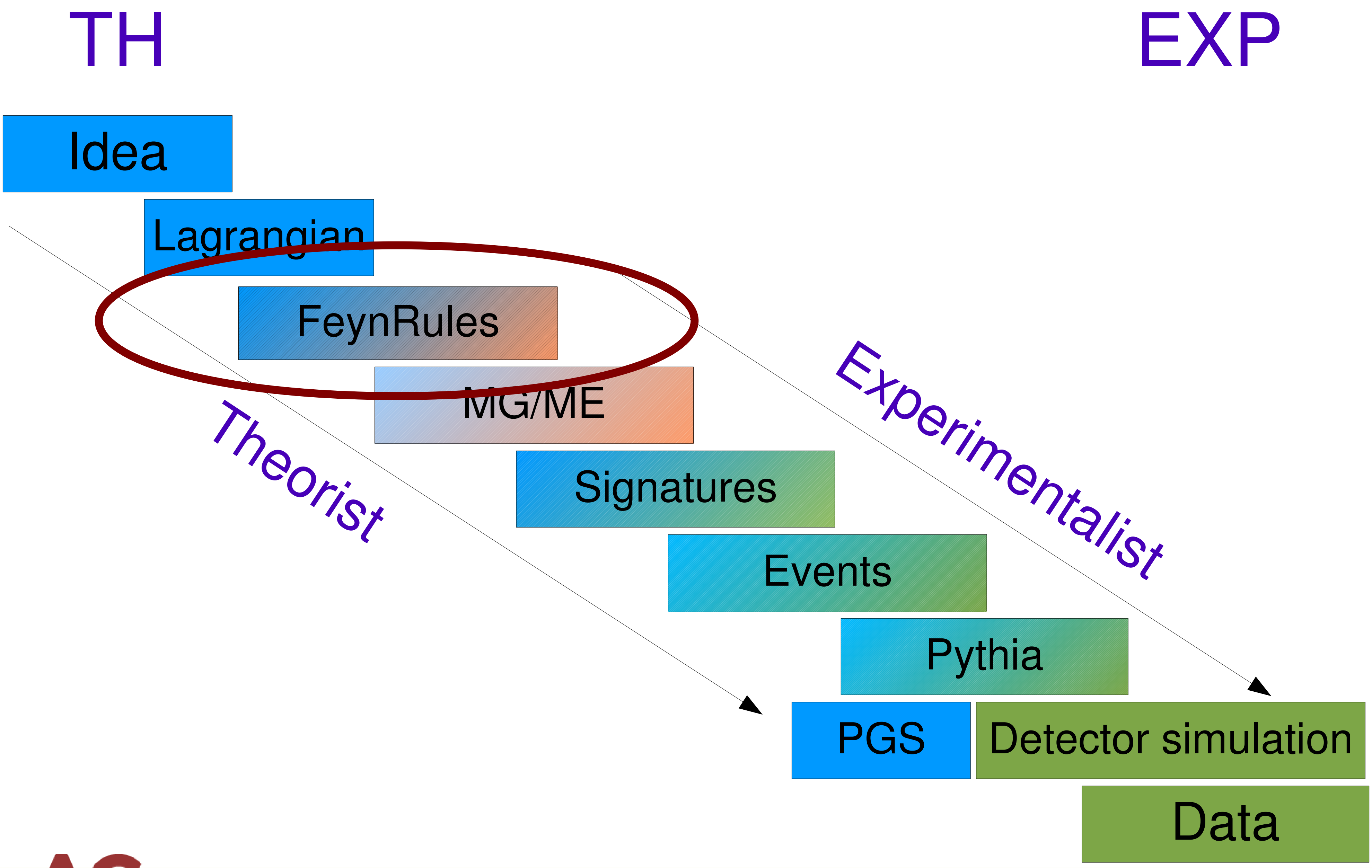
Freeway from theory to experiment

TH EXP



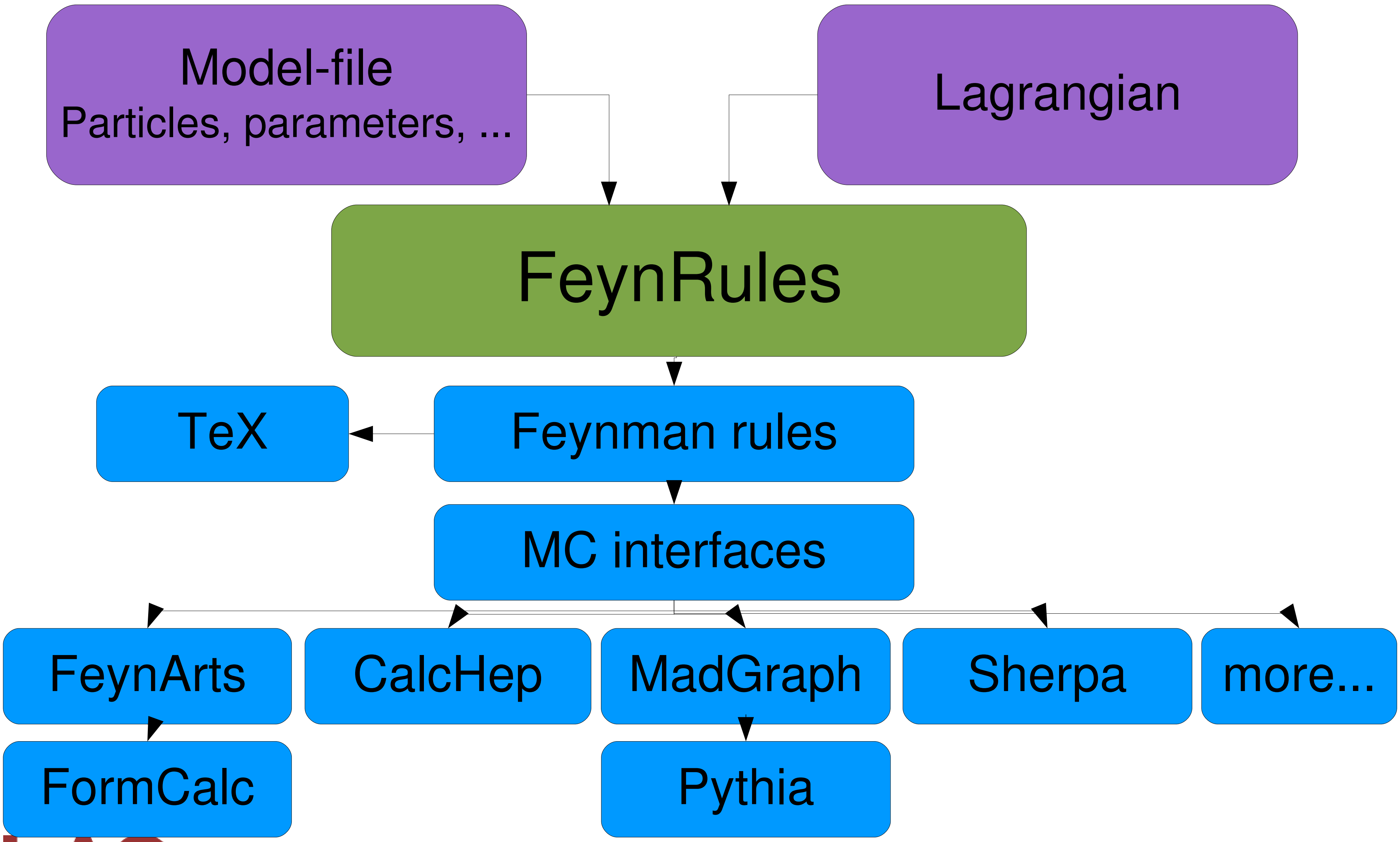
Signals and backgrounds in one framework!

Freeway from theory to experiment



FeynRules

[Christiansen, Duhr, arXiv:0806.4194]

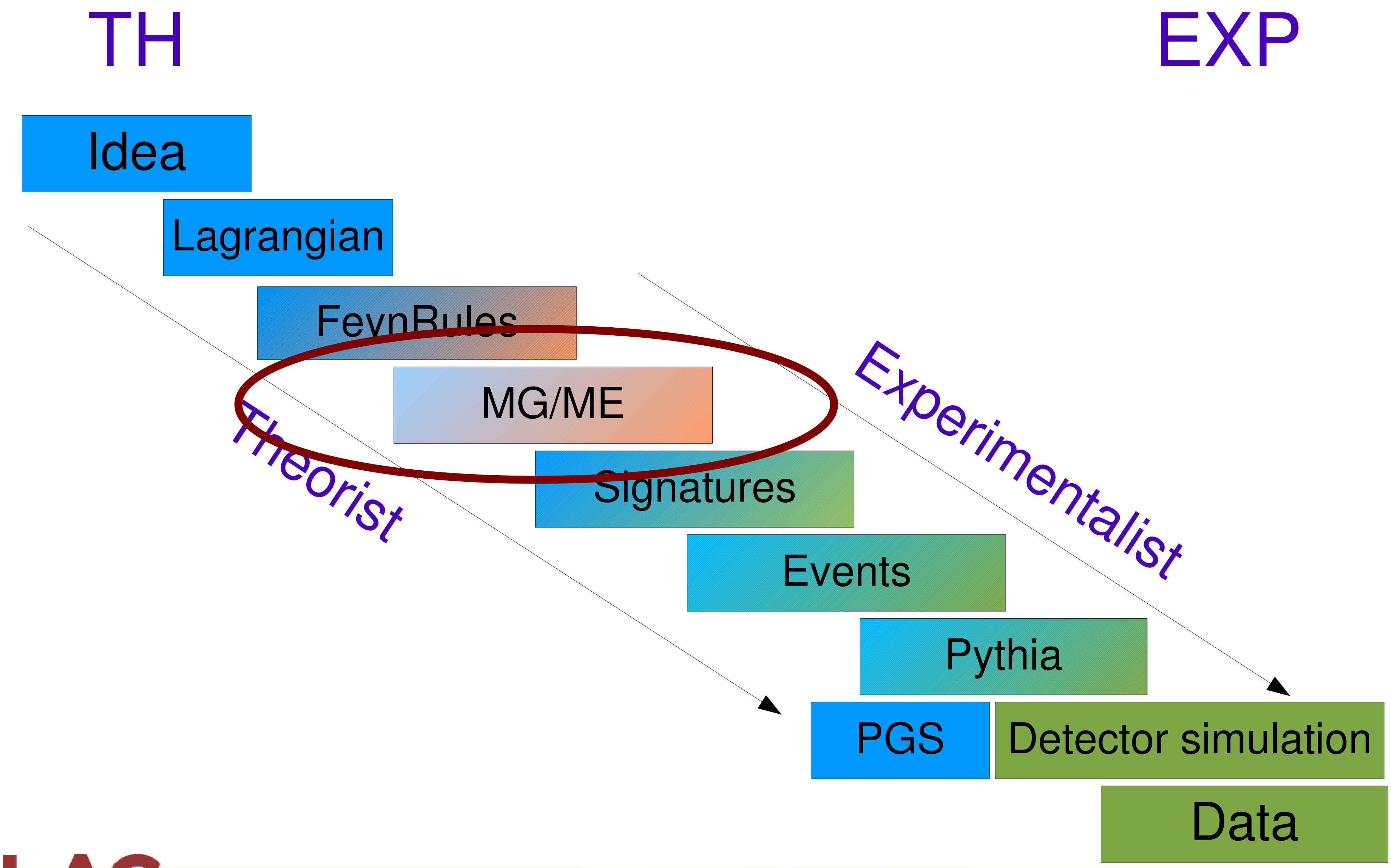


FeynRules

[Christiansen, Duhr, arXiv:0806.4194]

- Mathematica package for derivation of Feynman rules from any Lagrangian
- Specify model content (particles, coupling relations) and Lagrangian
- Interfaces to MC tools
  - Theory tools: FeynArts/CalcHep/MadGraph (loops, DM constraints, parton level MC/plots)
  - Experimental tools: MG/ME, Sherpa (already in exp. frameworks)

Freeway from theory to experiment



Recent developments (after v. 4.0)

- Matching for SM&BSM processes [JA]
- Staged web simulation :
  LHEF → Pythia → PGS [JA et al.]
- Decay chain specifications [JA, T. Stelzer]
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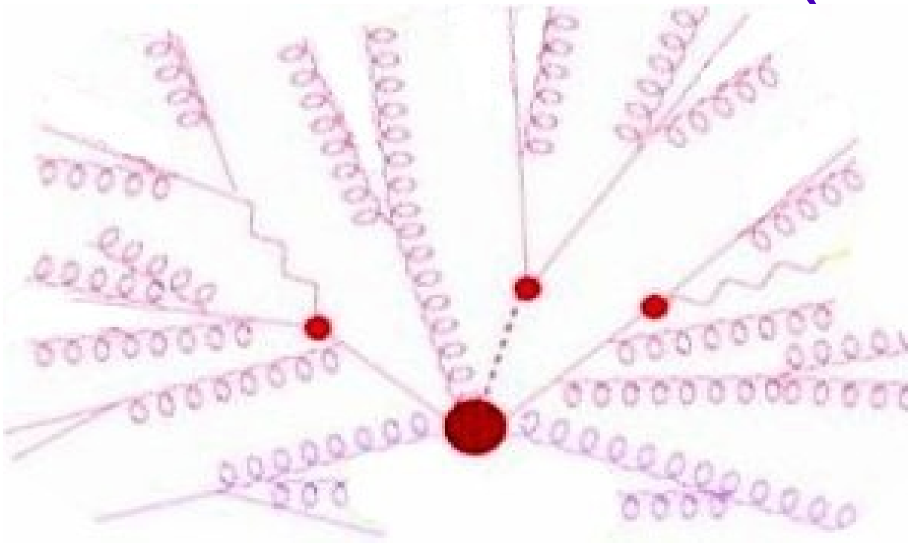
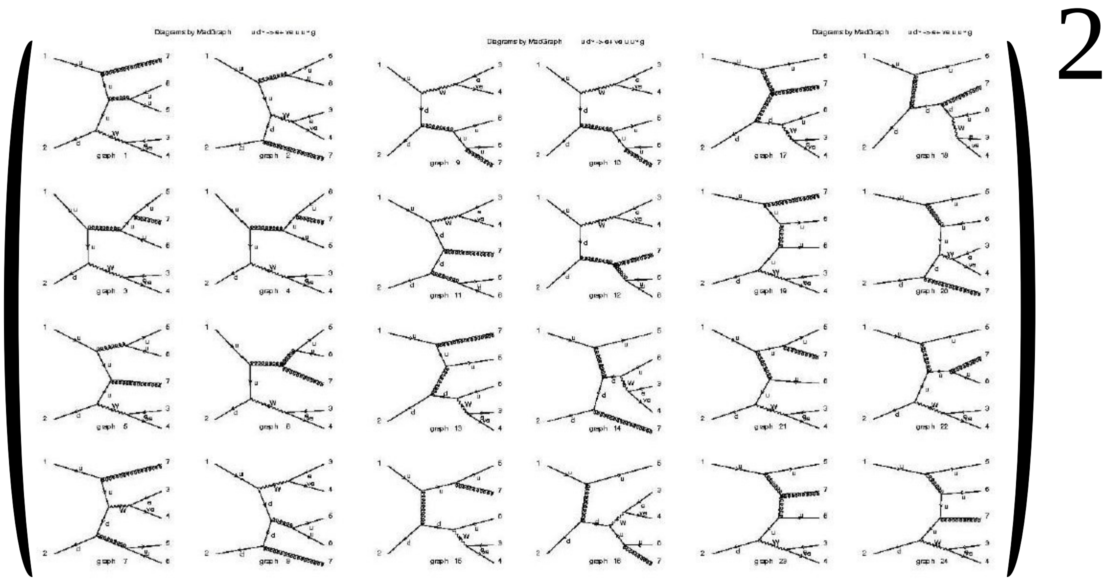
Parton Showers (PS)



- Based on soft-collinear approximation
- Step-by-step subsequent QCD emissions
  - Fast, computationally cheap (1→2 splittings)
  - No limit on particle multiplicity
- Necessary for interfacing to hadronization
- Formally correct only close to collinear region

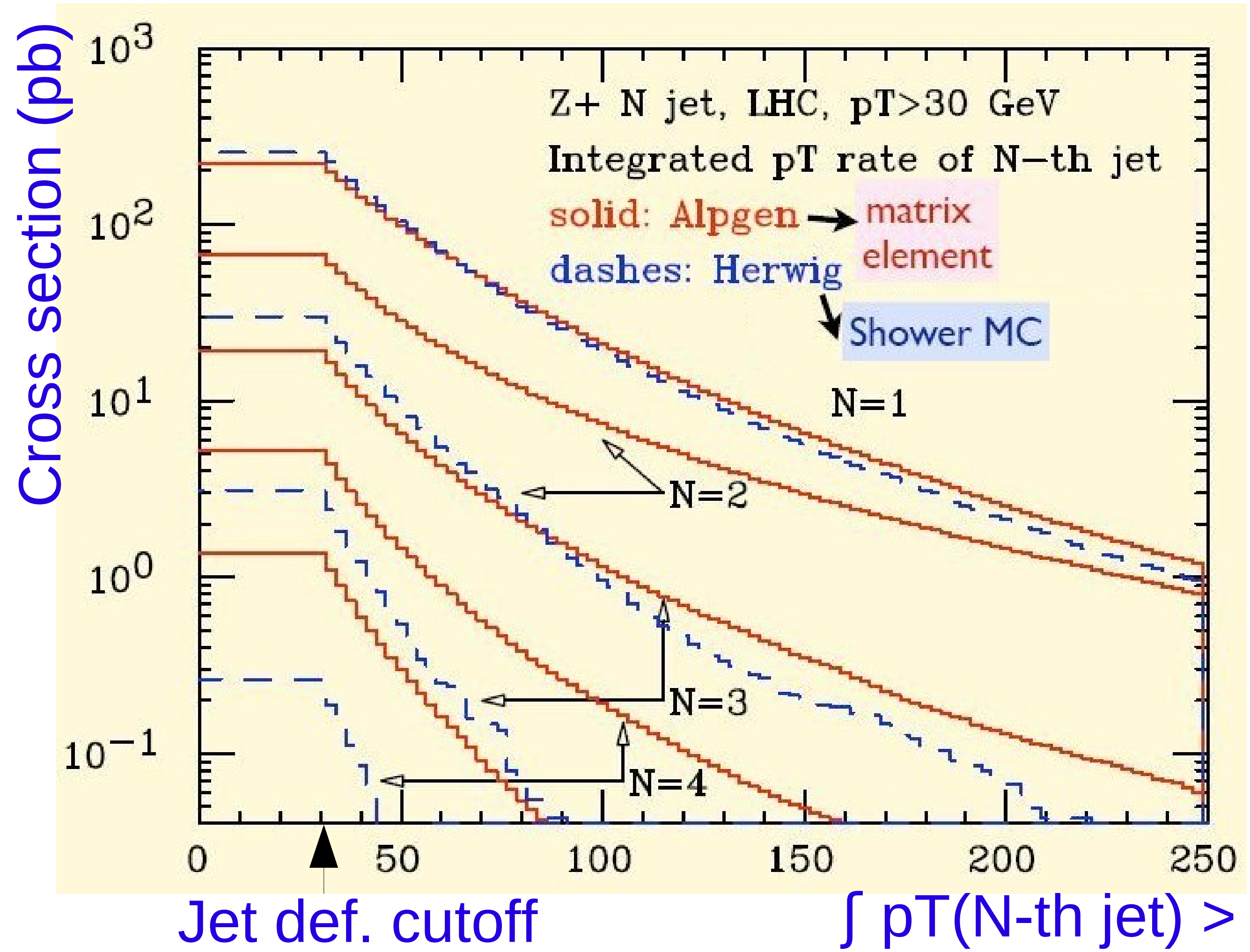
Matrix Elements (ME)



Diagrams for $u\bar{d} \to e^+\nu_e u\bar{u}g$ by MadGraph

- Correct description away from the collinear region
  - diverges in the collinear region
- Includes interference and finite terms
- Necessary for calculation of high-energy jets
- Fixed particle multiplicity
- Slow, computationally heavy

Importance of Matrix Elements



Parton showers get multiple hard jet production from QCD radiation wrong by orders of magnitude

Matching ME and PS

Difficulties combining the two descriptions:

- Same phase space configuration can be described by both n+1-parton ME event and n-parton event + PS
  → Double counting
- Transition between ME and PS should be smooth
- Cross section should not be affected
- Minimize dependence on highest ME multiplicity

Solutions:

- Catani, Krauss, Kuhn, Webber [2001]
- Lönnblad [2001]
- M.L. Mangano [2002, 2006]

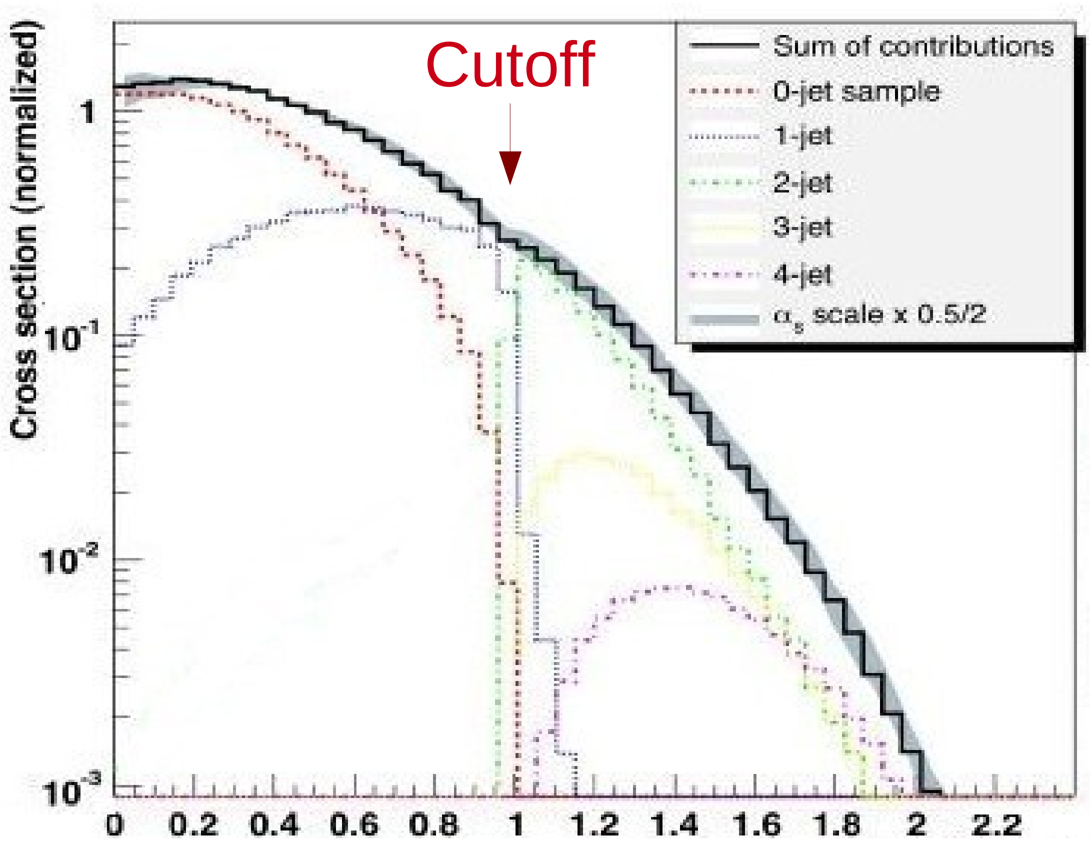
Matching ME and PS

Common approach for all matching schemes:

- Separate "hard jet" and "soft/collinear jet" regions using phase-space cutoff
- Allow ME jets to populate only "hard" region and PS emissions only "soft" region
- Modify ME description to mimick the parton shower near the cutoff
  - Reweighting of α_s in each emission vertex
  - Sudakov reweighting to account for no PS emissions in hard region and ensure stable cross section

Done differently in different schemes

Results of matching

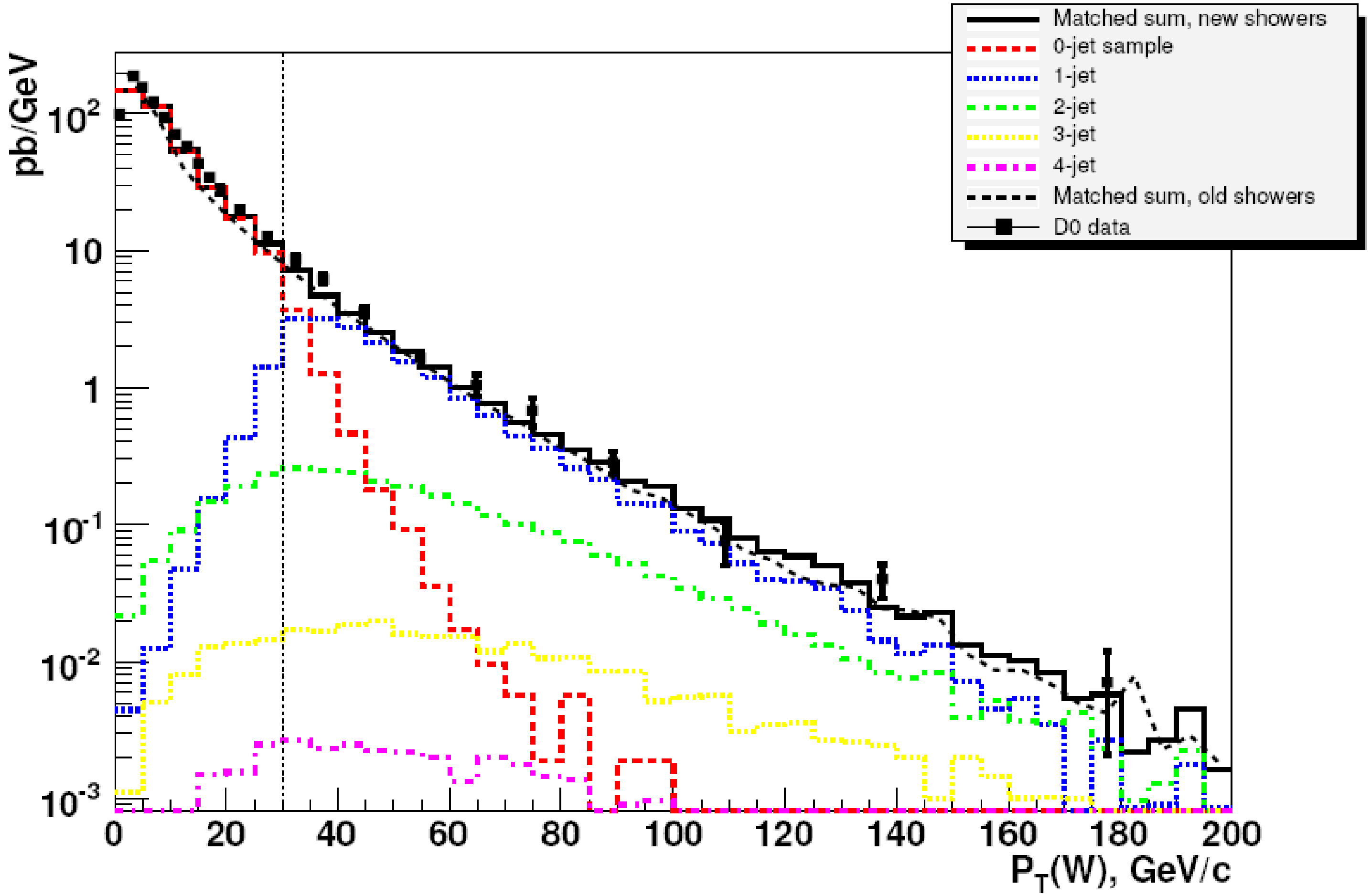


log(Jet resolution scale for 1 → 2 radiated jets ~ p_T(2^{nd} jet))

W+jets production at the Tevatron
MadEvent+Pythia (k_T-jet MLM scheme)

Comparison with Tevatron data

$p_T(W^{+/-})$ at the Tevatron



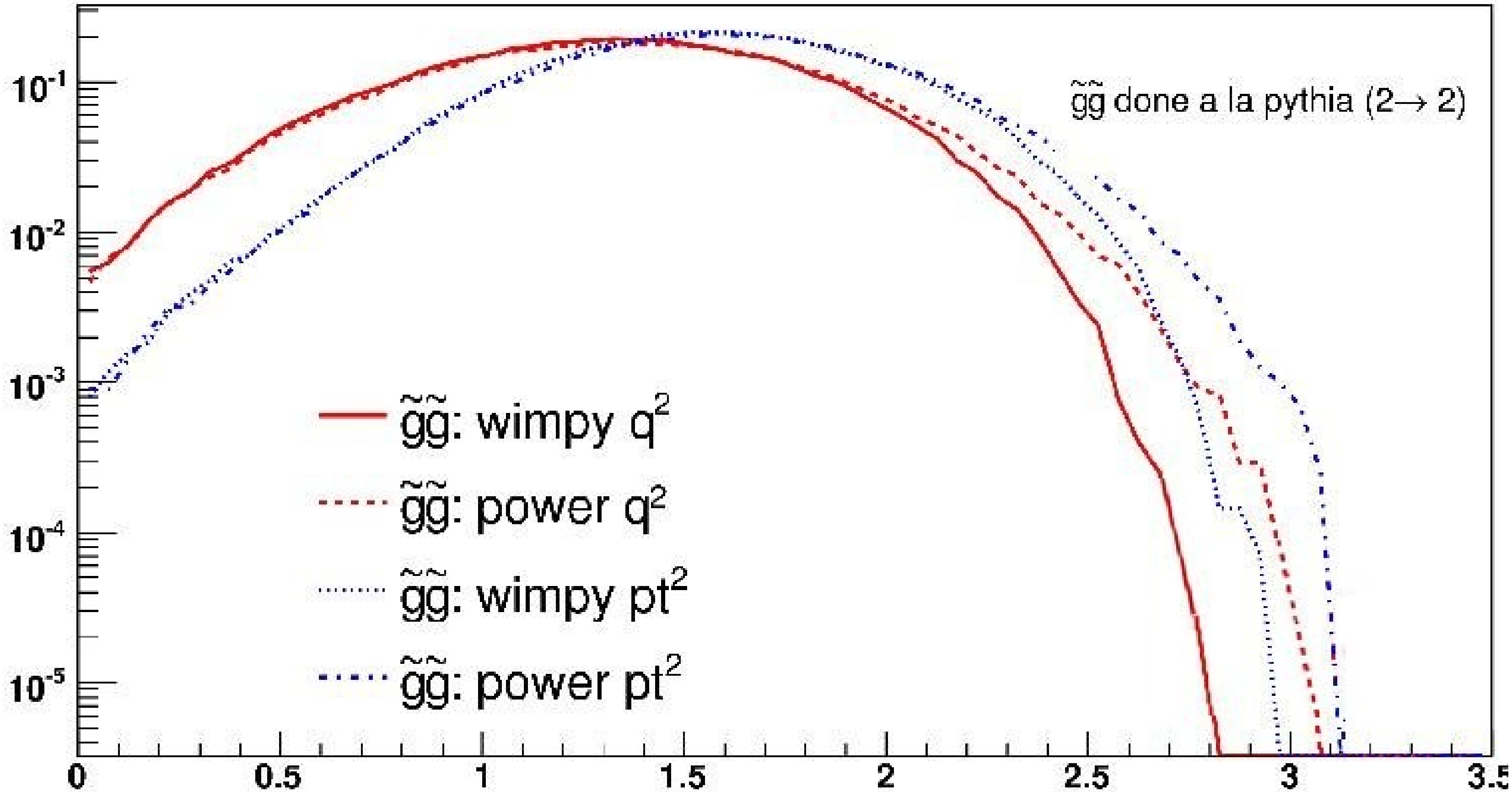
Matching in New Physics production

JA, de Visscher, Maltoni [arXiv:0810.5350]

- We know that matching of ME+PS is vital for jet production in SM backgrounds
- But is it relevant for heavy BSM particle production?
  - Very hard jets from decays
  - Parton showers expected to be more accurate for larger masses
  - Using gluino and squark production as example
- Turns out there are many cases where matching is necessary for precise description!

Shower parameter dependence

QCD radiation for different Pythia shower params

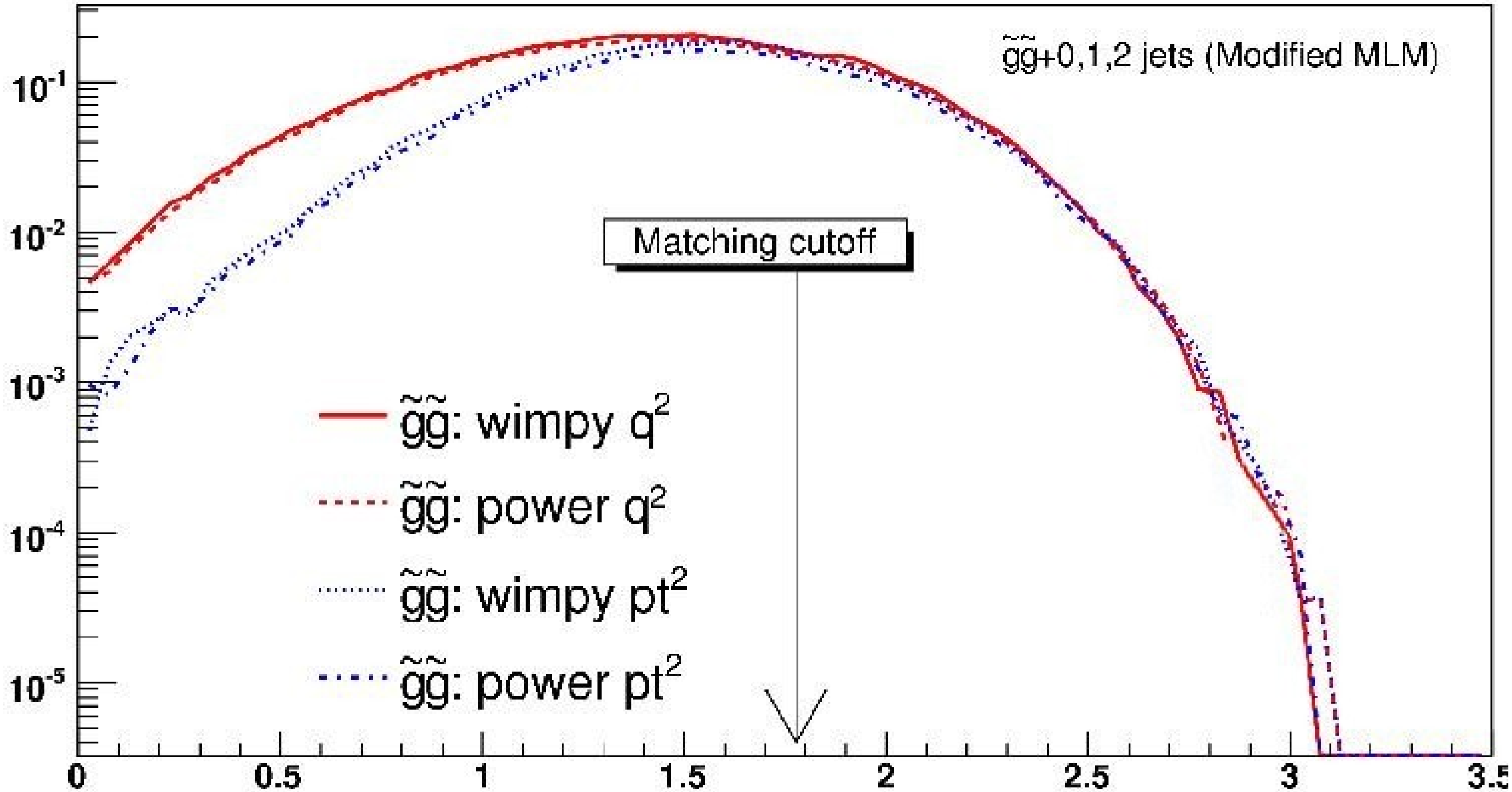


log(Jet resolution scale for 1 → 2 jets) (GeV)

600 GeV gluino pair production at the LHC

Shower parameter dependence

QCD radiation after matching with MG/ME

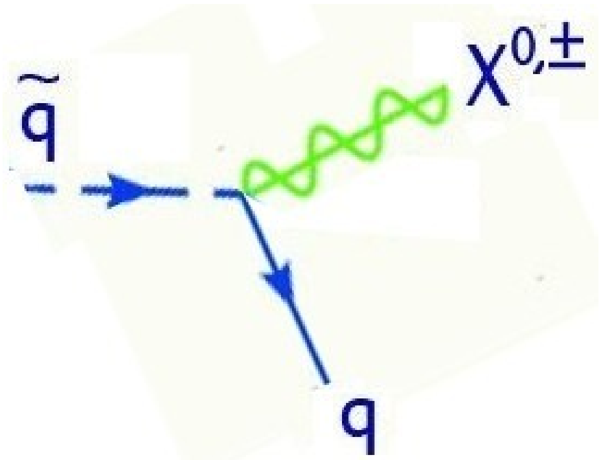


log(Jet resolution scale for 1 → 2 jets) (GeV)

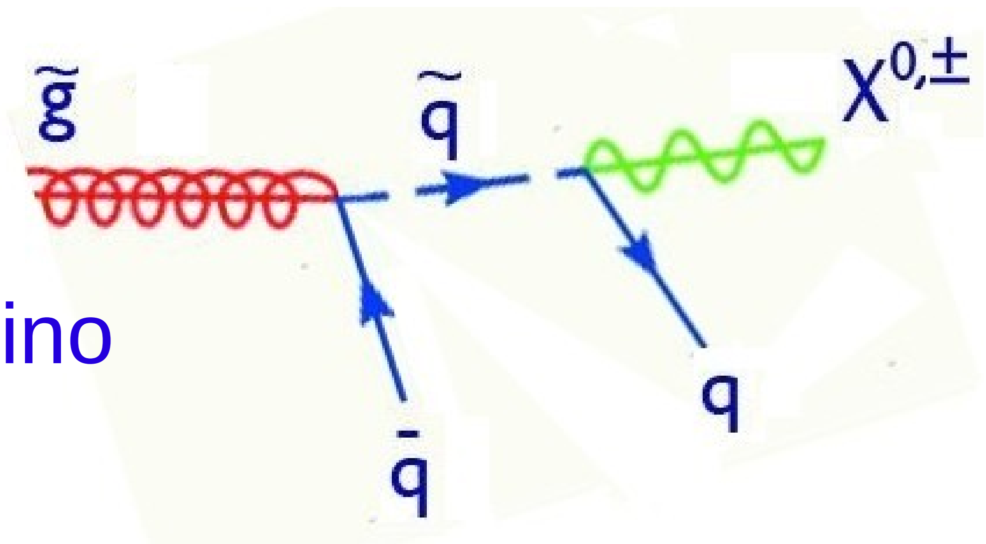
600 GeV gluino pair production at the LHC

Squark/Gluino separation

- Squark decay
  → quark + weak gaugino



- Gluino decay
  → squark + quark
  → 2 quarks + weak gaugino



- Differ by 1 jet – hard/soft depending on Δ(mass)

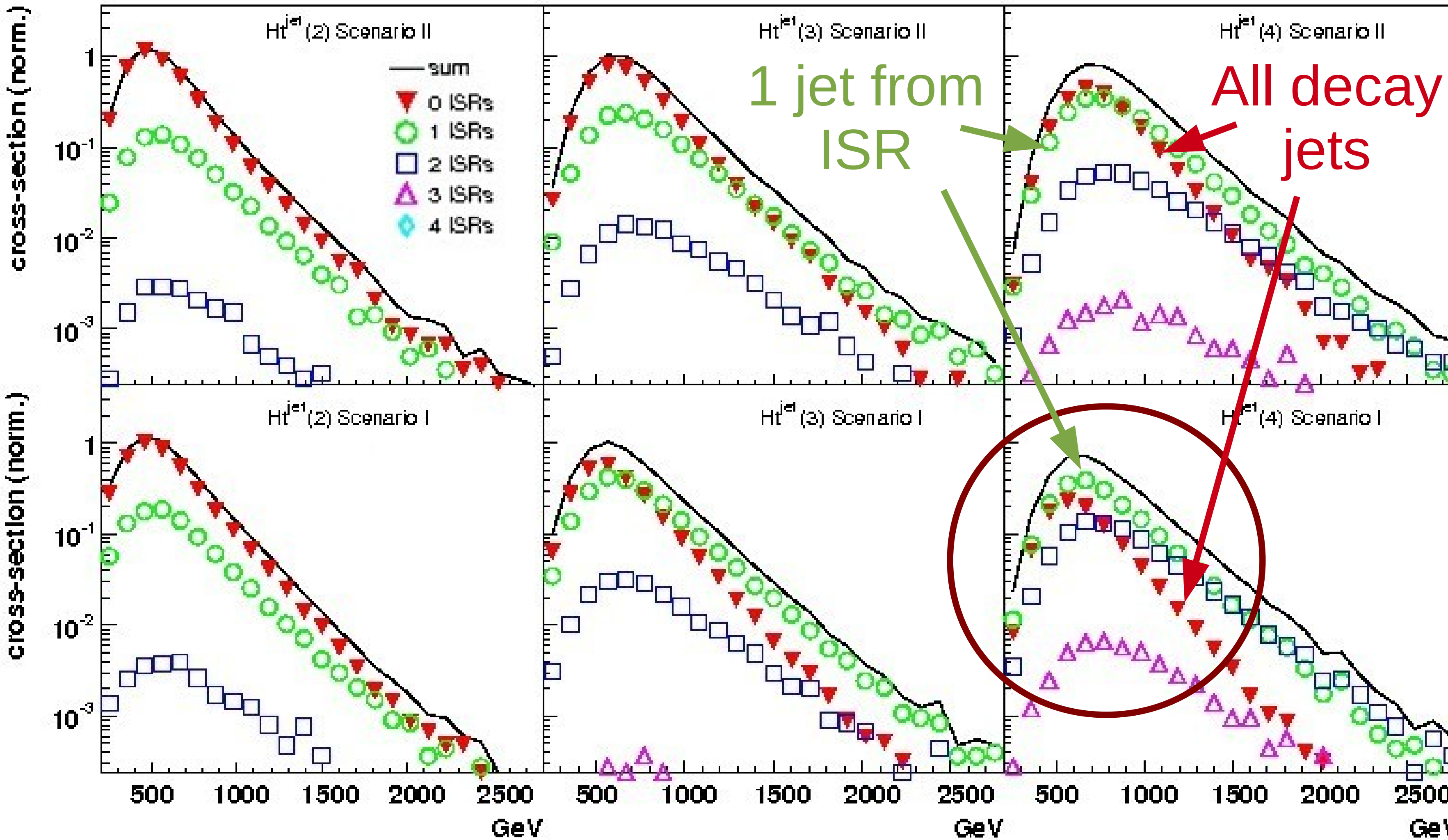
Jet counting in gluino decay

600 GeV gluino pair production

3-body $\tilde{g}$ decay

(squarks heavy)

M_g-M_q= 50 GeV



Σp_T(2 hardest jets) Σp_T(3 hardest jets) Σp_T(4 hardest jets)

Non-standard gluinos

- Common experimental approach to jets+MET: Exclusions in model space of minimal model (mSUGRA/mGMSB/mAMSB) with few (~4-5) parameters
- Problems:
  - Fixed relations between parameters, e.g. $m_{\tilde{g}}:m_{\tilde{W}}:m_{\tilde{B}} \sim 6:2:1$ ← LSP
  - Light flavor squark masses $\gtrsim$ gluino mass
  - Fixed decays and branching ratios

Non-standard gluinos

JA, Le, Lisanti, Wacker [arXiv:0803.0019, arXiv:0809.3264]

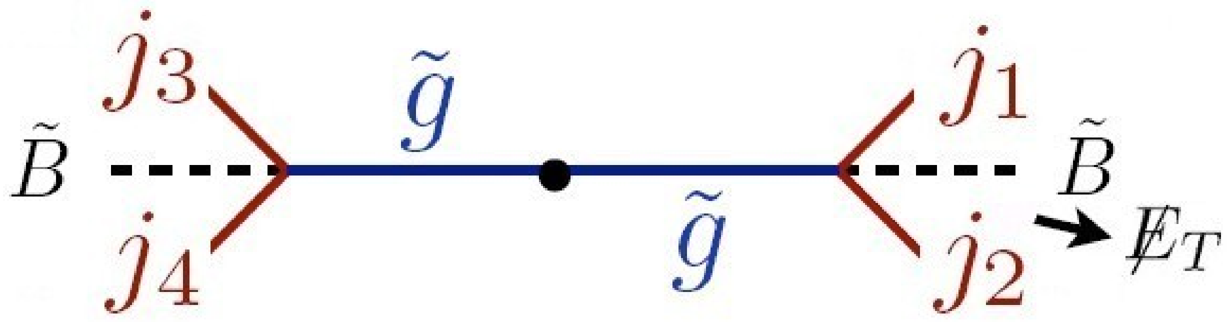
Non-unified/non-standard SUSY scenarios, and other models, can have $m_{\tilde{g}}:m_{\tilde{B}}$ ratio free

- A priori unclear where Tevatron is sensitive
- Need combination of $\not{E}_T$+1-jet, 2-jet, 3-jet and multijet searches to cover whole $\tilde{g}$-$\tilde{B}$ mass plane

Non-standard gluinos

Special difficulty when decay products nearly mass-degenerate with produced particle:

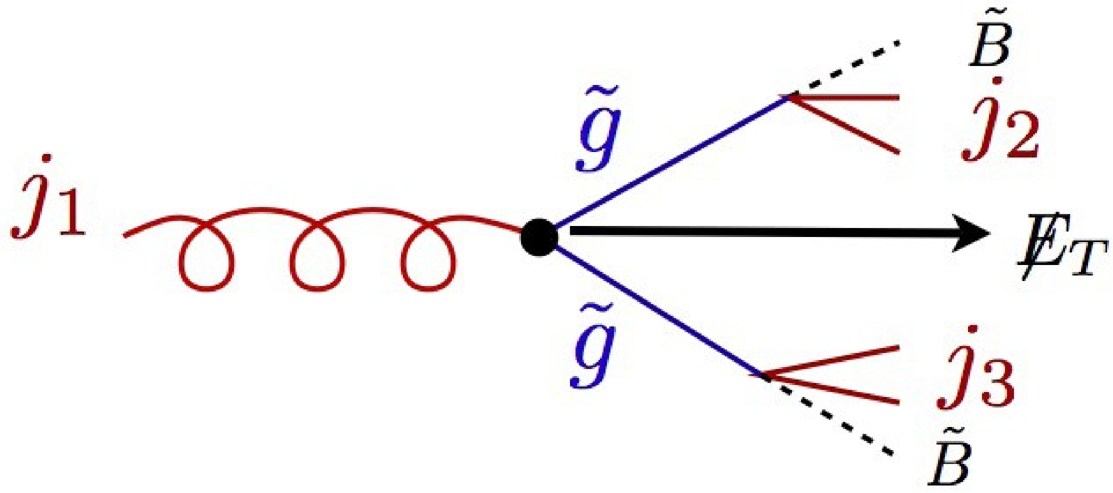
- No (small) missing transverse energy in decay



Non-standard gluinos

Special difficulty when decay products nearly mass-degenerate with produced particle:

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



Non-standard gluinos

Matched

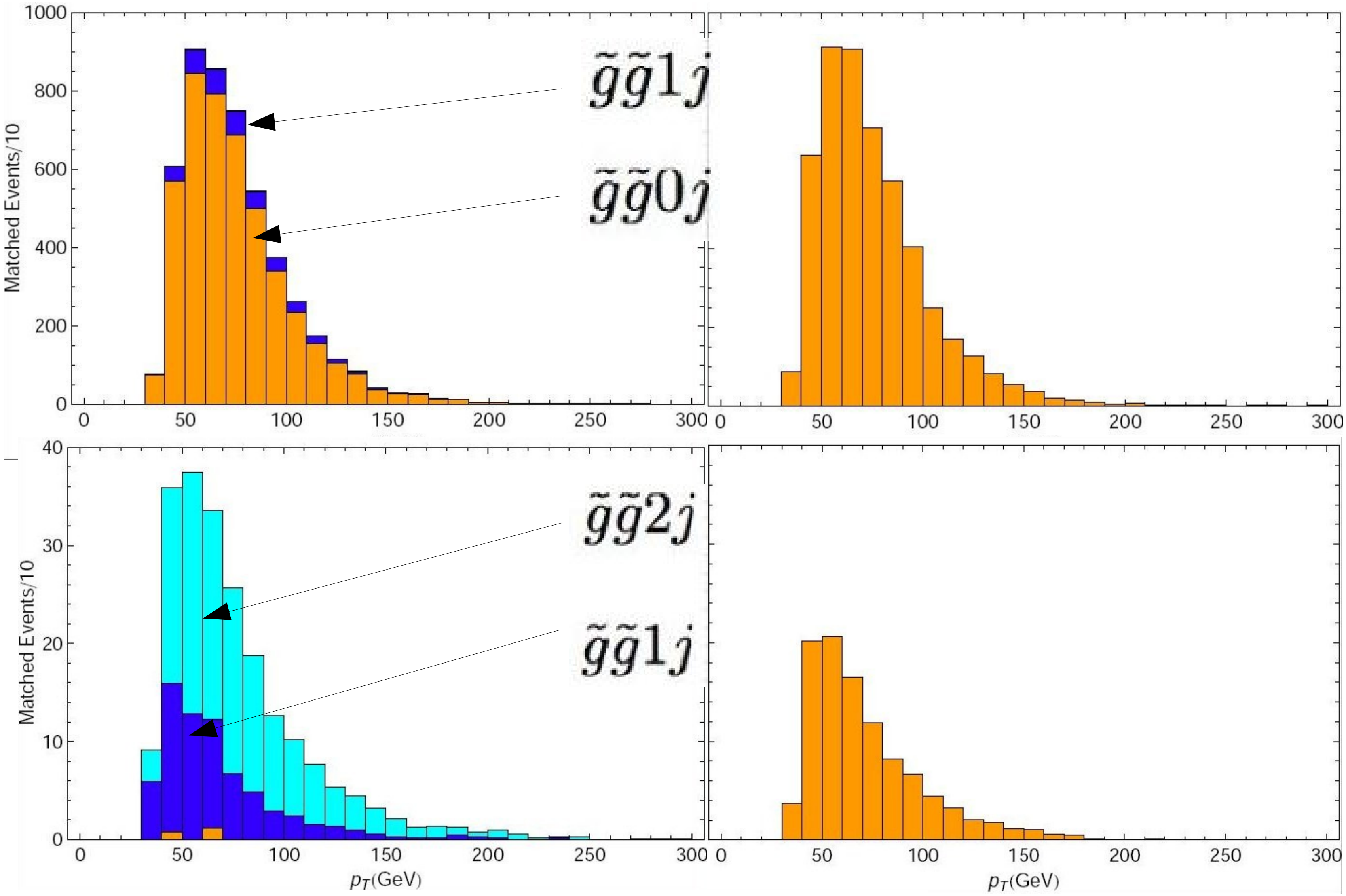
Unmatched

M_g=150 GeV

M_B=40 GeV

M_g=150 GeV

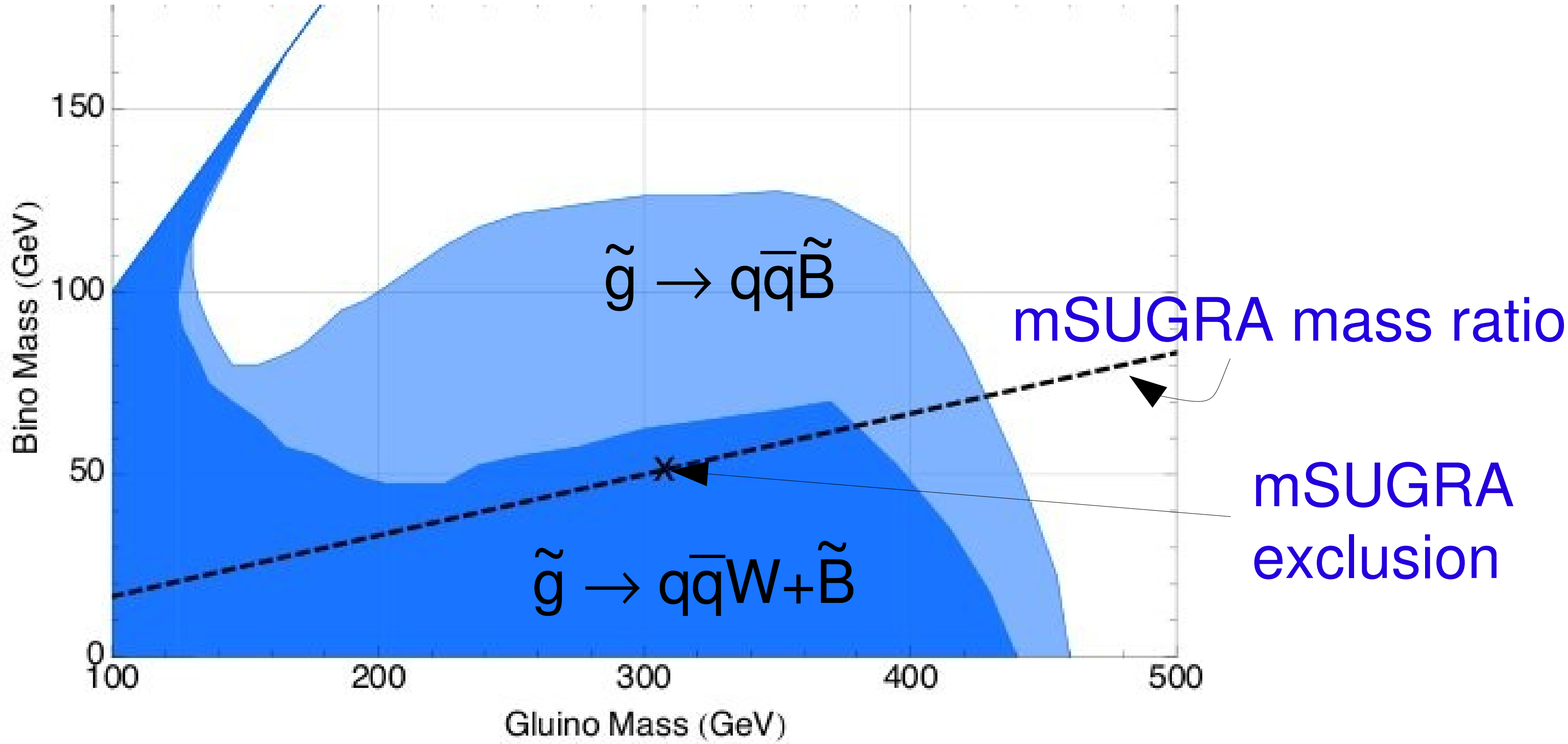
M_B=130 GeV



Tevatron, after 2-jet and missing E_T cuts

Non-standard gluinos

- Prejudice-free model scenario and improved simulation allows us to find exclusion region in $\tilde{g} - \tilde{B}$ mass plane



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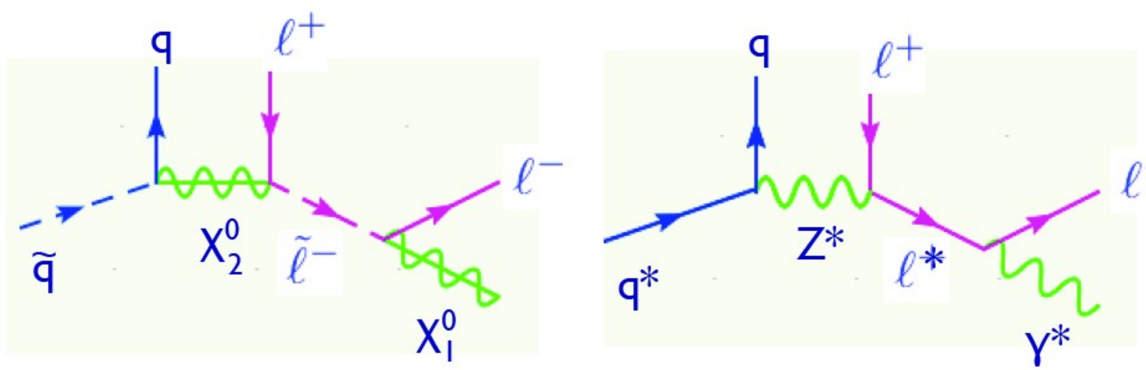
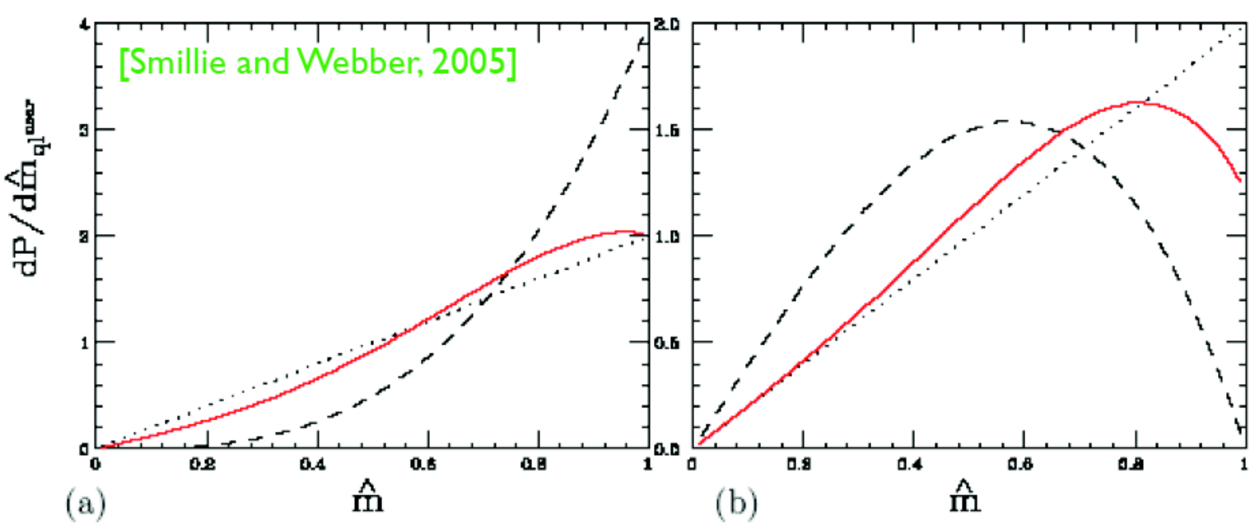
SUSY vs. UED – spin effects

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





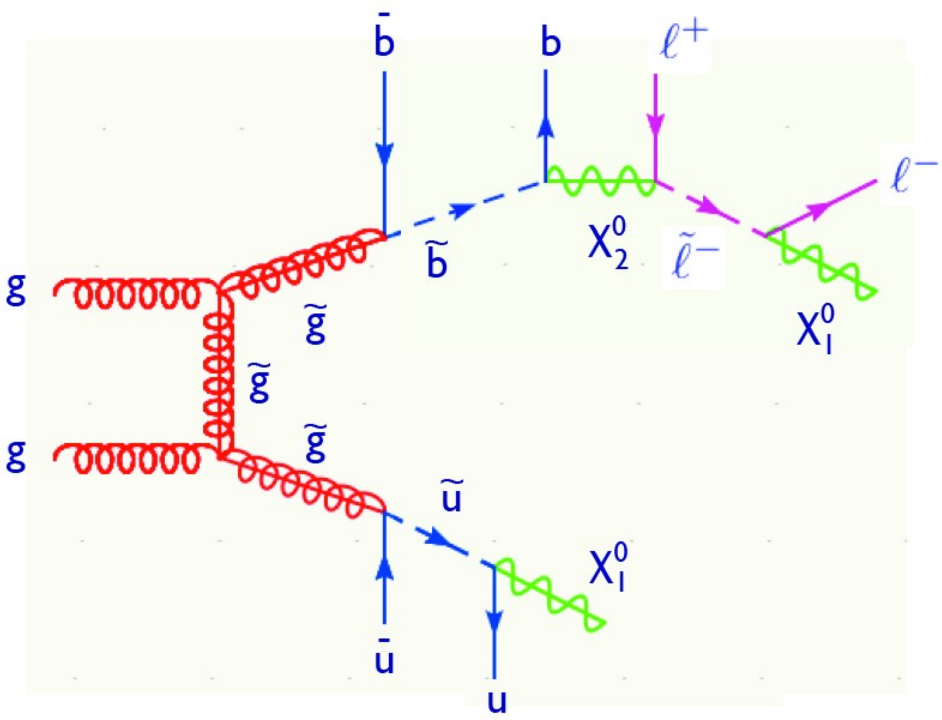
Beware of common simplifications:

0. Production and decay factorized
1. Spin ignored
2. Chains only through $1 \to 2$ decays.
3. Narrow width approximation employed.
4. 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 $\rightarrow$ N decays possible
3. BW for all resonances
4. Non-resonant contributions can be included only where relevant

Decay chains

[JA, T. Stelzer]

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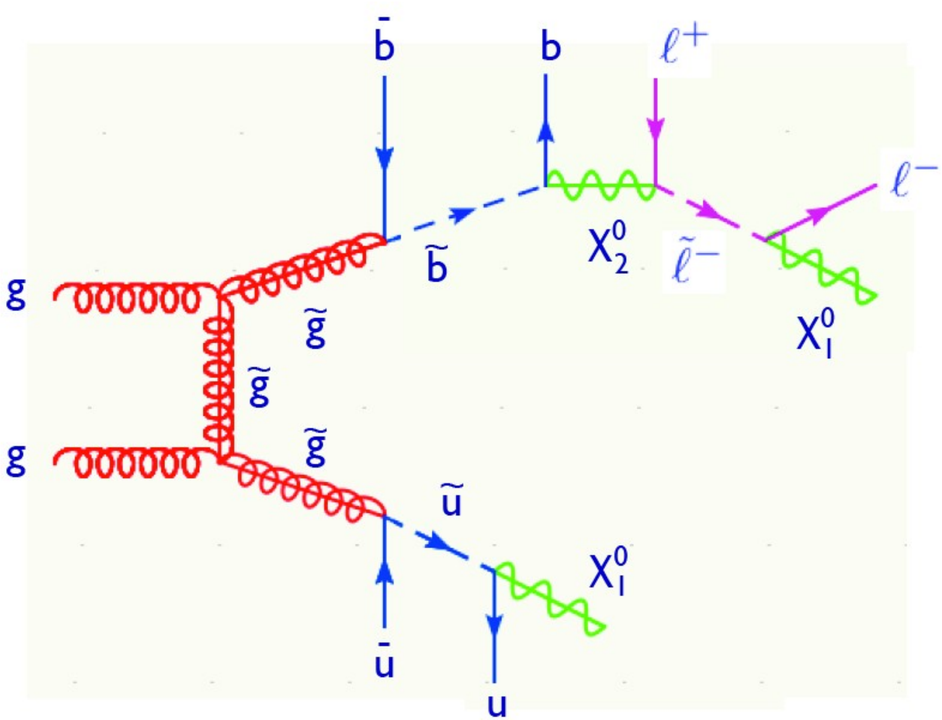


١. Full matrix element with all correlations between production and decay

٢. 1 → N decays possible

٣. BW for all resonances

٤. Non-resonant contributions can be included only where relevant

Example safe simplification: factorize process at scalar decay

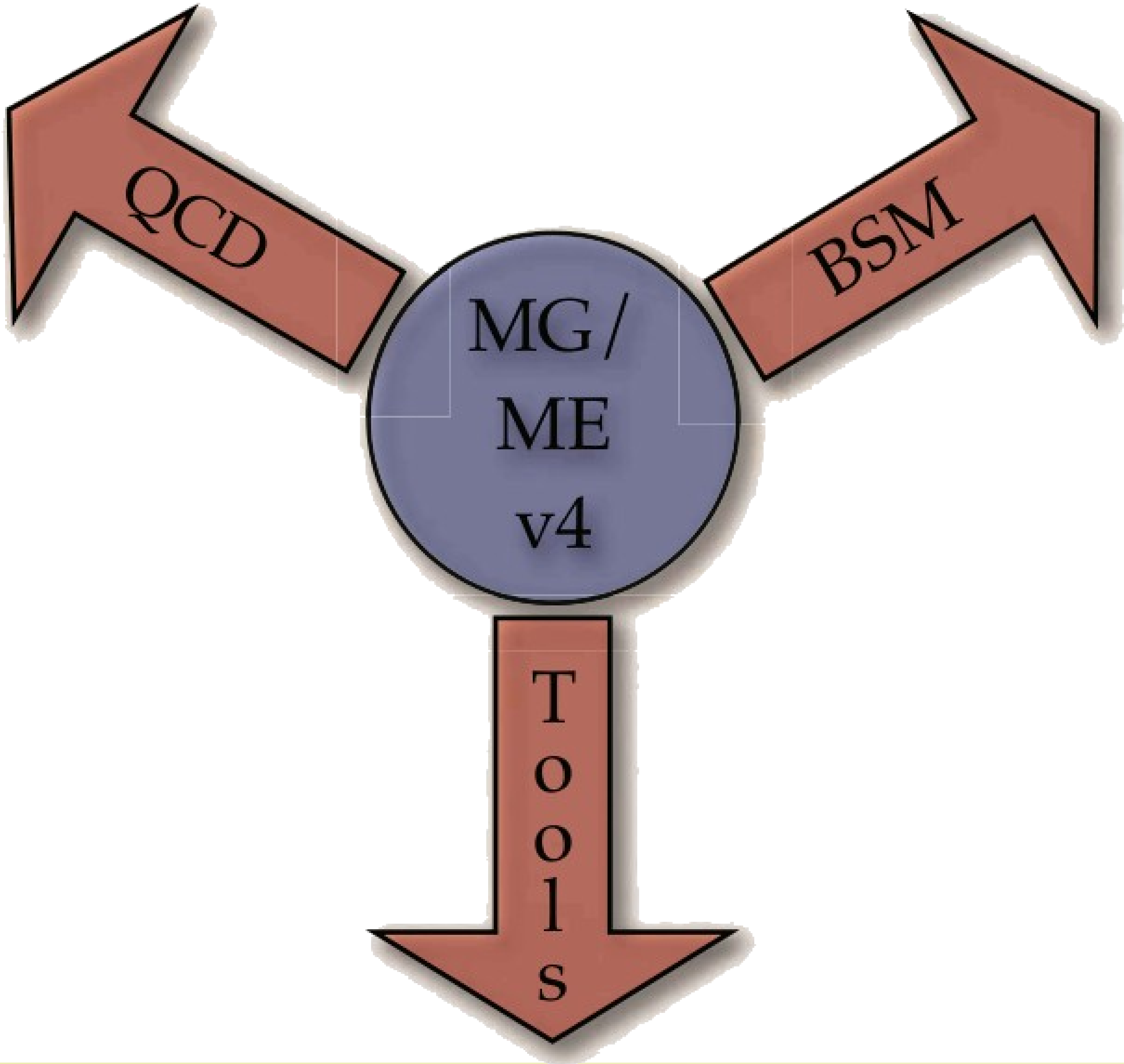
```
gg>(go>u~ ul)(go>b~ b1)
```

Decay scalars at event level with MG or BRIDGE

[P. Meade, M. Reece, 2007]

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

Future directions



Future directions (highlights)

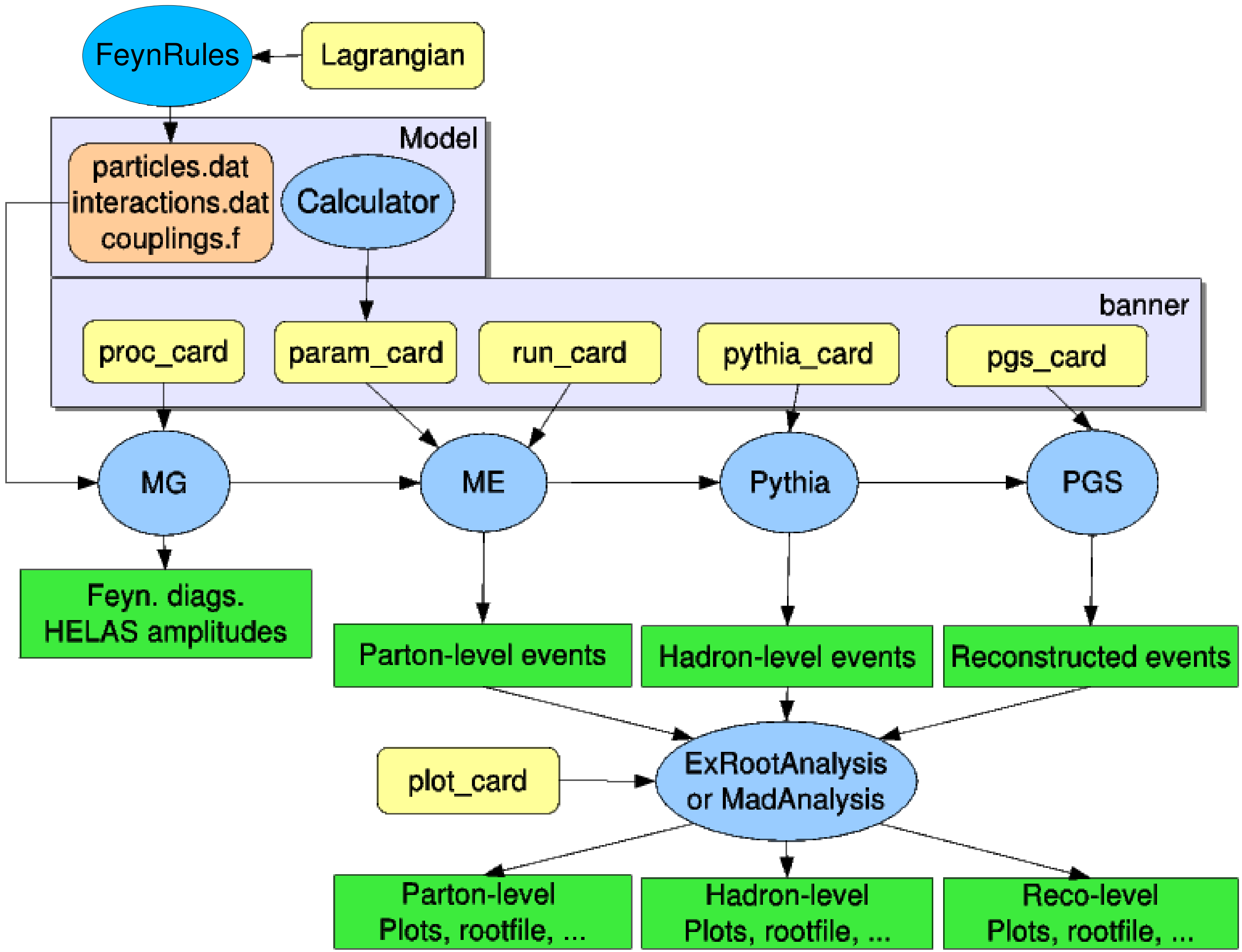
- BSM:
  - Automatic generation of HELAS routines by FeynRules
  - Generalized color structure
  - Online model repository (by theory community)
- QCD:
  - CKKW matching for Pythia 8 (in progress)
  - Matching for NLO processes
  - Improved efficiency for multi-gluon final states
- Tools:
  - Improved ME method ISR treatment using MadWeight

Conclusions

- LHC poses new challenges to the MC community
- MadGraph/MadEvent approach:
  - Building a community
    - Web based : public clusters with personal DB's, Wiki, open CVS repository
    - Support to spin-offs, independent projects, and custom MC needs (Ex: BRIDGE, FeynRules, NLO, BSM implementations, ...)
  - Providing a full-fledged platform for physics studies at colliders
    - Complete simulation chain via web + Grid version
    - SM and BSM: signal and backgrounds, including multi-jet samples with ME/PS merging and automatic implementation of any new model formulated as Lagrangian
    - TH and EXP tools : MadWeight, MadDipole, Analysis tools, ...

Backup slides

MG/ME workflow



The Hill model

SM SCALAR AND EXTRA SINGLET(S)

J. J. VAN DER BIJ
Institut für Physik, Albert-Ludwigs Universität Freiburg, H. Herderstr. 3, 79104 Freiburg i.B., Deutschland

[arXiv:0707.0359]

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

$$- \frac{1}{2}(\partial_\mu H)^2 \; - \frac{\lambda_1}{8}(2 f_1 H - \Phi^\dagger \Phi)^2$$

Slides contributed by C. Duhr

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},
```

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 contributed by C. Duhr

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 contributed by C. Duhr

Phenomenology with FeynRules

- Now we are ready to do some phenomenology...

- Let's consider the following process in the framework of Hill model

$$e^+e^- \to Zb\tilde{b} \quad \to \quad \mu^+\mu^-\, b\tilde{b}$$

  At a CoM energy of 500GeV.

- Let's first have a look at the one-loop corrections.

  ⇒ Use FeynArts

Slides contributed by C. Duhr

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 – – –

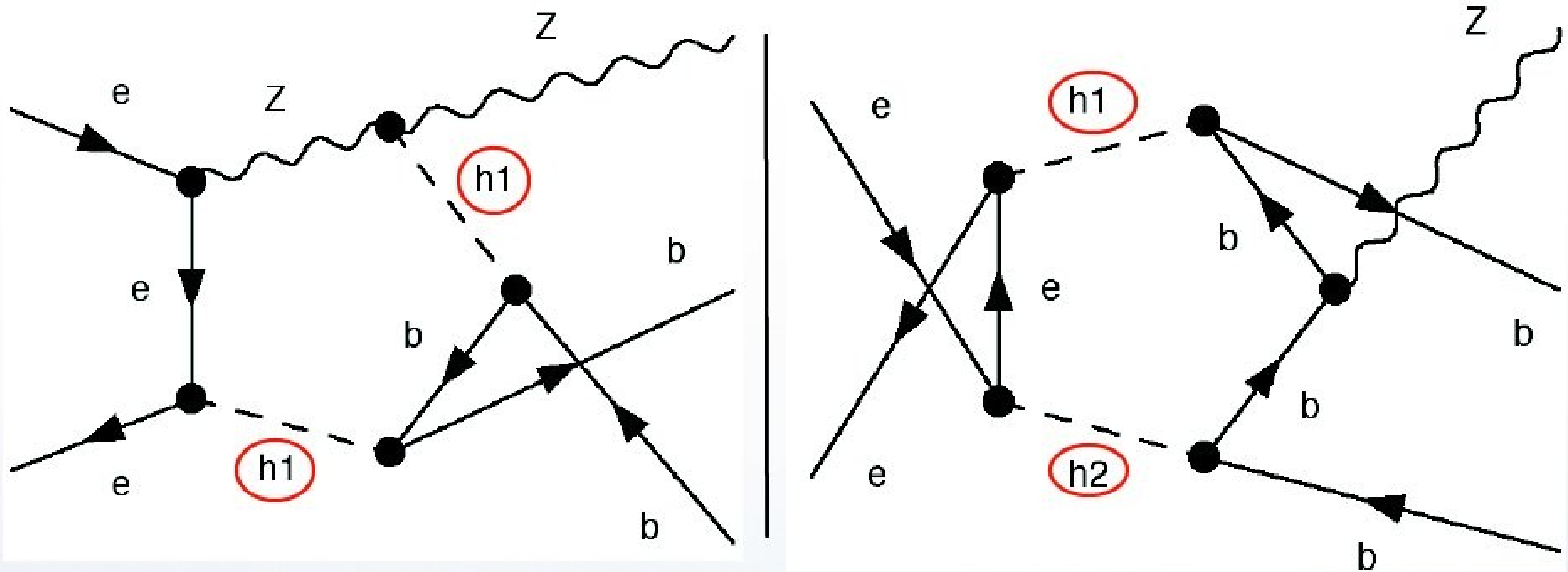
C. Duhr, 2007

- 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];
```

Slides contributed by C. Duhr

Phenomenology with FeynRules



Slides contributed by C. Duhr

Phenomenology with FeynRules

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

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

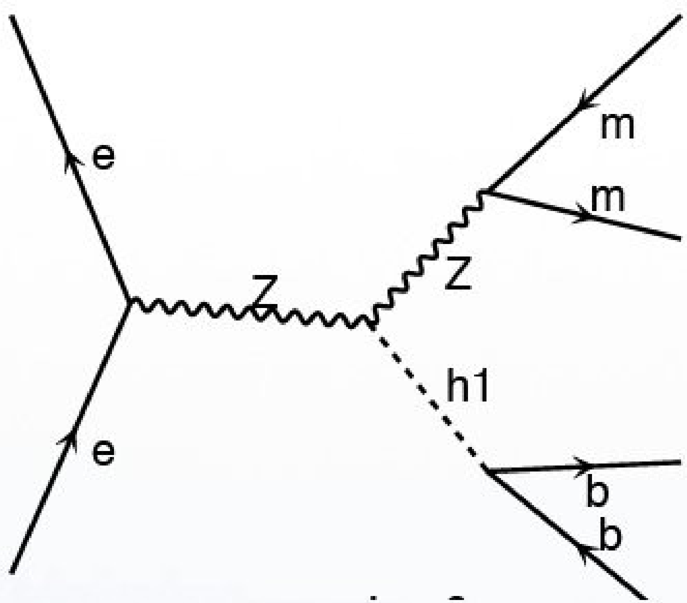
– – – FeynRules interface to MadGraph – – –

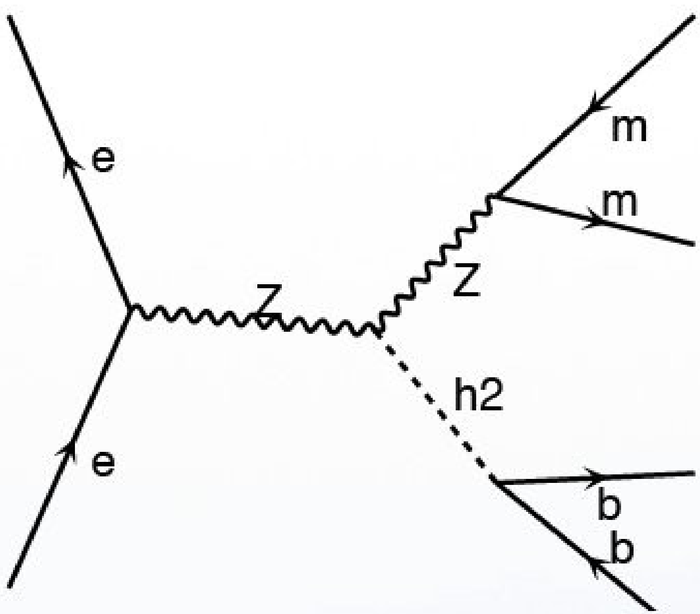
C. Duhr, M. Herquet, 2007

- This produces all the files needed to implement the Hill model into MadGraph. Let's have a look at our process!

Slides contributed by C. Duhr

Phenomenology with FeynRules





Slides contributed by C. Duhr

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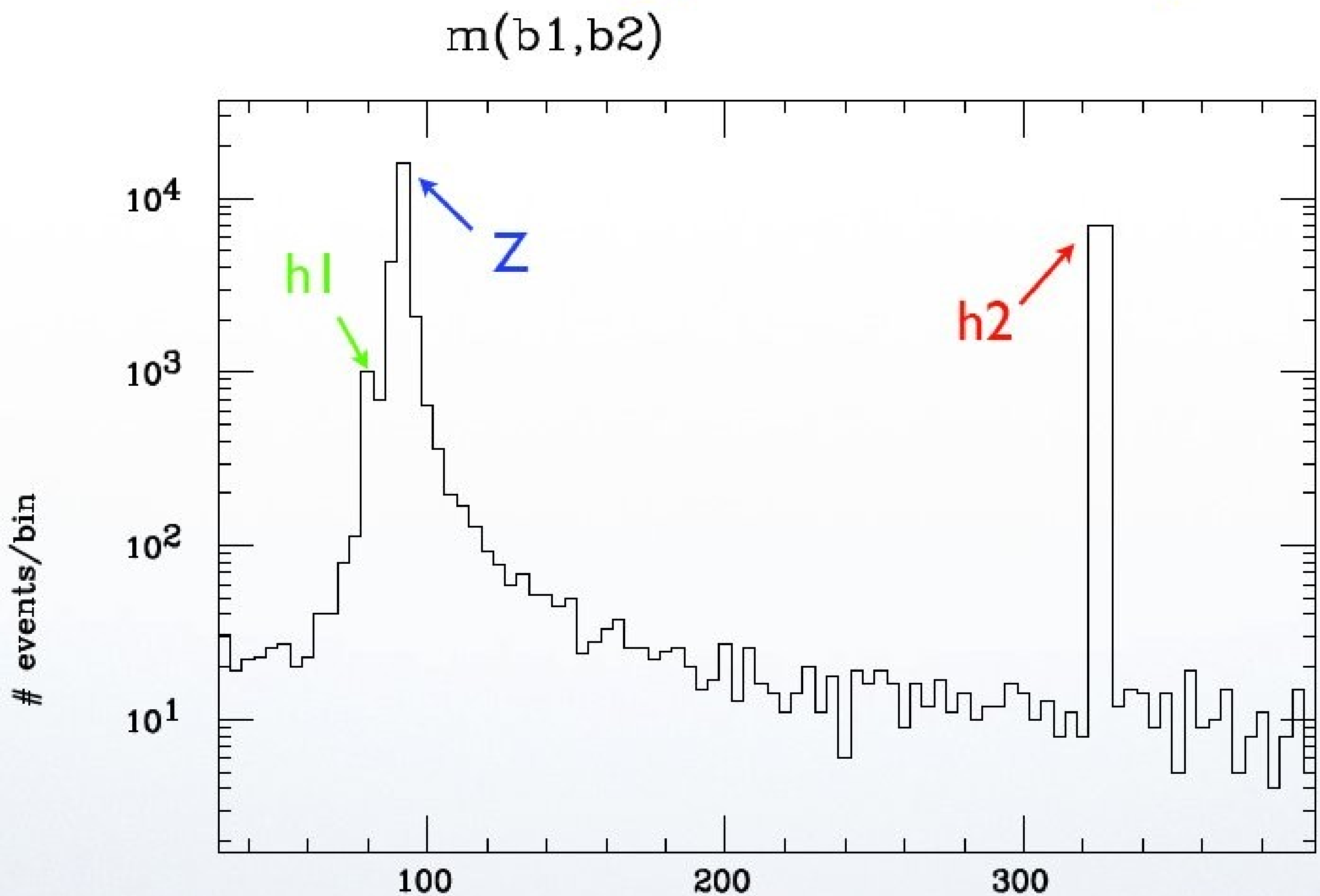


Slides contributed by C. Duhr

Details of matching schemes

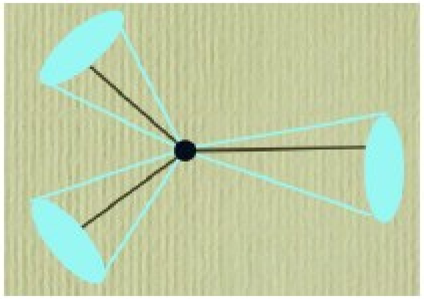
- CKKW scheme
  - Sudakov reweighting using analytical NLL Sudakovs
  - Analytically relatively well-understood
- Lönnblad scheme
  - Sudakov reweighting by using shower Sudakovs
- MLM scheme
  - Run shower and reject events with too hard emission
  - Can use any shower implementation

MLM matching

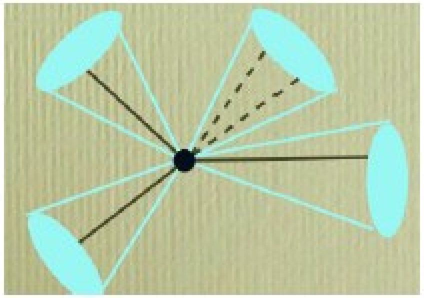
J.A. et al. [arXiv:0706.2569],
cf. M.L. Mangano [2002, Alpgen home page]

Use shower hardness to separate ME/PS

1. Generate multiparton event with cut on jet k_T
2. Cluster event and use k_T^2 for α_s scale
3. Shower event (using Pythia) starting from hard scale
4. Collect showered partons in k_T jets with $k_{T\mathrm{cut}} > k_{T\mathrm{min}}$
5. Keep event only if each jet matched to one parton
6. For highest multiplicity sample, allow extra jets softer than $k_{T\mathrm{min}}$



Keep



Discard unless highest multiplicity

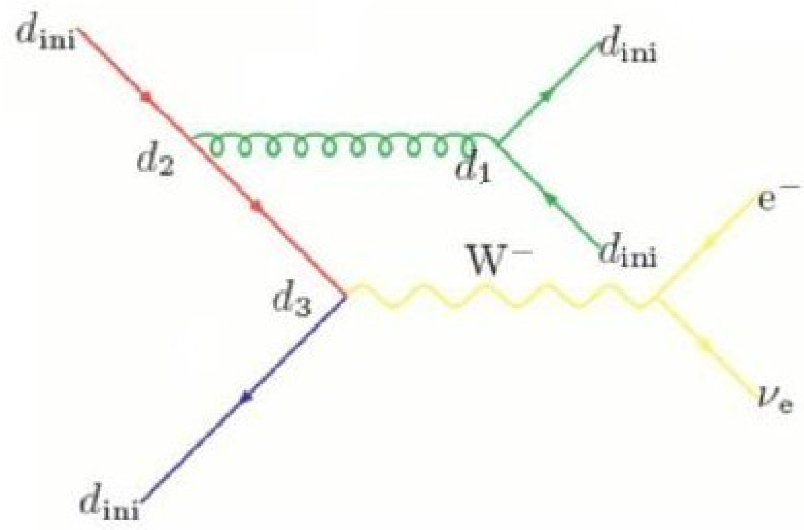
CKKW matching

Imitate parton shower procedure for matrix elements

1. Choose a cutoff (jet resolution) scale d_{ini}
2. Generate multiparton event with $d_{\text{min}} = d_{\text{ini}}$ and factorization scale d_{ini}
3. Cluster event with k_T algorithm to find "parton shower history"
4. Use $d_i \simeq k_T^2$ in each vertex as scale for α_s
5. Weight event with NLL Sudakov factor $\Delta(d_j, d_{\text{ini}})/\Delta(d_i, d_{\text{ini}})$ for each parton line between vertices i and j (d_j can be d_{ini})
6. Shower event, allowing only emissions with $k_T < d_{\text{ini}}$ ("vetoed showers")
7. For highest multiplicity sample, use $\min(d_i)$ of event as d_{ini}

Boost-invariant k_T measure:

$$\begin{cases} d_{iB} = p_{T,i}^2 \\ d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) F_{ij} \end{cases}$$
$$F_{ij} = 2\{\cosh(\eta_i - \eta_j) - \cos(\phi_i - \phi_j)\}$$



- For final-state showers: Combination of NLL Sudakov factors and vetoed NLL showers guarantees independenc of d_{ini} to NLL order
- For initial-state showers: No proof but works ok
- Problem in practice: No NLL shower implementation! (Sherpa uses Pythia-like showers)

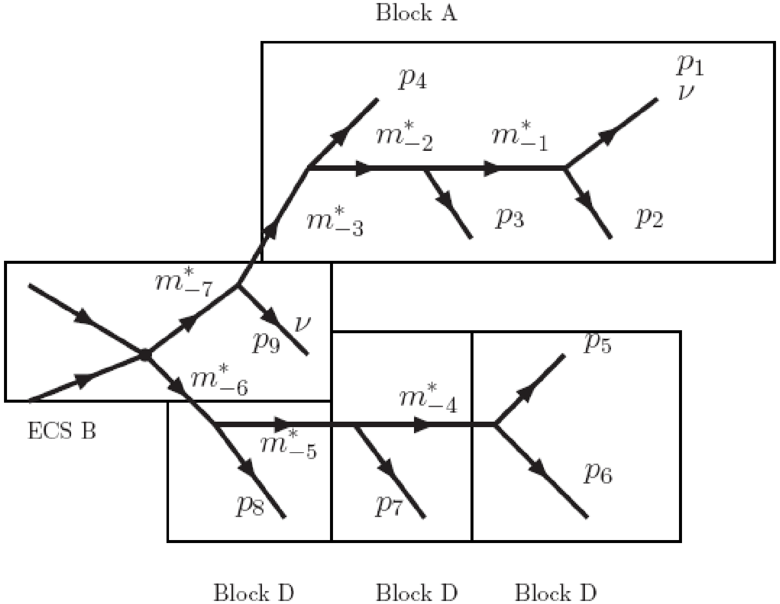
Shower k_T scheme

- 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)

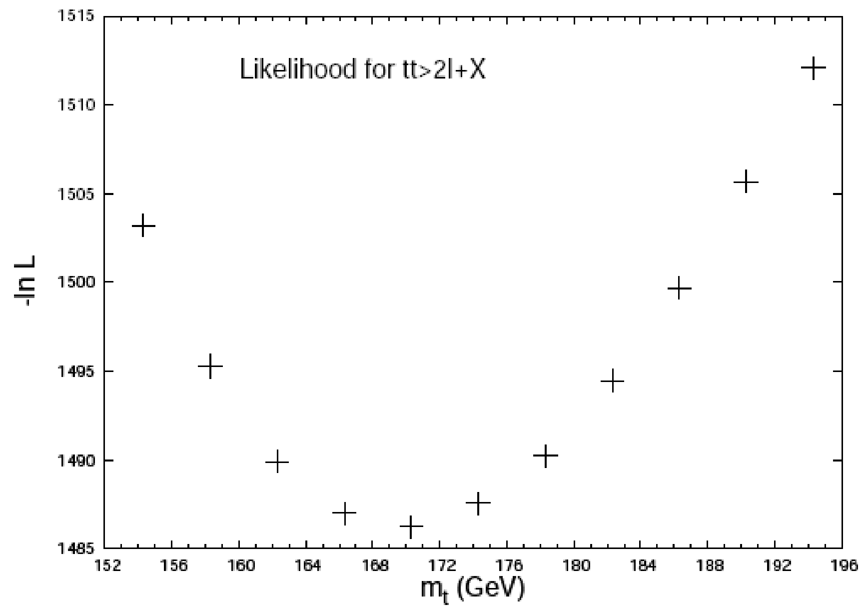
MadWeight

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

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



Phase space integration using automatic change of variables aligned with peaks



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

Automatic dipole subtraction

[R. Frederix et al, arXiv:0808.2128]

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

- Automatic divergence subtraction for the real corrections in any QCD NLO calculation
  - Catani-Seymour subraction scheme
  - Standalone implementation
  - Both for SM and BSM
  - Massless and massive external particles