The Sherpa Monte Carlo for BSM physics

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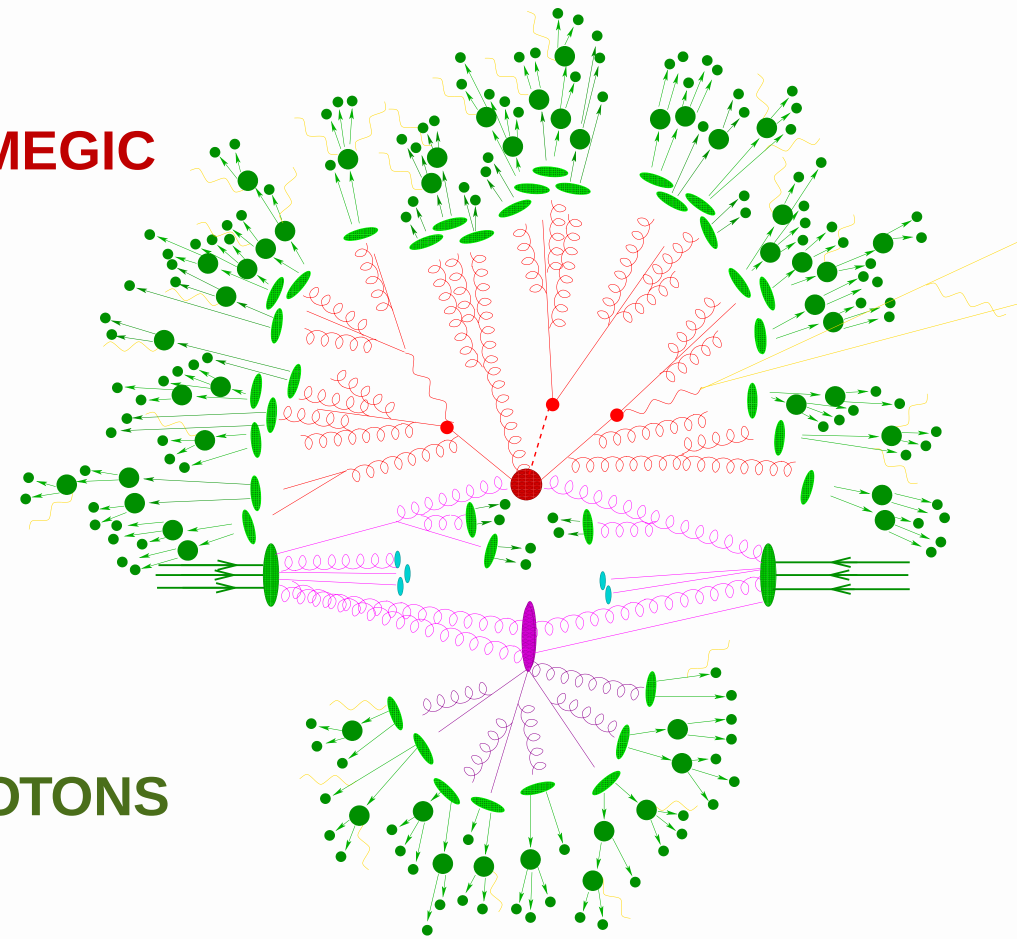
- realistic simulation of (B)SM signals & backgrounds
- include showering, hadronisation and underlying event
- hard processes described by multi-leg matrix elements

split simulation in phases

- **Signal/Background process: AMEGIC**
  exact matrix elements $|\mathcal{M}|^2$
- **QCD bremsstrahlung: APACIC**
  parton showers in the initial and final state
- **Multiple Interactions: AMISIC**
  beyond factorisation: modelling
- **Hadronisation: AHADIC**
  non perturbative QCD: modelling
- **Hadron Decays: HADRONS/PHOTONS**
  matrix elements or phase space / YFS



➔ **Sherpa is the framework that steers the event generation**

Monte Carlo Event Generators & BSM physics

issues to be handled

- matrix elements for production processes
  - provide a variety of models, easy to modify/extend
  - provide non-trivial production channels [e.g. associated prod. or VBF]
- proper treatment of unstable particles
  - include spin correlations, off-shell effects & quantum interferences
- parton showering off new coloured objects
- maybe hadronisation of new quasi-stable states

state of the art for matrix element calculations

➔ **automatic tree-level matrix element generators**

- e.g. MadGraph, O'Mega/Whizard, Amegic++ $\Rightarrow$ **built into Sherpa**
- deliver helicity amplitudes for multi-leg amplitudes
- suitable phase space integrators for parton level events

Sherpa's matrix element generator: Amegic++

working principles

- specify initial and final state [intermediate resonances can be enforced]

```
Process :  93 93 -> 1000022 1000023[a] 93 93
Order electroweak :  4
Decay :  1000023[a] -> 15 -1000015[b] ⇝ spin corr.  preserved
Decay :  -1000015[b] -> -15 1000022 ⇝ τ's by built-in decay-package
End process
```

Sherpa's matrix element generator: Amegic++

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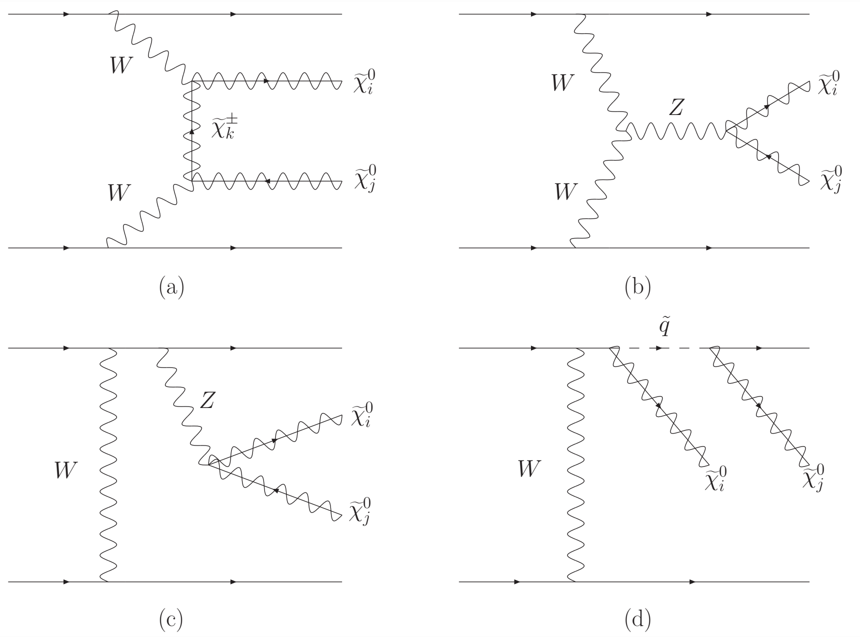
- from given sets of Feynman rules all possible diagrams are generated



Sherpa's matrix element generator: Amegic++

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- from given sets of Feynman rules all possible diagrams are generated
  - ➔ vertices defined through
    - in- & outgoing particles [$1 \to 2$, $1 \to 3$]
    - left- & right-handed coupling
    - $SU(3)$ colour structure [$1, \delta_{ij}, T^A_{ij}, f_{ABC}, \delta_{AB}$]
    - spin/Lorentz structure $SSS, SSV, VVS, VVV, FFS, FFV, SSSS, ...$
  - ➔ diagrams are then represented through trees of connected vertices

Sherpa's matrix element generator: Amegic++

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    - spin/Lorentz structure $SSS, SSV, VVS, VVV, FFS, FFV, SSSS, \ldots$
  - ➔ diagrams are then represented through trees of connected vertices
- algebraic evaluation of colour structures
- Lorentz structures are mapped onto helicity amplitude building blocks
- phase space mappings are constructed and stored together with amplitudes in library files

Model implementations in Sherpa/Amegic++

MODEL

Particles
Parameters

Interactions

Model_Base

- Standard_Model
- THDM
- MSSM
- ADD
- SM_AGC
- ...

Interaction_Model_Base

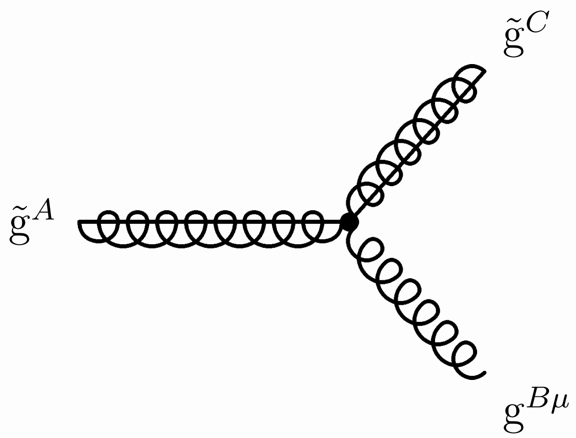
- Interaction_Model_SM
- Interaction_Model_THDM
- Interaction_Model_MSSM
- Interaction_Model_ADD
- Interaction_Model_SM_AGC
- ...

- C++ coded parameter setting routines and interaction vertices
- user implementation loadable as external library on the run

```
Sherpa SHERPA_LDADD=<mymodel_lib>
```

Model implementations in Sherpa/Amegic++

example: the gluino–gluino–gluon interaction



$$-g_3 f_{ABC}\gamma^\mu$$

```
// flavours
vertex[vanz].in[0]   = gluino;                    // incoming gluino
vertex[vanz].in[1]   = gluon;                     // outgoing gluon
vertex[vanz].in[2]   = gluino;                    // outgoing gluino
// couplings
Kabbala kcpl = -g3;
vertex[vanz].cpl[0]  = kcpl.Value();              // right coupling
vertex[vanz].cpl[1]  = kcpl.Value();              // left coupling
vertex[vanz].Str     = kcpl.String();
// colour structure
vertex[vanz].ncf     = 1;
vertex[vanz].Color   = new Color_Function(cf::F,0,1,2,'0','1','2');
// Lorentz structure
vertex[vanz].nlf     = 1;
vertex[vanz].Lorentz = new Lorentz_Function(lf::Gamma);
vertex[vanz].Lorentz->SetParticleArg(1);
```

Model implementations in Sherpa/Amegic++

MODEL

Particles
Parameters

Interactions

Model_Base

- Standard_Model
- THDM
- MSSM
- ADD
- SM_AGC
- ...
- FeynRules_Model

Interaction_Model_Base

- Interaction_Model_SM
- Interaction_Model_THDM
- Interaction_Model_MSSM
- Interaction_Model_ADD
- Interaction_Model_SM_AGC
- ...
- Interaction_Model_FeynRules

- model implementation "on the flight" [to be released soon]
- reads FeynRules generated ascii-files for particles, couplings, interactions

The MSSM implementation in Amegic++

implementation issues

- consider R-parity conserving MSSM
- implemented Feynman rules according to J. Rosiek Phys. Rev. D **41** (1990) 3464
  - sfermion mixing NOT restricted to third generation only
  - ino mixing param's taken to be real [negative ino masses in matrix elements]
- Majorana fermions treated according to Denner et al Nucl. Phys. B **387** (1992) 467
- spectra & parameters read from SLHA input files (so the LO widths)

validation

- compared $\mathcal{O}(500)$ xsec's with MadGraph/MadEvent & O'Mega/Whizard
- unitarity tests for $VV \to$ SUSY
  - published in K. Hagiwara et al., Phys. Rev. D **73** (2006) 055005
  - `www.sherpa-mc.de/susy_comparison/susy_comparison.html`

Other models in Amegic++

ADD model of large extra dimensions

[Arkani-Hamed, Dimopoulos, Dvali, Phys. Lett. B **429** (1998) 263]

- incorporated all 3- and 4-point interactions of SM particles and gravitons
- allows for both virtual and real graviton production
- generic implementation of helicity formalism for spin-2 particles

  $\rightsquigarrow$ T. Gleisberg et al., JHEP **0309** (2003) 001

anomalous electroweak gauge couplings

- triple- & quartic interactions

$$\begin{aligned}
\mathcal{L}_{WWV}/g_{WWV} &= ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu V_\nu W^{\mu\nu} \\
&\quad + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
&\quad + g_5^V \epsilon^{\mu\nu\rho\sigma}(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu) V_\sigma + \frac{i\tilde{\kappa}_V}{2}\epsilon^{\mu\nu\rho\sigma} W^\dagger_\mu W_\nu V_{\rho\sigma} + \frac{i\tilde{\lambda}_V}{2m_W^2}\epsilon^{\mu\nu\rho\sigma} W^\dagger_{\mu\lambda} W^\lambda_\nu V_{\rho\sigma} \\
\mathcal{L}_4 &= \alpha_4 e^4 \left(\frac{1}{2} W^\dagger_\mu W^{\dagger\mu} W_\nu W^\nu + \frac{1}{2}(W^\dagger_\mu W^\mu)^2 + \frac{1}{c_W^2} W^\dagger_\mu Z^\mu W_\nu Z^\nu + \frac{1}{4c_W^4}(Z_\mu Z^\mu)^2\right) \\
\mathcal{L}_5 &= \alpha_5 \left((W^\dagger_\mu W^\mu)^2 + \frac{1}{c_W^2} W^\dagger_\mu W^\mu Z_\nu Z^\nu + \frac{1}{4c_W^4}(Z^\mu Z^\mu)^2\right)
\end{aligned}$$

RS1 simulation with Sherpa

production of Kaluza-Klein gluons at LHC

[K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, hep-ph/0612015]

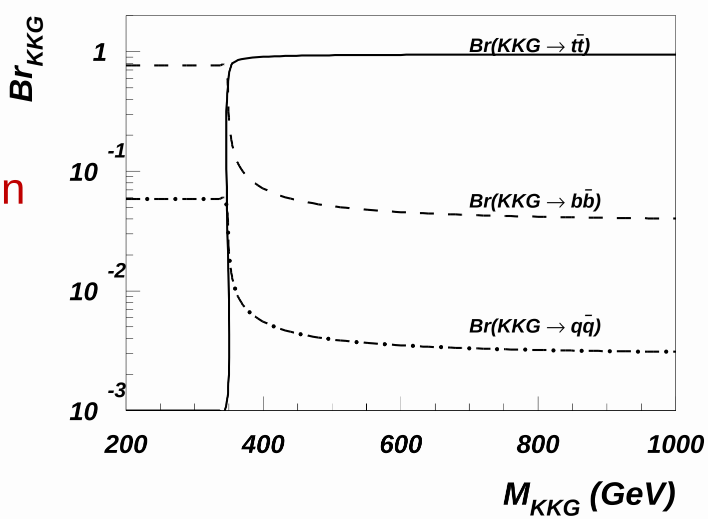
- RS1 type model of a warped extra dimension
- SM gauge and fermion fields propagating in the bulk
- different profiles for SM fermions, to meet EWPT KK scale $\simeq$ a few TeV

non-universal SM–to–KK gauge state couplings $\xi = \sqrt{\log(M_{Pl}/TeV)}$

$$\frac{g_{RS}^{q\bar{q},l\bar{l}G^1}}{g_{SM}} \simeq \xi^{-1} \approx \frac{1}{5}, \quad \frac{g_{RS}^{(t,b)_L(\bar{t},\bar{b})_L G^1}}{g_{SM}} \approx 1, \quad \frac{g_{RS}^{t_R\bar{t}_R G^1}}{g_{SM}} \simeq \xi \approx 5, \quad \frac{g_{RS}^{GGG^1}}{g_{SM}} \approx 0$$

distinct features of KK gauge boson production

- small couplings to proton constituents
- no "golden plated" $l\bar{l}$ decays $\rightsquigarrow$ focus on KK-gluon
- dominant decay to top-quarks



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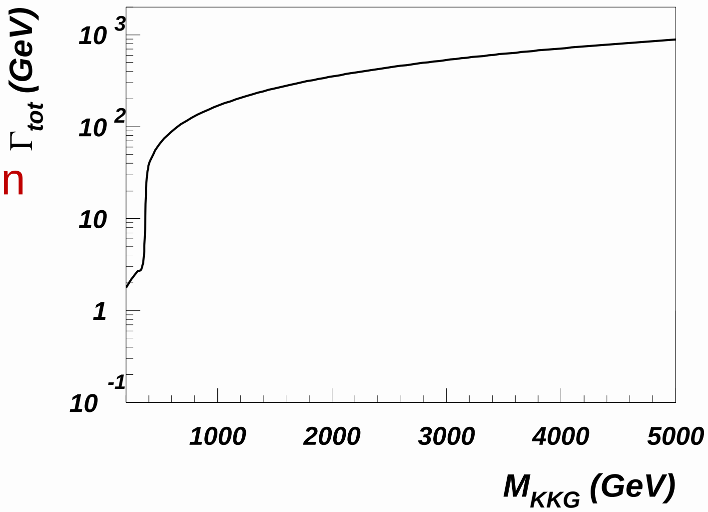
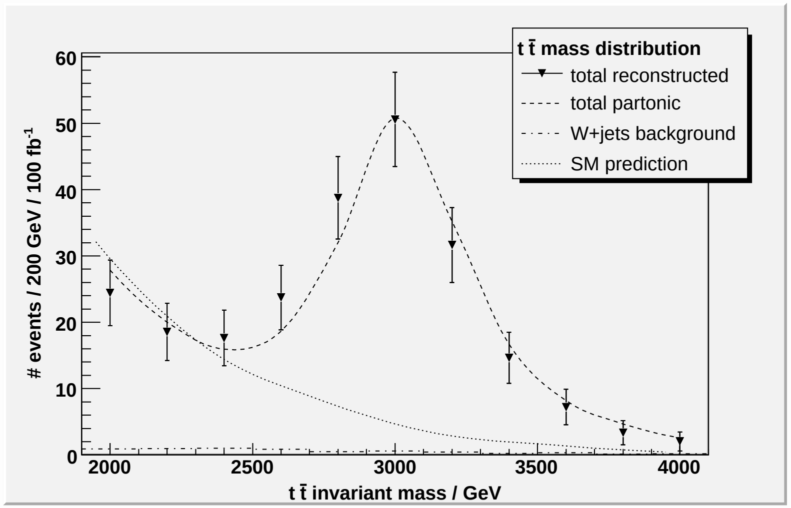
- dominant decay to top-quarks
- states broad and tops highly boosted
- need modified reconstruction methods



RS1 simulation with Sherpa

results of simulation with Sherpa $pp \xrightarrow{G^1/g/Z^*/\gamma^*} t\bar{t} \to b\bar{b}l\nu jj$

- significant peak in $M_{t\bar{t}}$ diff. cross section
- parton- to hadron level agree very well
- signal significance (100fb^{-1})
  - $S/\sqrt{B} \approx 11.0$ for $M_{KKG} = 3$ TeV
  - $S/\sqrt{B} \approx \ \ 4.2$ for $M_{KKG} = 4$ TeV



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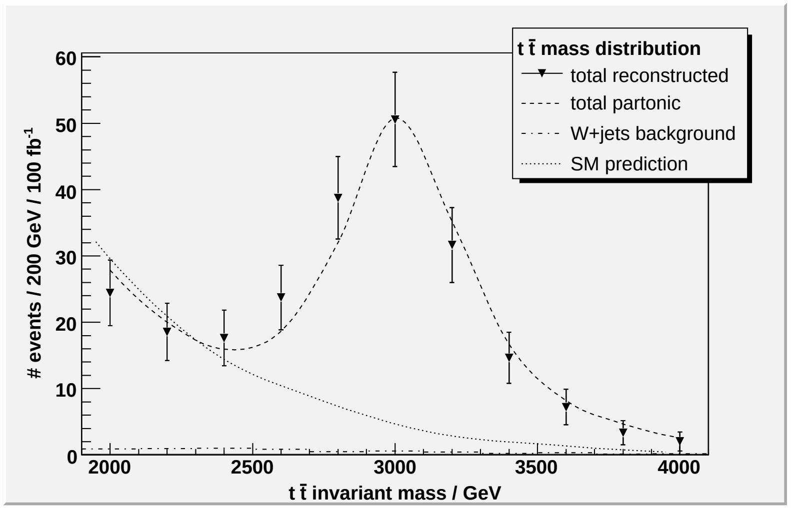
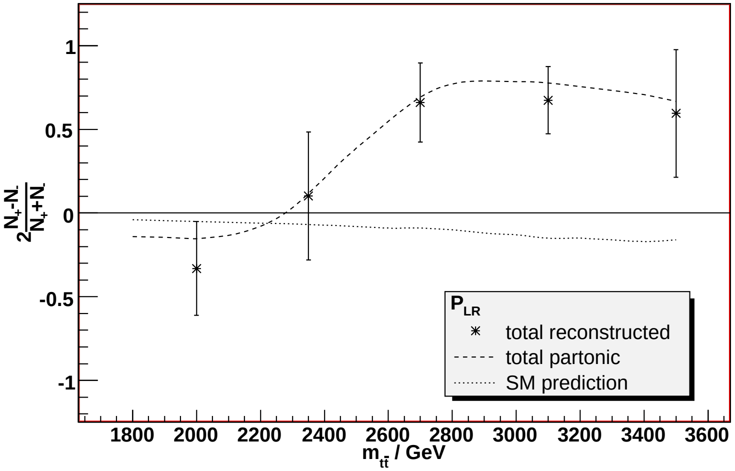


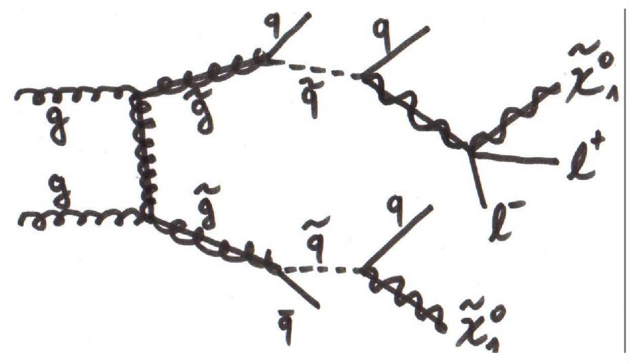
- observable lepton asymmetry due to dominant t_R production
  - requires correlated decays of the tops
  - included electroweak production for SM



$\Rightarrow$ **Strong need for sophisticated signal MC**

Simulation of SM backgrounds

example: cascade decays of heavy coloured states



- #-leptons + #-jets + $\not{E}_T$
- jet properties depend on NP nature

  [energies, flavours, edges]
- SM-BGs: W/Z+jets, $t\bar{t}$+jets, Jets

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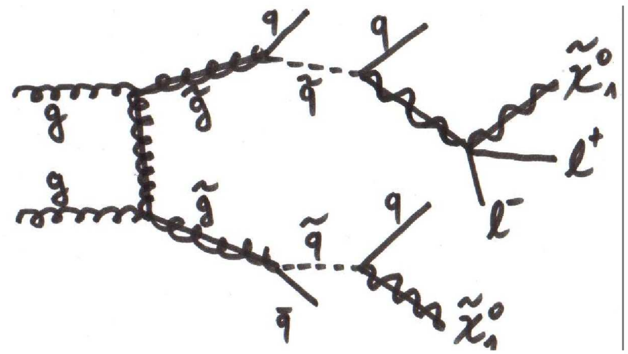

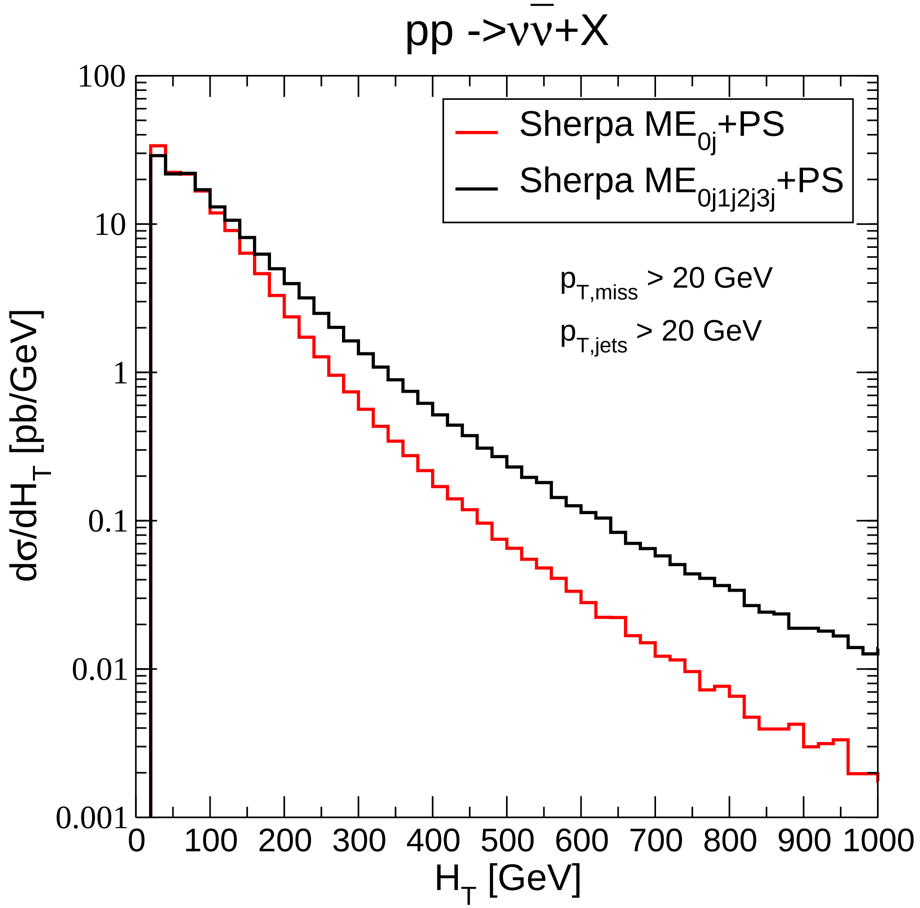

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- jet properties depend on NP nature
  [energies, flavours, edges]
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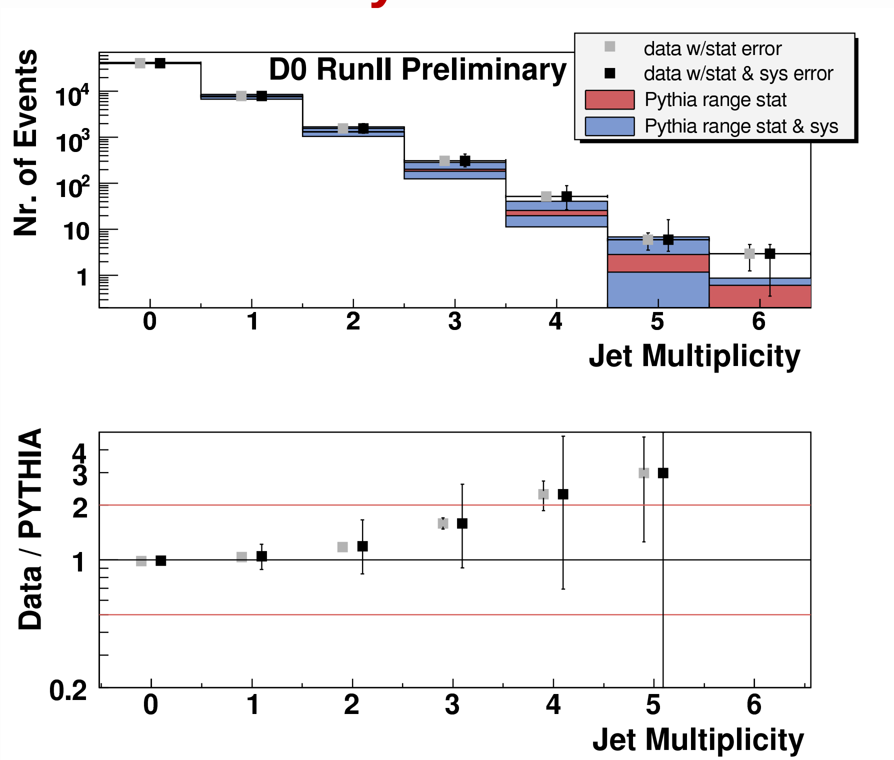
best we can do for multi-jet final states:

- multi-jet MEs merged with parton shower: CKKW, MLM

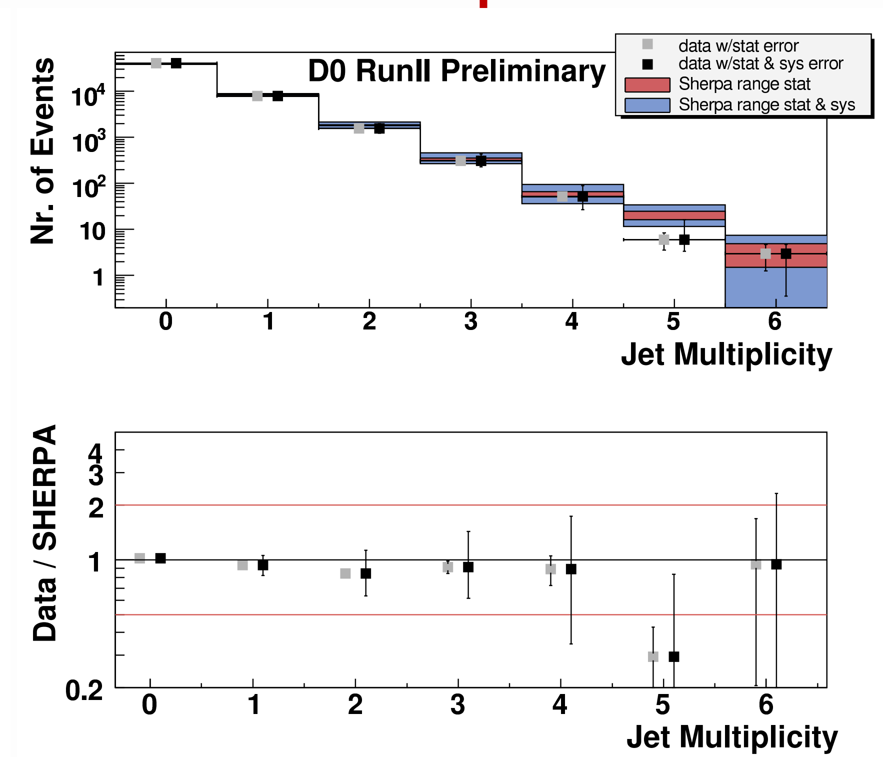
Simulation of SM backgrounds

e^+e^-+jets @ Tevatron RunII (DØ Note 5066): jet-multiplicities

Pythia



Sherpa

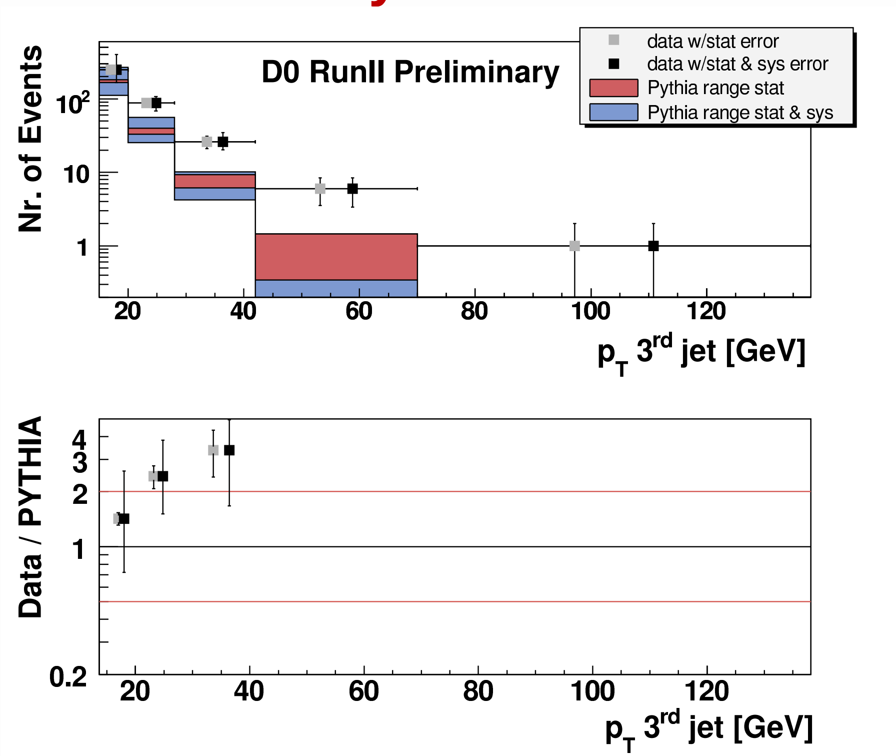


- inclusive samples normalised to total number of measured events

Simulation of SM backgrounds

e^+e^-+jets @ Tevatron RunII (DØ Note 5066): $p_\perp$ of the third jet

Pythia



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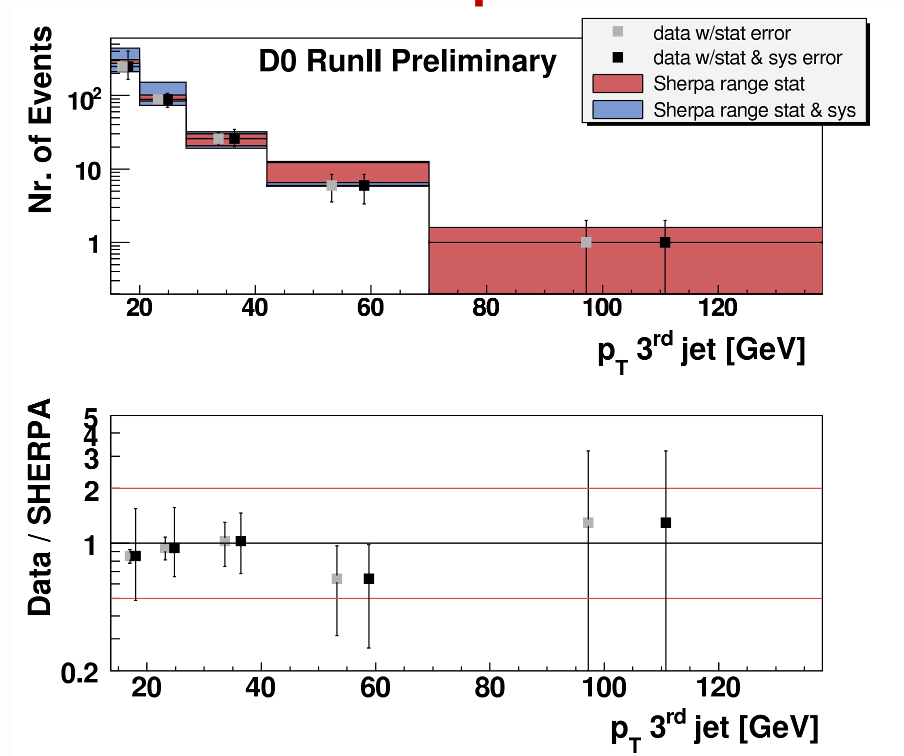

- Sherpa relying on CKKW method yields good description of extra hard jets

Summary/Outlook

current status

- well tested implementations of MSSM, ADD, AGC
- sophisticated simulation of SM and BSM processes
- Sherpa integrated in Genser, TeV and LHC experiments

current activities

- extension of the CKKW method to BSM production processes
- allow for particle decays without specifying the final state

  [similar to our τ-decay package]
- new BSM scenarios: FeynRules, RS1 model, TC, colorons, ...

sources, documentation, manual

- main reference T. Gleisberg et al. JHEP **0402** (2004) 056
- Sherpa can be downloaded from `www.sherpa-mc.de`
- the current release is Sherpa-1.1.1