Construction of new tools for automatic calculation of cross sections

Tanju Gleisberg [a]

Institute for Theoretical Physics
Dresden University of Technology

- Event generation with SHERPA
- The matrix elements generator AMEGIC++
  - Features
  - Optimization and phase space integration
- Physics implementation and applications

[a] The SHERPA collaboration: T. G., S. Höche, F. Krauss, S. Schumann, J. Winter

The event generator Sherpa

SHERPA (**S**imulation of **H**igh **E**nergy **R**eactions of **PA**rticles) is a new multipurpose event generator entirely written in C++.

T. Gleisberg, S. Höche, F. Krauss, A. Schälicke, S. Schumann and J. Winter, JHEP **0402** 056 (2004).

The Scope:

- Full simulation of high energy particle reactions at existing and future collider experiments, including e^+e^-, $\gamma\gamma$, $e\gamma$, $p\bar{p}$ and pp collisions
- Account for multi-jet production by using tree level matrix elements combined with the parton shower using the CKKW prescription

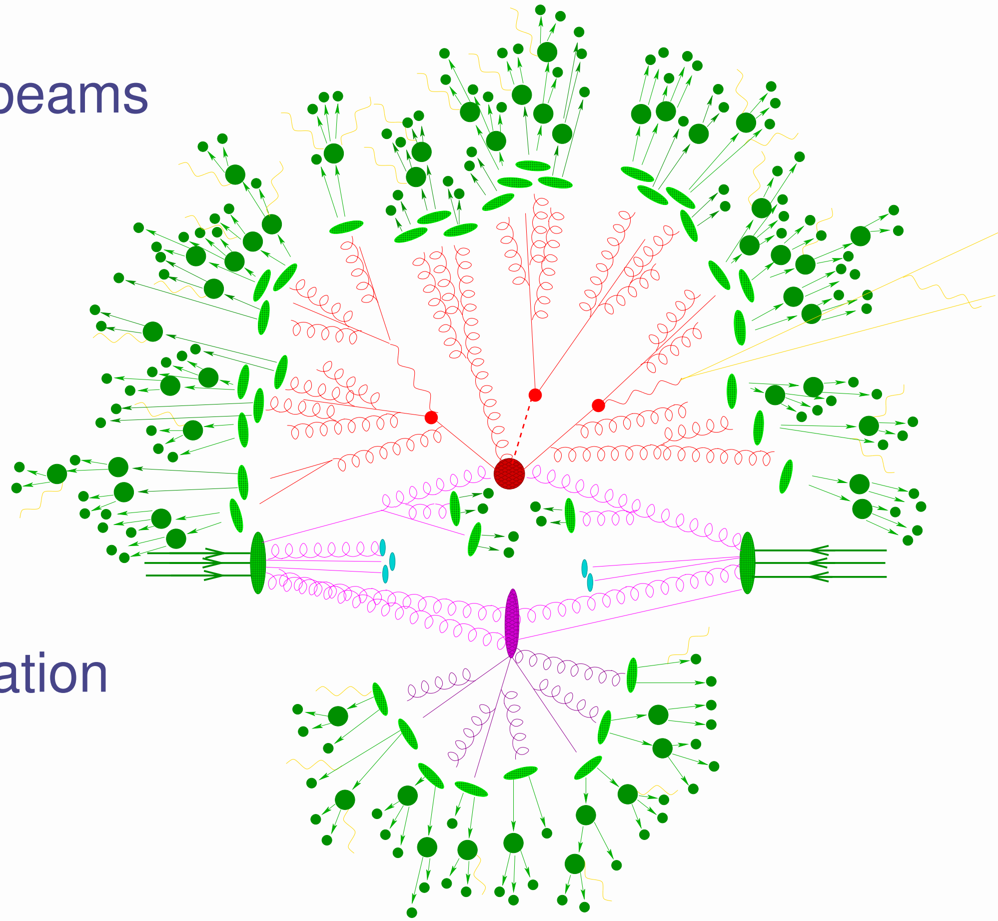
Features:

- Modular structure of independent physics modules
- Modules are interfaced through abstract handler classes
- Bottom-up approach (slim overhead that can be easily adapted)

Event generation with SHERPA

In its current version SHERPA includes:

- interface to various PDF sets for hadron beams
- initial state radiation and beam spectra for $e^+/e^-/\gamma$ beams
- the ME generator AMEGIC++ (hard process and decays)
- the parton shower module APACIC++
- combination of ME's and PS's via CKKW
- an interface to the Pythia string fragmentation and hadron decays
- a simple hard underlying event model



$\Rightarrow$ **Sherpa is the event generation framework.**

- **initialization of the different phases**
- **steering the event generation**

The domain of hard matrix elements

1. Precision signal processes studies
   - keep all interference terms
   - ME for the full SM interaction set (and beyond) or for subsets
2. Provide ME for the CKKW merging method to produce inclusive QCD samples

   S. Catani, F. Krauss, R. Kuhn and B. Webber, JHEP **0111** 063 (2001)

   F. Krauss, JHEP **0208** 015 (2002)

   - Key ideas:
     - combine NLL resumation of the Parton Shower with exact ME
     - Separation of the phase space for parton emission into a hard region of jet production (by ME) and a soft region of jet evolution (by PS)
     - Strategy to avoid double counting of equivalent phase space regions
   - merging reproduces shapes in NLO accuracy (but rates are LO)

     $\Rightarrow$ tests done and ongoing: $W/Z + jets$, $WW + jets$, pure $jets$, $higgs + jets$, ...
   - $\Rightarrow$ maximal order of ME corrections is given by the tree level generator (currently up to $X + 4\,jets \rightarrow \mathrm{O}(\alpha_s^4)$)

AMEGIC++ (A Matrix Element Generator in C++)

The matrix elements used in SHERPA are provided by the parton level generator **AMEGIC++**

- generates tree level matrix elements for arbitrary processes in the SM, the MSSM and the ADD model of LED
- universal approach: extending AMEGIC++ by Feynman rules of another model is rather simple
- completely automatic approach: a generator generator
  - First run: initialization
    $\longrightarrow$ generation of matrix elements
    $\longrightarrow$ generation of phase space mappings for a Multi-Channel PS-integration method
    $\Rightarrow$ stored as C++ libraries
  - Compilation of the libraries
  - Second run: integration/event generation

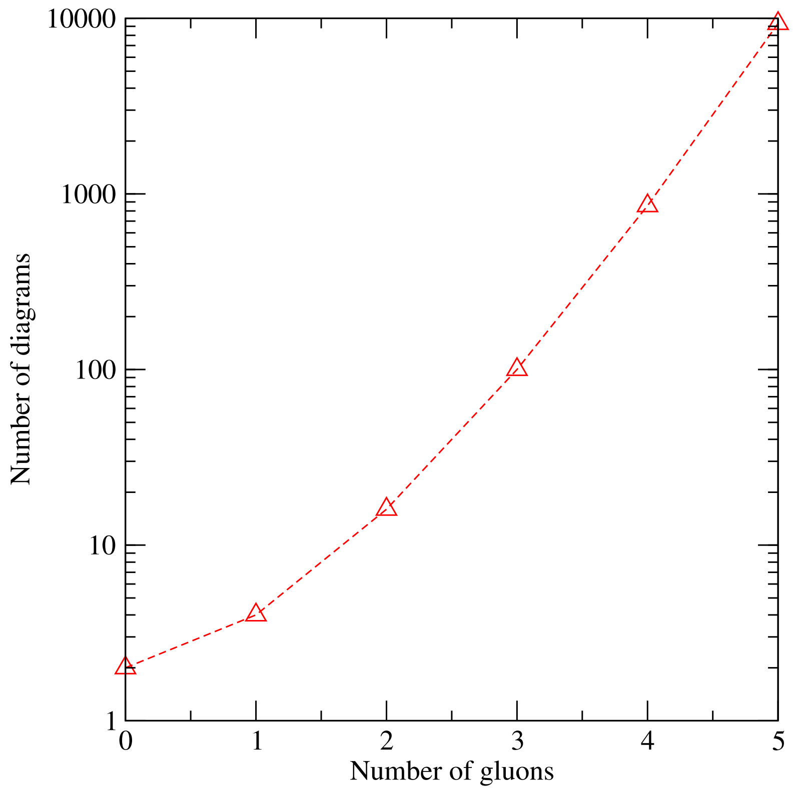
AMEGIC++ (A Matrix Element Generator in C++)

Computing exact (tree level) matrix elements

⇒ Basic difficulty: Factorial growth of the number of diagrams

- Example $e^+e^- \to q\bar{q} + ng$:

n	number of diagrams
0	2
1	4
2	16
3	100
4	856
5	9340



AMEGIC++ (A Matrix Element Generator in C++)

- direct computation of amplitudes as complex numbers using helicity amplitudes

R. Kleiss and W. J. Stirling, Nucl.Phys.B 262, 235 (1985)
A. Ballestrero and E. Maina, Phys.Lett.B 350, 225 (1995)

Further advantages of the helicity method:

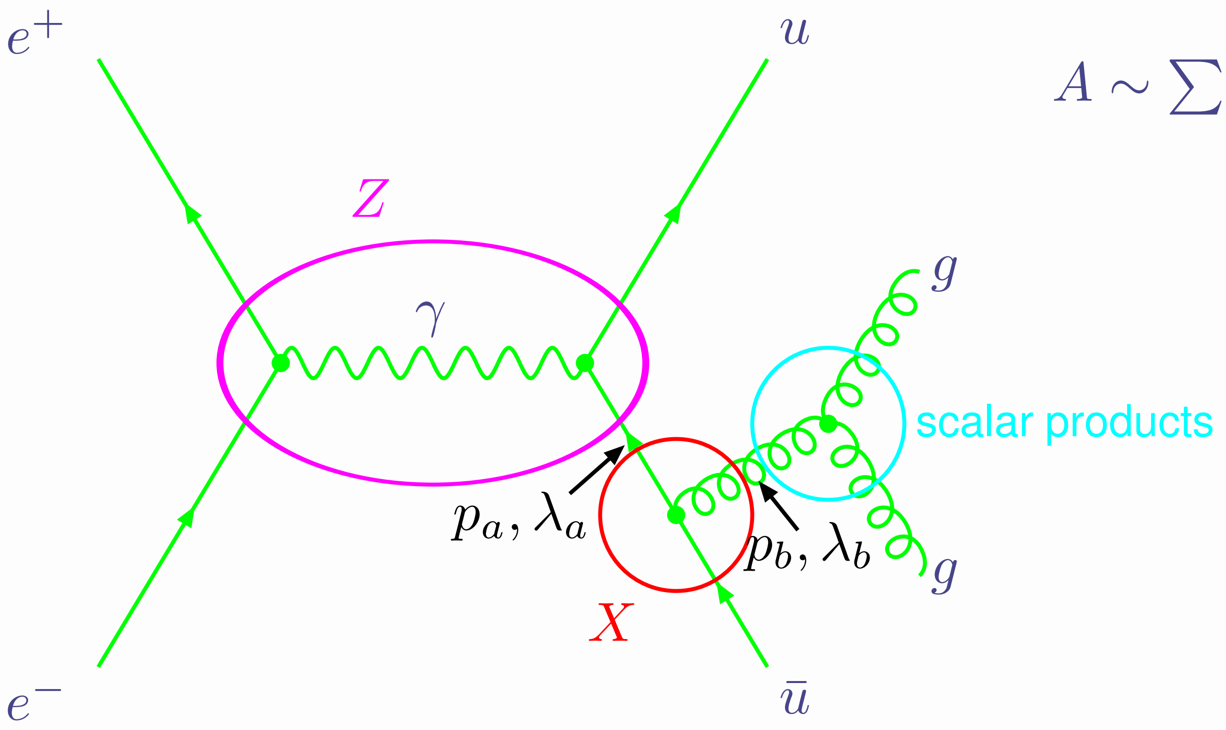
- Amplitudes are reduced to products of a few basic functions
- Straightforward computation of polarized cross-sections
- Easy to automate

Helicity Method

- Assemble amplitudes out of a small set of spinor products:

$$Y(p_1,\lambda_1;p_2,\lambda_2) = \bar{u}(p_1,\lambda_1)u(p_2,\lambda_2)$$
$$X(p_1,\lambda_1;p_2;p_3,\lambda_3) = \bar{u}(p_1,\lambda_1)\not{p}_2 u(p_3,\lambda_3)$$
$$Z(p_1,\lambda_1;p_2,\lambda_2;p_3,\lambda_3;p_4,\lambda_4) = \bar{u}(p_1,\lambda_1)\gamma^\mu u(p_2,\lambda_2)\ \bar{u}(p_3,\lambda_3)\gamma_\mu u(p_4,\lambda_4)$$

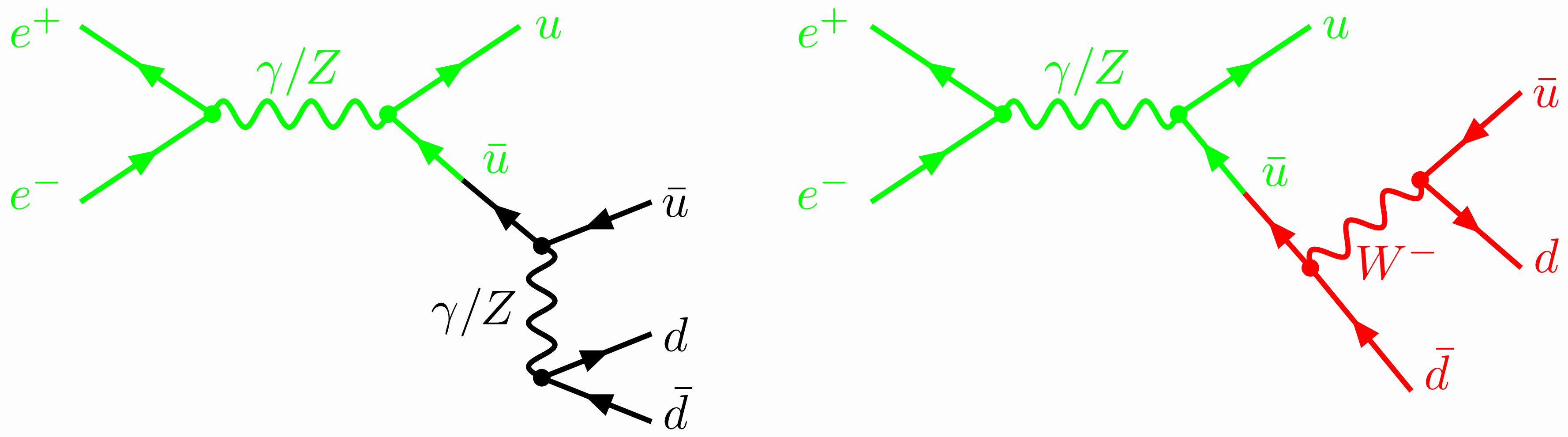
- $\Longrightarrow$ In principle sufficient to construct any tree-level amplitude



$$A \sim \sum_{\lambda_a,\lambda_b} Z(p_a,\lambda_a)\times X(p_a,\lambda_a,\epsilon^{\lambda_b}(p_b))\times V(\epsilon^{\lambda_b}(p_b),p_b)$$

Matrix elements

Tame the factorial growth:"Super-amplitudes"



Idea: Factorize out common Helicity building blocks of different amplitudes

$\Rightarrow$ reduce the number of complex multiplications

Matrix elements

Tame the factorial growth:"Super-amplitudes"

$e^+e^- \rightarrow$	Feynman diagrams	Super-amplitudes
e^+e^-	4	4
$e^+e^-\mu^+\mu^-$	50	10
$e^+e^-e^+e^-$	144	9
$e^+e^-e^+e^-\mu^+\mu^-$	3690	261
$e^+e^-e^+e^-e^+e^-$	13896	323

- So far only for amplitudes with equal color structure

Phase space integration

Multi-channel method

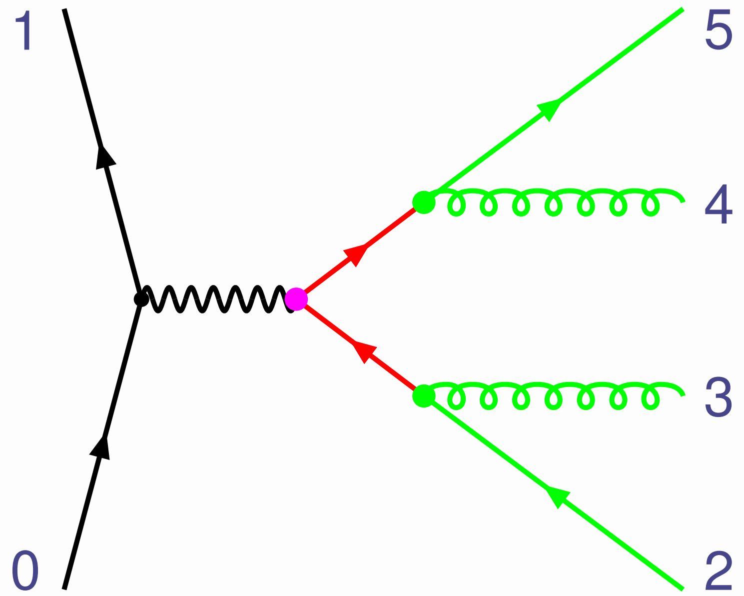
- Analyze peak structure for each amplitude
- Amplitudes are mapped on modular channels
- Each channel covers full phase space but enhances a certain peak distribution
- Channel weighted according to contribution

P_0 massless propagator

D_S symmetric decay

D_A asymmetric decay

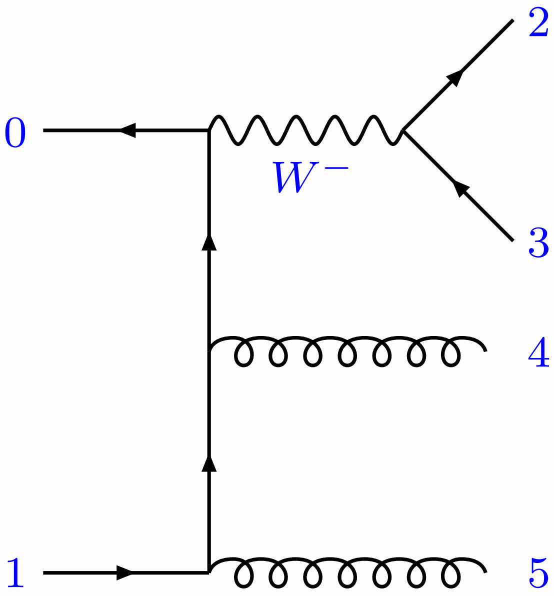
$\sim P_0(23) P_0(45)\ D_S(23,45)\ D_A(2,3)\ D_A(4,5)$

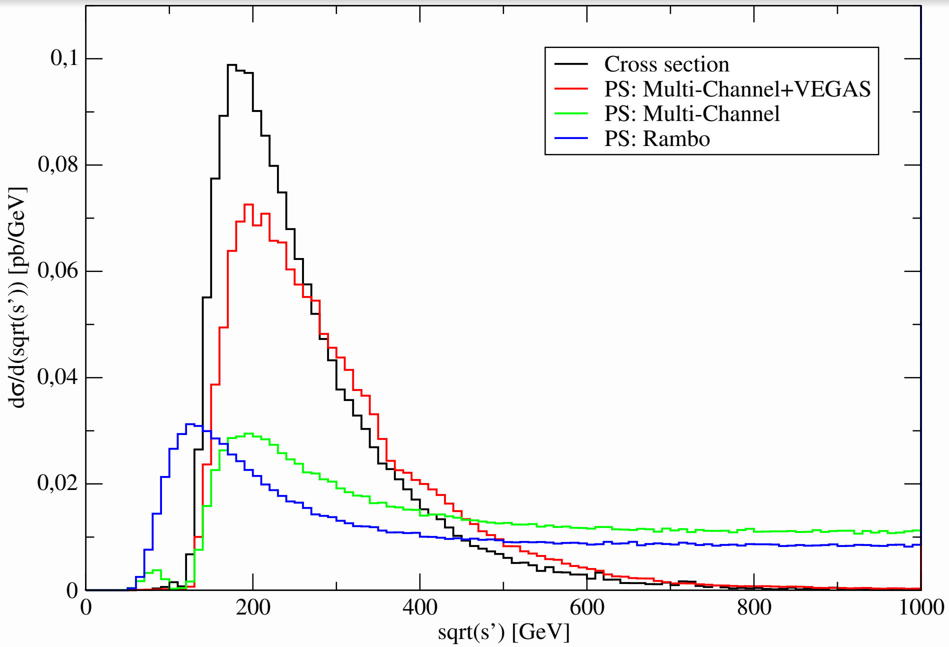


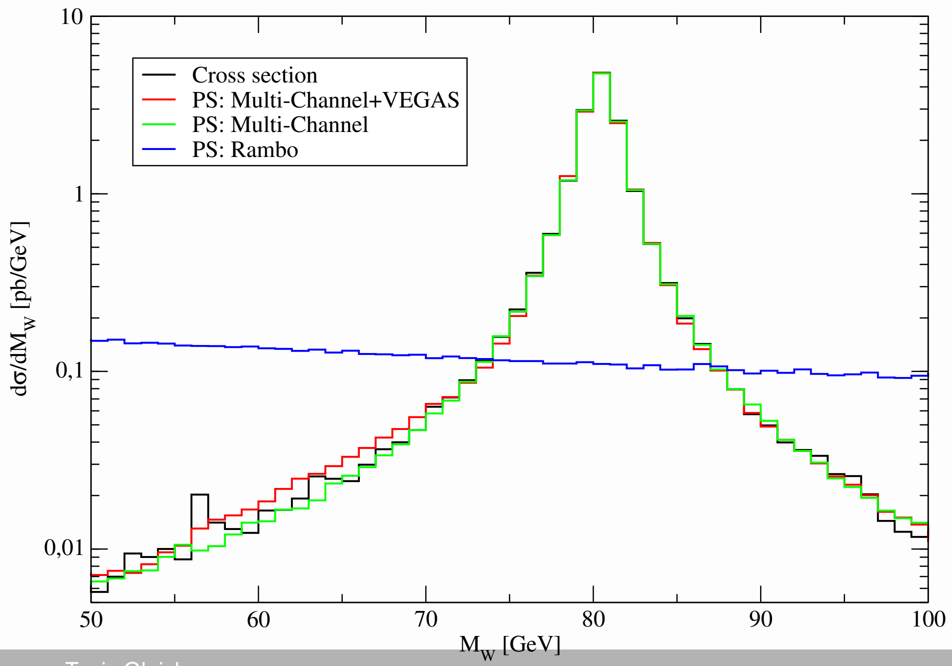
- Single channels are improved by an additional VEGAS adaptation

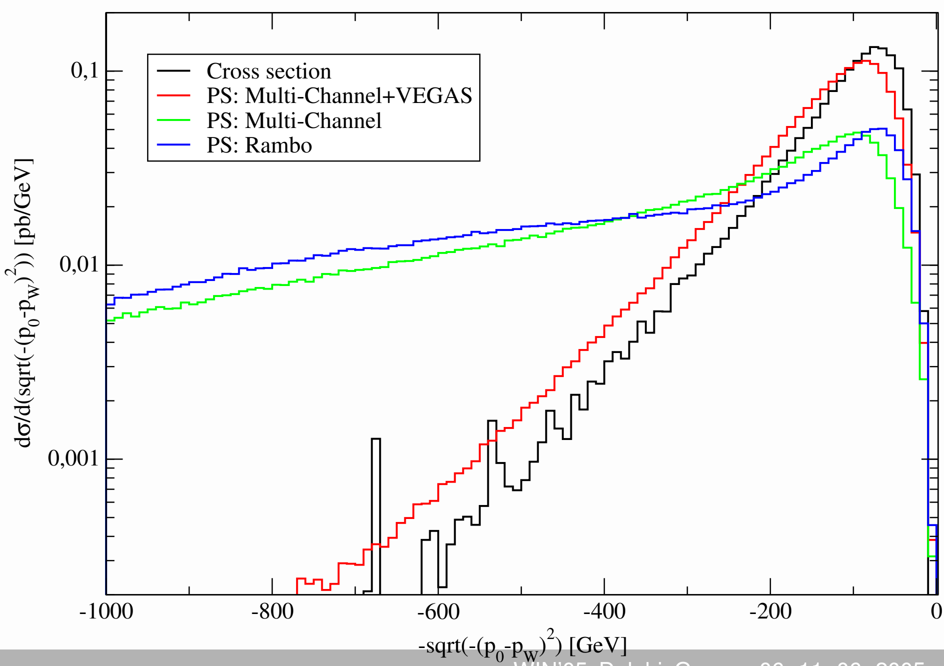
Performance example: $p\bar{p} \to W^- + 2$ jet

- 48 parton-level processes, e.g.









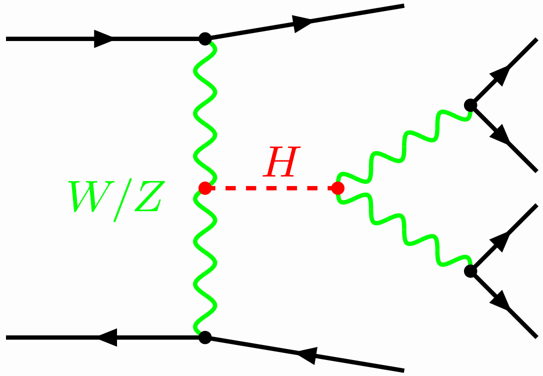
SM applications

AMEGIC++ successfully tested for:

- $e^+e^- \to 4/6$ massive or massless jets/fermions
- $\gamma\gamma \to 4f/4f + \gamma$
- $pp/p\bar{p} \to$
  - $e^-\bar{\nu}_e$, $e^+\nu_e$, e^+e^-, $\nu_e\bar{\nu}_e$, + up to 4 jets
  - $e^-\bar{\nu}_e b\bar{b}$, $e^+e^-b\bar{b}$, + up to 3 jets
  - γ, $\gamma\gamma$, + up to 4 jets
  - $t\bar{t}$, $b\bar{b}$, + up to 3 jets
  - 2-, 3-, 4-jet production

SM applications

Higgs-production via fusion of vector bosons:

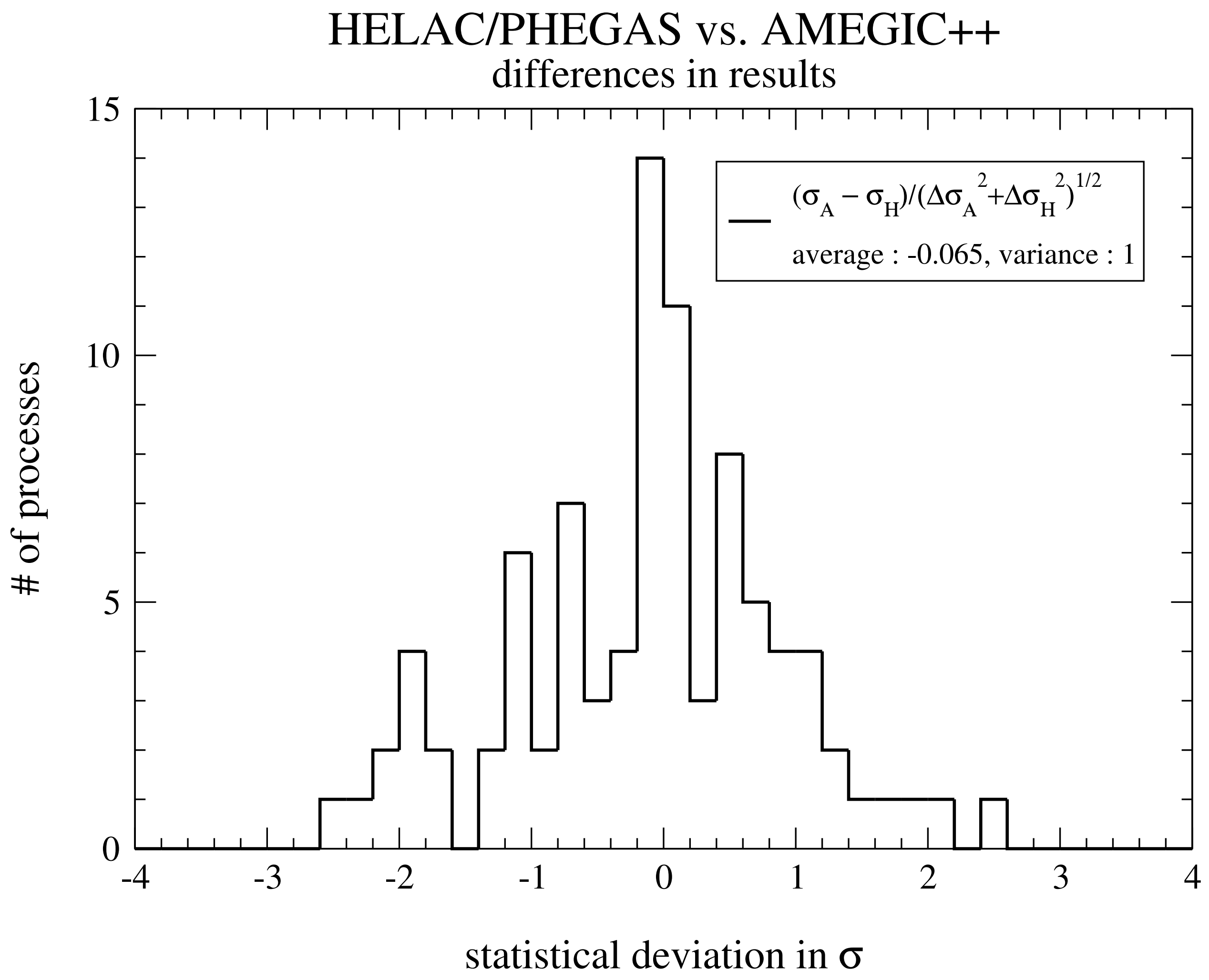


$e^+e^- \to$	$\sqrt{s}$=360 GeV [fb]	$\sqrt{s}$=500 GeV [fb]
$e^-e^+u\bar{u}d\bar{d}$	0.6842(85)	1.2704(12)
$e^-e^+u\bar{u}e^-e^+$	6.06(36)e-03	6.767(15)e-03
$e^-e^+u\bar{u}\mu^-\mu^+$	9.24(12)e-03	9.168(11)e-03
$\nu_e\bar{\nu}_e u\bar{d}d\bar{u}$	1.15(3)	2.4642(12)
$\nu_e\bar{\nu}_e u\bar{d}e^-\bar{\nu}_e$	0.426(11)	0.91212(46)
$\nu_e\bar{\nu}_e u\bar{d}\mu^-\bar{\nu}_\mu$	0.425(12)	0.8951(5)

SM applications

Comparison between AMEGIC++ and Helac/PHEGAS for a large number of processes $e^+e^- \to 6f$ ...

S. Schumann et al., EPJC **34**, 173 (2004)



SM applications

Validation for LHC purposes during and after the MC4LHC workshop at CERN, summer 2003 ...

X-sects		Number of jets				
Process + n QCD jets	Order	0	1	2	3	4
$e^-\bar{\nu}_e$ (pb)	$\alpha_{EM}^2\alpha_S^n$	3908(3)	1011(2)	362.3(9)	137.5(5)	54(1)
$e^+\nu_e$ (pb)	$\alpha_{EM}^2\alpha_S^n$	5432(5)	1277(2)	466(2)	184(1)	77.3(4)
e^-e^+ (pb)	$\alpha_{EM}^2\alpha_S^n$	723.1(7)	188.2(3)	69.7(2)	27.3(1)	11.1(1)
$\nu_e\bar{\nu}_e$ (pb)	$\alpha_{EM}^2\alpha_S^n$	3272(3)	716(1)	268.0(6)	105.6(5)	44.3(5)
$e^-\bar{\nu}_e$ + $b\bar{b}$ (pb)	$\alpha_{EM}^2\alpha_S^{n+2}$	9.37(1)	9.86(2)	6.87(5)	4.31(6)	
e^-e^+ + $b\bar{b}$ (pb)	$\alpha_{EM}^2\alpha_S^{n+2}$	18.86(3)	6.78(2)	3.10(5)		
(just jets) (mb)	α_S^n	–	–	330.9(3)	22.7(2)	4.99(11)
γ (nb)	$\alpha_{EM}\alpha_S^n$	–	89.1(2)	19.4(1)	7.55(8)	2.66(2)
$\gamma\gamma$ (pb)	$\alpha_{EM}^2\alpha_S^n$	45.6(1)	25.3(1)	18.5(2)	9.7(1)	
$t\bar{t}$ (pb)	α_S^{n+2}	754.0(8)	748.7(7)	519(1)	305(3)	
$b\bar{b}$ (mb)	α_S^{n+2}	470.7(5)	8.84(2)	1.817(6)	0.460(3)	

SM applications

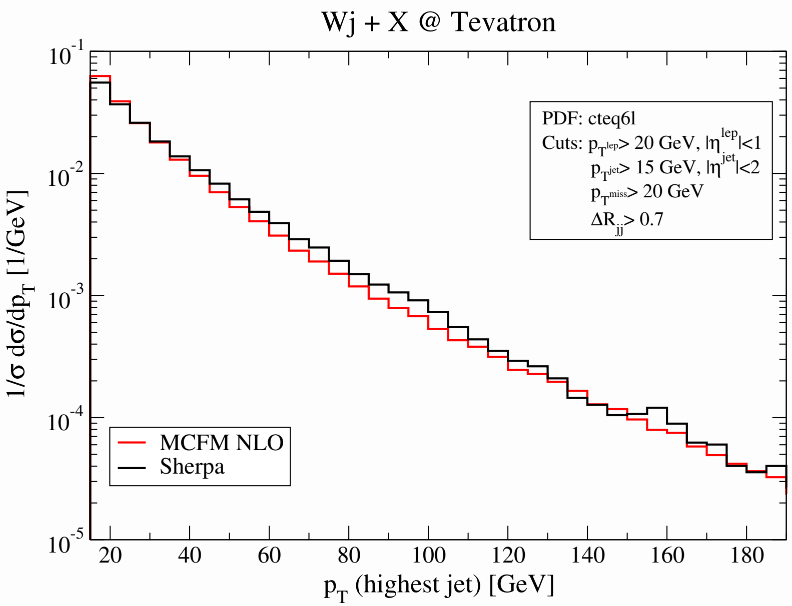
Validation for LHC purposes during and after the MC4LHC workshop at CERN, summer 2003 ...

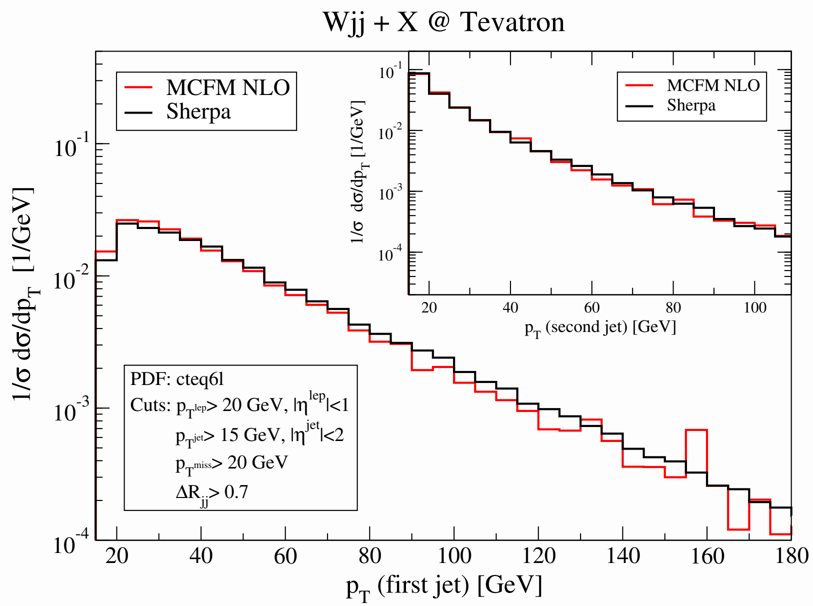
X-sects (pb)	Number of jets						
$e^- \bar{\nu}_e + n$ QCD jets	0	1	2	3	4	5	6
Alpgen	3904(6)	1013(2)	364(2)	136(1)	53.6(6)	21.6(2)	8.7(1)
CompHEP	3947.4(3)	1022.4(5)	364.4(4)				
MadEvent	3902(5)	1012(2)	361(1)	135.5(3)	53.6(2)		
Amegic++/Sherpa	3908(3)	1011(2)	362.3(9)	137.5(5)	54(1)		

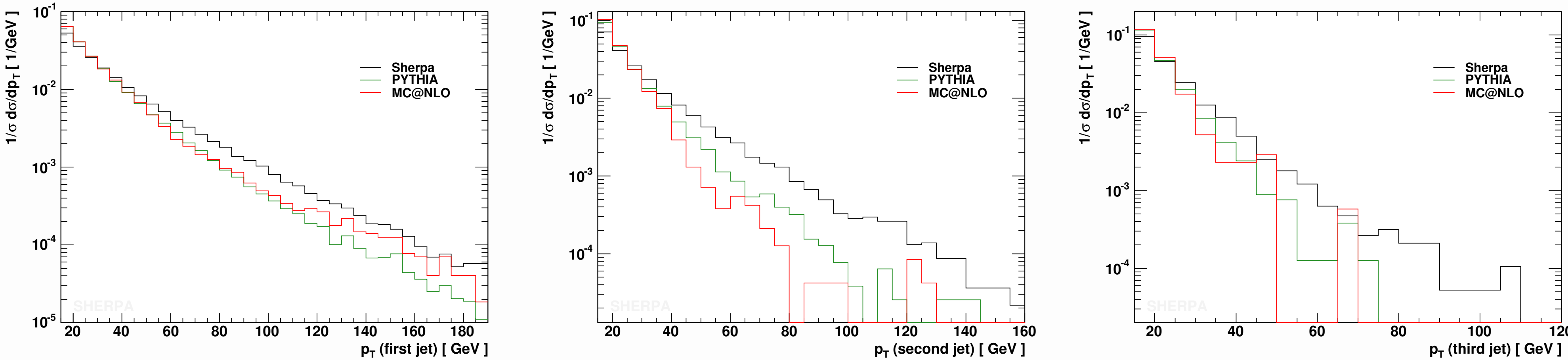
X-sects (pb)	Number of jets				
$e^- \bar{\nu}_e + b\bar{b}$	0	1	2	3	4
Alpgen	9.34(4)	9.85(6)	6.82(6)	4.18(7)	2.39(5)
CompHEP	9.415(5)	9.91(2)			
MadEvent	9.32(3)	9.74(1)	6.80(2)		
Amegic++/Sherpa	9.37(1)	9.86(2)	6.87(5)	4.31(6)	

SHERPA vs. NLO: Incl. W^- +jet prod. @ Tevatron Run II

F. Krauss, A. Schälicke, S. Schumann and G. Soff, Phys. Rev. D 70 (2004) 114009



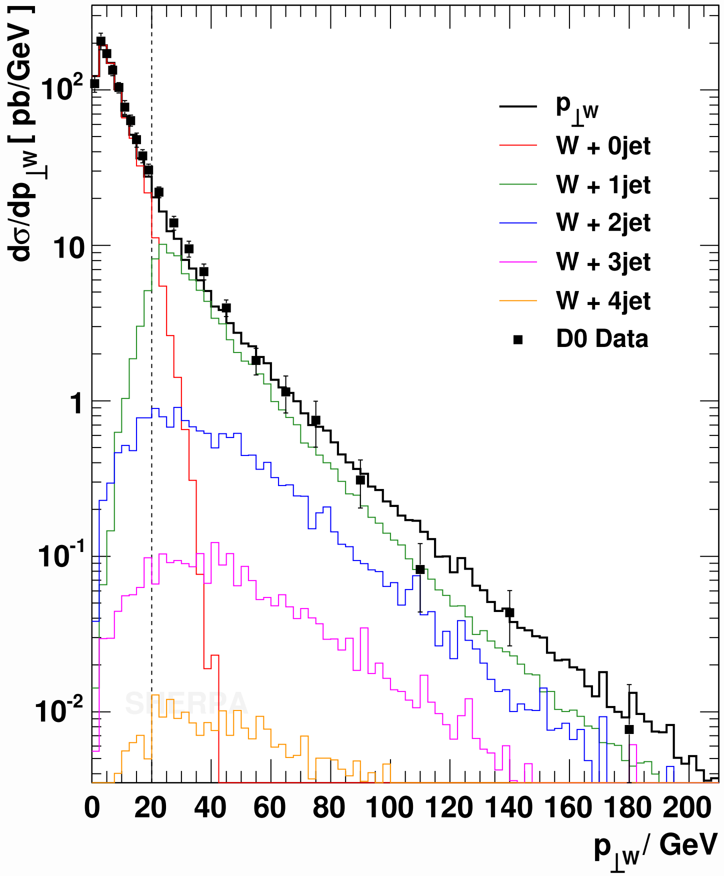


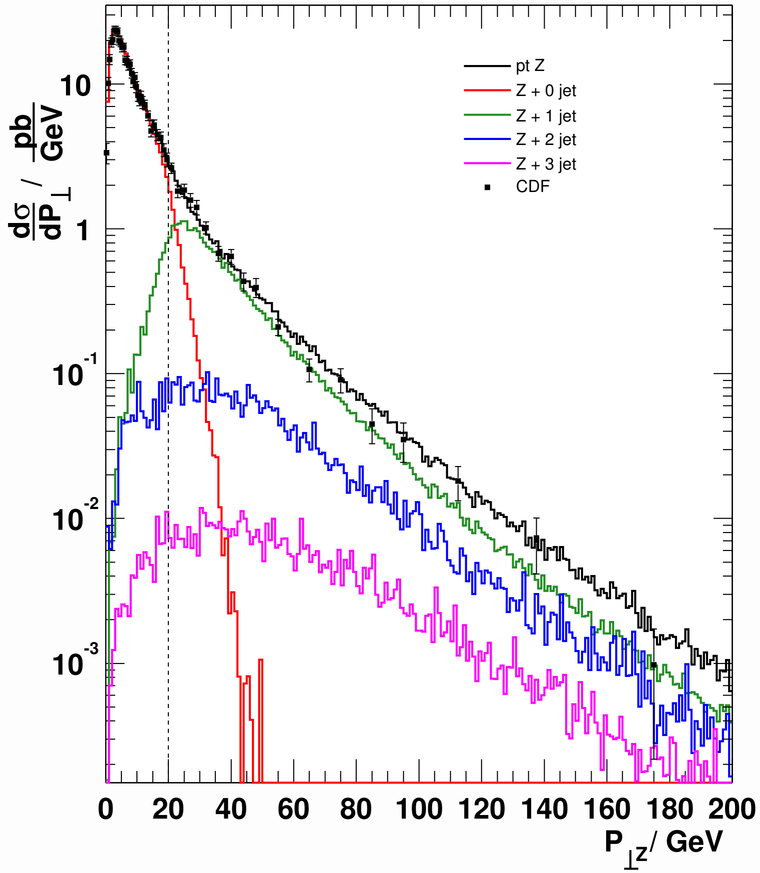


SHERPA vs. Data

Inclusive W and Z transverse momentum distributions from Tevatron Run I

- ME's with up to four (W) or three (Z) extra jets





D0: Phys. Lett. B **513**, 292 (2001)

CDF: Phys. Rev. Lett. **84**, 845 (2000)

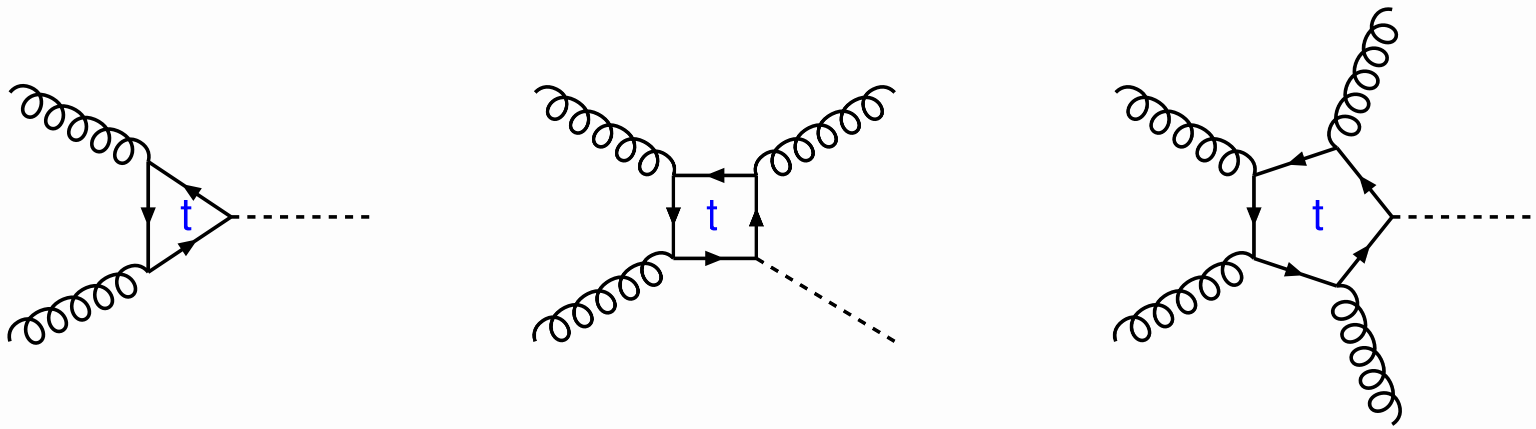
distributions multiplied by constant K factors: 1.25 and 1.6

SM: some effective vertices

Extension to SM-interactions: (will be available in the next release)

- gluon-gluon-higgs coupling via effective Lagrangian

$$\mathcal{L}_{ggH} \sim G^a_{\mu\nu} G^a_{\mu\nu} H \qquad \text{for } \; m_H \ll 2m_t$$



- Also: $\gamma\gamma$-higgs coupling

MSSM implementation

- Interface to ISASUSY for the MSSM spectrum
- General Feynman rules (unitary gauge, conserved R-party) according to J. Rosiek, Phys.Rev.D41:3436, 1990
- The violated fermion flow of Majorana fermions is cured by using appropriate Feynman rules
  - Implemented the approach of Denner *et al.* Nucl.Phys.B387, 1992
  - The relative sign of interfering Feynman graphs is determined avoiding the usage of charge-conjugated matrices
  - Instead an orientation (fermion flow) for each appearing fermion line is defined

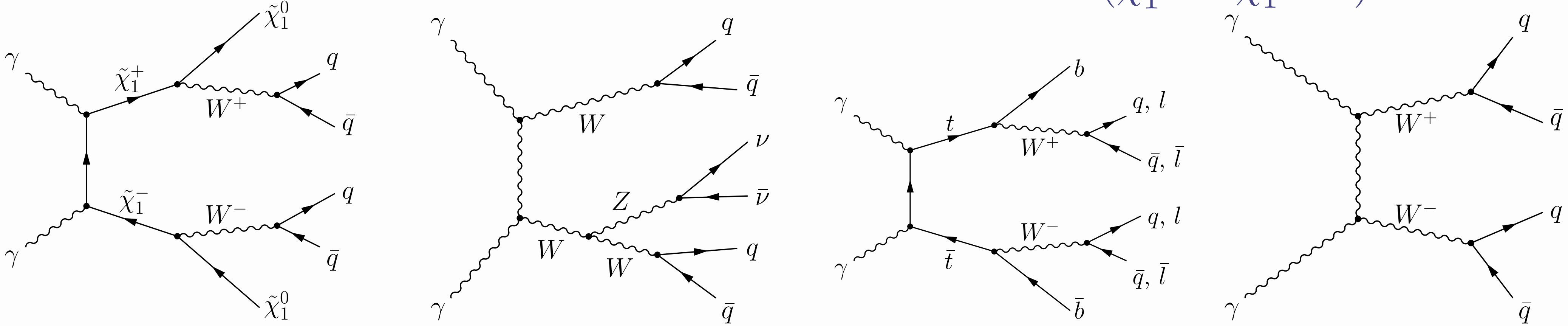
Application area

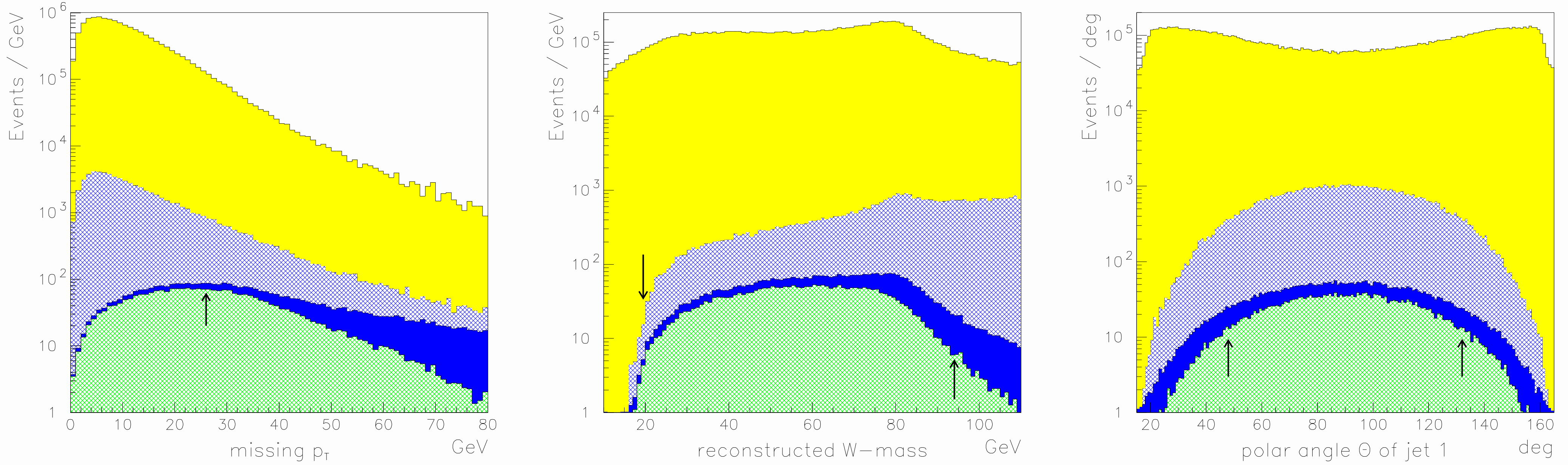
- Calculation of total and partial widths of sparticles
- Sparticle production processes at LHC or a future LC
- AMEGIC++ can provide SUSY signals and associated SM/SUSY backgrounds as well

Example: Chargino production and decay at γ collider

G. Klämke, K. Mönig, hep-ph/0503191

- mSUGRA scenario similar to SPS1a with enhanced BR$(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^\pm)$





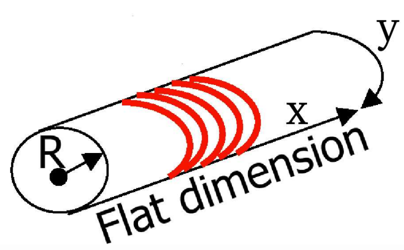
$\sqrt{s_{ee}} = 500$ GeV

The ADD model of Large Extra Dimensions

Large extra dimensions á la ADD

(Arkani-Hamed,Dimopoulos,Dvali, Phys. Lett. B429,263 (1998)

- n compact extra dimensions, accessible only to gravity



- Kaluza-Klein excitations lead to enhanced effective gravitational coupling

$$M_{\rm Pl}^2 \sim R^n M_{\rm D}^{n+2}$$

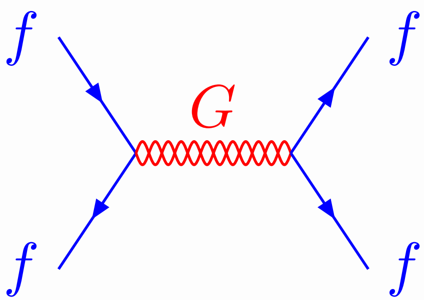
- Feynman rules:

  Han, Lykken, Zhang, Phys. Rev. D 59,105006 (1999)

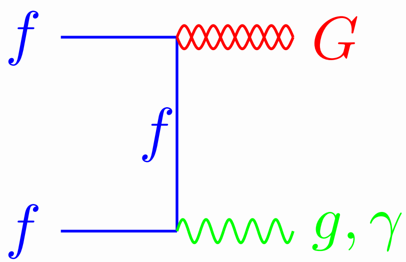
  Giudice, Rattazzi, Wells, Phys. Lett. B 544,3 (1999)

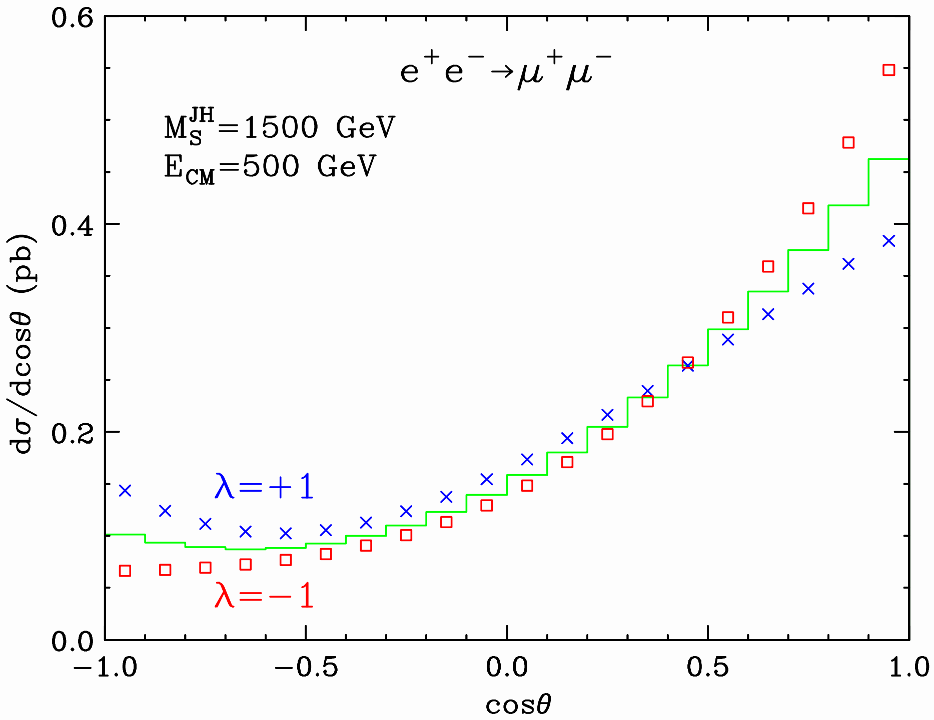
The ADD model of Large Extra Dimensions

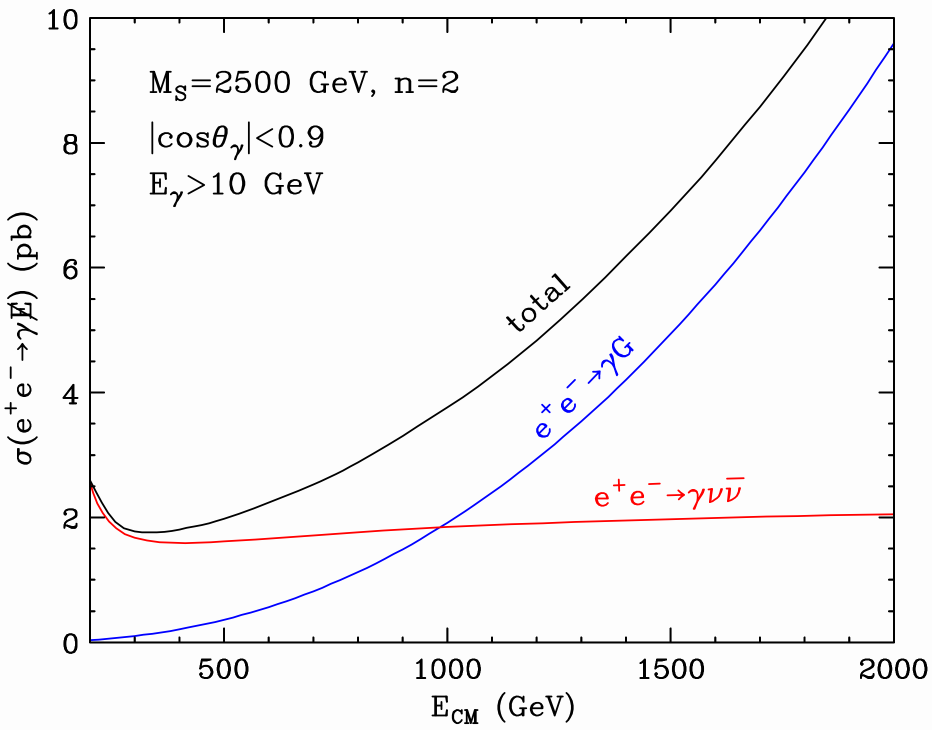
Virtual Graviton exchange



Real Graviton production







Conclusion and outlook

- AMEGIC++ is an automatic tool to generate tree-level matrix elements
- Tested for up to six-particle production processes
- Beyond SM the MSSM and the ADD model of large extra dimensions have been implemented
- As a module of the event generator SHERPA AMEGIC++ allows a huge variety for studies of signal and background processes in SM and BSM
  - Extension to further models is rather straightforward
    $\rightarrow$ in progress or planned in near future:
    - R-parity violating supersymmetry
    - anomalous EW gauge coupling
- Soon available: ME for production + fully correlated decay processes
  e.g. $p\bar{p} \rightarrow t\,[\rightarrow b\,W^+[\rightarrow ...]]\;\bar{t}\,[\rightarrow \bar{b}\,W^-[\rightarrow ...]]\;\,h[\rightarrow b\bar{b}]$

- The latest SHERPA version is available from our homepage:

  http://www.physik.tu-dresden.de/ krauss/hep

The SHERPA approach (CKKW)

Solution:

- Divide multi-jet phase space into two regimes (Durham measure $Q_{\rm cut}$)
  - Jet production by ME (if available)
  - Jet evolution down to fragmentation scale by the PS
- Reweight ME's to get exclusive samples at a resolution scale $Q_{\rm cut}$

  $\Rightarrow$ This allows to add samples of different jet multiplicities
- Veto on PS configurations that have already been taken into account by a higher order ME

Method:

- Select a jet multiplicity with probability:

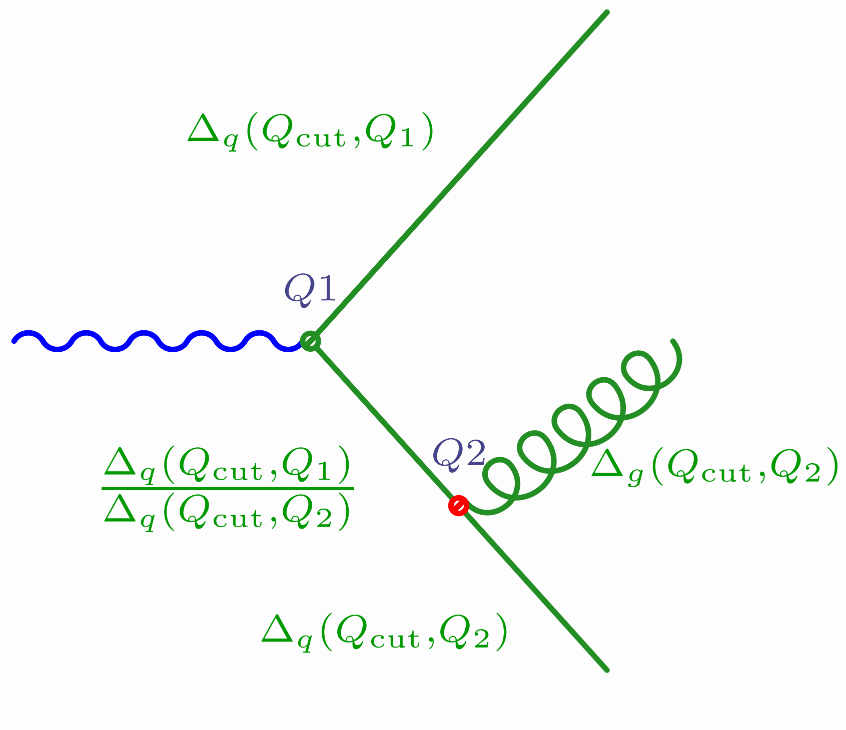
$$P_n = \frac{\sigma_n}{\sum_{i=0}^{N} \sigma_i}$$

  where σ_n is the n-jet matrix element taken at resolution scale $Q_{\rm cut}$. Use $Q_{\rm cut}$ as scale for PDF's and α_S.
- Generate final state momenta p_i according to the ME

The SHERPA approach (CKKW)

Method:

- k_T cluster backwards initial and final state particles until a core $2 \to 2$ process remains, this results in a chain of resolutions for 1,2,..n jets
- Recalculate α_S at each vertex in the tree at the corresponding k_T scale
- Apply Sudakov weights
  - $\Delta_{q,g}(Q_{\text{cut}}, Q_{\text{prod}})$ for outgoing partons
  - $\Delta_{q,g}(Q_{\text{cut}}, Q_{\text{prod}})/\Delta_{q,g}(Q_{\text{cut}}, Q_{\text{dec}})$ for lines between $Q_{\text{prod}} > Q_{\text{dec}}$
  - Reject events with a combined coupling and Sudakov weight smaller than random number $R \in [0, 1]$
  - Start the initial or final state parton shower for each parton of the event, starting at the scale where it was produced
  - Veto on emissions above the scale Q_{cut}



$$W = \Delta_g(Q_{\text{cut}},Q_2)[\Delta_q(Q_{\text{cut}},Q_1)]^2 \frac{\alpha_s(Q_2)}{\alpha_s(Q_{\text{cut}})}$$