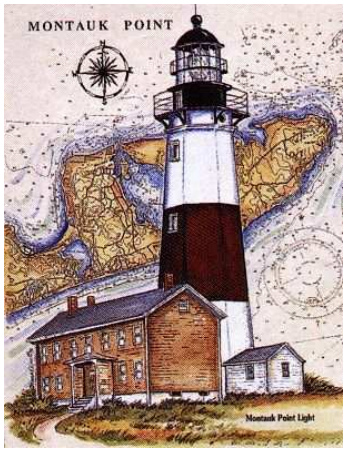
Loopfest II



BNL, May 14–16, 2003

The LoopVerein:

(not only) European activities

Stefan Dittmaier

MPI Munich

Contents

1 Introduction

Experiments at LEP/SLC/Tevatron

- confirmation of Standard Model as quantum field theory
  (quantum corrections significant)
- top mass m_{t} indirectly constrained by quantum corrections
  $\leftrightarrow$ in agreement with m_{t} measurement of Tevatron
- Higgs mass M_{H} indirectly constrained by quantum corrections
  $\hookrightarrow$ impact on Higgs searches

Great success of precision physics

$\hookrightarrow$ even greater potential at future $\mathrm{e}^+\mathrm{e}^-$ linear collider

- GigaZ/MegaW: precision increases by factor ~ 10 w.r.t. LEP/SLC
  EXP: $\Delta \sin^2 \theta_{\mathrm{eff}}^{\mathrm{lept}} \sim 0.00001, \qquad \Delta M_{\mathrm{W}} \sim 6\,\mathrm{MeV}$
  TH: go from a few 10^2 to a few 10^4 (more complicated) diagrams
- high-energy runs ($\sqrt{s} = 350, 500, 800, \ldots\,\mathrm{GeV}$):
  various cross sections at %-level, SUSY particle production (?)

LC physics program demands precision calculations

- progress on higher-order corrections
  - ◇ 2-loop accuracy for $2 \to 2$ and $1 \to 3$ reactions
  - ◇ full 1-loop calculations for $2 \to 3, 4, \ldots$ processes
- progress on simulation tools
  - ◇ Monte Carlo generators for multi-particle final states

This talk: summary of developments (more topical than comprehensive) achieved since spring 2001 (TESLA TDR)

– in the LoopVerein

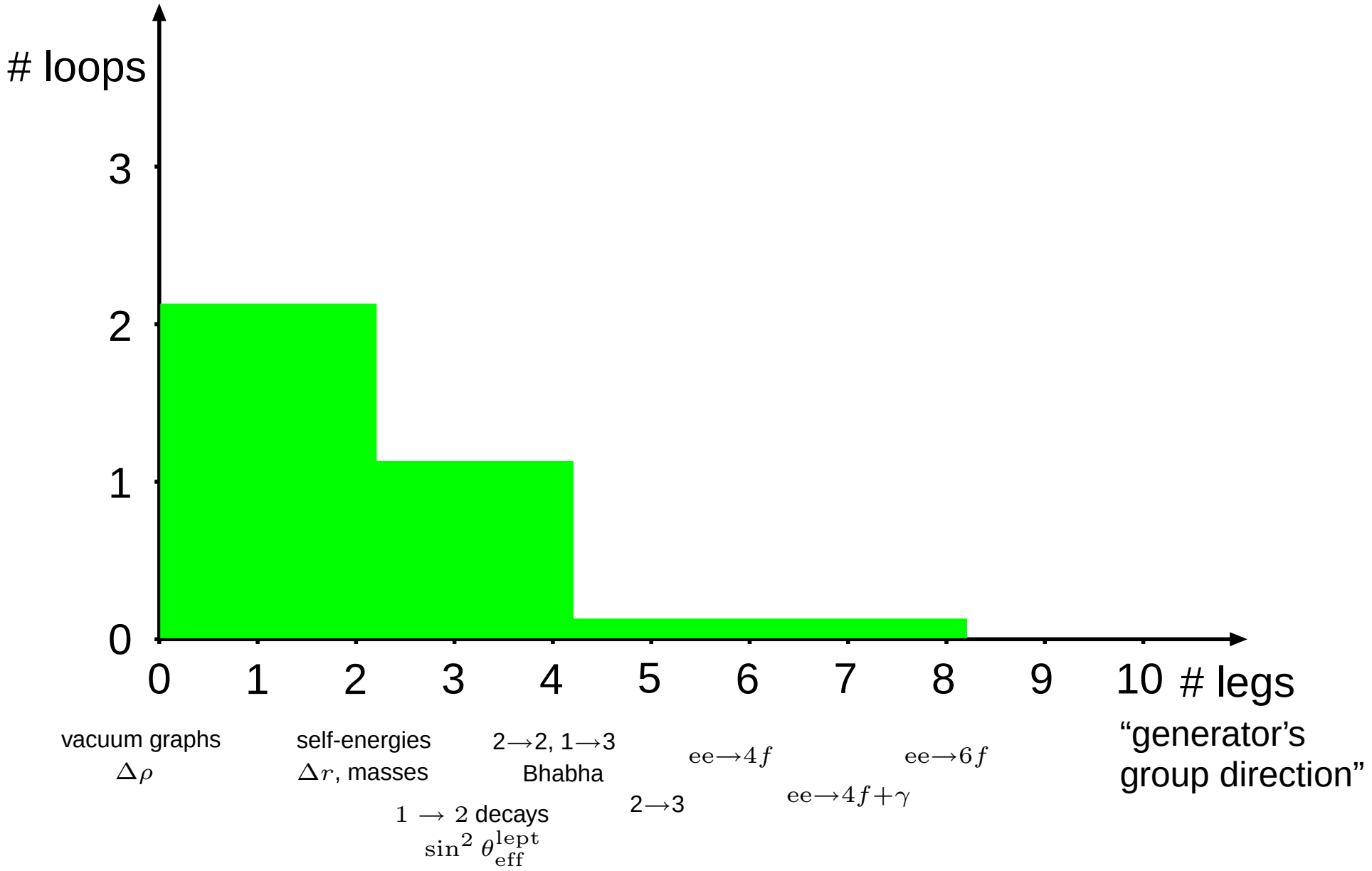
(conveners: S. Dittmaier (replacing F. Jegerlehner), W. Hollik)

– (partially) in the Event Generators Working Group of the ECFA/DESY workshop

(conveners: M. Antonelli, S. Jadach, S. Moretti)

“LoopVerein direction”

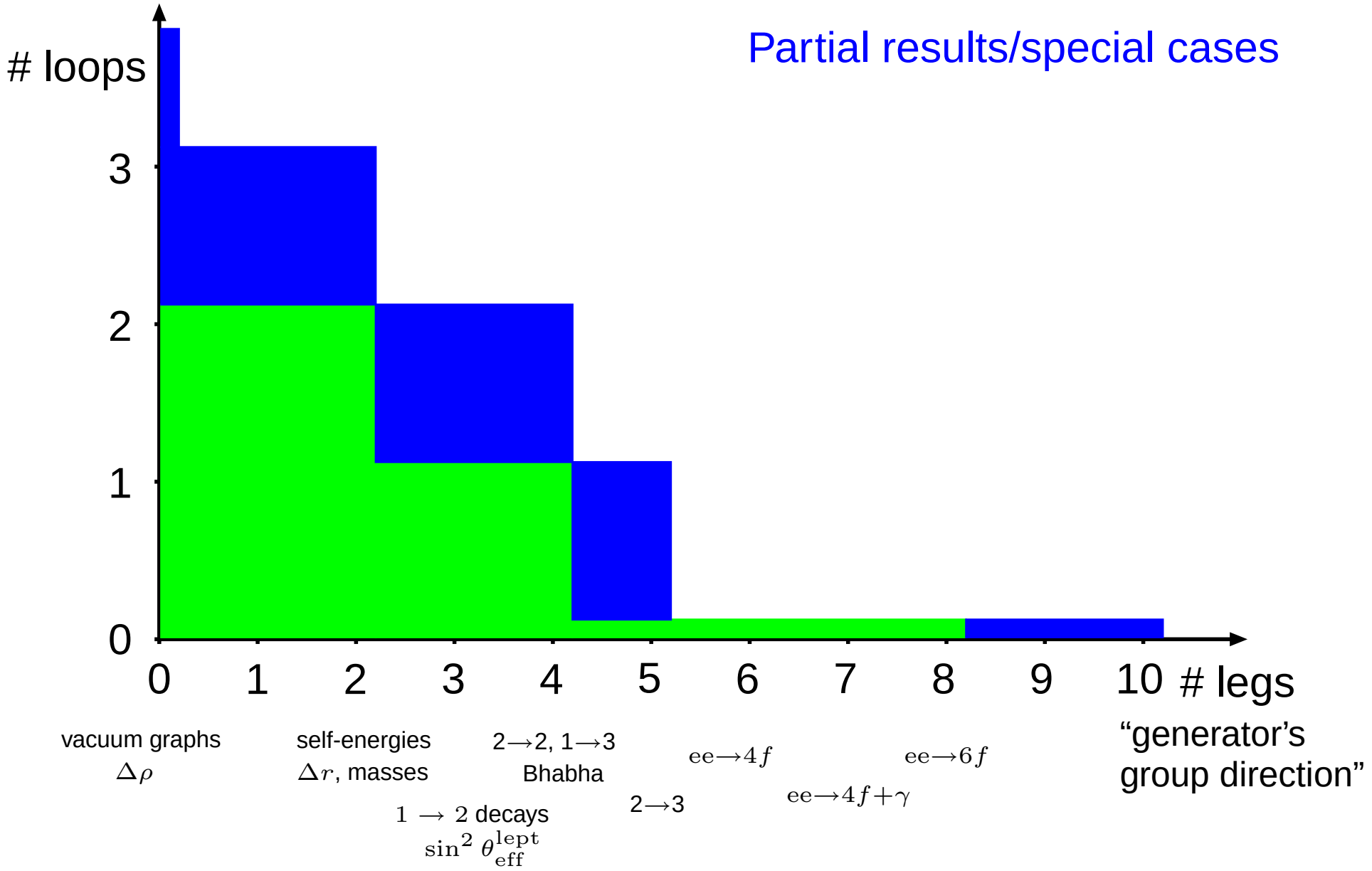
Technique well established



“LoopVerein direction”

Technique well established

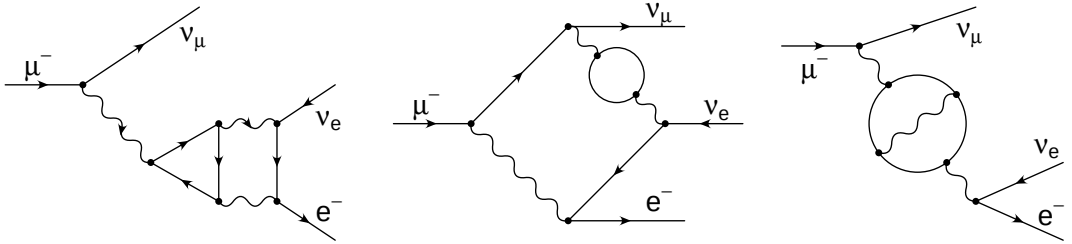
Partial results/special cases



2 Multi-loop calculations — progress on $2 \to 2$ and $1 \to 3$ reactions

2.1 Precision calculations for μ decay

- 2-loop contribution of closed fermion loops



Freitas, Hollik, Walter, Weiglein '00

$$\Delta M_{\mathrm{W}} = \mathcal{O}(50\,\mathrm{MeV})$$

NEW result by
Awramik, Czakon '03

  – diagram generation by FeynArts
  – algebraic reduction by TwoCalc
  – semianalytical evaluation of 2-loop master integrals

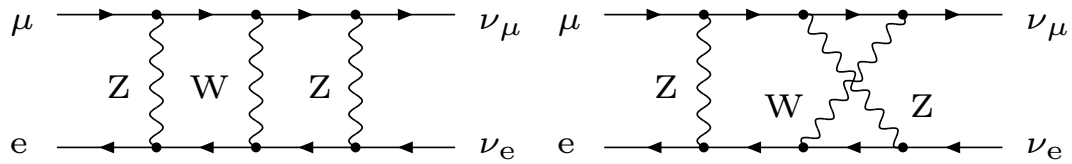
Böhm, Denner, Eck, Küblbeck '90-'92; Hahn '98-'02

Weiglein

- M_{H} dependence of 2-loop diagrams

Freitas, Hollik, Walter, Weiglein '02

- Complete 2-loop calculation of boson loops



Awramik, Czakon '02
Onishchenko, Veretin '02

$$\Delta M_{\mathrm{W}} = \mathcal{O}(1\,\mathrm{MeV})$$

  – diagram generation by Diagen (AC) and DIANA (OV)
  – algebraic reduction by FORM
  – semianalytical evaluation (AC) and asymptotic expansion (OV)

Fleischer, Tentyukov '99-'02

Recent progress: 3-loop contributions to $\Delta\rho$

Faisst, Kühn, Seidensticker, Veretin '03

– corrections of $\mathcal{O}(G_\mu^2 m_\mathrm{t}^4 \alpha_\mathrm{s})$ and $\mathcal{O}(G_\mu^3 m_\mathrm{t}^6)$

$\hookrightarrow \Delta M_\mathrm{W} = \mathcal{O}(5\,\mathrm{MeV})$ $\hookrightarrow \Delta M_\mathrm{W} = \mathcal{O}(0.5\,\mathrm{MeV})$

– diagrams generated by QGRAF and asymptotically expanded in FORM

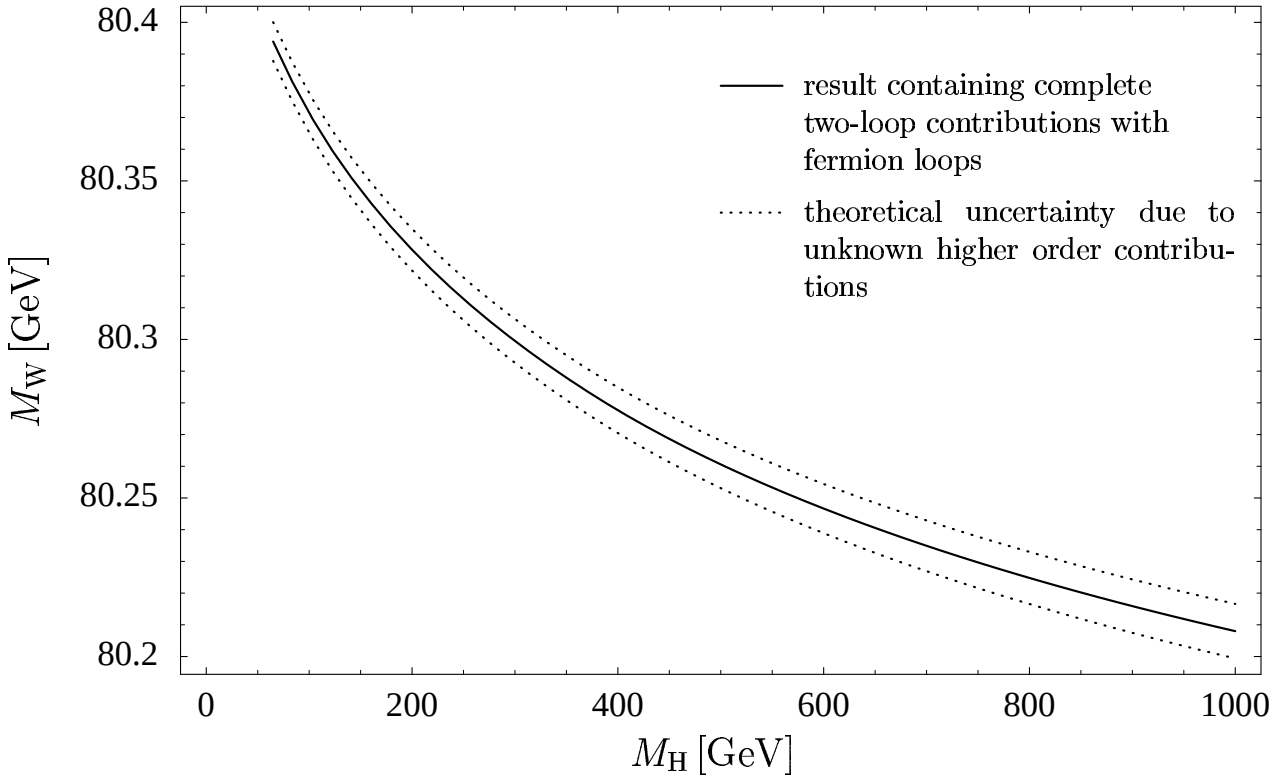
Nogueira '93

$\hookrightarrow$ tadpole diagrams computed with MATAD

Steinhauser '00

Prediction of M_W from muon decay:

Freitas, Hollik, Walter, Weiglein '00



Theoretical uncertainty:

status 2000:
$\Delta M_\mathrm{W} \sim 6\,\mathrm{MeV}$

status 2003:
$\Delta M_\mathrm{W} \sim 2\,\mathrm{MeV}$

2.2 Recent results from the 2-loop frontier

Genuine 2-loop corrections to $2 \to 2$, $1 \to 3$ processes

- Algebraic reduction to master integrals
  Anastasiou, Gehrmann, Glover, Laporta, Oleari, Remiddi, Smirnov, Tausk, Veretin '00

  by integration by parts, Lorentz invariance identities

  $\hookrightarrow$ calculation of master integrals by Mellin–Barnes technique,
  Anastasiou, Smirnov, Tausk, Tejeda-Yeomans '99-'02

  differential equations, numerical techniques
  Gehrmann, Remiddi '00, '01 Binoth, Heinrich '00

- Direct reduction of full 2-loop amplitudes
  Moch, Uwer, Weinzierl '02

  $\hookrightarrow$ higher transcendental functions $\to$ nested harmonic sums

- Explicit algebraic results:
  - 2-loop amplitudes for massless $2 \to 2$ processes
    (Bhabha, QCD parton scattering, etc.)
    Anastasiou, Bern, v.d.Bij, De Freitas, Dixon, Ghinculov, Glover, Oleari, Schmidt, Tejeda-Yeomans, Wong '01, '02
  - 2-loop QCD amplitudes for $e^+e^- \to 3$jets
    Garland, Gehrmann, Glover, Koukoutsakis, Moch, Remiddi, Uwer Weinzierl '02

Further activities:

- $\mathcal{O}(\alpha)$ correction to $\mathrm{e}^+\mathrm{e}^- \to f\bar{f} + \gamma$ — Jadach, Melles, Ward, Was, Yost '99-'01; Czyz, Kühn, Rodrigo '02
- Numerical approach to 2-loop diagrams
  $\hookrightarrow$ self-energies, some vertex corrections — Passarino, Uccirati '01, '02
- Progress on universal QED corrections
  to polarized $\mathrm{e}^\pm$ scattering in higher orders — Blümlein, Kawamura '02
- Part of 2-loop renormalization of massive Bhabha process:
  (1-loop graphs) $\times$ (1-loop counterterms) — Fleischer, Riemann, Tarasov, Werthenbach '02
- 2-parton bremsstrahlung for $\mathrm{e}^+\mathrm{e}^- \to 2$jets in NNLO
  leading colour terms for dipole subtraction approach — Weinzierl '03

2.3 Multi-loop calculations in the MSSM

Precision observables in the MSSM

- known: – precision observables in 1-loop order since ’94-’96
  – $\mathcal{O}(\alpha\alpha_s)$ corrections to $\Delta\rho$
  Djouadi, Gambino, Heinemeyer, Hollik, Jünger, Weiglein ’97, ’98
- new: corrections to $\Delta\rho$ of $\mathcal{O}(y_t^2)$, $\mathcal{O}(y_t y_b)$, $\mathcal{O}(y_b^2)$ Heinemeyer, Weiglein ’02

  obtained with *FeynArts / TwoCalc*

  $\hookrightarrow$ induced corrections: $\Delta M_W \sim 2\,\mathrm{MeV}, \quad \Delta \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} \sim 0.00001$

Precision calculations for MSSM Higgs masses and widths

- Higgs masses: progress in *FeynHiggs* Frank, Hahn, Heinemeyer, Hollik, Weiglein ’98-’03
  – subleading 2-loop corrections
  – Δm_b resummation
  – new 1-loop renormalization (mainly $\tan\beta$)
- Higgs decays: progress in *HDECAY* and *FeynHiggsDecay*
  Djouadi, Kalinowski, Spira ’97-’03 Heinemeyer, Hollik, Weiglein ’00-’03

  $\hookrightarrow$ Higgs and SUSY working groups of the ECFA/DESY workshop

Renormalization of the MSSM

- no regularization respects gauge invariance *and* SUSY

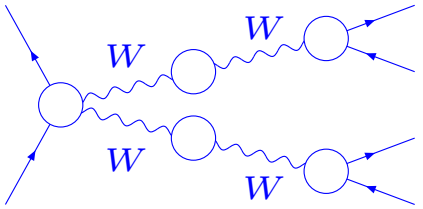
  $\hookrightarrow$ particular care needed $\Rightarrow$ algebraic renormalization

- symmetry identities, proof of renormalizability, non-renormalization theorems Hollik, Kraus, Roth, Rupp, Sibold, Stöckinger '02

  $\hookrightarrow$ construction of symmetry-restoring counterterms possible

3 Radiative corrections to $2 \to 3, 4, \ldots$ processes

3.1 Progress on $e^+e^- \to 4f$ since TESLA TDR



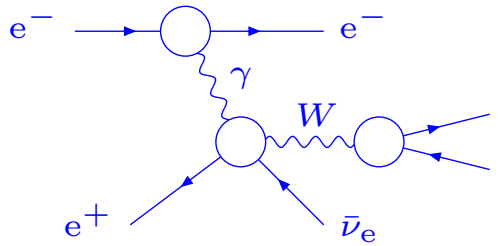
W-pair production $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f(+\gamma)$

- *RacoonWW* (Denner, S.D.,Roth,Wackeroth)
  - anomalous triple and quartic gauge couplings
  - unweighting procedure and interface to *Pythia*
- *YFSWW* (Jadach,Płaczek,Skrzypek,Ward)
  - combination with *KoralW* to concurrent MC code *KandY*

  $\hookrightarrow$ cross-talk via FIFO files under UNIX/LINUX
- Reliable estimates of theoretical uncertainties (TU) for
  - M_W reconstruction (Jadach et al. '01) $\quad \Delta M_\mathrm{W} \lesssim 5\,\mathrm{MeV}$
  - bounds on anomalous TGC λ (Brunelière et al. '02) $\quad \Delta\lambda \lesssim 0.005$

$\hookrightarrow$ State-of-the-art generators include
- full lowest-order matrix elements for $\mathrm{e^+e^-} \to 4f(+\gamma)$
- non-universal electroweak corrections in "double-pole approximation"
- improvements by leading higher-order corrections

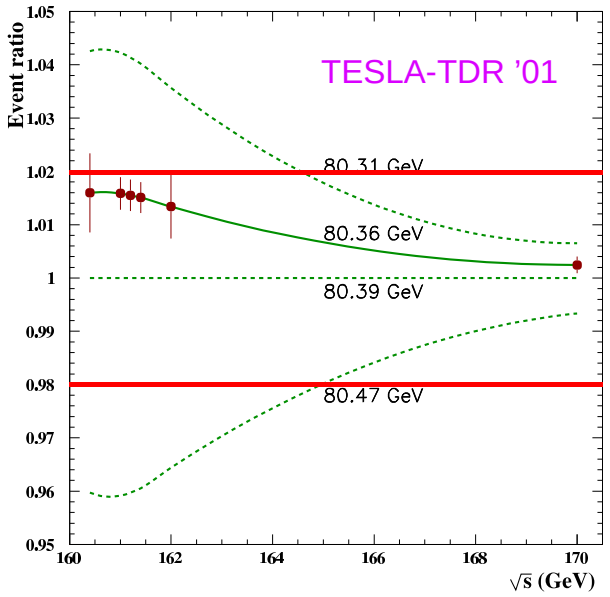
Single-W production $\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}\nu_\mathrm{e}\mathrm{W} \to \mathrm{e}\nu_\mathrm{e} + 2f(+\gamma)$



- *KoralW* (Jadach,Płaczek,Skrzypek,Ward,Was)
  - inclusion of ISR–FSR interference ("electric charge screening") by reweighting
  - improvement of running $\alpha(Q^2)$ in t-channels

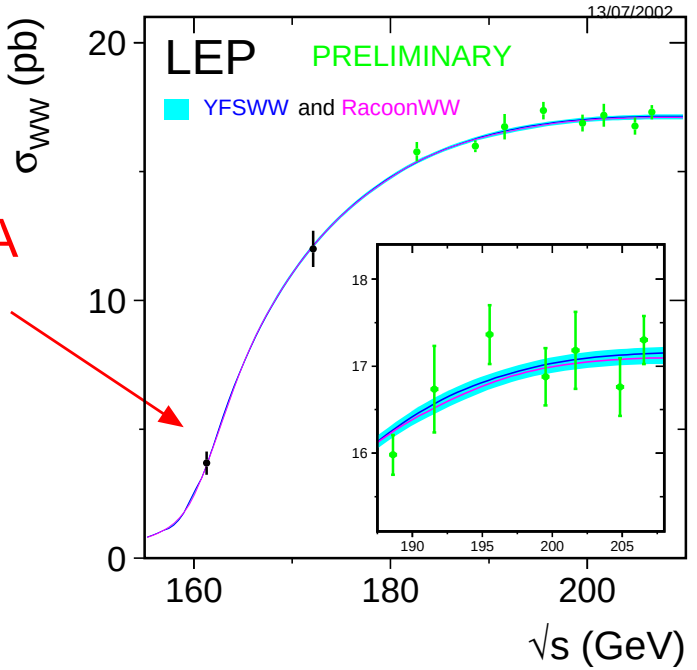
  $\hookrightarrow$ TU $\sim$ O(5%) as in other state-of-the-art programs *grc4f* (Kurihara et al.), *NEXTCALIBUR* (Berends et al.), *SWAP* (Montagna et al.), *WPHACT* (Accomando et al.), *WTO* (Passarino)

WW-threshold scan at MegaW:

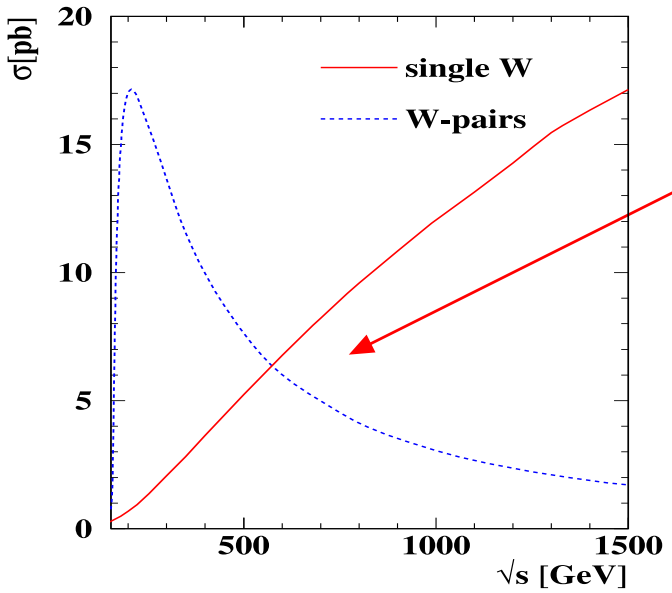


$\pm 2\%$ TU of IBA near threshold

WW cross section at LEP2:



σ_{WW} and σ_{W} at LC energies:



Measurements at %-level

Requirements for LC physics:

- Full $\mathcal{O}(\alpha)$ correction for $\mathrm{e}^+\mathrm{e}^- \to 4f$
- Leading corrections beyond $\mathcal{O}(\alpha)$

3.2 Electroweak corrections to $e^+e^- \to \nu\bar{\nu}H$

- Fermion-loop corrections (+sfermion loops in MSSM)

  Eberl, Majerotto, Spanos '02; Hahn, Heinemeyer, Weiglein '02

- Full $\mathcal{O}(\alpha)$ corrections calculated by different groups

  Jegerlehner, Tarasov '02 (only virtual corrections, no numerics)

  – diagrams generated by DIANA and reduced with FORM/MAPLE

  Bélanger, Boudjema, Fujimoto, Ishikawa, Kaneko, Kato, Shimizu '02

  – diagrams generated and calculated with GRACE

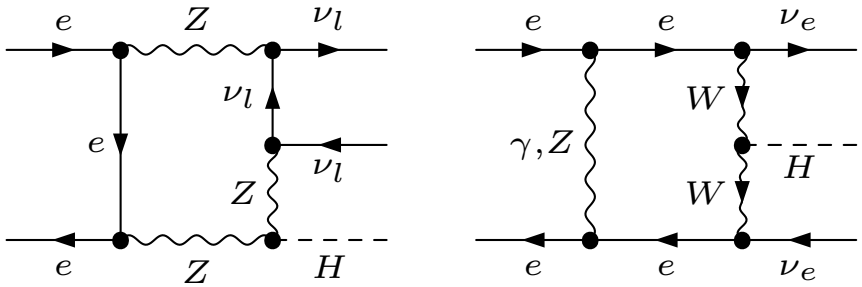
  Denner, S.D., Roth, Weber '03

  – diagrams generated by FeynArts

  – two independent calculations in Mathematica (one partially with LoopTools)

  Hahn '98-'02

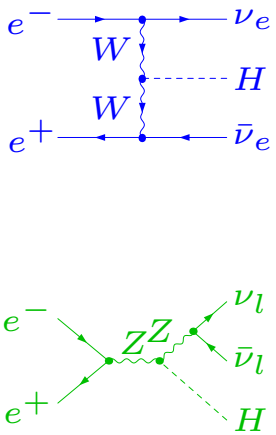
  Main complications: pentagon diagrams

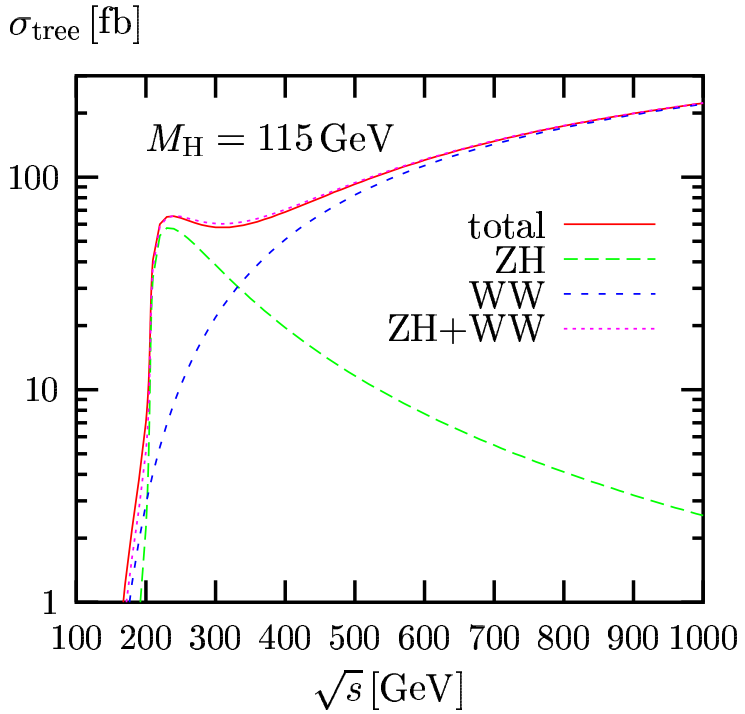


Calculational techniques improved

Total cross section for $e^+e^- \to \nu\bar{\nu}H$

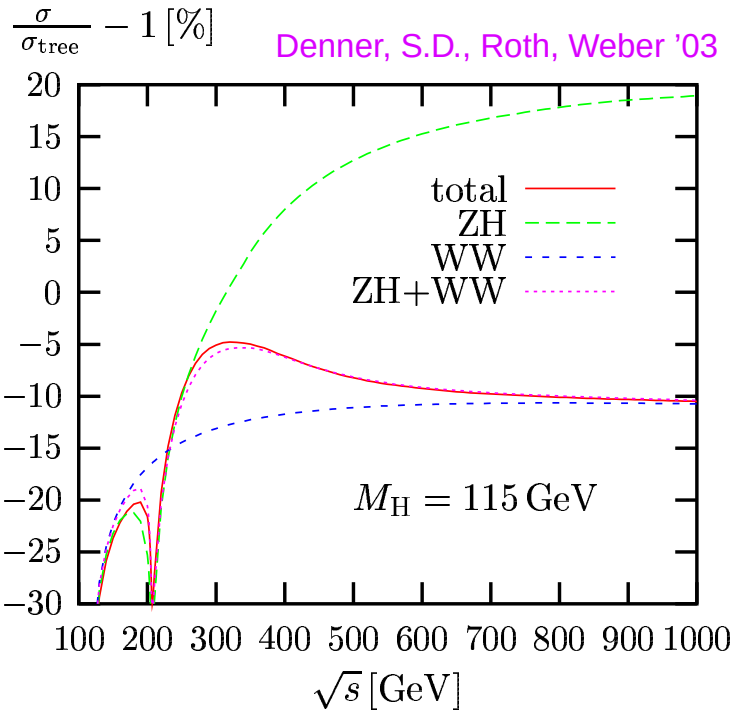
Lowest order:





Relative corrections (G_μ scheme):

Denner, S.D., Roth, Weber '03



Comparison of results: ($\sqrt{s} = 500\,{\rm GeV}$, $\alpha(0)$ scheme)

$M_{\rm H}$ [GeV]	$\sigma_{\rm tree}$ [fb]	σ [fb]	$\sigma/\sigma_{\rm tree} - 1$[%]	
150	61.074(7)	60.99(7)	−0.2	Bélanger et al.
	61.076(5)	60.80(2)	−0.44(3)	Denner et al.
300	10.758(1)	10.30(1)	−4.2	Bélanger et al.
	10.7552(7)	10.282(4)	−4.40(3)	Denner et al.

Agreement within $\mathcal{O}(0.2\%)$

4 Event generators for multi-particle final states

4.1 Generic generators for parton level

Basic idea: flexible event generator for a large set of final states

Existing programs:

- *AMEGIC++*
  Krauss, Kuhn, Schumann, Soff '01,'02
- *GRACE*
  MINAMI-TATEYA group '92
- *MadEvent + Madgraph*
  Maltoni, Stelzer '02; Stelzer, Long '94
- *PHEGAS + HELAC*
  Papadopoulos '00; Kanaki, Papadopoulos '00
- *Whizard + Omega/Madgraph/CompHEP*
  Kilian '01; Moretti, Ohl, Reuter '01 / Stelzer, Long '94 / Boos et al.'89-'02

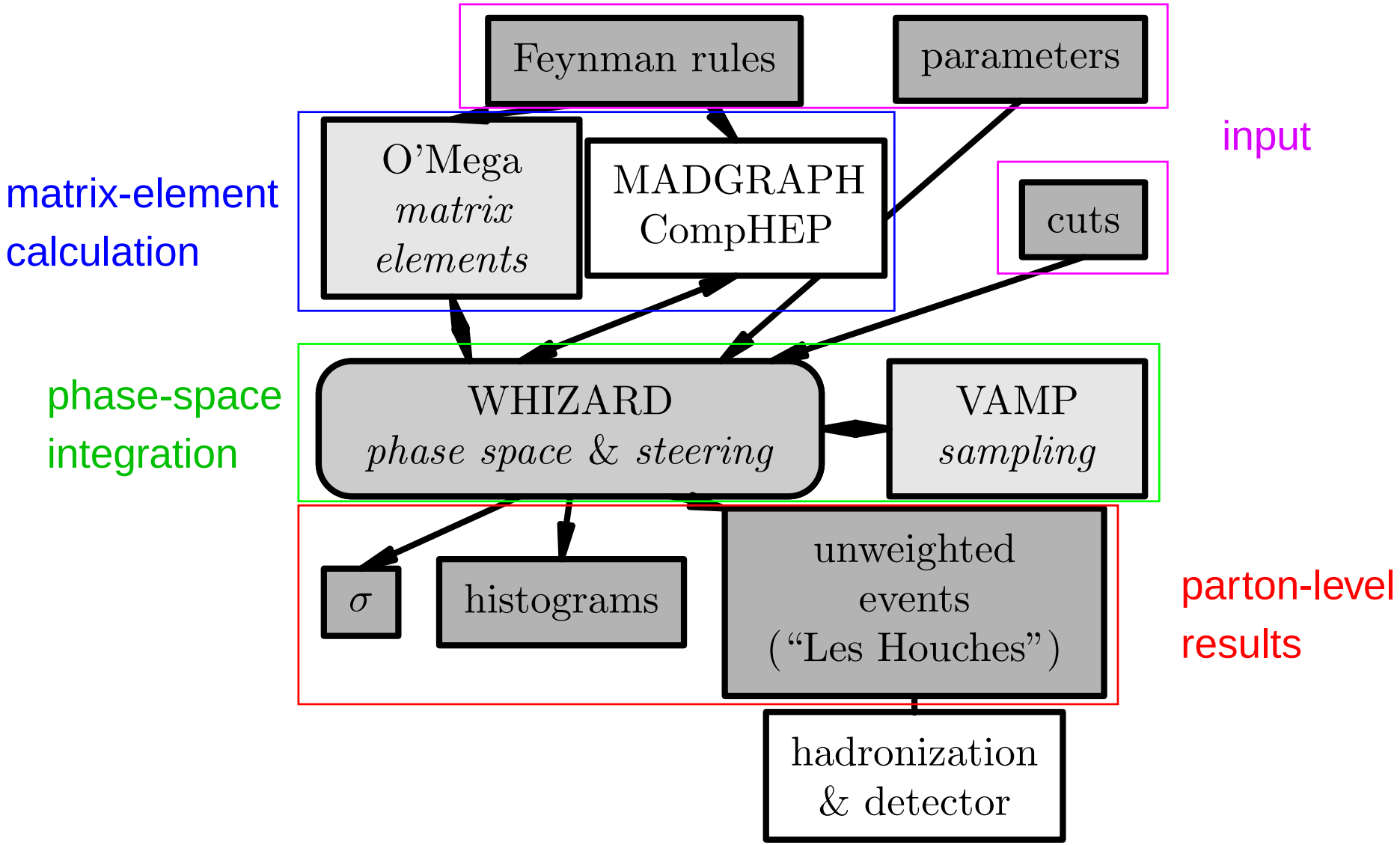
Typical features – differences to process-specific generators:

- lowest-order predictions
  improved by universal corrections (parton shower, LL ISR, etc.)

\+ many final states, uniform setup for different process classes, ideal for studying the physics potential of colliders

– long codes, improvements by radiative corrections problematic / limited
  ↪ usually not high-precision tools

Structure of *Whizard* – a typical flow chart of a generic generator



4.2 Event generators and results for $e^+e^- \to 6f$

- *eett6f* for $\mathrm{e^+e^-} \to \mathrm{t\bar{t}} \to \mathrm{b\bar{b}} + 4f$ Biernacik, Kołodziej '02

  no $\mathrm{e}^{\pm}$ in final state, massive fermions, not a generator

- *Lusifer* S.D., Roth '02

  all $6f$ final states, massless fermions

- *SIXFAP* Carloni Calame, Gangemi, Montagna, Moretti, Nicrosini, Piccinini '97-'03

  all $6f$ final states, massive fermions

- results from generic generators

  AMEGIC++, GRACE, PHEGAS+HELAC, Whizard+Omega/Madgraph

  all $6f$ final states, massive fermions

Tuned comparison in progress

for various final states including $6f$, $4f+2g$, $2f+4g$, $4f+\gamma$, $8f$, $4f+2\tilde{\chi}$, etc.

$\hookrightarrow$ *MC-tester* project Golonka, Pierzchała,Was '02

Some results on $e^+e^- \to t\bar{t} \to 6f$

- Full set of diagrams vs. signal diagrams vs. narrow-width approximation (NWA) for $e^+e^- \to \nu_\mu \mu^+ \mu^- \bar{\nu}_\mu b\bar{b}$:

$\sqrt{s}$[GeV]	$\sigma_{\rm full}$[fb]	$\sigma_{\rm signal}$[fb]	$\sigma_{\rm NWA}$[fb]
360	4.416(6)	4.262(1)	4.624(2)
500	6.705(6)	6.354(2)	6.400(7)
800	3.538(29)	3.058(2)	2.973(4)

eett6f

Biernacik, Kołodziej '02

$\hookrightarrow$ Full calculations necessary (at least for proper signal definition)

- Comparison of various calculations ($\sqrt{s}$=500 GeV, cuts applied, m_f=0):

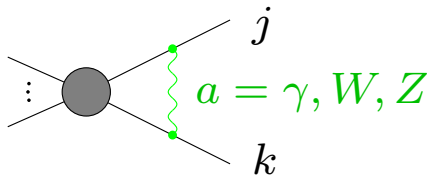
$\sigma_{\rm full}$[fb]	*AMEGIC++*	*eett6f*	*Lusifer*	*PHEGAS*	*SIXFAP*	*Whizard*
$\nu_e e^+ e^- \bar{\nu}_e b\bar{b}$	5.879(8)		5.853(7)	5.866(9)	5.854(3)	5.875(3)
$\nu_e e^+ \mu^- \bar{\nu}_\mu b\bar{b}$	5.827(4)		5.819(5)	5.822(7)	5.815(2)	5.827(3)
$\nu_\mu \mu^+ \mu^- \bar{\nu}_\mu b\bar{b}$	5.809(5)	5.807(3)	5.809(5)	5.809(5)	5.804(2)	5.810(3)
$\nu_\mu \mu^+ \tau^- \bar{\nu}_\tau b\bar{b}$	5.800(3)	5.820(3)	5.800(4)	5.798(4)	5.798(2)	5.796(3)
$\nu_\mu \mu^+ d\bar{u}b\bar{b}$	17.209(9)	17.275(28)	17.171(24)	17.204(18)		
without QCD:	17.097(8)		17.095(11)	17.107(18)	17.096(4)	17.103(8)

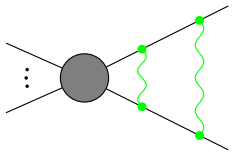
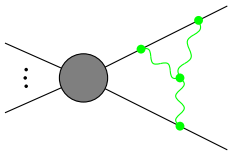
$\hookrightarrow$ Good agreement

5 Other theoretical developments

5.1 Electroweak radiative corrections at high energies

Sudakov logarithms induced by soft gauge-boson exchange



etc.

+ sub-leading logarithms from mass singularities

Typical impact on $2 \to 2$ reactions at $\sqrt{s} \sim 1\,\mathrm{TeV}$:

$$\delta_{\mathrm{LL}}^{1-\mathrm{loop}} \sim -\frac{\alpha}{\pi s_{\mathrm{W}}^2} \ln^2\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -26\%, \qquad \delta_{\mathrm{NLL}}^{1-\mathrm{loop}} \sim +\frac{3\alpha}{\pi s_{\mathrm{W}}^2} \ln\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 16\%$$

$$\delta_{\mathrm{LL}}^{2-\mathrm{loop}} \sim +\frac{\alpha^2}{2\pi^2 s_{\mathrm{W}}^4} \ln^4\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 3.5\%, \qquad \delta_{\mathrm{NLL}}^{2-\mathrm{loop}} \sim -\frac{3\alpha^2}{\pi^2 s_{\mathrm{W}}^4} \ln^3\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -4.2\%$$

$\Rightarrow$ Corrections still significant at 2-loop level

NOTE: differences to QED / QCD where Sudakov log's cancel

- massive gauge bosons W, Z can be reconstructed
  $\hookrightarrow$ no need to add "real W, Z radiation"
- non-Abelian charges of W, Z are "open" $\to$ Bloch–Nordsieck theorem violated

$\Rightarrow$ Aim: universal prescription for improving (e.g. 1-loop) calculations

Progress at the 2-loop level

Explicit calculations for

- LL level Melles '00; Hori, Kawamura, Kodaira '00; Beenakker, Werthenbach '00, '01
- LL + angular-dependent NLL level Denner, Melles, Pozzorini '03

Structure of result at ang.-dep. NLL level:

$$\mathcal{M} \sim \mathcal{M}_0 \otimes \left(\delta_{\rm ew} + \delta_{\rm em} + \tfrac{1}{2}\delta_{\rm ew}^2 + \delta_{\rm ew} \otimes \delta_{\rm em} + \tfrac{1}{2}\delta_{\rm em}^2\right)$$

with

$$\delta_{\rm ew} = \frac{\alpha}{4\pi}\left\{ -\frac{1}{2}\sum_j C_j^{\rm ew} \ln^2\frac{M_{\rm W}^2}{s} + \sum_{k\neq j}\sum_{a=\gamma,{\rm Z},{\rm W}^\pm} I_j^a I_k^{\bar a} \ln\frac{s}{|2p_jp_k|}\ln\frac{M_{\rm W}^2}{s}\right\}$$

$$\delta_{\rm em} = \frac{\alpha}{4\pi}\left\{ -\frac{1}{2}\sum_j Q_j^2\left[2\ln\frac{m_j^2}{s}\ln\frac{m_\gamma^2}{M_{\rm W}^2} - \ln^2\frac{m_j^2}{M_{\rm W}^2}\right] + \sum_{k\neq j} Q_jQ_k \ln\frac{s}{|2p_jp_k|}\ln\frac{m_\gamma^2}{M_{\rm W}^2}\right\}$$

Agreement with proposed resummations

based on a symmetric SU(2)×U(1) theory at high energies
matched with QED at electroweak scale

$$\mathcal{M} \sim \mathcal{M}_0 \otimes \exp\left(\delta_{\rm ew}\right) \otimes \exp\left(\delta_{\rm em}\right)$$

Fadin et al. '99; Melles '00, '01; Kühn, Moch, Penin, Smirnov '01

Progress in the MSSM

Explicit 1-loop results with proposed exponentiations Beccaria et al. '01, '02

5.2 Precision calculations for SUSY-particle production

Calculations widely performed with packages

FeynArts, FeynCalc (Denner, Mertig, Böhm '91) *FormCalc/LoopTools* (Hahn '98-'02)

- Pair production of selectrons/sleptons and charginos

  Freitas, v.Manteuffel '02 Blank, Hollik '00 Baer, Diaz, Rivera, Ross '02

  complete $\mathcal{O}(\alpha)$ corrections within MSSM

- Chargino / neutralino mass spectrum

  Fritzsche, Hollik '02; Öller et al. '03

  input masses of χ_1^+, χ_2^+, χ_1^0 $(\leftrightarrow\ M_1, M_2, \mu)$

  $\hookrightarrow$ 1-loop-corrected (by some GeV) predictions for masses of χ_2^0, χ_3^0, χ_4^0

- QCD and SUSY-QCD corrections of $\mathcal{O}(\alpha_s)$ to

  $e^+e^- \to q\bar{q}g, \tilde{q}\bar{\tilde{q}}g, \tilde{q}\bar{q}\tilde{g}, q\bar{\tilde{q}}\tilde{g}$ Brandenburg, Maniatis, Weber '02

  $\hookrightarrow$ test of SUSY relation between gauge and Yukawa couplings

gauge coupling g_s $\overset{\text{tree}}{=}$ Yukawa coupling $\hat{g}_s$

6 Conclusions

LC precision physics is great challenge

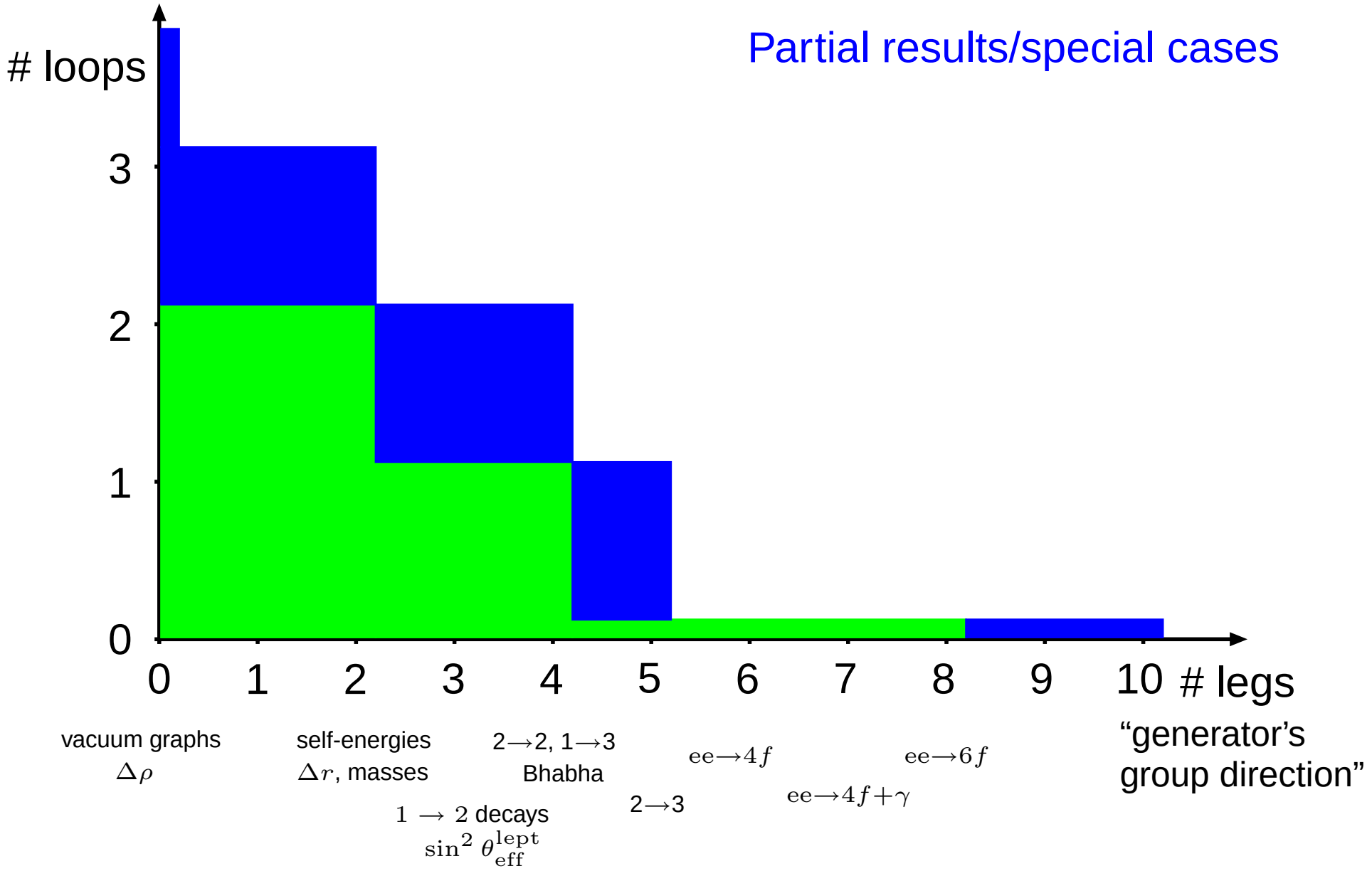
Good progress since TESLA TDR (3/2001) in various directions:

- 2-loop techniques for $2 \to 2$ and $1 \to 3$ reactions
- μ decay in full 2-loop accuracy and improved beyond
- 1-loop calculations for $2 \to 3$ processes ($\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\mathrm{H}$)
- multi-purpose Monte Carlo generators for many-particle final states (*AMEGIC++, GRACE, PHEGAS, Whizard*)
- studies of and generators for $\mathrm{e}^+\mathrm{e}^- \to 6f$ (*eett6f, Lusifer, SIXFAP*)
- leading electroweak 2-loop corrections at high energies
- etc.

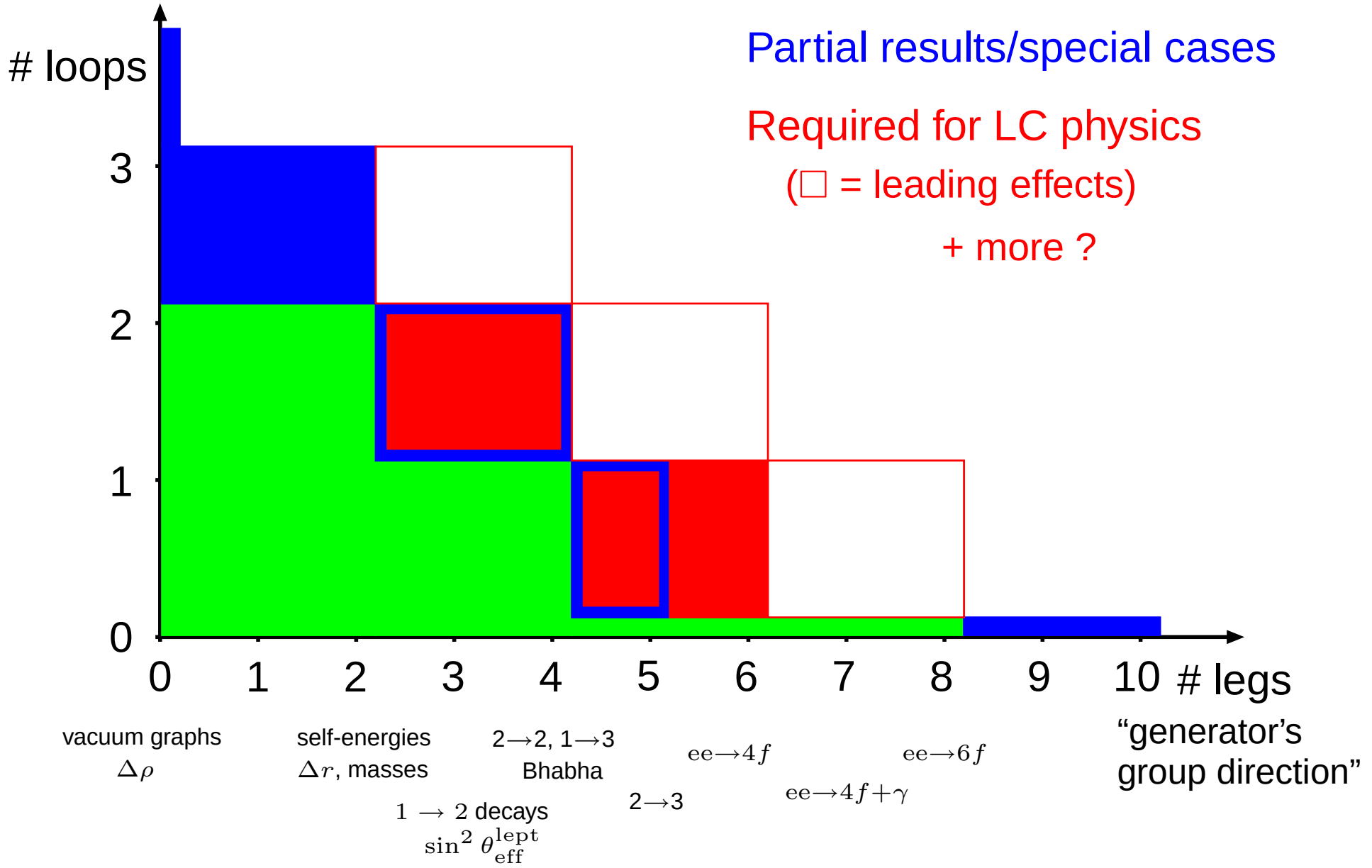
“LoopVerein direction”

Technique well established

Partial results/special cases



“LoopVerein direction”



Many issues for the future:

- complete 2-loop calculations for $1 \to 2,3$ and $2 \to 2$ reactions
  - ◇ Z line shape and Z-pole pseudo-observables ($\sin^2\theta^{\rm lept}_{\rm eff}$, etc.)
  - ◇ Bhabha scattering, $\mathrm{e^+e^-} \to 3\mathrm{jets}$, etc.
- complete 1-loop calculations for $\mathrm{e^+e^-} \to 4f$
- improvements in Monte Carlo generators
  - ◇ inclusion of radiative corrections
  - ◇ unweighting procedures
  - ◇ matching of matrix elements with parton showers in NLO
- general issues
  - ◇ resummation of leading higher-order corrections
  - ◇ treatment of unstable particles
  - ◇ parallelization / automatization / standardization

$\Rightarrow$ Many long-termed projects — continuous support needed !