Generators & LoopVerein (w/a little NNLO top)

Thorsten Ohl

Institute for Theoretical Physics and Astrophysics, University of Würzburg

ILC/ECFA Workshop 2008
Warsaw, June 9-12, 2008

CARLOMAT, a program for automatic computation of multiparticle cross sections

- Plan: provide a more efficient alternative for generating event samples for arbitrary $2 \to 8, \ldots, 12$ processes in the SM (incl. QCD)

carlomat

- a program written in Fortran 90/95
- generates the matrix element for a user specified process
- generates phase space parametrizations, which are later used for the multichannel Monte Carlo integration of the lowest order cross sections and event generation
- takes into account both the electroweak and QCD lowest order contributions
- fermion masses are not neglected
- the maximum number of external particles is 12
- only the Standard Model is implemented at the moment

carlomat – p. 7

- has been tested successfully against older programs for various $2 \to 6$ processes:

Top quark pair production in e^+e^- annihilation

Final state	$\sqrt{s}$	carlomat	AMAGIC++	HELAC
$b\bar{b}u\bar{u}d\bar{d}$	360	32.98(11)	32.90(15)	33.05(14)
	500	50.31(19)	49.74(21)	50.20(13)
$b\bar{b}u\bar{d}e^-\bar{\nu}_e$	360	11.448(26)	11.460(36)	11.488(15)
	500	17.424(56)	17.486(66)	17.492(41)
$b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$	360	3.843(5)	3.847(15)	3.848(7)
	500	5.856(11)	5.865(24)	5.868(10)
$b\bar{b}\mu^+\nu_\mu\mu^-\bar{\nu}_\mu$	360	3.837(5)	3.808(16)	3.861(19)
	500	5.834(10)	5.840(30)	5.839(12)

$\sqrt{s}$ in GeV, cross sections in fb. [T. Gleisberg, et al.] carlomat – p. 18

PHANTOM: a Monte Carlo event generator for six parton final states at high energy colliders

- a dedicated event generator for $2 \to 6$ processes (SM and QCD) at both ILC and LHC, building on the PHACT expertise at Torino:

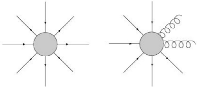
PHANTOM 1.0

Ballestrero, Belhouari, G.B., Kashkan, Maina arXiv:0801.3359 [hep-ph]

Event generator dedicated to six-parton physics at pp, $p\bar{p}$ and e^+e^- colliders

- Exact tree-level matrix elements at $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$
- Full coverage of Standard Model processes at fixed order

$$\begin{matrix} pp \\ p\bar{p} \\ e^+e^- \end{matrix} \longrightarrow \begin{cases} 6f \\ 5f + g \\ 4f + 2g \end{cases}$$



Holds the signal of

- Higgs production via Vector Boson Fusion $ffH \to ffVV$ ...
- Vector Boson Scattering $WW \to WW, WZ \to WZ$ ...
- triple gauge boson production
- $t\bar{t}$ production
- triple/quadruple-vertex EW interactions

together with all EW+QCD irreducible background at fixed order

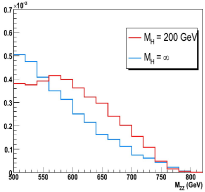
G. Bevilacqua ILC-ECFA 2008 6/22

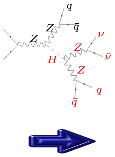
- e. g.: testing cuts that enhance the VV scattering signal over Higgsstrahlung for EWSB studies requires inclusion of all irreducible backgrounds:

Early on-set of EWSB effects is partially masked in the ZZ channel by residual non-scattering contributions. What's going on?

ISR and beamstrahlung limit the validity of the kinematical cut $M_{recoil} > 200$ GeV in suppressing *Higgs-strahlung* contributions

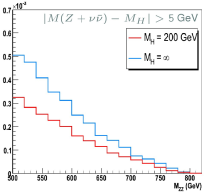
ZZ-resonant final states





No Higgs-strahlung

ZZ-resonant final states



Genuine $e^+e^- \to ZH \to jj + \nu\bar{\nu}jj$ events enter the analysis

G. Bevilacqua ILC-ECFA 2008 17/22

News from ***Herwig++***

- Lots of activity in the last two years

News from Herwig++

- Lots of activity in the last two years
- Herwig++ *"ready for prime time"*
- needs to be tuned and used

4. Summary

- Herwig++ group made a lot of progress in the last year
- The generator is now fully ready for hadron collisions
- A comprehensive manual is now available
- Support of experiments: herwig@projects.hepforge.org
- Further improvements will follow. News on wiki!

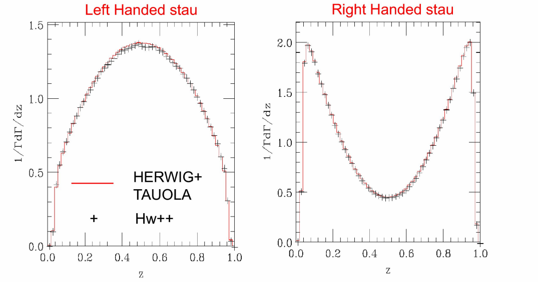
- e. g.: native description of τ-decays challenges TAUOLA (maybe not as flexible yet, but getting stronger):

Herwig++ (15/34)
└ Recent improvements/Tuning

Hadronic Decays

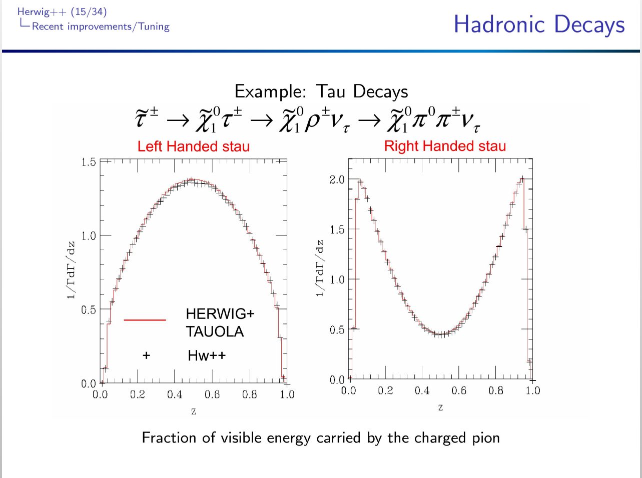
Example: Tau Decays

$$\tilde{\tau}^{\pm} \to \tilde{\chi}_1^0 \tau^{\pm} \to \tilde{\chi}_1^0 \rho^{\pm} \nu_\tau \to \tilde{\chi}_1^0 \pi^0 \pi^{\pm} \nu_\tau$$



Fraction of visible energy carried by the charged pion

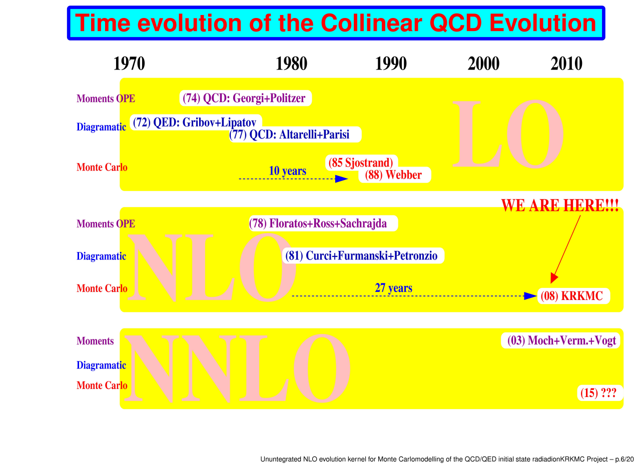
- e. g.: native description of τ-decays challenges TAUOLA (maybe not as flexible yet, but getting stronger):



- also: underlying event, p_T distribution, hard matrix elements, hadronic decay database, BSM, …

Unintegrated NLO evolution kernel for Monte Carlo modelling of the QCD/QED initial state radiation

- long roads from inclusive renormalization group evolution to exclusive event generation for the PDFs



- operational proof of concept for NLO parton shower:

Discussion, Conclusions

- Unintegrated NLO kernel within full 2-particle LIPS in the MC can be constructed.
- Dimensional regularization can be removed.
- The integrand of the NLO kernel features nice IR cancellations, such that only **short range correlation** remain for large y_i and α_i. No long tails! No cancellations between distant regions in the LIPS!
- Re-insertion of the NLO unintegrated kernel into LO MC model representing LO+NLO (DGLAP) evolution done for $n = 2$ and is perfectly feasible for $n > 2$.
- Monte Carlo weight looks regular/positive.
- A decisive/critical milestone towards NLO parton shower MC has been reached.

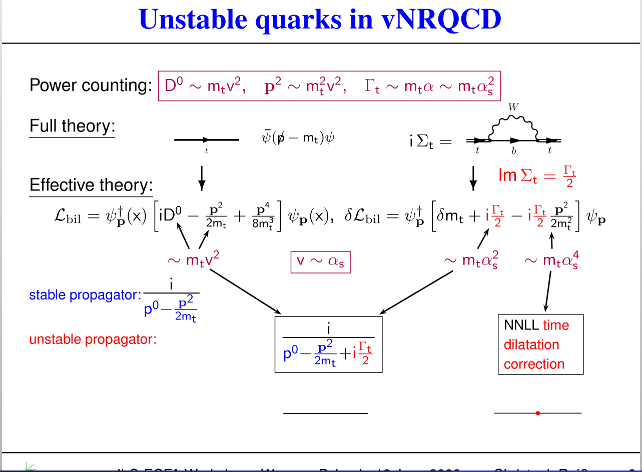
Ununtegrated NLO evolution kernel for Monte Carlomodelling of the QCD/QED initial state radiadionKRKMC Project – p.20/20

Finite lifetime effects in top quark pair production at threshold

- physics at the $\mathrm{t\bar{t}}$ threshold is governed by different scales: energy, momentum, width (lifetime)

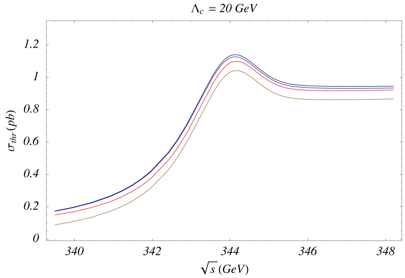
Finite lifetime effects in top quark pair production at threshold

- physics at the $t\bar{t}$ threshold is governed by different scales: energy, momentum, width (lifetime)
- needs effective field theory for correct power counting and running between scales



- sizable NNLO effects:

Numerical results



— Standard vNRQCD cross section

— plus usual electroweak corrections ⇒ change of normalization: $\approx -2\,\%$

— plus absorptive electroweak effects ⇒ top mass shift: $\approx$ 50 MeV

— plus phase space effects at NLO and NNLO ⇒ change of σ_{thr}: ≈ -60 fb

ILC-ECFA Workshop · Warsaw, Poland · 10 June 2008 Christoph Reißer – p.18

Dominant NNLO corrections to W-pair production near threshold

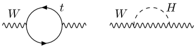
- ILC with $\sqrt{s} \approx 2M_W$ will improve ΔM_W, needs reliable theoretical predictions: avoid gauge invariance issues or unitarity violations

Motivation

Process of W-pair production near threshold has phenomenological relevance for accurate determination of the W boson mass at ILC

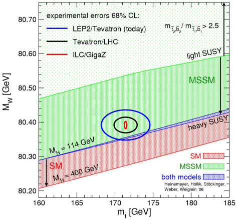
M_W

- Key observable for SM precision tests
- Combined with independent measurements of m_t and M_H constrains New Physics effects through virtual-particle exchange



$\Delta M_W^2 \propto m_t^2$ $\Delta M_W^2 \propto \ln M_H$

Threshold scan of WW cross section at ILC could reduce the total error on M_W to $\delta M_W \sim 6\text{MeV}$ [Wilson '01] with $\mathcal{L} = 100\text{fb}^{-1}$ (just one year!)



[Heinemeyer et al. '06]

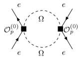
Total theoretical uncertainties must be reduced to 1‰!

- Effective Field Theory approach (again) provides excellent approximation for inclusive cross sections

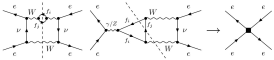
A toy example: the $e^- e^+ \to$ 4f Born cross section

How does the EFT work? $\to$ To understand apply it to the calculation of the Born cross section
Extract the total cross section from unitarity cuts of the forward-scattering amplitude

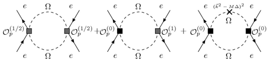
LO ($\sim \alpha_{ew} v$)
From leading-order operators and propagators



$\sqrt{\text{N}}$LO ($\sim \alpha_{ew}^2 \Gamma_W / M_W$)
From singly-resonant configurations



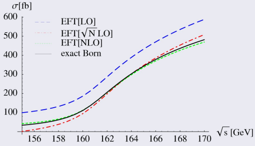
NLO ($\sim \alpha_{ew}^2 v \times (v^2, \Gamma_W / M_W)$)
From higher-dimensional operators



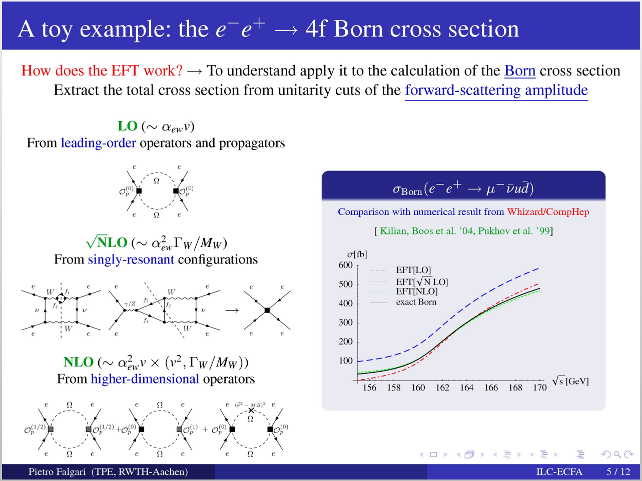
$\sigma_{\text{Born}}(e^- e^+ \to \mu^- \bar{\nu} u \bar{d})$

Comparison with numerical result from Whizard/CompHep

[Kilian, Boos et al. '04, Pukhov et al. '99]



- Effective Field Theory approach (again) provides excellent approximation for inclusive cross sections



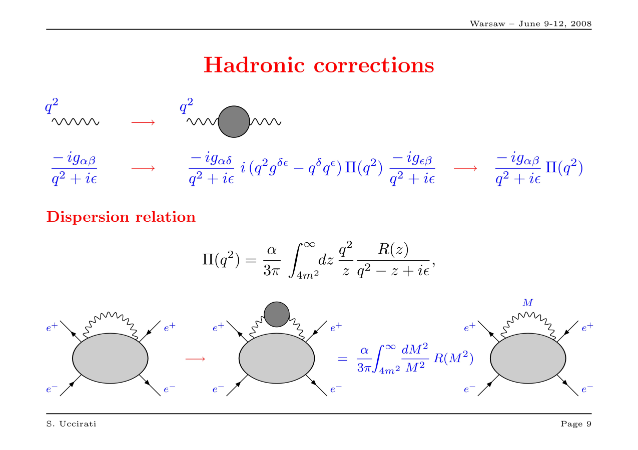
- cuts can be implemented as well

Two-loop hadronic corrections to Bhabha scattering

- Bhabha-Scattering essential for luminosity monitoring: at ILC not only at small angles!

Two-loop hadronic corrections to Bhabha scattering

- Bhabha-Scattering essential for luminosity monitoring: at ILC not only at small angles!
- non-perturbative hadronic contributions via disperion relation from the measured R ratio



Warsaw – June 9-12, 2008

Hadronic corrections

$$\frac{-ig_{\alpha\beta}}{q^2+i\epsilon} \longrightarrow \frac{-ig_{\alpha\delta}}{q^2+i\epsilon}\, i\,(q^2 g^{\delta\epsilon} - q^\delta q^\epsilon)\,\Pi(q^2)\,\frac{-ig_{\epsilon\beta}}{q^2+i\epsilon} \longrightarrow \frac{-ig_{\alpha\beta}}{q^2+i\epsilon}\,\Pi(q^2)$$

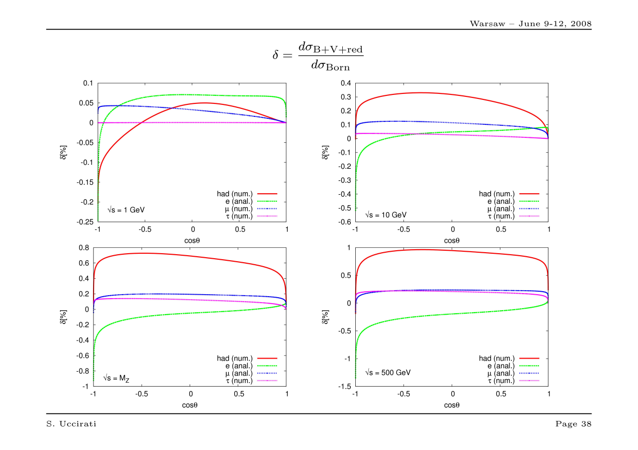
Dispersion relation

$$\Pi(q^2) = \frac{\alpha}{3\pi}\int_{4m^2}^{\infty} dz\, \frac{q^2}{z}\,\frac{R(z)}{q^2 - z + i\epsilon},$$

$$\longrightarrow \quad = \frac{\alpha}{3\pi}\int_{4m^2}^{\infty}\frac{dM^2}{M^2}\,R(M^2)$$

S. Uccirati Page 9

- hadronic NNLO corrections reach 1% at $\sqrt{s} = 500\,\text{GeV}$:

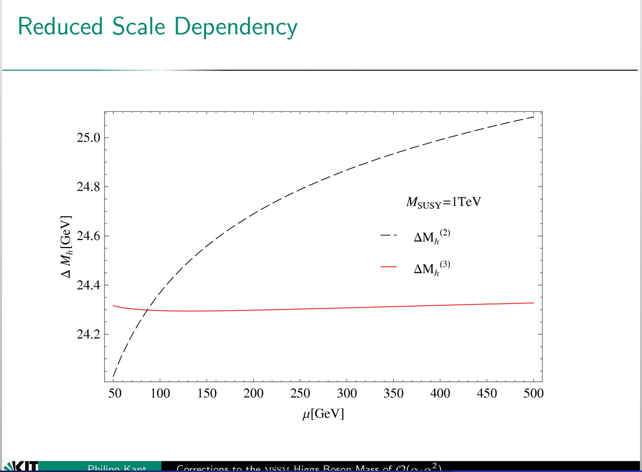


Three-Loop Corrections to the MSSM Higgs Boson Mass

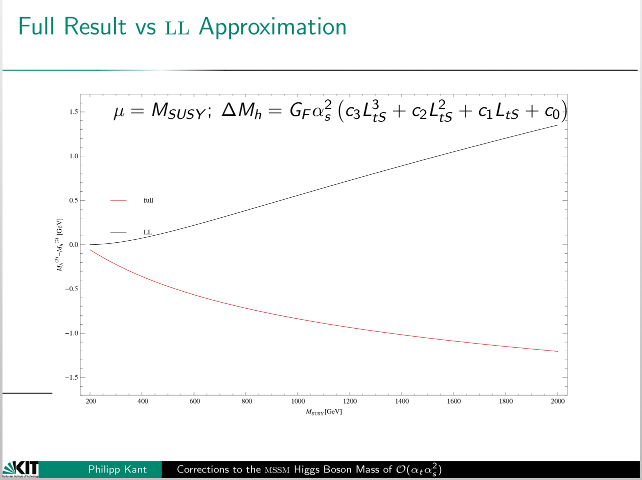
- if there were no NLO corrections, LEP2 would have found the lightest MSSM Higgs

Three-Loop Corrections to the MSSM Higgs Boson Mass

- if there were no NLO corrections, LEP2 would have found the lightest MSSM Higgs
- need to estimate NNNLO corrections for reliable predictions, because NNLO still suffer from sizable scale uncertainties:



- *caveat emptor*: leading logarithms can be misleading



Conclusions

theory is alive and well!!!

- leading order parton level event generators for 6 and more final state particles continue to multiply

theory is alive and well!!!

- leading order parton level event generators for 6 and more final state particles continue to multiply
- complete NLO parton level event generators for $2 \to 4$ have arrived

Conclusions

theory is alive and well!!!

- leading order parton level event generators for 6 and more final state particles continue to multiply
- complete NLO parton level event generators for $2 \to 4$ have arrived
- the next generation of general purpose event generators including the non-perturbative QCD muck (e. g. HERWIG++) has arrived

Conclusions

theory is alive and well!!!

- leading order parton level event generators for 6 and more final state particles continue to multiply
- complete NLO parton level event generators for $2 \to 4$ have arrived
- the next generation of general purpose event generators including the non-perturbative QCD muck (e. g. `HERWIG++`) has arrived
- NLO parton showers are on the horizon

theory is alive and well!!!

- leading order parton level event generators for 6 and more final state particles continue to multiply
- complete NLO parton level event generators for $2 \to 4$ have arrived
- the next generation of general purpose event generators including the non-perturbative QCD muck (e. g. HERWIG++) has arrived
- NLO parton showers are on the horizon
- the effective field theory technology for systematic threshold expansions (W^+W^- and $\mathrm{t}\bar{\mathrm{t}}$) has matured

Conclusions

theory is alive and well!!!

- leading order parton level event generators for 6 and more final state particles continue to multiply
- complete NLO parton level event generators for $2 \to 4$ have arrived
- the next generation of general purpose event generators including the non-perturbative QCD muck (e. g. HERWIG++) has arrived
- NLO parton showers are on the horizon
- the effective field theory technology for systematic threshold expansions (W^+W^- and $\mathrm{t}\bar{\mathrm{t}}$) has matured
- complete NNLO $2 \to 2$ cross sections are available

theory is alive and well!!!

- leading order parton level event generators for 6 and more final state particles continue to multiply
- complete NLO parton level event generators for $2 \to 4$ have arrived
- the next generation of general purpose event generators including the non-perturbative QCD muck (e. g. HERWIG++) has arrived
- NLO parton showers are on the horizon
- the effective field theory technology for systematic threshold expansions (W^+W^- and $\mathrm{t}\bar{\mathrm{t}}$) has matured
- complete NNLO $2 \to 2$ cross sections are available
- complete NNNLO corrections for some observables are waiting to be tested by experimental observations