LCWS05
2005.03.22
Stanford Univ.
K.Kato (Kogakuin)

group F : Loop Calculations

Highlights

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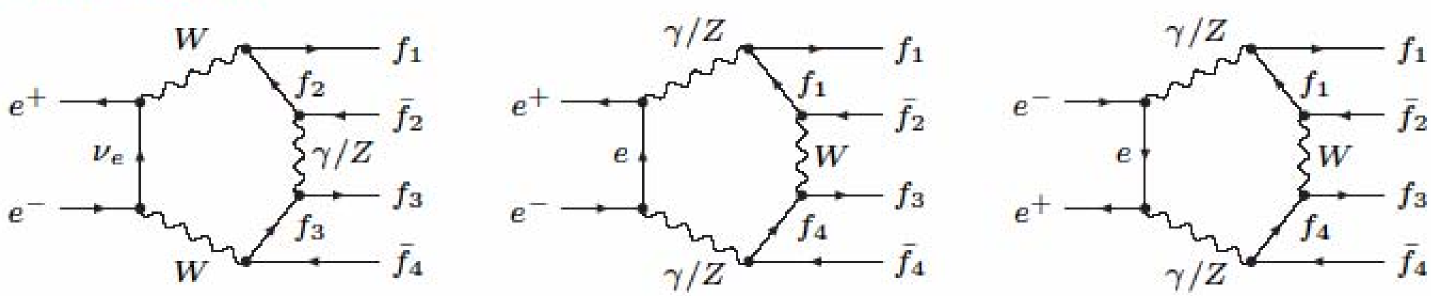
EW

$e^+e^- \rightarrow 4f$

1-loop

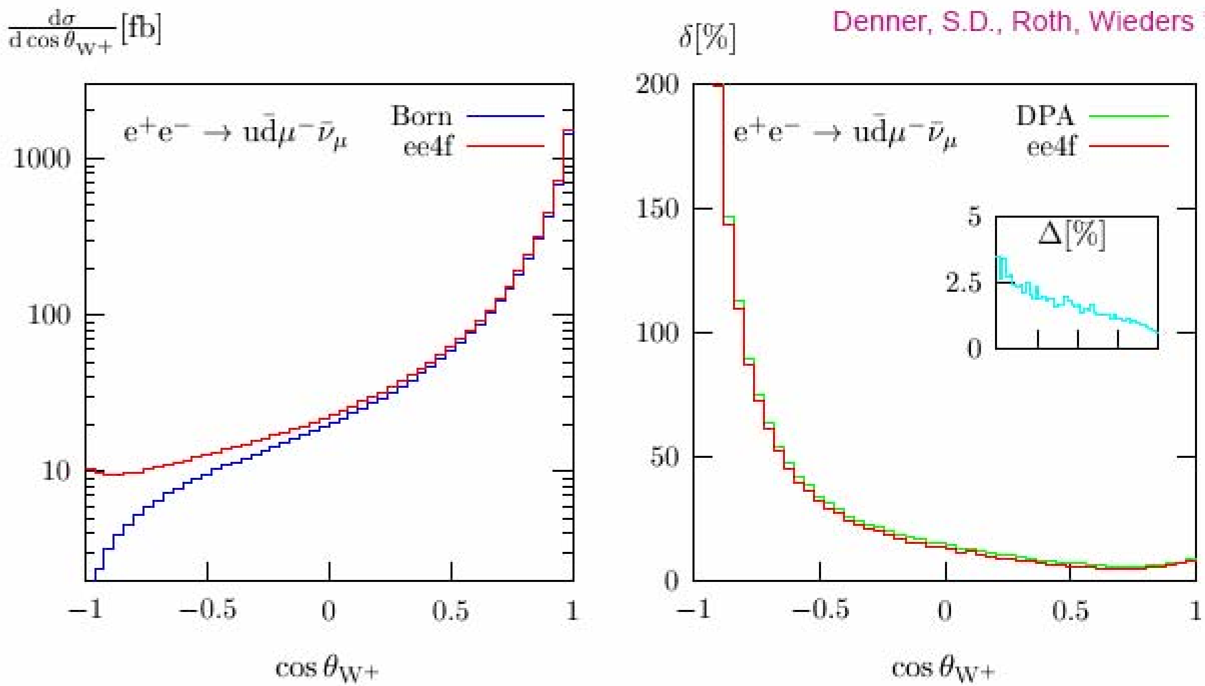
- The great job is accomplished by Denner, Dittmaier, Roth, Wieders   hep-ph/0502063
- Theoretical uncertainty at threshold
  2% → a few 0.1%
- RacoonWW → Racoon4f

- 40 hexagons



W-production angle distribution at $\sqrt{s} = 500\,\mathrm{GeV}$

Denner, S.D., Roth, Wieders '05

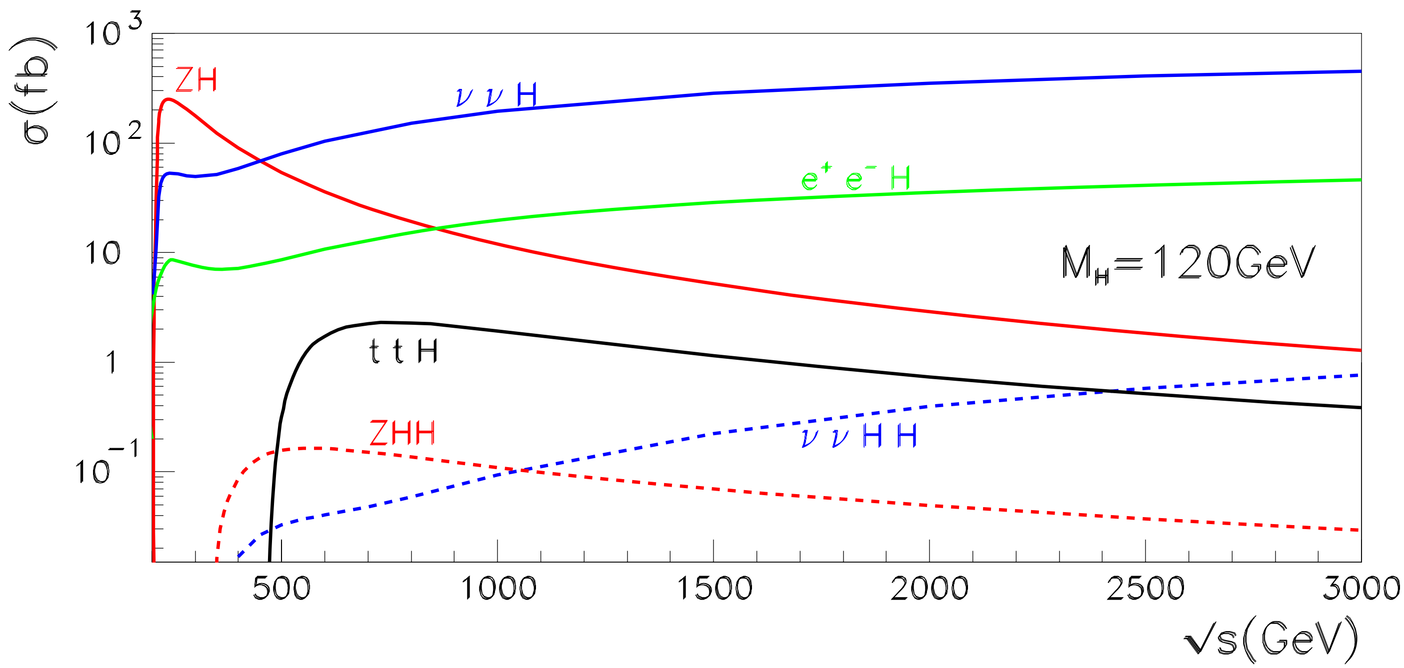


$\Delta = \mathrm{DPA} - \mathrm{ee4f}$

Significant distortion of shape w.r.t. DPA at ILC energies

$\hookrightarrow$ Important for TGC studies at ILC

Higgs@ILC



Now, RC for important 3,4 body channels are available

Full 1-loop RC available

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

GRACE, PLB559(2003)252
Denner et al., NPB660(2003)289

$e^+e^- \to t\bar{t}H$

GRACE, PLB571(2003)163
You et al., PLB571(2003)85
Denner et al., PLB575(2003)290

$e^+e^- \to ZHH$

GRACE, PLB576(2003)152
Zhang et al., PLB578(2004)349

$e^+e^- \to e^+e^-H$

GRACE, PLB600(2004)65

$e^+e^- \to \nu\bar{\nu}\gamma$ $\quad \nu = \nu_\mu, \nu_e$

GRACE, NIM A534(2004)334

$\gamma\gamma \to t\bar{t}H$

Chen Hui etal.,
NPB683 (2004) 196

$\boxed{e^+e^- \to \nu\bar{\nu}HH}$ **LCWS05**

GRACE, Talk by Y.Yasui at
Durham(Sep.2004)

EW

H→γγ

2-loop

- SM Higgs has intermediate mass: $M_H = 114^{+69}_{-45}$ (EWWG).
- $B(H \to \gamma\gamma) \lesssim 0.3\%$ in this M_H range.
- $H\gamma\gamma$ coupling sensitive to new charged heavy particles.
- At ILC, $H \to \gamma\gamma$ has clear signal.
- At photon collider, $\sigma(\gamma\gamma \to H) \propto \Gamma(H \to \gamma\gamma)$.
- At LHC, $H \to \gamma\gamma$ important discovery mode.

By B.Kniehl

Method

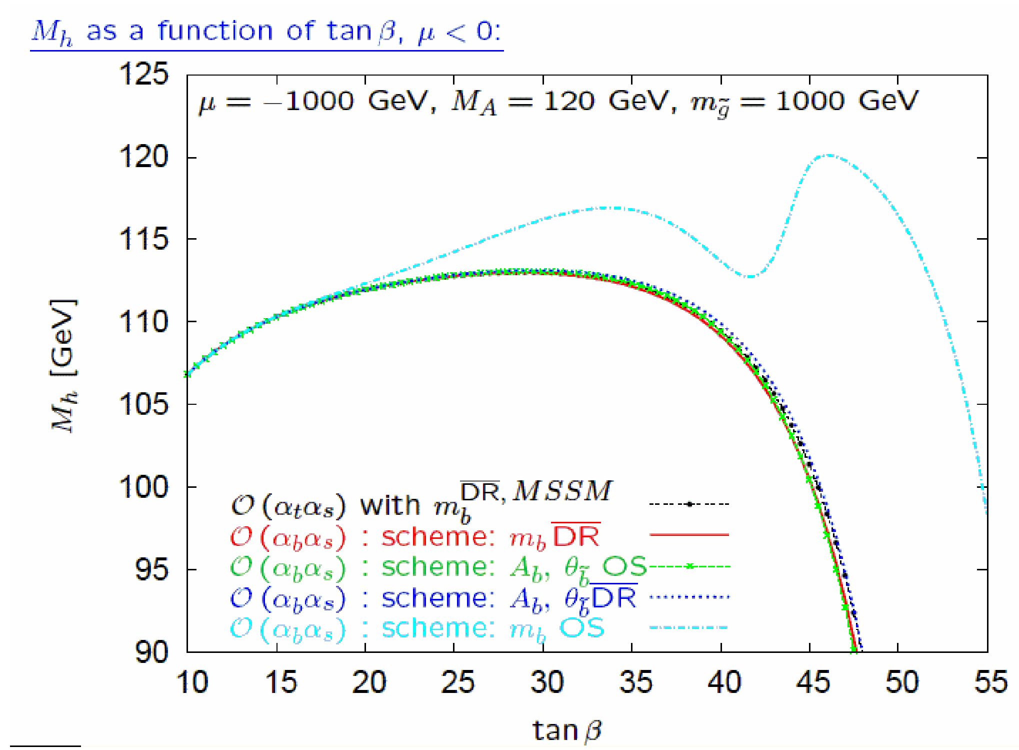
- Automatize calculation:
  - QGRAF Nogueira: generates diagrams
  - q2e Seidensticker: converts output
  - exp Seidensticker: performs asymptotic expansion and generates relevant subdiagrams according to hard-mass procedure
  - MATAD Steinhauser: calculates diagrams

Conclusion

- Dominant two-loop electroweak $\mathcal{O}(G_F M_t^2)$ correction to $\Gamma(H \to \gamma\gamma)$ for $M_W \lesssim M_H \lesssim 2M_W$ available as expansion in $\tau_W = (M_H/2M_W)^2$ through $\mathcal{O}(\tau_W^4)$.
- Reduction by approx. -2.5% – -2%.
- Positive QCD correction slightly overcompensated.
- Net effect of known corrections -2% – -1%.

r/cMSSM Higgs

MSSM Higgs is connected to other sectors through loops.
→ Require theoretical understanding in high precision.



by S.Heinemeyer

4. Conclusinos

- The LC will provide high precision results for a light r/cMSSM Higgs
- MSSM Higgs masses and couplings is connected via radiative corrections to all other sectors
- Evaluation of $\mathcal{O}(\alpha_s\alpha_s)$ corrections in the rMSSM:
  - new result for $\tan\beta \neq \infty$
  - investigation of different renormalization schemes
    $\Rightarrow$ error estimate from scheme and scale dependence
  - $\mu > 0$: corrections $\mathcal{O}(100\ \text{MeV}) \Rightarrow$ under control
  - $\mu < 0$: corrections $\mathcal{O}(2-3\ \text{GeV})$
    error estimate $\mathcal{O}(2\ \text{GeV}) \Rightarrow$ not under control
- Evaluation of $\mathcal{O}(\alpha_s\alpha_t)$ corrections in the cMSSM:
  - new renormalization for complex parameters
  - $\tilde{b}$ sector enters
  - ϕ_{A_t} dependence modified
  - ϕ_{M_3} dependence $\mathcal{O}(1\ \text{GeV})$

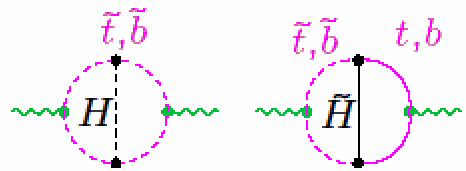
MSSM

Δρ

2-loop

GigaZ-precision: $\delta M_W \approx \pm 7\text{MeV}, \delta \sin^2 \theta^{\text{lept}}_{\text{eff}} \approx \pm 1.3 \times 10^{-5}$ ⇔ sensitive to contributions $\delta(\Delta\rho) \approx 10^{-4}$

Two-loop contributions $\Delta\rho(\mathcal{O}(\alpha^2_{t,b}))$ in MSSM



$\sim 10^{-5} \ldots 10^{-4}$

$\Delta\rho(\mathcal{O}(\alpha^2_{t,b}))$ only well-defined in gaugeless limit $\Rightarrow M_h = 0$ in the MSSM!

- Either clean MSSM-calculation with $M_h = 0$
- Or calculation with $M_h \neq 0$ and different $m_{\tilde{b}}$-renormalization: can be interpreted as 2HDM-calculation $\Rightarrow$ explanation why it is still finite M_h-effect significant

Renormalization scheme dependence reduced from 1-Loop → 2-Loop

by D.Stoeckinger

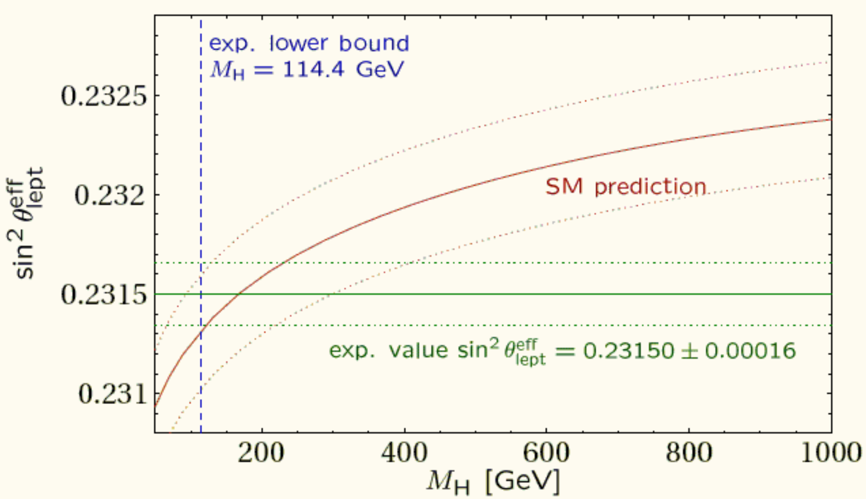
weak mixing angle 2-loop

Final result for $\sin^2\theta^{\text{eff}}_{\text{lept}}$ uses G_μ as input

$\rightarrow$ include corrections to M_W

Present result in terms of fitting formula:

$$
\begin{aligned}
\sin^2\theta^{\text{eff}}_{\text{lept}} = \sin^2\theta^{\text{eff}}_{\text{lept}(0)} &+ d_1 \log\left(\frac{M_H}{100}\right) + d_2 \log^2\left(\frac{M_H}{100}\right) + d_3 \log^4\left(\frac{M_H}{100}\right) \\
&+ d_4\left[\left(\frac{M_H}{100}\right)^2 - 1\right] + d_5\left[\frac{\Delta\alpha}{0.05907} - 1\right] \\
&+ d_6\left[\left(\frac{m_t}{178}\right)^2 - 1\right] + d_7\left[\left(\frac{m_t}{178}\right)^2 - 1\right]^2 \\
&+ d_8\left[\left(\frac{m_t}{178}\right)^2 - 1\right] \times \left[\frac{M_H}{100} - 1\right] \\
&+ d_9\left[\frac{\alpha_s}{0.117} - 1\right] + d_{10}\left[\frac{M_Z}{91.1876} - 1\right]
\end{aligned}
$$



by A.Freitas

MSSM sfermion masses 2-loop

TSIL=Two-Loop Self-energy Integral Library

- Two-loop calculations for self-energies in the MSSM are necessary, possible
- I favor a Strategy based on:
  - $\overline{\mathrm{DR}}'$ scheme (complementary to on-shell scheme results)
  - Reusable, generic calculations
  - Efficient computations of basis two-loop integrals
- 2-loop SUSYQCD corrections to squarks now known, typically $\lesssim 1\%$
- 2-loop sfermion pole masses are implicitly known
- Some 3-loop calculations (e.g. for h^0, maybe for gluino, squarks) will eventually be necessary to compete with measurement accuracy from a Linear Collider

by S.Martin

MSSM

$M_W \quad \sin^2\theta_{\rm eff} \quad \Delta\rho \quad M_{h^0}$

1-loop

Non Minimal Flavor Violation in MSSM

- Precision observables can

  constrain MSSM parameter space already today, and even more for the increasing precision at future colliders

- MSSM with NMFV:

  general 4×4 mixing in $\tilde{t}/\tilde{c}$ and $\tilde{b}/\tilde{s}$ sectors

  $\Rightarrow$ Evaluation of M_W, $\sin^2\theta_{\rm eff}$, M_{h^0}

- Analytical results: for arbitrary mixing

  Numerical results: only for LL mixing, parametrized with λ ($(\delta_{LL})_{23}$)

- Large effects possible for M_W, $\sin^2\theta_{\rm eff}$:

  $\lambda \lesssim 0.2 \Rightarrow \delta M_W \lesssim 20$ MeV $\qquad$ $\lambda \lesssim 0.2 \Rightarrow \delta \sin^2\theta_{\rm eff} \lesssim 10^{-4}$

  $\rightarrow$ We have shown that the effects of scalar quark generation mixing enters essentially through $\Delta\rho$

- Moderate effects possible for M_{h^0} only for large λ

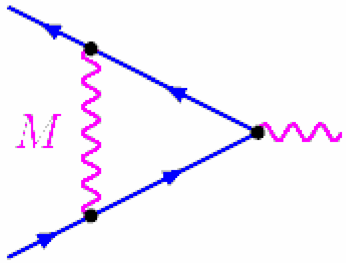
- FeynArts, FormCalc, LoopTools include:
  NMFV MSSM : 6×6 generalized squarks mixing matrices

by S.Penaranda

massive form factor 2-loop

One-Loop

example: massive U(1)



$$\Rightarrow \quad \text{Born} * \left[1 + \frac{\alpha}{4\pi}\left(-\ln^2\frac{s}{M^2} + 3\ln\frac{s}{M^2} - \frac{7}{2} + \frac{\pi^2}{3}\right)\right]$$

magnitude $\left(\frac{\alpha_w}{4\pi} = 3 \cdot 10^{-3}\right)$

$\frac{s}{M^2}$	$-\ln^2\frac{s}{M^2}$	$+3\ln\frac{s}{M^2}$	$-\frac{7}{2}+\frac{\pi^2}{3}$	Σ	$* 4\,\frac{\alpha_w}{4\pi}$
$\left(\frac{1000}{80}\right)^2$	-25.52	$+15.15$	-0.21	-10.6	-13%
$\left(\frac{2000}{80}\right)^2$	-41.44	$+19.31$	-0.21	-22.3	-27%

(four-fermion cross section $\Rightarrow$ factor 4)

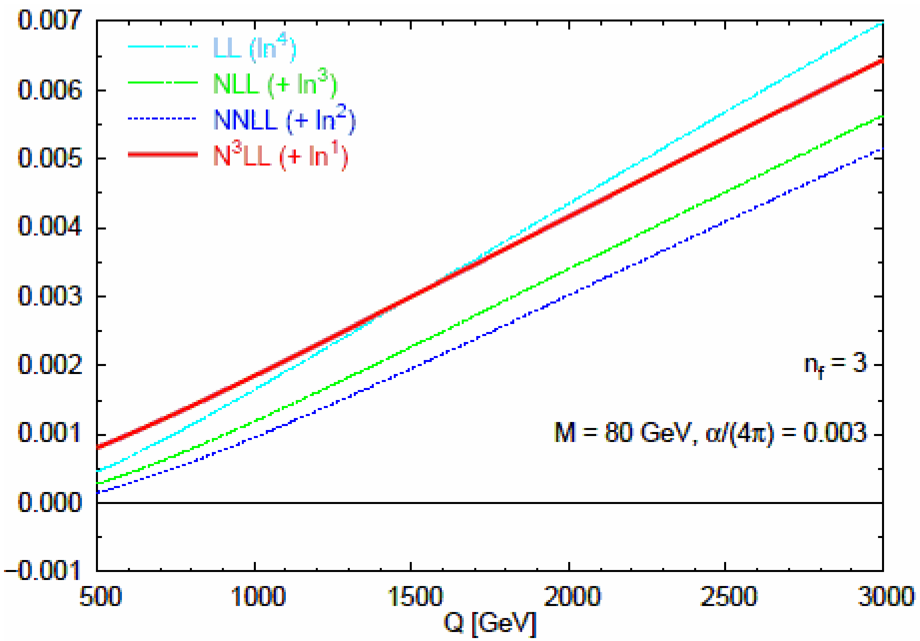
by J.Kuehn

Massive SU(2) form factor in 2-loop approximation: result

$$\alpha^2 F_2 = \left(\frac{\alpha}{4\pi}\right)^2 \left[+\frac{9}{32}\ln^4\left(\frac{Q^2}{M^2}\right) - \frac{19}{48}\ln^3\left(\frac{Q^2}{M^2}\right) - \left(-\frac{7}{8}\pi^2 + \frac{463}{48}\right)\ln^2\left(\frac{Q^2}{M^2}\right) \right.$$

N^{3}LL approximation
$M_{\text{Higgs}} = M$
$n_f = 3$

$$\left. + \left(\frac{39}{2}\frac{\mathrm{Cl}_2\left(\frac{\pi}{3}\right)}{\sqrt{3}} + \frac{45}{4}\frac{\pi}{\sqrt{3}} - \frac{61}{2}\zeta_3 - \frac{11}{24}\pi^2 + 29\right)\ln\left(\frac{Q^2}{M^2}\right) \right]$$



N^{3}LL and N^{4}LL (partly) available for form factor

special role of massless bosons (γ and g)
$\rightarrow$ factorization of IR singularities

first applications: LHC
important issue for LC

QCD

Heavy Quark Fragmentation function

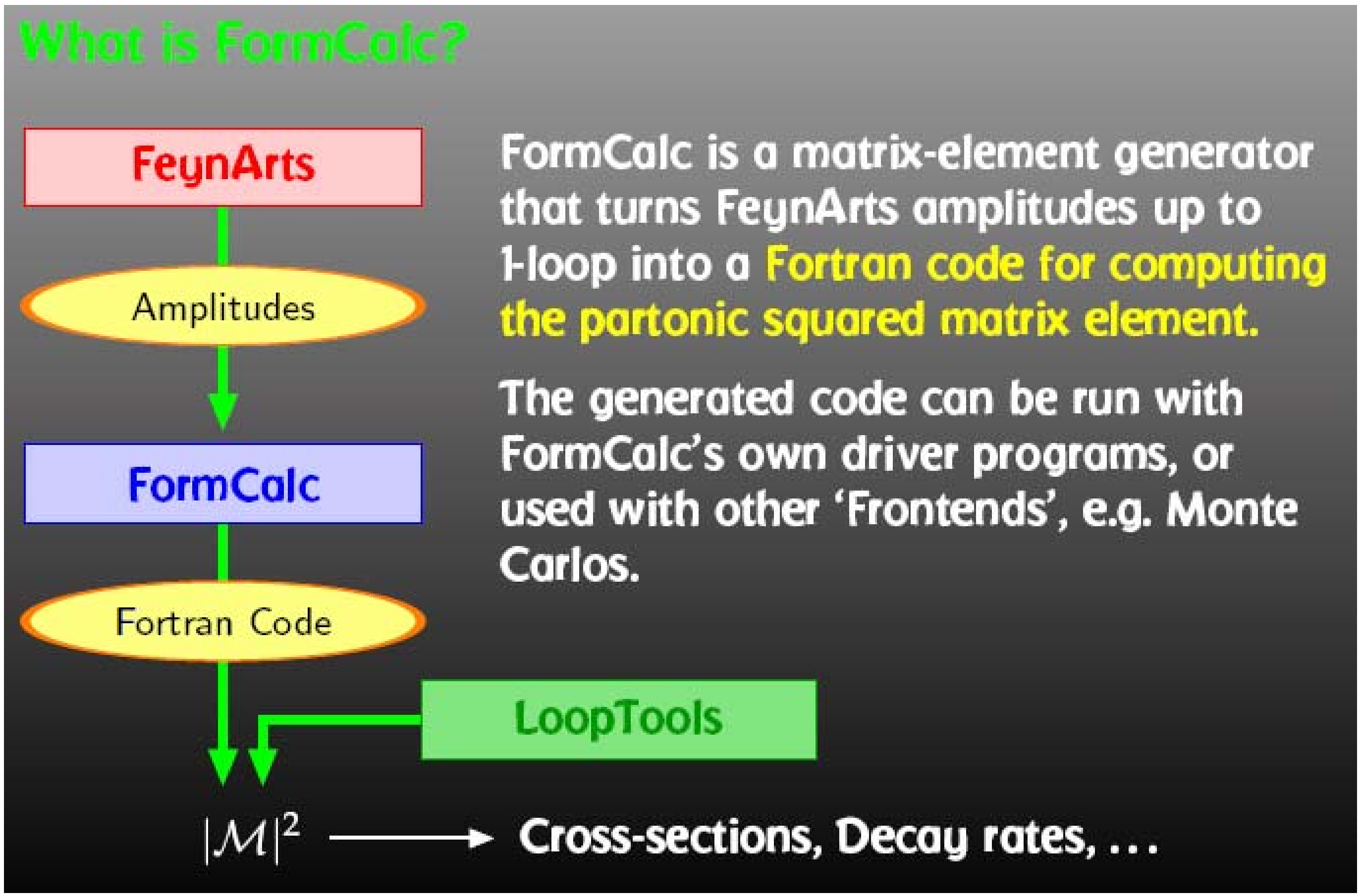
2-loop

- We have calculated all components of the initial condition for the perturbative fragmentation function at order α_s^2 (NNLO), thus extending the PFF formalism to NNLL level.
- We followed a process independent approach for the computation of D^{ini} that exploits the universal behavior of the collinear radiation.
- To evaluate the two-loop integrals we apply powerful techniques for multi-loop calculations: IBP, reduction to MI's and their solving.
- I discussed the general properties of our result as well as the checks with partial results existing in the literature.
- I discussed some of the many possible applications of our result, like:
- Fixed order spectra for heavy particles from massless results,
- Resummations of quasi-collinear logs with NNLL accuracy and accurate extraction of non-perturbative fragmentation function from data.

by A. Mitov

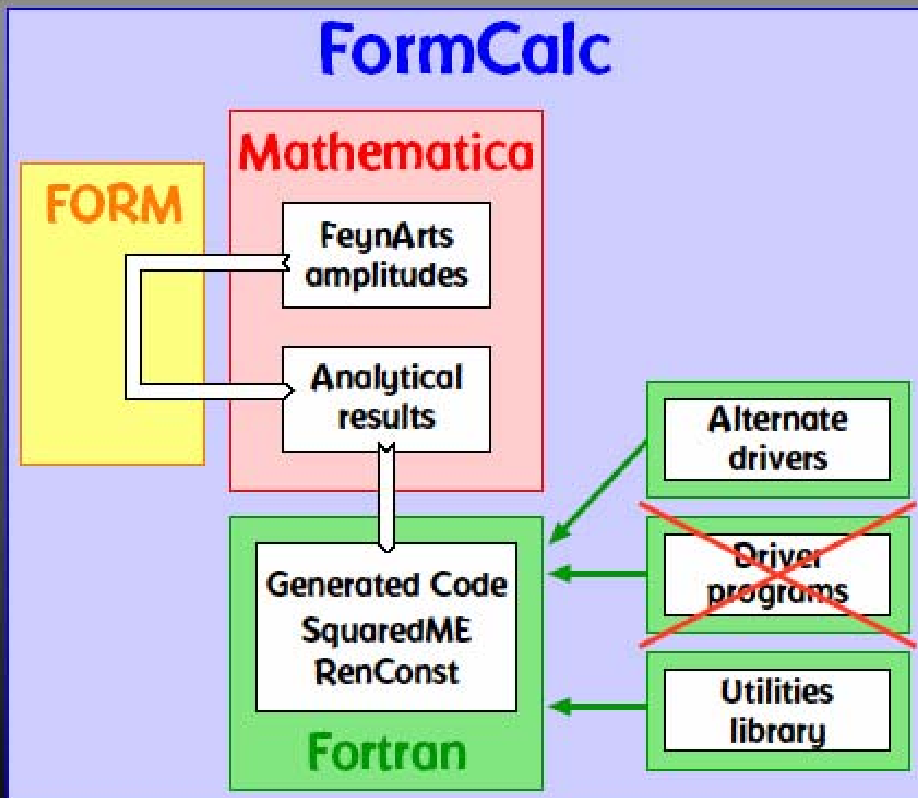
Tool

New FormCalc



by T.Hahn

New Stuff



Weyl-van der Waerden spinor formalism for external fermions

Multidimensional integration with CUBA

Optimized public code-generation funcs

FeynHiggs interface and NMFV

Useful scripts

HadCalc by M. Rauch

Tool

New method from twister space

- Much progress in computational techniques gauge theories in last year or so is attributable (directly or indirectly) to development of twistor string theory
- So far, practical spinoffs mostly for trees, and for loops in supersymmetric theories
- However, loop-level versions of BCF recursion relations look promising
- Try to determine polynomial terms in non-SUSY (QCD) loop amplitudes this way (unitarity for branch-cut terms)
- Expect much more progress along these lines in future

by L.Dixon

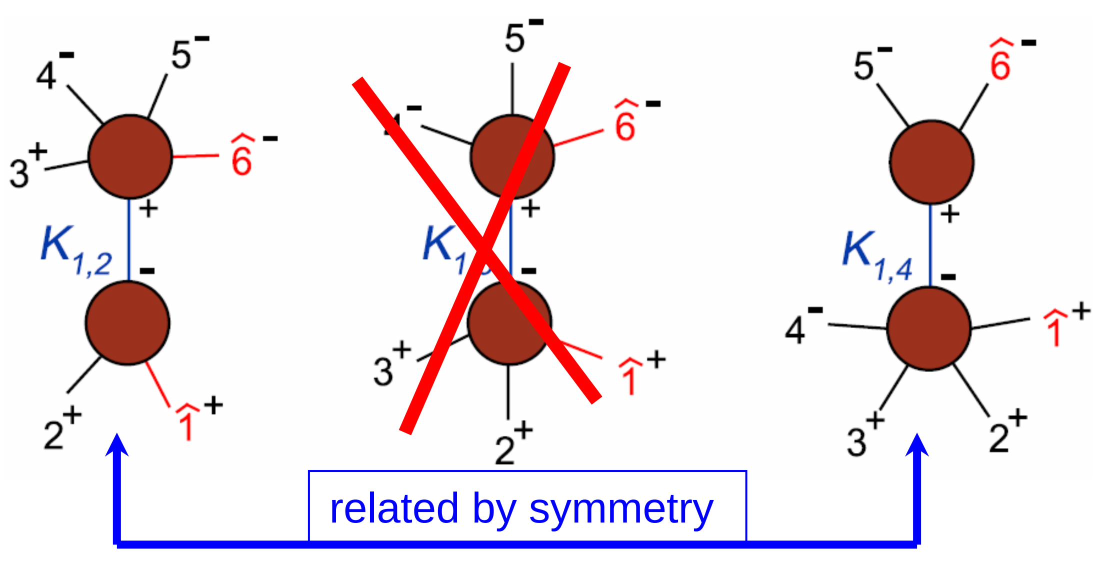
A 6-gluon example

220 Feynman diagrams for *gggggg*

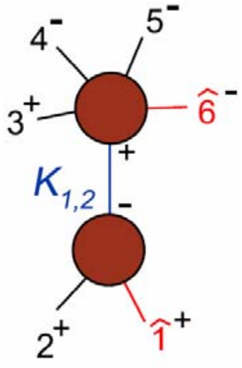
Helicity + color + MHV (--++++) results + symmetries

$\Rightarrow$ only $\boxed{A_6(1^+,2^+,3^+,4^-,5^-,6^-)}$, $A_6(1^+,2^+,3^-,4^+,5^-,6^-)$

3 BCF diagrams



The one $A_6(1^+,2^+,3^+,4^-,5^-,6^-)$ diagram



$$= -\frac{i}{s_{12}}\frac{[\hat{1}\,2]^3}{[2\,\hat{K}][\hat{K}\,\hat{1}]}\frac{[\hat{K}\,3]^3}{[3\,4][4\,5][5\,\hat{6}][\hat{6}\,\hat{K}]}$$

$$= -\frac{i}{s_{12}}\frac{[1\,2]^3}{([2\,\hat{K}]\langle\hat{K}\,6\rangle)(\langle 6\,\hat{K}\rangle[\hat{K}\,1])}\frac{(\langle 6\,\hat{K}\rangle[\hat{K}\,3])^3}{[3\,4][4\,5][5\,\hat{6}]([\hat{6}\,\hat{K}]\langle\hat{K}\,6\rangle)}$$

$$= i\,\frac{\langle 6^-|(1+2)|3^-\rangle^3}{\langle 6\,1\rangle\langle 1\,2\rangle[3\,4][4\,5]s_{612}\langle 2^-|(6+1)|5^-\rangle}$$

$$\begin{aligned}\langle 6\,\hat{K}\rangle[\hat{K}\,a] &= \langle 6\,1\rangle\,[1\,a]+\langle 6\,2\rangle\,[2\,a]\\ &= \langle 6^-|(1+2)|a^-\rangle\end{aligned}$$

$$[5\,\hat{6}] = [5\,6]+\frac{s_{12}[5\,1]}{\langle 6\,2\rangle[2\,1]} = \frac{\langle 5^+|(6+1)|2^+\rangle}{\langle 6\,2\rangle}$$

$$[\hat{6}\,\hat{K}]\langle\hat{K}\,6\rangle = \langle 6^+|(1+2)|6^+\rangle + s_{12} = s_{612}$$

Last comments

- Higher order calculation required for ILC is steadily in progress including the full EW one-loop $e^+e^- \to \nu_\tau \tau^+ \mu^- \overline{\nu}_\mu, u\overline{d}\mu^- \overline{\nu}_\mu, u\overline{d}s\overline{c}$
- Higgs at ILC : O (α) calculation is ready for most of processes.
- Two-loop in EW/MSSM/QCD/QCD-EW available for a class of physical observables.
- High-precision sometimes requires large scale computation → Importance of the development of tools for HEP.