Physics beyond the SM
with CompHEP

M. Dubinin on behalf of the

CompHEP Collaboration
Moscow State University

Nonstandard models with CompHEP
Examples
- full chain from Lagrangian to detector simulation packages

New developments in CompHEP

CompHEP version 4.xx

CompHEP Collaboration:
E. Boos, V. Bunichev, M. Dubinin, L. Dudko, V.Edneral,
V.Ilyin, A. Kryukov, V. Savrin, A. Semenov, A.Sherstnev

Nucl.Instrum.Meth. A534 (2004) 250-259

http://theory.sinp.msu.ru/comphep

CompHEP version 3.xx

A.Pukhov, E.Boos, M.Dubinin, V.Edneral, V.Ilyin,
V.Kovalenko, A.Kryukov, V.Savrin, S.Shichanin, A.Semenov

hep-ph/9908288

Beyond the SM with CompHEP: main fields of interest (theory)

Effective operators of higher dimensions (ndim>4)

- anomalous triple $\gamma W+W-$, Z W+W- couplings
- anomalous quartic Z,W± couplings
- anomalous t-quark (Wtb) couplings
- anomalous Higgs self-couplings ndim=6
- contact 4-fermion interactions

SUSY particles

- chargino, neutralino and sfermion production

SUSY Higgs bosons

- h, H, A and H± production
- intense coupling regime in the Higgs sector
- explicit CP violation in the Higgs sector

Quantum gravity and extra dimensions

- universal extra dimensions; constraining SUSY
- neutral gauge boson from extra dimensions
- Higgs signals in large extra dimensions
- graviton production in KK with large extra dimensions
- relic density of KK dark matter

Extensions of SM (other than SUSY) and exotica

- Leptoquarks, scalar and vector
- excited quarks and leptons
- extra generations and heavy neutrino
- $SU(2)L\times SU(2)R\times U(1)$ model, W' and Z'
- $SU(3)L\times U(1)$ model, W' and Z', Higgs bosons
- lepton flavor violation, FCNC

Dark matter and relic density

little Higgs models

doubly charged Higgs bosons

KARMEN time anomaly

EGRET excess

....

The list of topics is based on the analysis of about 1000 papers quoting CompHEP.

Published experimental analyses beyond the SM quoting CompHEP

DELPHI	'98	chargino, neutralino, gravitino at	LEP2
ALEPH	'98	SUSY in γ+miss ET,	LEP2
DELPHI	'99	H in events with isolated γ	LEP2
D0	'01	leptoquark pairs –› ν+jets	Tevatron
H1	'02	excited ν	HERA
H1	'03	e and μ with miss PT	HERA
ZEUS	'03	single top production	HERA
D0,CDF	'03	single top production	Tevatron
OPAL	'03	single production of H++, H--	LEP2
D0	'04	three and four body stop decays	Tevatron
CDF	'05	excited and exotic lepton –› eγ	Tevatron
CMS	'05	discovery of SUSY with μμ	LHC
H1	'05	doubly charged Higgs bosons	HERA
H1	'05	search for monopole	HERA

List is not full. A number of CMS and Tevatron studies '05-'06 in progress or not yet appeared.

General instruction

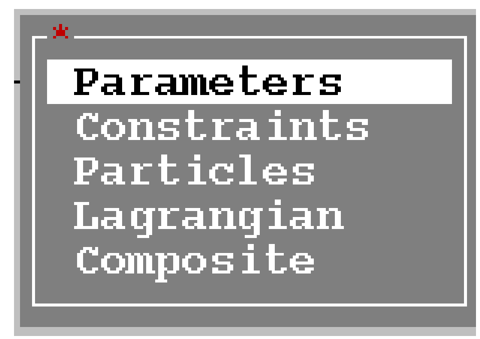
- Modify SM Feynman rules or write your own set. If too complicated,
- Install LanHEP

`http://theory.sinp.msu.ru/~semenov/lanhep.html`

- Print Lagrangian in LanHEP file modelBSM.mdl
- Type the command lanhep modelBSM.mdl
- Check the output Feynman rules, constraints, etc. in

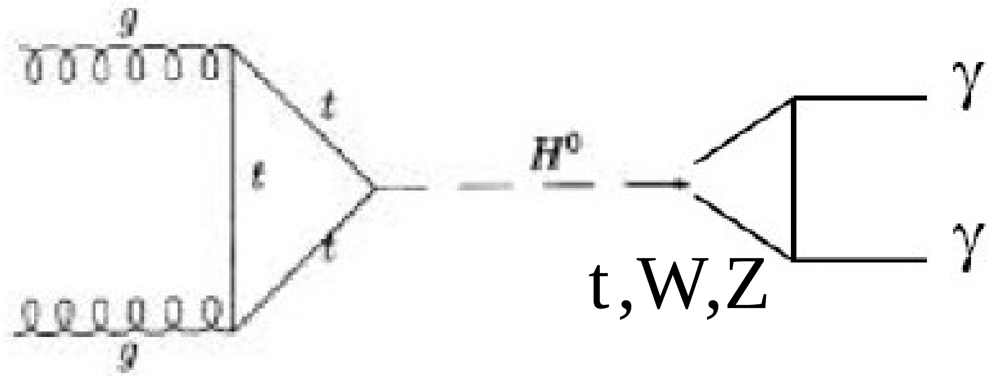
```
vars.mdl
func.mdl.
prtcls.mdl
lgrng.mdl
```

$\Leftrightarrow$



- Install CompHEP. Move *.mdl files to user/models dir
  `http://theory.sinp.msu.ru/comphep`
- Open new model. Input physical process of interest. Generate unweighted events.

Simple exaple: how to implement gg→$\gamma\gamma$ at the one-loop to CompHEP model



The effective Lagrangian $\mathcal{L}^{eff}_{\gamma\gamma H} = -\frac{\lambda_{\gamma\gamma H}}{4} F_{\mu\nu} F^{\mu\nu} H$

The effective vertex $\Gamma^{\mu\nu}_{\gamma\gamma H/\gamma Z H}(k_1, k_2) = \lambda_{\gamma\gamma H/\gamma Z H}[(k_1 k_2) g^{\mu\nu} - k_1^\nu k_2^\mu]$

where $$\lambda_{\gamma\gamma H} = 8\sqrt{\frac{\pi}{m_H^3}\Gamma^{tot} Br(H \to \gamma\gamma)}$$

find using HDECAY (Djouadi, Kalinowski, Spira, CPC 108(1998)56) or other loop package (e.g. FeynHiggs)

add `lterm` to LanHEP model file `model_FFH.mdl`

```
% effective lagrangian term FFH

parameter lambda_ggH=1e-5.

lterm   - lambda_ggH/4
        *(deriv^mu*A^nu-deriv^nu*A^mu)
        *(deriv^mu*A^nu-deriv^nu*A^mu)*H.
```

and generate `lgrng.mdl` in CompHEP format

```
Stand. Model+VVH (un. gauge)
 Lagrangian
P1   |P2   |P3   |P4   |>   Factor               <|> dLagrangian/ dA(p1) dA(p2) dA(p3)
A    |A    |H    |     |lambda_ggH               |p1.p2*m1.m2-m2.p1*m1.p2
A    |W+   |W-   |     |-EE                      |m3.p2*m1.m2-m1.p2*m2.m3-m2.p3*m1.m3+m1.p3*m2.m3+m2.p1*m1.m3-
B    |b    |A    |     |EE/3                     |G(m3)
B    |b    |G    |     |GG                       |G(m3)
B    |b    |H    |     |-EE*Mb/(2*MW*SW)         |1
B    |b    |Z    |     |-EE/(12*CW*SW)           |2*SW**2*G(m3)*(1+G5)-(3-2*SW**2)*G(m3)*(1-G5)
B    |c    |W-   |     |-EE*Sqrt2*Vcb/(4*SW)     |G(m3)*(1-G5)
B    |t    |W-   |     |-EE*Sqrt2*Vtb/(4*SW)     |G(m3)*(1-G5)
B    |u    |W-   |     |-EE*Sqrt2*Vub/(4*SW)     |G(m3)*(1-G5)
C    |b    |W+   |     |-EE*Sqrt2*Vcb/(4*SW)     |G(m3)*(1-G5)
C    |c    |A    |     |-2*EE/3                  |G(m3)
C    |c    |G    |     |GG                       |G(m3)
C    |c    |H    |     |-EE*Mc/(2*MW*SW)         |1
C    |c    |Z    |     |-EE/(12*CW*SW)           |(3-4*SW**2)*G(m3)*(1-G5)-4*SW**2*G(m3)*(1+G5)
```

(I) Anomalous interactions of top-quark

$$L_{eff} = L_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + O(\frac{1}{\Lambda^4})$$

Seven SU(2)⊗U(1) invariant effective operators of dimension six contributing to the Wtb vertex

$$\begin{aligned}
O_{tW\Phi} &= [(\bar{q}_L \sigma^{\mu\nu} \tau^I t_R)\Phi + \Phi^+ (\bar{t}_R \sigma^{\mu\nu} \tau^I q_L)] W^I_{\mu\nu} \\
O_{bW\Phi} &= [(\bar{q}_L \sigma^{\mu\nu} \tau^I b_R)\Phi + \Phi^+ (\bar{b}_R \sigma^{\mu\nu} \tau^I q_L)] W^I_{\mu\nu} \\
O_{t3} &= i[(\Phi^+ D_\mu \Phi)(\bar{t}_R \gamma_\mu b_R) - (D_\mu \Phi)^+ \Phi (\bar{b}_R \gamma_\mu t_R)] \\
O_{Dt} &= (q_L D_\mu t_R) D^\mu \Phi + (D^\mu \Phi)^+ (\overline{D_\mu t_R} q_L) \\
O_{qW} &= [\bar{q}_L \gamma^\mu \tau^I D^\nu q_L + \overline{D^\nu q_L} \gamma^\mu \tau^I q_L] W^I_{\mu\nu} \\
O^3_{\Phi q} &= i[\Phi^+ \tau^I D_\mu \Phi - (D_\mu \Phi)^+ \tau^I \Phi] \bar{q}_L \gamma_\mu \tau^I q_L \\
O_{Db} &= (q_L D_\mu b_R) D^\mu \Phi + (D_\mu \Phi)^+ (\overline{D_\mu b_R} q_L)
\end{aligned}$$

$$q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \qquad W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g \epsilon_{IJK} W^J_\mu W^K_\nu$$

O_tWΦ and O_bWΦ give the effective Lagrangian

$$\mathcal{L} = \frac{g}{\sqrt{2}} \frac{1}{2m_W} W_{\mu\nu} \bar{t} \sigma^{\mu\nu} (f_{2R} P_L + f_{2L} P_R) b + \mathrm{h.c.}$$

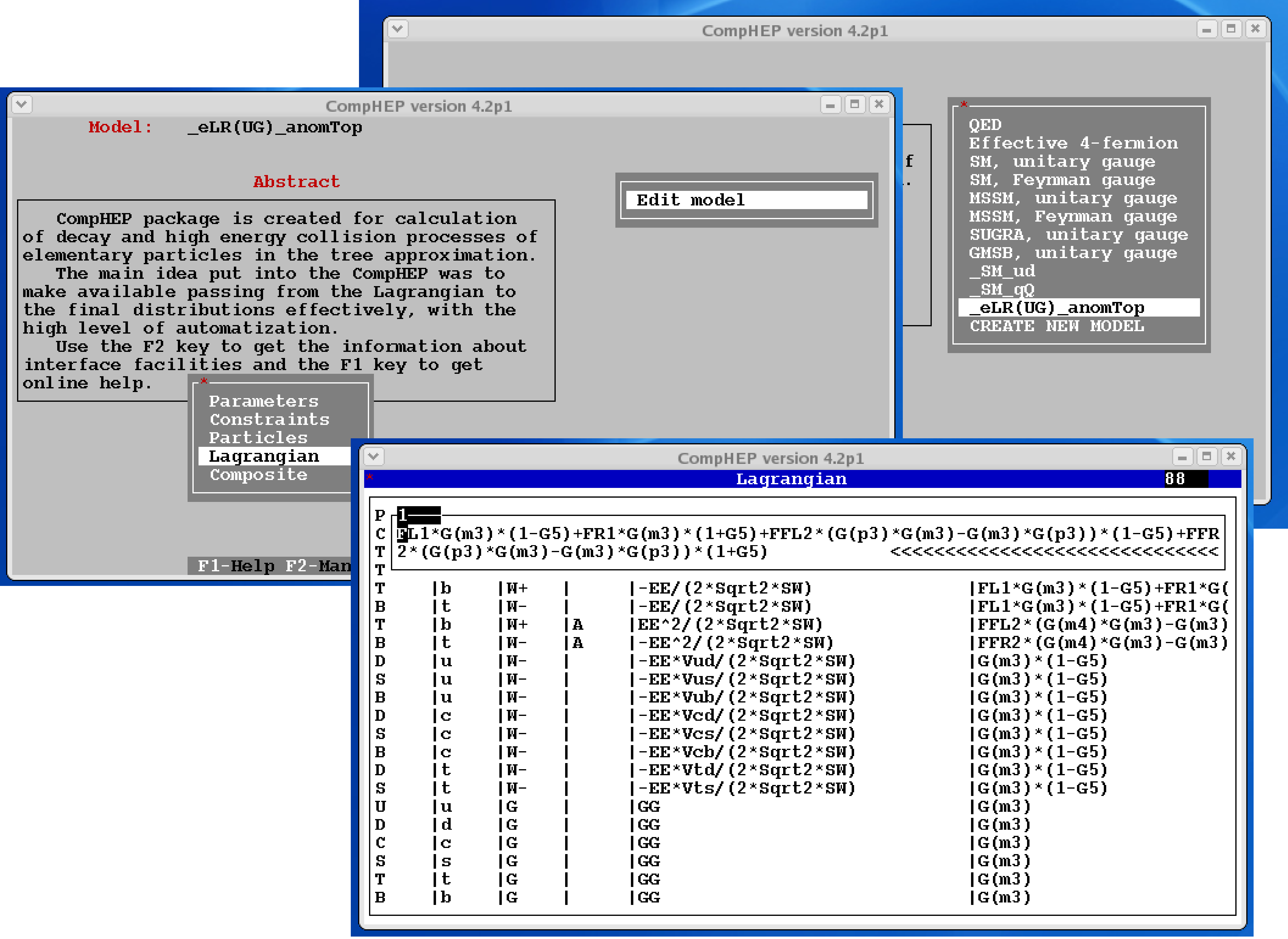
where f_2L and f_2R are the Wtb anomalous couplings

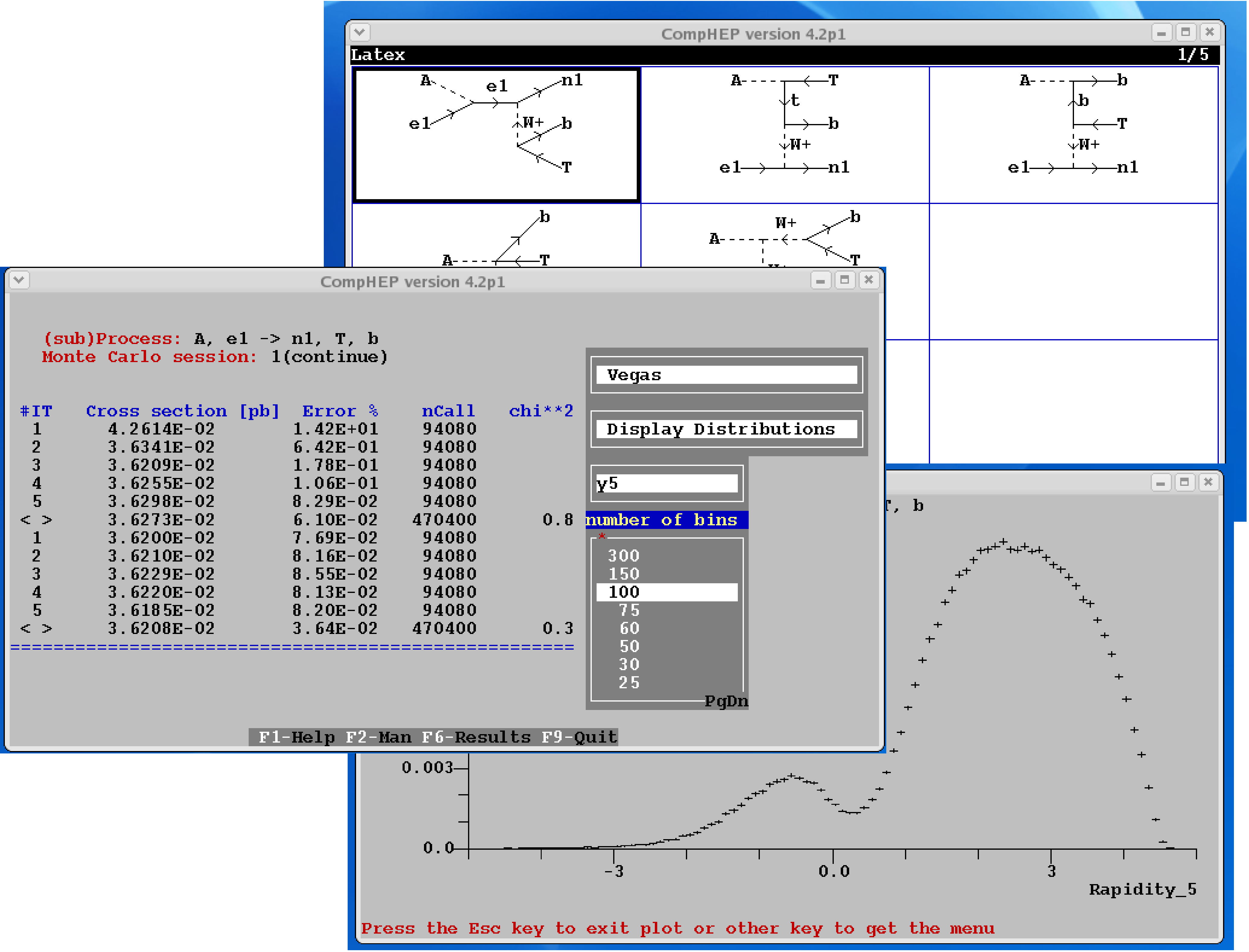
$$f_{2L} = \frac{C_{tW\Phi}}{\Lambda^2} \frac{v\sqrt{2} m_W}{g}, \quad f_{2R} = \frac{C_{bW\Phi}}{\Lambda^2} \frac{v\sqrt{2} m_W}{g}$$

$$W_{\mu\nu} = D_\mu W_\nu - D_\nu W_\mu, \qquad D_\mu = \partial_\mu - ieA_\mu$$

$$P_{R,L} = \frac{1}{2}(1 \pm \gamma_5), \qquad \sigma_{\mu\nu} = \frac{i}{2}(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)$$

E.Boos, L.Dudko, M.D., T.Ohl, A.Pukhov, M.Sachwitz, H.Schreiber
EPJC 21(2001) 81, EPJC C16(2000)269, EPJC C11(1999)473


CompHEP version 4.2p1
QED
Effective 4-fermion
SM, unitary gauge
SM, Feynman gauge
MSSM, unitary gauge
MSSM, Feynman gauge
SUGRA, unitary gauge
GMSB, unitary gauge
_SM_ud
_SM_qQ
_eLR(UG)_anomTop
CREATE NEW MODEL
CompHEP version 4.2p1
Model: _eLR(UG)_anomTop
Abstract
CompHEP package is created for calculation of decay and high energy collision processes of elementary particles in the tree approximation.
The main idea put into the CompHEP was to make available passing from the Lagrangian to the final distributions effectively, with the high level of automatization.
Use the F2 key to get the information about interface facilities and the F1 key to get online help.
Edit model
Parameters
Constraints
Particles
Lagrangian
Composite
F1-Help F2-Man
CompHEP version 4.2p1
Lagrangian
88
FL1*G(m3)*(1-G5)+FR1*G(m3)*(1+G5)+FFL2*(G(p3)*G(m3)-G(m3)*G(p3))*(1-G5)+FFR
2*(G(p3)*G(m3)-G(m3)*G(p3))*(1+G5)
T |b |W+ | |-EE/(2*Sqrt2*SW) |FL1*G(m3)*(1-G5)+FR1*G(
B |t |W- | |-EE/(2*Sqrt2*SW) |FL1*G(m3)*(1-G5)+FR1*G(
T |b |W+ |A |EE^2/(2*Sqrt2*SW) |FFL2*(G(m4)*G(m3)-G(m3)
B |t |W- |A |-EE^2/(2*Sqrt2*SW) |FFR2*(G(m4)*G(m3)-G(m3)
D |u |W- | |-EE*Vud/(2*Sqrt2*SW) |G(m3)*(1-G5)
S |u |W- | |-EE*Vus/(2*Sqrt2*SW) |G(m3)*(1-G5)
B |u |W- | |-EE*Vub/(2*Sqrt2*SW) |G(m3)*(1-G5)
D |c |W- | |-EE*Vcd/(2*Sqrt2*SW) |G(m3)*(1-G5)
S |c |W- | |-EE*Vcs/(2*Sqrt2*SW) |G(m3)*(1-G5)
B |c |W- | |-EE*Vcb/(2*Sqrt2*SW) |G(m3)*(1-G5)
D |t |W- | |-EE*Vtd/(2*Sqrt2*SW) |G(m3)*(1-G5)
S |t |W- | |-EE*Vts/(2*Sqrt2*SW) |G(m3)*(1-G5)
U |u |G | |GG |G(m3)
D |d |G | |GG |G(m3)
C |c |G | |GG |G(m3)
S |s |G | |GG |G(m3)
T |t |G | |GG |G(m3)
B |b |G | |GG |G(m3)


CompHEP version 4.2p1
Latex
1/5
A
e1
n1
W+
b
T
t
CompHEP version 4.2p1
(sub)Process: A, e1 -> n1, T, b
Monte Carlo session: 1(continue)
#IT Cross section [pb] Error % nCall chi**2
1 4.2614E-02 1.42E+01 94080
2 3.6341E-02 6.42E-01 94080
3 3.6209E-02 1.78E-01 94080
4 3.6255E-02 1.06E-01 94080
5 3.6298E-02 8.29E-02 94080
< > 3.6273E-02 6.10E-02 470400 0.8
1 3.6200E-02 7.69E-02 94080
2 3.6210E-02 8.16E-02 94080
3 3.6229E-02 8.55E-02 94080
4 3.6220E-02 8.13E-02 94080
5 3.6185E-02 8.20E-02 94080
< > 3.6208E-02 3.64E-02 470400 0.3
Vegas
Display Distributions
y5
number of bins
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100
75
60
50
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F1-Help F2-Man F6-Results F9-Quit
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3
Rapidity_5
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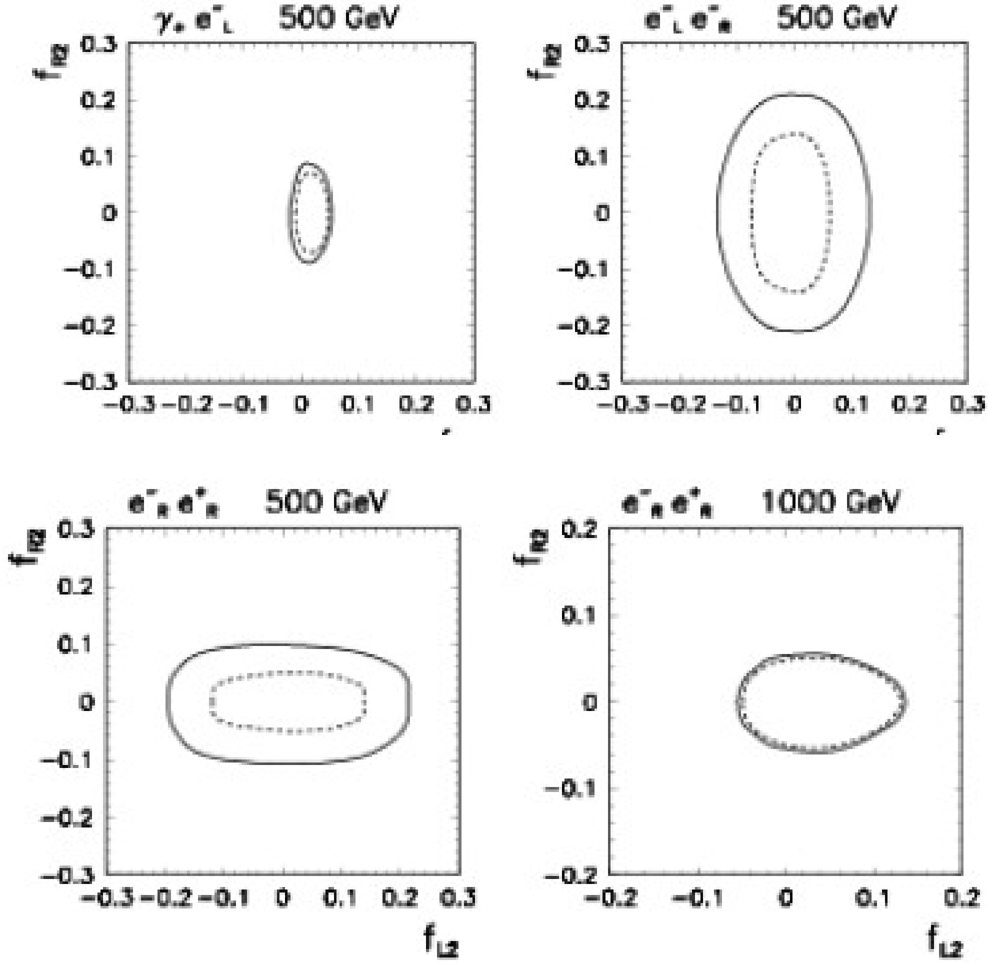
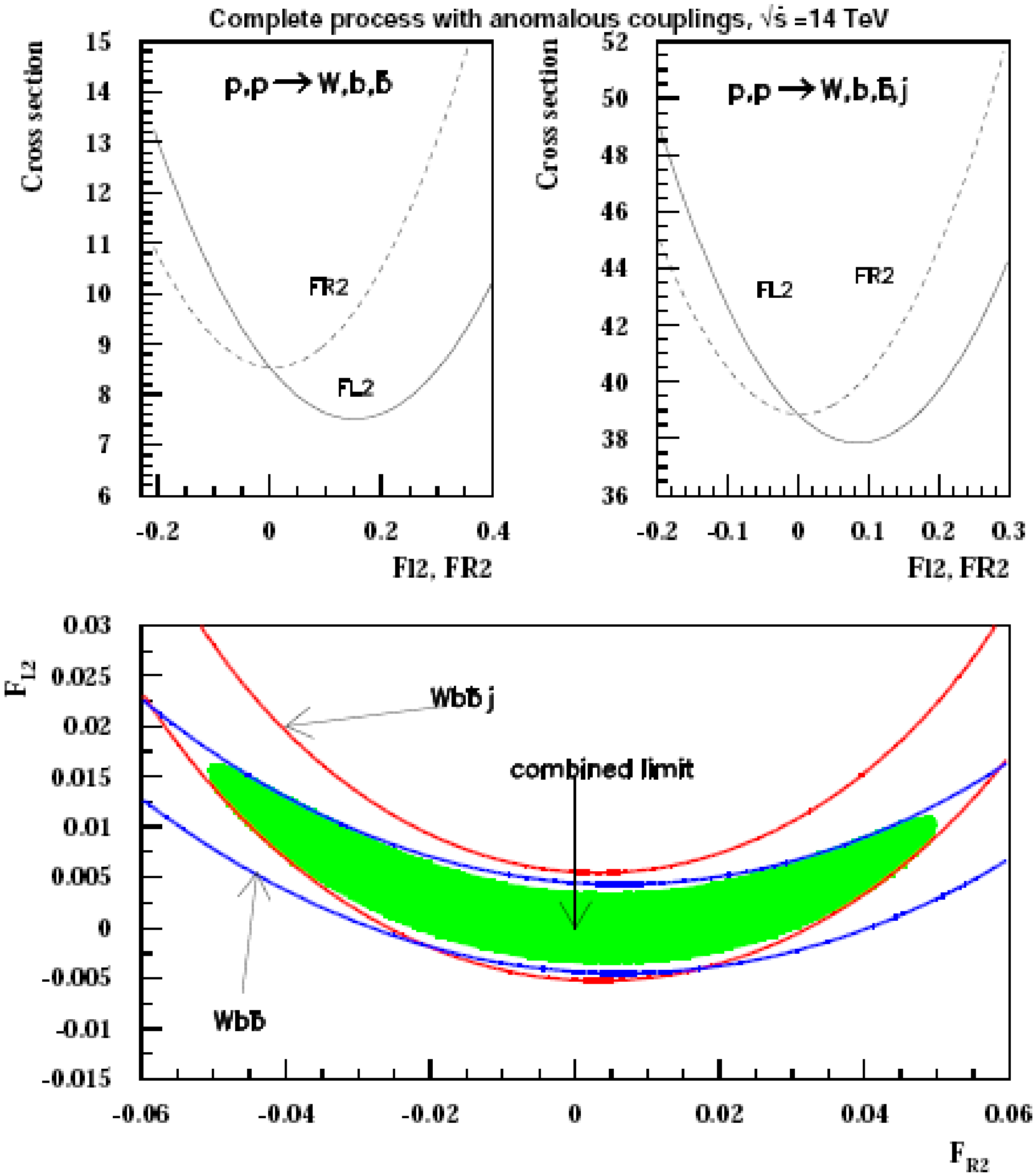
Anomalous top couplings: tt and single t production, NLC



2σ bounds on the anomalous couplings f_{2L} and f_{2R} from the reactions $\gamma_+ e_L^- \rightarrow \nu_e \bar{t} b$, $e_L^- e_R^- \rightarrow e^- \nu_e \bar{t} b$ and $e_R^- e_R^+ \rightarrow e^- \bar{\nu}_e t \bar{b}$ at $\sqrt{s}$ =0.5 TeV and 1.0 TeV, for integrated luminosities of 100 fb^{-1} (solid lines) and 500 fb^{-1} (dashed lines).

Anomalous top couplings: single top production, LHC



(II) MSSM. Determination of tan β and trilinear couplings A_τ,b,t in the sfermion pair production with polarization measurement in stau decays to τ-lepton, stop/sbottom → top

E.Boos, H.Martyn, G.Moortgat-Pick, M.Sachwitz, A.Sherstnev, P.Zerwas, EPJC 30(2003)395

Exact decay distributions of the 5-body final state

$$e^+e^- \to \tilde{b}_1 + t\,\tilde{\chi}_1^{\pm} \to \tilde{b}_1 + bc\bar{s}\,\tilde{\chi}_1^{\pm}.$$

calculated by CompHEP. The infinitely small width approximation $\frac{1}{(q^2-m^2)^2+m^2\Gamma^2} \Rightarrow \frac{\pi}{m\Gamma}\delta(q^2-m^2).$

is not meaningful for chain decays.

Polarisation in sfermion ⇨ fermion + neutralino/chargino

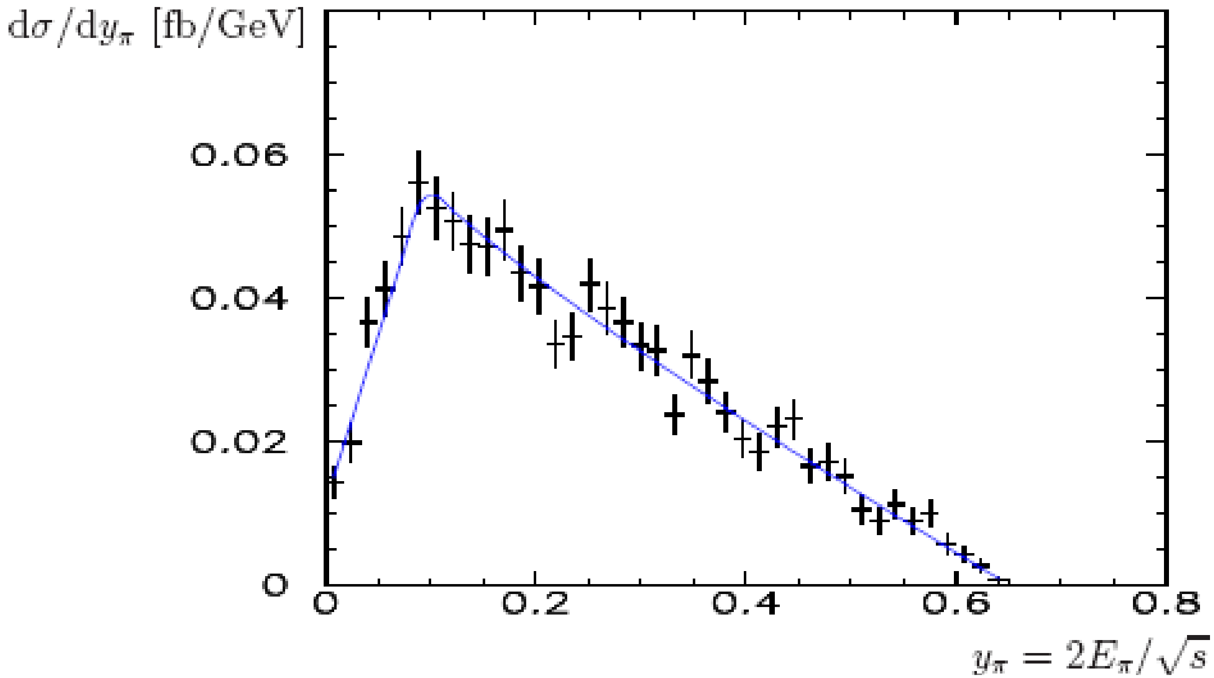


Figure 3: *Pion energy spectrum* $y_\pi = 2E_\pi/\sqrt{s}$ *from* $\tau \to \pi\nu$ *decays of* $e^+_L e^-_R \to \tilde{\tau}^+_1 \tilde{\tau}^-_1 \to \tau^+ \tilde{\chi}^0_1 + \tau^- \tilde{\chi}^0_1$ *production with* $P_{e^-} = +0.8$, $P_{e^+} = -0.6$ *at* $\sqrt{s} = 500$ GeV, *corresponding to* $\mathcal{L} = 500$ fb^{-1}*; reference scenario RP. The curve represents a fit to a* τ *polarisation of* $P_\tau = 0.82 \pm 0.03$.

$$\frac{1}{\sigma}\frac{d\sigma}{dy_\pi} = \frac{1}{x_+ - x_-}\begin{cases}(1-P_\tau)\,\log\frac{x_+}{x_-} + 2P_\tau\, y_\pi\,(\frac{1}{x_-} - \frac{1}{x_+}) & 0 < y_\pi < x_- \\ (1-P_\tau)\,\log\frac{x_+}{y_\pi} + 2P_\tau\,(1 - \frac{y_\pi}{x_+}) & x_- < y_\pi < x_+\end{cases}$$

where

$$x_{+/-} = \frac{m_{\tilde{\tau}}}{\sqrt{s}}\left(1 - \frac{m^2_{\tilde{\chi}}}{m^2_{\tilde{\tau}}}\right)\frac{1 \pm \beta}{\sqrt{1-\beta^2}} \quad \text{with} \quad \beta = \sqrt{1 - 4m^2_{\tilde{\tau}}/s}\ .$$

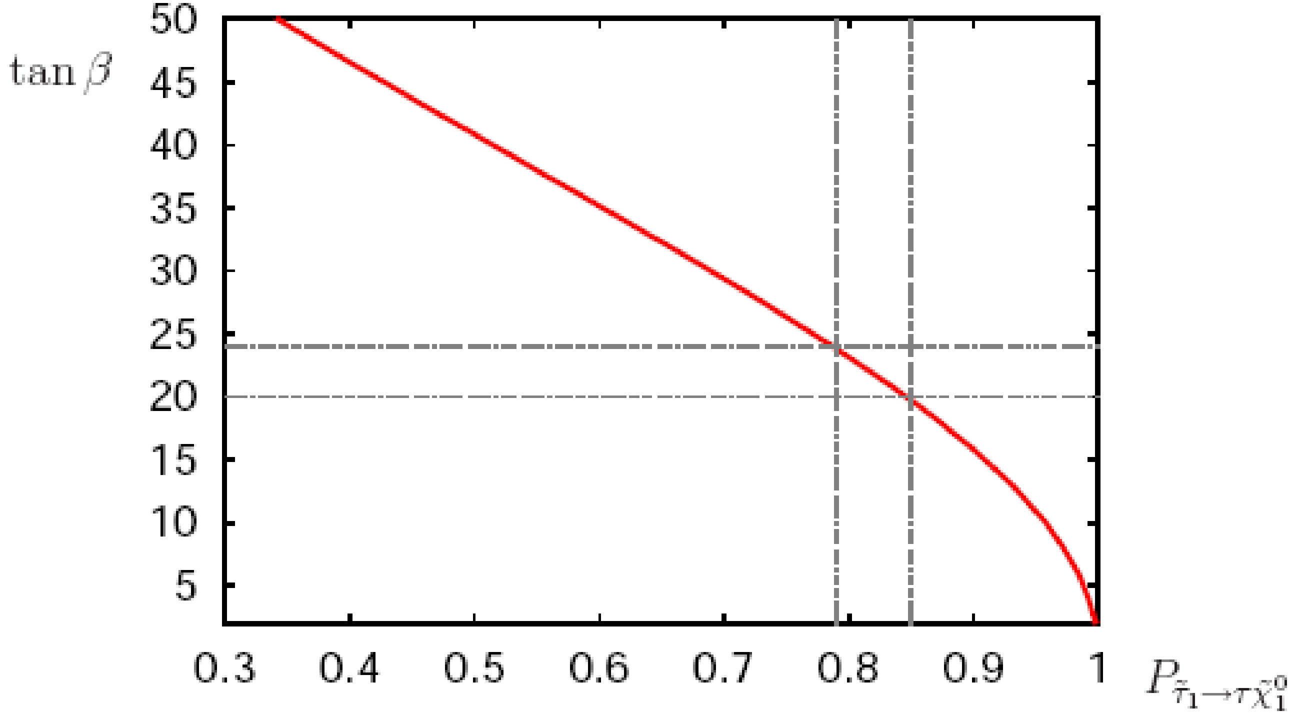
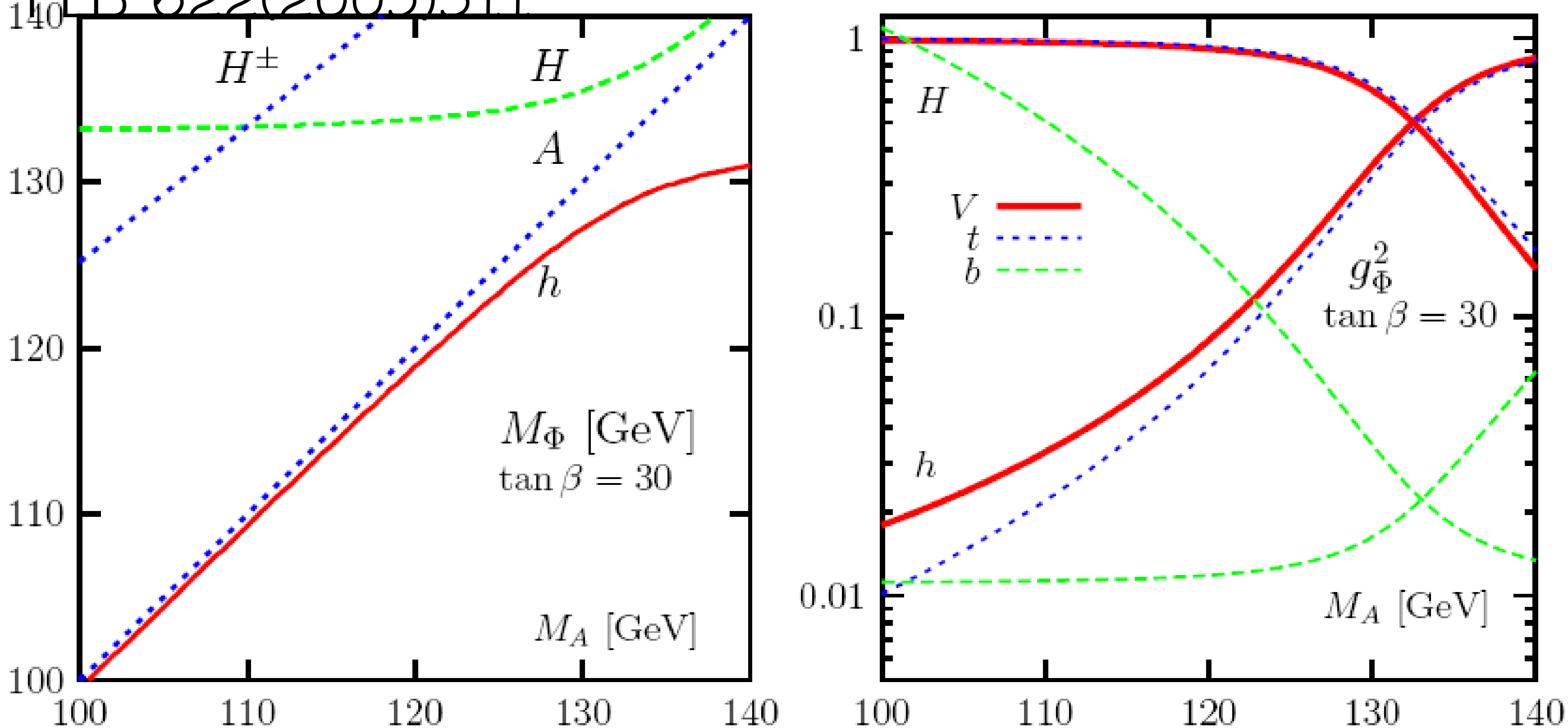


Figure 4: $\tan\beta$ *versus* τ *polarisation* $P_{\tilde{\tau}_1\to\tau\tilde{\chi}_1^0}$ *for the reference scenario RP. The bands illustrate a measurement of* $P_\tau = 0.82 \pm 0.03$ *leading to* $\tan\beta = 22 \pm 2$.

(III) Intense coupling regime for the MSSM Higgs bosons

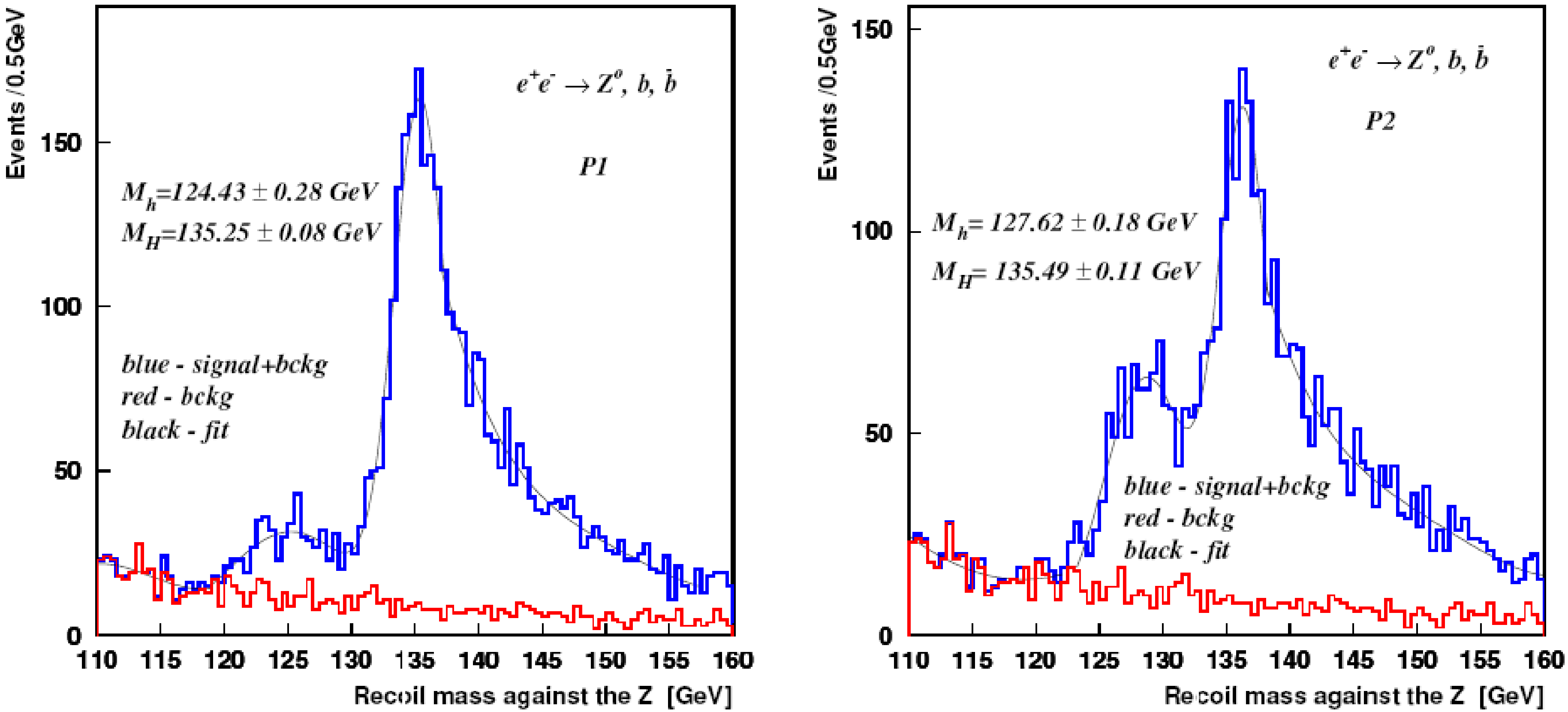
Masses of CP-even/CP-odd states are very close, widhts are large, at large tan β couplings and Br are different from the decoupling regime.

E.Boos, V.Bunichev, A.Djouadi, M.Muhlleitner, A.Nikitenko, H.Schreiber, PRD 66(2002)055004, PLB 578(2004)384, PLB 622(2005)311



H and h reconstruction in the llbb final state using the invariant mass recoiling against the Z, intense coupling regime, NLC

Recoil mass in the Zbb sample at 300 GeV LC



(IV) MSSM with explicit CP violation in the Higgs sector. Strong mixing of CP-even/CP-odd states (the CPX scenario)

$$
\begin{aligned}
U(\Phi_1,\Phi_2) = \quad & -\mu_1^2(\Phi_1^+\Phi_1) - \mu_2^2(\Phi_2^+\Phi_2) \\
& -\mu_{12}^2(\Phi_1^+\Phi_2) - \mu_{12}^{*2}(\Phi_2^+\Phi_1) \\
& +\lambda_1(\Phi_1^+\Phi_1)^2 + \lambda_2(\Phi_2^+\Phi_2)^2 + \lambda_3(\Phi_1^+\Phi_1)(\Phi_2^+\Phi_2) + \lambda_4(\Phi_1^+\Phi_2)(\Phi_2^+\Phi_1) \\
& +\frac{\lambda_5}{2}(\Phi_1^+\Phi_2)(\Phi_1^+\Phi_2) + \frac{\lambda_5^*}{2}(\Phi_2^+\Phi_1)(\Phi_2^+\Phi_1) \\
& +\lambda_6(\Phi_1^+\Phi_1)(\Phi_1^+\Phi_2) + \lambda_6^*(\Phi_1^+\Phi_1)(\Phi_2^+\Phi_1) \\
& +\lambda_7(\Phi_2^+\Phi_2)(\Phi_1^+\Phi_2) + \lambda_7^*(\Phi_2^+\Phi_2)(\Phi_2^+\Phi_1)
\end{aligned}
$$

$\lambda_5,\ \lambda_6\ \lambda_7$ are complex variables,

$$
(h,H,A)\, M^2 \begin{pmatrix} h \\ H \\ A \end{pmatrix} = (h_1,h_2,h_3)\, a^T_{ik}\, M^2_{kl}\, a_{lj} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}
$$

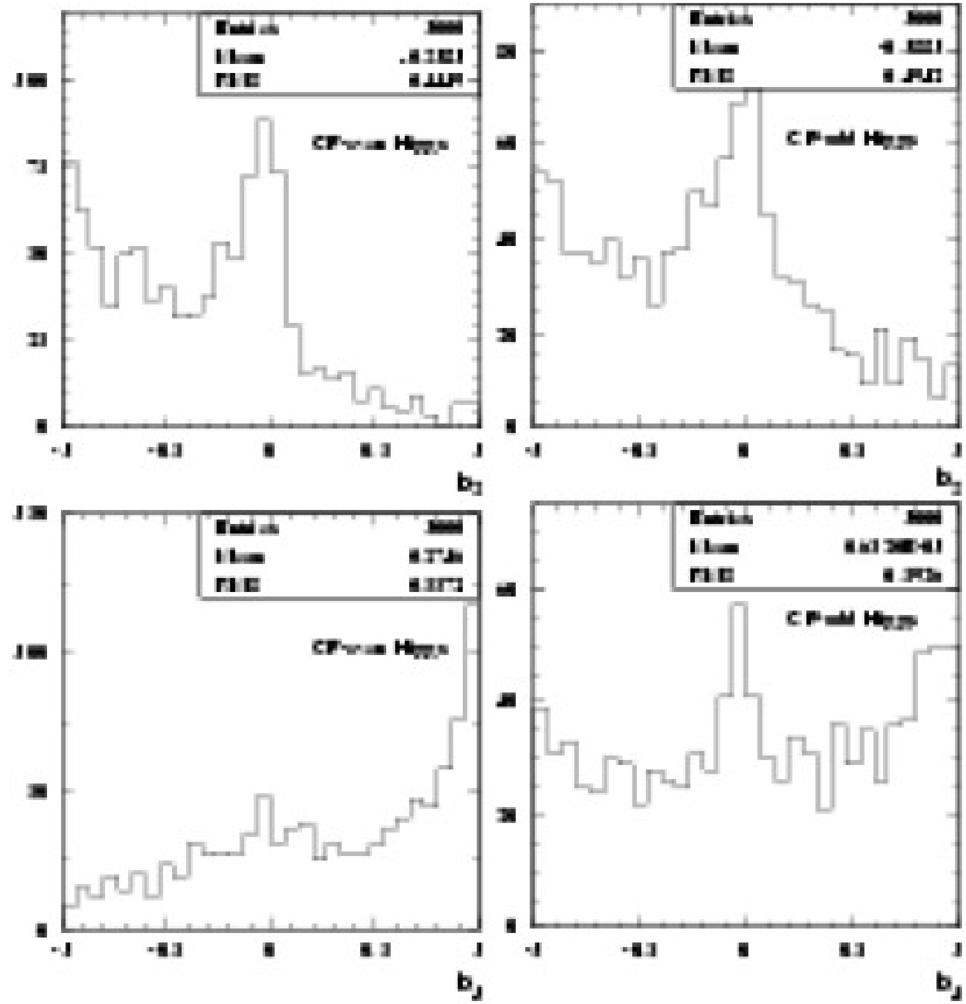
h1,h2,h3 are mass eigenstates without definite CP-parity

Reconstruction of Gunion-He variables in the tth channel with full CMS detector simulation

$$a_1 = \frac{(\vec{p}_{\pm} \times \hat{n}) \cdot (\vec{p}_{\mp} \times \hat{n})}{|(\vec{p}_{\pm} \times \hat{n}) \cdot (\vec{p}_{\mp} \times \hat{n})|}, \quad a_2 = \frac{p^x_{\pm} p^x_{\mp}}{|p^x_{\pm} p^x_{\mp}|}$$

$$b_1 = \frac{(\vec{p}_{\pm} \times \hat{n}) \cdot (\vec{p}_{\mp} \times \hat{n})}{p^T_{\pm} p^T_{\mp}}, \quad b_2 = \frac{(\vec{p}_{\pm} \times \hat{n}) \cdot (\vec{p}_{\mp} \times \hat{n})}{|\vec{p}_{\pm}||\vec{p}_{\mp}|}$$

$$b_3 = \frac{p^x_{\pm} p^x_{\mp}}{p^T_{\pm} p^T_{\mp}}, \quad b_4 = \frac{p^z_{\pm} p^z_{\mp}}{|\vec{p}_{\pm}||\vec{p}_{\mp}|},$$

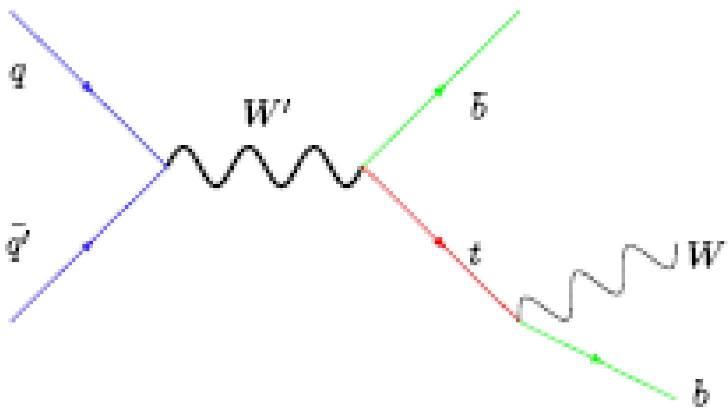


for the interaction $t(c+id\gamma 5)tH$

J.Albert, M.D., V.Litvin, H.Newman, in:
Proc.of the Workshop on CP-violation and Nonstandard Higgs Physics (CPNSH), CERN Yellow report, 2006.

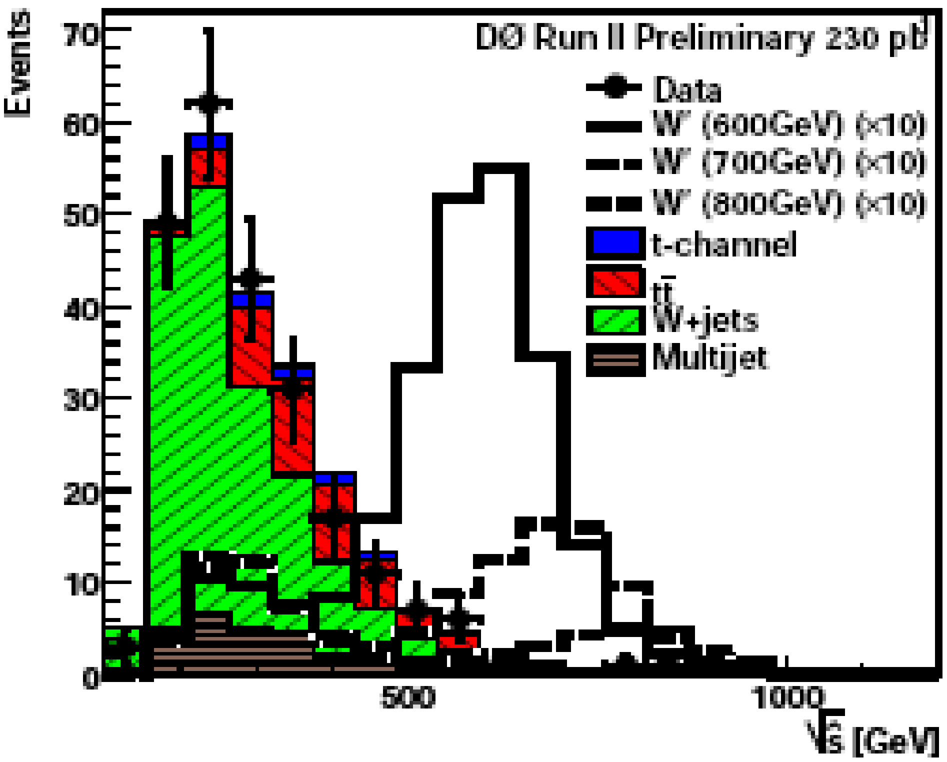
E.Akhmetzyanova, M.Dolgopolov, M.D., A.Semenov,
EPJC 28(2003)223 , PRD 71(2005)075008

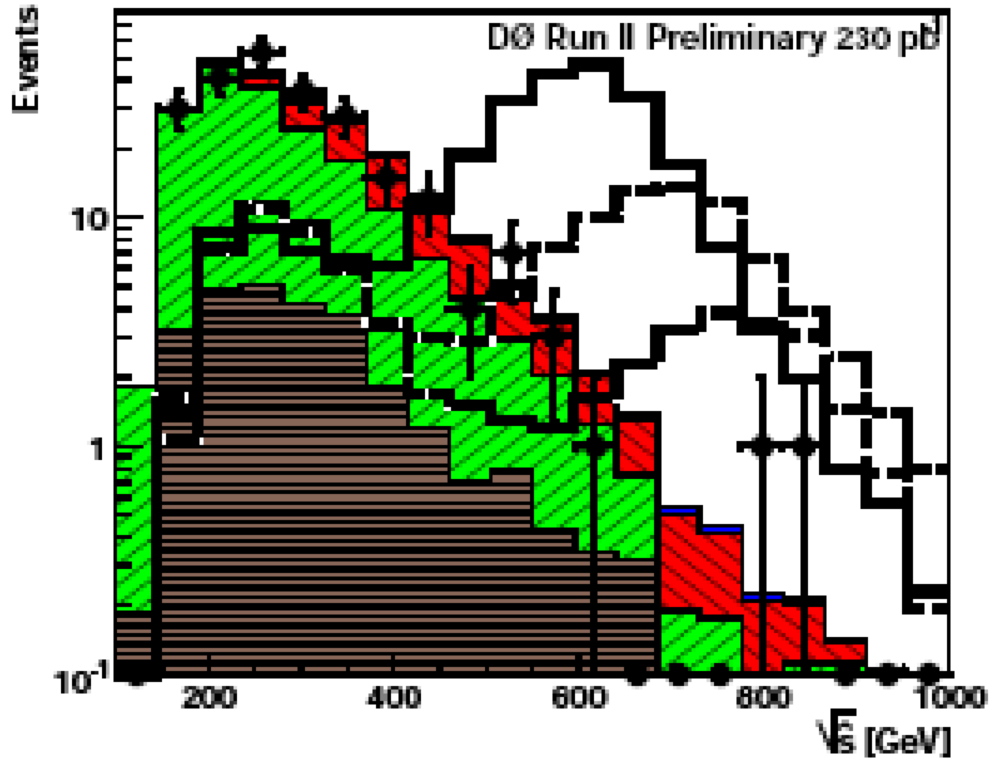
(V) W' reconstruction in the single top quark production
D0, Tevatron Run II



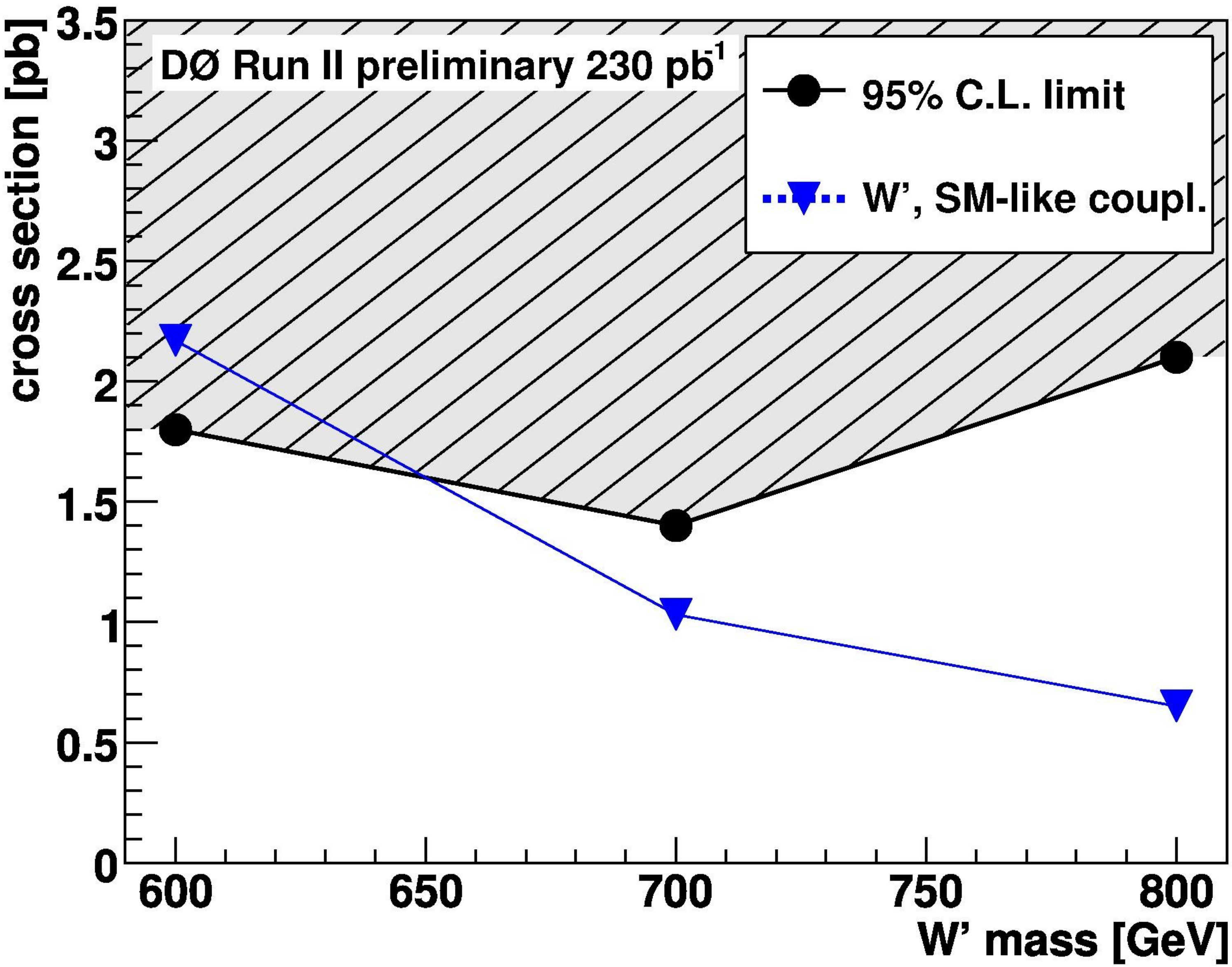
The W' coupling to fermions is SM-like. The CKM mixing matrix for the W' is one. Complete set of the the 4-body final state (lepton, missing E_T, b,b) diagrams calculated by CompHEP.

W' boson invariant mass reconstructed in the M(tb) distribution, Tevatron





Cross section limits at the 95% CL vs W' mass. Also shown are the W' cross sections with SM-like couplings.The shaded region is excluded.



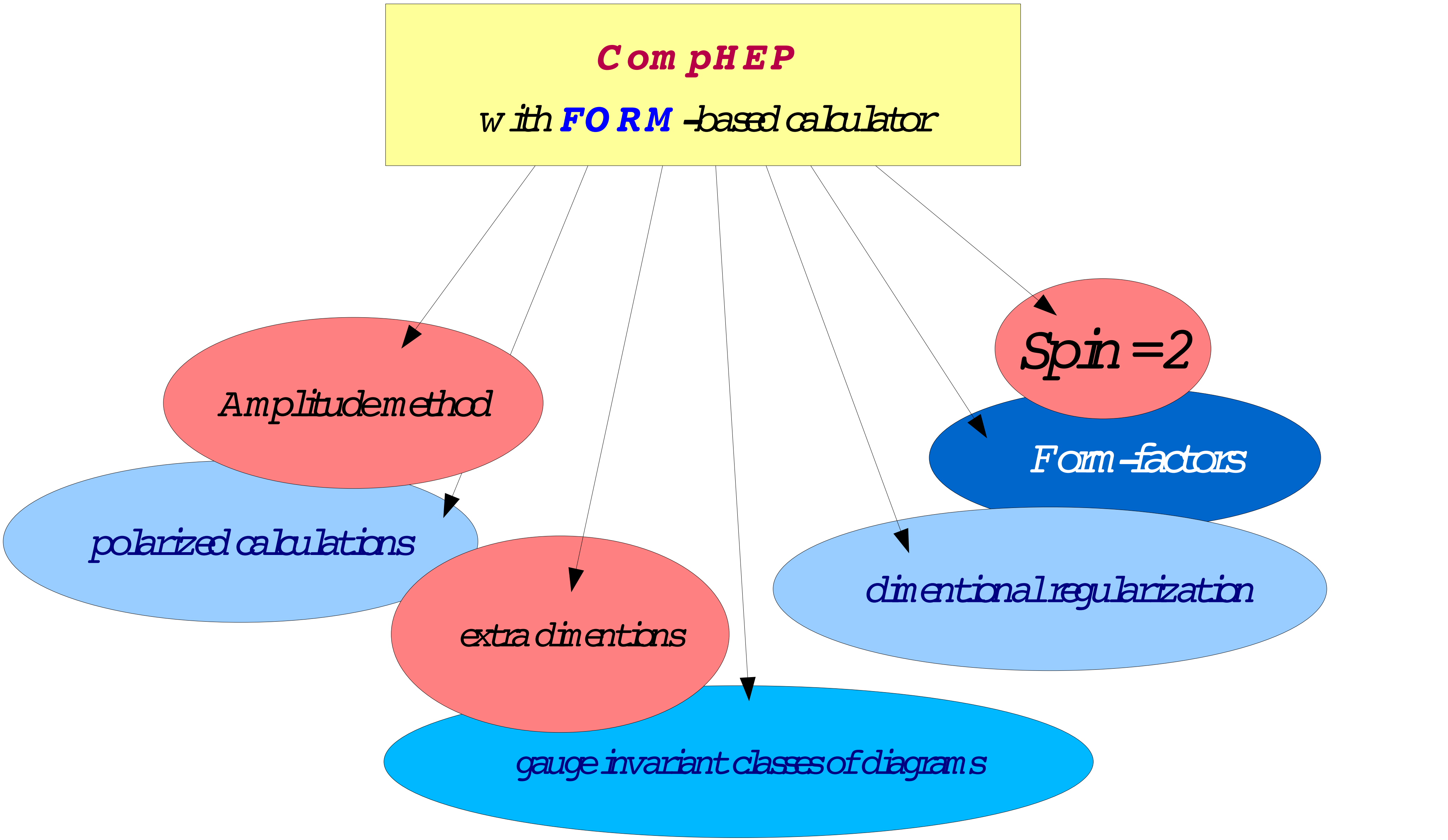
New features of last CompHEP versions (v.4.4 and later)

- Developments in the built-in SUSY models: effective potential in the Higgs sector (by FeynHiggsFast), SUGRA and GMSB models (linked to ISAJET), R-parity violation, model with gravitino and sgoldstino
- Effective field theory for MSSM with explicit CP-violation in the Higgs sector
- Reduction of a number of partonic subprocesses (“hash models” _SM _ud, _SM _qQ with u#, d#)
- New CompHEP-PYTHIA interface compatible with the detector simulation packages SIMDET(NLC), OSCAR(CMS), ATHENA(ATLAS) and D0(Tevatron) Run II software.

- Symblic and numerical batch modes for calculations with parallel processors (compatible with PBS and LSF)
- “ Colliding beams option” -a possibility to introduce arbitrary initial states with the following assignement of parton distribution functions to them

- FORM 3 based symbolic calculator

New features of parallel version of CompHEP, based on FORM language



Conclusions

Why CompHEP is an optimal tool for collider phenomenology beyond the SM:

It is automated and has a developed user interface

- LanHEP generates Feynman rules in CompHEP format from the Lagrangian in coordinate space
- Once the Feynman rules are defined, any (up to 6-body) final state can be calculated at complete tree level set of diagrams. Spin correlations and irreducible backgrounds are included.

Experimentalists are familiar with it

- The package generates unweighted events
- Interfaced to PYTHIA and HERWIG for showering and hadronization.
- Interfaced to full detector simulation packages ('mass production' can start from HEP CW Ntuples directly)
- Optimized and tested for simulation of large event samples at LHC, ILC and Tevatron, corresponding to realistic luminosities (10 inv. fb ⇔ up to 10 million events)