"Tell me that you have found no sign of New Physics again, I dare you. I double dare you. Tell me one more goddamn time!"

Precision Predictions for BSM Models at the ILC

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3. Challenge # 2: Inclusion of best SM Prediction
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Motivation

Why should we care for predictions in concrete (UV-complete) BSM models?

EFTs have many virtues!

But they also have many (un?)known short-comings:

- all BSM physics is assumed to be very heavy,
  out of the direct reach of current/future colliders
  (Not my favorite future physics scenario . . .)
- if one finds large effects in the EFT predictions,
  it is not clear whether this can be reproduced by any real model
- EFTs as such leave unclear to what underlying real model
  a certain effect corresponds
  $\Rightarrow$ this requires a "model by model" prediction for the EFT
- . . .

Let us assume that we do see a deviation from the SM

What do we learn from that?
How do we learn something from that?

⇒ We have to compare the observed deviation with predicted deviations

⇒ Preferrably with the predicted deviations in a concrete models

⇒ We want to learn which physics is responsible for the deviations

Needed:

– sufficiently precise predictions in BSM model
– . . . including uncertainty estimates
– Analysis of patterns of deviations?!

– Precise predictions in the ILC environment
– Inclusion of best SM prediction crucial
– Parameter scans possible?

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– Precise predictions in the ILC environment ⇐ focus
– Inclusion of best SM prediction crucial ⇐ focus
– Parameter scans possible? ⇐ focus

Challenge # 1: Precision Predictions in the Collider Environment

What I can do?!

What I cannot do!

Are there solutions? Easy solutions?

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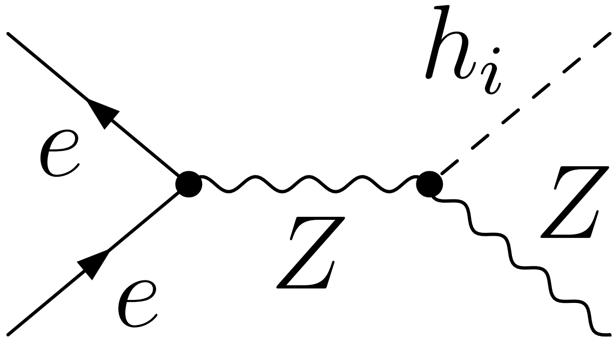
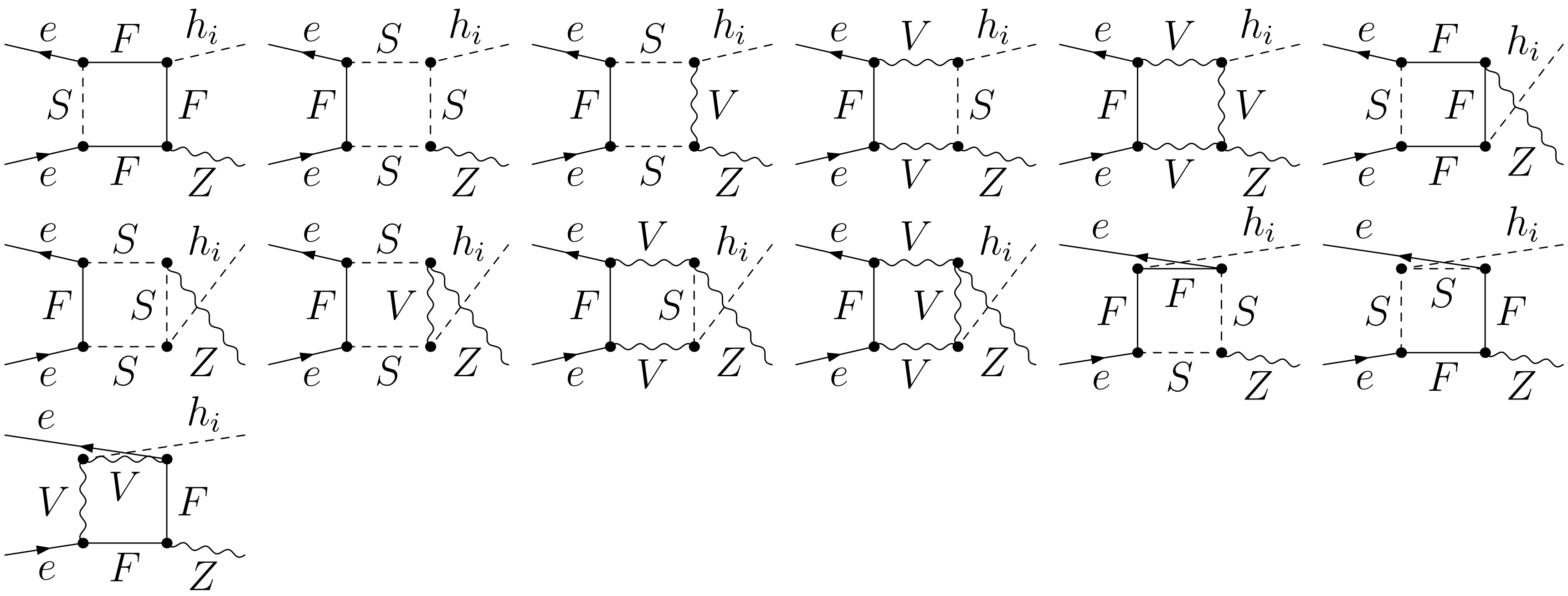
I can do full one-loop calculations:

– BSM particle production
– BSM particle decay
– up to $2 \to 3$
– including QED (and QCD) radiation
  soft, hard, collinear, . . .

$\Rightarrow$ caveats will come in the next two challenges ;-)

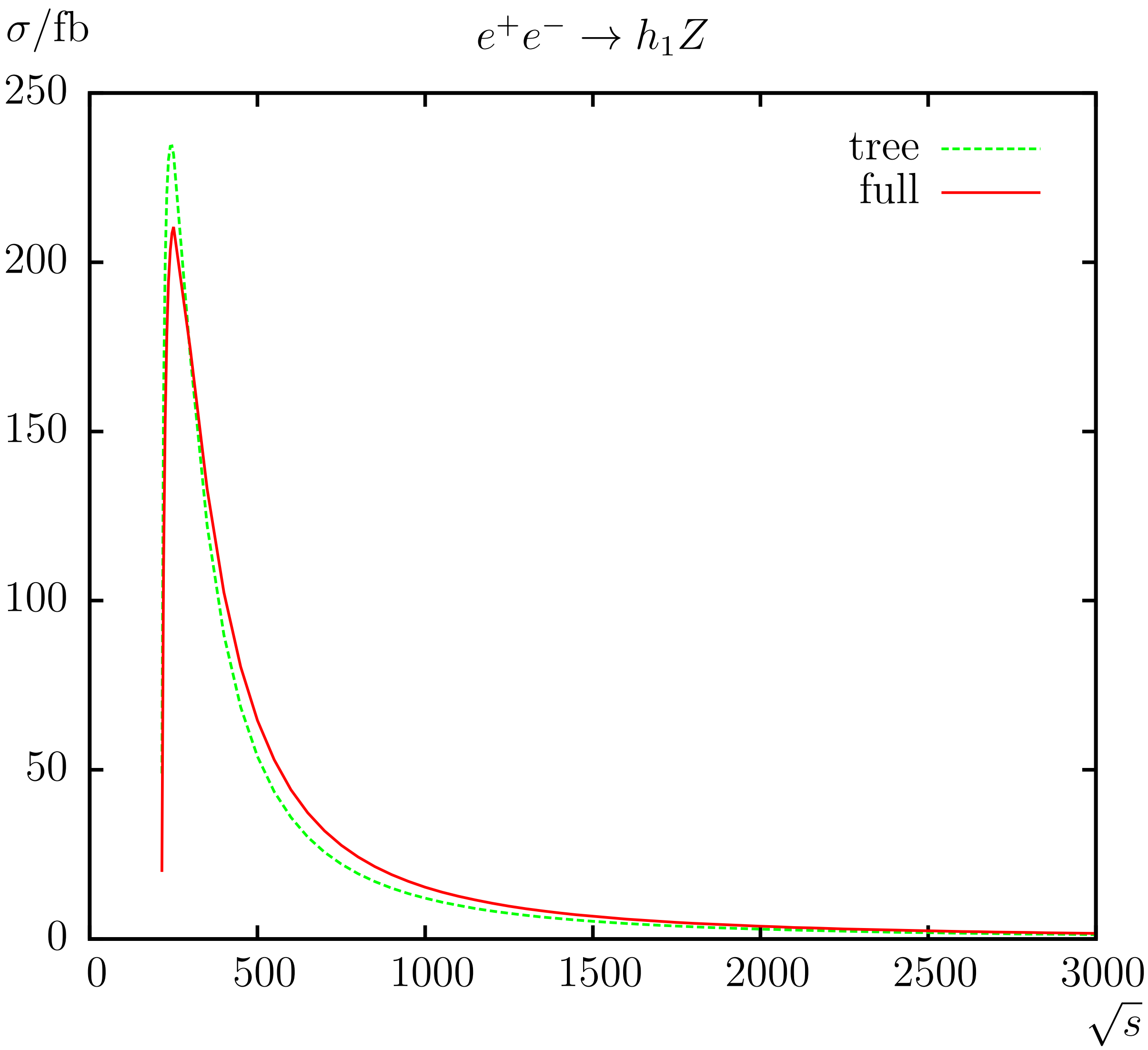
Prime example: $e^+e^- \to h_i Z$ (e.g. in multi-Higgs models/MSSM):





$\to$ plust QED ISR etc. in $\mathcal{O}(\alpha)$

$e^+e^- \to h_1 Z$ in the complex MSSM at full one-loop: [S.H., C. Schappacher '15]



$\Rightarrow$ loop corrections crucial

What I cannot do:

but I guess Whizard et al. can do at least in the SM . . .
$\Rightarrow$ so I am here to learn/search cooperation/collaboration :-)

– embed these full one-loop calculations into the ILC environment

– include higher-order QED

– realistic treatment of particle decays

– realistic Monte Carlo generation of these events

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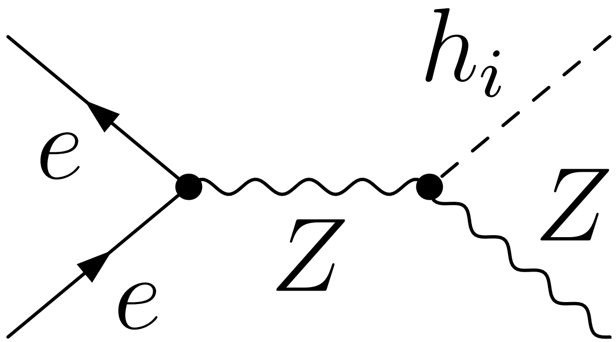
⇒ other challenges may make the life more complicated . . .

Challenge # 2: Inclusion of best SM prediction

Coming back to the prime example, focusing on a h_i at $\sim$ 125 GeV:



Something crucial is missing to be able to find deviations from $e^+e^- \to H_{\text{SM}}Z$

$\Rightarrow$ Inclusion of "best" SM prediction (of the "hard process")

– SM: full one-loop plus $\mathcal{O}(\alpha\alpha_s)$

– SM: Ayres is working on the rest $\Rightarrow$ next talk?!

Q: how can one include beyond one-loop SM corrections?

. . . in an easy/fast way (ready for parameter scans)?

. . . avoiding double counting (SM-like loops in BSM calculation)?

To my knowledge: Only known solved case (in the MSSM): M_W

SM result for M_W:

- full one-loop
- full two-loop
- leading 3-loop via $\Delta\rho$ (not yet n_f^3 ;-)
- leading 4-loop via $\Delta\rho$

Best MSSM result for M_W: *[S.H., W. Hollik, G. Weiglein, L. Zeune '13]*

- full SM result (via fit formel) *[M. Awramik, M. Czakon, A. Freita, G. Weiglein '03]*
- full MSSM one-loop (subtracting H_{SM} contributions)
- all existing two-loop $\Delta\rho$ contributions ($\Delta\rho^{\alpha\alpha_s}$, $\Delta\rho^{\alpha_t^2,\alpha_t\alpha_b,\alpha_b^2}$)

$\Rightarrow$ much more complicated for collider processes!

Challenge # 3: Parameter Scans and Renormalization

BSM models have several problems:

Problem # 1:

we do not know the values of the BSM parameters

⇒ "normal" in the investigation of BSM models: parameter scans
or at least predictions as a function of the relevant parameters

Problem # 2:

External (BSM) particles should be on-shell particles

⇒ OS renormalization of BSM model required

⇒ known cases that no "good" renormalization scheme exists
for the "full" parameter space

⇒ point-by-point decision on RS?!

Example: chargino/neutralino renormalization in the MSSM:

4+2 masses, but only 3 free parameters: M_1, M_2, μ

$\Rightarrow$ OS renormalization for 3 masses: [S.H., C. Schappacher '17]

$$\text{CCN1:}\quad \left(\left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}^-}(p)\right]_{ii}\tilde{\chi}_i^-(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_i^\pm}} = 0 \qquad (i=1,2)\ ,$$

$$\left(\left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}^0}(p)\right]_{11}\tilde{\chi}_1^0(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_1^0}} = 0$$

$\Rightarrow$ Scheme can easily be extended to other variants, e.g.

CCNi $(i=1,2,3,4)$ or CNNijk $(i=1,2;j,k=1,2,3,4)$

$\Rightarrow$ relevant for $|\mu| \approx M_2$ $\Rightarrow$ CCNi breaks down

$\Rightarrow$ Scheme requires a shift of three (neutralino) masses to their OS value:

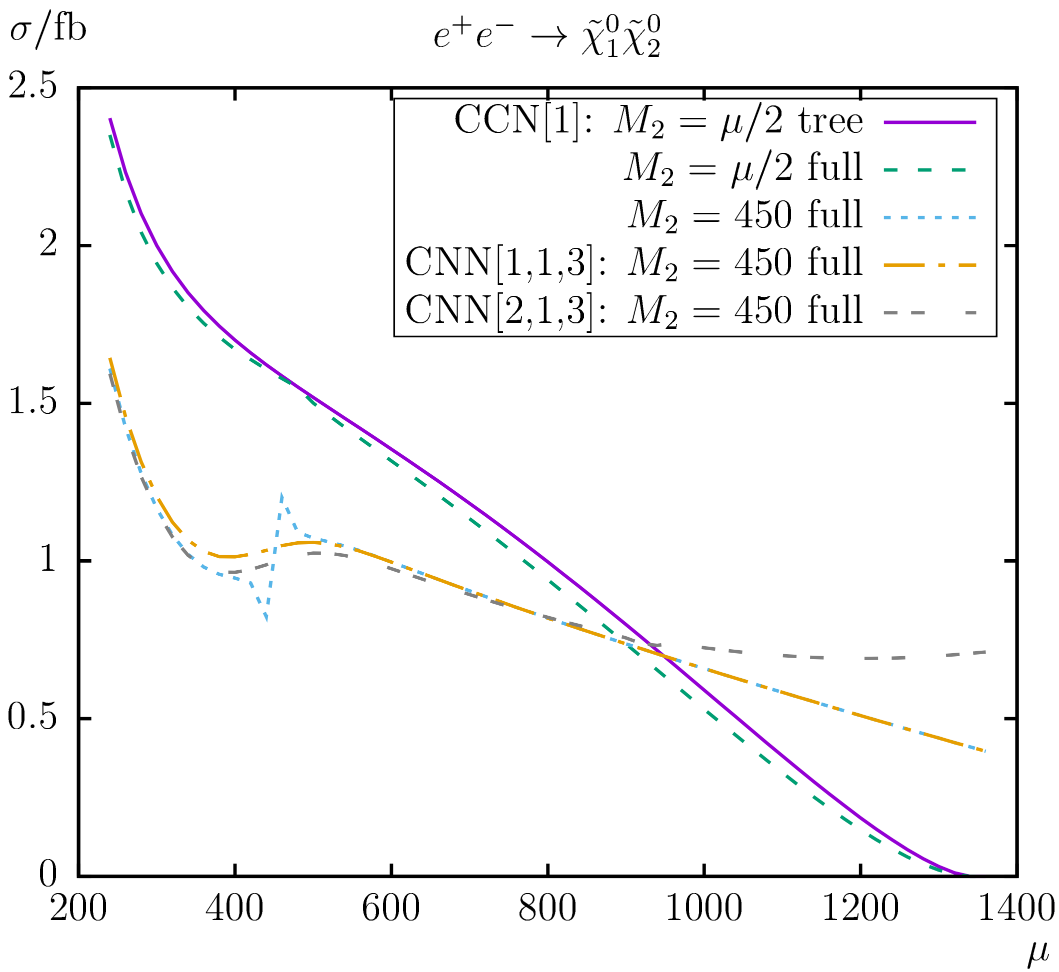
$$\Delta m_{\tilde{\chi}_i^0} = -\frac{1}{2}\text{Re}\Big\{m_{\tilde{\chi}_i^0}\left(\hat{\Sigma}^L_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^R_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0})\right) + \hat{\Sigma}^{SL}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^{SR}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0})\Big\}$$

$$m^{\text{OS}}_{\tilde{\chi}_i^0} = m_{\tilde{\chi}_i^0} + \Delta m_{\tilde{\chi}_i^0}$$

$\Rightarrow$ large (unphysical) shifts possible for wrong RS choice

Example: $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$:

[S.H., C. Schappacher '17]



$\Rightarrow$ CCN1 breaks down for $\mu = M_2$ $\Rightarrow$ other schemes!

In our example:

⇒ CCN1 breaks down for $\mu = M_2$ ⇒ other schemes!

– which other scheme is good in this parameter region?

– does a “best” RS exist?

– how to choose the “best” RS?

– the problem becomes visible shown as a continous function of one parameter!
But how to handle this in a (random) parameter scan?

Needed:

Automated scheme choice that works for single points

⇒ inclusion into codes for “ILC realistic predictions” !

Conclusions

- High precision prediction for SM/BSM processes needed for the detection of BMS physics at the ILC
- Challenge # 1:
  How to include full 1-loop BSM prediction into
  "ILC realistic predictions"?
  Are there solutions? Easy solutions? Also for external BSM particles?
- Challenge # 2:
  Inclusion of "best" SM pred. ⇒ crucial for detection of BSM effects
  Needed in an easy/fast way (ready for parameter scans)
  . . . avoiding double counting (SM-like loops in BSM calculation)
- Challenge # 3:
  OS renormalization of BSM models required
  → known cases that no "good" renormalization scheme exists
  for the "full" parameter space
  Needed: Automated scheme choice that works for single points

  ⇒ inclusion into codes for "ILC realistic predictions"!
- Not covered: uncertainty estimates for BSM predictions


Further Questions?

cMSSM parameters:

Table 2: MSSM default parameters for the numerical investigation; all parameters (except of t_β) are in GeV (calculated masses are rounded to 1 MeV). The values for the trilinear sfermion Higgs couplings, $A_{t,b,\tau}$ are chosen such that charge- and/or color-breaking minima are avoided [76], and $A_{b,\tau}$ are chosen to be real. It should be noted that for the first and second generation of sfermions we chose instead $A_f = 0$, $M_{\tilde{Q},\tilde{U},\tilde{D}} = 1500$ GeV and $M_{\tilde{L},\tilde{E}} = 500$ GeV.

Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
$\mathcal{S}$	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

m_{h_1}	m_{h_2}	m_{h_3}
123.404	288.762	290.588

with $\sqrt{s}$, $M_{H^\pm}$, $\tan\beta$, ϕ_{A_t} varied

– Scenario chosen such that many processes are possible at the same time
– not chosen to maximize loop corrections

Numerical example scenario for $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production:

$\sqrt{s}$	$\tan\beta$	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\|A_t\|$	A_b	A_τ	$\|M_1\|$	M_2	M_3
1000	10	450	500	1500	1500	2000	$\|A_t\|$	$M_{\tilde{L}}$	$\mu/4$	$\mu/2$	2000

	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$
tree	212.760	469.874	110.434	213.002	455.162	469.226
CCN1	212.760	469.874	110.434	212.850	455.195	469.560

Parameters varied: $\sqrt{s}$, μ, $M_{\tilde{L},\tilde{E}}$, $\tan\beta$, φ_{M_1}, ϕ_{A_t}

– in agreement with exp. data

– opens up many (all) production channels

– relevant parameters varied

– . . .

$\Rightarrow$ show some relevant examples