Theoretical Impact of Results from Z- and WW-Threshold Running

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1. Introduction
2. Theoretical predictions for precision observables and m_h
3. Numerical analysis of different scenarios
4. Indirect determination of m_h
5. B physics
6. Conclusions

LC at low energies: high precision
high luminosity $\left(\sim 10^9\, Z/\text{year}\right)$ } **GigaZ**

– at the Z peak (one year): 6×10^8 b quarks
– at the Z peak (via A_{LR}): $\Delta \sin^2\theta_{\text{eff}}$
– at the 2 W threshold (one year): ΔM_W

B physics: $\mathcal{CP}$ violation, rare decays
B spectroscopy, polarized b quarks

Precision observables: Stringent test of theory
$\Rightarrow$ Sensitivity to new physics?

Expected accuracy:

	LEP2/Tev.	LHC	LC	GigaZ
M_W	30 MeV	15 MeV	15 MeV	6 MeV
$\sin^2\theta_{\text{eff}}$	0.00018	0.00018	0.00018	0.00001
m_t	3 GeV	2 GeV	0.2 GeV	0.2 GeV
m_h	?	0.2 GeV	0.05 GeV	0.05 GeV
M_{SUSY}	?	10%	0.1%	0.1%

What can we learn from improved accuracy in M_W and $\sin^2\theta_{\text{eff}}$?

What can we learn from 6×10^8 b quarks?

observables and m_h

EW Precision data:		Theory:
$\Delta\rho, \Delta r, M_W, \sin^2\theta_{\rm eff} \ldots$	$\leftrightarrow$	SM, MSSM, ...

Test of theory, sensitivity to unknown sectors

$\Rightarrow$ Precision observable M_W, $\sin^2\theta_{\rm eff}$:

1.) Δr determines the relation between M_W and M_Z, G_μ, α:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu} \left(\frac{1}{1 - \Delta r}\right)$$

$\Rightarrow$ theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$

SM prediction for Δr, one-loop:
[A. Sirlin '80] [W. Marciano, A. Sirlin '80]

$\Delta r_{\text{1-loop}}$: m_t enters via $\sim m_t^2$, m_h via $\sim \log\left(\frac{m_h^2}{M_W^2}\right)$

2.) Effective mixing angle:

$$\sin^2\theta_{\rm eff} = \frac{1}{4\,|Q_f|}\left(1 - \frac{\text{Re}\,g_V^f}{\text{Re}\,g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f + \Delta g_V^f, \quad g_A^f \to g_A^f + \Delta g_A^f$$

- SM: leading terms up to $\mathcal{O}(G_\mu^2 m_t^4)$
  [J. van der Bij, F. Hoogeveen '87]
  [R. Barbieri, M. Beccaria, P. Ciafaloni, G. Curci, A. Vicere '92]
  [J. Fleischer, O.V. Tarasov, F. Jegerlehner '93]
- SM: QCD corrections up to $\mathcal{O}(\alpha\alpha_s^2)$
  [A. Djouadi, C. Verzegnassi '87]
  [K. Chetyrkin, J. Kühn, M. Steinhauser '95]
  [L. Avdeev, J. Fleischer, S. Mikhailov, O. Tarasov '95]
- MSSM: full one-loop corrections to Δr
  [P. Chankowski, A. Dabelstein, W. Hollik, W. Mösle, S. Pokorski, J. Rosiek '94] [D. Garcia, J. Solà '94]
- MSSM: Z-boson observables, one-loop
  [D. Garcia, R. Jiménez, J. Solà '95]
  [D. Garcia, J. Solà '95]
  [A. Dabelstein, W. Hollik, W. Mösle '95]
  [P. Chankowski, S. Pokorski '96]
- MSSM: leading $\mathcal{O}(\alpha\alpha_s)$ corrections
  [A. Djouadi, P. Gambino, S. H., W. Hollik, C. Jünger, G. Weiglein '97] [S. H, W. Hollik, G. Weiglein '98]

Not included: SM: next-to-leading m_t^2 terms
($\to$ not available for MSSM)
[G. Degrassi, P. Gambino, A. Vicini '96]
[G. Degrassi, P. Gambino, A. Sirlin '97]

Todays theoretical uncertainty:

$$\Delta M_W^{\text{theo}} \approx 4 \text{ MeV}$$

$$\Delta \sin^2\theta_{\text{eff}}^{\text{theo}} \approx 0.00004$$

SM: m_h is a free parameter

MSSM: m_h is calculable in terms of other parameters

Dominant corrections to m_h from $t-\tilde{t}$-sector

Leading one-loop term:

$$\sim \quad m_t^4 \log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right)$$

$$\approx \quad m_t^4 \log\left(\frac{(M_{\text{SUSY}}^2 + m_t^2)^2 - m_t^2\left(M_t^{LR}\right)^2}{m_t^4}\right)$$

$\tilde{t}$ -mass-matrix:

$$M_{\tilde{t}}^2 = \begin{pmatrix} M_{\text{SUSY}}^2 + m_t^2 + DT_1 & m_t M_t^{LR} \\ m_t M_t^{LR} & M_{\text{SUSY}}^2 + m_t^2 + DT_2 \end{pmatrix}$$

$\rightarrow$ one-loop corrections of O(100%)

$\Rightarrow$ two-loop calculation necessary

Used in this analysis:

Diagrammatic 2-loop result for m_h up to $\mathcal{O}(\alpha\alpha_s)$

[*S. H., W. Hollik, G. Weiglein '98, '99*] free parameters: m_t, m_h

$\to$ direct contribution via loop effects

$\Rightarrow$ Prediction for precision observables
M_W, $\sin^2\theta_{\text{eff}}$

MSSM:

free parameters: $m_t, M_{\text{SUSY}}, M_t^{LR}$

$\to$ direct contribution via loop effects

$\to$ indirect effect via contribution to m_h

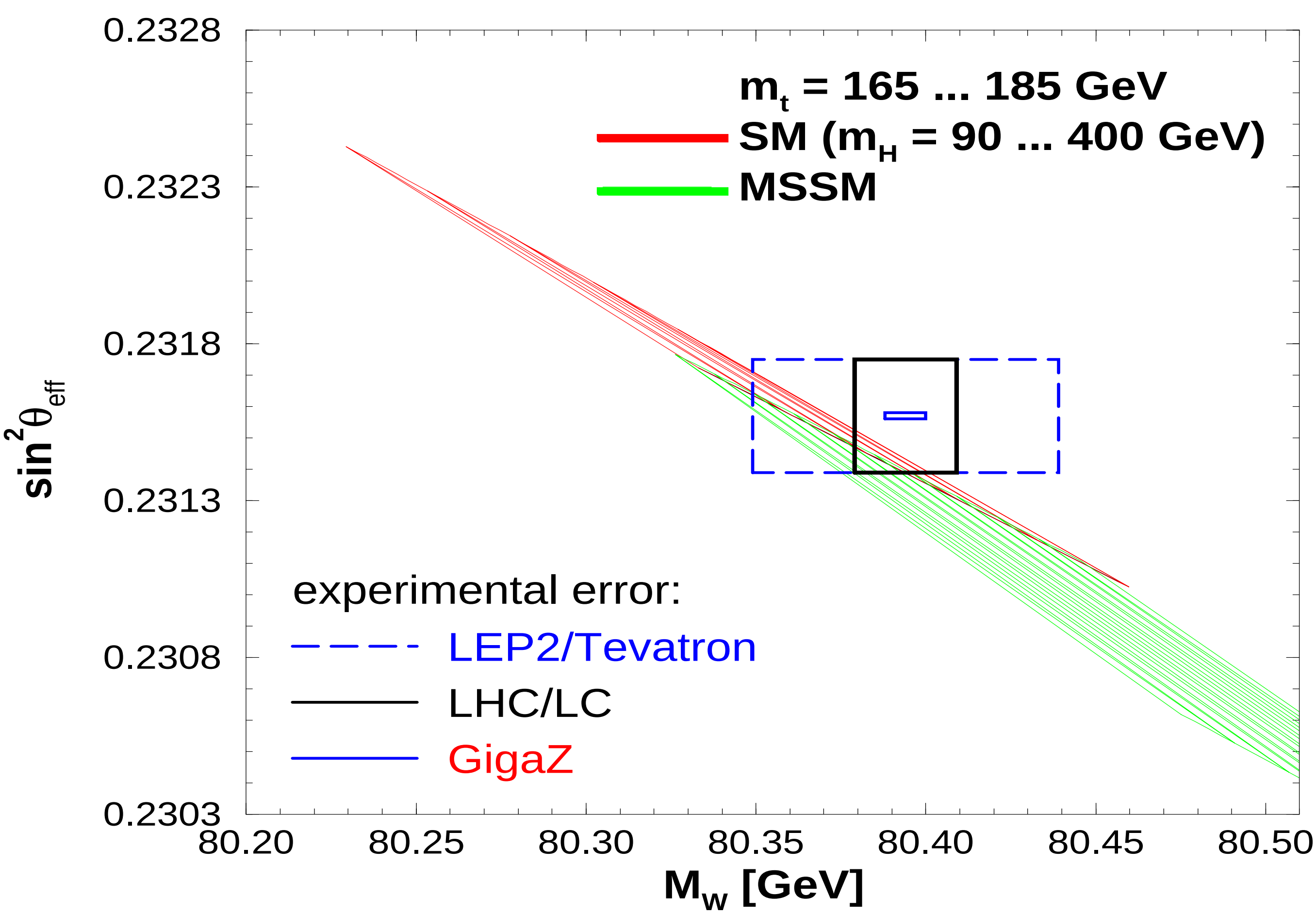
$\Rightarrow$ Prediction for precision observables
M_W, $\sin^2\theta_{\text{eff}}$

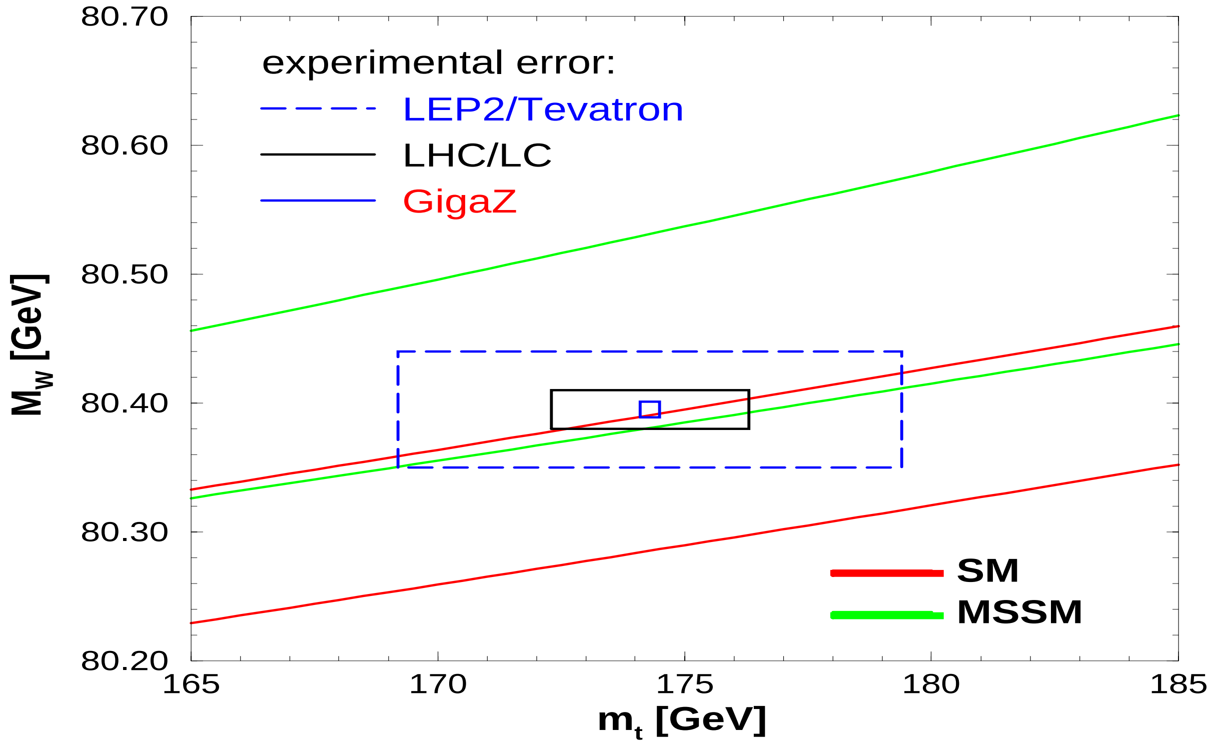
Current prediction for M_W and $\sin^2\theta_{\rm eff}$ in the SM and the MSSM:

Comparison of experimental precisions at LEP/Tevatron, LHC/LC and GigaZ

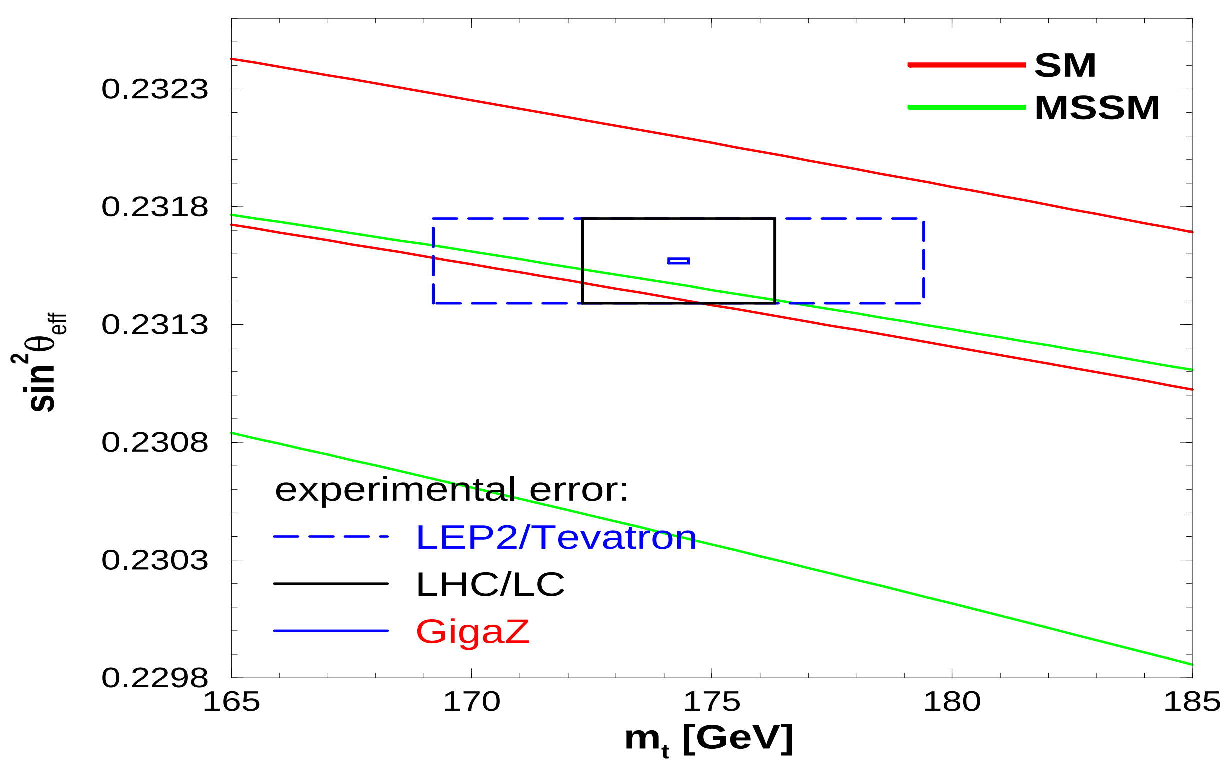
Here: no additional information assumed for input parameters in the theoretical predictions (m_t, $M_{\rm SUSY}$, ...)

Prediction for M_W, $\sin^2\theta_{\rm eff}$ in SM and MSSM:





Prediction for $\sin^2\theta_{\rm eff}$ in the SM and the MSSM:



accuracy LEP/Tevatron $\to$ LHC/LC $\to$ GigaZ:
$\Rightarrow$ Very sensitive test of theory

If experimental values of M_W, $\sin^2\theta_{\text{eff}}$ stay in current 1-σ bounds:
$\Rightarrow$ Hard to distinguish between SM, MSSM from precision data
But sensitivity to deviations from both SM and MSSM

Important:
Need to have theoretical uncertainties under control
– from unknown higher-order corrections
– from input parameters: $\alpha(M_Z)$, α_s, ...

In the following:
Assume also information from LHC/LC on input parameters in theoretical predictions:
m_t, m_h, M_{SUSY}, ...

$\Rightarrow$ Discuss different scenarios

→ Higgs found with $m_h \leq m_h^{\text{max,MSSM}}$

→ SUSY particles found

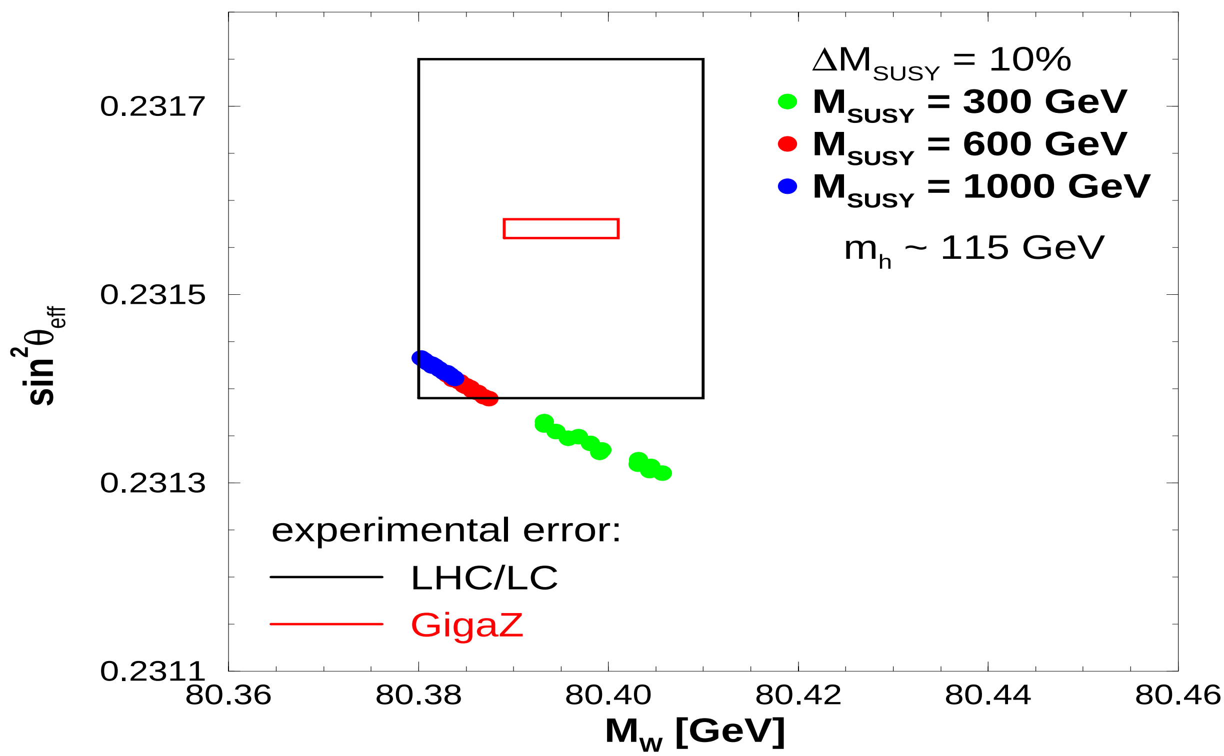
Assume:

$\Delta M_{\text{SUSY}} = 10\%$ at LHC

$\Delta m_t = 0.2$ GeV at LC

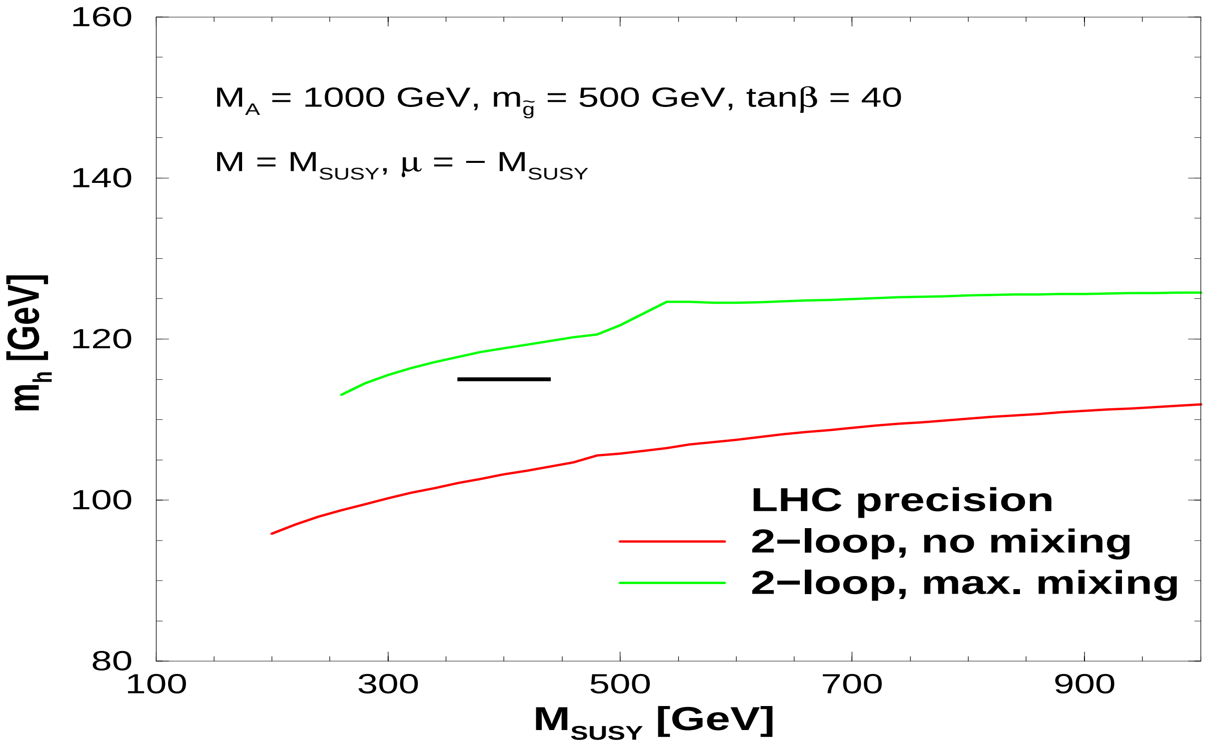
$\Delta m_h = 0.05$ GeV at LC

Prediction for M_W, $\sin^2\theta_{\text{eff}}$ in MSSM at LHC/LC and GigaZ , Higgs mass constraint included:

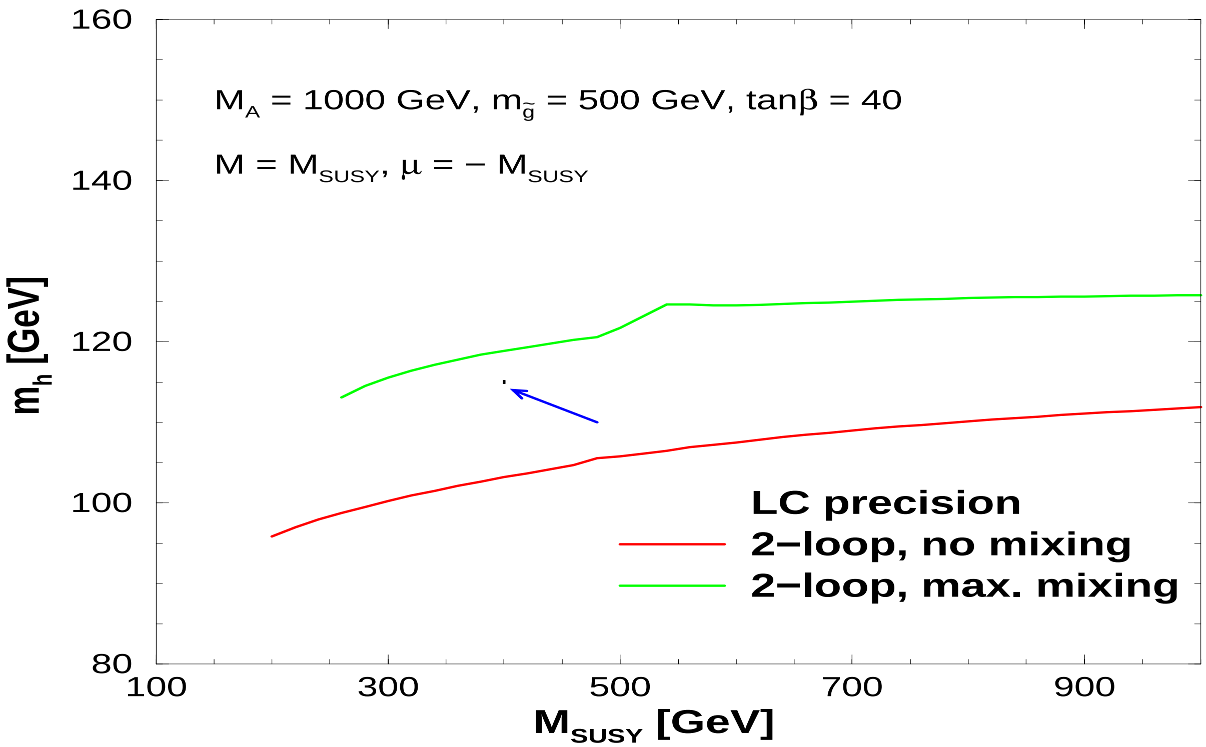


GigaZ precision ⇒ sensitivity to M_{SUSY}

Access to mixing: m_h measurement
(assume: large M_A, $\tan\beta$,
$m_h = 115$ GeV, $M_{\text{SUSY}} = 400$ GeV) → F



M_A = 1000 GeV, $m_{\tilde{g}}$ = 500 GeV, tanβ = 40
M = M_{SUSY}, μ = − M_{SUSY}
LHC precision
2−loop, no mixing
2−loop, max. mixing
m_h [GeV]
M_{SUSY} [GeV]
160
140
120
100
80
100
300
500
700
900



M_A = 1000 GeV, $m_{\tilde{g}}$ = 500 GeV, tanβ = 40
M = M_{SUSY}, μ = − M_{SUSY}
LC precision
2−loop, no mixing
2−loop, max. mixing
m_h [GeV]
M_{SUSY} [GeV]
160
140
120
100
80
100
300
500
700
900

→ Higgs found with $m_h > m_h^{\text{max,MSSM}}$
→ no SUSY particles found at LHC, LC
⇒ MSSM excluded

Assume:

$\Delta m_t = 2$ GeV, $\Delta m_h = 0.2$ GeV at LHC
$\Delta m_t = 0.2$ GeV, $\Delta m_h = 0.05$ GeV at LC

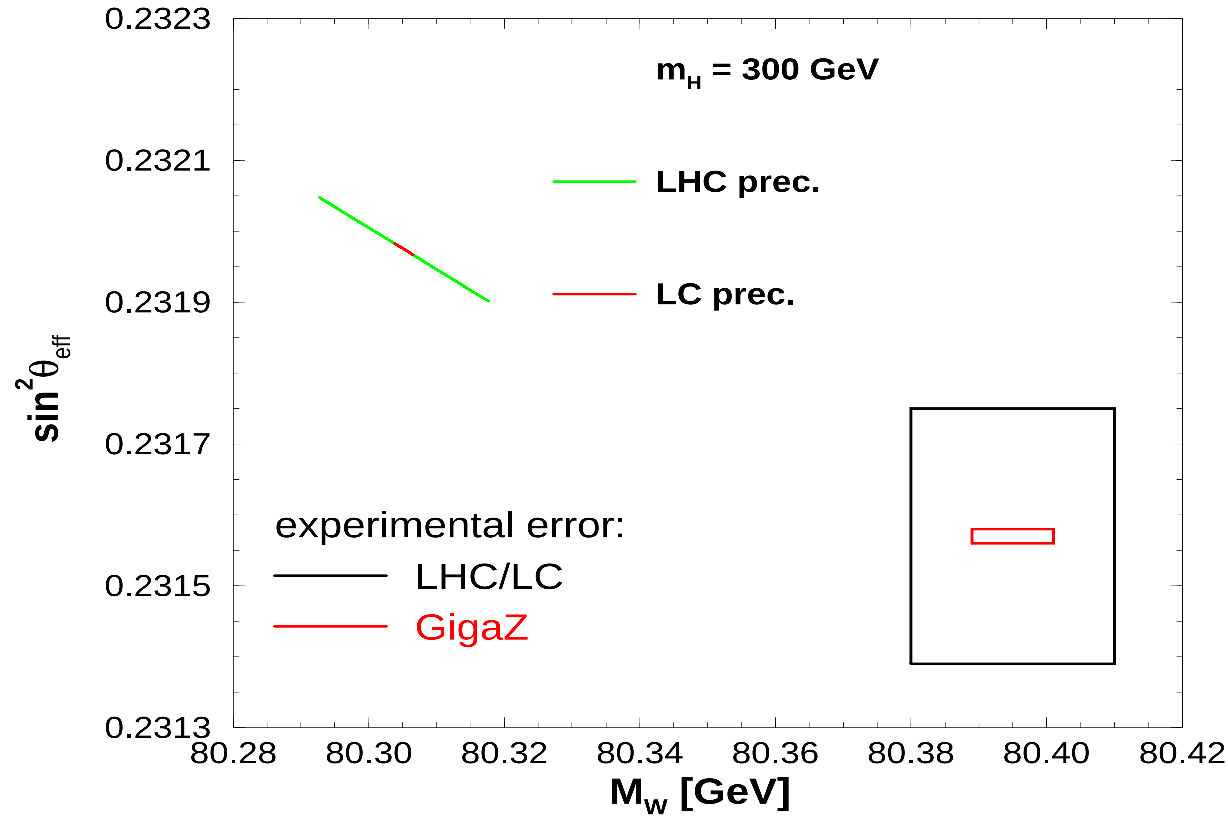
Example: $m_h^{\text{exp}} = 300$ GeV

→ F

⇒ $m_h = 300$ GeV disfavored by current experimental data

⇒ Consistency check strongly improved by 'GigaZ precision'

⇒ precision not spoiled for $\delta(\Delta\alpha) = 0.000075$ ($\to \Delta \sin^2\theta_{\text{eff}} \sim 0.00002$)



Uncertainty from $\Delta\alpha$:

Variation of $\Delta\alpha$ by ± 0.00017

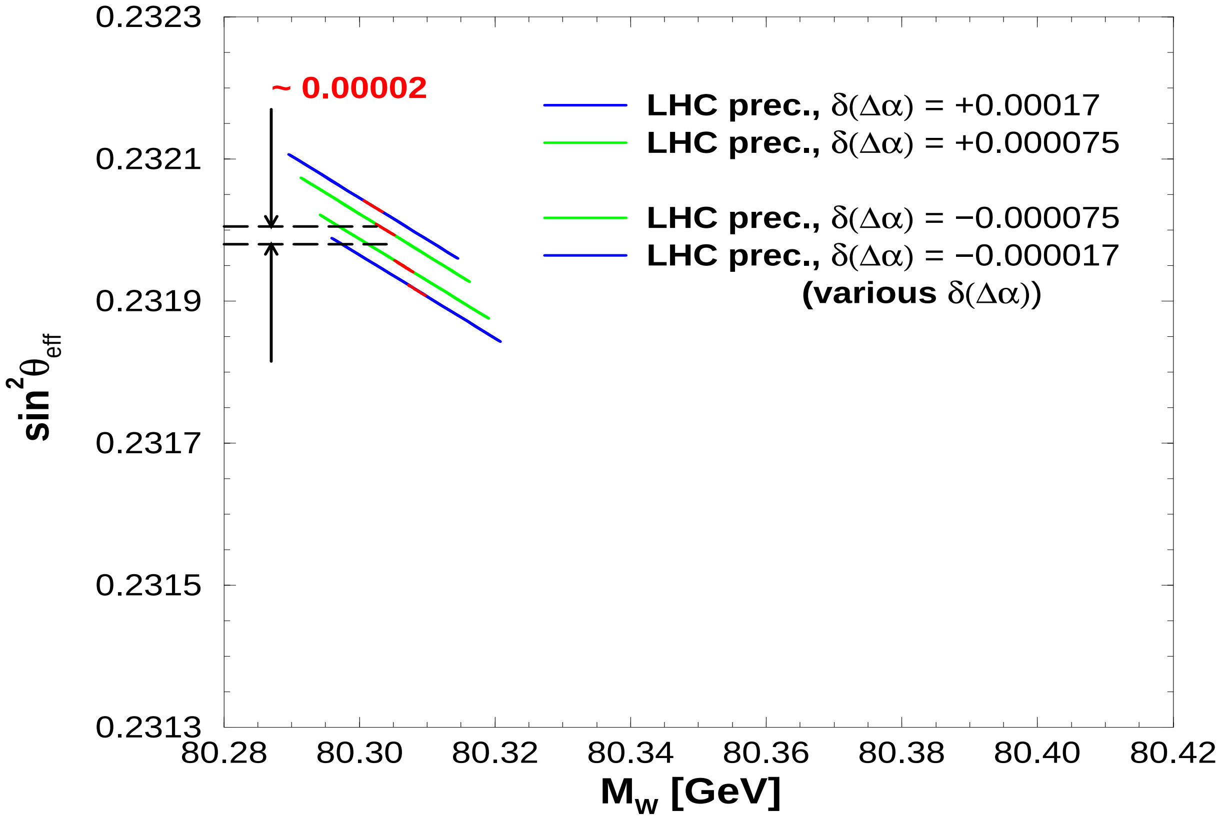
[*J. Kühn, M. Steinhauser '98*]

[*M. Davier, A. Höcker '98*]

Variation of $\Delta\alpha$ by ± 0.000075

(optimistic future estimation, obtainable from DAΦNE, BEPC, Novosibirsk) [*F. Jegerlehner*]

$\Rightarrow$ reduction of experimental error of $\Delta\alpha$ very important for stringent consistency check



~ 0.00002
LHC prec., δ(Δα) = +0.00017
LHC prec., δ(Δα) = +0.000075
LHC prec., δ(Δα) = −0.000075
LHC prec., δ(Δα) = −0.000017
(various δ(Δα))
0.2323
0.2321
0.2319
0.2317
0.2315
0.2313
80.28
80.30
80.32
80.34
80.36
80.38
80.40
80.42
M_W [GeV]
sin²θ_eff

Test via extra contribution to $\Delta\rho$

Two examples:

Model 1: Strong interacting Higgs bosons

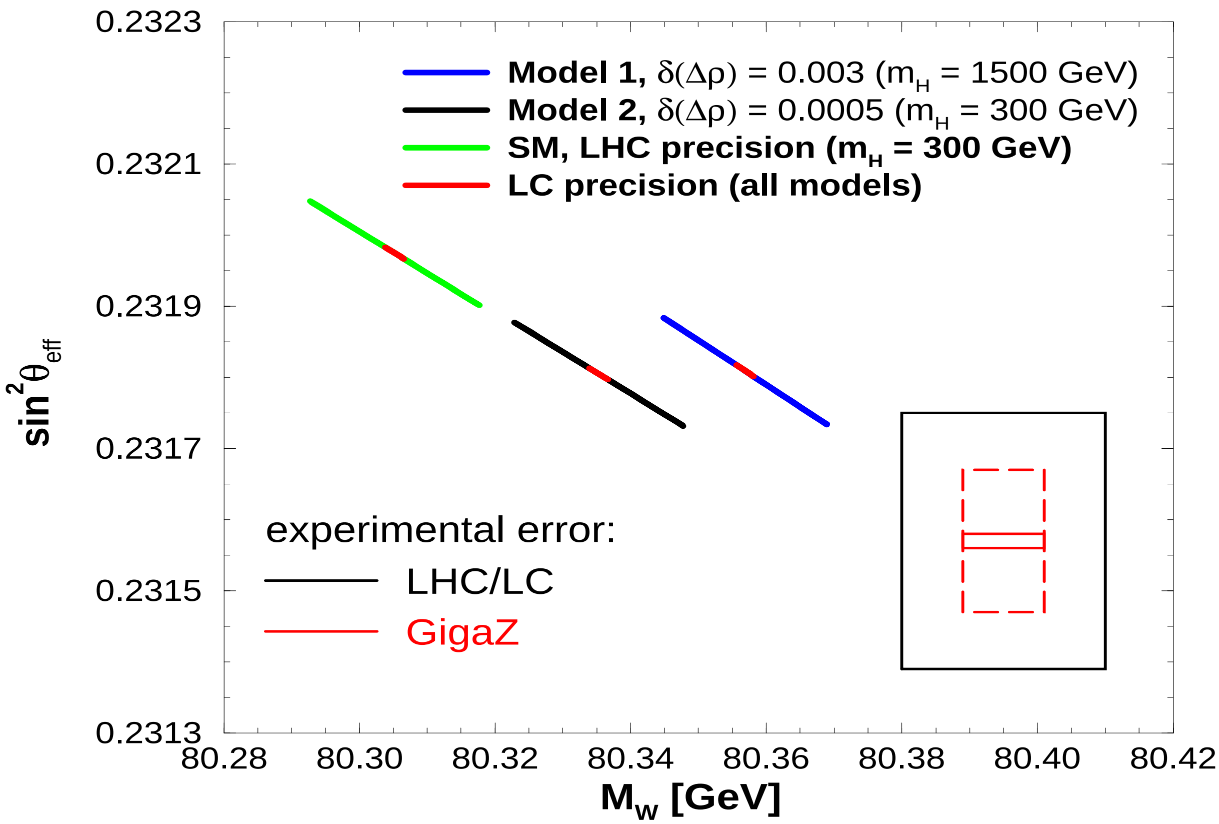
$\to M_H \gtrsim 900$ GeV (plot: $M_H = 1500$ GeV)

$\Delta\rho^{extra} = \mathcal{O}(3 \times 10^{-3})$

Model 2: Extra dimensions at low energies

[*M. Masip, A. Pomarol '99*]

$\Lambda = 2.5$ TeV $\Rightarrow \Delta\rho^{extra} = \mathcal{O}(5 \times 10^{-4})$



$\Rightarrow$ Test possible with improved accuracy

direct $\longleftrightarrow$ indirect
mass determination

$\rightarrow$ stringent test of EWSB mechanism

$\Rightarrow$ Determination of $\Delta M_H/M_H$ via precision observable M_W or via $\sin^2\theta_{\rm eff}$:

$$
\begin{aligned}
M_W &= f_w(\log(M_H), \Delta\alpha, \ldots) \\
\sin^2\theta_{\rm eff} &= f_s(\log(M_H), \Delta\alpha, \ldots)
\end{aligned}
$$

Inversion:

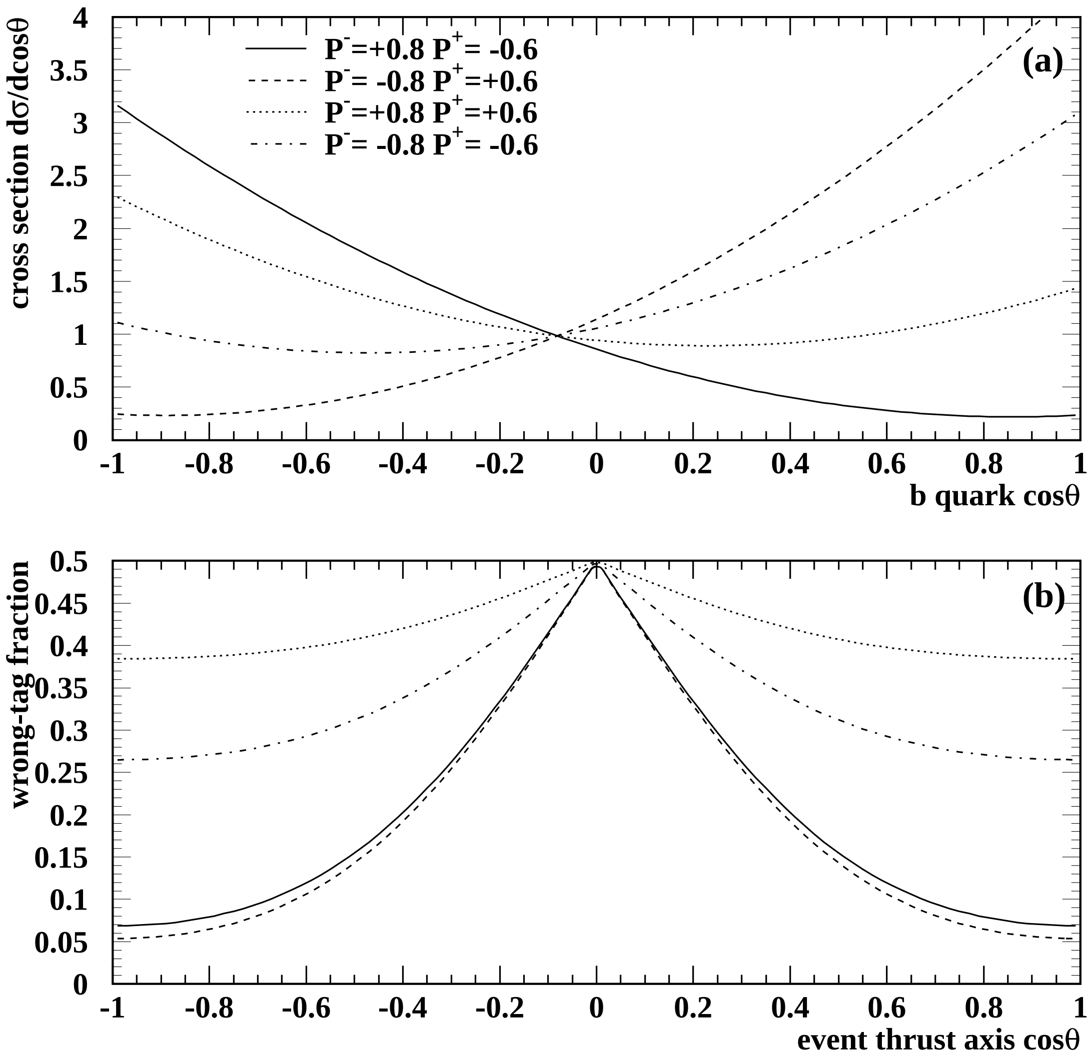
$$
\begin{aligned}
\log(M_H) &= f'_w(M_W, \Delta\alpha, \ldots) \\
\log(M_H) &= f'_s(\sin^2\theta_{\rm eff}, \Delta\alpha, \ldots)
\end{aligned}
$$

collider	M_W	$\sin^2\theta_{\rm eff}$
LEP2/Tevatron	78 %	41 %
LHC	36 %	39 %
LC	28 %	37 %
GigaZ ($\delta(\Delta\alpha) = 17\ 10^{-5}$)	13 %	12 %
GigaZ ($\delta(\Delta\alpha) = 7.5\ 10^{-5}$)	12 %	**6%**

Relevant parameters:

	LHCb	GigaZ
# b per year	$10^{12} - 10^{13}$	6×10^8
signal/background	0.5 %	15 %
Tagging efficiency	6 %	45 %

$\rightarrow$ use fb asymmetry with pol. beams:



Neutral B meson decays to $\mathcal{CP}$ Eigenstates f

$$a_{\mathcal{CP}}(B_q \to f; t) = \frac{\Gamma(B_q(t) \to f) - \Gamma(\overline{B}_q(t) \to f)}{\Gamma(B_q(t) \to f) + \Gamma(\overline{B}_q(t) \to f)}$$
$$= a_{\cos} \cos(\Delta M_q t) + a_{\sin} \sin(\Delta M_q t)$$

Unitarity triangle: α, β, γ, $\delta\gamma$

1. $B \to J/\Psi\, K_s \;\Rightarrow \beta$
   GigaZ: $\sim$ 1900 events $\Rightarrow \delta(\sin 2\beta) = 0.04$
   LHCb: $\delta(\sin 2\beta) = 0.01 - 0.02$
   $\Rightarrow$ LHCb wins due to statistics

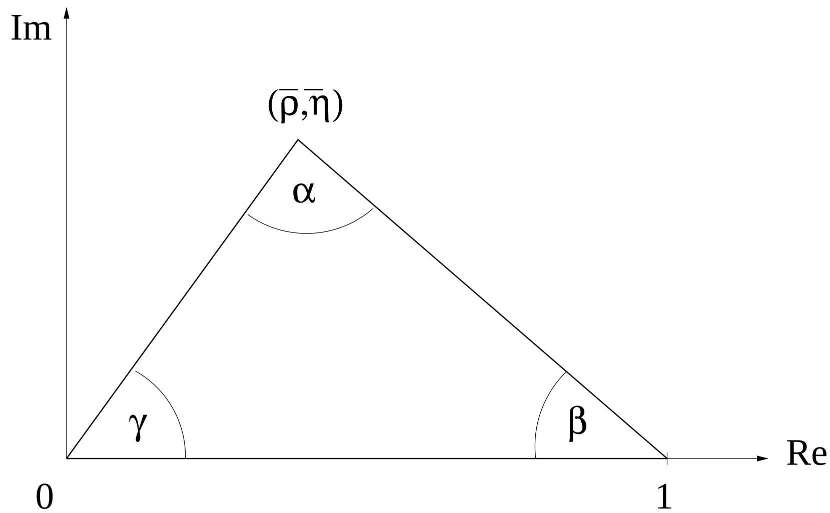
2. $B_d \to \pi\pi \;\Rightarrow \alpha$
   Penguin problem
   $\Rightarrow B \to \pi^+\pi^-, B \to \pi^0\pi^0, B^+ \to \pi^+\pi^0$ needed
   $B \to \pi^0\pi^0$ hardly accessible at LHCb
   $\Rightarrow$ GigaZ competitive:
   $\delta(a_{\sin}) = 0.05, \delta(a_{\cos}) = 0.07 \Rightarrow \sigma_\alpha$

3. $B_{...} \to \ldots \;\Rightarrow \gamma, \delta\gamma$
   B_s decay: $\Rightarrow$ LHCb wins due to statistics
   $B_d \to D\, K^*$: $\sigma_\gamma = 4° - 14°$
   $\Rightarrow$ GigaZ maybe competitive
   $B_s \to J/\Psi\Phi$: $\sigma_{\delta\gamma} = (0.8 - 1.4) \times 10^{-2}$

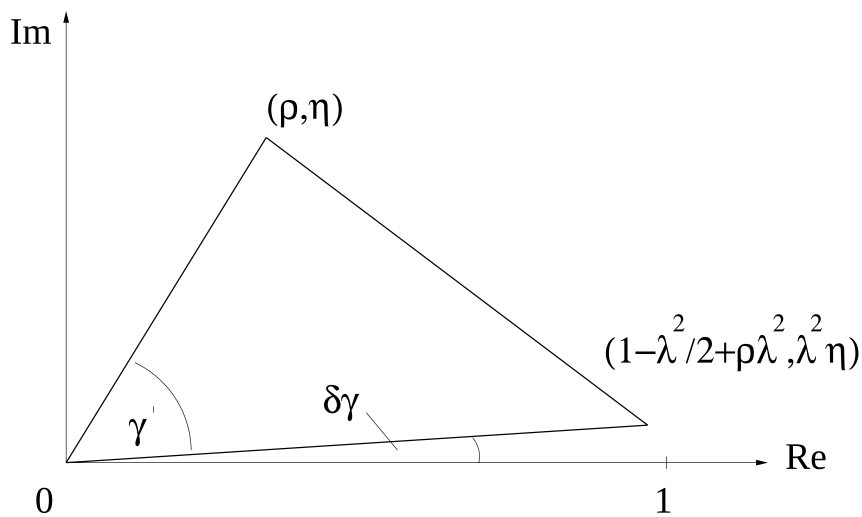
Unitarity Triangle Reminder

There are two unitarity triangles:

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$



$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0$$



Advantage of LC over hadron colliders:
cleaner environment $\Rightarrow$ better efficiency

mode	BR	# events
$B \to K \sum \nu\bar{\nu}$	6×10^{-6}	2880
$B \to K^* \sum \nu\bar{\nu}$	2×10^{-5}	9600
$\Lambda_b \to \Lambda\gamma$	4×10^{-5}	1920
$\Lambda_b \to \Lambda l^+ l^-$	2×10^{-6}	96

$\Rightarrow$ Enhancement of rare decays: clear signal for 'new physics'

B physics: hadron spectroscopy

- At GigaZ enough statistics for exclusive reconstruction
- Orbitally and radially excited B_u, B_d, B_s
- Bottom baryons
- Doubly heavy systems

Even with unpolarized beams:

Z decay produces highly polarized b quarks:

$$\mathcal{P}_b = \frac{2\, g_A g_V}{g_V^2 + g_A^2} \approx 95\%$$

$\to$ hadronization of a polarized b quark

$b \to B_d^{(*)}, b \to B_s^{(*)}$: polarization is washed out

$b \to \Lambda_b$ (general: $b \to$ bottom baryon) :

$\Rightarrow$ polarization effects should survive

$\to$ study of b hadronization

$\to$ study of polarized b baryon decays

– Spin structure of $\Lambda_b \to \Lambda_c$

– Spin structure of the $\Lambda_b \to \Lambda$ FCNC decay

- **GigaZ:** $\rightarrow \Delta M_W = 6$ MeV,
  $\Delta \sin^2\theta_{\text{eff}} = 0.00001$
  6×10^8 b quarks

- Analysis: $M_W, \sin^2\theta_{\text{eff}}$ calculated within SM/MSSM from $m_t, M_{\text{SUSY}}, \ldots$
  $\rightarrow$ comparison with direct measurement

- LC gives precise input ($m_t, M_{\text{SUSY}}, \ldots$)
  Low energy run: high accuracy for precision observables
  $\Rightarrow$ MSSM: strong consistency check:
  $\rightarrow M_{\text{SUSY}}, M_t^{LR}$
  $\Rightarrow$ SM: strong consistency check: $\rightarrow m_h$
  reduction of $\delta(\Delta\alpha) \gtrsim 0.0001$ desirable
  $\Rightarrow$ Test for new physics (via $\Delta\rho$) possible

- Improved precision of $M_W, \sin^2\theta_{\text{eff}}$
  $\Rightarrow$ $\Delta M_H/M_H \leq 6\%$ (for $\delta(\Delta\alpha) = 0.000075$)

- B physics:
  – α, γ : GigaZ is competitive with LHCb
  – low energy run interesting for rare decays, b spectroscopy, polarized b quarks

Via precision observables obtained in a low energy run with GigaZ nearly any assumed model can be tested for small deviations!