❽ Precision measurements at lower energies

- Introduction
- Measurements of electroweak quantities on the Z
- Measurement of m_{W}
- Theoretical aspects
- Study of CP-violation in the B-sector

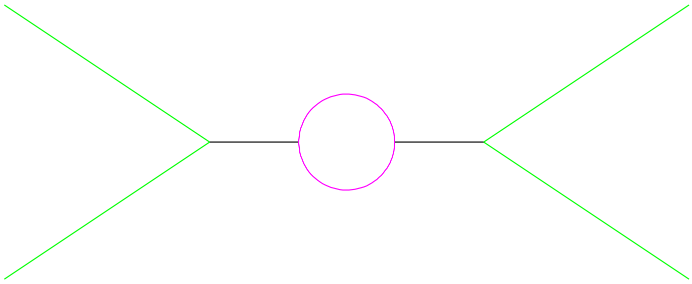
Introduction

Interest in precision measurements

Test consistency of the theory on the loop level

Two types of loop corrections:

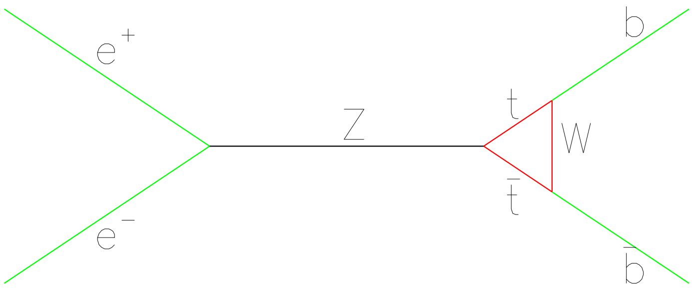
- universal corrections to propagator



  parameters:

  – $\Delta\rho$: absolute normalization of Z couplings
  – $\Delta\kappa$ ($\sin^2\theta^l_{eff}$): effective weak mixing angle in Z-fermion couplings
  – Δr: Relation $G_\mu \leftrightarrow m_{\rm W}$

- vertex corrections (only interesting fir b-quarks as partner of top)



Contributions to loop corrections

- corrections from isospin masssplitting
  ($\propto m_{\mathrm{t}}^2$ in SM)
- corrections from Higgs sector
  ($\propto \log(m_{\mathrm{H}})$ in SM)

Contributions to vertex corrections for b-quarks

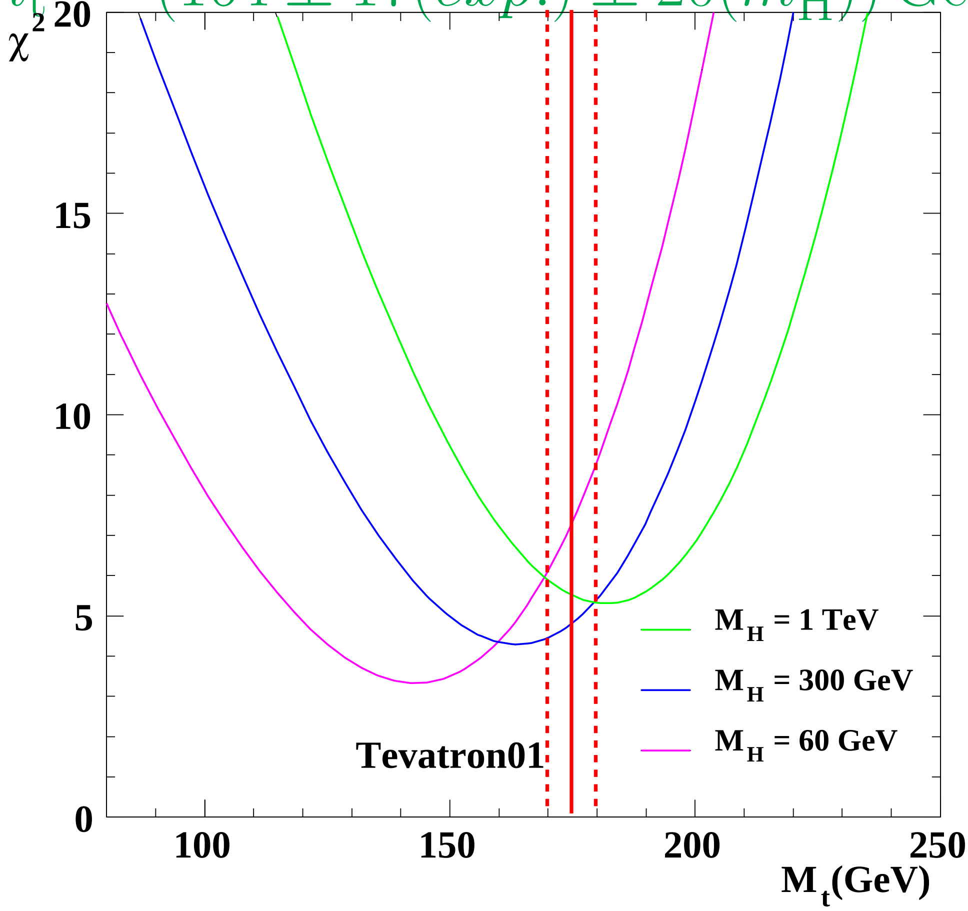
- corrections from b-t masssplitting ($\propto m_{\mathrm{t}}^2$)
- corrections from charged Higgs sector and its SUSY partners, if exists
- corrections from special role of top-quark e.g. in technicolor models

Aim: see effects of new physics in precision data

Historical example: Top mass prediction (1993)

Fit to all electroweak precision data gave

$$m_t = (164 \pm 17(exp.) \pm 20(m_H))\,\text{GeV}$$



In 1995 the top-quark was discovered at the TEVA-TRON with $m_t \sim 175\,\text{GeV}$

Hope at least to repeat this with the Higgs Boson

LEP+SLD+TEVATRON measure electroweak observables on the permille level

Quantities:

- Z-lineshape: Partial widths of $\mathrm{Z} \rightarrow \mathrm{f\bar{f}}$, $\Delta\rho$, N_ν
- Asymmetries: Weak mixing angle in Z-decays, $\sin^2\theta^\ell_{\mathrm{eff}}$
- b-quark partial width and asymmetries (R_b, $\mathcal{A}_\mathrm{b}$) Mass dependent vertex corrections
- W-mass: Δr

Present situation:

- LEP: $\sim 4 \times 4 \cdot 10^6$ Zs with unpolarized beams $\sim 4 \times 500\,\mathrm{pb}^{-1}$ above the W-threshold
- SLD: $\sim 5.5 \cdot 10^5$ Zs with $\mathcal{P} \sim 75\%$ electron polarization

Assumptions

- The linear collider can produce $\sim 10^9$ Zs on resonance
(corresponds to $\sim 30\,\mathrm{fb}^{-1}$ or 50 days)
$\mathcal{L} = 7 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow 230\,\mathrm{Hz}$ of $\mathrm{Z} \to \mathrm{q\bar{q}}$

- similar luminosity is possible near the W-threshold

- electrons and positrons can be polarized with $\mathcal{P}_{e^-} = \pm 80\%$, $\mathcal{P}_{e^+} = \pm 60\%$
(corresponds to an effective polarization of $\frac{\mathcal{P}_{e^+}+\mathcal{P}_{e^-}}{1+\mathcal{P}_{e^+}\mathcal{P}_{e^-}} \sim 95\%$)

- positive and negative polarizations can be switched randomly from bunch to bunch (or train to train) independent for electrons and positrons

- polarimeters are available for relative measurements

Lineshape parameters

Cross section around Z-peak:

$$\sigma_f(s) = \frac{12\pi}{m_Z} \frac{\Gamma_e \Gamma_f s}{\left(s - m_Z^2\right)^2 + \left(\frac{s}{m_Z}\right)^2 \Gamma_Z^2}$$
$$+\sigma_{\mathrm{int}} + \sigma_\gamma + \mathrm{rad.\,corr.}$$

$$\Gamma_\ell \approx (1 + \Delta_\rho)\Gamma_\ell^{(B)}$$
$$\Gamma_{\mathrm{had}} = (1 + \alpha_s/\pi + \ldots)\Gamma_{\mathrm{had}}^{(0)}$$

Minimally correlated observables:

	LEP precision
m_Z	$0.2 \cdot 10^{-4}$
Γ_Z	$0.9 \cdot 10^{-3}$
$\sigma_0^{\mathrm{had}} = \frac{12\pi}{m_Z^2} \frac{\Gamma_e \Gamma_{\mathrm{had}}}{\Gamma_Z^2}$	$0.9 \cdot 10^{-3}$
$R_\ell = \frac{\Gamma_{\mathrm{had}}}{\Gamma_l}$	$1.2 \cdot 10^{-3}$

$\Rightarrow$ Need to scan

$\Rightarrow$ Need absolute cross sections

Assumptions:

- relative beam energy error around Z-pole: 10^{-5}
  $\Rightarrow \Delta\Gamma_Z/\Gamma_Z = 0.4 \cdot 10^{-3}$
  (Currently under debate if $\Delta E_b = 10^{-5}$ is possible and if beamstrahlung and beamspread are enough under control)
- selection efficiency for μs, τs, hadrons (and exp error on $\mathcal{L}$) improved by a factor three relative to the best LEP experiment
  $\Rightarrow \Delta R_\ell/R_\ell = 0.3 \cdot 10^{-3}$
- theoretical error on luminosity stays at 0.05%
  $\Rightarrow \Delta\sigma_0^{\rm had}/\sigma_0^{\rm had} = 0.6 \cdot 10^{-3}$
  (again if beamspread/-strahlung understood)

Improvement on lineshape related quantities:

	LEP	Giga-Z
m_Z	91.1874 ± 0.0021 GeV	± 0.0021 GeV
$\alpha_s(m_Z^2)$	0.1183 ± 0.0027	± 0.0009
$\Delta\rho$	$(0.55 \pm 0.10) \cdot 10^{-2}$	$\pm 0.05 \cdot 10^{-2}$
N_ν	2.984 ± 0.008	± 0.004

R_b

scale DELPHI analysis:

$$
\begin{aligned}
R_b = 0.21634 &\pm 0.00075\ (stat\,dat + MC) \\
&\pm 0.00028\ (uds - bg) \\
&\pm 0.00030\ (c - bg) \\
&\pm 0.00027\ (hem\ corr)
\end{aligned}
$$

DELPHI working point: $\varepsilon_b \approx 30\%$ purity $\approx 98\%$
Possible for TESLA: $\varepsilon_b \approx 40\%$ purity $\approx 99.5\%$

- statistical error down by a factor 20
- c-background down by a factor 4
- uds-background mainly from gluon splitting to $b\bar{b}$ can be measured much better with TESLA
- hemisphere correlation is mainly QCD
  - detector resolution factor 10 better than LEP
  - losses are mainly due to mass cut (Lorenz invariant)
  - energy dependence should be much smaller
  - also this source should decrease by a factor 4-5
- $\Delta R_b = 0.00014$ should be possible (factor 5 to LEP)

$A_{\rm LR}$

Definition

$$\sigma = \sigma_u \left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\rm LR}(\mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right]$$

with $\mathcal{P}_{e^+}$ ($\mathcal{P}_{e^-}$) longitudinal polarizations of the positrons (electrons)

$A_{\rm LR}$ measures weak mixing angle $\sin^2\theta^{\ell}_{\rm eff}$:

$$A_{\rm LR} = \mathcal{A}_\ell$$
$$\mathcal{A}_\ell = \frac{2 g_{Vl} g_{Al}}{g_{Vl}^2 + g_{Al}^2}$$
$$\frac{g_{Vl}}{g_{Al}} = 1 - 4|Q_l| \sin^2\theta^{\ell}_{\rm eff}$$

- $\sin^2\theta^{\ell}_{\rm eff}$ is a very sensitive variable to see loop corrections to the Z-couplings.
- $A_{\rm LR}$ is the variable most sensitive to $\sin^2\theta^{\ell}_{\rm eff}$

The (extended) Blondel scheme

Four independent measurements:
(4 combinations with positive/negative electron/ positron polarization)

$$\begin{aligned}
\sigma_{++} &= \sigma_u\left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\mathrm{LR}}(\ \ \mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right] \\
\sigma_{-+} &= \sigma_u\left[1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\mathrm{LR}}(-\mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right] \\
\sigma_{+-} &= \sigma_u\left[1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\mathrm{LR}}(\ \ \mathcal{P}_{e^+} + \mathcal{P}_{e^-})\right] \\
\sigma_{--} &= \sigma_u\left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\mathrm{LR}}(-\mathcal{P}_{e^+} + \mathcal{P}_{e^-})\right]
\end{aligned}$$

$\Longrightarrow$ A_{LR} can be measured without knowing $\mathcal{P}_{e^+}$, $\mathcal{P}_{e^-}$:

$$A_{\mathrm{LR}} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}}$$

About 10% of the statistics is needed on the small cross sections

Only difference between $|\mathcal{P}^+_{e^\pm}|$ and $|\mathcal{P}^-_{e^\pm}|$ needs to be known from polarimetry

Can be brought under control with polarimeters a la SLD

Polarization difference ($\Delta\mathcal{P}_{e^\pm} = |\mathcal{P}^+_{e^\pm}| - |\mathcal{P}^-_{e^\pm}|$):

- Need SLD like polarimeter
- Asymmetry in one polarimeter channel: $A_i = a_i \mathcal{P}_e \mathcal{P}_\gamma$ (a_i =analyzing power)
- Laser polarization can be switched pulse to pulse
- Allow for different laser currents dependent on the polarization
- Need two polarimeter channels with different analyzing power
- combined fit of Z-rates and polarimeter rates can get $\Delta\mathcal{P}_{e^\pm}$ and a_i as well
- However need polarimeter counting rates about 10 times the Z rate (ok for SLD)

Statistical precision:

$$\Delta A_{\rm LR} = 4 \cdot 10^{-5} \cdot \sqrt{\frac{10^9}{N_Z}}$$

Systematic uncertainties

- Beam energy: $\Delta A_{\rm LR}/\Delta\sqrt{s} \approx 2 \cdot 10^{-2}/\,{\rm GeV}$
  $\Rightarrow$ need $\Delta\sqrt{s} \approx 1\,{\rm MeV}$ relative to $m_{\rm Z}$
- Luminosity difference: Only relative precision needed.
  Should be no problem if luminometer inside the mask is possible
- Backgrounds: To be kept below 10^{-4}
  According to LEP experience no problem
- Beamstrahlung: $\Delta A_{\rm LR} = 9 \cdot 10^{-4}$
  Needs to be known on the few percent level (partially covered by Z-scan)

Assume $\Delta A_{\rm LR} = 10^{-4} \Rightarrow \Delta \sin^2\theta^{\ell}_{\rm eff} = 0.000013$

$\mathcal{A}_\mathrm{b}$

Without polarized beams (LEP) the forward-backward asymmetries can be measured:

$$A_{FB}^{q} = \frac{\sigma_F^{(q)} - \sigma_B^{(q)}}{\sigma_T^{(q)}} = \frac{3}{4}\mathcal{A}_\mathrm{e}\mathcal{A}_\mathrm{q}$$

With polarized beams (SLD,TESLA) the left-right-forward-backward asymmetries can be measured:

$$A_{FB,LR}^{q} = \frac{\sigma_{L,F}^{(q)} - \sigma_{L,B}^{(q)} - \sigma_{R,F}^{(q)} + \sigma_{R,B}^{(q)}}{\sigma_L^{(q)} + \sigma_R^{(q)}} = \frac{3}{4}\mathcal{P}\mathcal{A}_\mathrm{q}$$

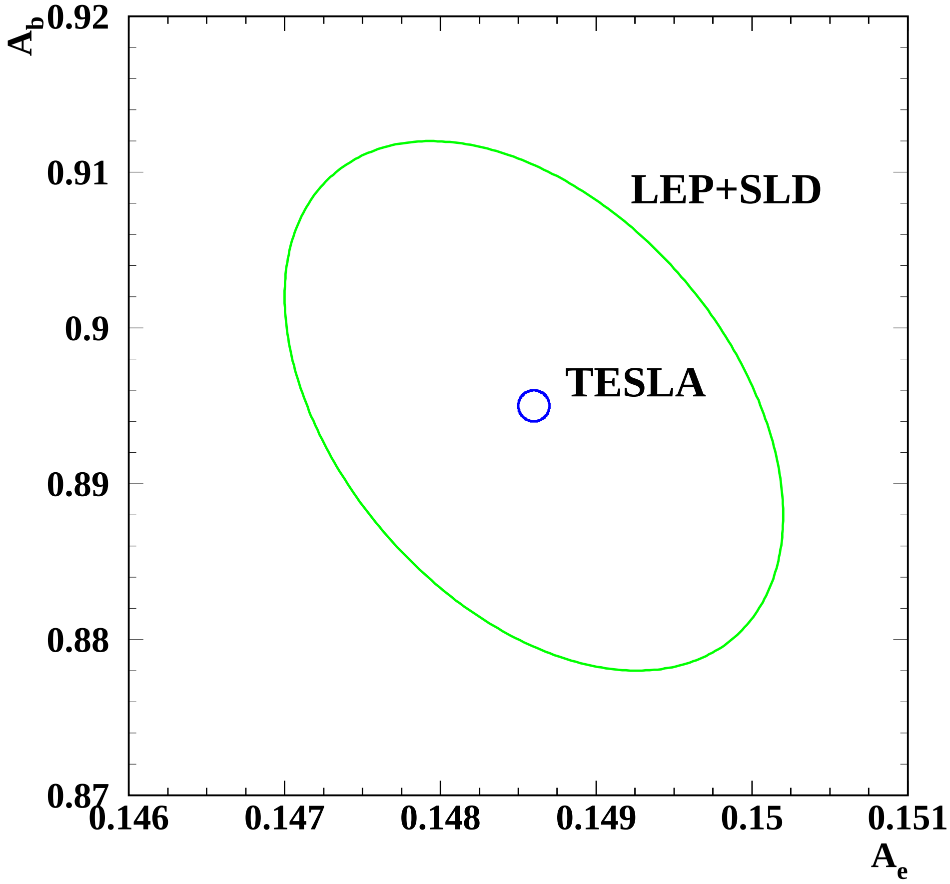
Statistically factor $\mathcal{P}/\mathcal{A}_\mathrm{e} \sim 6$ more sensitive to $\mathcal{A}_\mathrm{b}$

However most systematics scale with the asymmetry

Two main techniques: leptons and jetcharge

- Statistical error $\Delta\mathcal{A}_\mathrm{b} \approx 4 \cdot 10^{-4}$ in both cases
- Light quark systematics can be reduced by a (harder) lifetime tag
- For jetcharge reduce hemisphere correlations by a thrust cut
- leptons will be dominated by $B\overline{B}$-mixing (statistical error!)
- A total error of $\Delta\mathcal{A}_\mathrm{b} = 1 \cdot 10^{-3}$ seems realistic

Similar improvement as for $\mathcal{A}_\mathrm{e}$



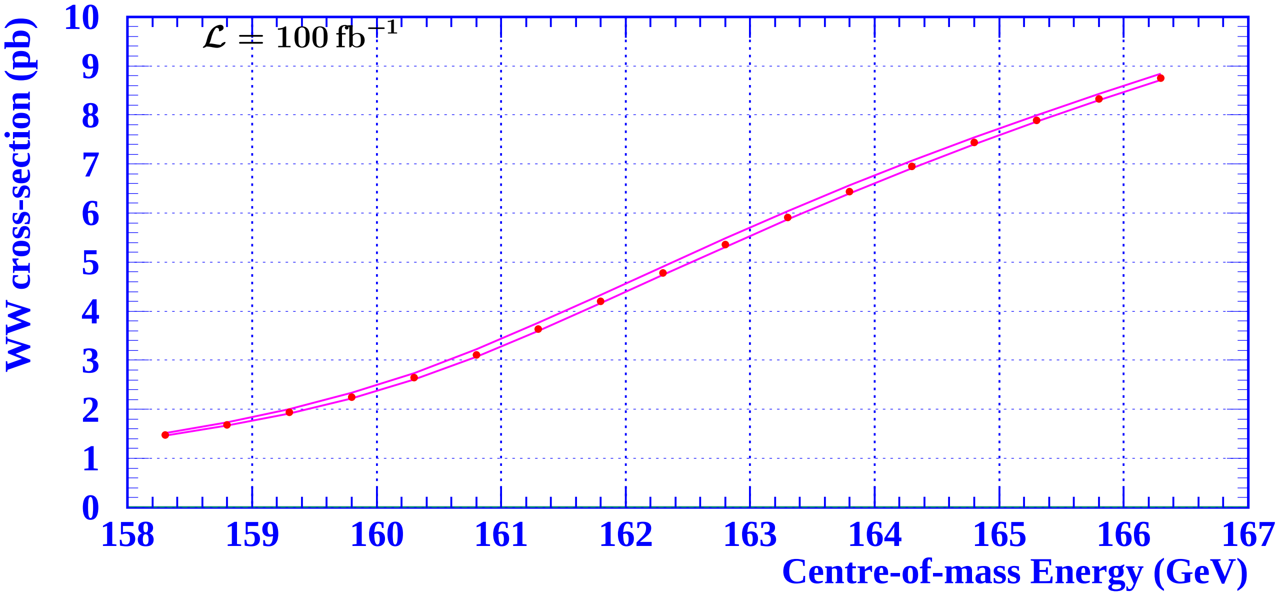
m_W

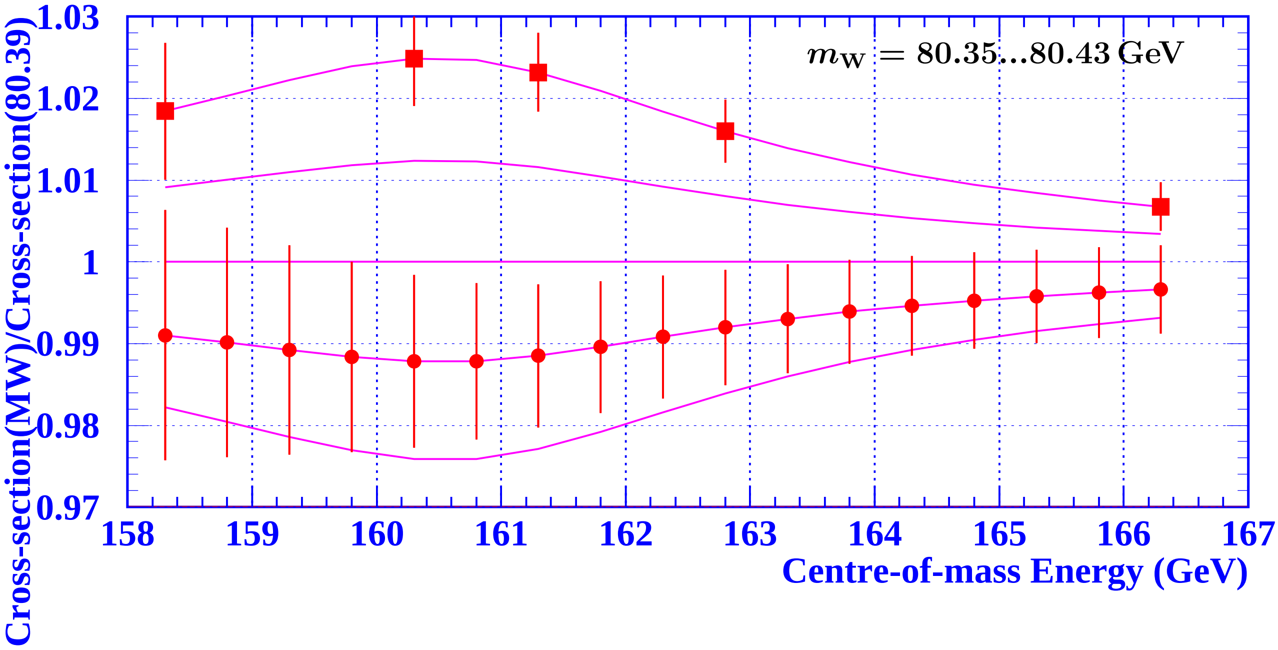
Best possible method: threshold scan

- spend $100\,\mathrm{fb}^{-1}$ at $\sqrt{s} \sim 161\,\mathrm{GeV}$ (1 year!)
- polarization is very useful to enhance cross section or measure background

$$\sigma_{\mathrm{WW}} = 3\sigma_{\mathrm{WW}}^{\mathrm{unpol}} \qquad \mathcal{P}_{e^-} = -0.8,\ \mathcal{P}_{e^+} = 0.6$$
$$\sigma_{\mathrm{WW}} = 0.1\sigma_{\mathrm{WW}}^{\mathrm{unpol}} \qquad \mathcal{P}_{e^-} = 0.8,\ \mathcal{P}_{e^+} = -0.6$$

- assume efficiency/background as at LEP
- perform 5-point scan
- assume point to point systematics negligible
- beam energy is known to well below 5 MeV (A relative calibration to the Z-mass is fine)





Results

$\Delta\varepsilon/\varepsilon = 0.5\%$, $\Delta\mathcal{L}/\mathcal{L} = 0.25\%$ $\quad \Delta m_W = 6\,\mathrm{MeV}$

$\Delta\varepsilon/\varepsilon$, $\Delta\mathcal{L}/\mathcal{L}$ fitted $\quad \Delta m_W = 7\,\mathrm{MeV}$

Measurement is statistics limited

Precision data and the LHC

m_{W}

- LHC has infinite statistics for W-production
- two main sources of error:
  - energy scale of the detector
  - parton distribution function
- $\Delta m_{\mathrm{W}} = 15\,\mathrm{MeV}$ might be possible although extremely difficult

$\sin^2\theta^l_{eff}$

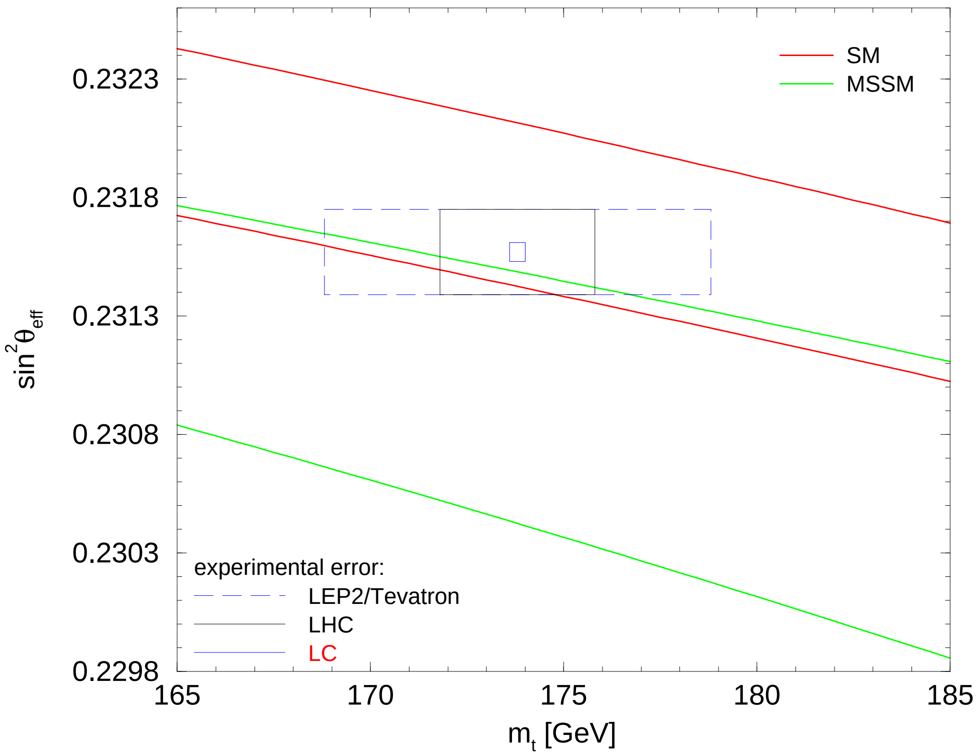
- in principle $\sin^2\theta^l_{eff}$ can be measured from forward backward asymmetry $q\bar{q} \to \ell^+\ell^-$
  (At $\sqrt{s} = m_{\mathrm{Z}}$: $A^0_{FB} = \frac{3}{4}\mathcal{A}_i\mathcal{A}_f$)
- select events with $m(\ell^+\ell^- \approx m_{\mathrm{Z}}$ and large boost
- the high energy quark is then on average a valence quark, the low energy one a (sea) antiquark
- possible statistical precision $\Delta\sin^2\theta^l_{eff} = 0.0001$
- unclear if systematics can be brought to this level

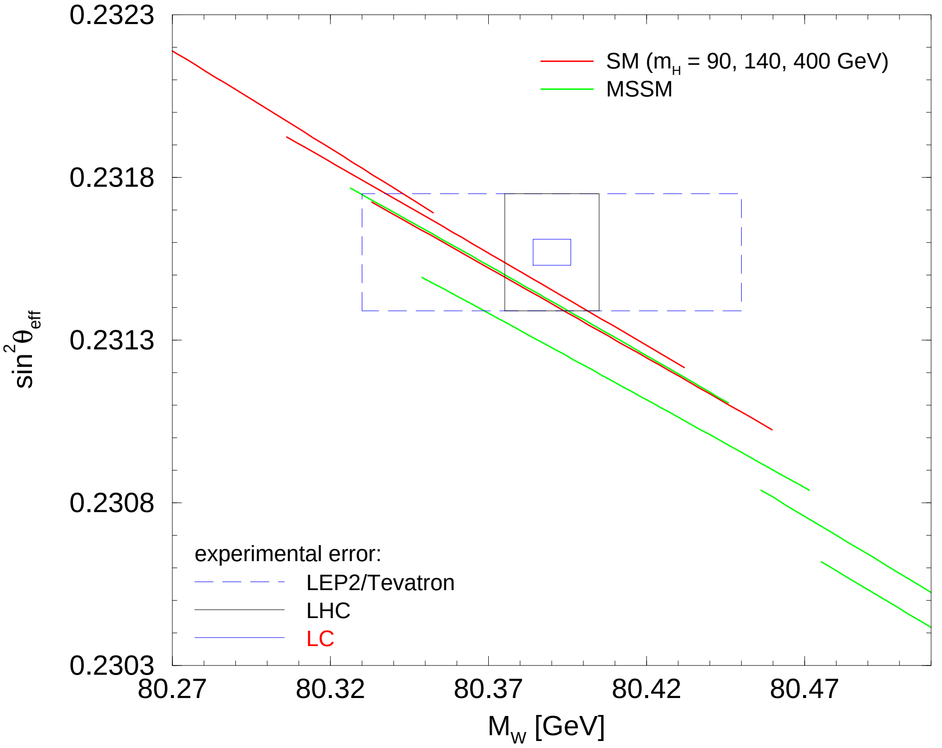
Interpretation of precision measurements

Parametric errors

- largest effect: Running of α
  $(\alpha(m_Z) = \alpha(0)\frac{1}{1-\Delta\alpha})$
  - Using data only (without the latest BES results) ($\delta(\Delta\alpha) = 0.00065$):
    $\Delta\sin^2\theta^\ell_{eff} = 0.00023$, $\Delta m_W = 12\,\mathrm{MeV}$
  - $\sim$ factor three improvement using perturbative QCD at low energy
  - with $\sigma(e^+e^- \to \mathrm{had})$ below the Υ to 1%
    ($\delta(\Delta\alpha) = 0.000046$):
    $\Delta\sin^2\theta^\ell_{eff} = 0.000017$, $\Delta m_W < 1\,\mathrm{MeV}$
- 2 MeV error on m_Z gives
  $\Delta\sin^2\theta^\ell_{eff} = 0.000014$, $\Delta m_W = 1\,\mathrm{MeV}$
  (if W-mass calibrated to m_Z)
- $\Delta m_t = 1\,\mathrm{GeV}$ gives
  $\Delta\sin^2\theta^\ell_{eff} = 0.00003$, $\Delta m_W = 6\,\mathrm{MeV}$
  $\Rightarrow$ no problem with LC precision of m_t ($<$ 200 MeV)

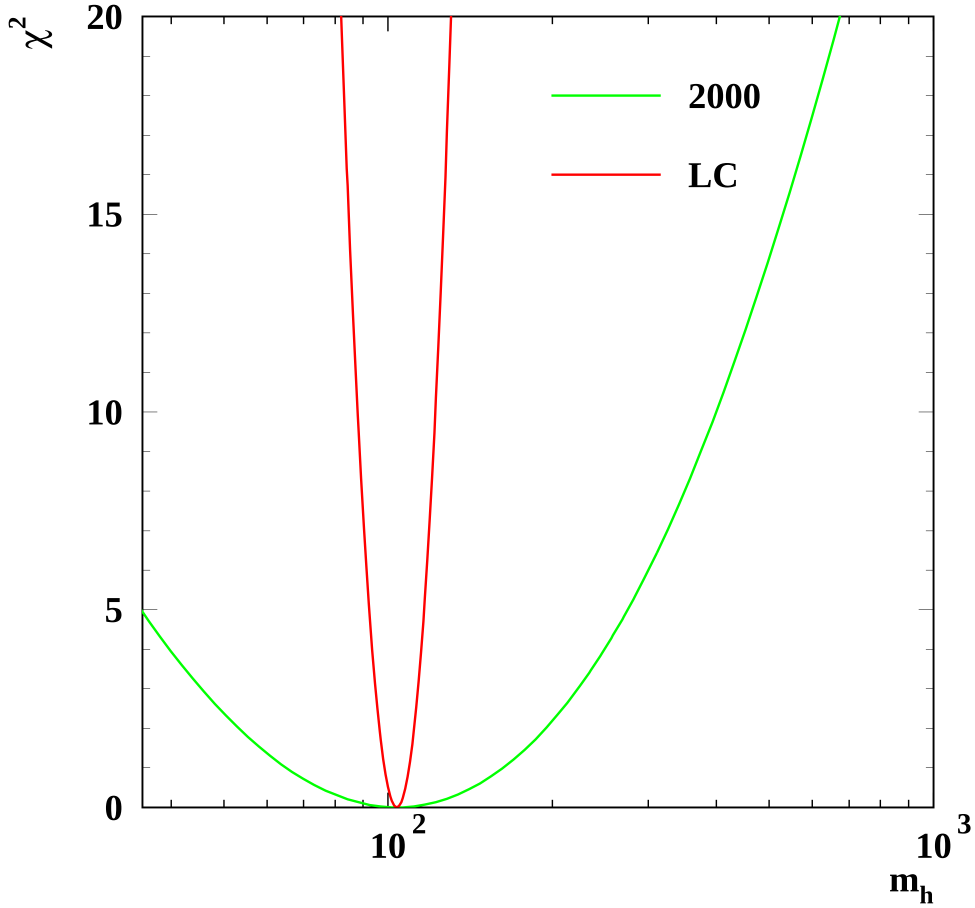
SM and MSSM make accurate predictions for $\sin^2\theta_{\rm eff}^{\ell}$ and $m_{\rm W}$





If no new physics found up to then:

Standard Model Higgs can be predicted to 5% accuracy:

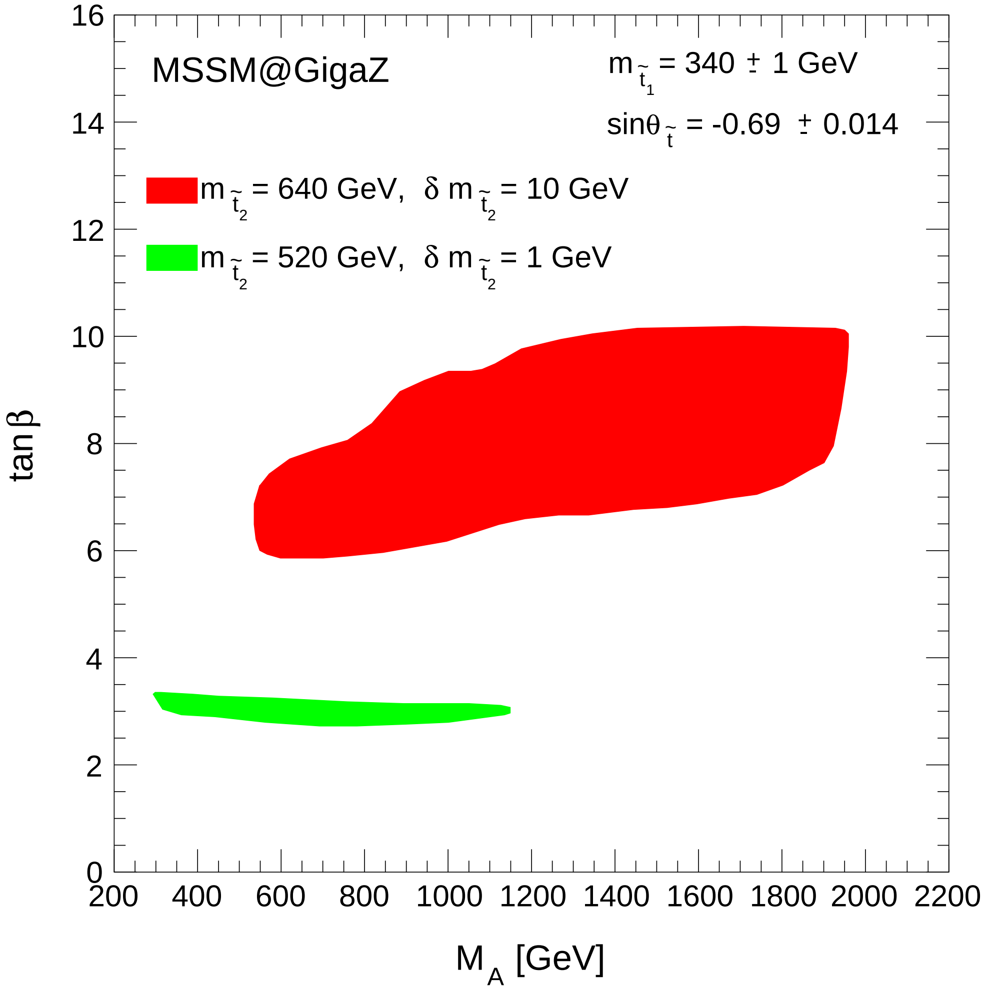


Can test the theory if a Higgs of $m_{\mathrm{H}} \sim 170\,\mathrm{GeV}$ is found

Possible scenario inside the MSSM:

- some SUSY parameters measured at LHC e.g. stop sector
- however some of the parameters still uncertain

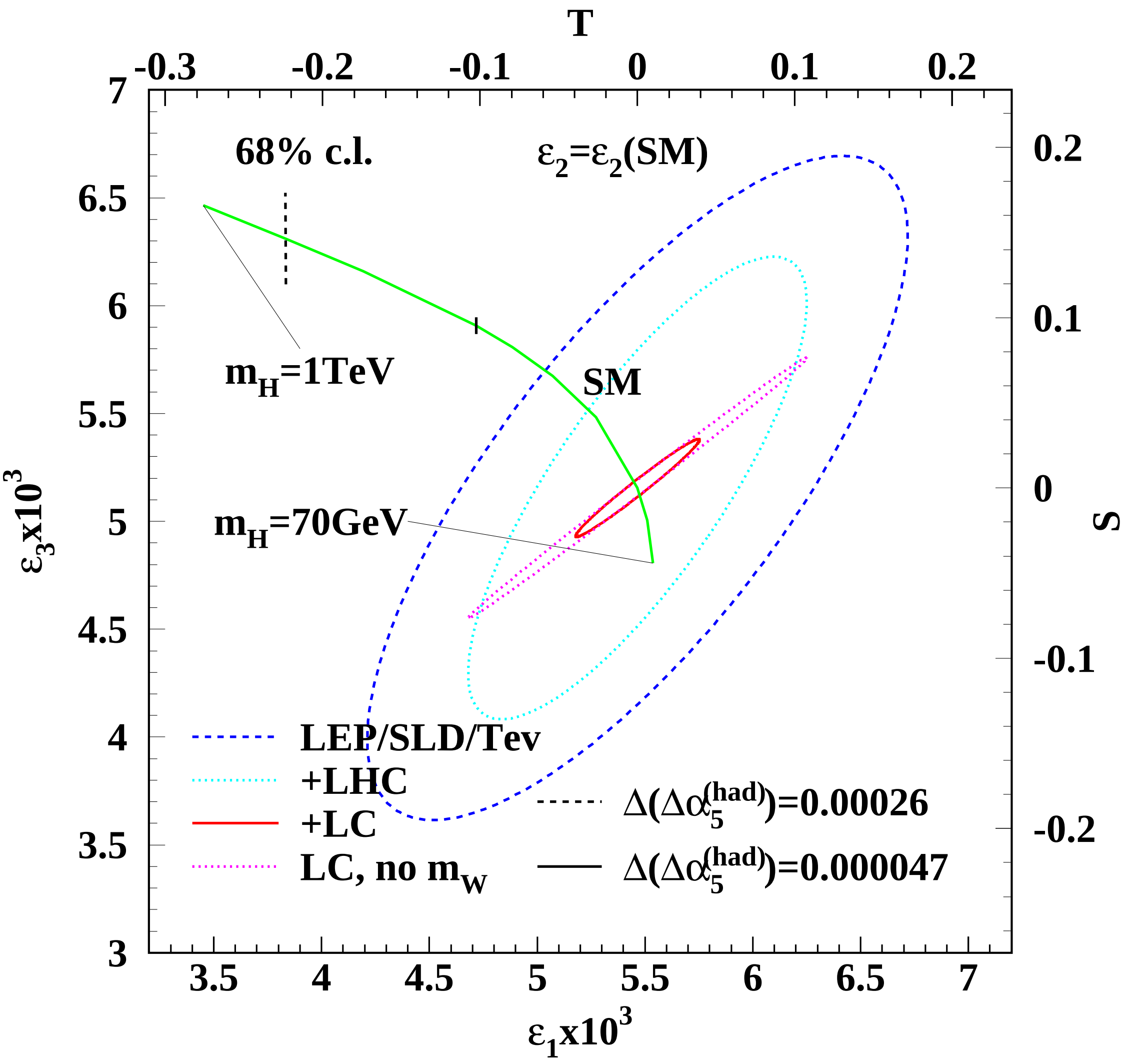
Precision measurements can constrain allowed SUSY parameter range



In this example one can get a fairly good measurement of $\tan\beta$ and some ideas on m_A

Model independent analysis (ε, ST parameters)

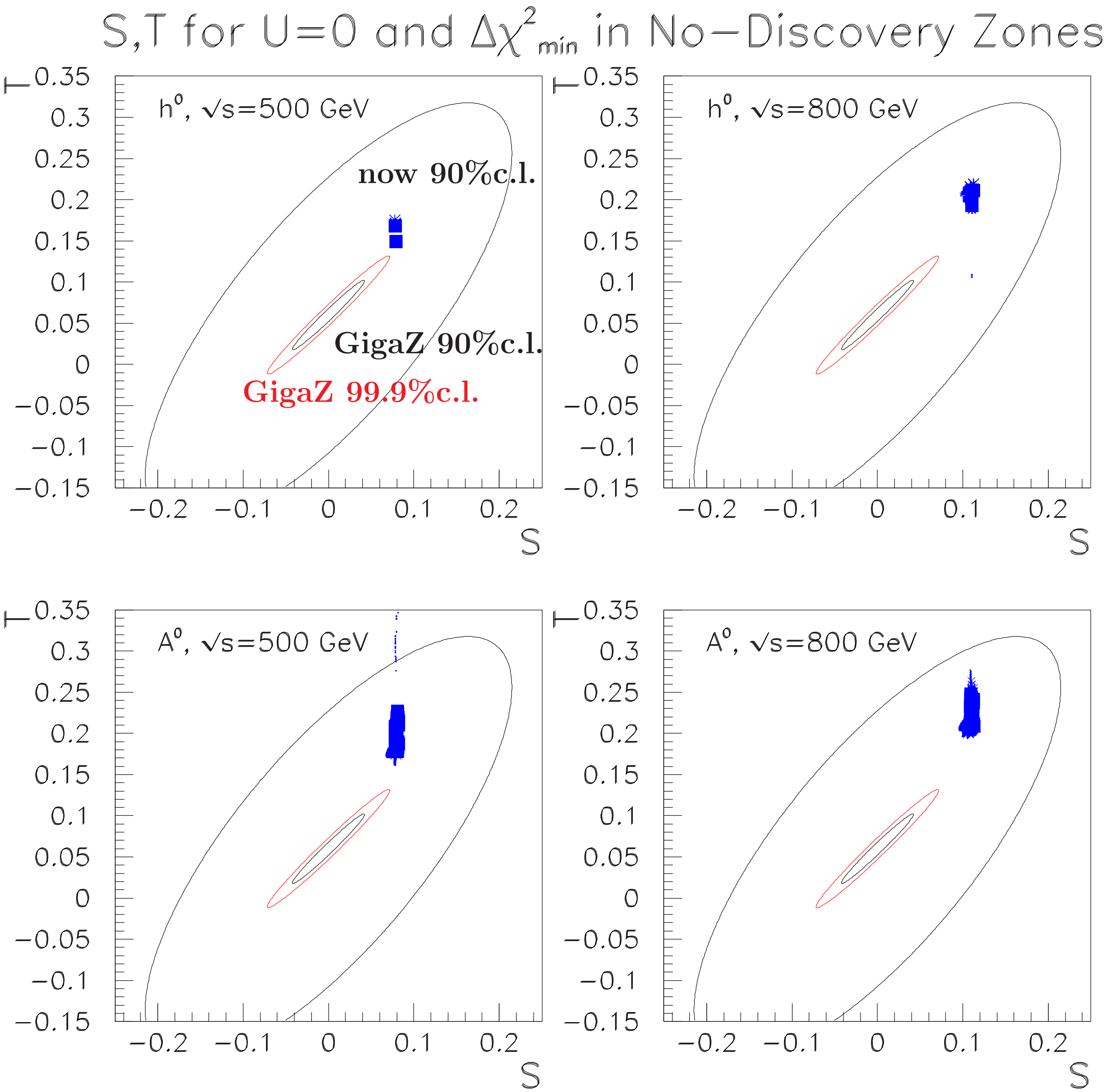
- ε_1 (T): absorbs large isospin splitting corrections
- ε_3 (S): only logarithmic dependencies
- ε_2 (U): additional (small) correctins to m_{W}



- dramatic improvement in m_{H} direction
- improvement perpend. to m_{H} largely due to m_{W}
- significant Higgs constraint independent of ε_1 (T) possible

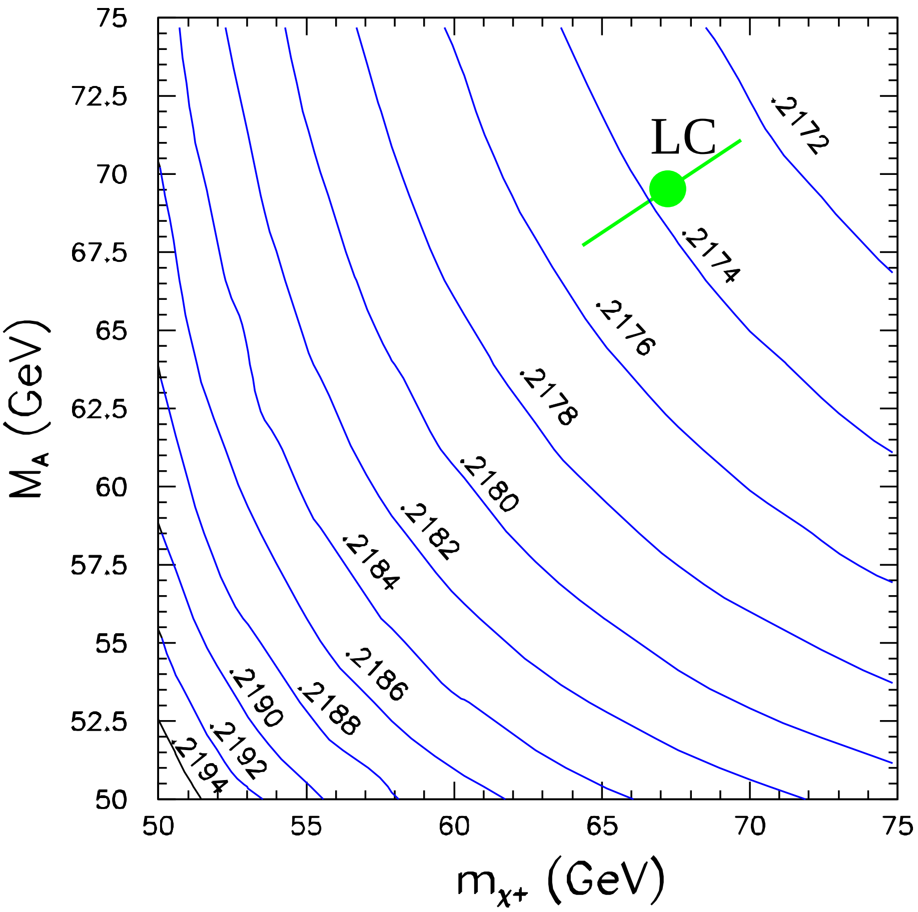
E.g. exclusion of a two Higgs doublet model with a light Higgs

(that cannot be excluded by direct searches)



For these types of exclusions m_{W} is important!

R_b is sensitive e.g. to masses within Supersymmetry



CP-violation studies

measure time dependent asymmetries

$$A(t) = \frac{N_{B^0}(t) - N_{\bar{B}^0}(t)}{N_{B^0}(t) + N_{\bar{B}^0}(t)} = a_{\cos}\cos\Delta mt + a_{\sin}\sin\Delta mt$$

mainly two examined decay modes

- $B^0 \to J/\Psi K_s^0$:
  - $a_{\sin} = -\sin 2\beta, \ \ a_{\cos} = 0$
- $B^0 \to \pi^+\pi^-$:
  - $a_{\sin} = -\sin 2\alpha, \ \ a_{\cos} = 0$ if penguin diagrams can be ignored
  - however $a_{\sin}, a_{\cos}$ modified by penguin contributions, hard to calculate
  - can be disentangled by measuring branching ratios $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$, $B^+ \to \pi^+\pi^0$

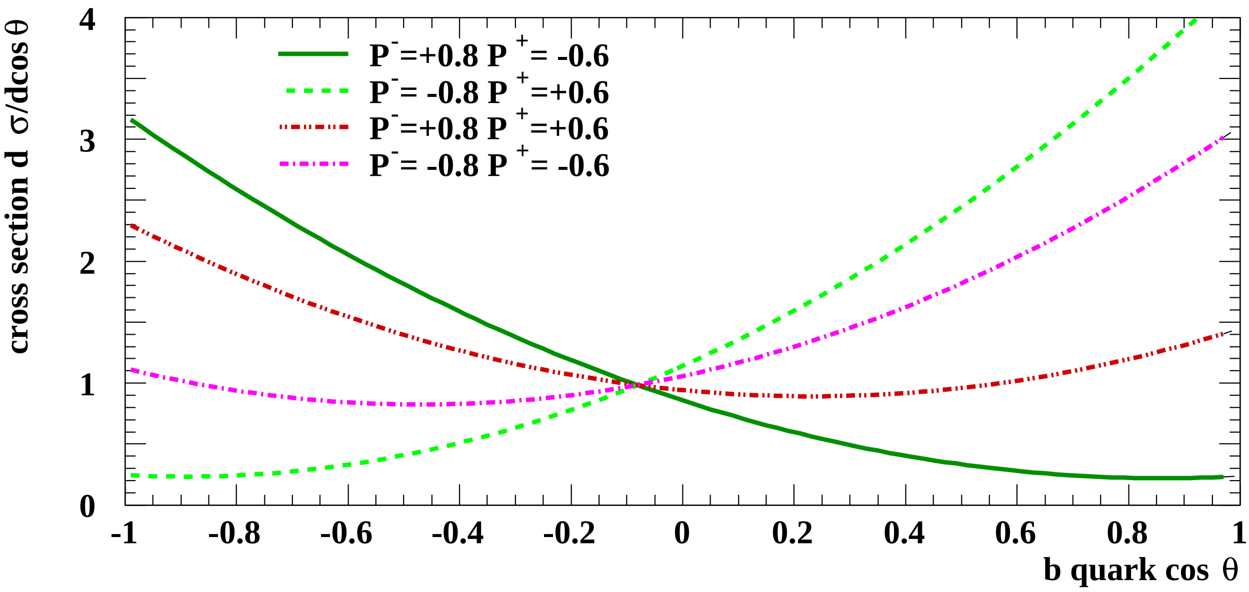
Experimental analysis:

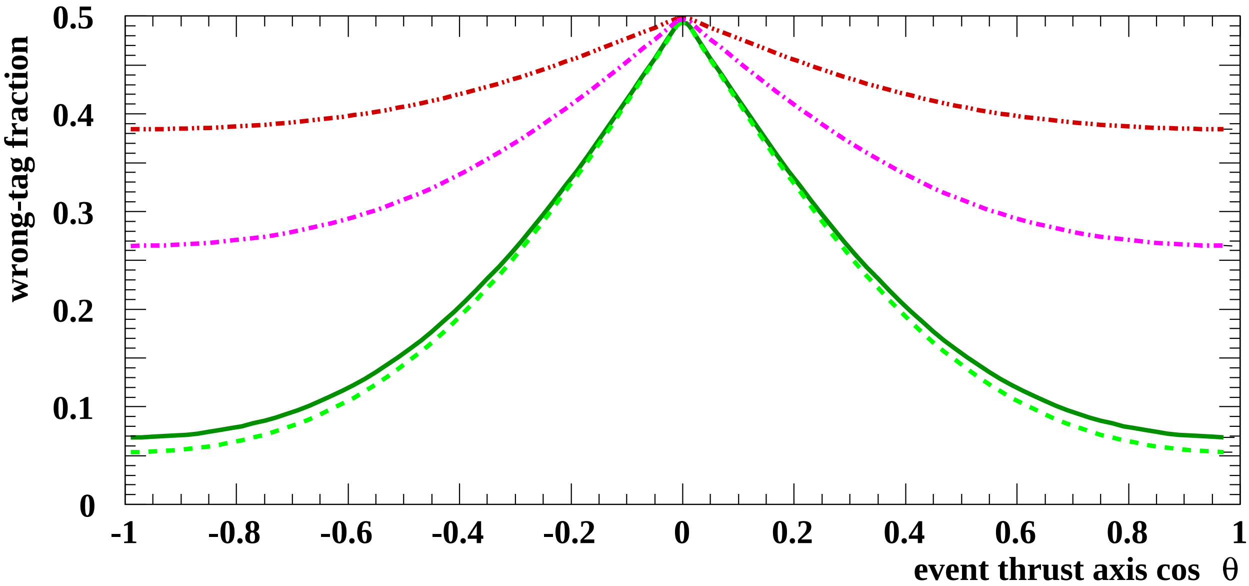
- identify initial state b-charge
- reconstruct decay mode
- measure eigentime to decay (easy in LC environment with fully reconstructed decays)

total statistics: $4 \cdot 10^8$ b-hadrons

Tagging of primary b-charge:

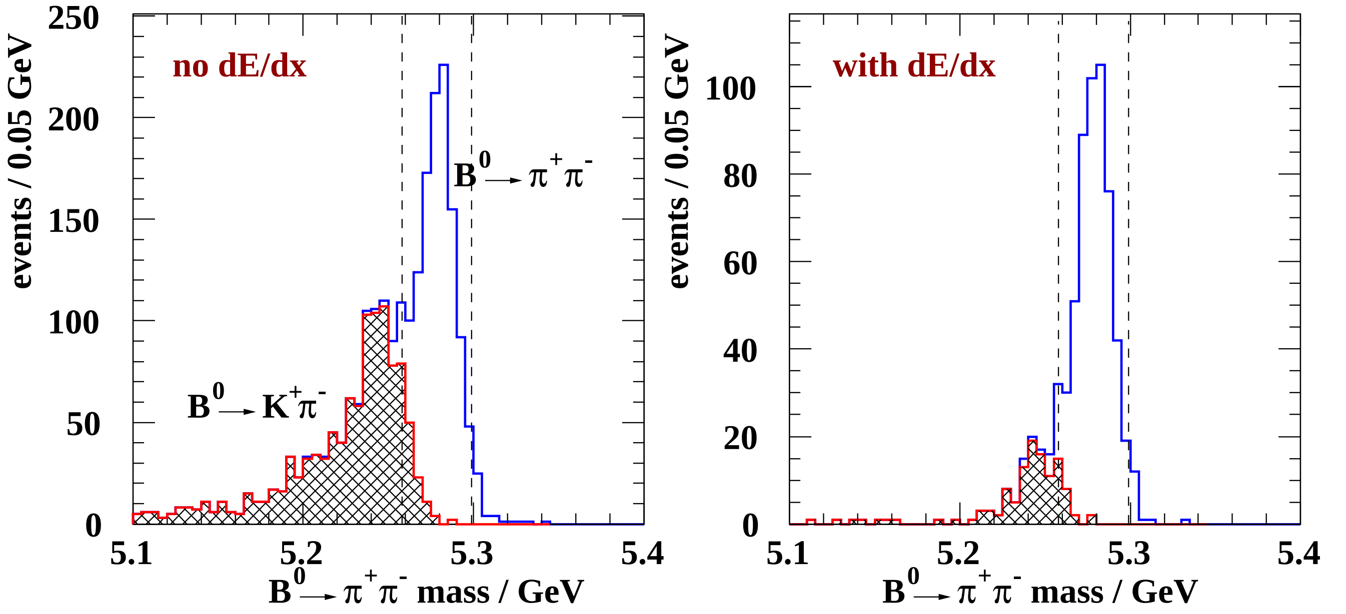
- Polarization gives primary flavor tagging "for free"





Final state identification:

- Missing particle ID can be replaced by excellent momentum resolution



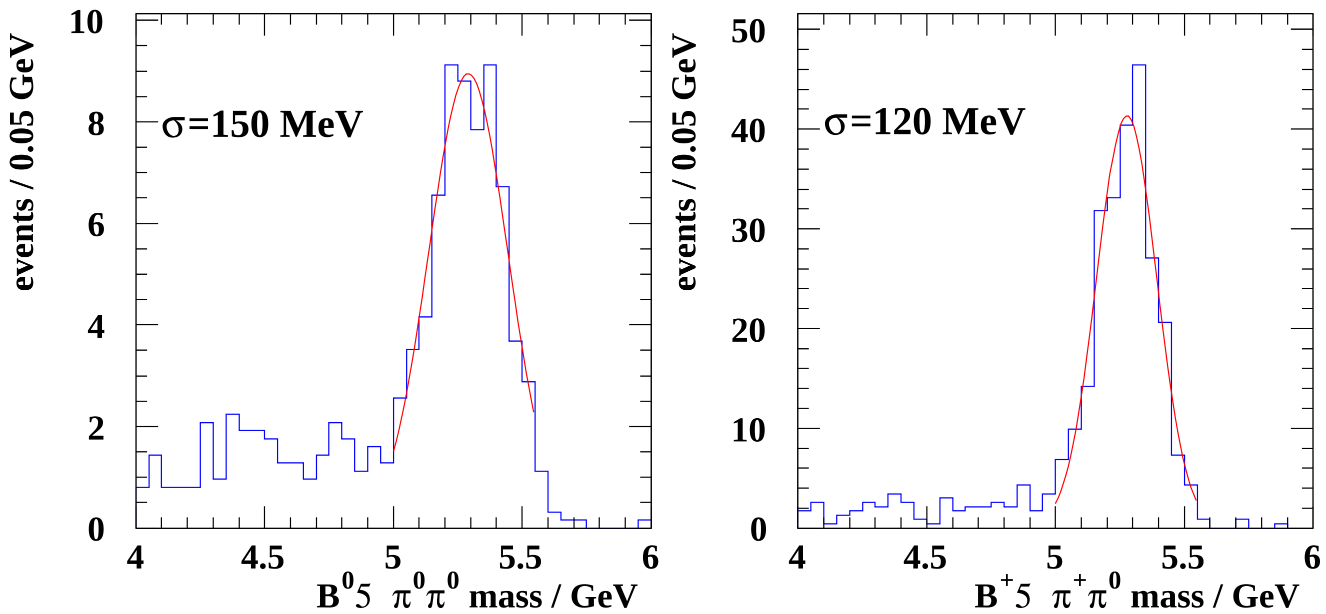
Results

	$\sin 2\beta$	"$\sin 2\alpha$"
BaBar	0.12	0.26
CDF	0.08	0.10
ATLAS	0.02	0.14
LHC-b	0.01	0.05
TESLA	0.04	0.07

Not the best, but interesting cross check!

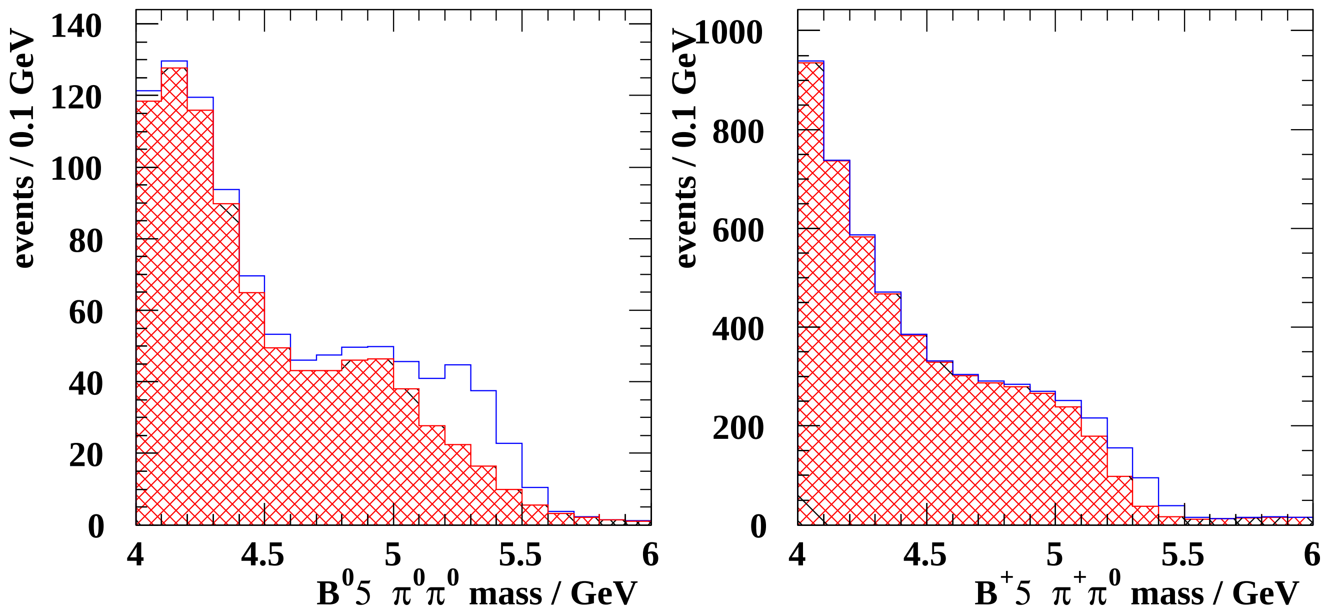
Branching ratios $B^0 \to \pi^0\pi^0$, $B^+ \to \pi^+\pi^0$

- needed to disentangle direct from penguin contributions in $B^0 \to \pi^+\pi^-$
- only possible in e$^+$e$^-$-machines
- Needs at a linear collider:
  - b-tagging opposite to signal hemisphere for b$\bar{\text{b}}$-selection
  - anti-b-tagging in signal hemisphere to suppress other b-decays
  - good calorimeter resolution (mainly spatial) for mass measurement



(Resolution depends strongly on the calorimeter design)

Finally a signal should be seen above background

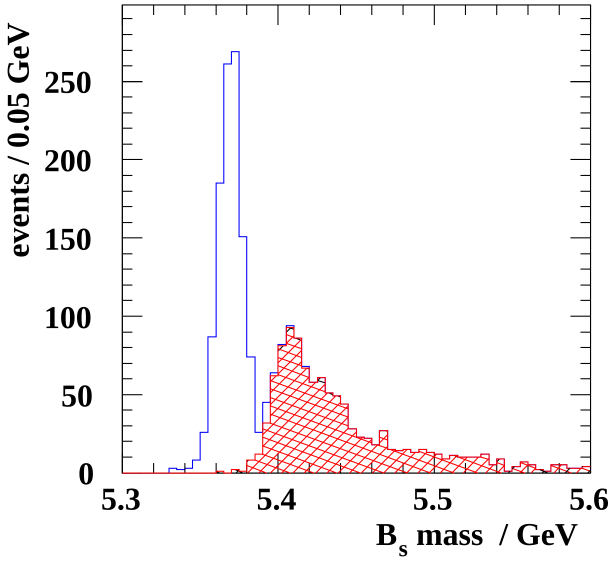


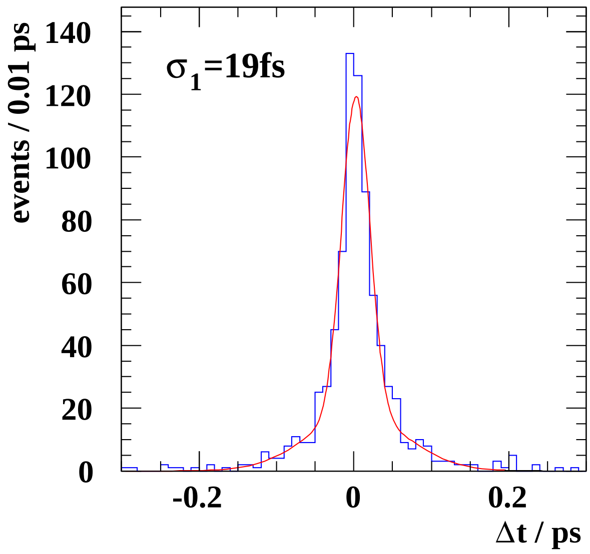
	$\frac{\Delta BR(B^+ \to \pi^+ \pi^0)}{BR}$ $(5 \cdot 10^{-6})$	$\frac{\Delta BR(B^0 \to \pi^0 \pi^0)}{BR}$ $(2 \cdot 10^{-6})$
BaBar $(300\,\mathrm{fb}^{-1})$	11	17
GigaZ (10^9 Zs)	15	24

Competitive with 10^9 Zs, leading with 10^{10} Zs

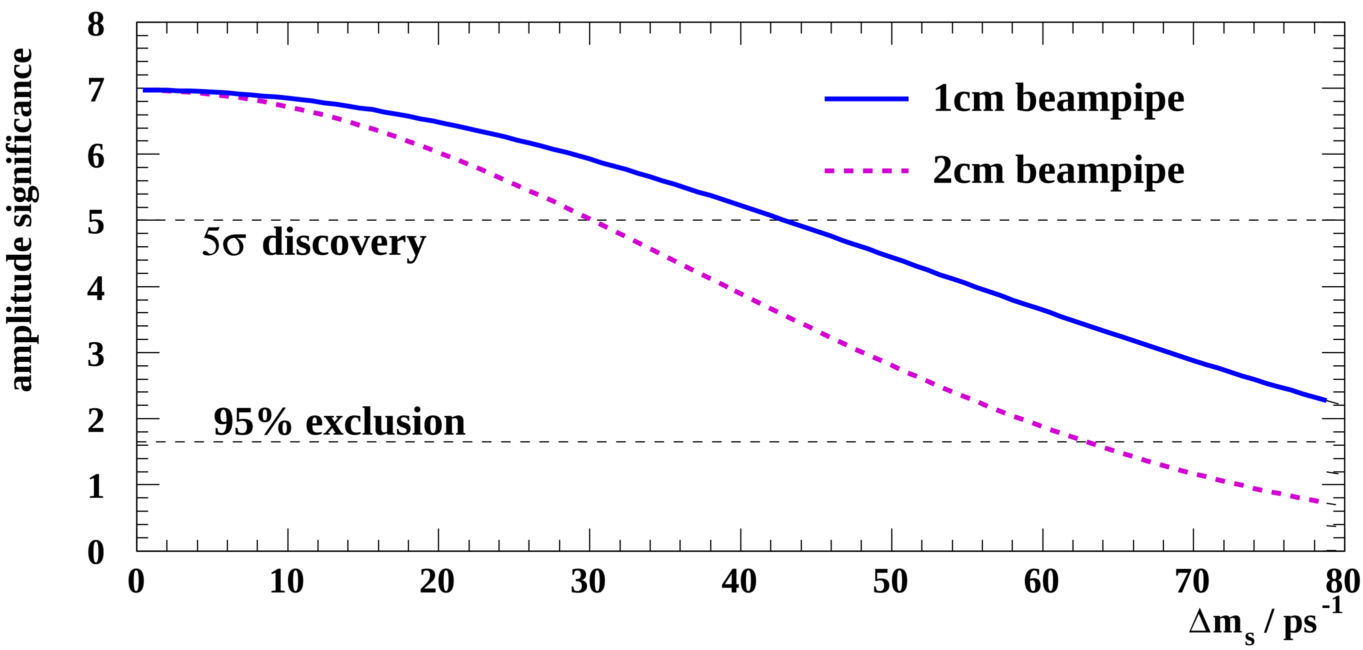
$B_s\overline{B}_s$-oscillations

- "golden" mode: $B_s \rightarrow D_s\pi$, $D_s \rightarrow \phi\pi, KK$ can be reconstructed almost background free
- proper time res. dominated by vertex res.





- $\Delta m_s \sim 40\text{ps}^{-1}$ possible with 10^9 Zs
- resolution limit around $\Delta m_s \sim 80\text{ps}^{-1}$



Conclusions on lower energy running

- With less than a year of running on the Z huge progress on some important electroweak precision observables can be made
- With an additional year around the W-pair threshold also a significant improvement on $m_{\rm W}$ can be obtained
- It seems that with some effort at Beijing/ Novosibirsk the running of α can be measured to a high enough precision
- Only with the precise data from TESLA the experimental measurements can match the theoretical predictions after the Higgs is found
- Some interesting cross checks in B-physics, however no "golden channel" (yet)