DUSTING FOR SUSY'S FINGERPRINTS IN PRECISION DATA

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Outline

1 Introduction

2 Calculations

3 Analyses

4 Conclusions

INTRODUCTION

Electroweak precision calculations,
why bother?

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Electroweak precision calculations, why bother?

	central value	absolute error	relative error
M_W [GeV]	80.398	± 0.025 TEV/LHC: $\pm 0.020/0.015$ ILC: ± 0.007	$\pm 0.03\%$
$\sin^2\theta_{\text{eff}}$	0.23153	± 0.00016 ILC: ± 0.000013	$\pm 0.07\%$
Γ_Z [GeV]	2.4952	± 0.0023 ILC: ± 0.001	$\pm 0.09\%$

- Negligible errors for α, G_F, M_Z, ...

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- Negligible errors for α, G_F, M_Z, ...

$\Rightarrow$ Precise predictions needed to match this accuracy!

- Calculate M_W, $\sin^2\theta_{\text{eff}}$, $\Gamma_Z \ldots$ in terms of α, G_F, M_Z, $\ldots$.
- Theoretical predictions for precision observables are model dependent.

$\Rightarrow$ Test models by comparing experimental value with theory predictions.

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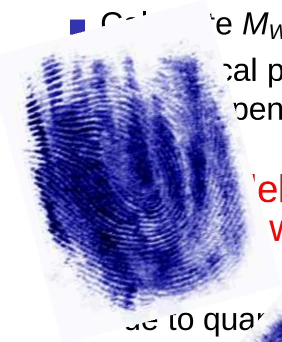
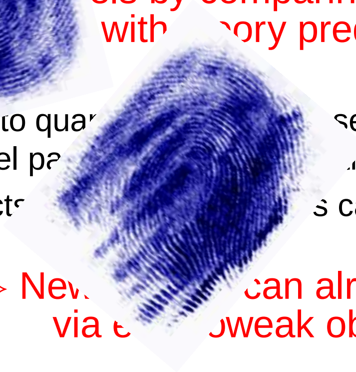
$\Rightarrow$ Test models by comparing experimental value with theory predictions.

- Due to quantum corrections sensitivity to unknown model parameters & new particles .
- Effects of unknown particles can be observed.

$\Rightarrow$ New physics can already be probed via electroweak observables.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SUSY's fingerprints can already be observed...

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- **M**inmal **S**upersymmetric extension of the **S**tandard **M**odel.
- Every Standard Model fermion/boson obtains SUSY partner boson/fermion.
- Two Higgs doublets needed to give masses to up and down type quarks and to avoid anomalies.

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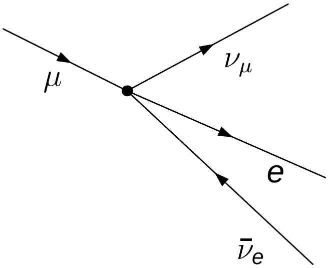
- Popular constrained model: **mSUGRA**
  - No flavour violating terms & complex phases.
  - Unification of soft breaking paramters at GUT scale.

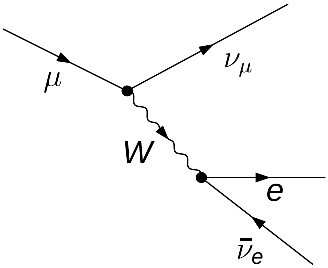
$\Rightarrow$ Free parameters: $\{m_0, M_{1/2}, A_0, B, \mu\}$.

The W boson mass

- M_W calculated from μ-decay using the Fermi constant G_F (as well as $M_Z, \alpha \ldots$).

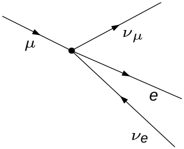


Fermi Model
[Fermi,1934]
(effective theory)

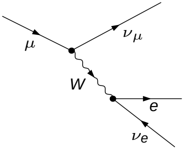


Standard Model
[Glashow,Salam,Weinberg,1970]
(Born level)

Born level



$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8\left(1-\frac{M_W^2}{M_Z^2}\right)M_W^2}$$



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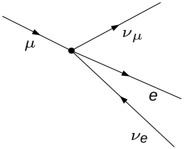

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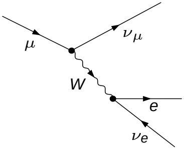

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- Summarise electroweak radiative corrections by Δr.

[Marciano,Sirlin]

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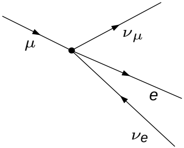

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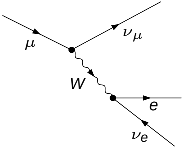

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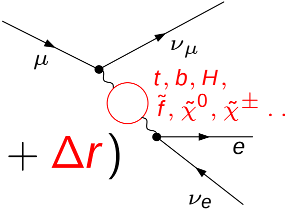
Loop order

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8(1-\frac{M_W^2}{M_Z^2})M_W^2}\,(1+\Delta r)$$



The quantity Δr

- Δr model dependent: $\Delta r = \Delta r(M_W, M_Z, m_t, \alpha, \alpha_s, X, \dots)$

$$X = M_H \quad \text{(SM)}$$

$$X = M_{h^0}, M_{H^0}, M_{A^0}, M_{H^\pm}, \tan\beta, M_{\tilde{f}}, m_{\chi^{0,\pm}}, A_f, \dots \text{(MSSM)}$$

$\Rightarrow$ Model prediction for M_W solves above equation.

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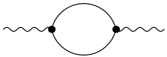
$\Rightarrow$ Model prediction for M_W solves above equation.

- At one-loop order Δr commonly decomposed into leading and remainder terms.

$$\Delta r = \Delta\alpha - \frac{c_w^2}{s_w^2}\Delta\rho + \Delta r_{\text{rem}}$$



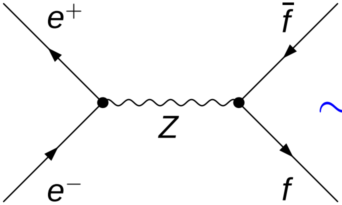
$t, b, \tilde{t}, \tilde{b} \ldots$

$\Rightarrow \Delta\rho$ very sensitive to new physics.

(Little Higgs, Littlest Higgs *[Chen,Dawson], [Csaki,Hubisz,Kribs,Meade,Terning],...*)

Z pole observables

- LEP1/SLC/ILC GigaZ: $e^+e^- \to f\bar{f}$ @ $s \sim M_Z^2$.

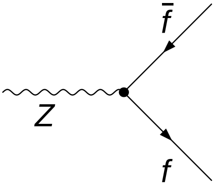


$$\sim \frac{1}{s - M_Z^2 + i\Gamma_Z M_Z}$$

- Radiative corrections can be absorbed into effective couplings (up to small non-resonant contributions).

$\Rightarrow$ Z pole pseudo observables defined in terms of these effective couplings.

Born level



$$\Longrightarrow \quad \mathcal{M}_{\text{Born}} = \bar{u}_f \gamma_\alpha [g_{f,v}^{\text{Born}} - \gamma_5 g_{f,a}^{\text{Born}}] v_f \epsilon_Z^\alpha$$

$g_{f,\{a/v\}}^{\text{Born}}$: axial/vector Born coupling

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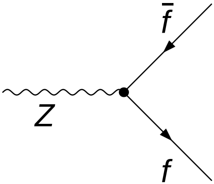

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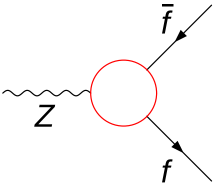

$$\Longrightarrow \qquad \mathcal{M}_{\mathrm{eff}} = \bar{u}_f \gamma_\alpha [\mathcal{G}_{f,V}^{\mathrm{eff}} - \gamma_5 \mathcal{G}_{f,A}^{\mathrm{eff}}] v_f \epsilon_Z^\alpha$$

$\mathcal{G}_{f,\{A/V\}}^{\mathrm{eff}}$: effective axial/vector coupling

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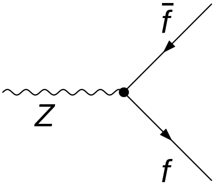

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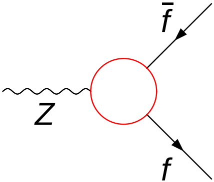

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$\mathcal{G}_{f,\{A/V\}}^{\text{eff}}$: effective axial/vector coupling

$$\boxed{\mathcal{G}_{f,\{A/V\}}^{\text{eff}} = \mathcal{G}_{f,\{A/V\}}^{\text{eff}}(M_W, M_Z, m_t, \alpha, \alpha_s, X, \ldots)}$$

Effective mixing angles

- Born level:

$$\sin^2\theta_\mathrm{w} = \frac{1}{4|Q_f|}\left(1 - \frac{g_{f,v}^{\mathrm{Born}}}{g_{f,a}^{\mathrm{Born}}}\right) \equiv s_w^2$$

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Partial Z widths

$$Z \to f\bar{f}$$

$$\Updownarrow$$

$$\Gamma_f = N_c^f \frac{\alpha}{3} M_Z \left(|\mathcal{G}_{f,V}^{\text{eff}}|^2 R_V^f + |\mathcal{G}_{f,A}^{\text{eff}}|^2 R_A^f \right)$$

- $R_{V,A}^f$: QED and QCD interaction & fermion masses.

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Further observables at the Z resonance

- Z pole observables defined in terms of $\sin\theta^f_{\text{eff}}$ & Γ_f :

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- Z pole observables defined in terms of $\sin\theta^f_{\text{eff}}$ & Γ_f :
  - Asymmetry parameter

$$\mathcal{A}_f = 2\frac{1-4|Q_f|\sin^2\theta^f_{\text{eff}}}{1+\left(1-4|Q_f|\sin^2\theta^f_{\text{eff}}\right)^2}$$

  - Z pole Asymmetries

$$A^{0,f}_{\text{FB}} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f, \qquad A^{0,f}_{\text{LR}} = \mathcal{A}_e$$

  - Peak cross-sections

$$\sigma_f = 12\pi\frac{\Gamma_e\Gamma_f}{M_Z^2\Gamma_Z^2}$$

  - Ratios of partial widths

$$R_l = \frac{\Gamma_h}{\Gamma_e}, \qquad R_{b,c} = \frac{\Gamma_{b,c}}{\Gamma_h}$$

CALCULATIONS

Status of M_W & $\sin^2\theta_{\mathrm{eff}}$ calculation

Standard Model:

- Full electroweak calculation up to two-loop order, full $\mathcal{O}(\alpha\alpha_s)$, $\mathcal{O}(\alpha\alpha_s^2)$ result.
- Leading universal terms in the relevant parameters at $\mathcal{O}(\alpha_s G_F^2 m_t^4)$,$\mathcal{O}(G_F^3 m_t^6)$, $\mathcal{O}(\alpha\alpha_s^3)$.

[Freitas, Hollik, Walter, Weiglein], [Awramik, Czakon], [Onishchenko, Veretin],

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MSSM in previous analyses:

- One-loop with assumptions (real parameters,. . .).
  [Dabelstein, Hollik, Mösle]
- Leading SM and universal SUSY $O(\alpha\alpha_s)$ terms.
  [Dabelstein, Hollik] & [Heinemeyer, Weiglein]

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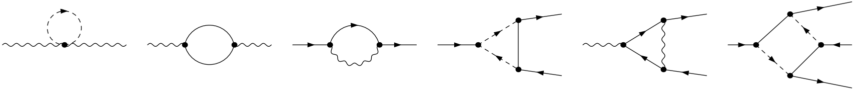

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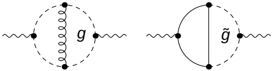

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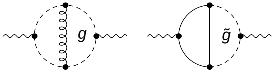

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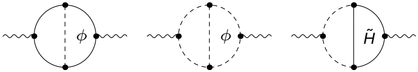

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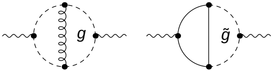

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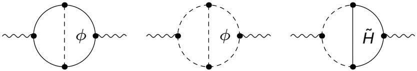

  - Resummation of reducible one-loop contributions.

    [Consoli, Hollik, Jegerlehner]

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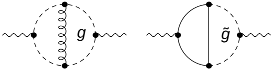

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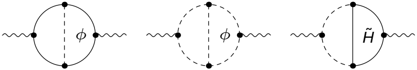

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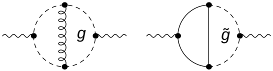

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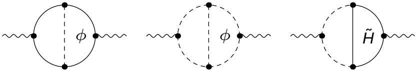

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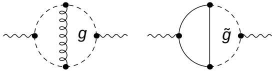

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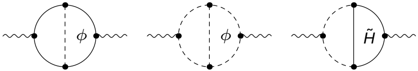

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$\delta M_W^{\text{th}} \approx 4 \ldots 8$ MeV $\qquad \delta \sin^2\theta_{\text{eff}}^{\text{th}} \approx (5.1 \ldots 7.3) \times 10^{-5}$

ANALYSES

- Leading contributions from sfermion sector (in particular stop-sbottom doublet $\Rightarrow$ ρ-parameter).
- Smaller, but non negligible contributions from neutralinos and charginos.
- Standard Model and MSSM gauge boson & Higgs sector yield numerically similar contributions.

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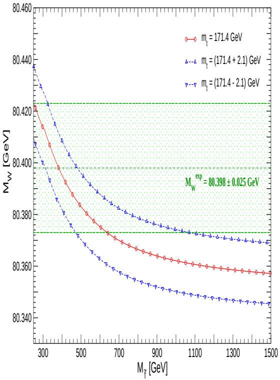
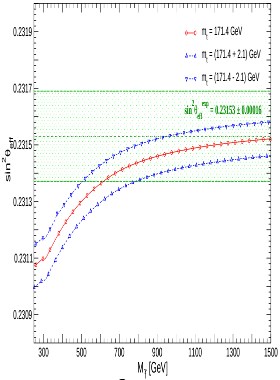
Plots

- Parametric uncertainty induced by top mass.
- Dependence on complex MSSM parameters.
- SPS scenarios.
- Scatter plots.
- Global fits to collider and cosmology data in mSUGRA.

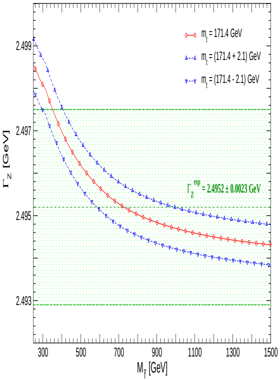
Sfermion mass scale varied, $m_t = (171.4 \pm 2.1)$ GeV.



$M_W(M_{\tilde f})$



$\sin^2\theta^l_{\rm eff}(M_{\tilde f})$



$\Gamma_Z(M_{\tilde f})$

$M_{\tilde f} = 250 \ldots 1500$ GeV, $A_{\tau,t,b} = 2 \cdot M_{\tilde f}$, $\tan\beta = 10$, $\mu = M_2 = m_{\tilde g} = M_A = 300$ GeV

$\Rightarrow$ Sizeable parametric uncertainties induced in $M_W, \sin^2\theta^l_{\rm eff}, \Gamma_Z$ by $\delta m_t = 2.1$ GeV[TEVEWWG,Aug'06].

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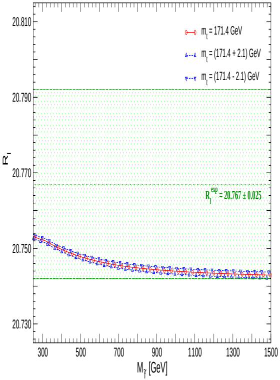
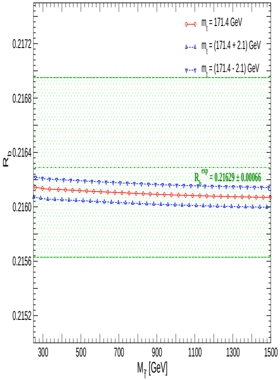
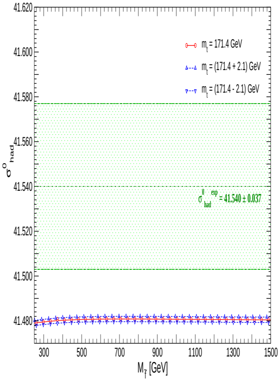


$R_l(M_{\tilde f})$



$R_b(M_{\tilde f})$



$\sigma^0_{\text{had}}(M_{\tilde f})$

$M_{\tilde f} = 250 \ldots 1500$ GeV, $A_{\tau,t,b} = 2 \cdot M_{\tilde f}$, $\tan\beta = 10$, $\mu = M_2 = m_{\tilde g} = M_A = 300$ GeV

$\Rightarrow$ Only weak constraints on MSSM parameters from $R_l, R_b, \sigma^0_{\text{had}}$.

Some complex parameters, in particular ϕ_μ, strongly constrained by EDMs, $\phi_{A_{t,b}}$ almost unconstrained. *[Barger,Falk,Han,Jiang,Plehn]*

$\Rightarrow$ Effects of phases often assumed to be negligible.

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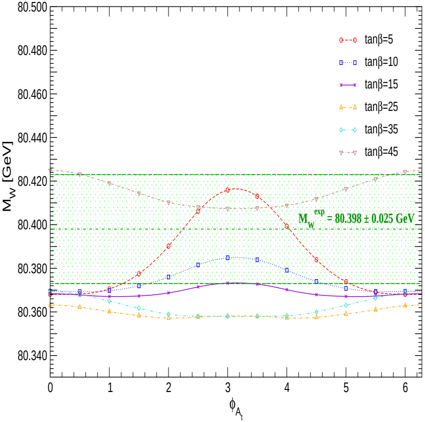
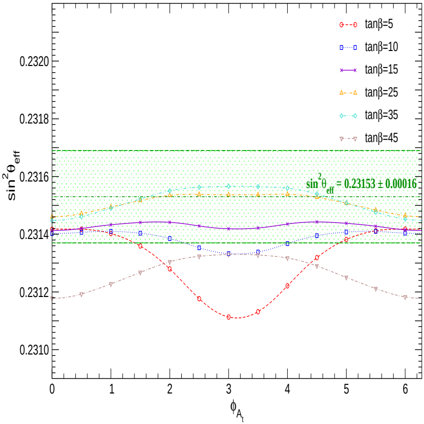


$M_W(\phi_{A_t})$



$\sin^2\theta_{\text{eff}}(\phi_{A_t})$

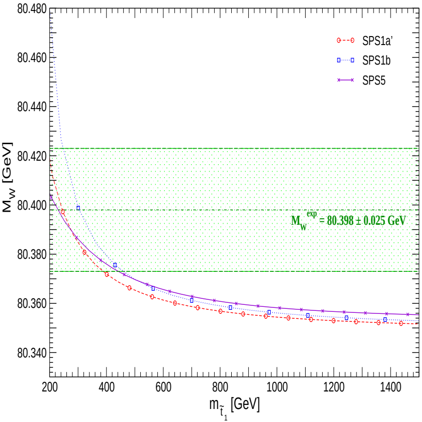
$M_{\tilde{f}} = M_{H^\pm} = M_2 = m_{\tilde{g}} = 500$ GeV, $A_{\tau,t,b} = \mu = 1000$ GeV, $\phi_{A_b,\mu,M_1} = 0$

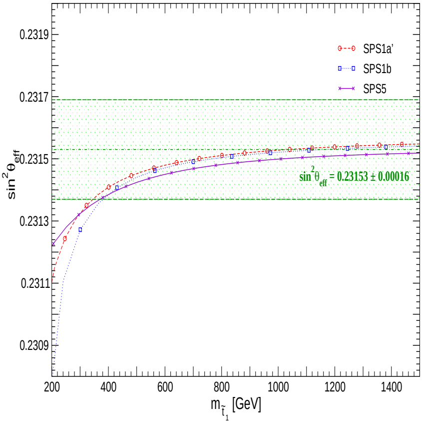
$\Rightarrow$ Large shifts can be induced by complex parameters.

SPS benchmark scenarios

- Benchmark points within “typical” constrained MSSM scenarios.
- SPS scenarios fix low-energy MSSM parameters.
- *here:*

$$M_{A^0} = \text{scalefactor} \cdot M_{A^0}^{\text{SPS}},\ M_{\tilde{F},\tilde{F}'} = \text{scalefactor} \cdot M_{\tilde{F},\tilde{F}'}^{\text{SPS}},$$
$$A_{t,b} = \text{scalefactor} \cdot A_{t,b}^{\text{SPS}},\ \mu = \text{scalefactor} \cdot \mu^{\text{SPS}},$$
$$M_{1,2,3} = \text{scalefactor} \cdot M_{1,2,3}^{\text{SPS}}.$$



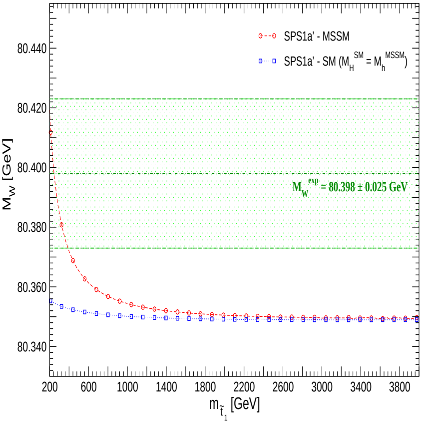


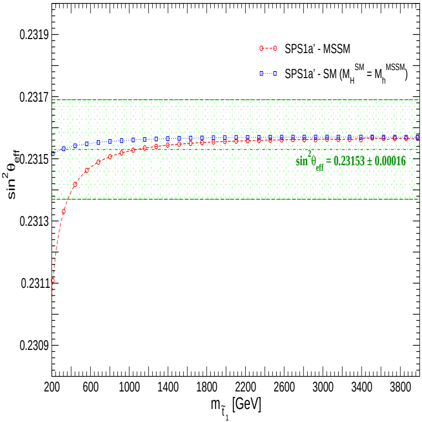
M_W $\sin^2\theta_{\text{eff}}$

SUSY mass scale varied.

$\Rightarrow$ Slight preference for light SUSY from M_W.

$\Rightarrow$ No clear preference for light SUSY from $\sin^2\theta_{\text{eff}}$.





M_W $\qquad\qquad$ $\sin^2\theta_{\text{eff}}$

SUSY mass scale varied.

$\Rightarrow$ MSSM slightly favoured over Standard Model from M_W.

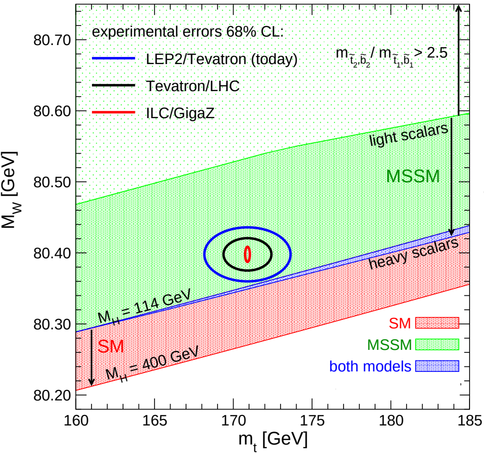
$\Rightarrow$ No preference for MSSM from $\sin^2\theta_{\text{eff}}$.

Scatter plots

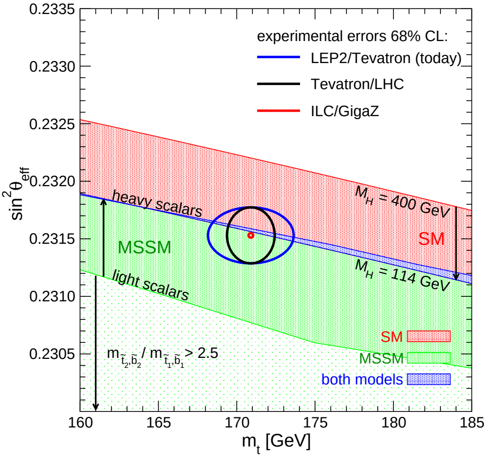
- SUSY parameters:

$$
\begin{aligned}
\text{sleptons} &: \quad M_{\tilde{F},\tilde{F}'} = 100\ldots 2000\ \text{GeV} \\
\text{light squarks} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100\ldots 2000\ \text{GeV} \\
\tilde{t}/\tilde{b}\ \ \text{doublet} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100\ldots 2000\ \text{GeV} \\
& \quad\ \ A_{t,b} = -2000\ldots 2000\ \text{GeV} \\
\text{gauginos} &: \quad M_{1,2} = 100\ldots 2000\ \text{GeV} \\
& \quad\ \ m_{\tilde{g}} = 195\ldots 1500\ \text{GeV} \\
& \quad\ \ \mu = -2000\ldots 2000\ \text{GeV} \\
\text{Higgs} &: \quad M_A = 90 - 1000\ \text{GeV} \\
& \quad\ \ \tan\beta = 1.1\ldots 60
\end{aligned}
$$

- Unconstrained scan, only Higgs mass required to be in agreement with LEP data.



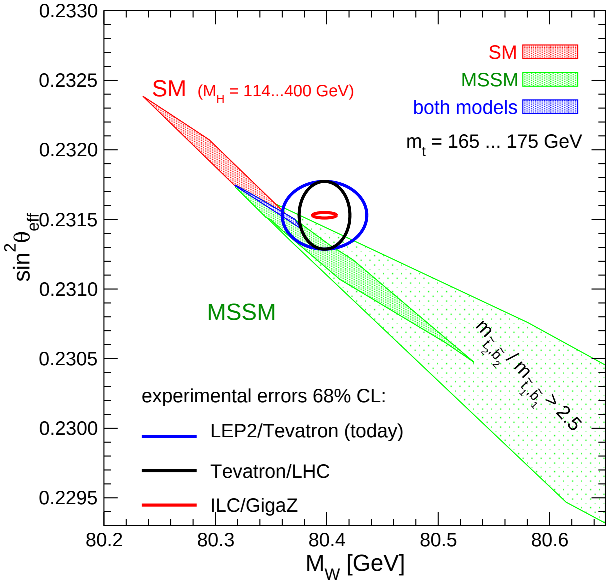
M_W



$\sin^2 \theta_{\text{eff}}$

$\Rightarrow$ Preference of MSSM over SM from M_W.

$\Rightarrow$ MSSM and SM equally good for $\sin^2 \theta_{\text{eff}}$.



$\Rightarrow$ Combination of M_W and $\sin^2\theta_{\text{eff}}$ slightliy favours MSSM.

Global mSUGRA fits & forecasts

[Allanach, Lester, AMW] – JHEP12(2006)065 & forthcoming pub.

- Application of Markov Chain Monte Carlo techniques & Bayesian stats as extension of previous analyses.
  [Allanach, Lester], [Baltz, Gondolo], [Ellis, Heinemeyer, Olive, Weiglein]

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- Bayes theorem :
  *[Bayes, *1702 - †1761]*

$$\underbrace{p(\text{model}|\text{data})}_{\text{posterior probability}} = \underbrace{p(\text{data}|\text{model})}_{\text{likelihood}} \times \underbrace{\frac{\overbrace{p(\text{model})}^{\text{prior}}}{p(\text{data})}}_{\text{probability of data being reproduced}}$$

Prior: subjective prejudice *before* data is taken into account.

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Prior: subjective prejudice *before* data is taken into account.

- Markov Chain MC sampling: efficient way of sampling mSUGRA and Standard Model parameter space.
  $\Rightarrow$ Final density of points in chain $\propto$ posterior probability.
  $\Rightarrow$ Required number of samples goes linearly with number of dimensions.

- mSUGRA parameters:
  - Before EW symmetry breaking

$$A_0, m_0, M_{1/2}, B, \mu$$

  - After EW symmetry breaking

$$A_0, m_0, M_{1/2}, \tan\beta, \mathrm{sign}(\mu), M_Z^{\mathrm{exp}}$$

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- Application of different priors:
  - Flat priors on $A_0, m_0, M_{1/2}, \tan\beta$.
  - Flat priors on $A_0, m_0, M_{1/2}, B, \mu$ & favour mSUGRA parameters within same order of magnitude.

same order prior: e.g. $p(m_0|M_{\mathrm{SUSY}}) = \frac{1}{\sqrt{2\pi w^2} m_0} \exp\left(-\frac{1}{2w^2}\log^2(m_0/M_{\mathrm{SUSY}})\right)$, $w = 1, 2\ldots$

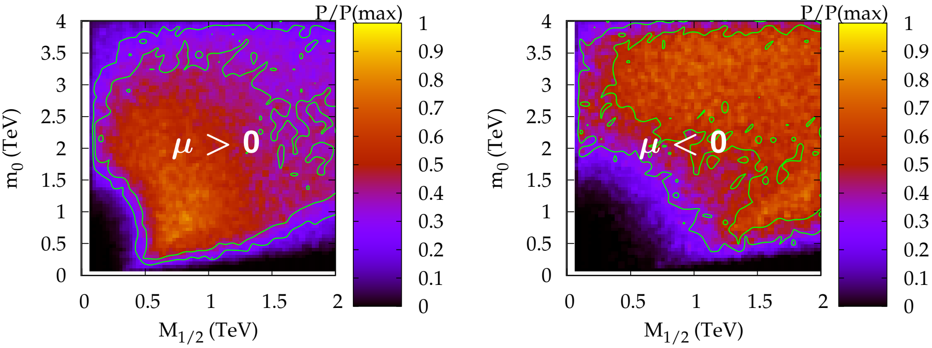
$$\Rightarrow \log\left(m_0/M_{\mathrm{SUSY}}\right) \text{ within } \pm w \quad @68\%\mathrm{CL}$$

$\Rightarrow$ Flat prior before EWSB “natural”.

For global fit:

- SM input varied in 4σ range (χ^2 penalty applied).
- MSSM spectrum from `SOFTSUSY2.0.10`.
  [Allanach]
- mSUGRA parameter space constrained by
  - Dark matter relic density $\Omega_{DM}h^2$.
    [`microOMEGAS1.3.6`]
  - Branching ratios $BR(b \to s\gamma)$, $BR(B_s \to \mu^+\mu^-)$.
    [`microOMEGAS1.3.6`]
  - Higgs mass m_h.
    [`SOFTSUSY2.0.10`]
  - Anomalous magnetic moment $\delta a_\mu \equiv \delta\frac{(g-2)_\mu}{2}$.
    [`microOMEGAS1.3.6`, *D. Stöckinger]*
  - W boson mass M_W and effective leptonic mixing angle $\sin^2\theta_{\text{eff}}$

Posterior probability maps, flat priors on $A_0, m_0, M_{1/2}, \tan\beta$ after EWSB



no DM constraints

$\Rightarrow$ Without WMAP data hardly any predictivity.

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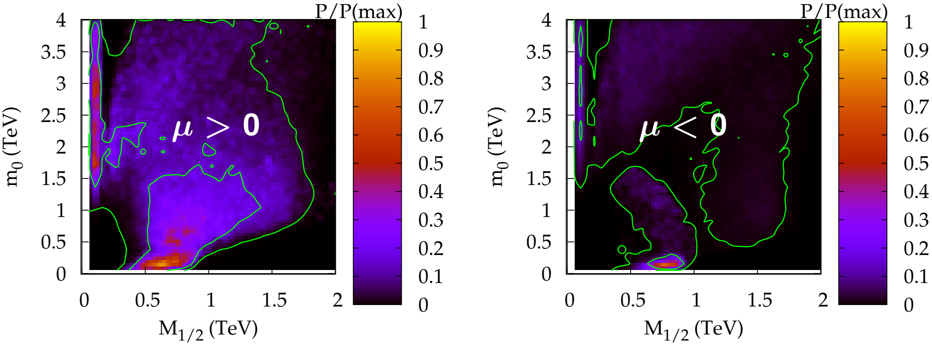
Stringent constraints from DM relic density.



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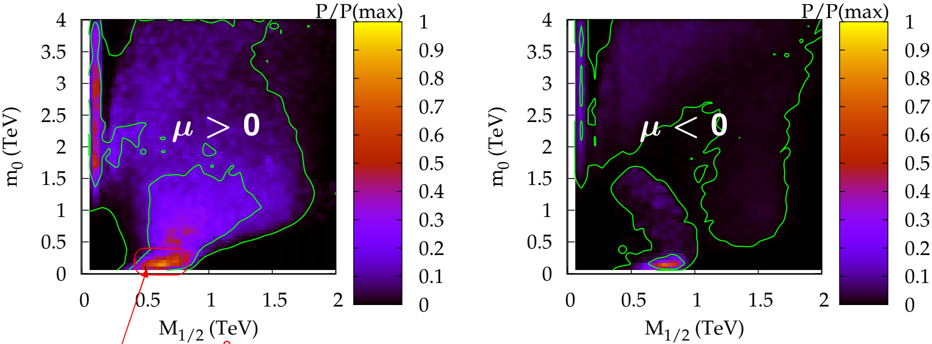

$\tilde{\tau}$ co-annihilation, $\tilde{\tau}_1 \tilde{\chi}_1^0 \to \tau\gamma$

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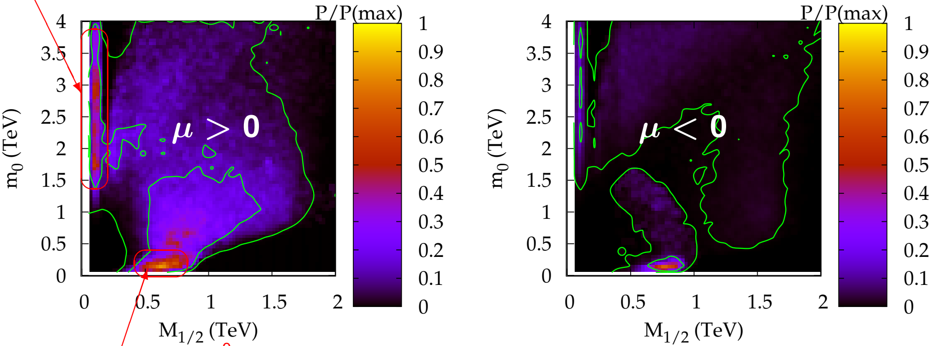

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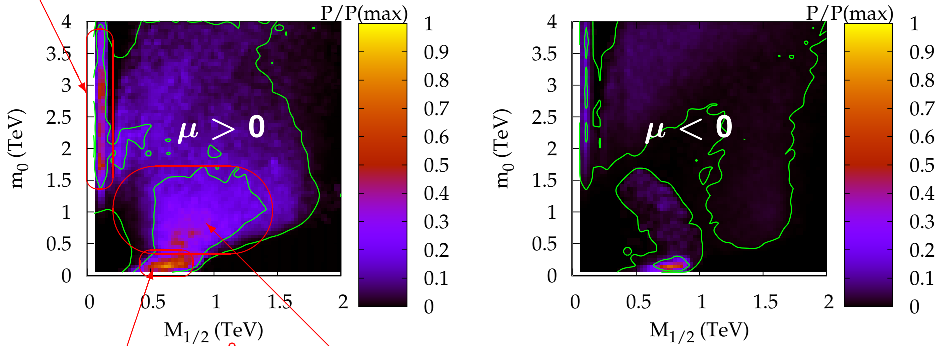

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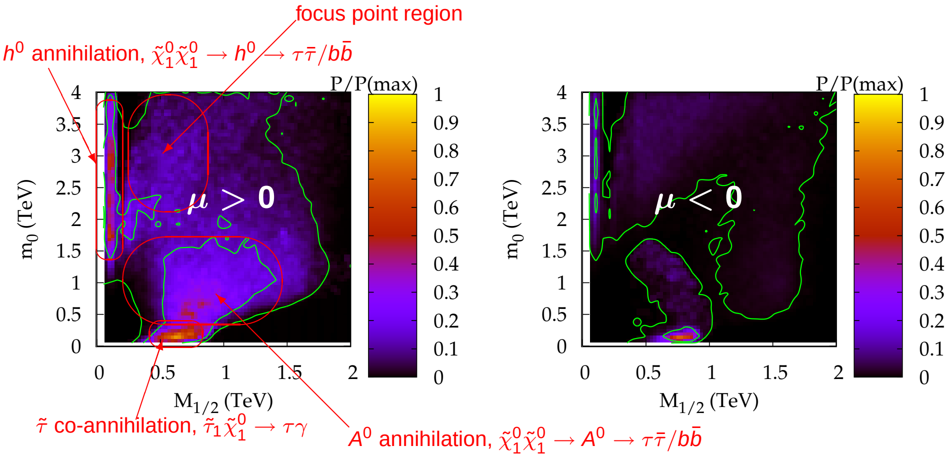

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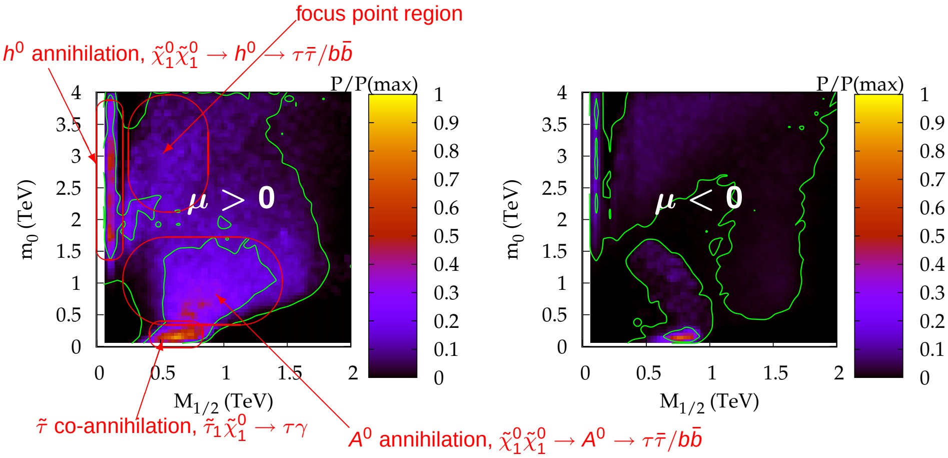

$P(\mu < 0)/P(\mu > 0) = 0.07 - 0.16$

$\Rightarrow \mu < 0$ not completely ruled out by $(g-2)_\mu$ as often assumed (for flat priors on $A_0, m_0, M_{1/2}, \tan\beta$).

Now: flat priors on $A_0, m_0, M_{1/2}, B, \mu$ before EWSB
& mSUGRA parameters of same order

$\Rightarrow$ large $\tan\beta$ disfavoured $\Rightarrow$ A^0 pole region suppressed
$\Rightarrow$ large values of A_0 disfavoured $\Rightarrow$ h^0 pole region suppressed
$\Rightarrow$ large m_0 disfavoured $\Rightarrow$ focus point region suppressed

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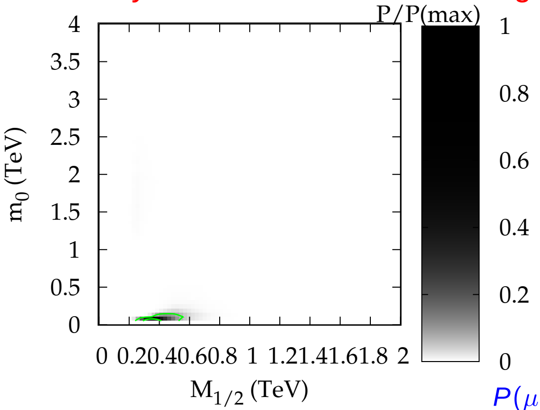
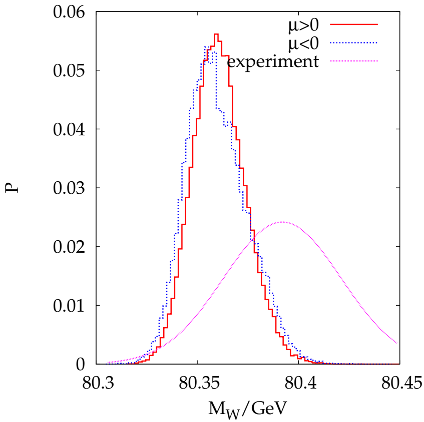
$\Rightarrow$ Good fit only for stau co-annihilation region.



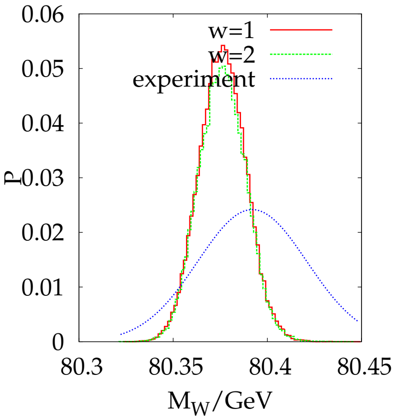
$\Rightarrow$ Light SUSY spectra.

$P(\mu < 0)/P(\mu > 0) = 0.002 - 0.006$

posterior probability M_W



flat priors on $A_0, m_0, M_{1/2}, \tan\beta$

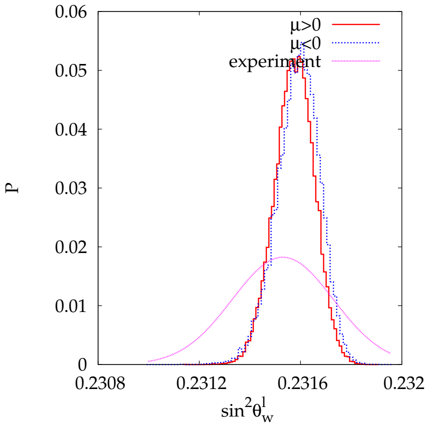


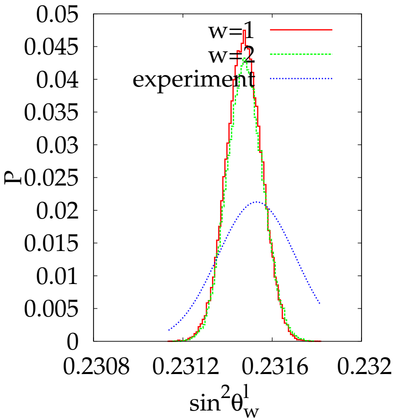
natural priors

flat prior: M_W distribution peak considerably below experimental value.

natural prior: M_W distribution peak close to experimental value.

$\Rightarrow$ Light SUSY favoured for natural priors posterior probability $\sin^2\theta_{\text{eff}}$





flat priors on $A_0, m_0, M_{1/2}, \tan\beta$

natural priors

flat prior: $\sin^2\theta_{\text{eff}}$ distribution peak above experimental value.

natural prior: $\sin^2\theta_{\text{eff}}$ distribution peak below experimental value.

$\Rightarrow$ Light SUSY favoured for natural priors

CONCLUSIONS

- Why precision physics?
    - Match experimental accuracy.
    - Test Standard Model and its extensions.
    - Dust for fingerprints of new physics.

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  - Sizeable effects from phases.
  - Slight preference for light SUSY.
  - Slight preference for MSSM over Standard Model.

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  - Sizeable effects from phases.
  - Slight preference for light SUSY.
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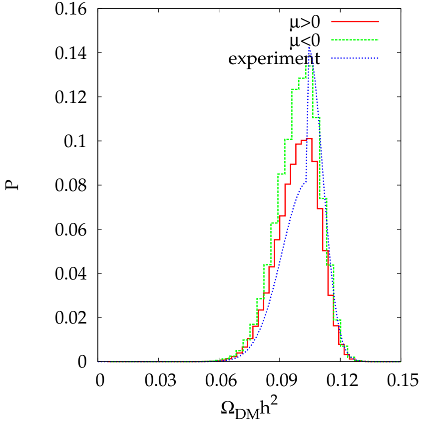
- Global mSUGRA fits:
  - Dominated by DM constraints.
  - Preference for light SUSY for natural priors.

Outlook

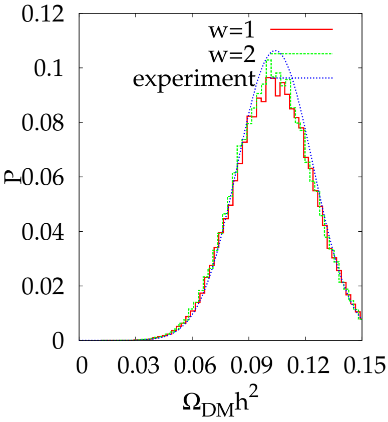
- Publication of results for Z observables in the MSSM & latest mSUGRA analysis.
- Extend computation and analysis to non-minimal models.
- Further detailed studies in constrained MSSM scenarios (NUHM, AMSB,$\ldots$).
- Preparation of public computer code ($\Rightarrow$ LHC analyses).

Supplementary material

Fits closely follow constraints from DM relic density



flat priors on $A_0, m_0, M_{1/2}, \tan\beta$



natural priors

Split SUSY

- Heavy scalar sfermions.
- Standard Model like Higgs sector.
- Relatively light SUSY fermions (neutralinos & charginos), i.e. still good cold dark matter candidate.

$\Rightarrow$ Preserve nice SUSY properties, “remove” troublesome scalars from phenomenology.

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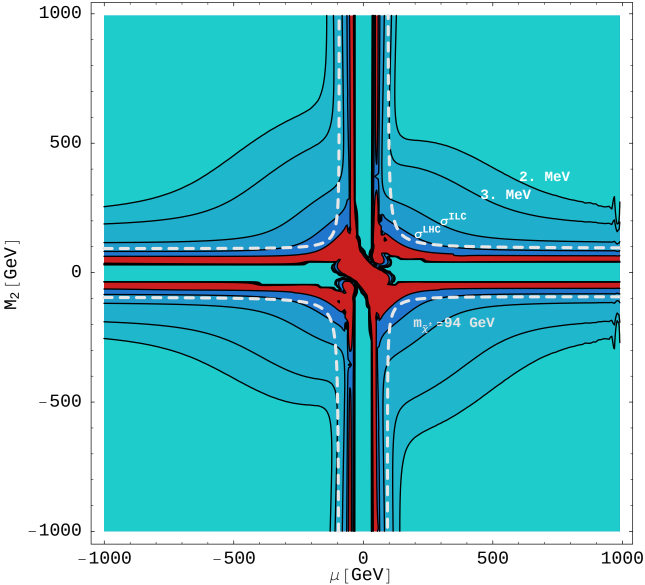
- Can we tell Standard Model and Split SUSY apart?

$\Rightarrow$ Plots for:

$$\delta M_W = M_W^{\text{MSSM}} - M_W^{\text{SM}}$$

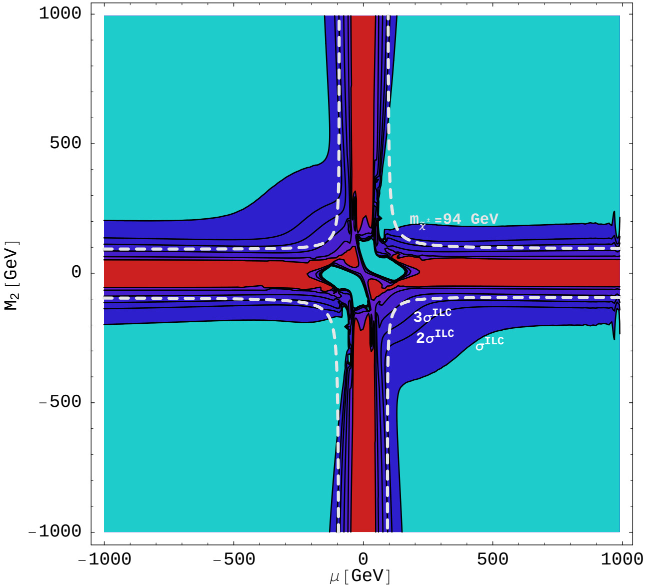
$$\delta \sin^2\theta_{\text{eff}} = \sin^2\theta_{\text{eff}}^{\text{MSSM}} - \sin^2\theta_{\text{eff}}^{\text{SM}}$$

Limited potential via M_W, even at ILC



$M_{\tilde{f}} = 5000$ GeV, $A_{\tau,t,b} = 2M_{\tilde{f}}$, $\tan\beta = 10$, $M_A = 2500$ GeV, $m_{\tilde{g}} = 500$ GeV

Situation slightly more promising for $\sin^2\theta_{\text{eff}}$



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