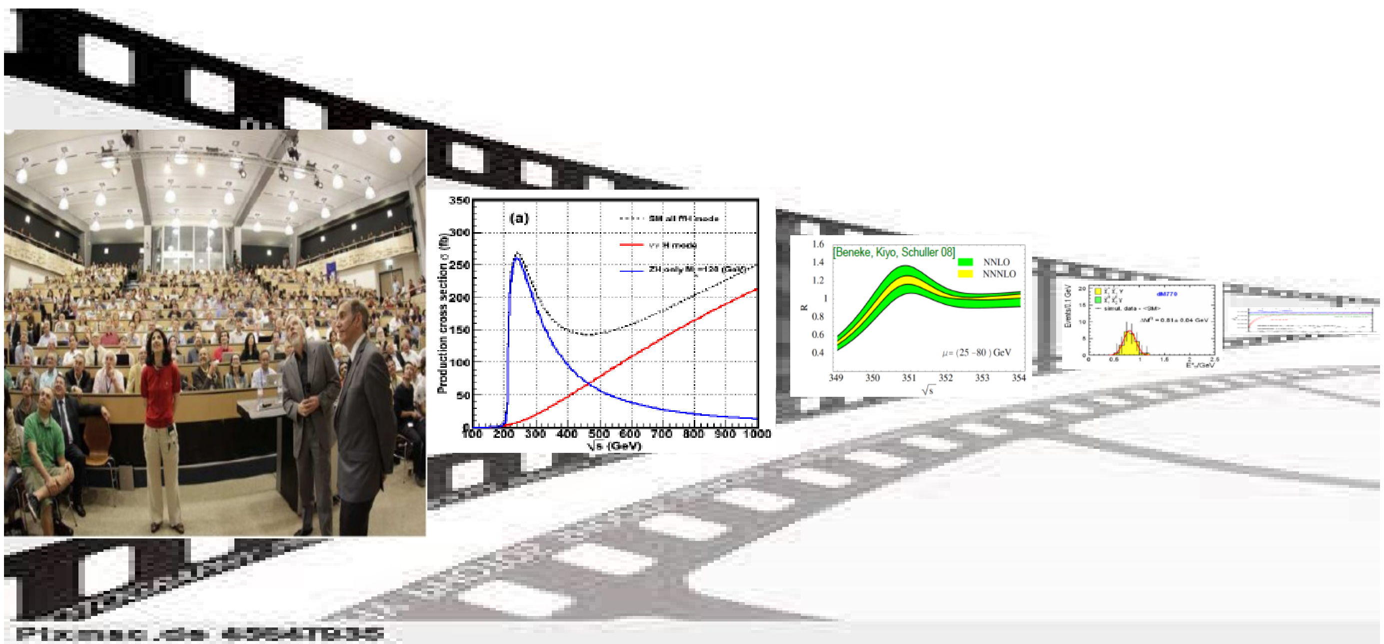
LC Physics School
BSM Theory

G. Moortgat-Pick
(Uni Hamburg/DESY)



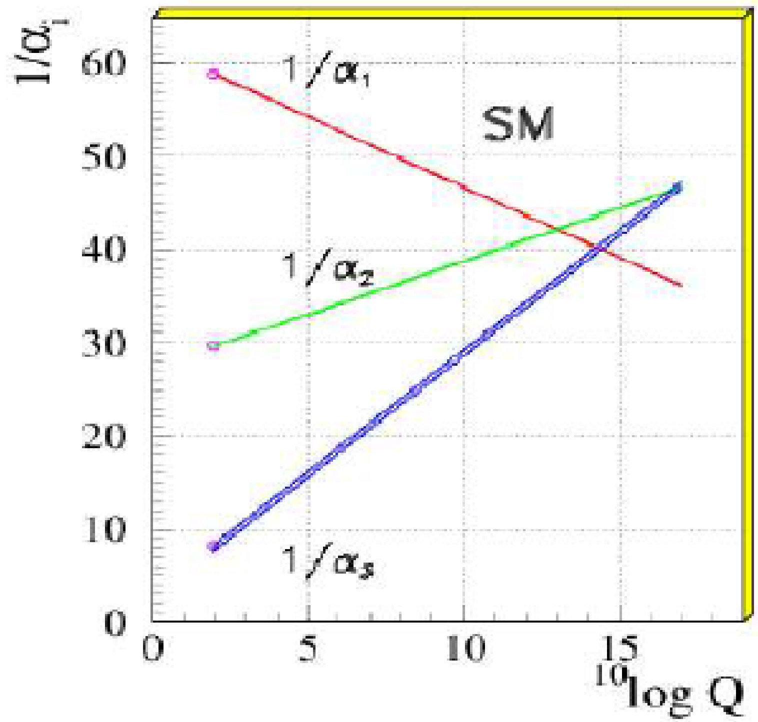
LINEAR COLLIDER COLLABORATION

Why is the SM incomplete?

The SM is tremendously successful description of the physics that we have tested so far at experiments.

Why are we not happy?

- doesn't contain gravity
- doesn't explain neutrino masses
- doesn't have candidate for dark matter
  - → 23% of universe is cold dark matter!
- no unification of gauge couplings possible
- further problem: `hierachy problem'
  - → Higgs mass unstable w.r.t. large quantum corrections: $\delta M_H^2 \sim \Lambda^2$

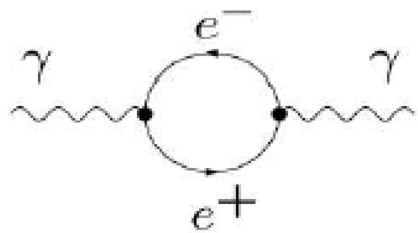


The Hierarchy Problem

Consider loop corrections to propagators ⟷ corrections to masses

$$\Delta(p^2) \sim \frac{1}{p^2 - m^2 + \Sigma(p^2)}$$

- Photon self-energy in QED:



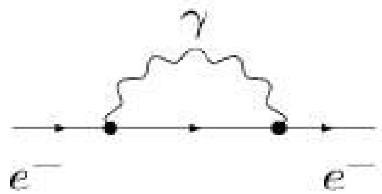
$$\Sigma^{\gamma\gamma}(0) = 0$$

- consequence of U(1) gauge invariance of QED ⟶ photon stays massless

$$\Delta^{-1}_{\gamma\gamma}(p^2) \rightarrow 0 \text{ for } p^2 \rightarrow 0$$

Hierarchy II

- **Electron self-energy in QED:**



for $\Lambda \to \infty$: $\Sigma^{ee} \sim m_e \int^{\Lambda} \frac{dk}{k} \to \ln \Lambda$

$\longrightarrow$ **logarithmically divergent correction to electron mass** δm_e

Within QED: divergence can be removed via renormalization
$\Rightarrow k \to \infty$ possible

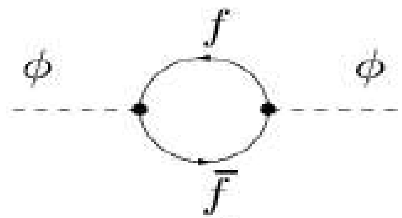
QED as effective theory, underlying more fundamental theory at scale $\Lambda \Rightarrow$ cutoff scale

For $\Lambda = M_{\rm PL}$: $\delta m_e \approx 2\frac{\alpha}{\pi} m_e \log(M_{\rm PL}/m_e) \approx 0.2 m_e$
$\longrightarrow$ modest correction, proportional to m_e
reason: chiral symmetry in limit $m_e \to 0$, $\psi_e \to \exp(i\gamma_5\theta)\psi_e$

$\longrightarrow$ breaking proportional to m_e $\longrightarrow$ symmetry protects m_e

Hierarchy III

Contribution of heavy fermions to Higgs self-energy:



$$\Sigma_f^{\phi\phi} \sim -2\,N(f)\,\lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

for $\Lambda \to \infty$: $$\Sigma_f^{\phi\phi} \sim -2\,N(f)\,\lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

→ quadratically divergent!

For $\Lambda = M_{\mathrm{P}}$: $\delta M_\phi^2 \sim M_{\mathrm{P}}^2 \Rightarrow \delta M_\phi^2 \approx 10^{30}\, M_\phi^2$ ($M_\phi \lesssim 1$ TeV)

no additional symmetry for M_Φ =0, no protection against large corrections

→ in general: scalar masses tend to be near highest theory mass scale

→ hierarchy problem, extreme fine-tuning necessary to get small M_Φ

Requests to BSM models

- New physics model should explain all SM shortcomings?
  - → unification of all interactions?
  - → hierarchy?
  - → explain three families?
  - → embed gravity?
  - → embed neutrino masses?
  - → be consistent with all experimental bounds (electroweak precision, EDM,...)?
  - → baryon asymmetry in the universe? dark matter?
- Renormalizable (up to which scale)? (SM up to $\Lambda < M_{\mathrm{Pl}} \approx 10^{19}$ GeV !)
- Should recover the SM?

⟶ SUSY is a mature candidate ! (provides an answer to almost all questions)

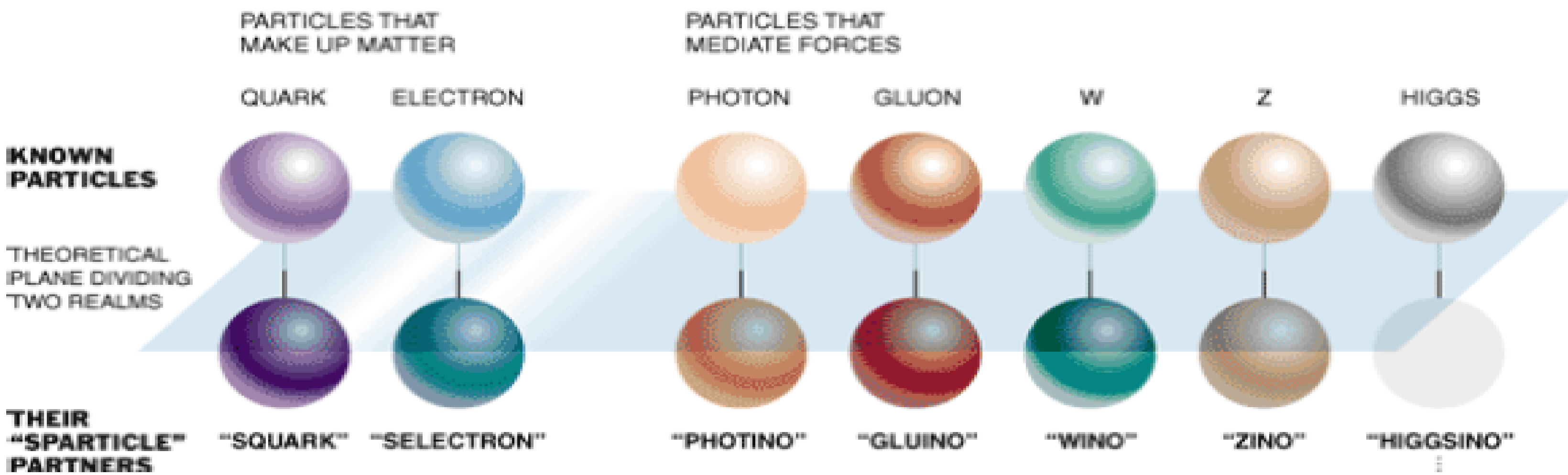
Does not mean that it will be the right theory, but one learns a lot!

Supersymmetry

- **Idea:** ***New symmetry relating internal symmetries (gauge invariance) to space-time symmetries (general relativity)?***

fermions ⟷ **bosons**

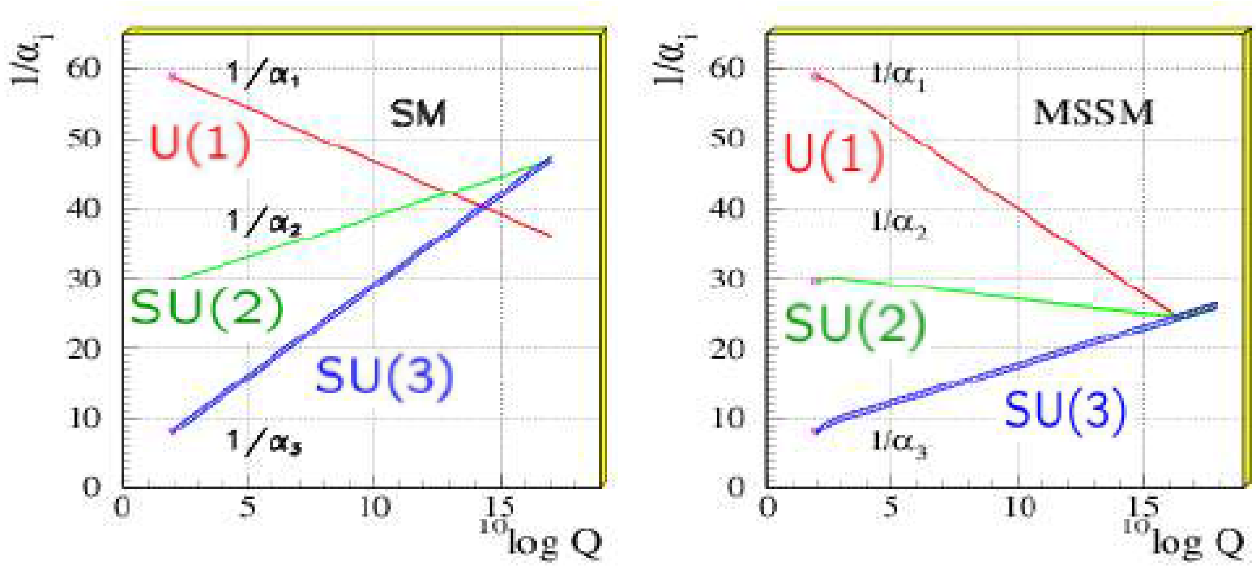
Postulates "superpartners" for all known particles



Lightest supersymmetric particle: stable, best candidate for dark matter in the Universe

Properties of SUSY theories -- Unification

- **Gauge coupling unification:**
  - Running of gauge couplings: $$\frac{1}{g^2(\mu^2)} = \frac{1}{g^2(\mu_0^2)} + \beta \ln\left(\frac{\mu^2}{\mu_0^2}\right)$$



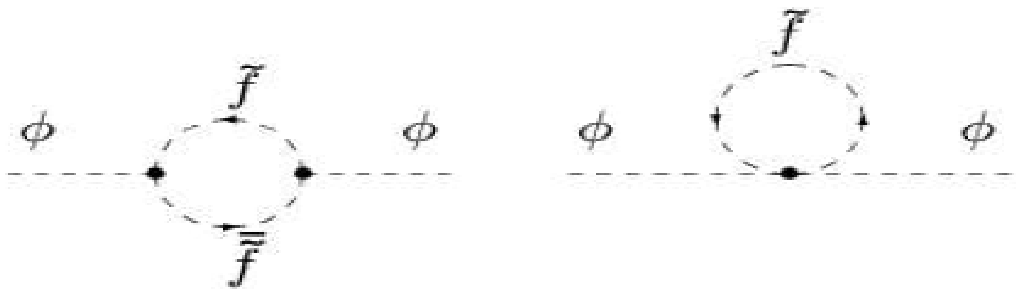
  - coupling constant unification in MSSM for $M_{SUSY} \lesssim 1$ TeV

Unification of couplings at high scale ↔ `Grand unified theories' (GUT)

  - E.g. SO(10) GUTs, can naturally accommodate right-handed neutrinos

Hierarchy problem in SUSY

- **Symmetry between fermions and bosons**
  - → Q | boson > = | fermion >   and   Q | fermion > = | boson >
  - → In other words: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)
- <u>SUSY:</u>



$$\Sigma_{\tilde{f}}^{\phi\phi} \sim N(\tilde{f})\, \tilde{\lambda}_f \int d^4k \left(\frac{1}{k^2 - m^2_{\tilde{f}_L}} + \frac{1}{k^2 - m^2_{\tilde{f}_R}} \right) + \text{terms without quadratic divergencies}$$

for $\Lambda \to \infty$: $\Sigma_{\tilde{f}}^{\phi\phi} \sim 2\, N(\tilde{f})\, \tilde{\lambda}_f\, \Lambda^2$

Hierarchy problem in SUSY

- **Quadratic divergencies cancel for:** $N(\tilde{f}_L) = N(\tilde{f}_R) \;=\; N(f)$
  $\tilde{\lambda}_f \;=\; \lambda_f^2$

  complete correction vanishes if furthermore: $m_{\tilde{f}} = m_f$

  For $m_{\tilde{f}}^2 = m_f^2 + \Delta^2, \quad \tilde{\lambda}_f = \lambda_f^2,$ "soft SUSY breaking"

  $$\Rightarrow \Sigma_{f+\tilde{f}}^{\phi\phi} \sim N(f)\,\lambda_f^2\,\Delta^2 + \ldots$$

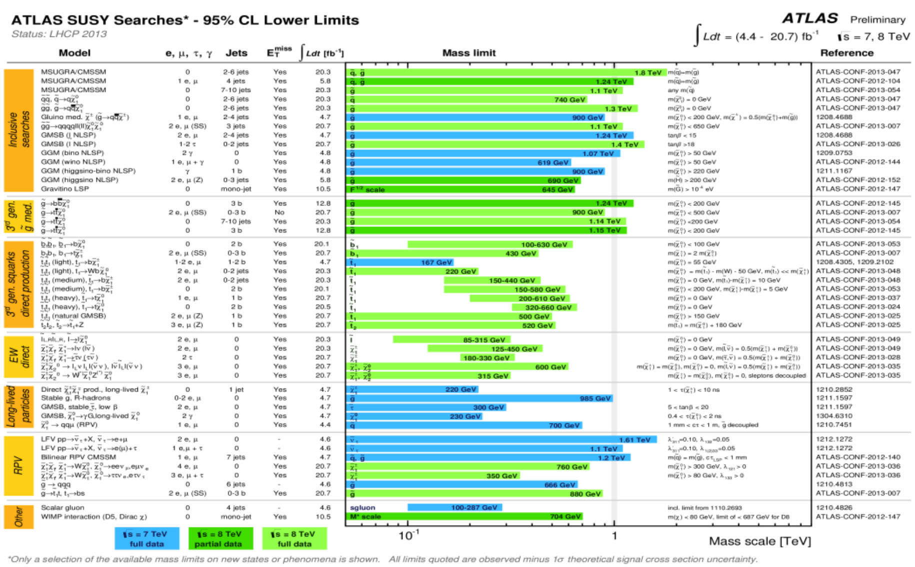
  → correction acceptable small if mass splitting is of weak scale
- **realized if mass scale of SUSY partners**

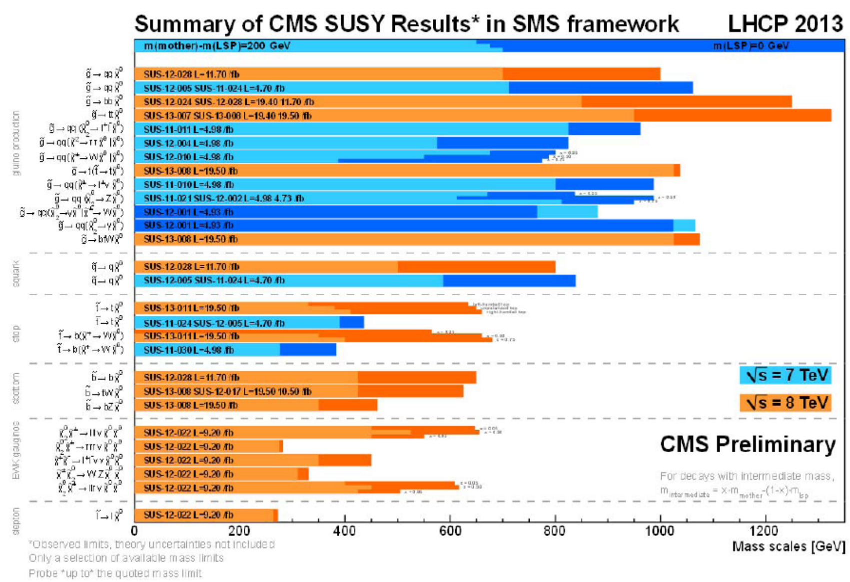
  $$M_{\mathrm{SUSY}} \lesssim 1\ \mathrm{TeV}$$

→ SUSY at TeV scale provides attractive solution of hierarchy problem

Impact from LHC BSM limits

- **SUSY: still strongly motivated and beautiful, but**
  - so far, no hints of a signal, only rather high exclusion limits in the coloured sector
  - Constrained models (CMSSM,…) + Simpl. Models under tension!





- **But is this the full story? Which assumptions are made?**

Soft SUSY Breaking

- Exact SUSY: $m_f = m_{\tilde{f}}$ $\longrightarrow$ SUSY must be broken in nature!
- Only way for model of SUSY breaking:

  $\rightarrow$ spontaneous SUSY breaking

  > specific SUSY-breaking schemes yield effective Lagrangian at low energies, which is supersymmetric except for explicit soft breaking terms

- Soft SUSY-breaking terms: do not alter dimensionless couplings (i.e. dimension of coupling constants of soft SUSY-breaking terms > 0)

$\longrightarrow$ no quadratic divergences (in all orders of perturbation theory)
scale of SUSY-breaking terms: $M_{\text{SUSY}} \lesssim 1$ TeV

SUSY breaking schemes

`Hidden sector': → Visible sector:

SUSY breaking → MSSM

` Gravity-mediated': mSUGRA

`Gauge-mediated': GMSB

`Anomaly-mediated': AMSB

.....

- SUGRA: mediating interactions are gravitational
- GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions
- AMSB: SUSY breaking happens on a different brane in a higher-dimensional theory

- Feature of schemes: lead to 'characteristic' mass spectra

➢ **But these are strong assumptions…. !**

Free Parameters in the MSSM

- mass matrices are 3 x 3 hermitian

  → m_Q^2, m_u^2, m_d^2, m_L^2, m_e^2 : 45 parameters

- gaugino masses M_1, M_2, M_3 are complex numbers: 6
- trilinear couplings a_u, a_d, a_e are 3 x 3 complex matrices: 54
- bilinear coupling b is 2 x 2 matrix: 4
- Higgs masses m^2_{Hu}, m^2_{Hd} : 2

→ altogether 111 parameter ???

Symmetries (lepton + baryon number, Peccei-Quinn, R symmetry) lead to'rotations':

-4 non-trivial field redifinitions

-2 in the Higgs sector (since minimal model only 2 parameters in the Higgs sector)

→ $\boxed{\text{remain 105 free new parameters in the MSSM!}}$

Relations between SUSY parameters

- Symmetry properties of MSSM Lagragian (SUSY, gauge invariance) give conditions to couplings and mass relations

  → z.B. gauge-boson-fermion coupling = gaugino-fermion-sfermion coupling for U(1), SU(2) and SU(3) gauge groups

  → In SM: all masses are free input parameters (except m_W--m_Z interdependence)

  → MSSM:

  relations between chargino and neutralino masses (soft breaking+ew breaking)

  sfermion mass relations (gauge invariance): $m^2_{\tilde{e}_L} = m^2_{\tilde{\nu}_L} - M^2_W \cos(2\beta)$

  upper bound on mass of lightest CP-even Higgs boson

- All relations receive contributions from loop effects

→ experimental verification of relations is crucial test of SUSY

→ experimental tests of all quantum numbers required

Any further hints ?

- **Low energy experiments, $(g\text{-}2)_\mu$:**
  - favours rather low SUSY masses in electroweak sector:

$$\delta a_\mu(\mathrm{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$$

    - C very model dependent, SUSY/ED ~ $O(\alpha/4\pi \ldots)$
  - LHC results prefer rather heavy coloured sector in 1^{st} +2^{nd} generation
  - Way out: rather simple
    - Decouple uncoloured and coloured sector and/or take hybrid models of SUSY breaking
    - Just leave out the constrained minimal models, that's all

Remember: Minimal SUSY contains 105 new parameter… why should nature be too simple ?

Why 'should' light SUSY be preferred?

- **Minimization of 1-loop Higgs Potential:**

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2$$

- **To keep EWFT ~ 3%:**
  - **rather small μ (~200 GeV) required**
  - **'naturalness'**
  - **Several 'natural' scenarios, e.g. light higgsinos,…**

Papucci,Ruderman,Weiler 2011
Baer,Barger,Huang, Tata, 2012

Higgsino-like scenarios

- Can be embedded in hybrid gauge-gravity mediation
  - 'M' driven by gauge-mediation
  - 'μ' driven by gravity mediation
- Two examples as 'prototypes' under study

Bruemmer,List,GMP, Rolbiecki,Sert'13

$$M_1 = 1.70\,\text{TeV},\; M_2 = 4.36\,\text{TeV},\; \mu = 165.66\,\text{GeV},\; \tan\beta|_{m_Z} = 44,$$
$$M_{\tilde\chi^\pm_1} = 165.77\,\text{GeV},\; M_{\tilde\chi^0_1} = 164.17\,\text{GeV},\; M_{\tilde\chi^0_2} = 166.87\,\text{GeV},\; m_h = 124\,\text{GeV};$$
$$M_1 = 5.30\,\text{TeV},\; M_2 = 9.51\,\text{TeV},\; \mu = 167.22\,\text{GeV},\; \tan\beta|_{m_Z} = 48,$$
$$M_{\tilde\chi^\pm_1} = 167.36\,\text{GeV},\; M_{\tilde\chi^0_1} = 166.59\,\text{GeV},\; M_{\tilde\chi^0_2} = 167.63\,\text{GeV},\; m_h = 127\,\text{GeV}.$$

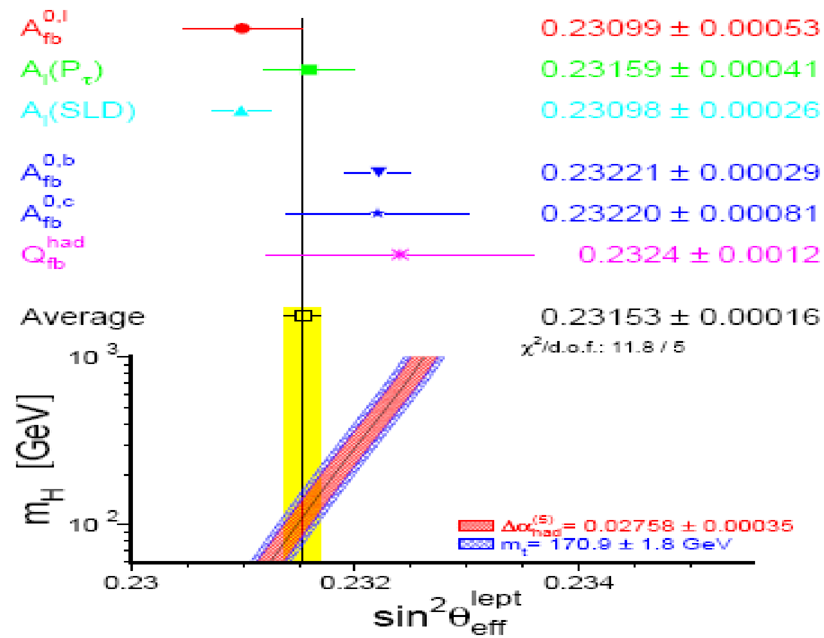
- Higgsino masses: $m_{\chi 0_1}$ ~165 GeV, $m_{\chi 0_2}$ ~167 GeV, $m_{\chi\pm_1}$ ~166 GeV
- Feature: $\Delta m(_{\chi\pm 1-\chi 01})$~770 MeV (1.6 GeV), $\Delta m(_{\chi 02-\chi 01})$~1.04 (2.7) GeV
  - Challenges: mass degeneration, many π's, soft γ, E_{miss} from decay
  - How to resolve such scenarios? *(pst, top secret, see Hale Serts's talk.....only remember ISR........!)*

What if nothing else than H is found now?

- Since m_H is free parameter in SM at tree level
  - Crucial relations exist, however, between m_{top}, m_W and $\sin^2\theta_{eff}$
  - If nothing else appears in the electroweak sector, these relations have to be urgently checked in order to
    a) distinguish between SM and Higgs in BSM models (remember $\Delta m_H \sim m^4_{top}$ in BSM!)
    b) Close the SM picture ?
- Which strategy should one aim?
  - exploit precision observables and check whether the measured values fit together at quantum level
  - m_Z ,m_W,α_{had}, $\sin^2\theta_{eff}$ und m_{top}
- Exploit `GigaZ' option: high lumi run at $\sqrt{s}$ = 91 GeV

Pe-=80% and Pe+=60% required ! (If only Pe-=90% : precision ~factor 4 less!)

Higgs story has just started … $\sqrt{s}$=91 GeV



LEP:

$\sin^2\theta_{eff}(A_{FB}{}^b)$= 0.23221±0.00029

SLC:

$\sin^2\theta_{eff}(A_{LR})$= 0.23098±0.00026

World average:

$\sin^2\theta_{eff}$ = 0.23153±0.00016

Goal GigaZ: $\Delta\sin\theta$=1.3 10^{-5}

- **Uncertainties from input parameters: Δm_Z, $\Delta\alpha_{had}$, m_{top} ,…**

Heinemeyer, Kraml, Porod, Weiglein

- **Δm_Z=2.1 MeV:** $\Delta\sin^2\theta_{eff}{}^{para}$~$1.4\times10^{-5}$
- **$\Delta\alpha_{had}$~10 (5 future) x 10^{-5} :** $\Delta\sin^2\theta_{eff}{}^{para}$~3.6 (1.8 future)$\times10^{-5}$
- **Δm_{top}~1 GeV (Tevatron/LHC):** $\Delta\sin^2\theta_{eff}{}^{para}$~$3\times10^{-5}$
- **Δm_{top}~0.1 GeV (ILC):** $\Delta\sin^2\theta_{eff}{}^{para}$~$0.3\times10^{-5}$

Higgs story has just started … $\sqrt{s}=91$ GeV

$A_{fb}^{0,l}$ 0.23099 ± 0.00053

$A_l(P_\tau)$

A_l(SLD

$A_{fb}^{0,b}$

$A_{fb}^{0,c}$

Q_{fb}^{had}

Averag

00029

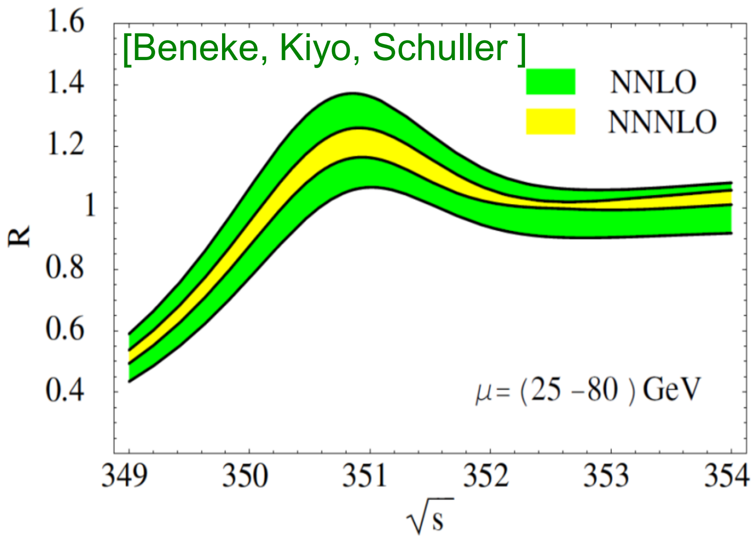
00026

6

- Unce

- But such a precision requires Δm_{top}=0.1 GeV

$\sqrt{s}=350$ GeV



Important shift due to non-logarithmic NNNLO terms

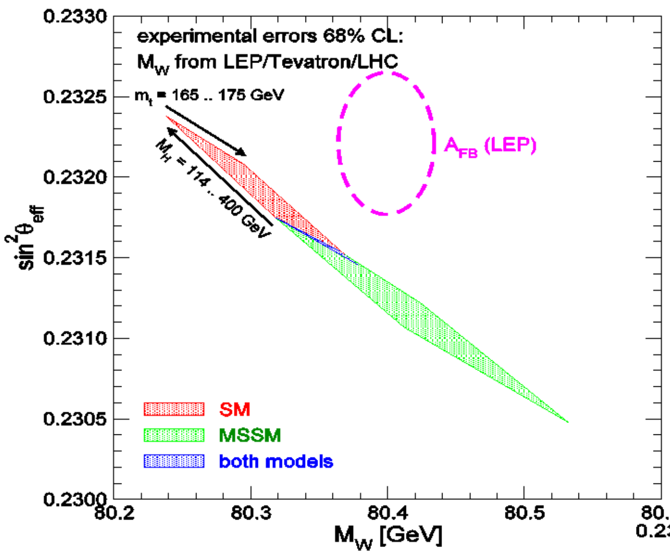
Weiglein

- LC: Peak position remains stable: Δm_t=100 MeV
- includ. exp uncertainty + theo. uncertainty !
- expected accuracy confirmed by full simulation studies!
- Dedicated threshold scan required with about ~100fb^{-1}

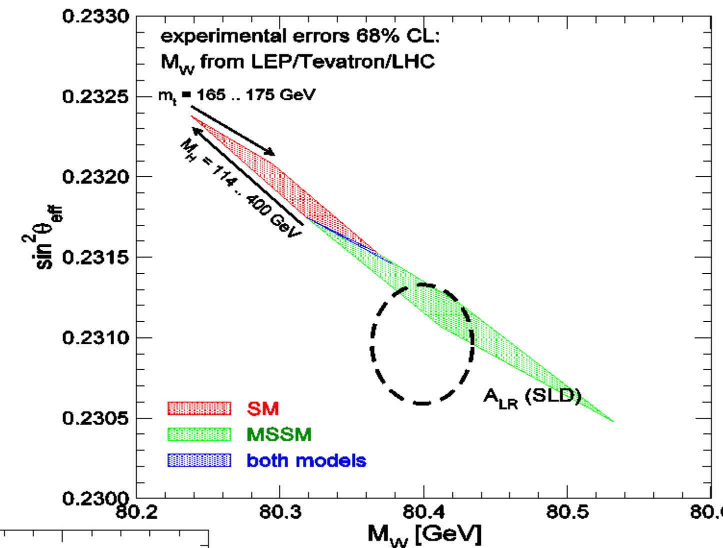
To close the story… GigaZ $\sqrt{s}$=91 GeV

- **Measure $\sin^2\theta_{eff}$ via A_{LR} with high precision: $\Delta\sin\theta = 1.3\ 10^{-5}$**

Heinemeyer, Hollik, Weber, Weiglein



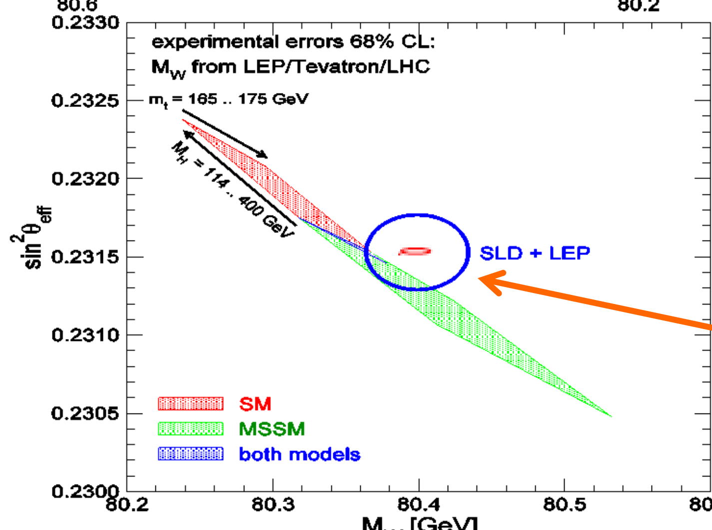
← LEP value disfavours both, SM+MSSM



↑ SLD value disfavours SM

World average → happy with both!

Central value has large impact !!!

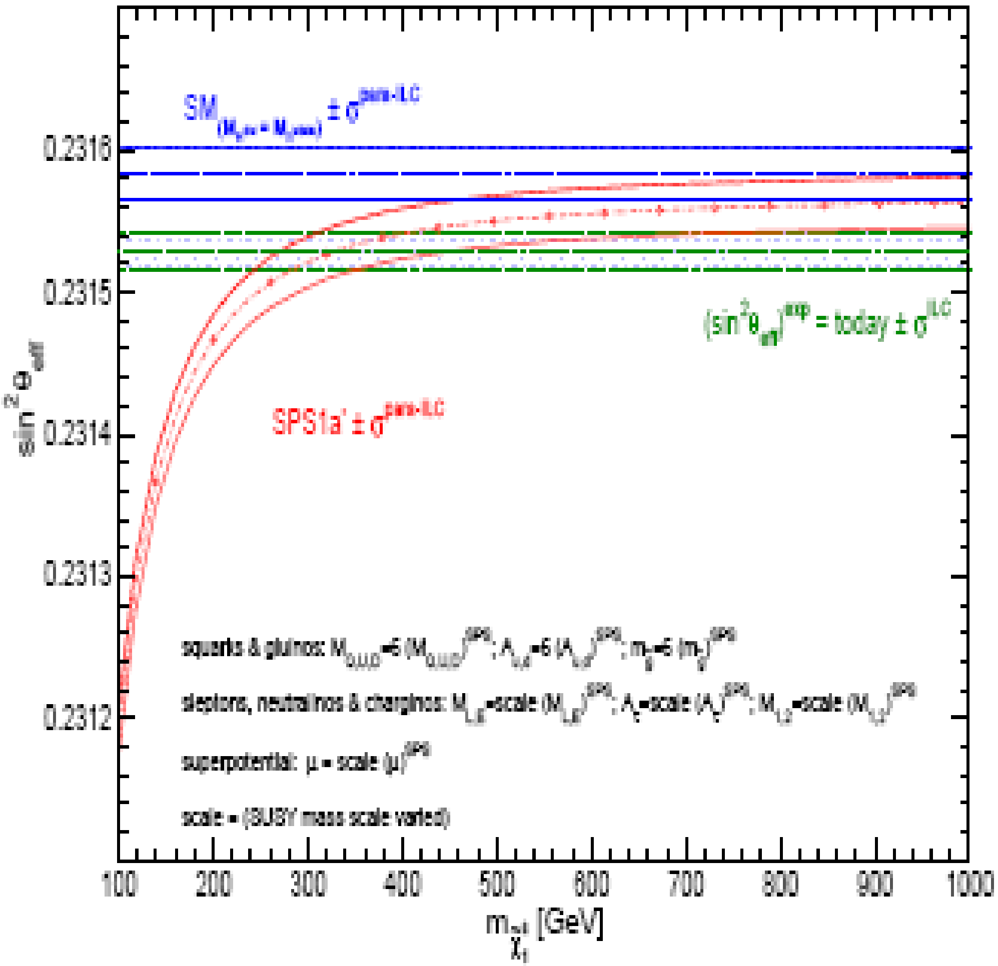


GigaZ precision!

What else could we learn? $\sqrt{s}$=91 GeV

- **Assume only Higgs@LHC but no hints for SUSY:**
  - Really SM?
  - Help from $\sin^2\theta_{eff}$?

Heinemeyer, Hollik, Weber, Weiglein



- **If GigaZ precision:**
  - i.e. Δm_{top}=0.1 GeV…
  - Deviations measurable

- **$\sin^2\theta_{eff}$ can be the crucial quantity to reveal effects of NP!**

Conclusions

- **SM can not be complete**
- **Many models are on the market……**
  - **A well defined candidate is SUSY and is not dead!**
  - **SUSY gets constraints from the measured Higgs mass**
- **Pinning down the underlying structure is challenging**
- **The LC provides a large variety of necessary tools:**
  - **High precision measurements**
  - **Beam polarization**
  - **Tunable, but precise energy**

- ***My personal opinion: the LC is mandatory to really pin down the stucture of the 'new' and being prepared for the 'Unexpected' !***

Be prepared for the 'Unexpected'…

- **the LC is mandatory………!**