SUSY: From the Basics to Phenomenology

Sven Heinemeyer, IFCA (CSIC, Santander)

Dubna, 07/2009

1. SUSY Lagrangian and algebra

2. The MSSM and simplified versions

3. The Higgs sector of the MSSM

4. SUSY at the LHC and the ILC

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SUSY lectures (IV):
SUSY at the LHC and the ILC

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1. The LHC and the ILC

2. SUSY Higgs bosons at the LHC and the ILC

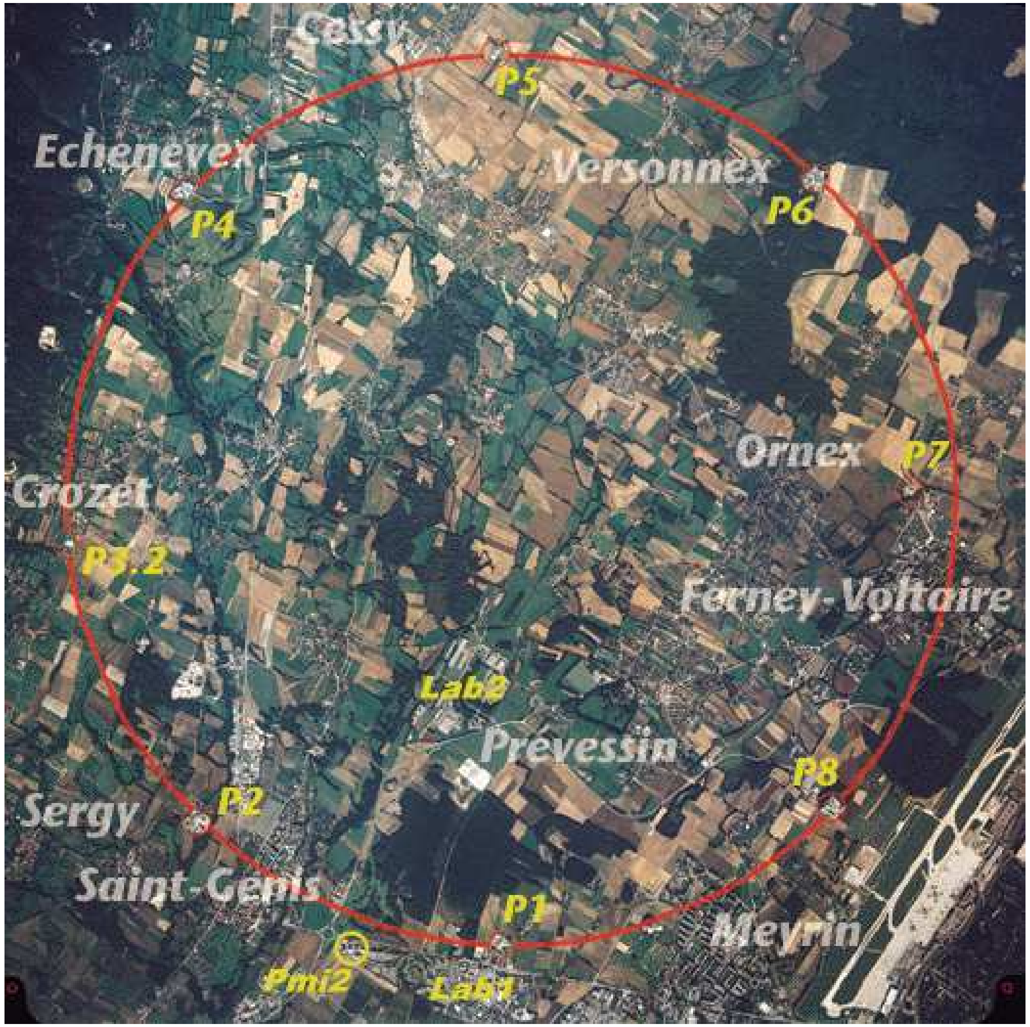
3. SUSY at the LHC and the ILC

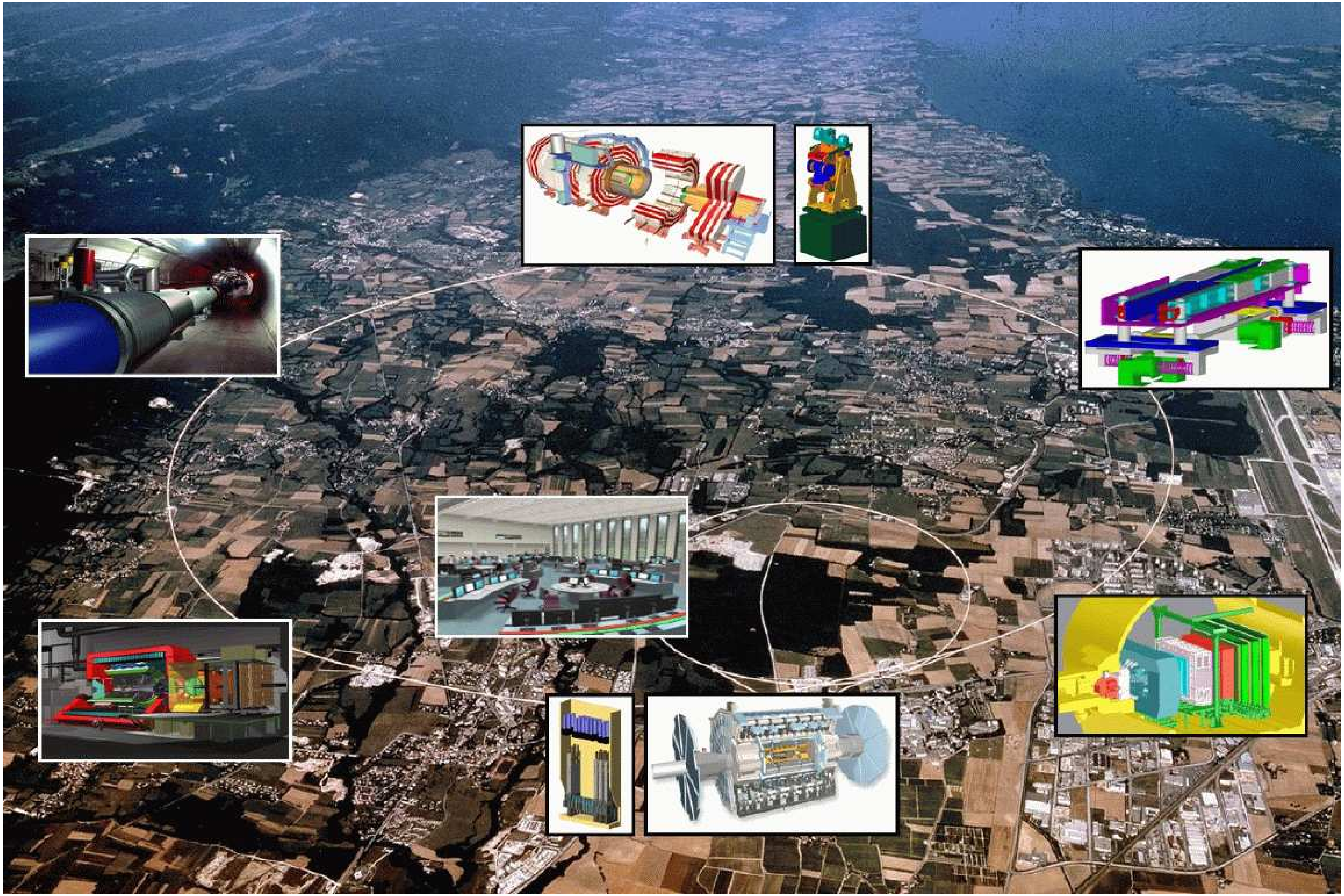
1. The LHC and the ILC

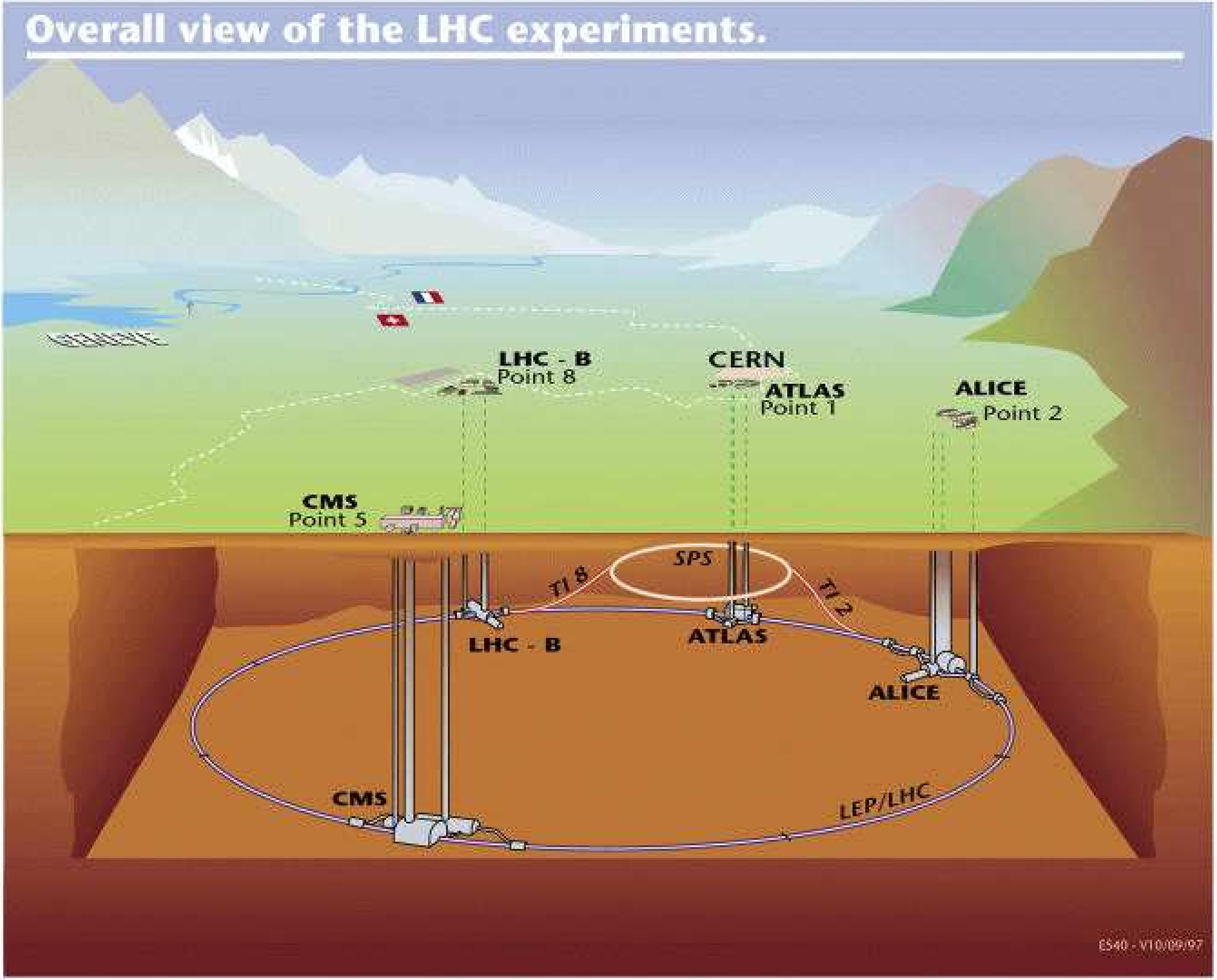
LHC:

$p\,p$ collisions at $\sqrt{s} = 14$ TeV

- 27 km circumference
- two general purpose detectors: ATLAS and CMS
- one B physics detector: LHCb
- one heavy ion detector: Alice







Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

The (un)official (optimistic?) LHC time line:

2009: repairs, cool-down etc.,
first collisions by the end of the year?

2010: 0.1 fb^{-1} – 0.2 fb^{-1} (at $\sqrt{s} = 10$ TeV) $\Rightarrow$ first physics results?

2011: $\mathcal{O}$ (few) fb^{-1} $\Rightarrow$ first physics results?

2012 – 2015: 10 fb^{-1} per year $\Rightarrow$ physics results with "low" luminosity

2016 – ?: 100 fb^{-1} per year $\Rightarrow$ physics results with "high" luminosity

2019 + X (X > 0): upgrade to SLHC?

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2019 + X (X > 0): upgrade to SLHC?

YOU live in an exciting time!!!

Physics at the LHC: basics

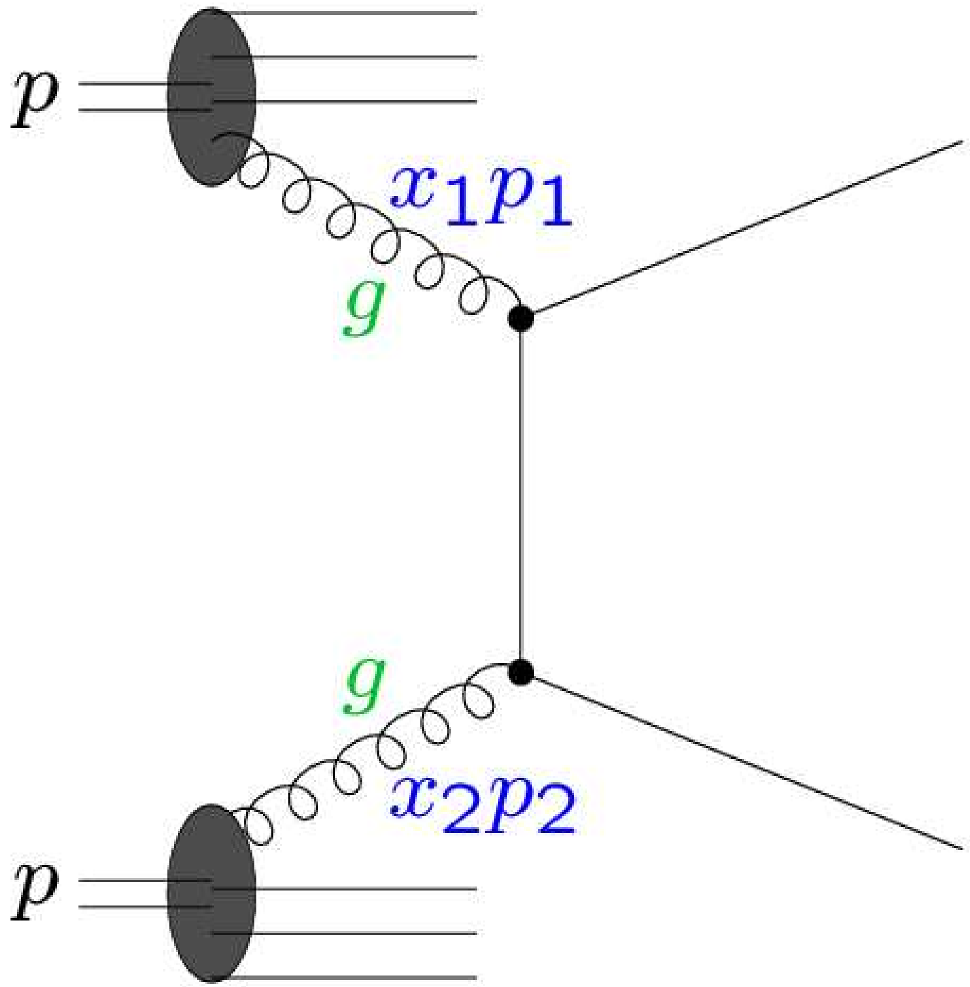
$p\,p$ scattering at $\sqrt{s} = 14$ TeV

Scattering process of proton constituents (q, $\bar{q}$, g) with energy up to several TeV,
strongly interacting

⇒ huge QCD backgrounds,
low signal–to–background ratios

interaction rate of 10^9 events/s

⇒ can trigger on only
1 event in 10^7



How to calculate cross sections at the LHC?

First step:

Calculate cross section for incoming partons and outgoing X:

$$\hat{\sigma}(ij \to X), \; i,j = q, \bar{q}, g$$

Perturbative calculation is possible:

– α_s is sufficiently small at LHC energies

– α is sufficiently small anyway

Still to be done:

1. connect incoming quarks and gluons with the (incoming) colliding protons

2. connect the outgoing particles with the observed (outgoing) jets

Making the connections:

1. To connect protons with quarks an gluons we need to know the probability that a quark or gluon is carrying a certain fraction x of the proton momentum,
   provided by parton distribution functions (PDFs):

   $$f_i(x, \mu_f)$$

   μ_f: factorization scale

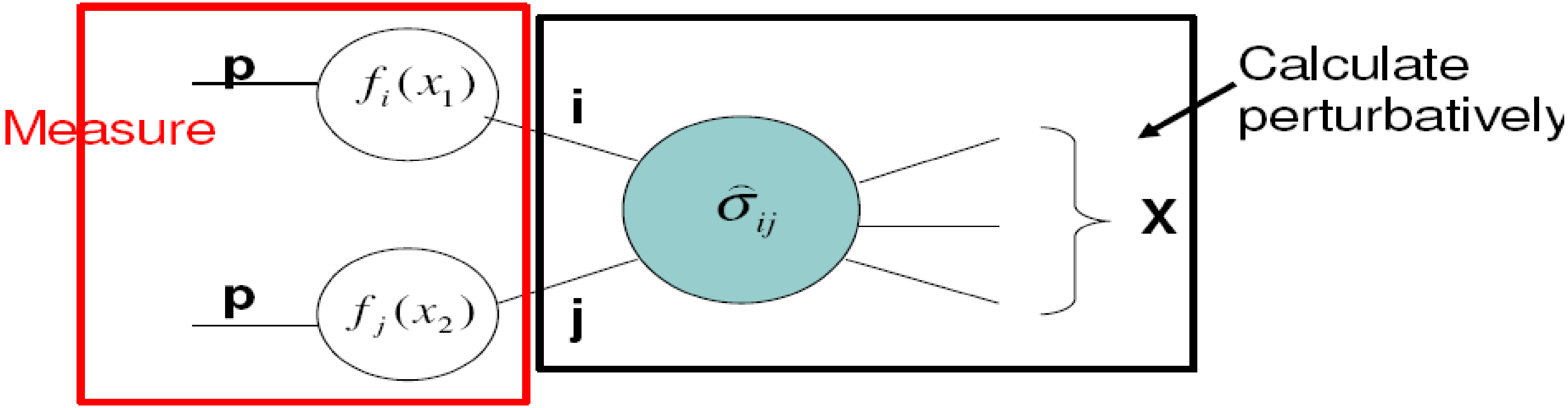
2. at lowest order: each outgoing quark or gluon is identified with a hadronic jet – provided they are well separated in
   pseudo-rapidity – azimuth space:

   $$\Delta R := \left(\Delta\eta^2 + \Delta\Phi^2\right)^{-1/2} > R_{\text{min}}$$

   Φ: angle in plane perpendicular to beam axis
   η : pseudo rapidity: $\eta = -\log(\tan\theta/2)$

The Master formula for all LHC cross section calculations:

$$\sigma(pp \to X) = \sum_{ij} \int dx_1 dx_2\, f_i(x_1, \mu_f)\, f_j(x_2, \mu_f)\, \hat{\sigma}(ij \to X)$$



$x_{1,2}$: momentum fraction carried by the incoming quarks, gluons
$\hat{\sigma}$: partonic cross section, calculated perturbatively

Parton Density Functions (PDFs):

- PDFs cannot be calculated perturbatively
  $\Rightarrow$ they have to be measured experimentally (at a certain scale)

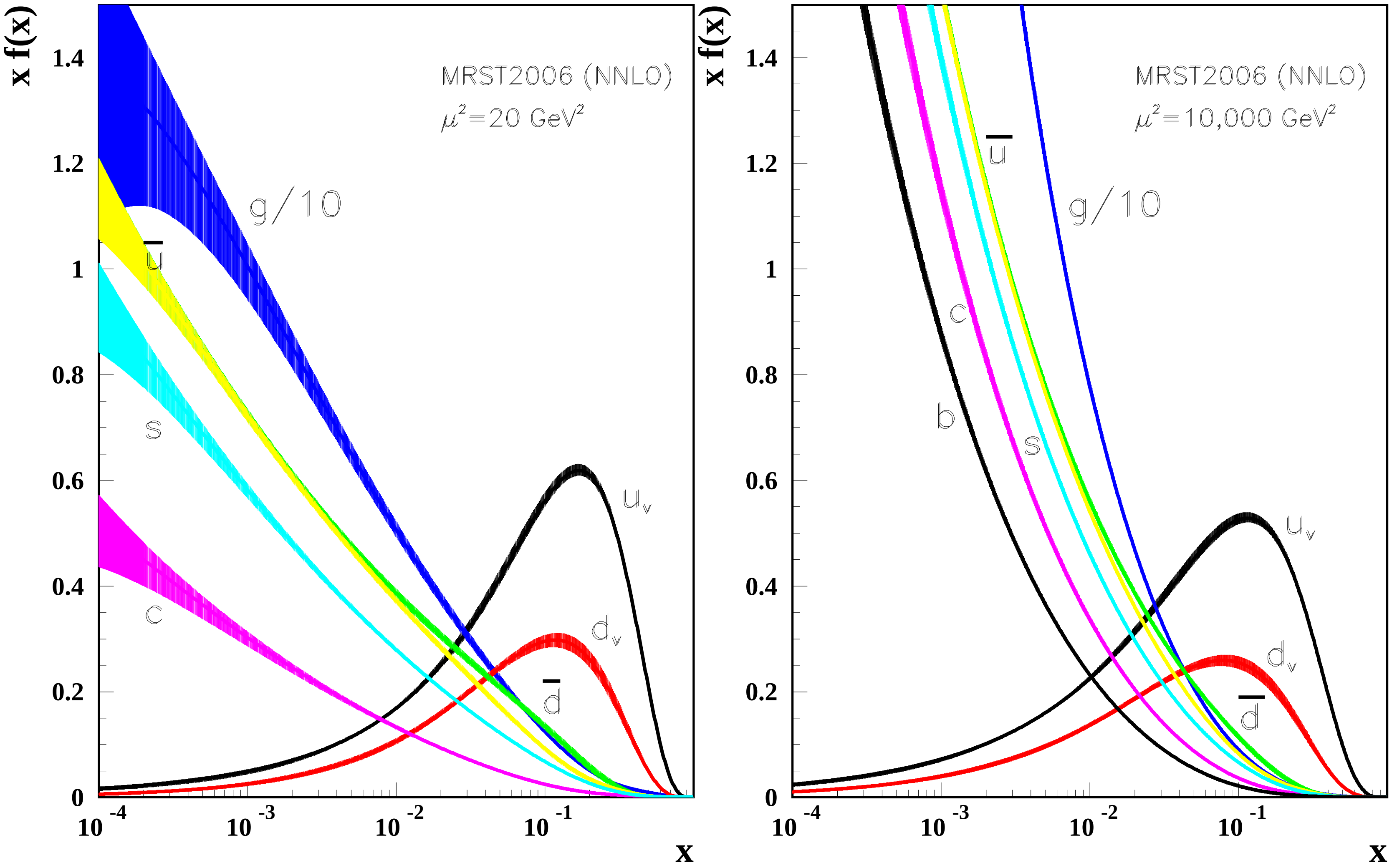
- QCD predicts the evolution of the PDFs via the
  Altarelli-Parisi equations,
  i.e. once we know the PDFs for a certain scale, QCD predicts them for all other scales

- PDFs are universal, e.g. PDFs determined at HERA can directly be used for LHC calculations

- PDFs are different for valence and sea quarks

- PDFs come in the form of Fortran codes, mainly by two groups:
  MRST and CTEQ collaborations

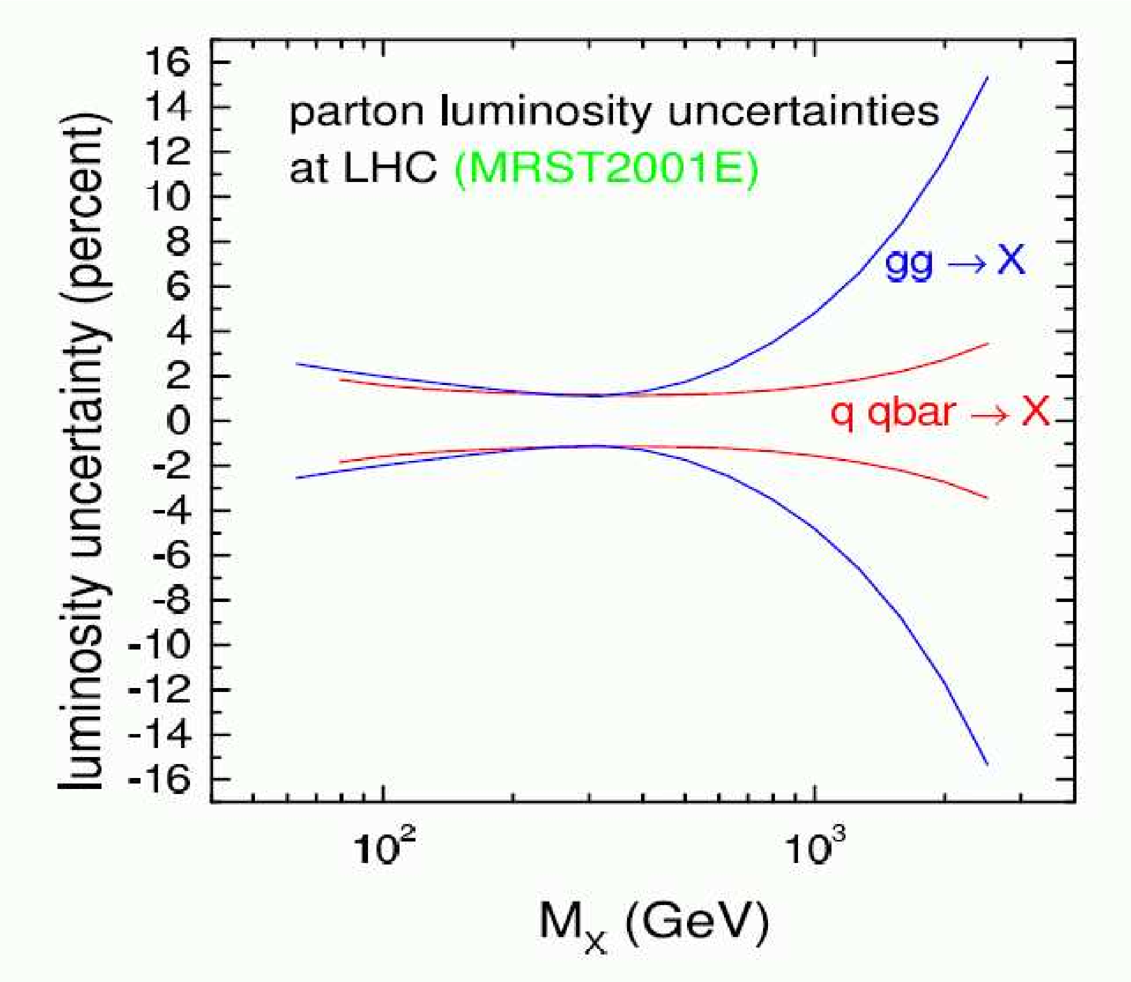
Example for PDFs of the proton:



⇒ The LHC is (mainly) a gluon gluon collider

Uncertainties in cross section calculations

induced by uncertainties in PDFs:



Final state X
with mass M_X:

PDF induced uncertainties
mostly below 5%

[MRST, CTEQ, Alekhin, . . .]

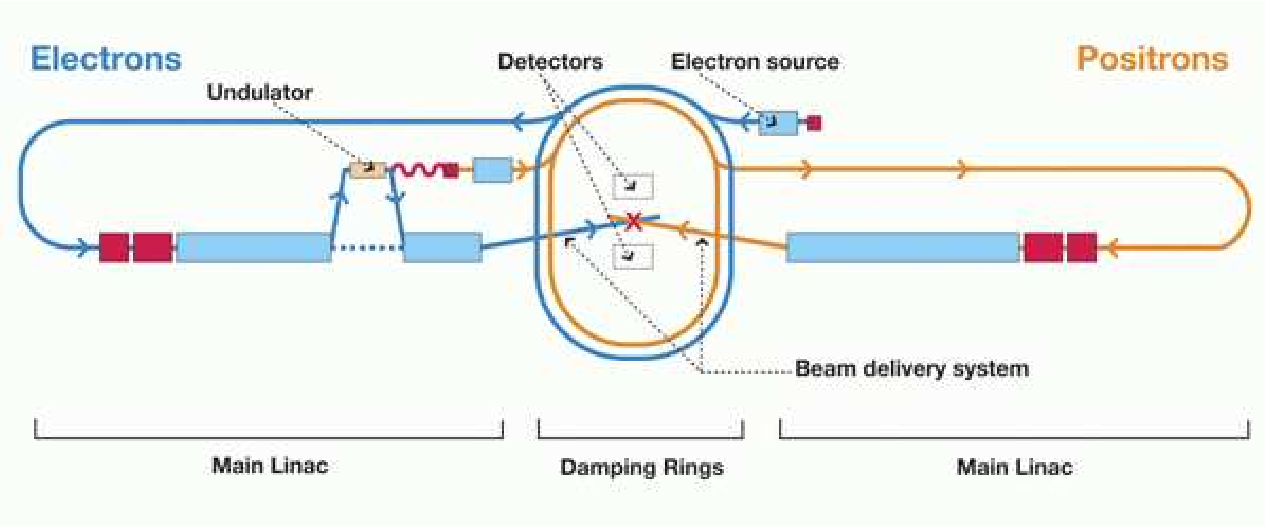
The “dirty” LHC might not be precise enough . . . what then?

The "dirty" LHC might not be precise enough . . . what then?

Linear e^+e^- collider, $\sqrt{s} = 500 - 1000$ GeV

based on superconducting cavities (cold technology) (ITRP decision 2004)

Schematic:



– two detectors in one interaction region (push-pull)
– undulator based e^+ source
– polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)

Other options:

- GigaZ:
  running with high luminosity at low energies (Z pole, WW threshold)

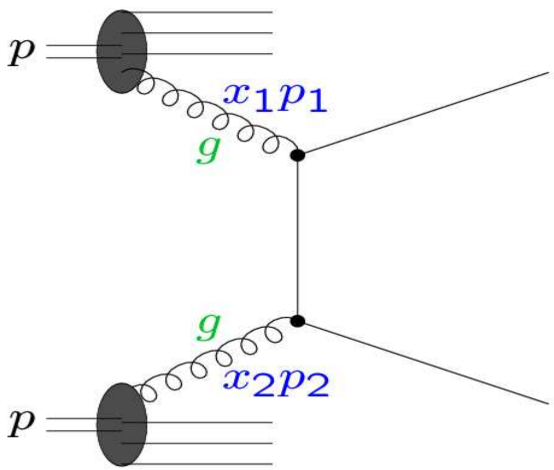
- e^-e^-:
  produce doubly charged particles in the s channel

- $e^-\gamma$:
  use one e^- beam to produce high-energy photons
  produce charged particles in the s channel

- $\gamma\gamma$:
  use both beams to produce high-energy photons
  (e.g. heavy Higgs production in the s channel)

Mini-comparison of LHC and ILC:

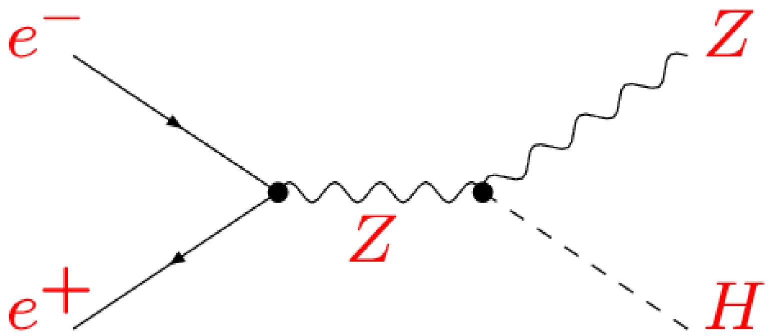
LHC: pp scattering at 14 TeV



Scattering process of proton constituents with energy up to several TeV,
strongly interacting

⇒ huge QCD backgrounds,
low signal–to–background ratios

ILC: e^+e^- scattering
at ≈0.5–1 TeV

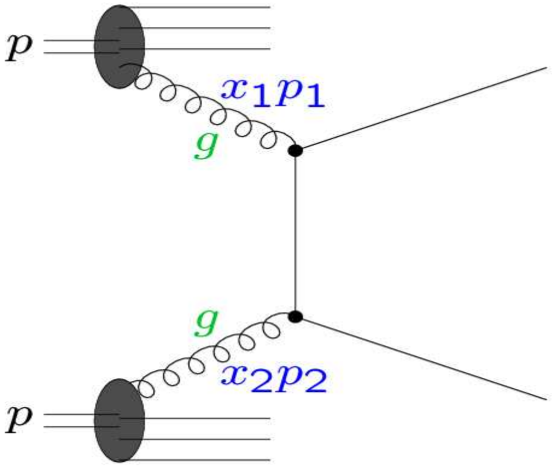


Clean exp. environment:
well-defined initial state,
tunable energy,
beam polarization, GigaZ,
$\gamma\gamma$, $e\gamma$, e^-e^- options, . . .

⇒ rel. small backgrounds
high-precision physics

Mini-comparison of LHC and ILC:

LHC: pp scattering at 14 TeV



interaction rate of 10^9 events/s

$\Rightarrow$ can trigger on only
1 event in 10^7

ILC: e^+e^- scattering
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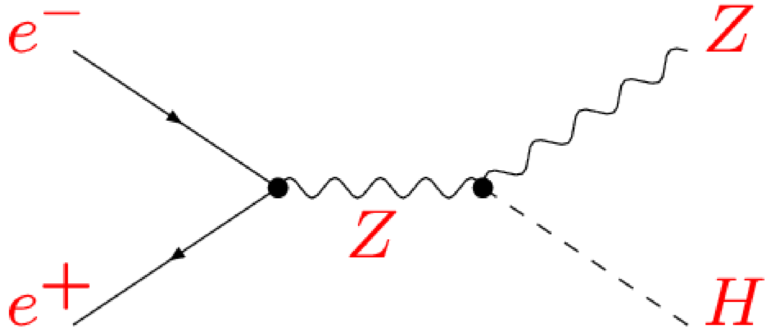


untriggered operation

$\Rightarrow$ can find signals of unexpected new physics (direct production + large indirect reach) that manifests itself in events that are not selected by the LHC trigger strategies

2. SUSY Higgs bosons at the LHC and ILC

Discovering the Higgs boson

What has to be done?

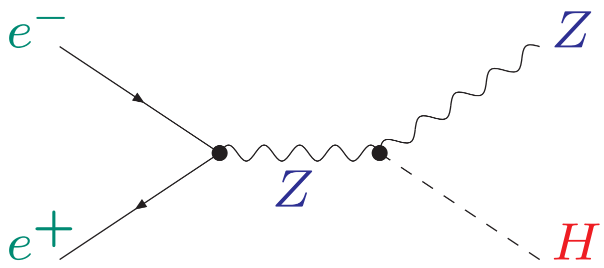
1. Find the new particle	T	L	I
2. measure its mass (⇒ ok?)	T	L	I
3. measure coupling to gauge bosons		L	I
4. measure couplings to fermions		L	I
5. measure self-couplings			I
6. measure spin, . . .			I

T = Tevatron, L = LHC, I = ILC

We need the ILC to find the Higgs
and to establish the Higgs mechanism!
The LHC can do a crucial part . . .

Higgs search at LEP:

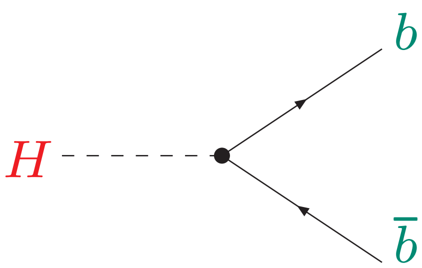
Dominant SM production process:
$e^+e^- \to ZH$:



$$\sigma(e^+e^- \to ZH) = \frac{G_\mu^2 M_Z^4}{96\,\pi\,s}\left[v_e^2 + a_e^2\right]\beta\,\frac{\beta^2 + 12 M_Z^2/s}{(1 - M_Z^2/s)^2}$$

with $\beta^2 = (1 - (M_H + M_Z)^2/s)\,(1 - (M_H - M_Z)^2/s)$ (1)

Dominant decay process: $H \to b\bar{b}$



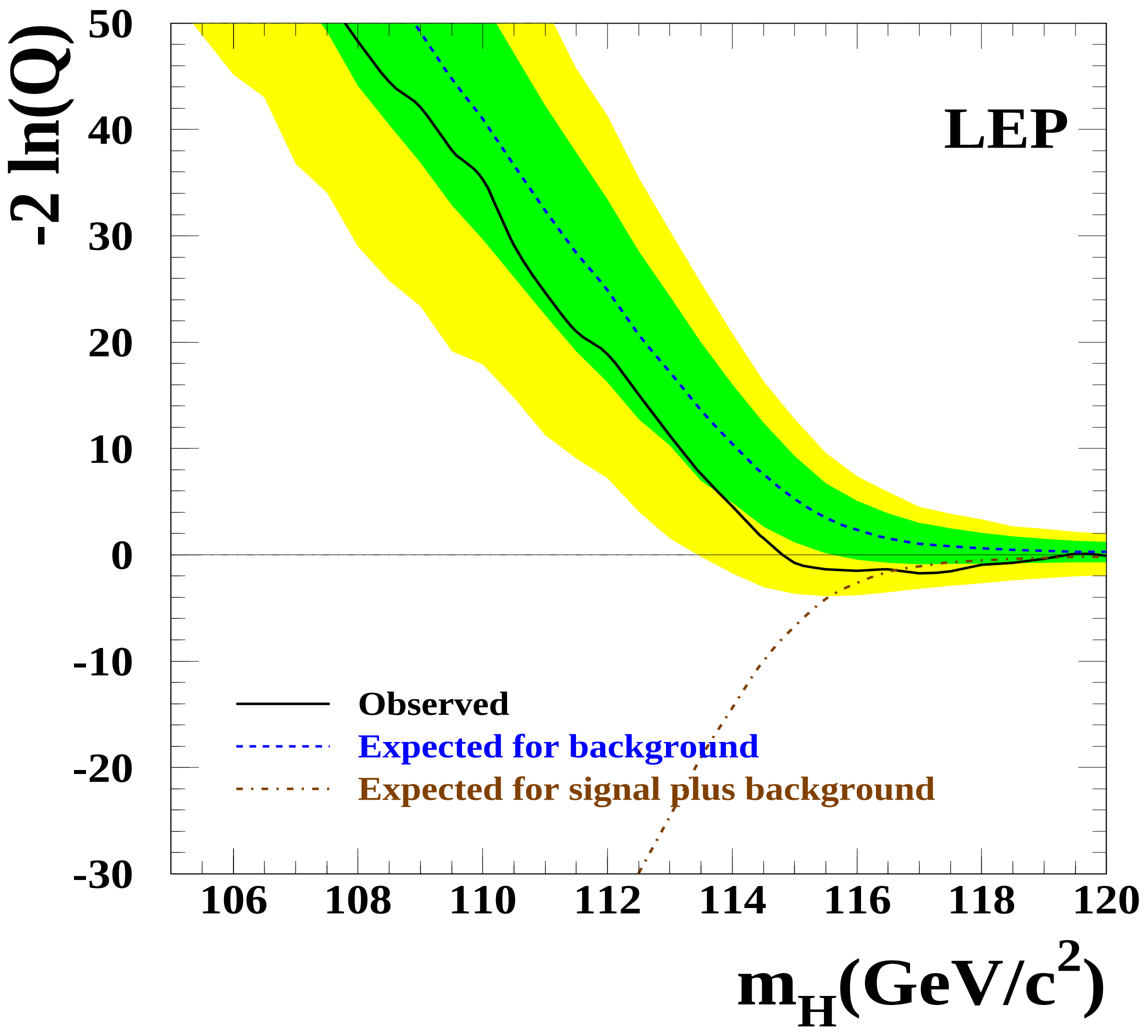
Search for the Standard Model Higgs at LEP: [*LEP Higgs WG '03*]

Exclusion limit
at the 95% C.L.:

$M_H >$ 114.4 GeV

expected: 115.3 GeV

(LEP has seen exactly as many Higgs-like events as could be expected for $M_H \approx 116$ GeV, not more, not less)



Search for the MSSM Higgs bosons:

Situation is more involved due to many SUSY parameters

$\rightarrow$ investigate benchmark scenarios:

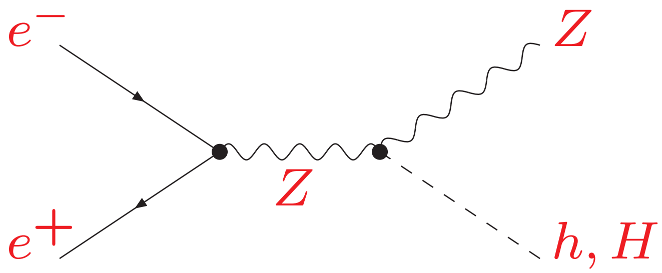
$\rightarrow$ Vary only M_A and $\tan\beta$
$\rightarrow$ Keep all other SUSY parameters fixed

1. m_h^{max} scenario:
   $\rightarrow$ obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\text{SUSY}}$)
2. no-mixing scenario
   $\rightarrow$ no mixing in the scalar top sector ($X_t = 0$)
3. small α_{eff} scenario
   $\rightarrow$ $hb\bar{b}$ coupling $\sim \sin\alpha_{\text{eff}}/\cos\beta$ can be zero: $\alpha_{\text{eff}} \rightarrow 0$:
   main decay mode vanishes, important search channel vanishes
4. gluophobic Higgs scenario
   $\rightarrow$ hgg coupling is small: main LHC production mode vanishes

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

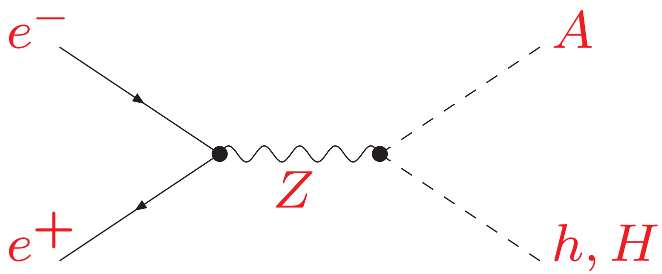
Search for neutral SUSY Higgs bosons:

$e^+e^- \to Zh, ZH$



$$\sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$
$$\sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$e^+e^- \to Ah, AH$

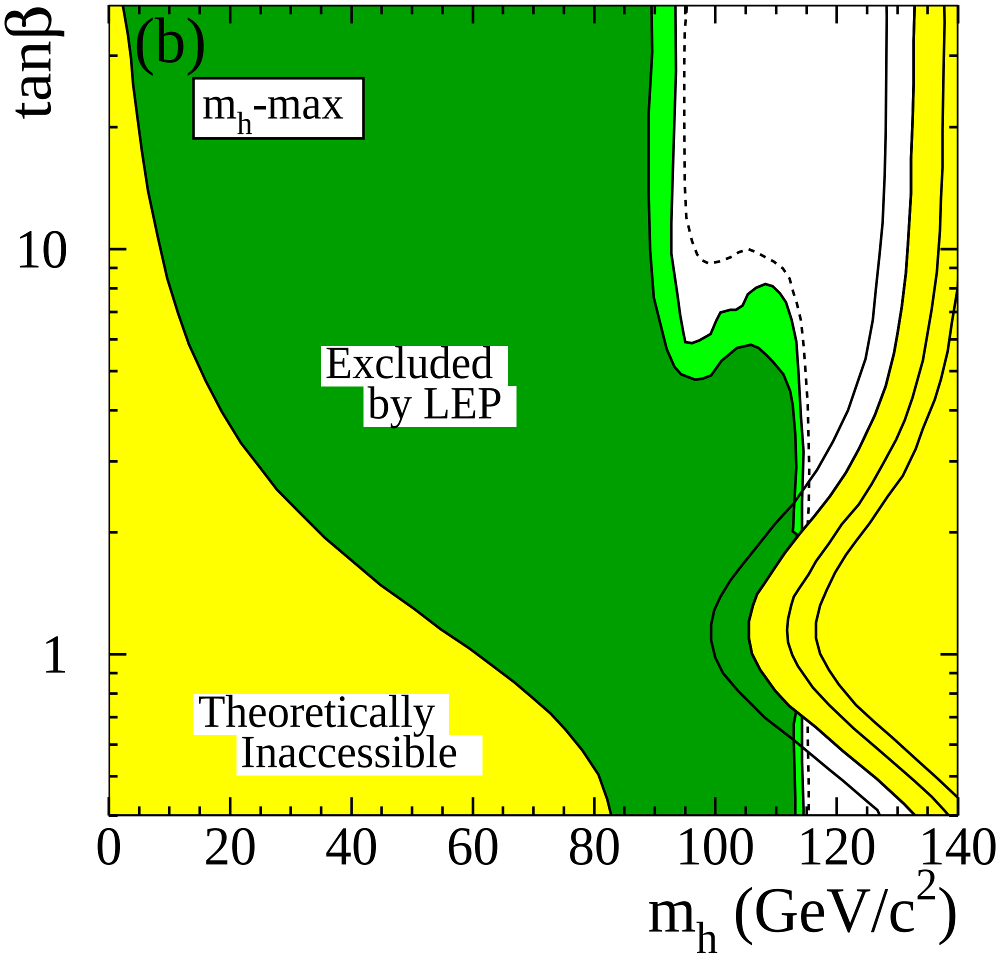


$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$
$$\sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

Constraints from the Higgs search at LEP [*LEP Higgs Working Group '06*]

Experimental search vs. upper m_h-bound (*FeynHiggs* 2.0)

$m_h^{\rm max}$-scenario ($m_t = 174.3$ GeV, $M_{\rm SUSY} = 1$ TeV):

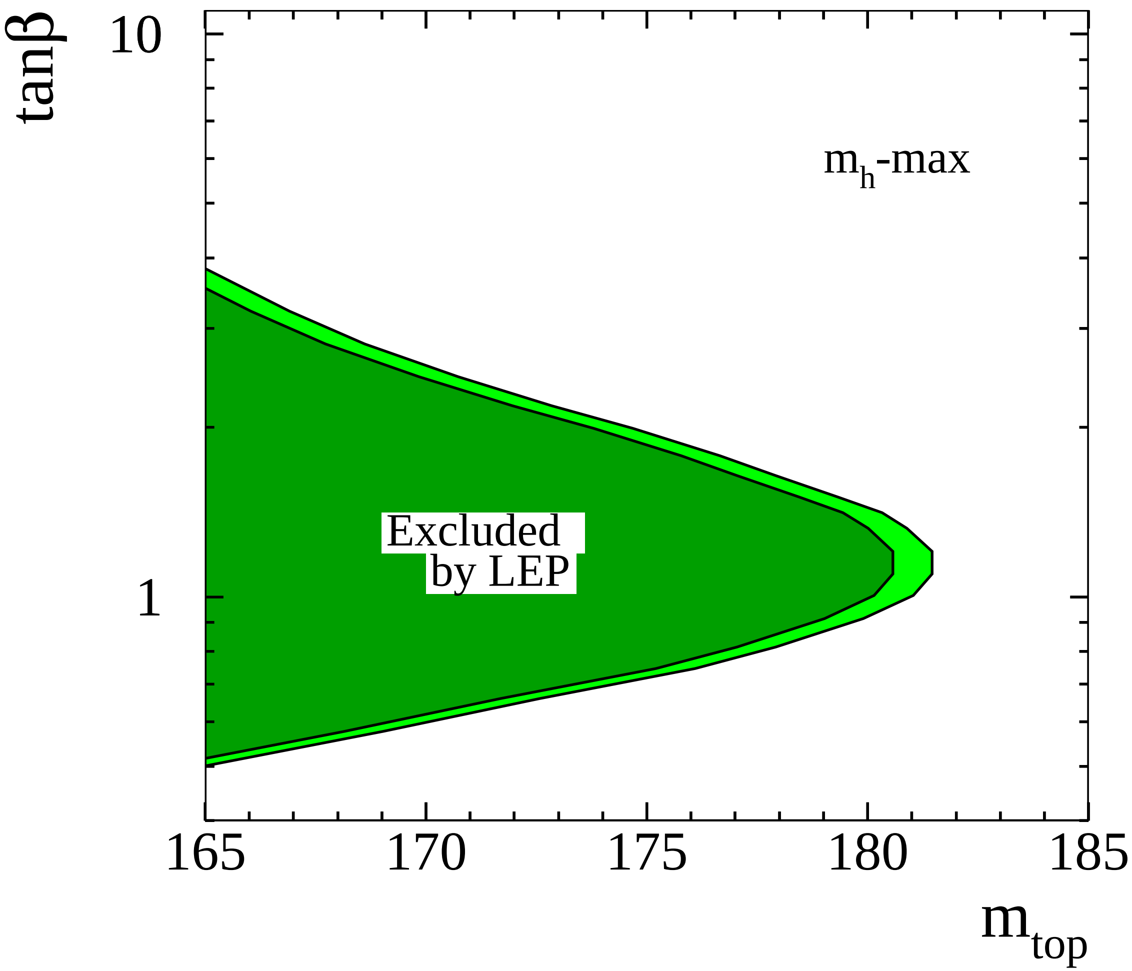


$m_h > 92.8$ GeV
(expected: 94.9 GeV), 95% C.L.

$M_A > 93.4$ GeV
(expected: 95.2 GeV)

Parameter region where experimental lower bound on M_h is significantly lower than SM bound, $M_H > 114.4$ GeV, corresponds to $\sin^2(\beta - \alpha_{\text{eff}}) \ll 1$

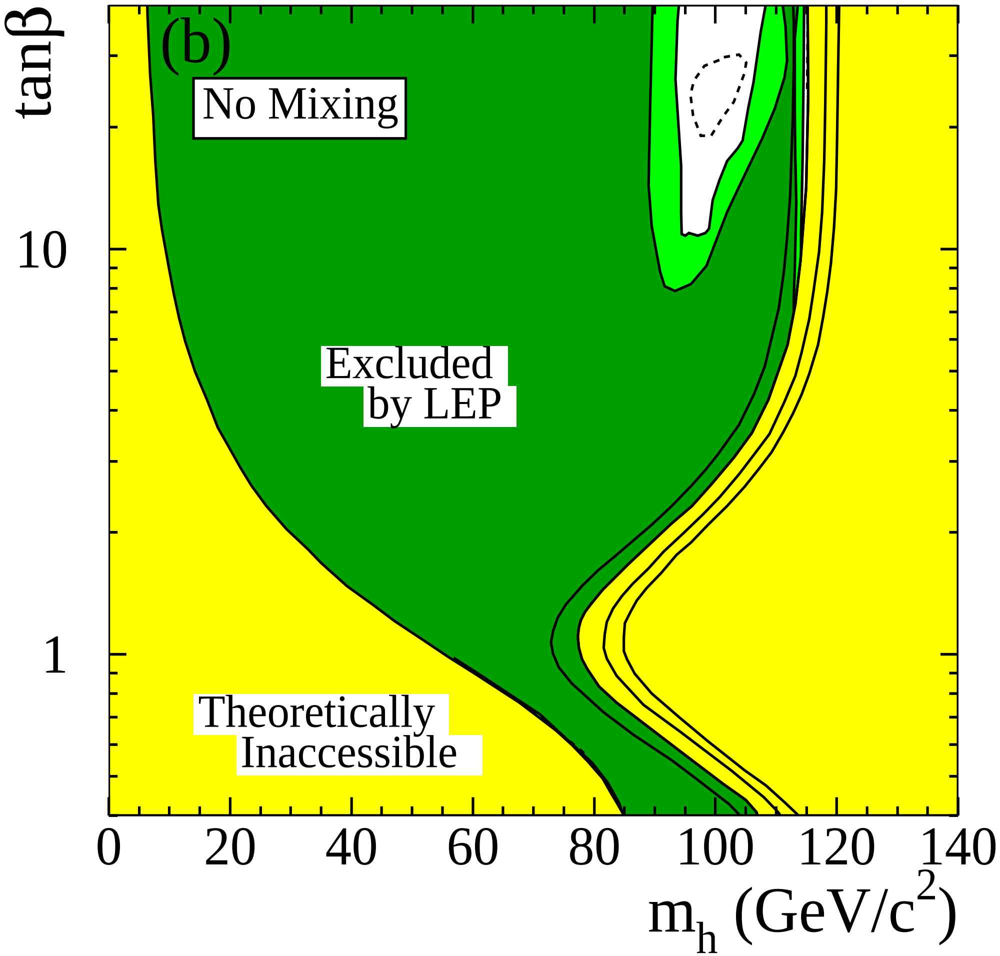
"Excluded" $\tan\beta$ region:



Constraints from the Higgs search at LEP [*LEP Higgs Working Group '06*]

Experimental search vs. upper m_h-bound (*FeynHiggs* 2.0)

no-mixing scenario ($m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV):



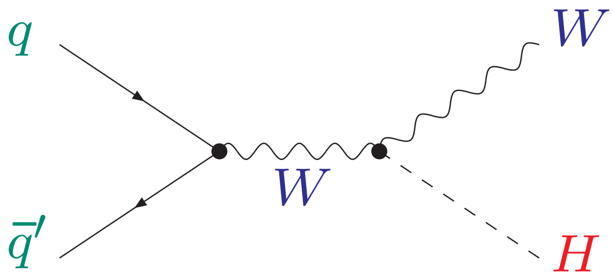
$m_h > 93.6$ GeV
(expected: 96.0 GeV), 95% C.L.

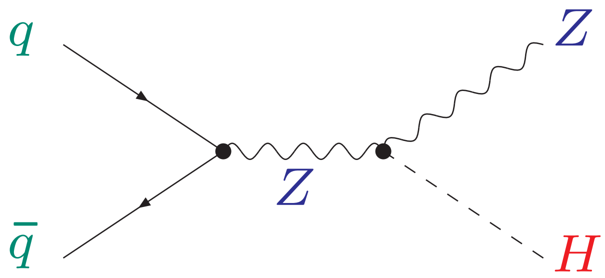
$M_A > 93.6$ GeV
(expected: 96.4 GeV)

Higgs search at the Tevatron

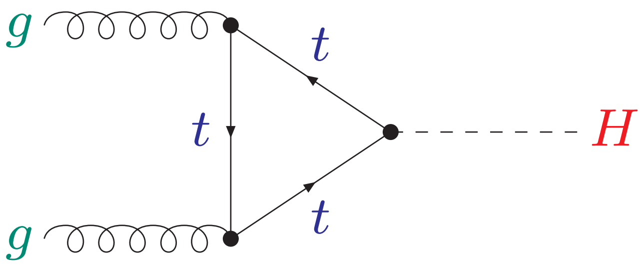
Tevatron: $p\bar{p}$ accelerator: $\rightarrow$ T

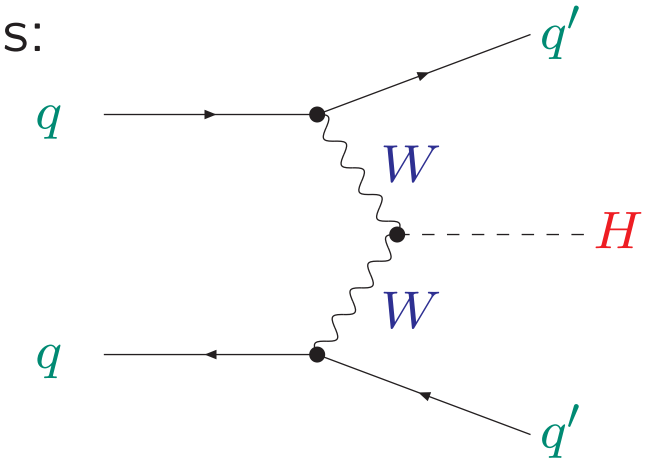
Production processes as at LEP:



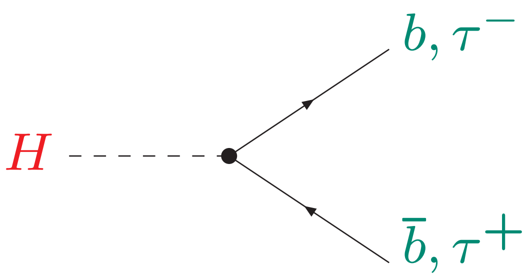


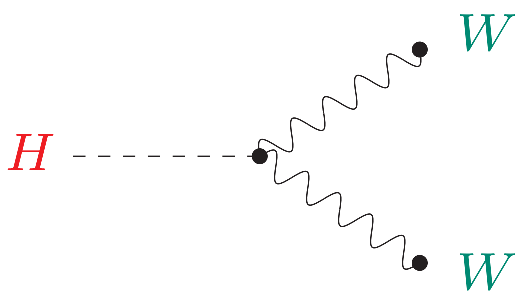
Other important production channels:





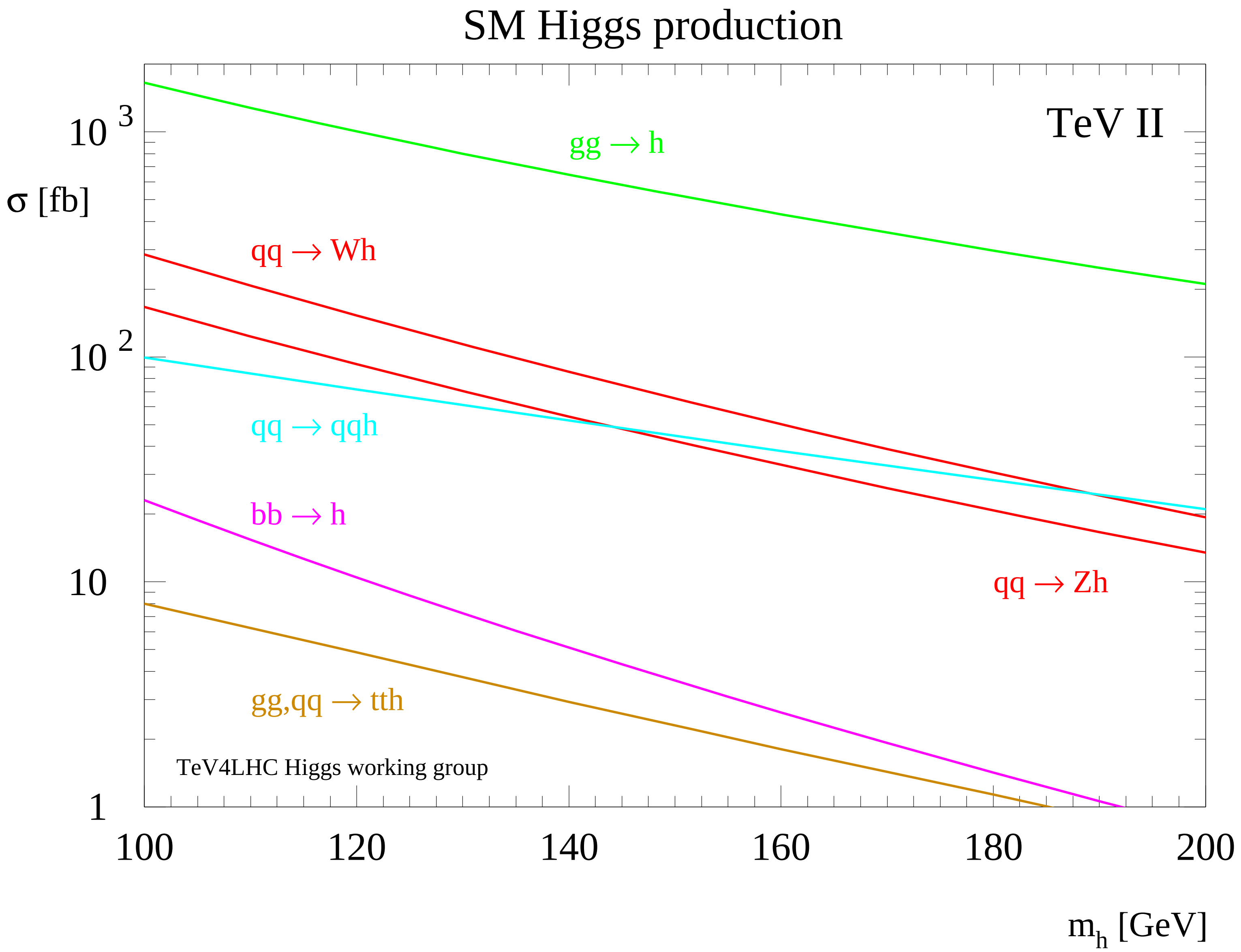
Dominant decays:



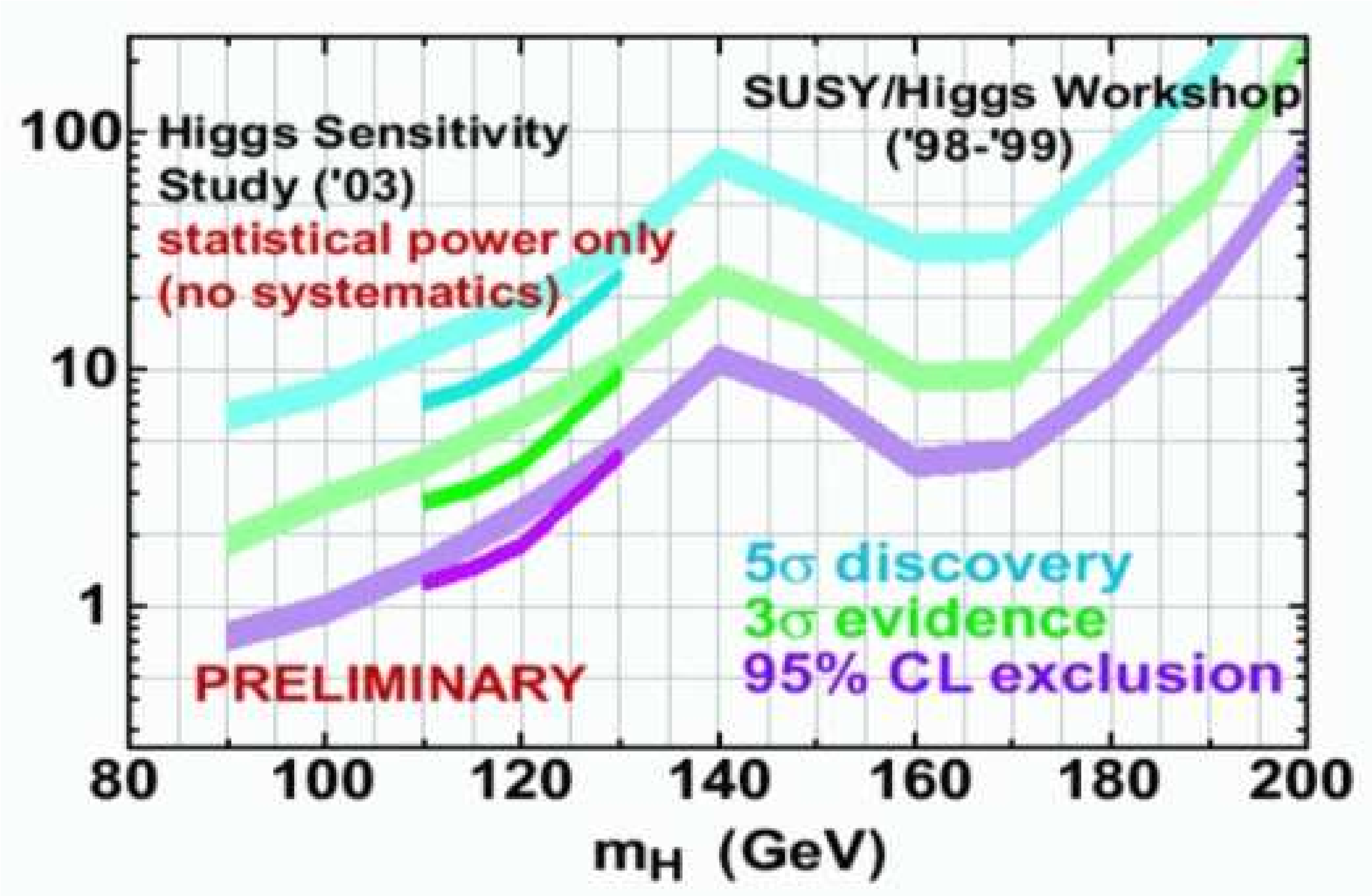


Overview of SM production cross sections:

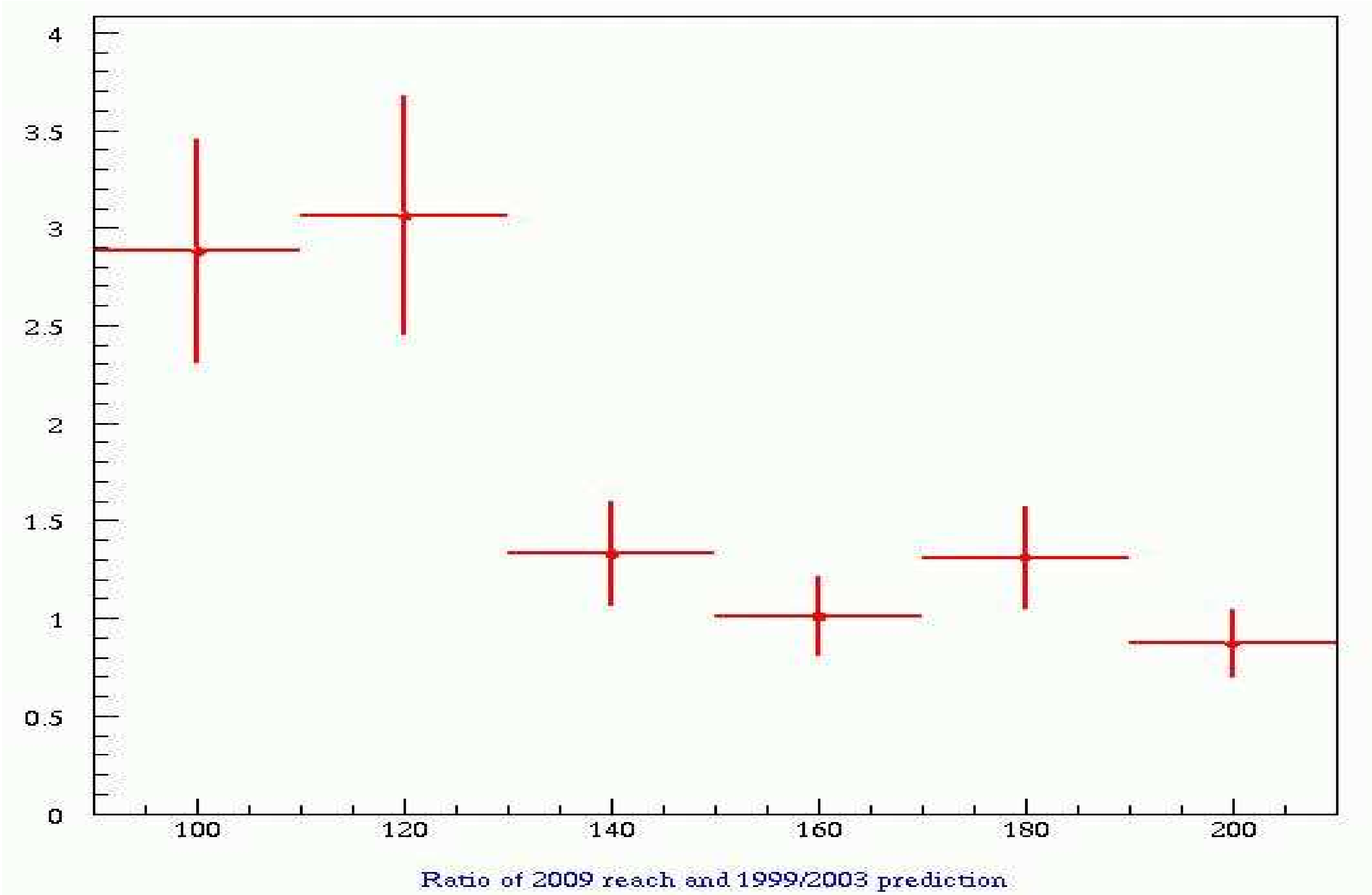
[F. Maltoni et al. '05]



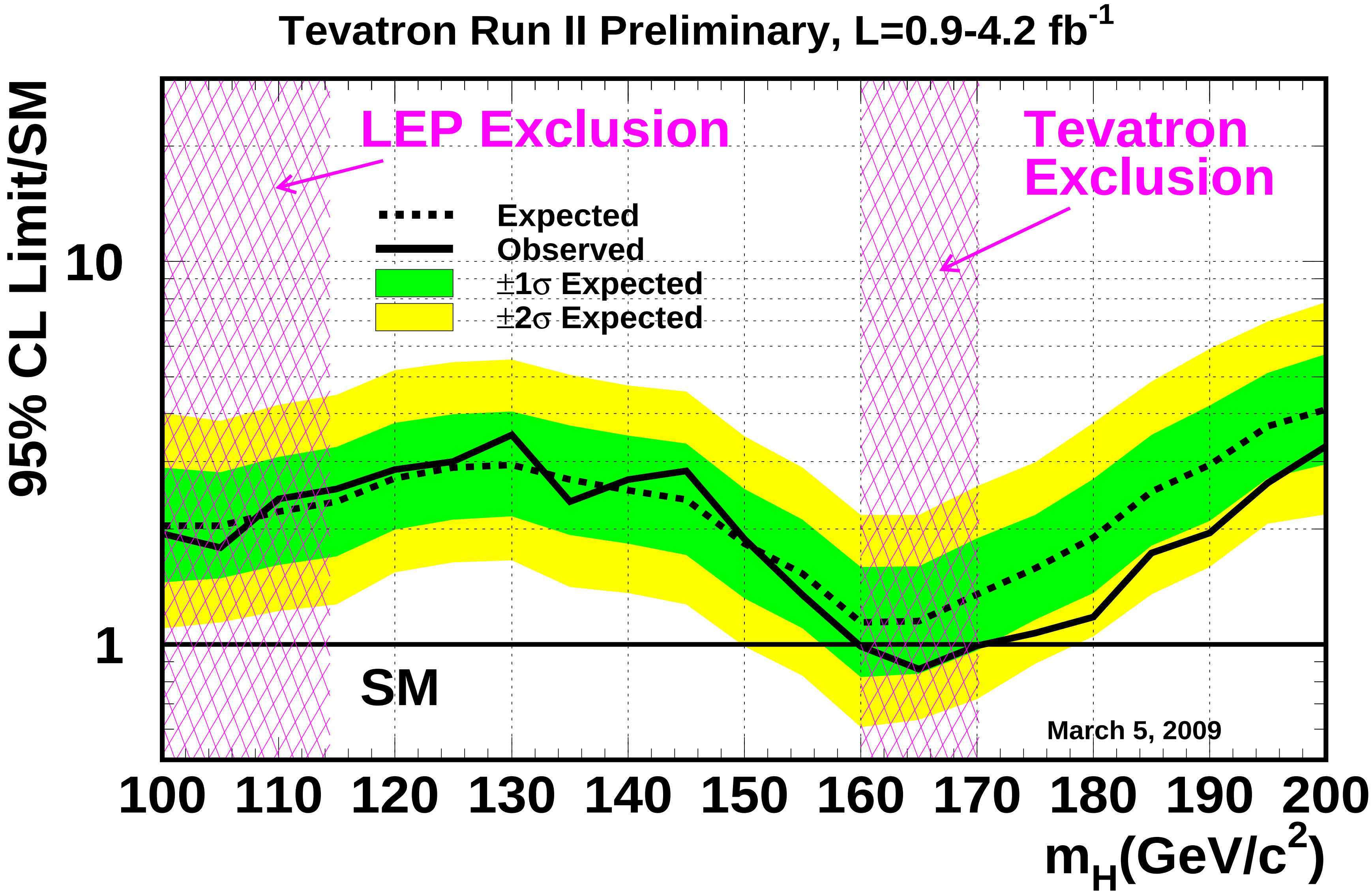
Expectations for Higgs discovery at the Tevatron:



Real performance compared with expectations:



Current Status of SM Higgs searches at the Tevatron:



⇒ applies also to a SM-like light MSSM Higgs boson

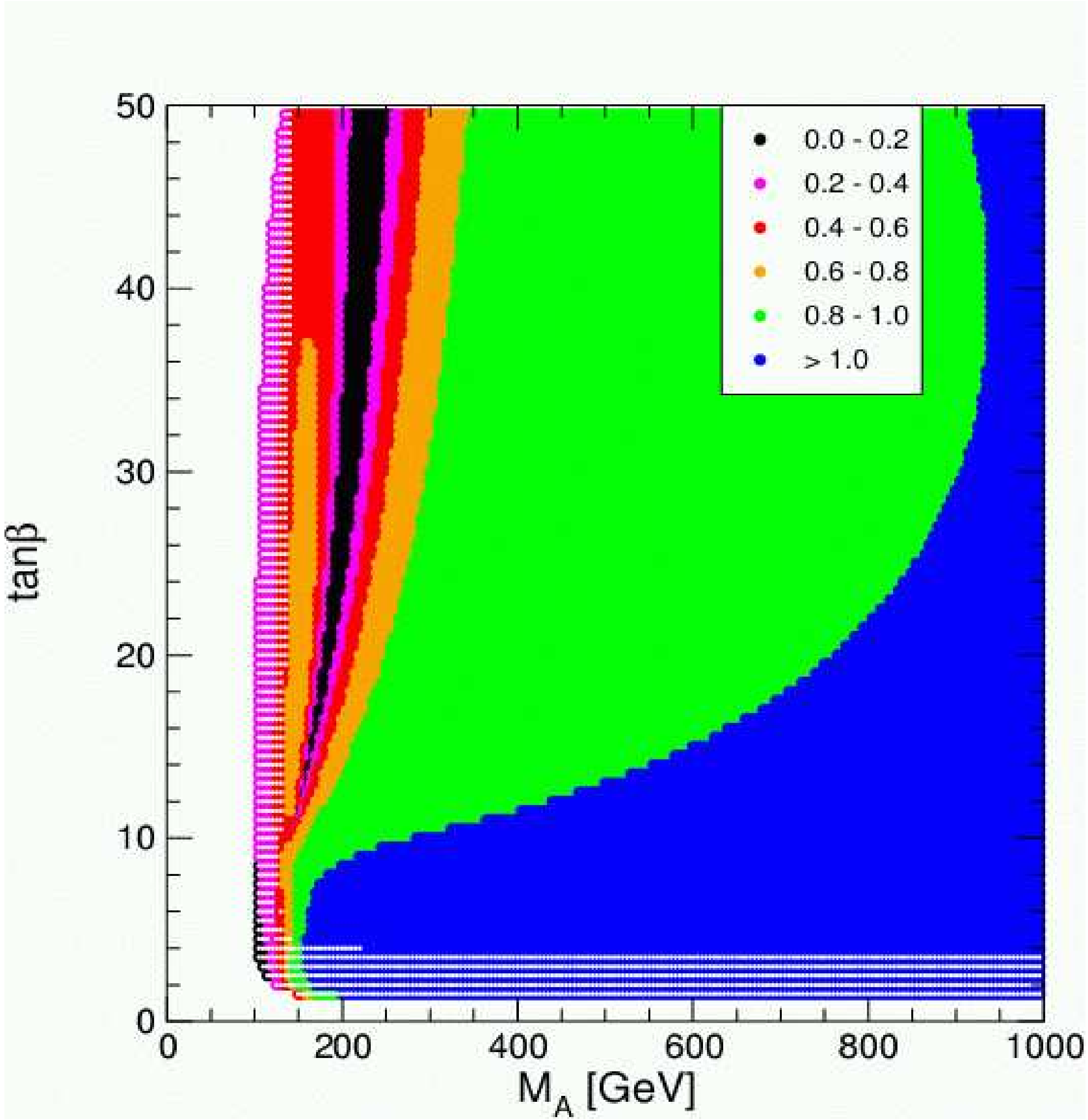
Possible problem in SUSY:

$h \to b\bar{b}$

can be strongly suppressed

$\to$ "Small $\alpha_{\rm eff}$ scenario"

[M. Carena, S.H., C. Wagner, G. Weiglein '02]



$\Rightarrow$ Strong suppression of $h \to b\bar{b}$ possible, up to $M_A \lesssim$ 350 GeV

(not realized in mSUGRA/CMSSM, GMSB, AMSB, . . .)

Tevatron MSSM Higgs searches: “Heavy” MSSM Higgs bosons

Search modes:

$$b\,\bar{b} \to \phi\, b\,\bar{b}\ , \quad \phi = h, H, A$$
$$p\,\bar{p} \to \phi \to \tau^+\,\tau^-\ , \quad \phi = h, H, A$$

Strong enhancement compared to the SM:

$$\sigma(b\bar{b}A) \times \mathrm{BR}(A \to b\bar{b}) \;\simeq\; \sigma(b\bar{b}A)_{\mathrm{SM}}\, \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

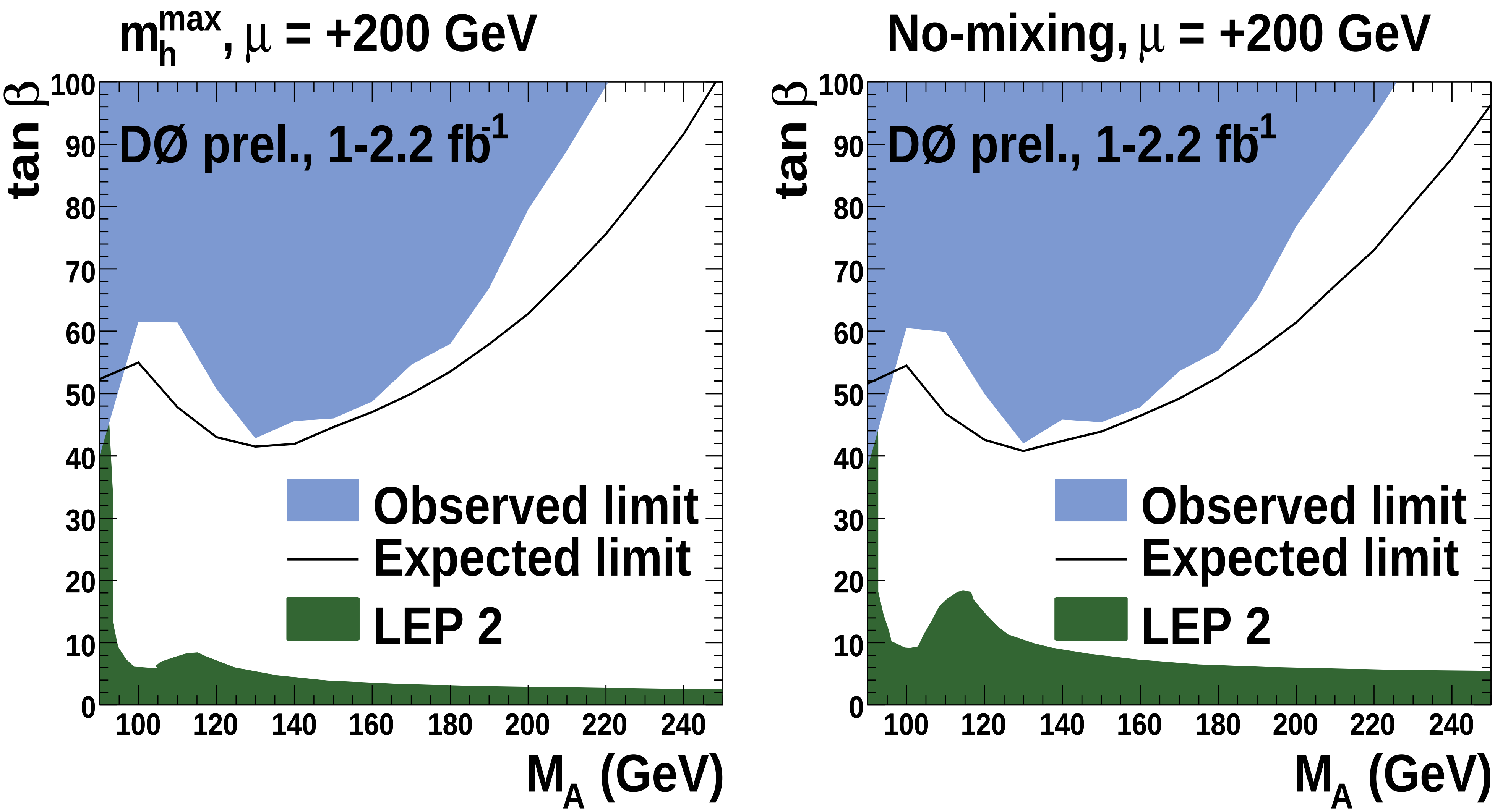
$$\sigma(gg, b\bar{b} \to A) \times \mathrm{BR}(A \to \tau^+\tau^-) \;\simeq\; \sigma(gg, b\bar{b} \to A)_{\mathrm{SM}}\, \frac{\tan^2\beta}{(1+\Delta_b)^2+9}$$

$$\Delta_b = \frac{2\alpha_s}{3\,\pi} m_{\tilde{g}}\,\mu\,\tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\,\pi} A_t\,\mu\,\tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

Either $H \approx A$ or $h \approx A$ $\Rightarrow$ another factor of 2

Example: $p\bar{p} \to h/H/A \to \tau^+\tau^-$ at D0 with 2 fb^{-1}

[*D0 '08*]

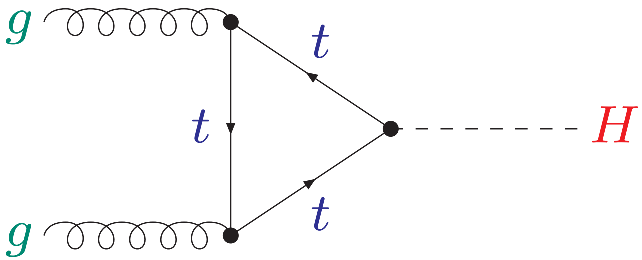


⇒ exclusion for light M_A and large $\tan\beta$

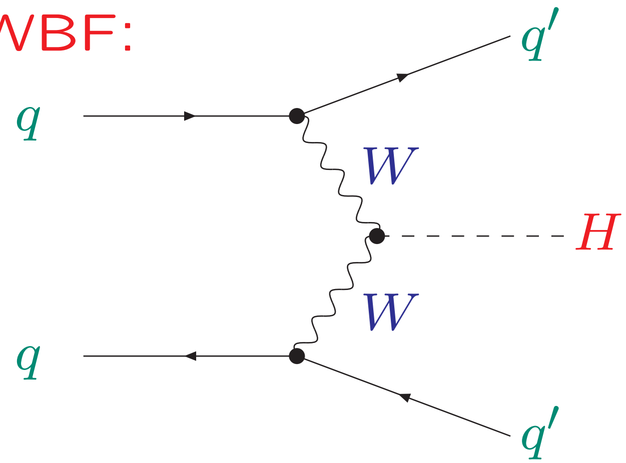
Higgs search at the LHC:

Important SM production channel at the LHC:

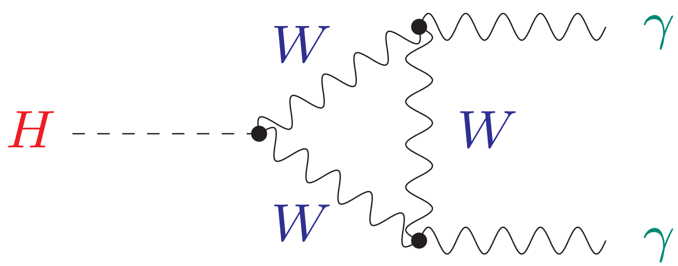
Gluon-Fusion:

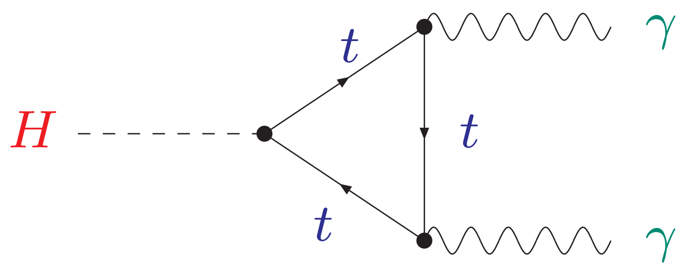


WBF:

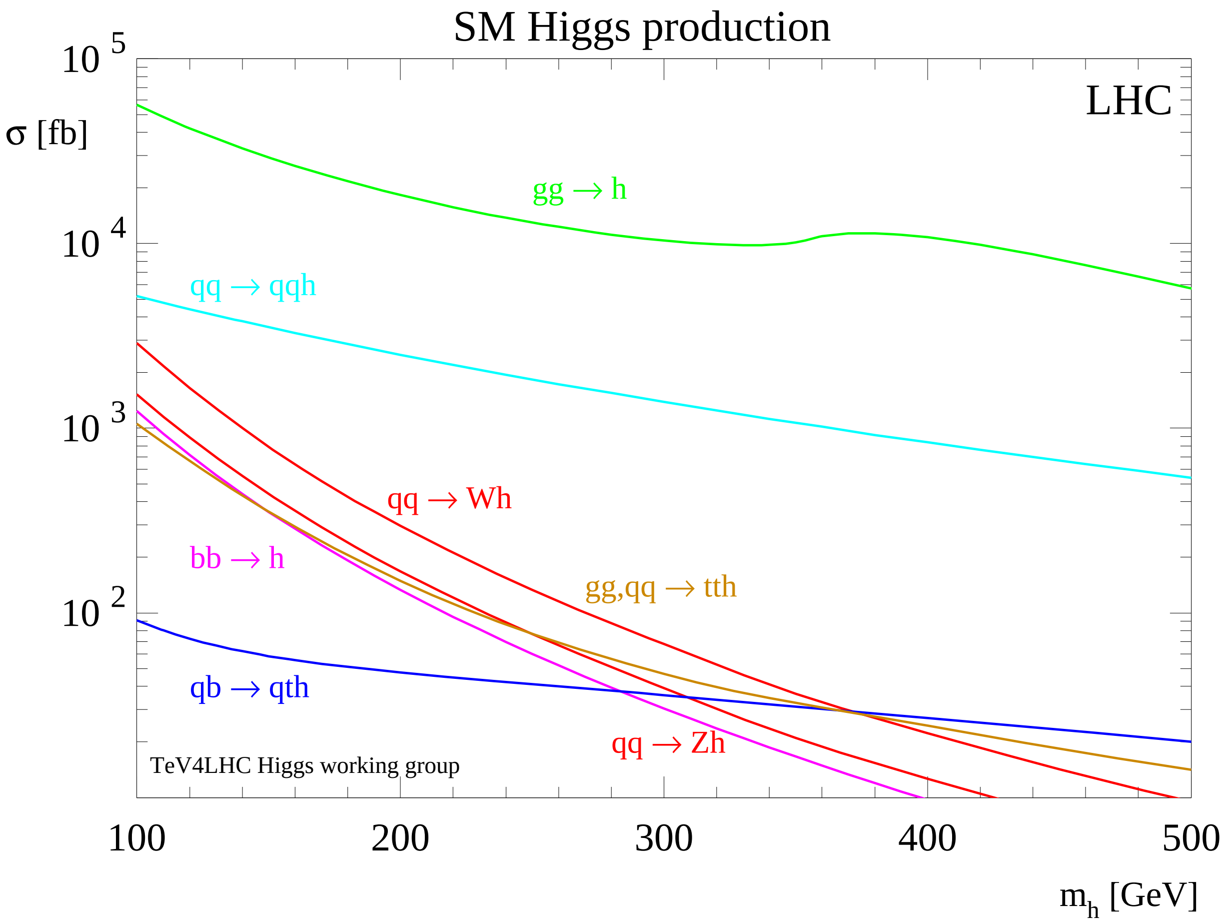


Important decay for Higgs mass measurement:





Overview of SM Higgs production at the LHC:



gluon fusion: $gg \to H$

weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$

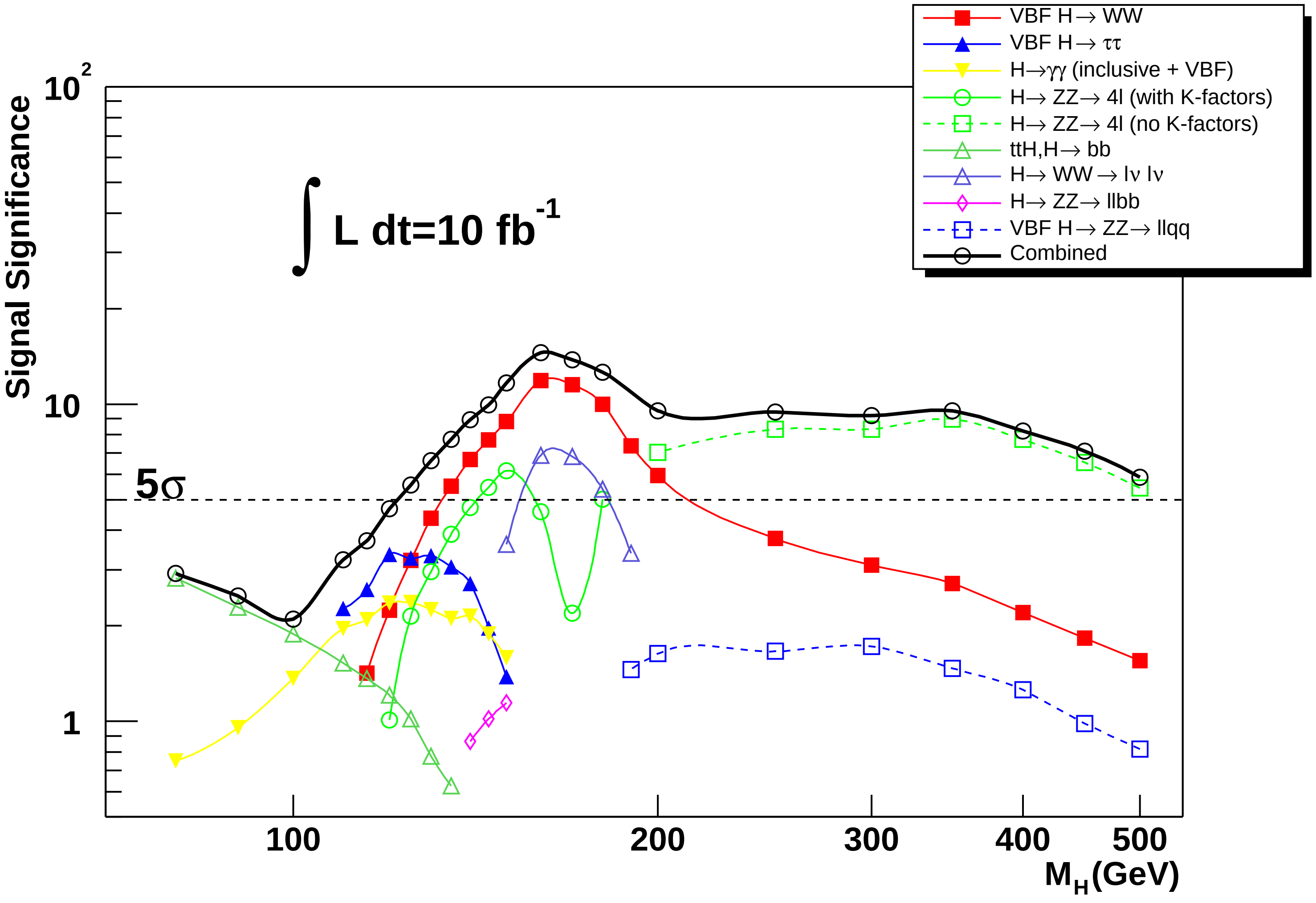
top quark associated production: $gg, q\bar{q} \to t\bar{t}H$

weak boson associated production: $q\bar{q}' \to WH, ZH$

SM Higgs search at the LHC: $\Rightarrow$ full parameter space accessible!?

SM Higgs search at the LHC: ⇒ full parameter space accessible

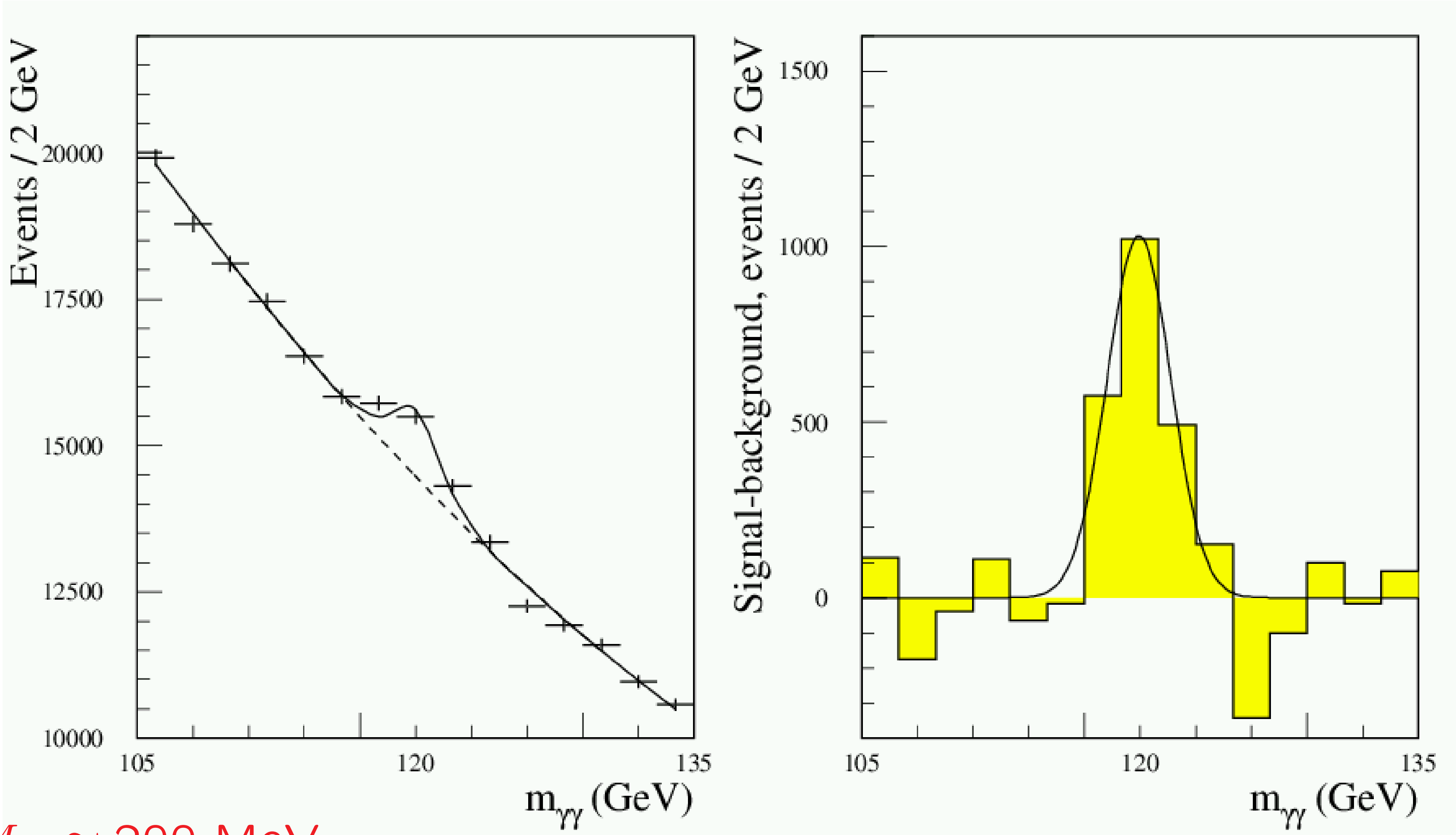
[*ATLAS '05*]



⇒ most problematic case also at the LHC: $M_H = 115 \ldots 120$ GeV

Step 2: Measurement of the mass

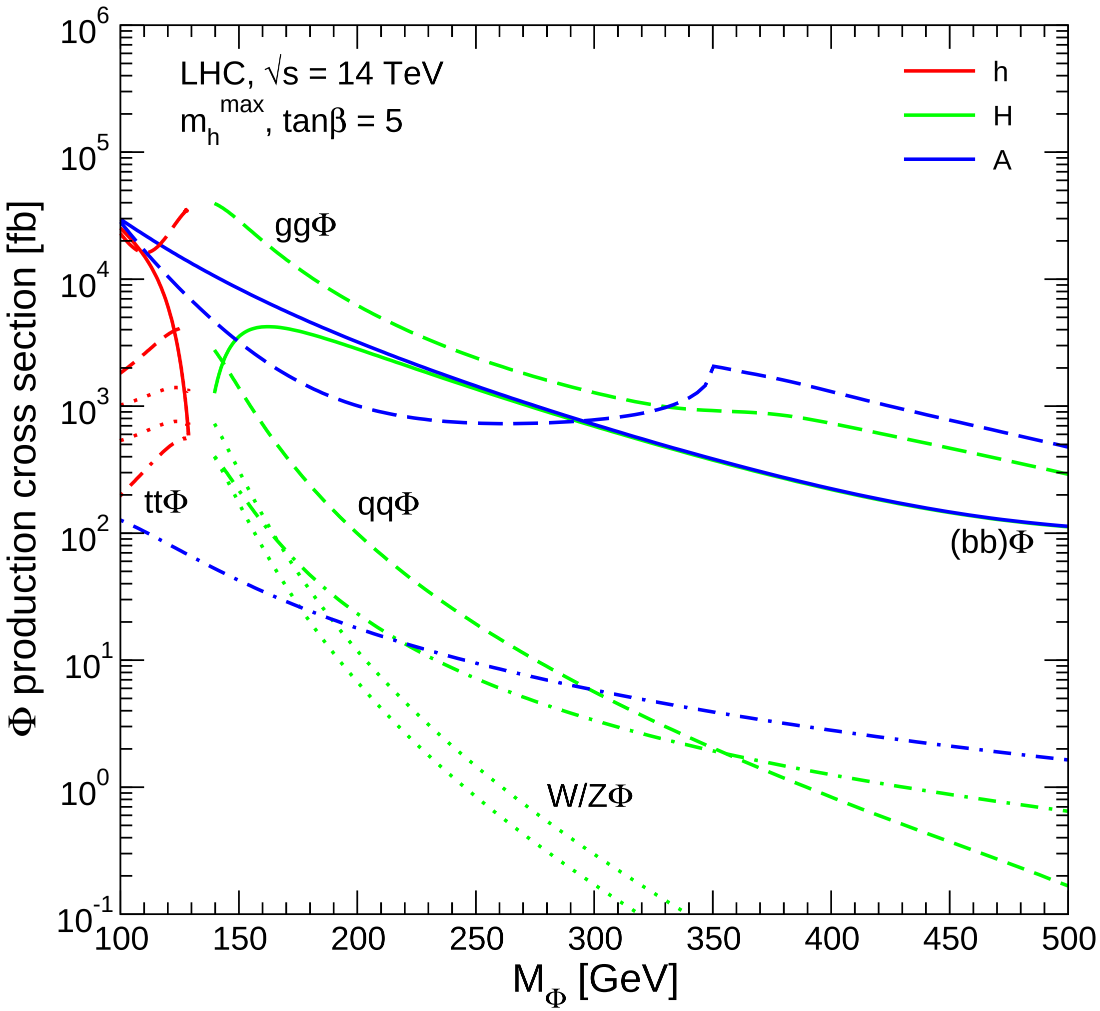
Best channel for mass measurement in the SM: $H \to \gamma\gamma$
[*ATLAS '99*]



$\Rightarrow \delta M_H \approx 200$ MeV

Situation is a bit more complicated for SUSY Higgses ($\phi = h, H, A$)

[*Tev4LHC Higgs working group report '06*]



gluon fusion: $gg \to \phi$

weak boson fusion (WBF):
$q\bar{q} \to q'\bar{q}'\phi$

top quark associated
production: $gg, q\bar{q} \to t\bar{t}\phi$

weak boson associated
production: $q\bar{q}' \to W\phi, Z\phi$

NEW: $b\bar{b}\phi$

Search for the lightest MSSM Higgs at the LHC:

$\Rightarrow$ full parameter accessible   But there might be problems . . .

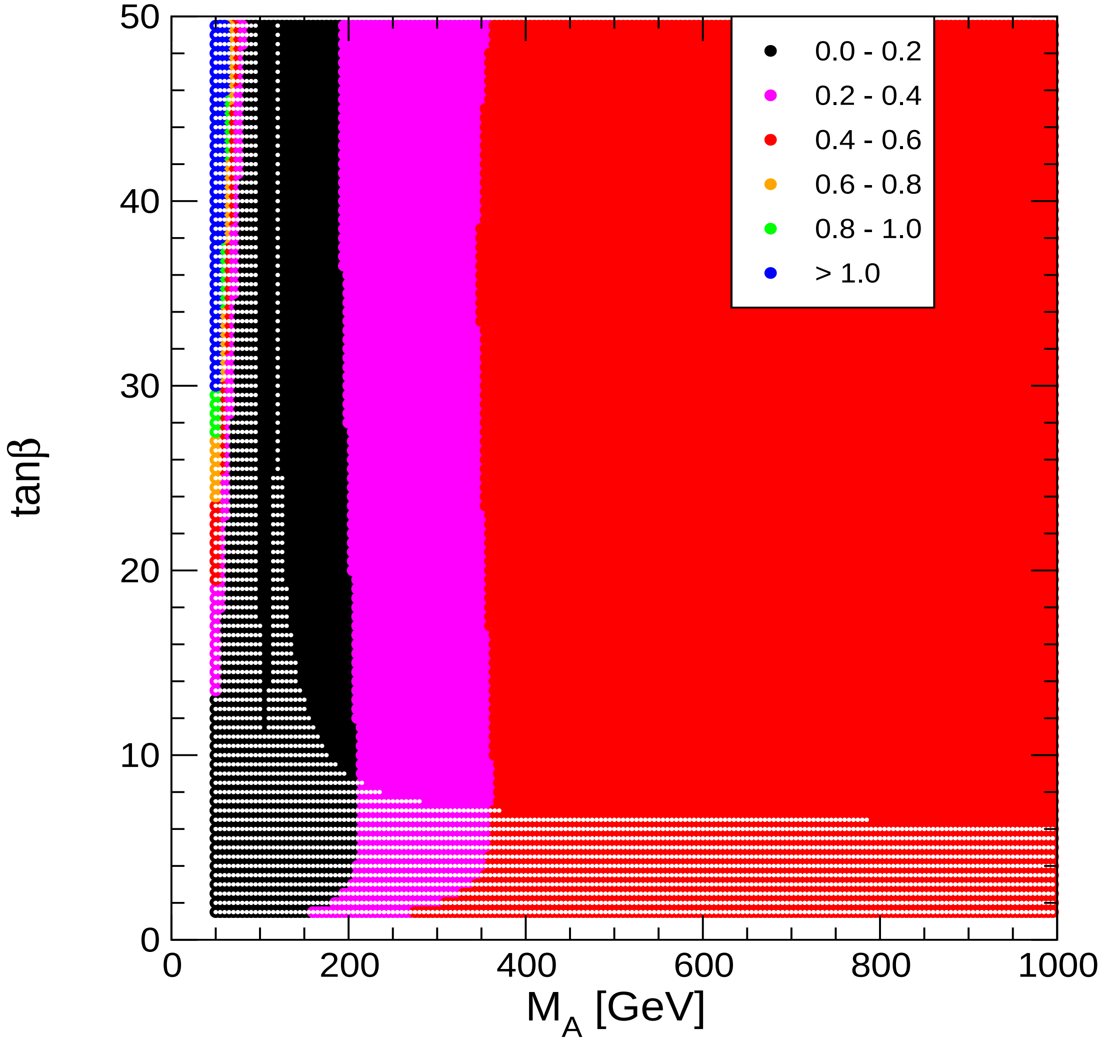
Possible problem in SUSY:

$$gg \to h \to \gamma\gamma$$

can be strongly suppressed

$\to$ "gluophobic Higgs scenario"

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

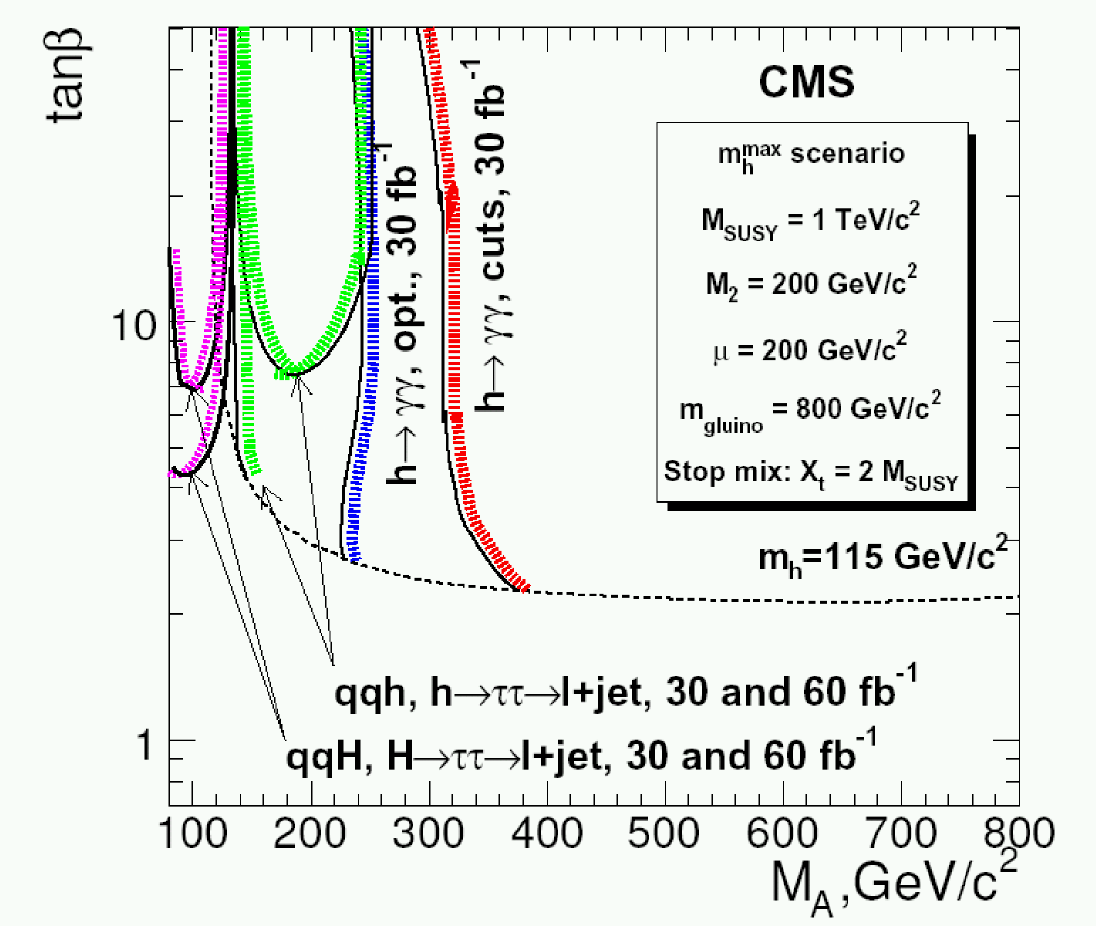


$\Rightarrow$ Strong suppression of $gg \to h \to \gamma\gamma$ possible over the whole parameter space

(not realized in mSUGRA/CMSSM, GMSB, AMSB, . . .)

M_h measurement in the "nice" $m_h^{\max}$ scenario:

[*CMS '06*]



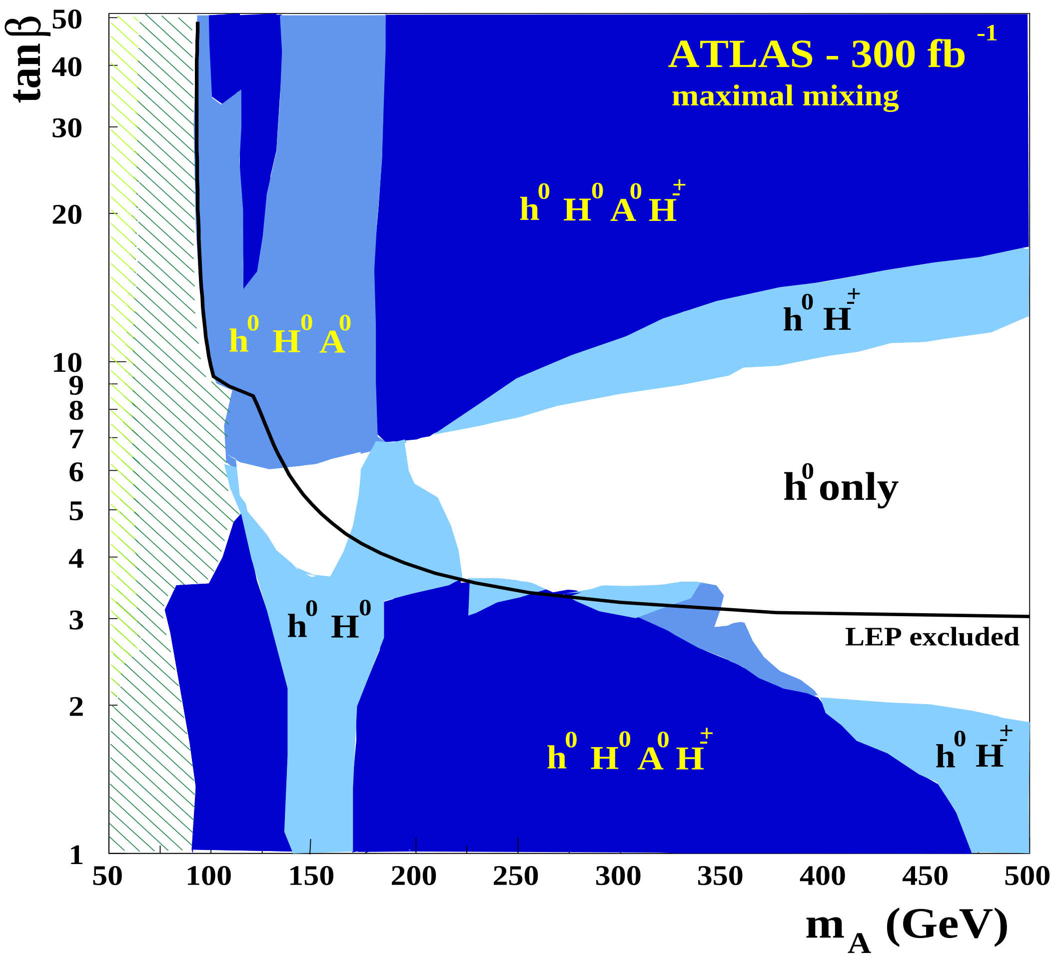
Measurement possible only for
$M_A \gtrsim 250$ GeV
$\Rightarrow \delta M_h \approx 200$ MeV

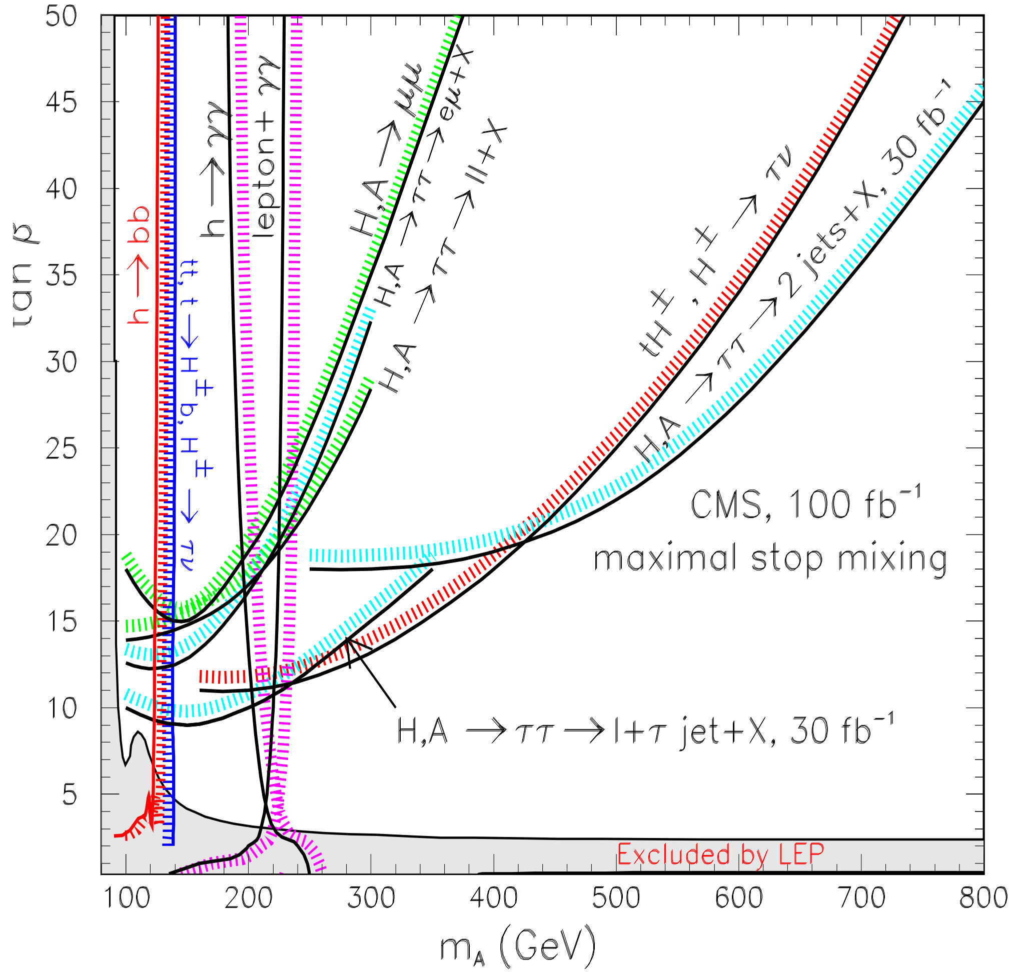
other channels:
$h \to ZZ^* \to 4\mu$ ($M_h \gtrsim 130$ GeV)

otherwise: $\delta M_h \gtrsim 1-2$ GeV

The heavy MSSM Higgs bosons

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane
($m_h^{\rm max}$ benchmark scenario): [*ATLAS '99*] [*CMS '03*]

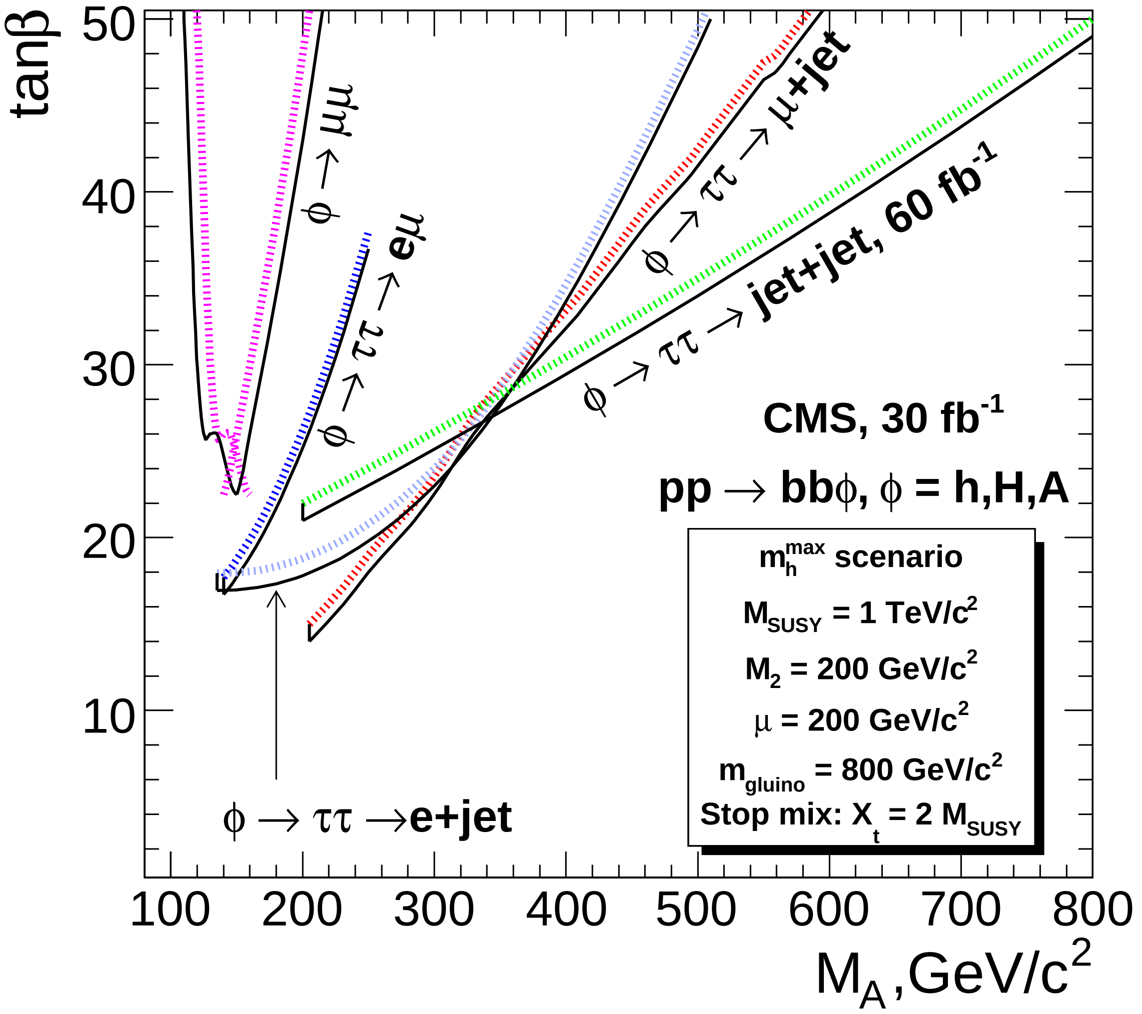




areas where only h is observable ⇒ "LHC wedge"

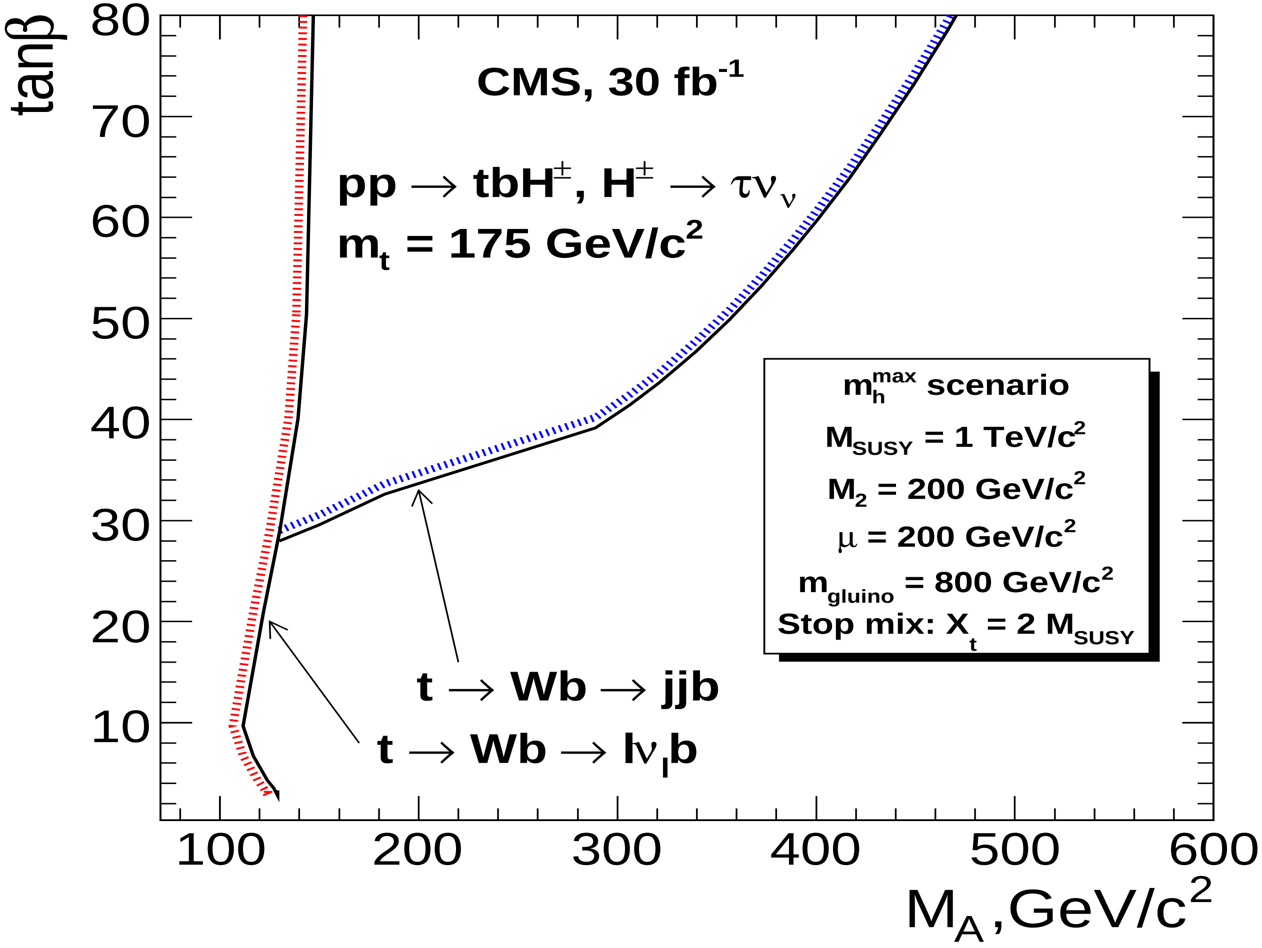
Latest results for neutral heavy Higgs bosons:

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane $(\Phi = H, A)$
$(m_h^{\rm max}$ benchmark scenario): [*CMS PTDR '06*]



Charged Higgs boson searches:

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane ($m_h^{\rm max}$ benchmark scenario): [*CMS PTDR '06*]



light charged Higgs:

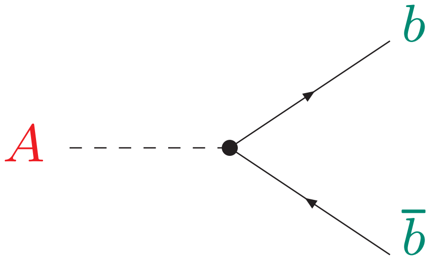
$$M_{H^\pm} < m_t$$

heavy charged Higgs:

$$M_{H^\pm} > m_t$$

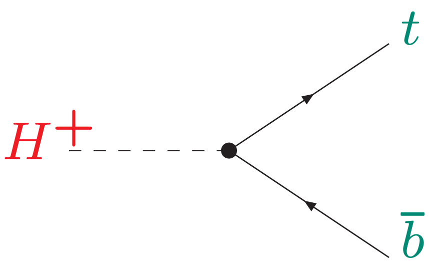
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



$$y_b \quad \longrightarrow \quad y_b \, \frac{\tan\beta}{1+\Delta_b}$$

At large $\tan\beta$: either $H \approx A$ or $h \approx A$



$$y_b \, \frac{\tan\beta}{1+\Delta_b}$$

$$\Delta_b = \frac{2\alpha_s}{3\,\pi} m_{\tilde g}\, \mu \tan\beta \times I(m_{\tilde b_1}, m_{\tilde b_2}, m_{\tilde g}) + \frac{\alpha_t}{4\,\pi} A_t\, \mu \tan\beta \times I(m_{\tilde t_1}, m_{\tilde t_2}, \mu)$$

$\Rightarrow$ other parameters enter $\Rightarrow$ strong μ dependence

Most powerful search modes for heavy MSSM Higgs bosons:

$$b\bar{b} \to H/A \to \tau^+\tau^- + X$$
$$gb \to tH^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$
$$pp \to t\bar{t} \to H^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$

Enhancement factors compared to the SM case:

$$H/A \;\; : \;\; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{\mathrm{BR}(H \to \tau^+\tau^-) + \mathrm{BR}(A \to \tau^+\tau^-)}{\mathrm{BR}(H \to \tau^+\tau^-)_{\mathrm{SM}}}$$

$$H^\pm \;\; : \;\; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \mathrm{BR}(H^\pm \to \tau\nu_\tau)$$

$\Rightarrow$ Δ_b effects so far neglected by ATLAS/CMS

also relevant for $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

also relevant: correct evaluation of $\Gamma(H/A/H^\pm \to \mathrm{SUSY})$

$\Rightarrow$ additional effects on $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

Suggestion for new benchmark scenarios:

[*M. Carena, S.H., C. Wagner, G. Weiglein '05*]

$\rightarrow$ investigate benchmark scenarios:

$\rightarrow$ Vary only M_A and $\tan\beta$ (large!)
$\rightarrow$ Keep all other SUSY parameters fixed

$\rightarrow$ Vary in addition μ: $\mu = \pm 1000, \pm 500, \pm 200$ GeV
(if perturbativity allows)

1. m_h^{max} scenario:
   $\rightarrow$ obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\text{SUSY}}$)

   A_t large $\Rightarrow$ large $\mathcal{O}(\alpha_t)$ contribution to Δ_b

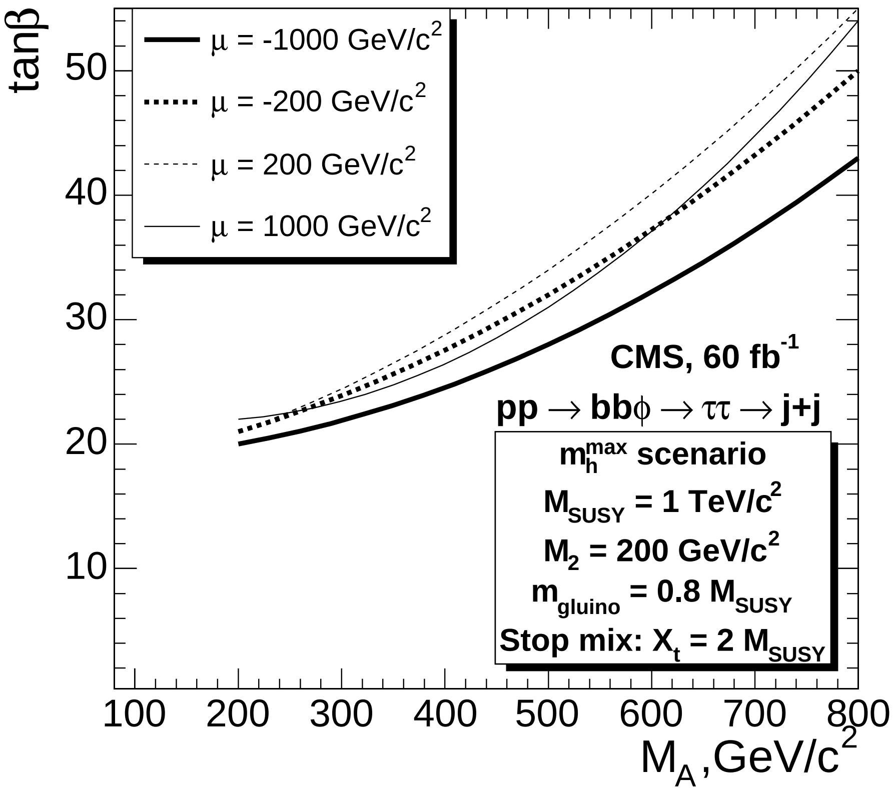
2. no-mixing scenario
   $\rightarrow$ no mixing in the scalar top sector ($X_t = 0$)

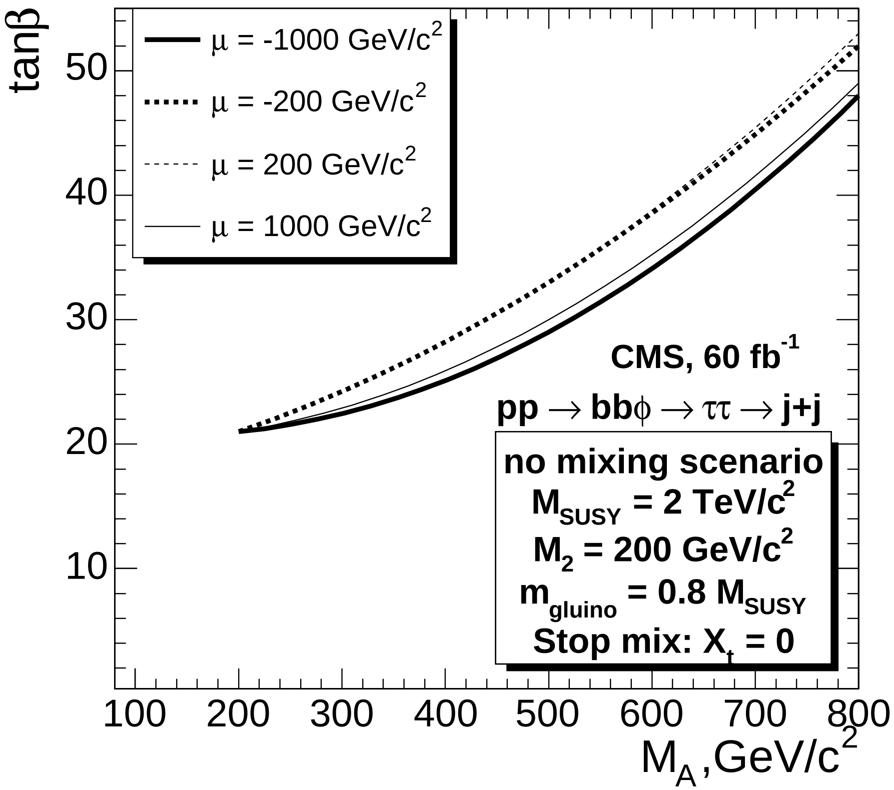
   A_t small $\Rightarrow$ small $\mathcal{O}(\alpha_t)$ contribution to Δ_b

   $\Rightarrow$ large difference to m_h^{max} scenario

Dependence of LHC wedge from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,\text{jets}$ on μ:

[S.H., A. Nikitenko, G. Weiglein et al. '06]



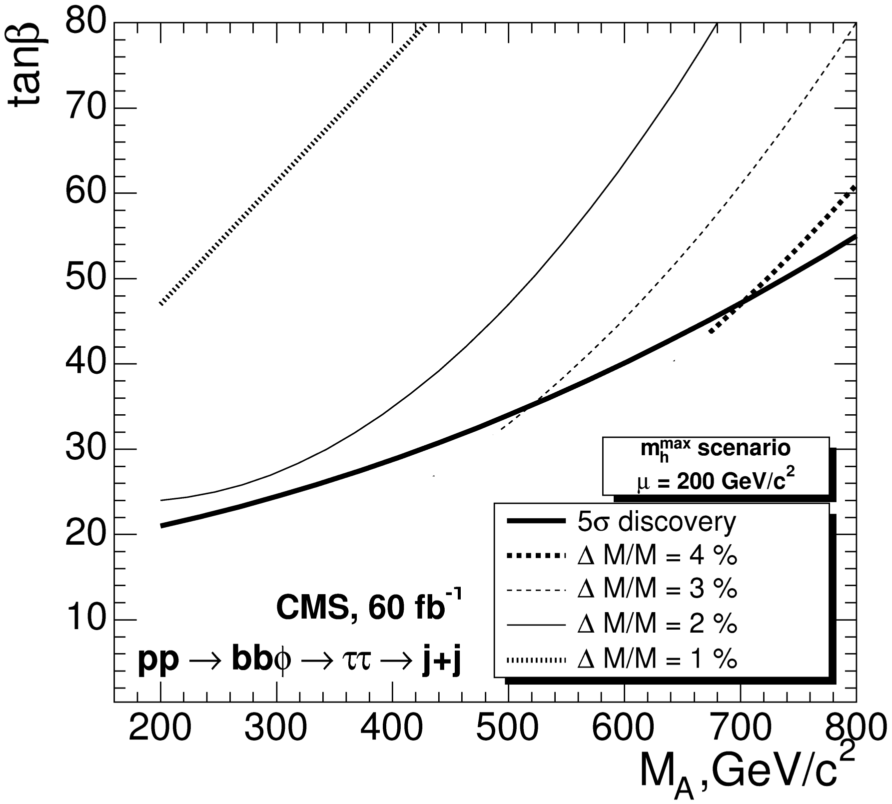


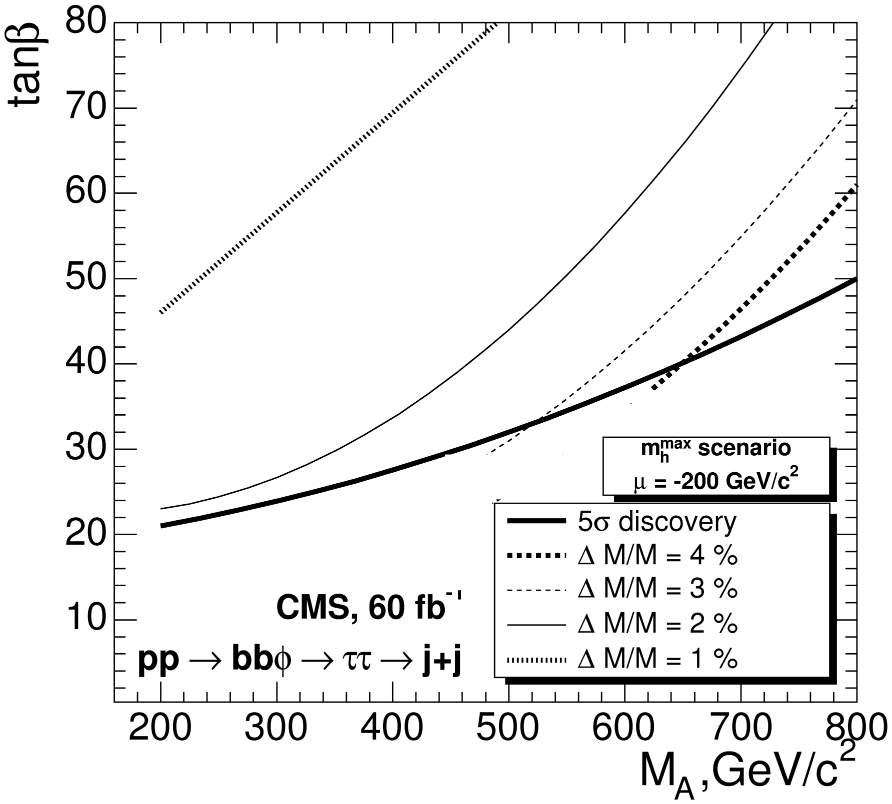
⇒ now based on full CMS simulation

⇒ non-negligible variation with the sign and absolute value of μ
(→ numerical compensations in production and decay)

Precision of $\delta M/M$ from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,$jets:

[*S.H., A. Nikitenko, G. Weiglein et al. '06*]



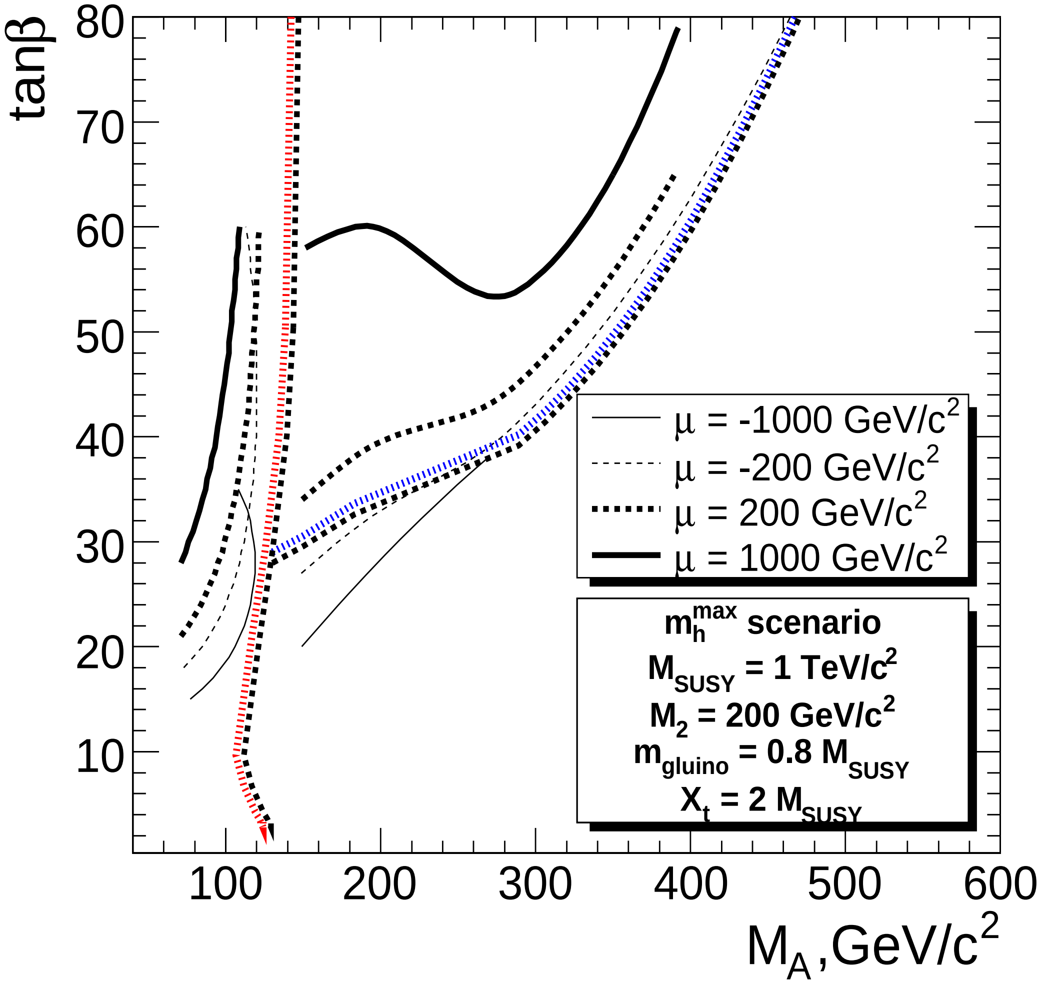


$\Rightarrow$ now based on full CMS simulation

$\Rightarrow$ high precision measurement of heavy Higgs boson masses possible

Charged Higgs: comparison with CMS PTDR (m_h^{max} scenario):

[*M. Hashemi, S.H., R. Kinnunen, A. Nikitenko, G. Weiglein '07*]



→ note: M_A–$\tan\beta$ plane

light charged Higgs:

always worse than PTDR

better $M_{H^\pm}$ calculation!

inclusion of Δ_b effects

heavy charged Higgs:

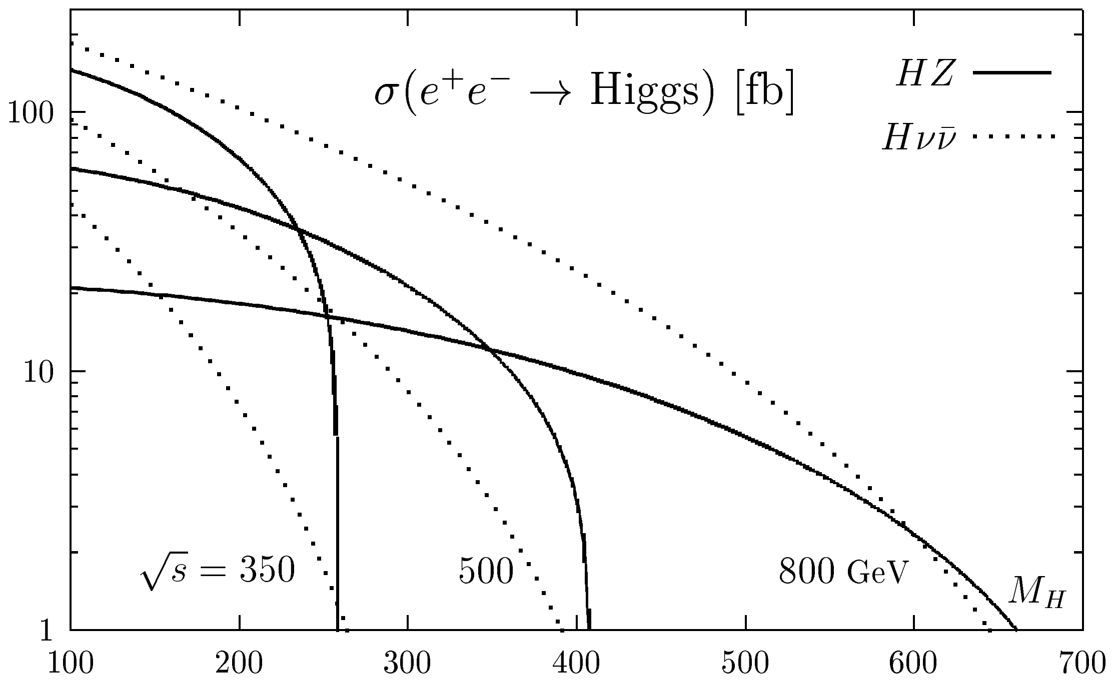
PTDR in "the middle"

new results partially

substantially worse

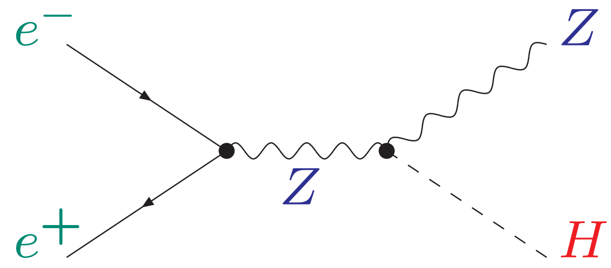
Higgs physics at the ILC

Higgs production at the ILC:



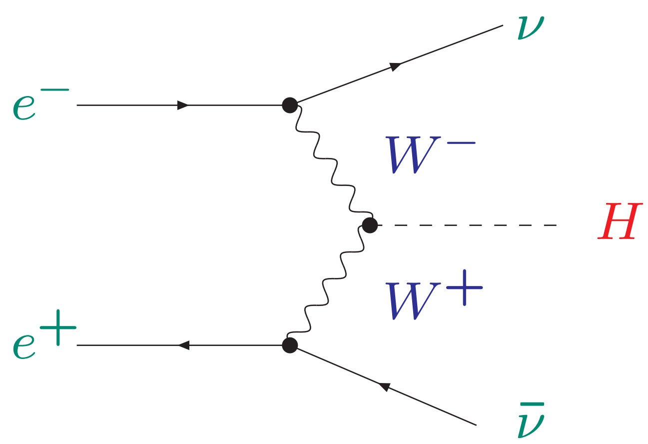
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

$e + e- \to \nu\bar{\nu}H$



$\Rightarrow$ Measurement of masses, couplings, . . . in per cent/per mille

Some ILC specifics:

recoil method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ all observable channels can be measured with high accuracy

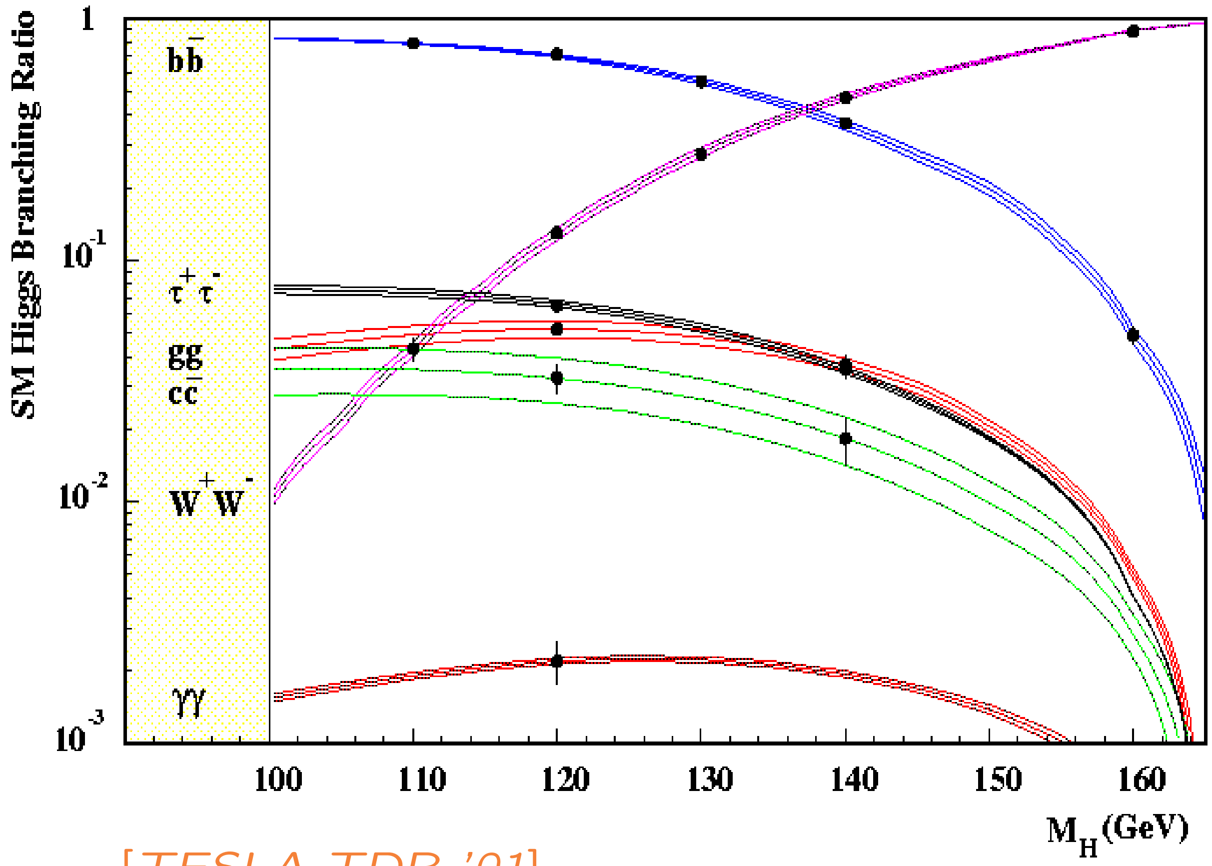
Some ILC results (500 fb^{-1}@$\sqrt{s} = 350$ GeV):

$\delta M_H \approx 50$ MeV
$\delta g_{ZZH} \approx 2.5\%$, $\delta g_{WWH} \approx 2-5\%$
$\delta g_{Hb\bar{b}} \approx 1-2\%$ (for $M_H \lesssim 150$ GeV)

Higgs physics at the ILC:

SM Higgs @ ILC:
Precise measurement of:

1. Higgs boson mass,
   $\delta M_H \approx 50$ MeV
2. Higgs boson width
   (direct/indirect)
3. Higgs boson couplings,
   $\mathcal{O}$ (few%) $\Rightarrow$
4. Higgs boson quantum
   numbers: spin, . . .



[TESLA TDR '01]

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SM Higgs @ ILC:
Precise measurement of:

1. Higgs boson mass, $\delta M_H \approx 50$ MeV
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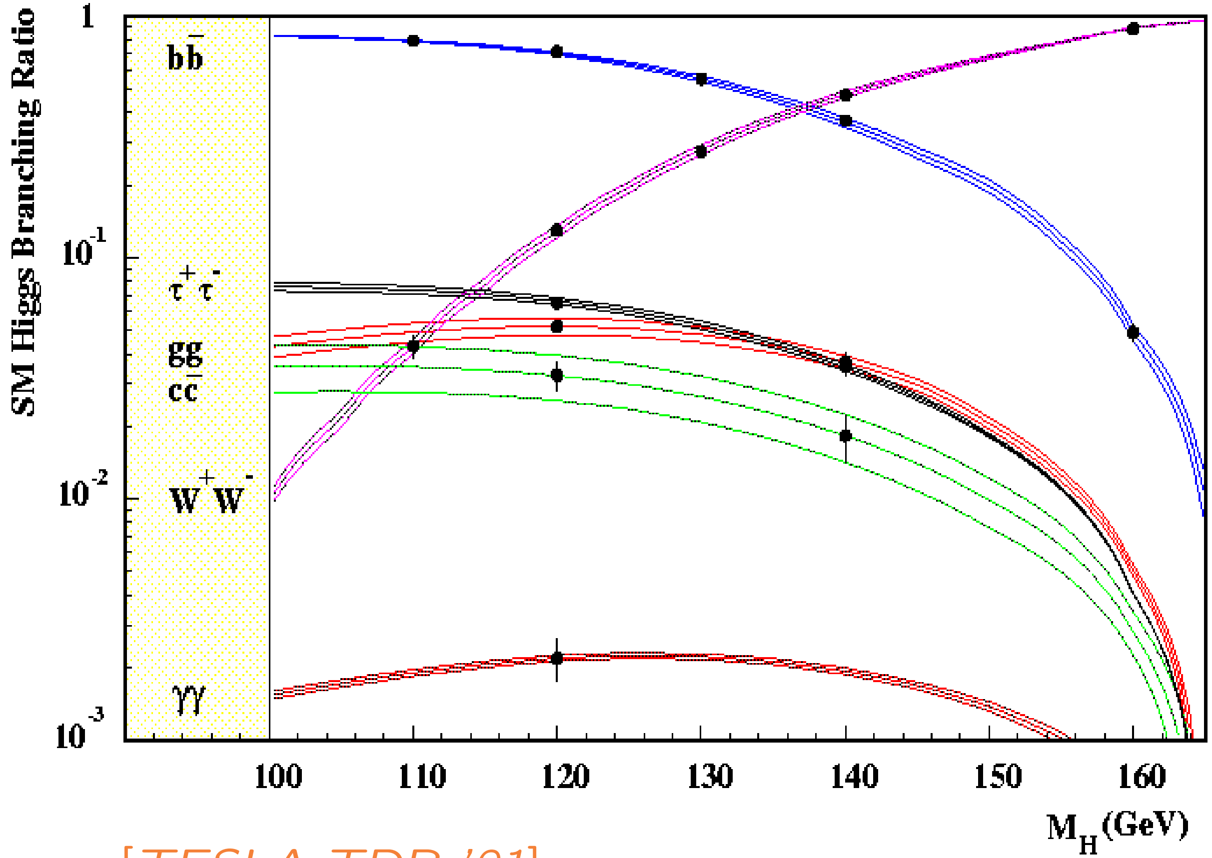

[*TESLA TDR '01*]

But do we need the ILC precision?

Higgs physics at the ILC:

SM Higgs @ ILC:
Precise measurement of:

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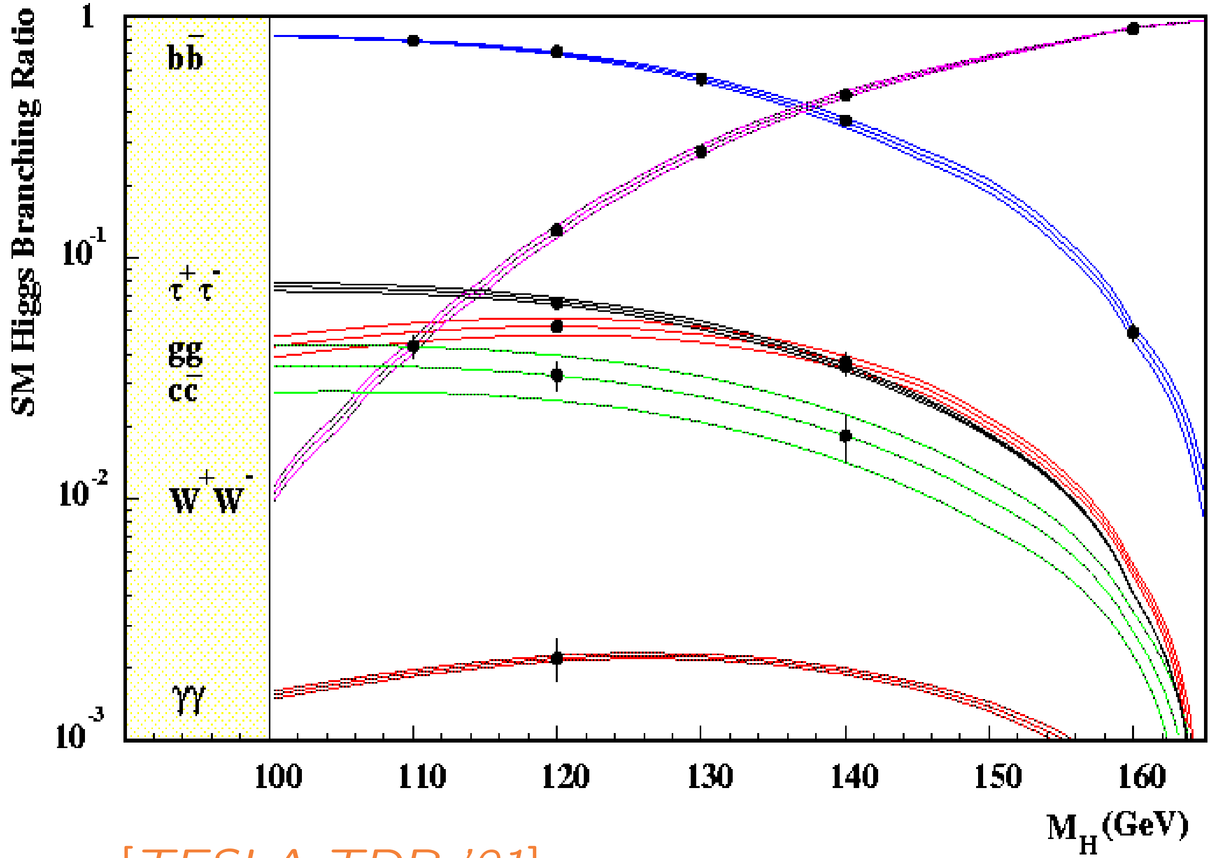
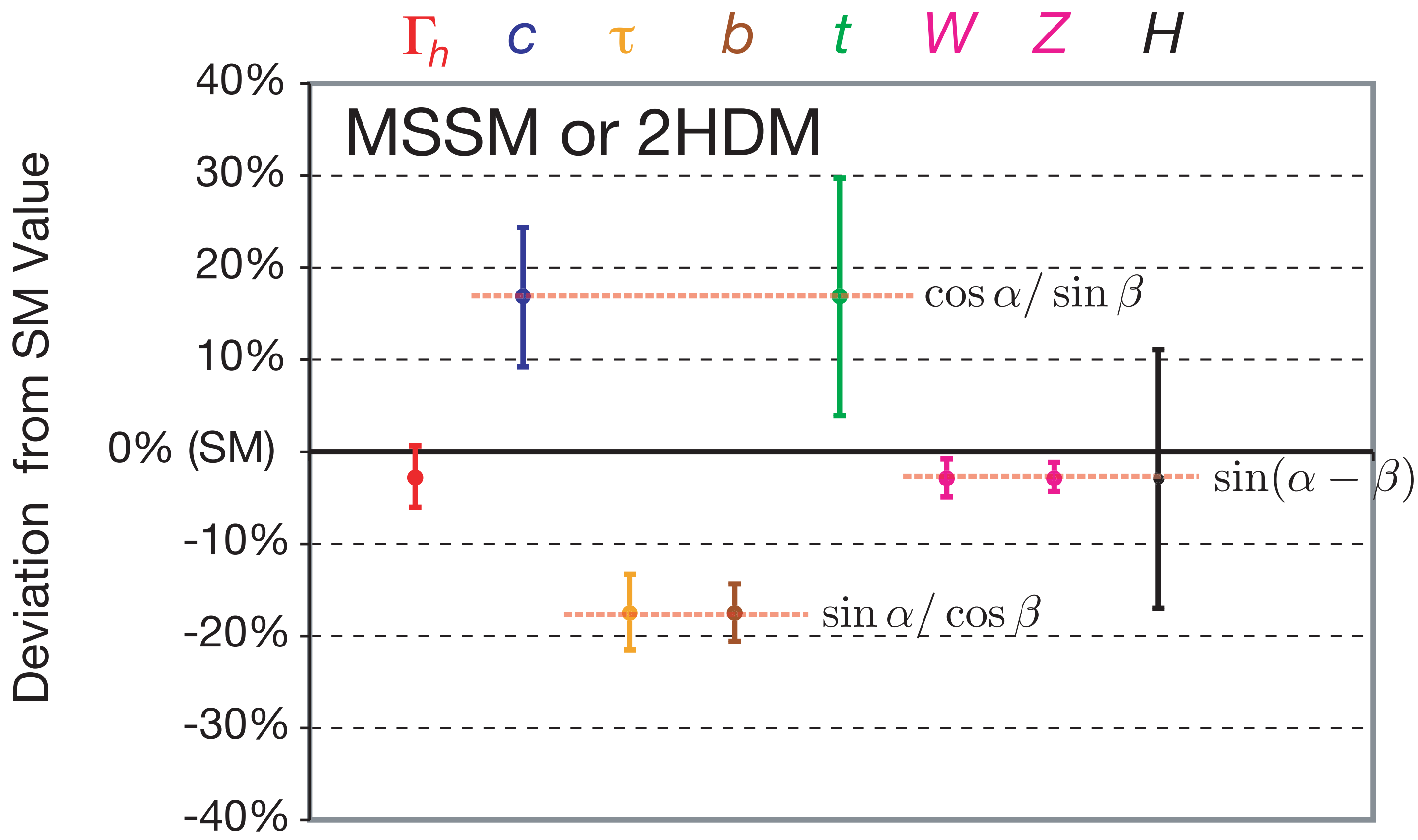


[*TESLA TDR '01*]

But do we need the ILC precision?
YES! To discriminate between the SM and extensions

Example I: Higgs couplings in the MSSM:

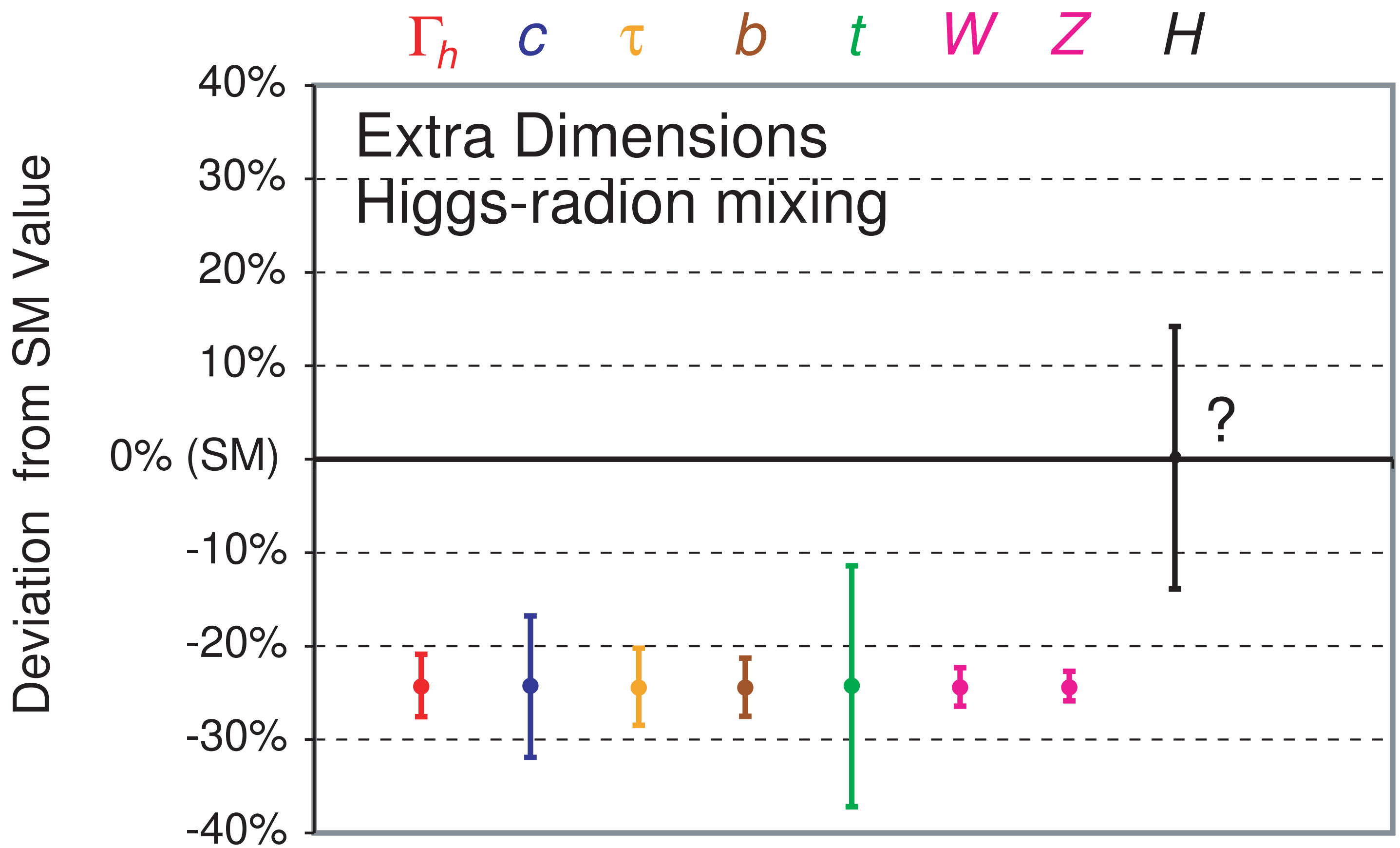
"Normal" MSSM scenario:



⇒ measurable deviations over large parts of the parameter space

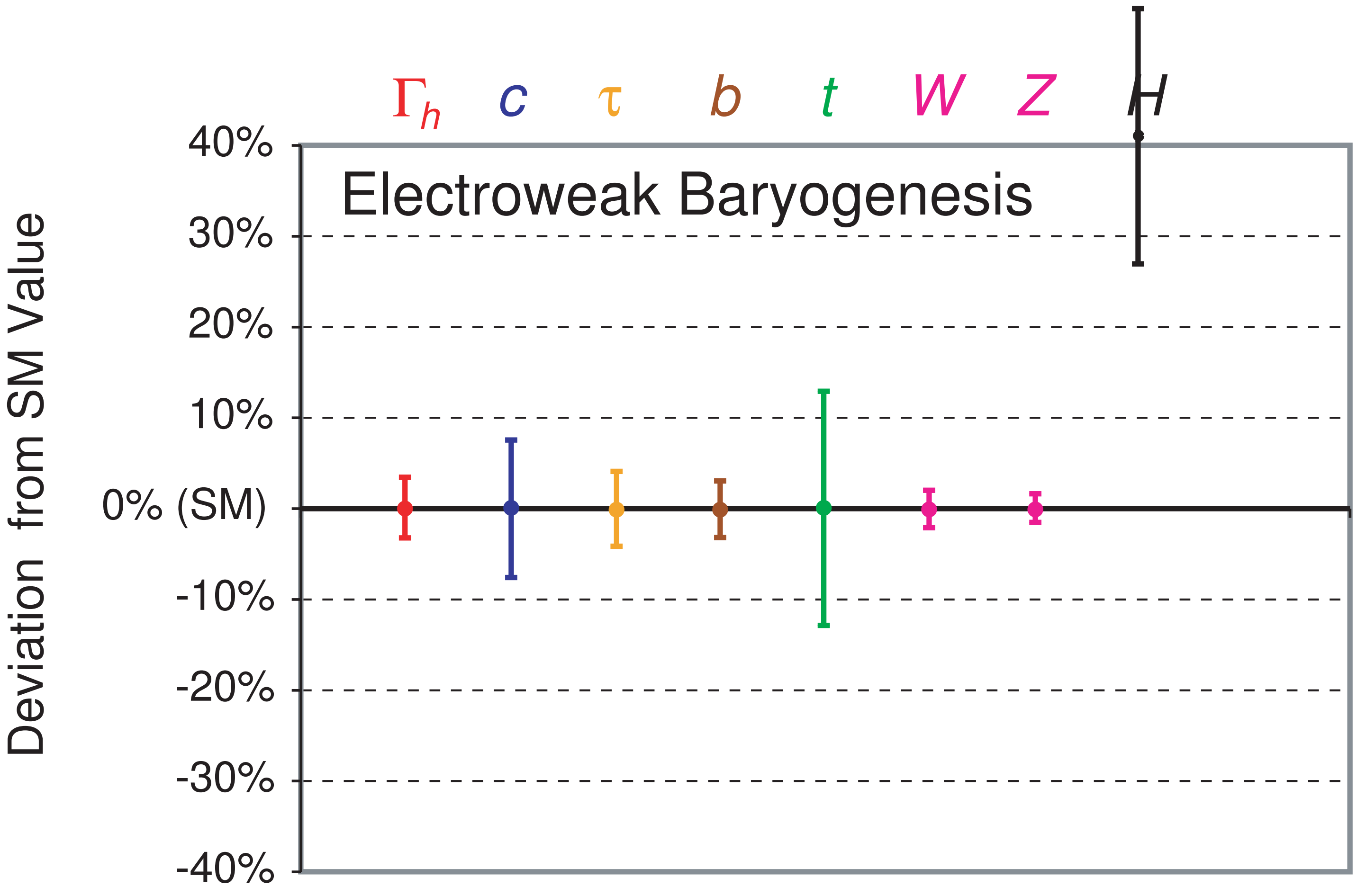
Example II: Higgs couplings in model with extra dimensions:

Effects of Kaluza Klein towers:



⇒ measurable deviations over large parts of the parameter space

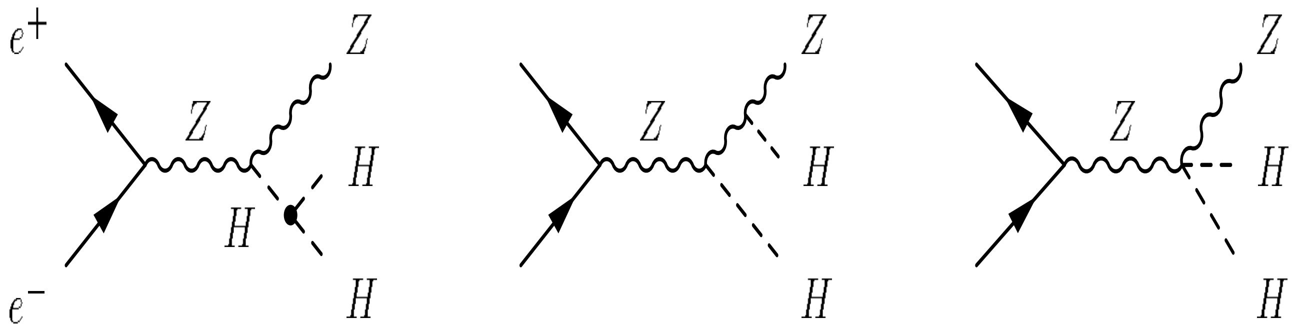
Example III: Higgs couplings in a baryogenis motivated SM extension:

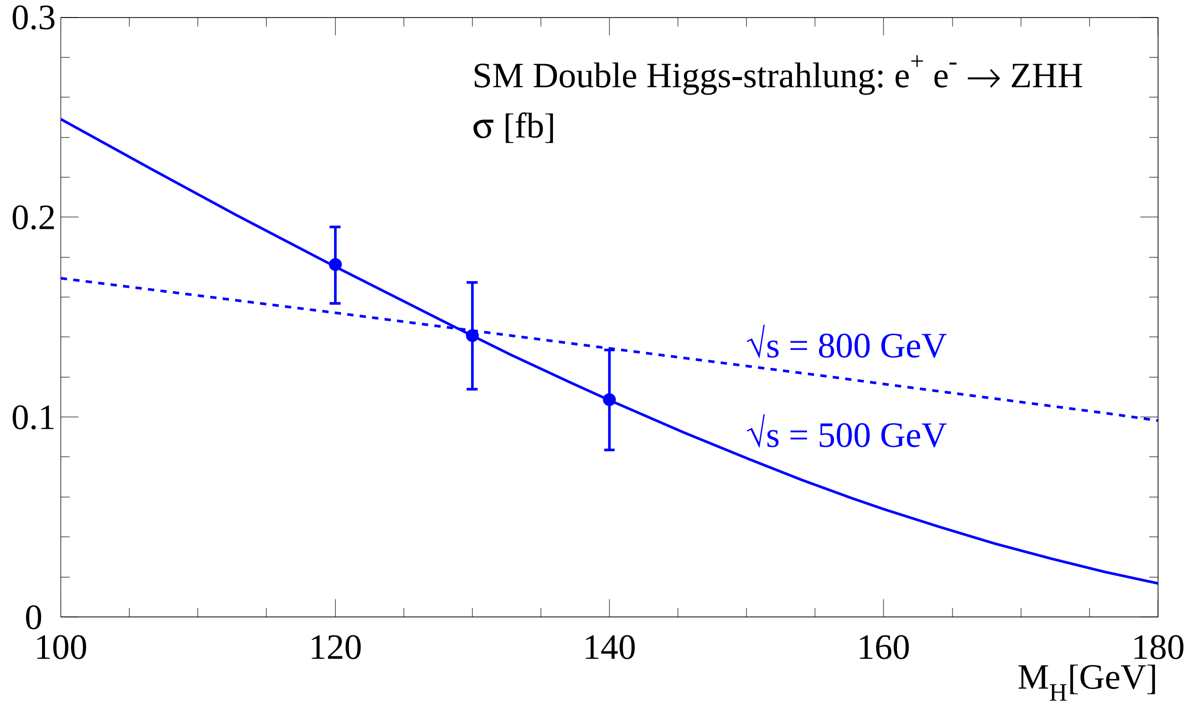


⇒ Only Higgs self coupling deviates, measurement possible!

Step 5: measurement of the Higgs boson self-coupling

$\Rightarrow$ only possible at the ILC





Parton-level study:

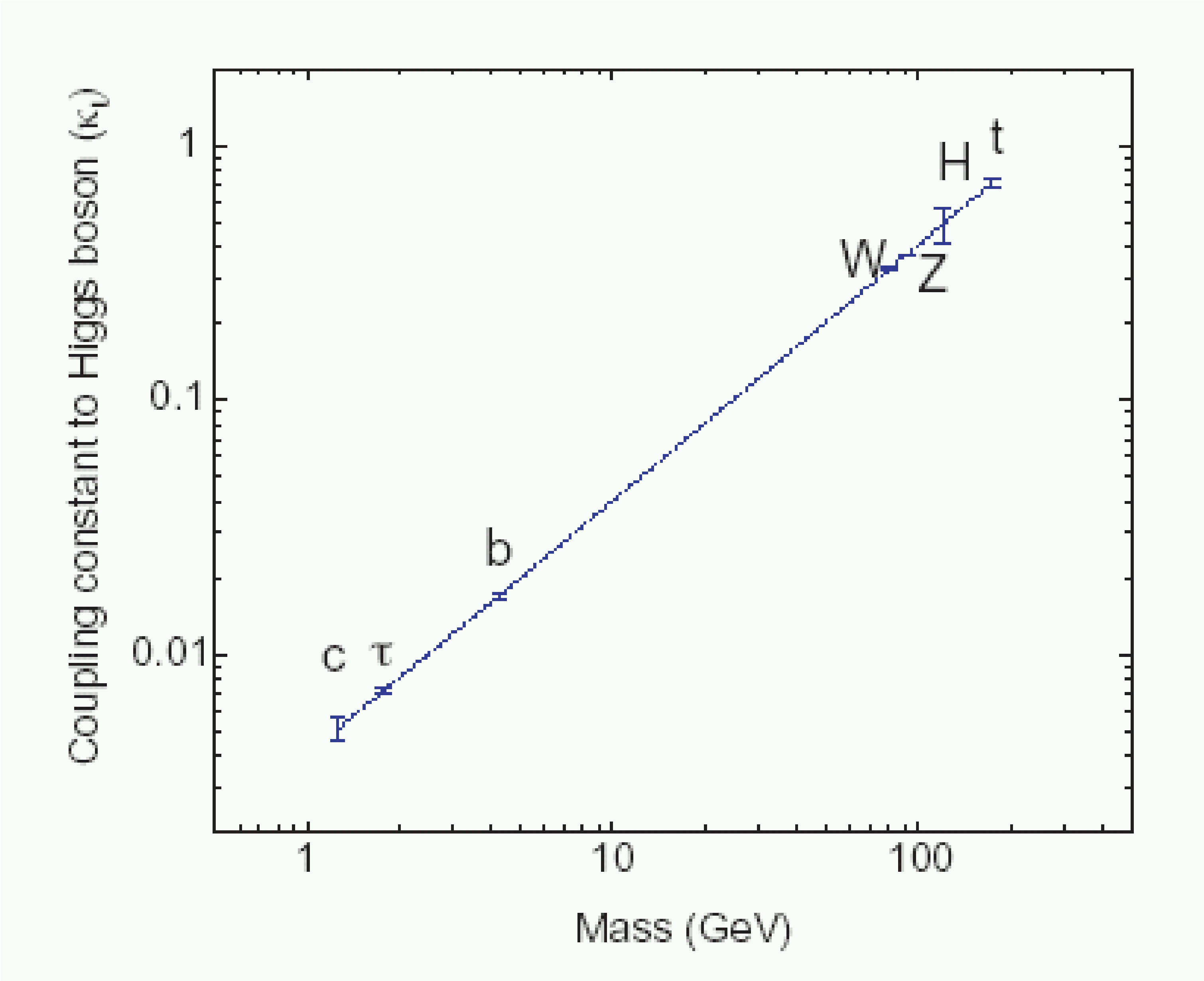
[*Djouadi, Kilian, Mühlleitner, Zerwas '99*]

1 ab^{-1} $\Rightarrow$ 20–30% measurement of $\lambda = \lambda_{HHH}$

However:

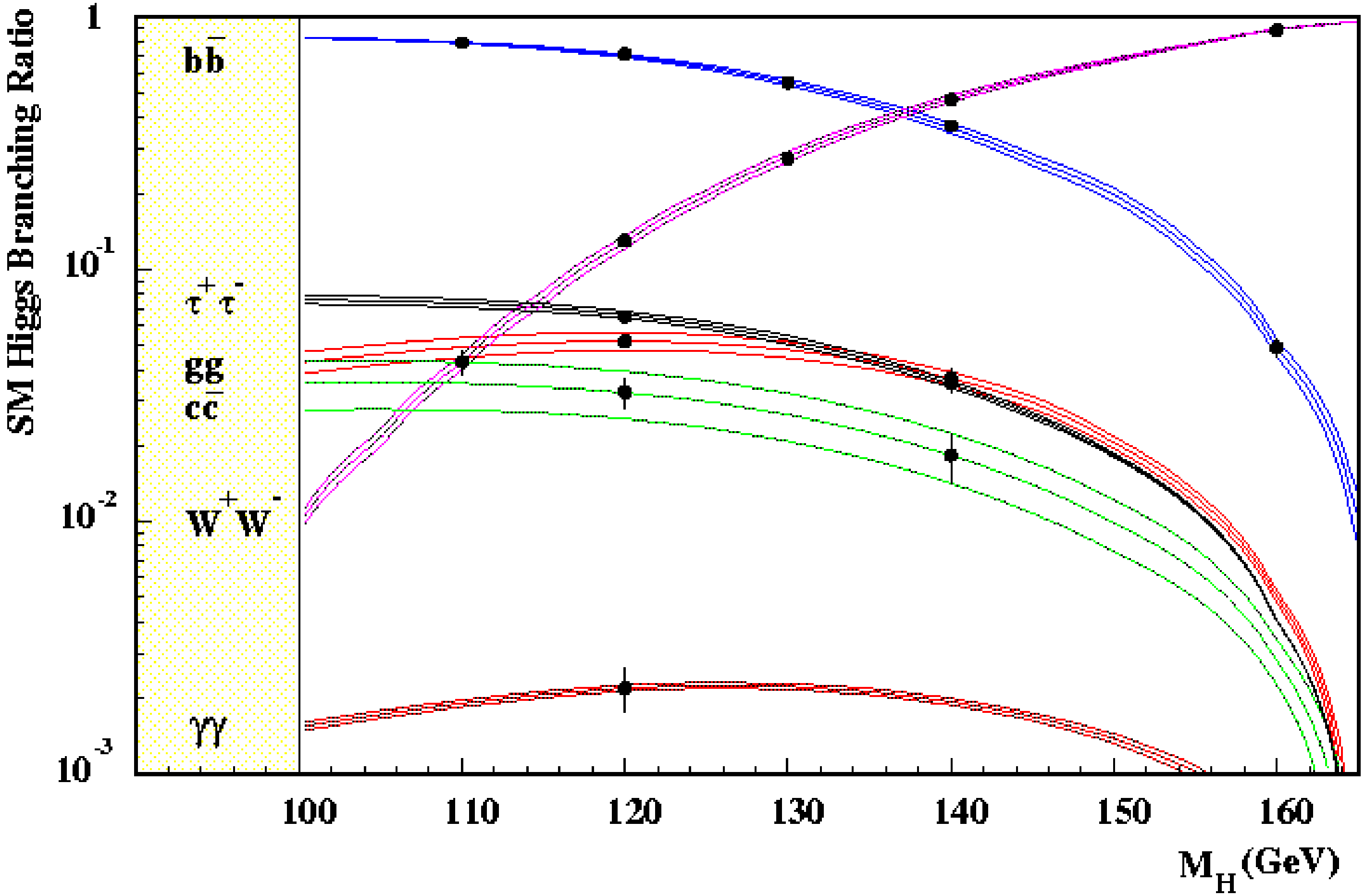
$\lambda = \lambda_{HHHH}$ out of reach for all foreseeable colliders

$\Rightarrow$ only Lepton Colliders can "verify" the Higgs mechanism



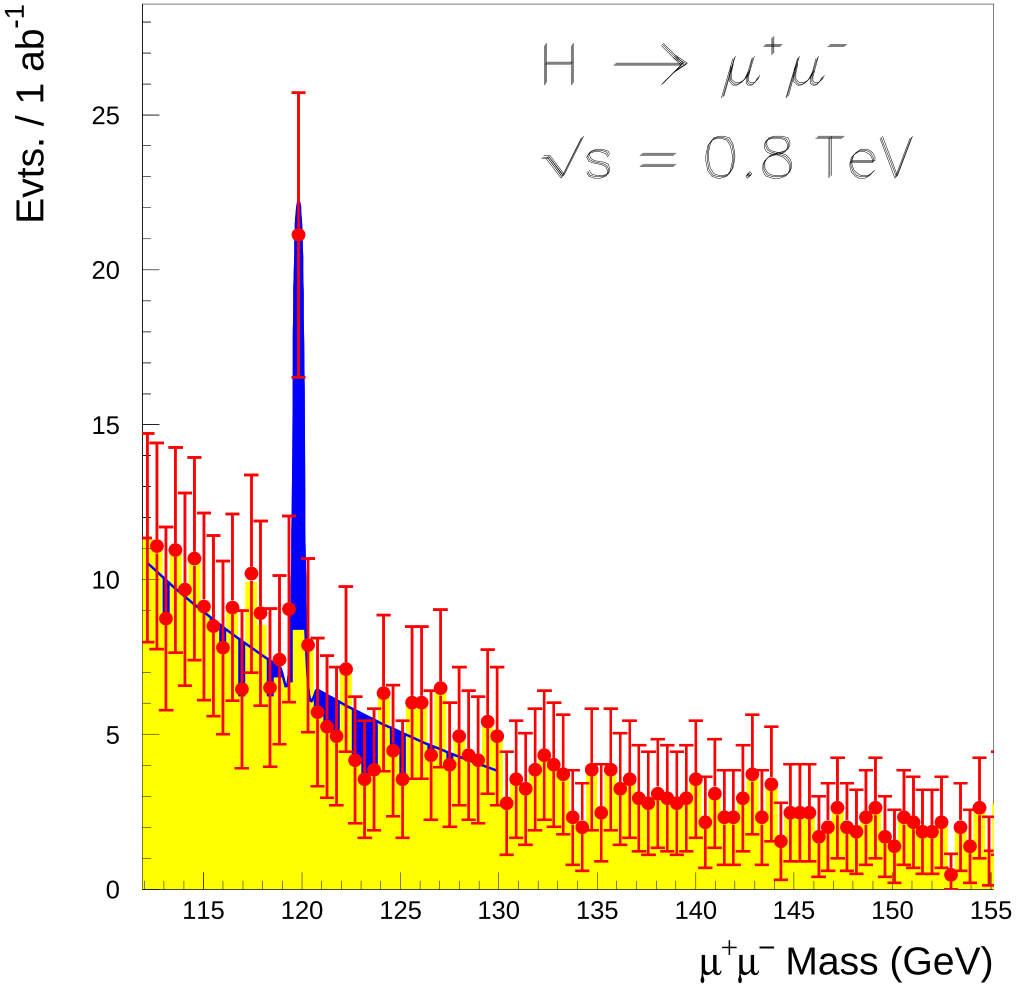
. . . including couplings to the second family!

⇒ coupling to the c quark:



. . . including couplings to the second family!

⇒ coupling to the muon:



$(M_H = 120$ GeV, $\sqrt{s} = 800$ GeV, $\mathcal{L}_{\rm int} = 1$ ab$^{-1})$

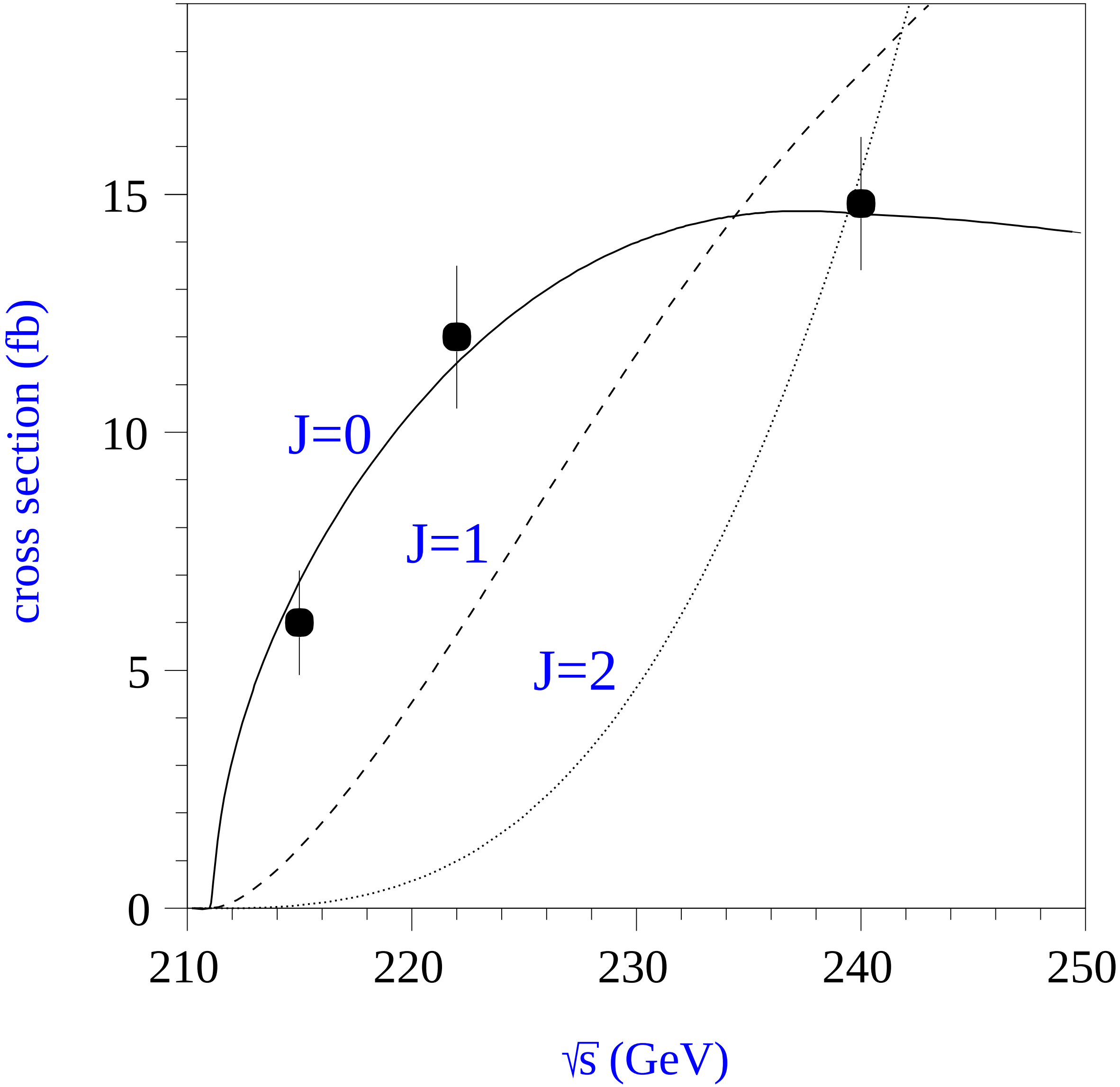
Step 6: measurement of the Higgs boson spin

$\Rightarrow$ easy at the ILC

Threshold scan for
$\sigma(e^+e^- \to ZX)$:

$X = H \Rightarrow \sigma \sim \beta$
(β from kinematics)

20 fb^{-1}
$\Rightarrow$ identification easy



Indirect determination of unknown Higgs sector parameters

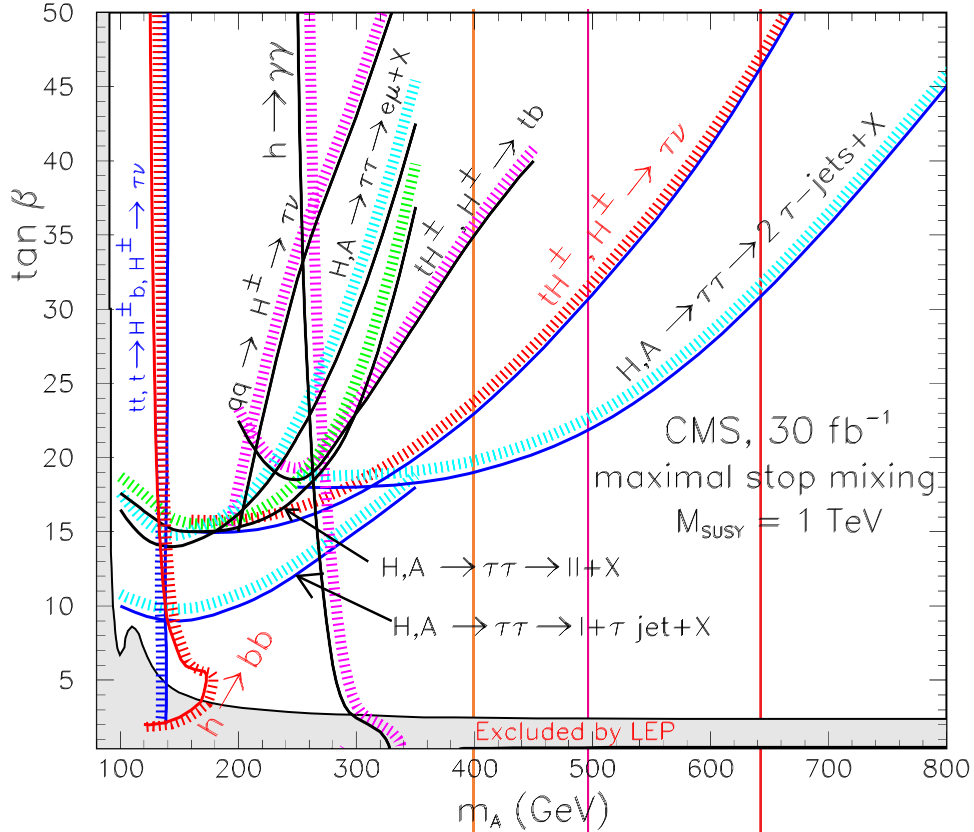
LHC/ILC reach for MSSM Higgs bosons:

LHC:

h : all $M_A - \tan\beta$ plane

H, A : unreachable parts

CMS, 30 fb^{-1}, $m_h^{\max}$ scenario: $\Rightarrow$



ILC: $\sqrt{s} = 800$ GeV

$\sqrt{s} = 1000$ GeV

ILC:

kinematic limit: $M_A \lesssim \sqrt{s}/2$

$\rightarrow \sqrt{s} = 800$ GeV

$\rightarrow \sqrt{s} = 1000$ GeV

$\gamma\gamma$:

kinematic limit: $M_A \lesssim 0.8\sqrt{s}$

$\gamma\gamma$: $\sqrt{s} = 800$ GeV

Q: Is it possible to extend the reach for heavy Higgs bosons ?

A: Yes, by direct and indirect measurements

⇒ indirect determination of M_A in LHC wedge

Existing LHC analyses neglect:

– MSSM intrinsic uncertainties
– parametric SM uncertainties
– anticipated parametric MSSM uncertainties

⇒ existing analyses unrealistic

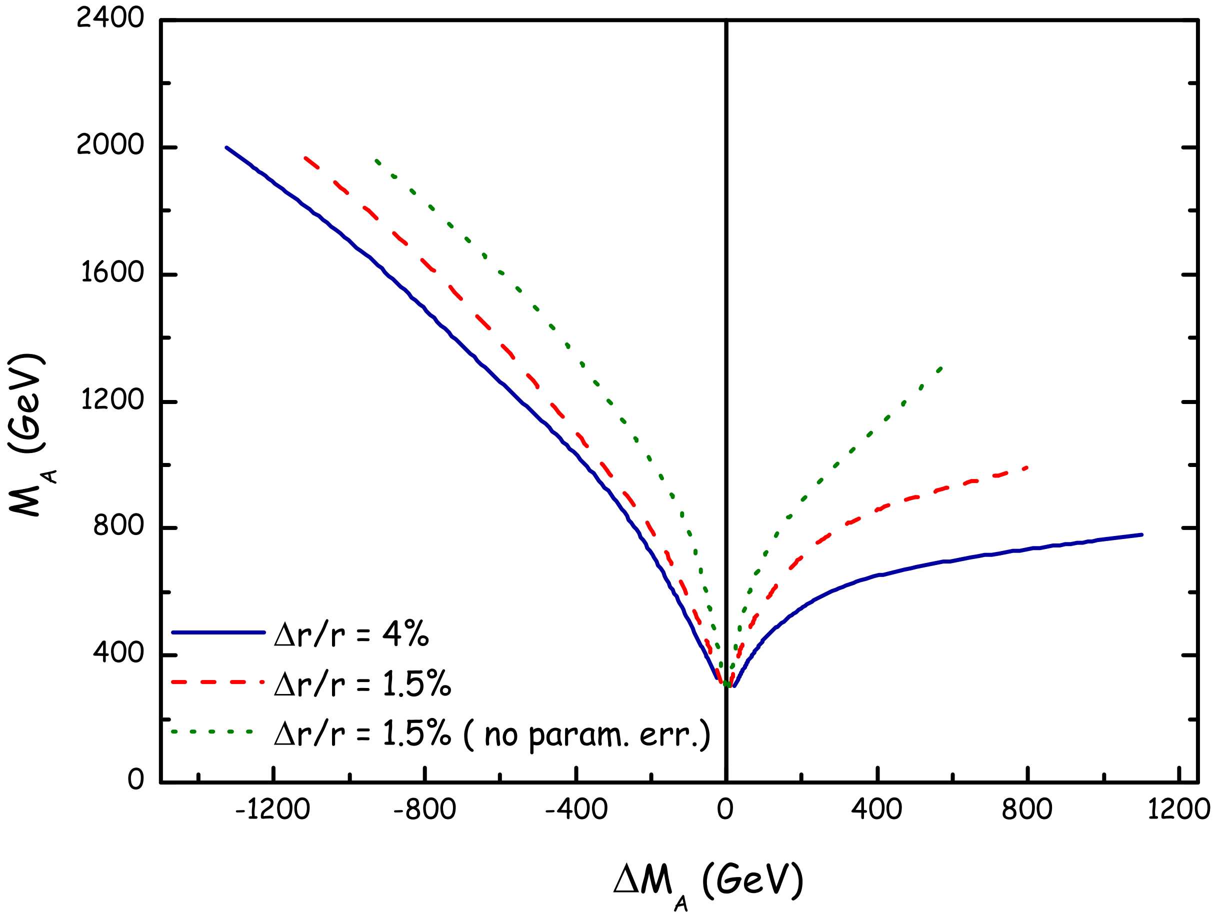
One analysis includes all uncertainties: [*K. Desch et al. '04*]

⇒ needs ILC uncertainty of

$$r \equiv \frac{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{MSSM}}}{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{SM}}}$$

\+ input for masses, mixing angles from LHC ⊕ ILC

Analysis using r: [K. Desch et al. '04]



$\Delta r/r = 4\%$: upper limit on M_A up to $M_A \lesssim 800$ GeV

$\Delta r/r = 1.5\%$: $\Delta M_A/M_A = 20(30)\%$ for $M_A = 600(800)$ GeV

inclusion of parametric errors crucial for reliable bounds

3. SUSY at the LHC and the ILC

In order to establish SUSY experimentally:

Need to demonstrate that:

- every particle has superpartner
- their spins differ by 1/2
- their gauge quantum numbers are the same
- their couplings are identical
- mass relations hold

. . .

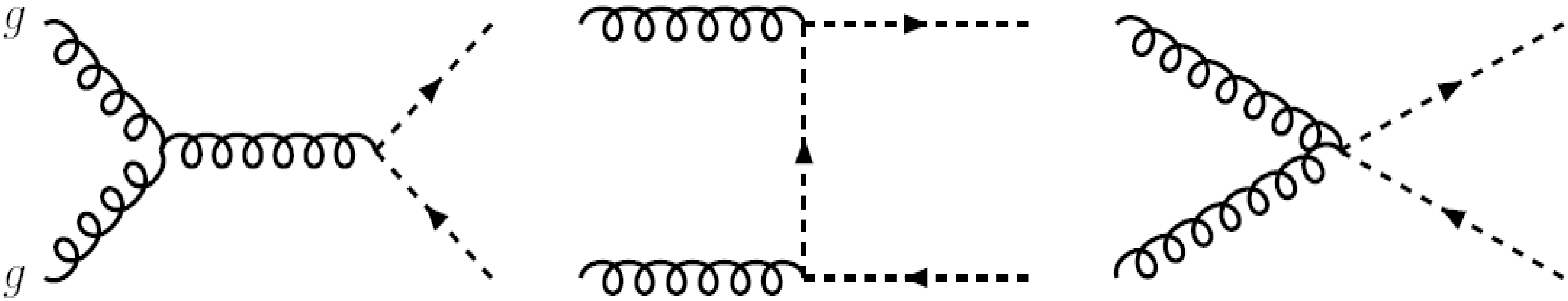
⇒ Precise measurements of masses, branching ratios, cross sections, angular distributions, . . . mandatory for

  - establishing SUSY experimentally
  - disentangling patterns of SUSY breaking

⇒ We (probably) need both: hadron colliders (Tevatron/LHC) and high luminosity ILC

SUSY particle production at the LHC:

⇒ colored (s)particles are copiously produced

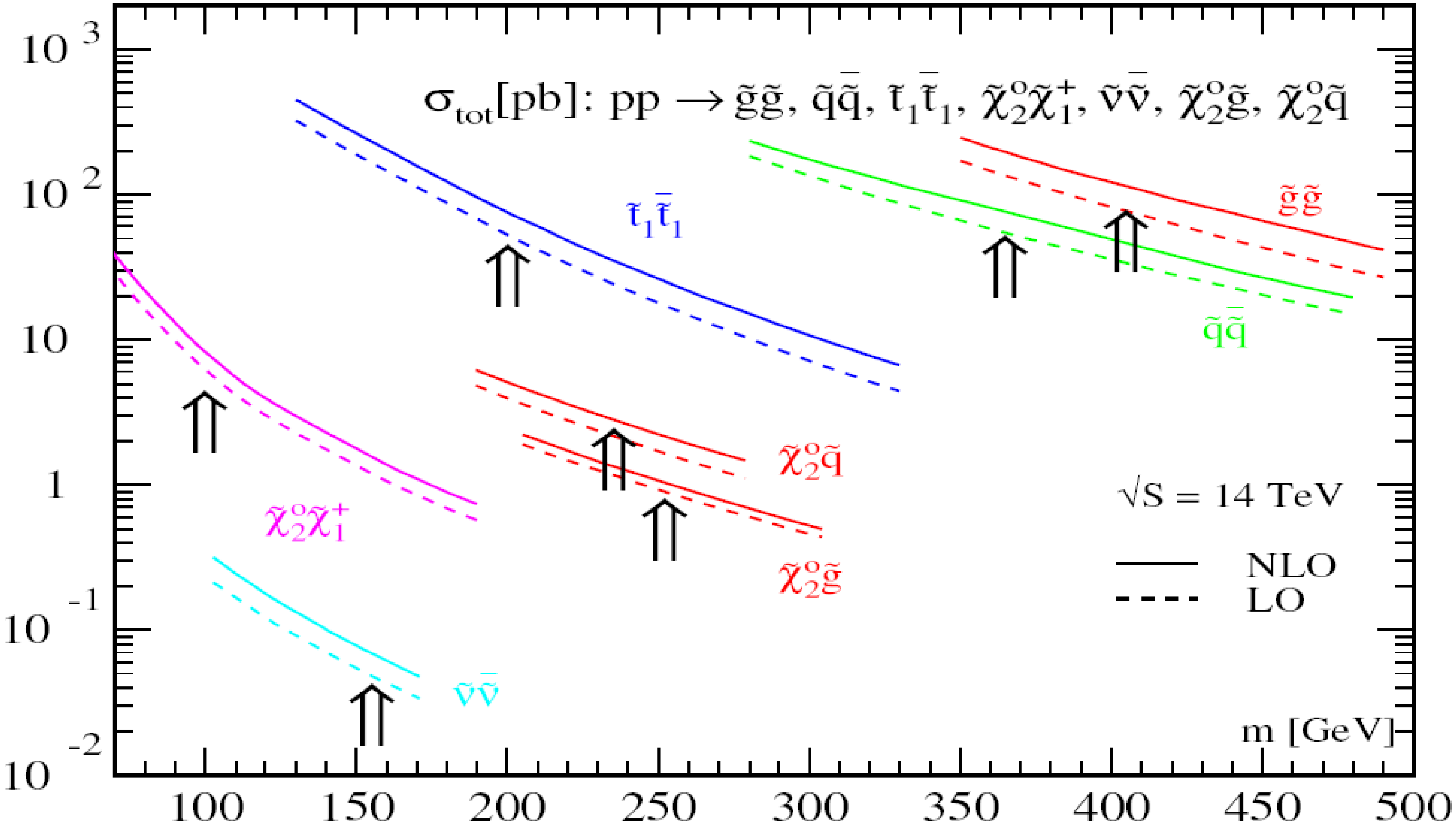


⇒ production of gluinos, squarks, . . .

As in QCD: NLO corrections are crucial!

Example for SUSY production:

[*Prospino collaboration*]



As in QCD: NLO corrections are crucial!

Production of SUSY particles at the LHC

will in general result in complicated final states
⇒ cascade decays

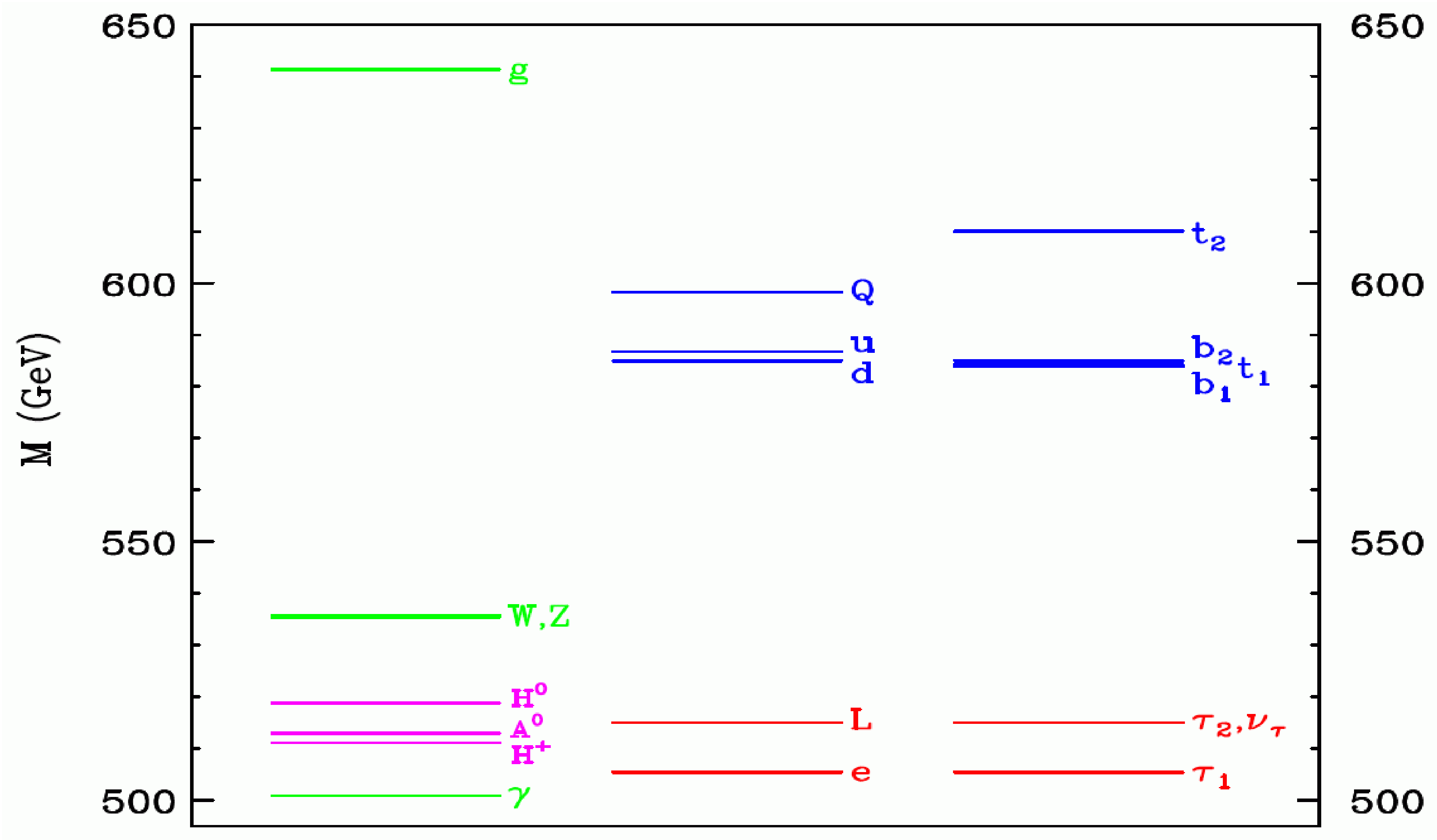
$$\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$$

Production of uncolored particles via cascade decays often dominates over direct production

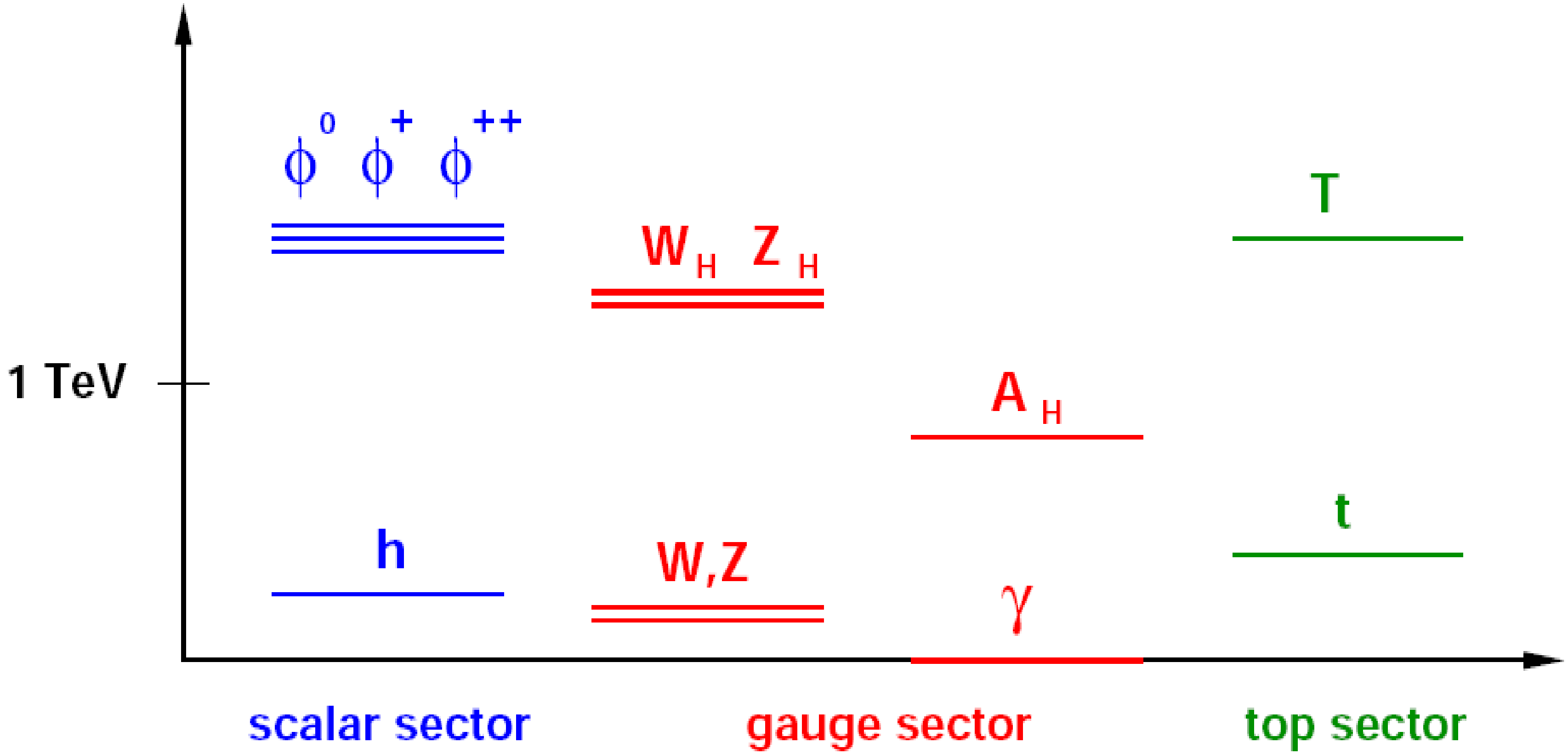
Many states are produced at once

⇒ **Main background for SUSY is SUSY itself!**

Another model beyond the SM: Extra dimensions

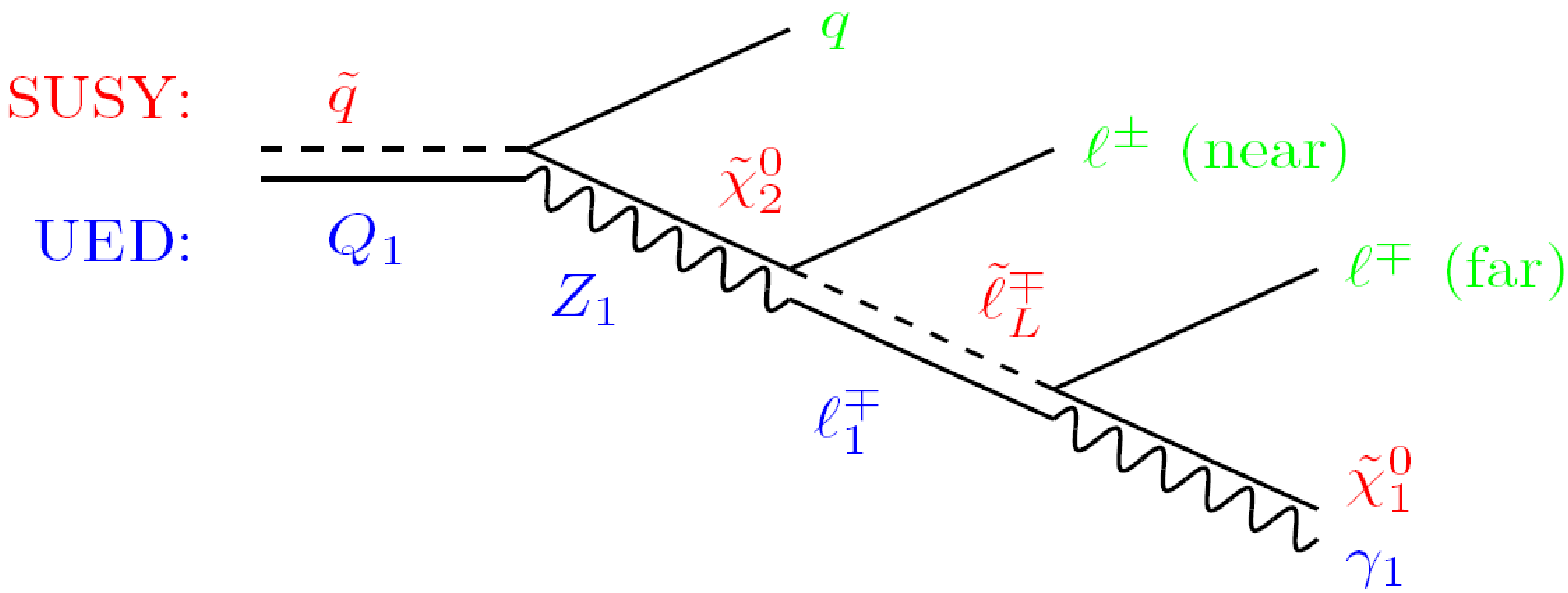


Another model beyond the SM: Little Higgs



Comparison of SUSY with e.g. Extra Dimensions:

$\Rightarrow$ cascades may look very similar:



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- establishing SUSY experimentally
- disentangling patterns of SUSY breaking

⇒ We need both: hadron colliders (Tev./LHC) and high luminosity ILC

Requires clean experimental environment, high luminosity, beam polarization, . . .

$\Rightarrow$ High luminosity ILC necessary, complementary to hadron machines

SUSY searches at the ILC:

Clean signatures, small backgrounds

Thresholds for pair production of SUSY particles

$\Rightarrow$ precise determination of mass and spin of SUSY particles, mixing angles, complex phases, . . .

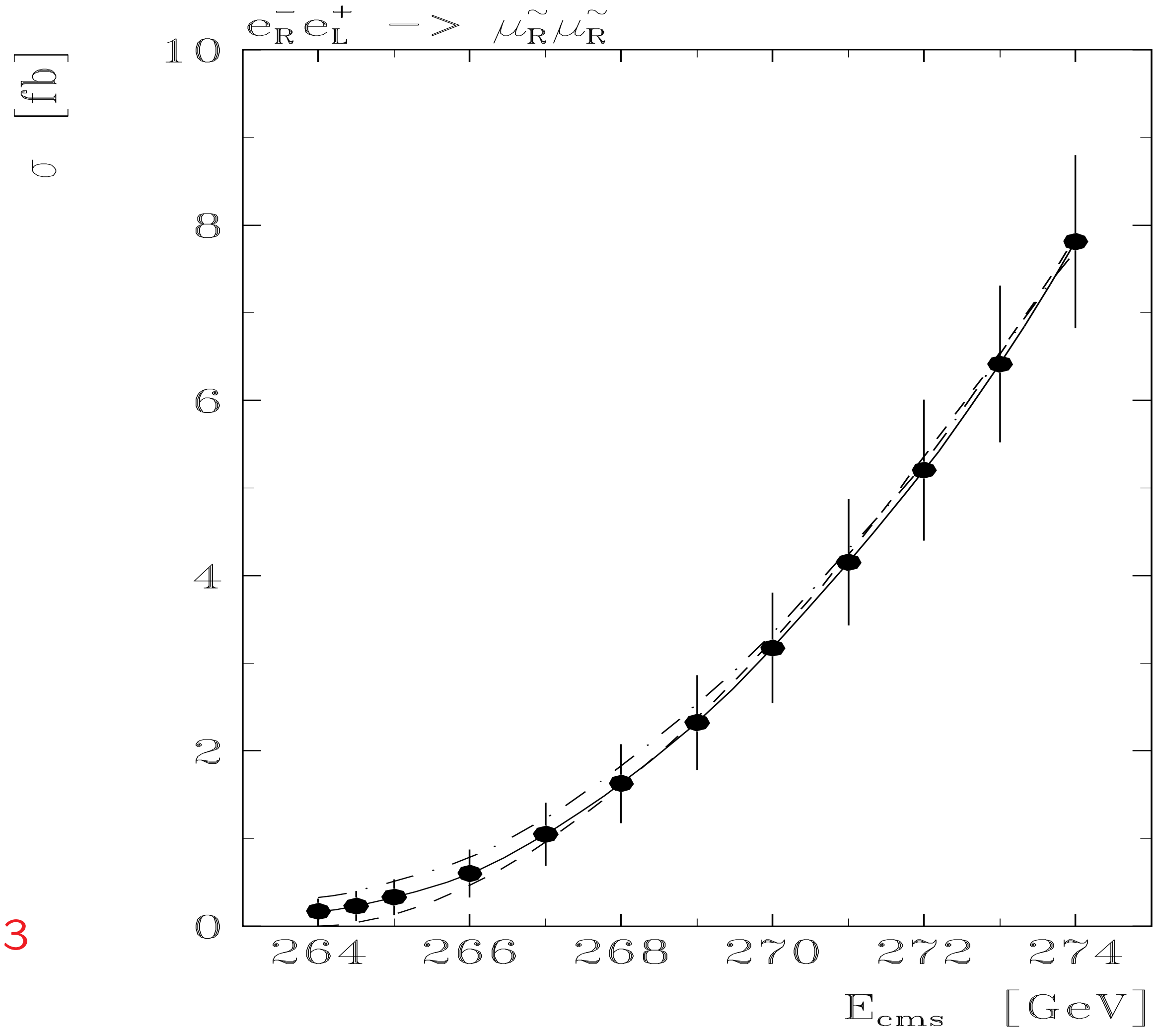
Limited by kinematic reach

Good prospects for production of uncolored particles

$\Rightarrow$ LHC / ILC complementarity

Example for SUSY physics at the ILC (I):

Determination of mass and spin of $\tilde{\mu}_R$ from production at threshold:
[*TESLA TDR '01*]



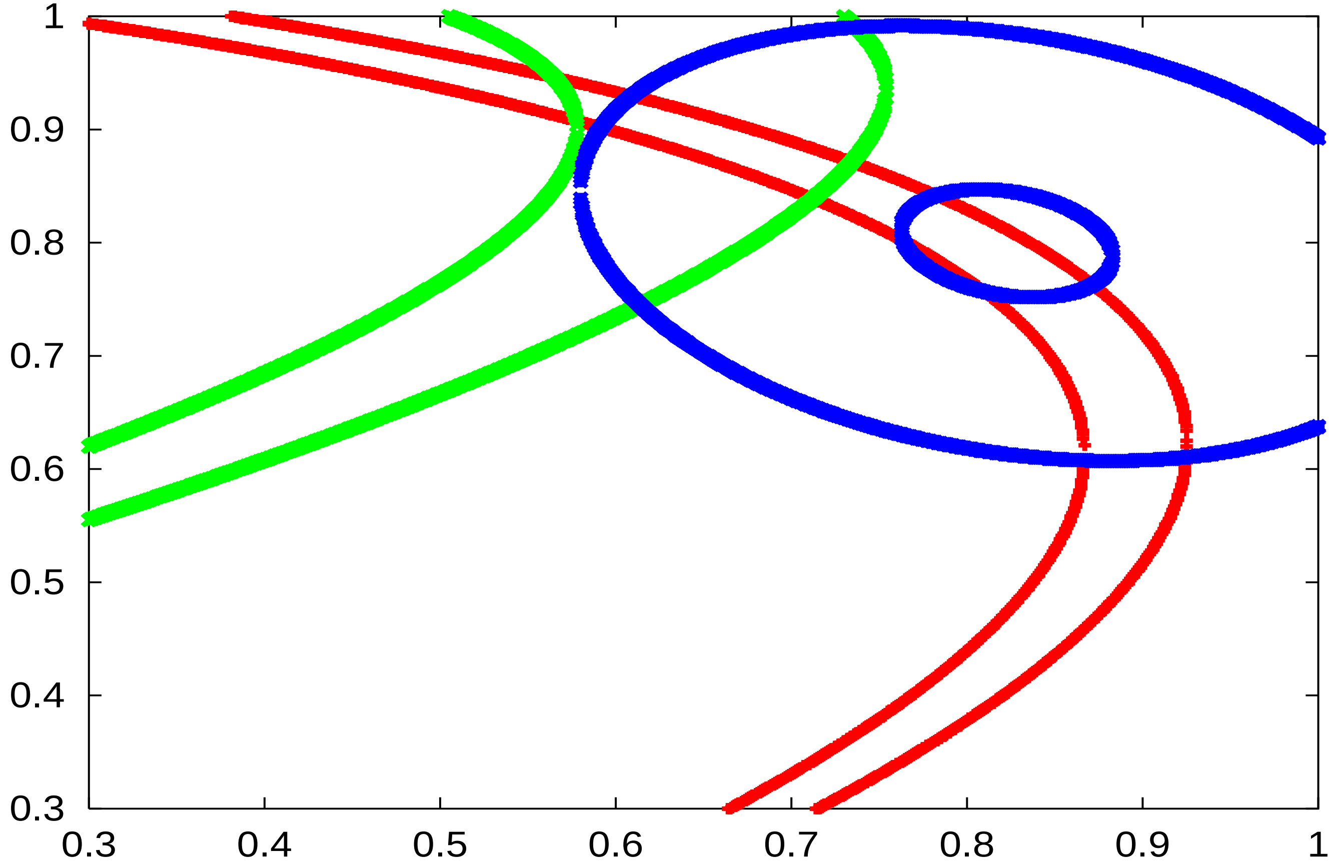
$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

$\Rightarrow$ test of $J = 0$ hypothesis

Example for SUSY physics at the ILC (II):

Determination of ϕ_R, ϕ_L in neutralino sector from measurement of $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ and $P_{e^-} = \pm 80\%, P_{e^+} = \pm 60\%$ $\mathcal{L} = 500$ fb^{-1}:

[K. Desch, J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello '03]

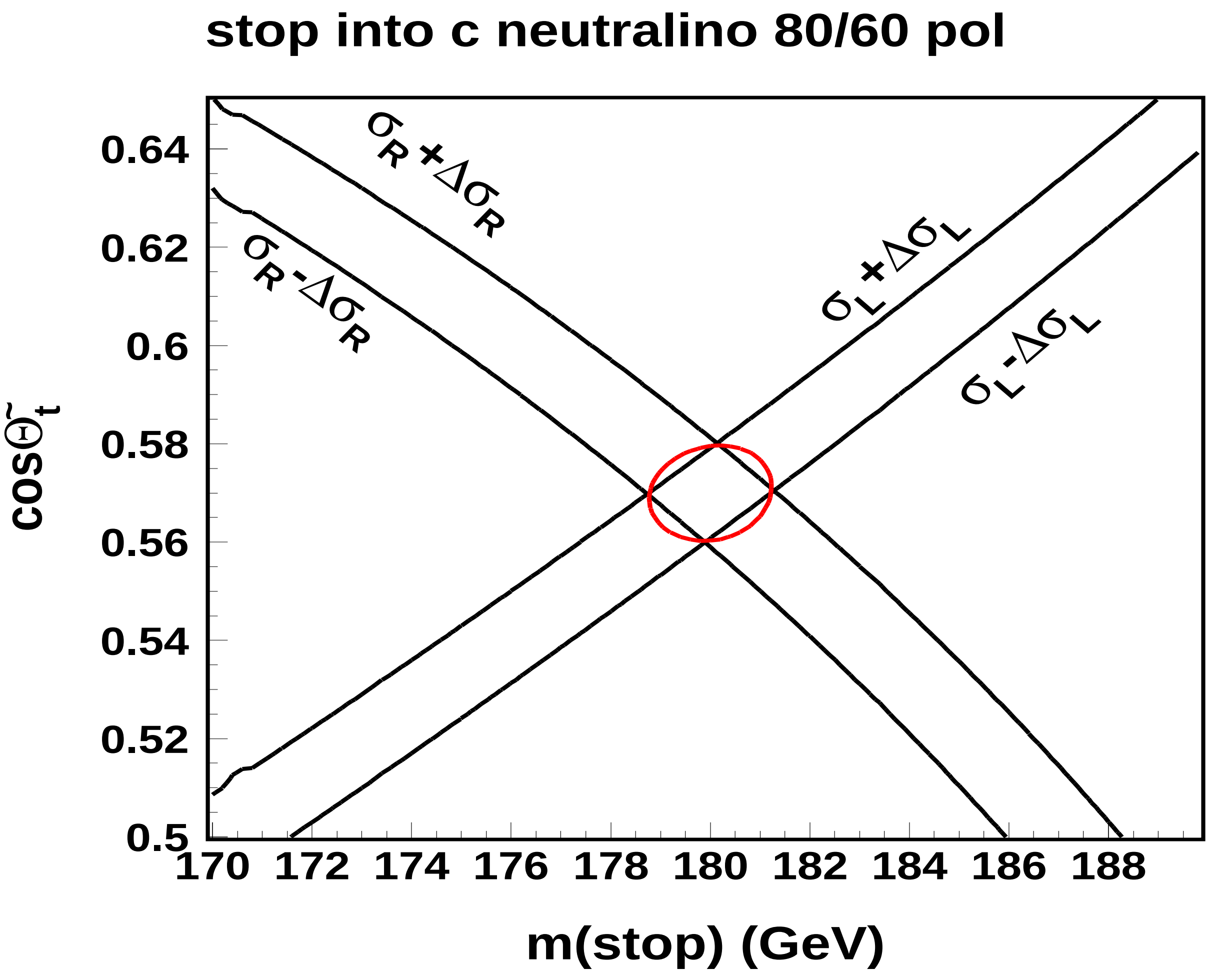


$\Rightarrow \cos 2\phi_L = [0.62, 0.72]$, $\cos 2\phi_R = [0.87, 0.91]$

Example for SUSY physics at the ILC (III):

Determination of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$ from $\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1)$ with polarized beams:

[*R. Keränen, H. Nowak, A. Sopczak '00*]



$$\Rightarrow \frac{\Delta m_{\tilde{t}_1}}{m_{\tilde{t}_1}} \approx 0.5\%,$$

$$\frac{\Delta \cos\theta_{\tilde{t}}}{\cos\theta_{\tilde{t}}} \approx 1.5\%$$

Example IV: Synergy of LHC and ILC

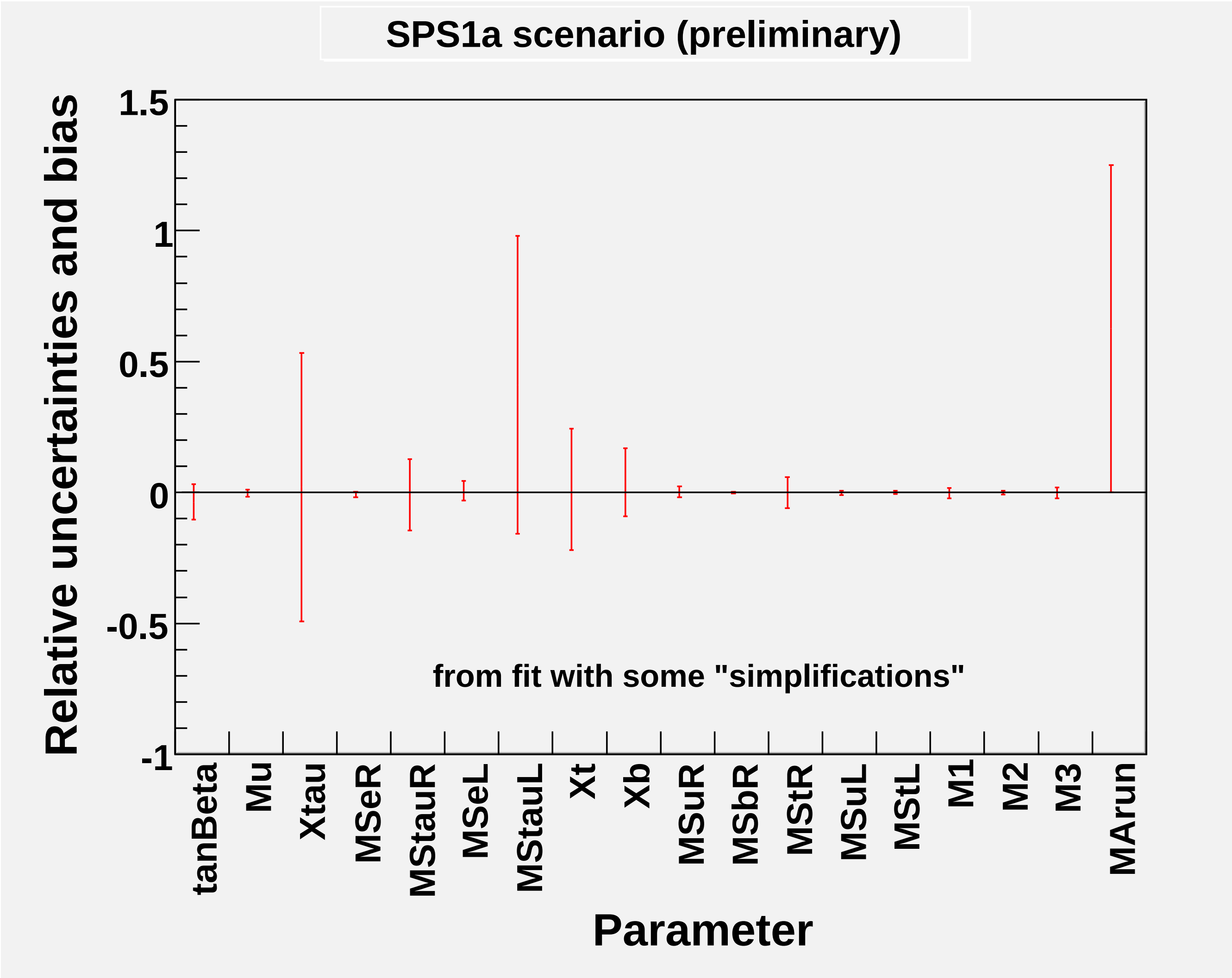
Accuracies for the case of the LHC alone (left) and with the ILC measurement of the LSP mass with $\delta m_{\mathrm{LSP}} = \pm 0.05$ GeV:
[LHC/ILC Study Group report '04]

	LHC [GeV]	LHC + ILC [GeV]
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05
$\Delta m_{\tilde{\chi}_2^0}$	4.2	0.08
$\Delta m_{\tilde{l}_L}$	4.8	0.05
$\Delta m_{\tilde{b}_1}$	7.1	5.7
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	7-12	5-11
$\Delta m_{\tilde{g}}$	8.0	6.5

$\Rightarrow$ ILC input improves accuracy significantly

Next-to-final goal: reconstruct the SUSY Lagrangian

⇒ use all available information: masses, BRs , . . .

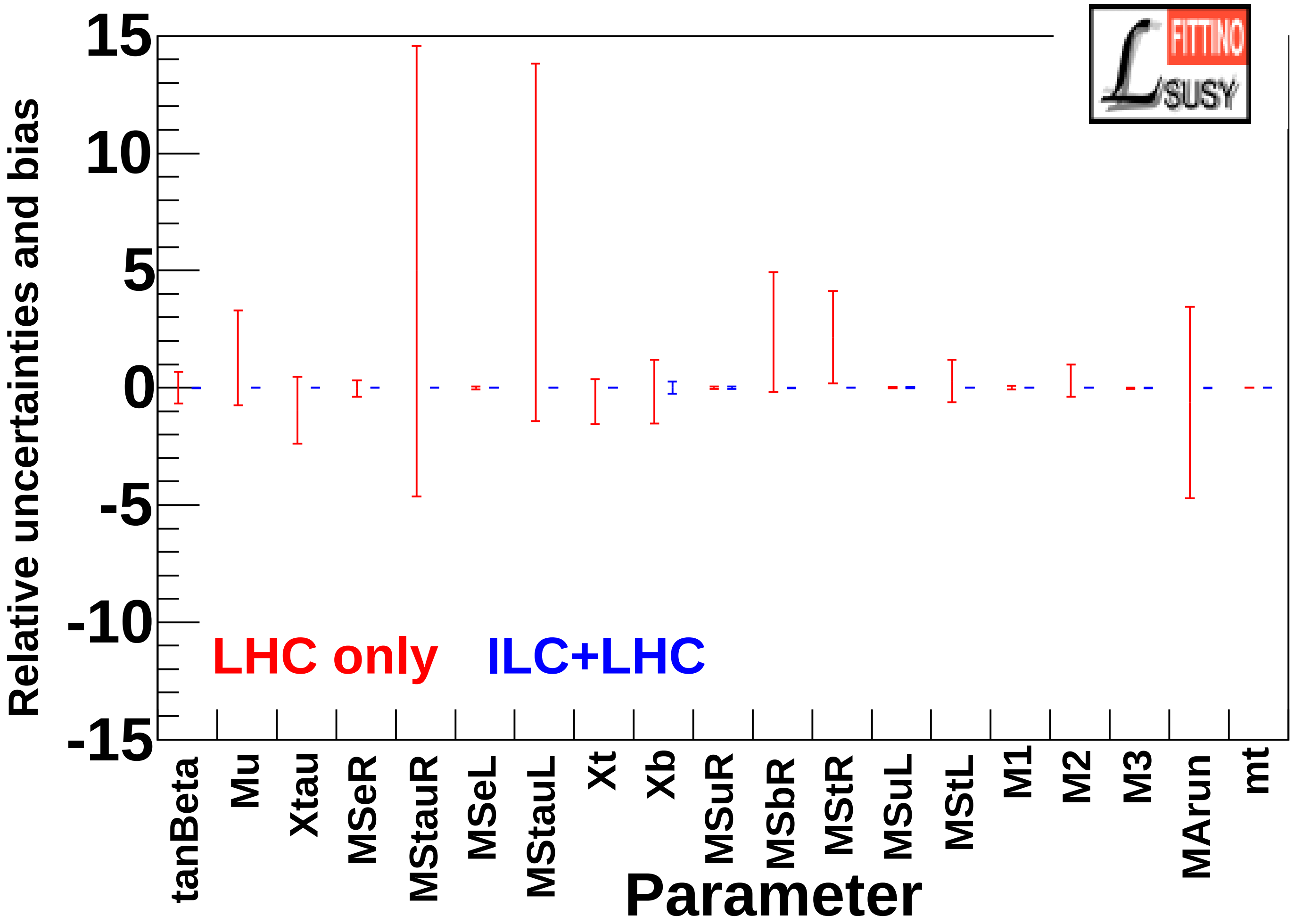


[*P. Bechtle, K. Desch, M. Uhlenbrock, P. Wienemann '08*]

Global fit for SUSY Lagrangian: LHC vs. LHC $\oplus$ ILC

[*P. Bechtle, K. Desch, P. Wienemann '05*]

Compare LHC and LHC $\oplus$ ILC :

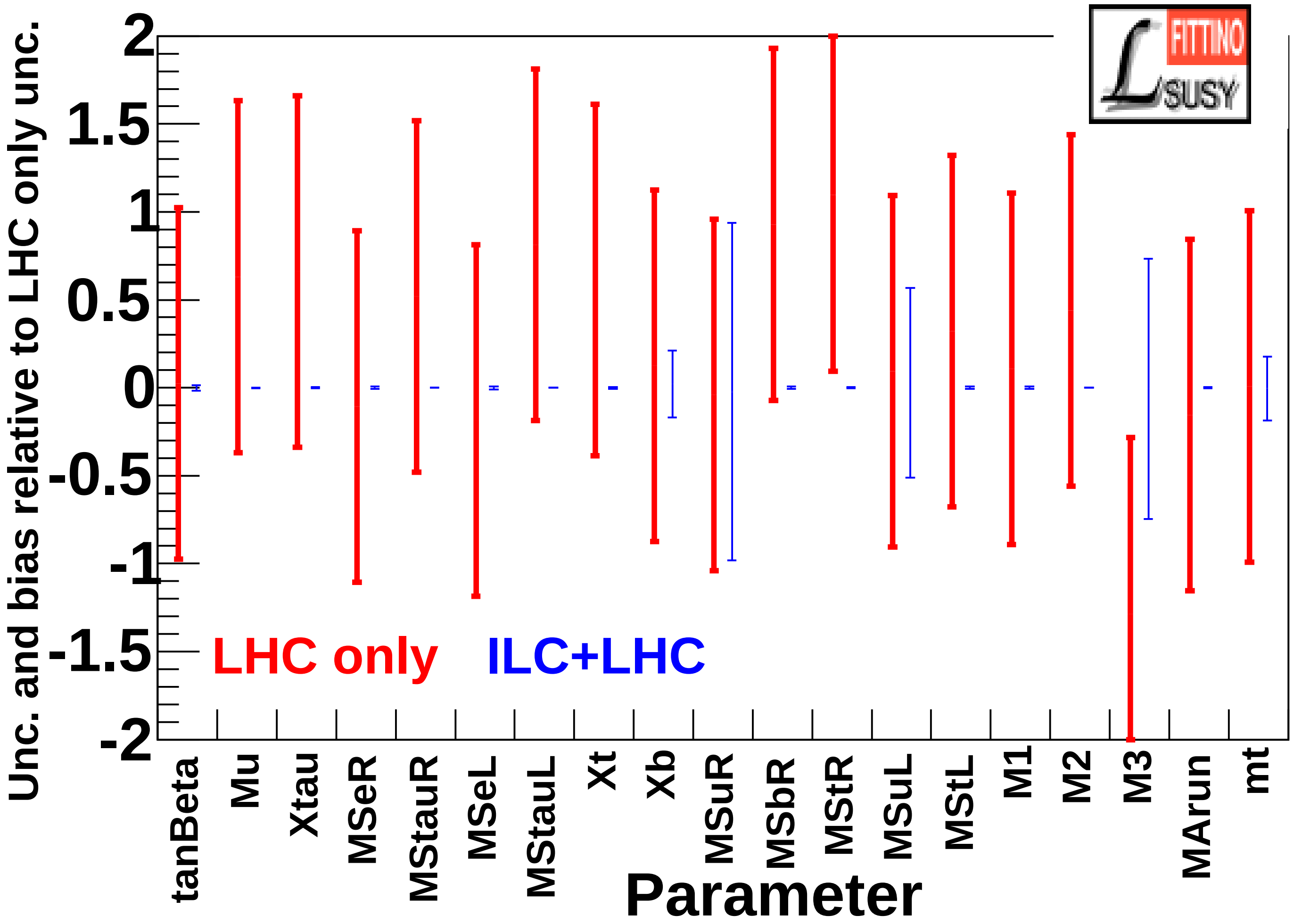


$\Rightarrow$ interesting improvement from ILC measurements

Global fit for SUSY Lagrangian: LHC vs. LHC $\oplus$ ILC

[*P. Bechtle, K. Desch, P. Wienemann '05*]

Compare LHC and LHC $\oplus$ ILC :



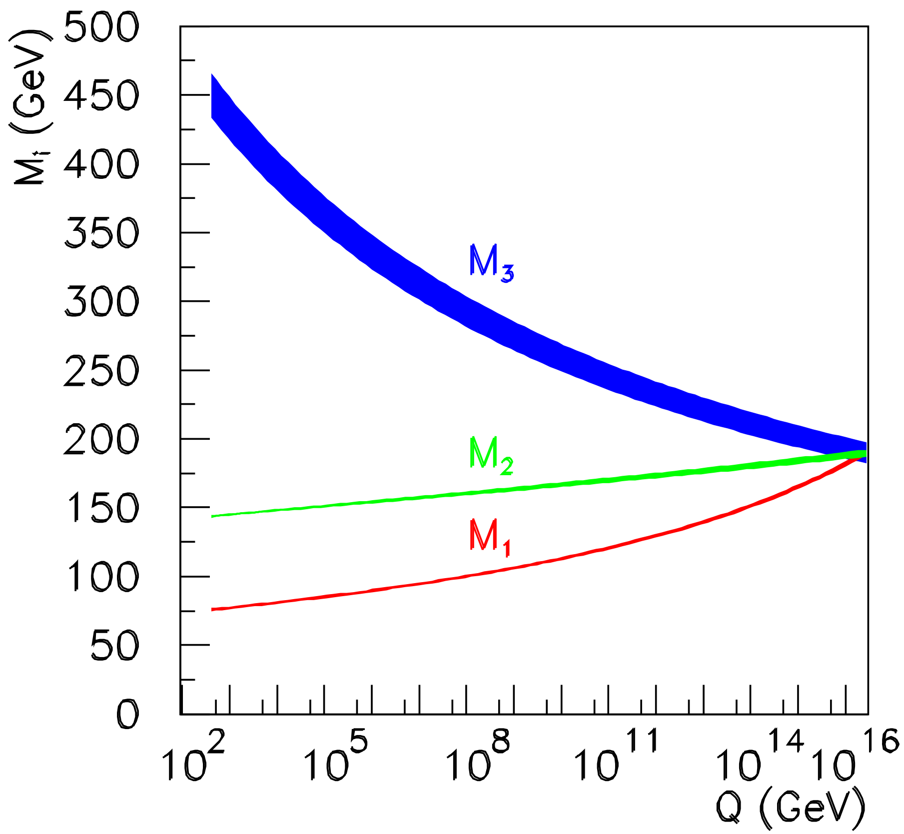
$\Rightarrow$ interesting improvement from ILC measurements

Final goal: reconstruct soft SUSY-breaking mechanism

$\Leftrightarrow$ GUT scale physics

$\Rightarrow$ use all parameters at low energies $\Rightarrow$ scale up to the GUT scale

$\Rightarrow$ What unifies where? $\Rightarrow$ soft SUSY-breaking mechanism



[G. Blair, W. Porod, P. Zerwas '01]

Interested in Theory Predictions?

Interested in

- theory predictions for the Tevatron?
- theory predictions for the LHC?
- theory predictions for the ILC?
- phenomenology analyses in Higgs/SUSY?

⇒ You can do your PhD at IFCA (Santander, Spain)

contact: Sven.Heinemeyer @ cern.ch

Santander, Spain: (15 minutes by foot from the institute :-)

contact: Sven.Heinemeyer @ cern.ch