# SUSY: From the Basics to Collider Phenomenology

*Sven Heinemeyer, IFCA (Santander)*

Louvain, 05/2007

1. Introduction to SUSY

2. SUSY Lagrangians and the MSSM

3. “Simplified versions” and special sectors

4. SUSY Phenomenology

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# SUSY lectures (IV):
# SUSY Phenomenology

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1. Discovering the Higgs

2. Discovering SUSY particles

3. Discovering Cold Dark Matter

# 1. Discovering the Higgs boson

## What has to be done?

1. Find the new particle

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2. measure its mass ($\Rightarrow$ ok?)

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6. measure spin, . . .

# 1. Discovering the Higgs boson

## What has to be done?

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

T = Tevatron,

# 1. Discovering the Higgs boson

## What has to be done?

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

T = Tevatron, L = LHC,

# 1. Discovering the Higgs boson

## What has to be done?

| | T | L | I |
|---|---|---|---|
| 1. Find the new particle | T | L | I |
| 2. measure its mass ($\Rightarrow$ 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 (International Linear $e^+e^-$ collider)

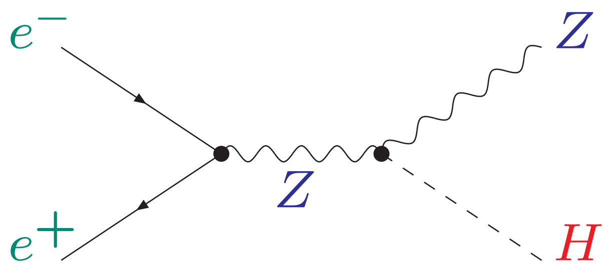
We need the LHC and the ILC to find the Higgs
and to establish the Higgs mechanism!

The LHC can do a crucial part . . .

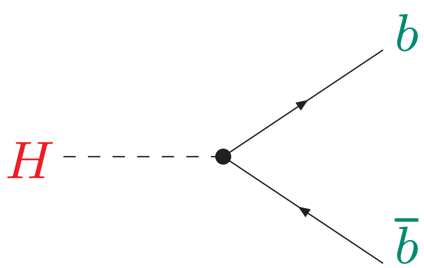
# 1A. Past: Higgs search at LEP:

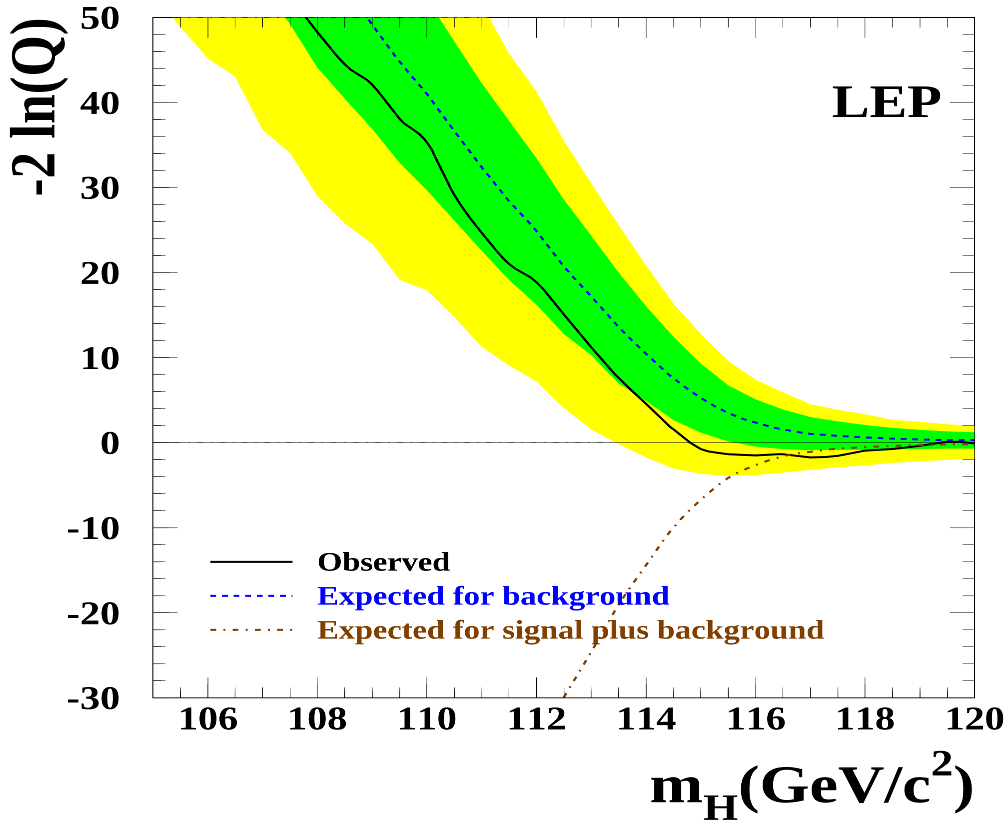
Search for the Standard Model Higgs at LEP: *[LEP Higgs WG '03]*

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




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




Exclusion limit, 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

$\to$ investigate benchmark scenarios:

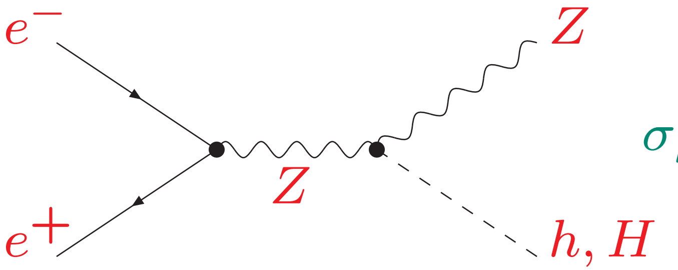
| |
|---|
| $\to$ Vary only $M_A$ and $\tan\beta$ |
| $\to$ Keep all other SUSY parameters fixed |

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

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

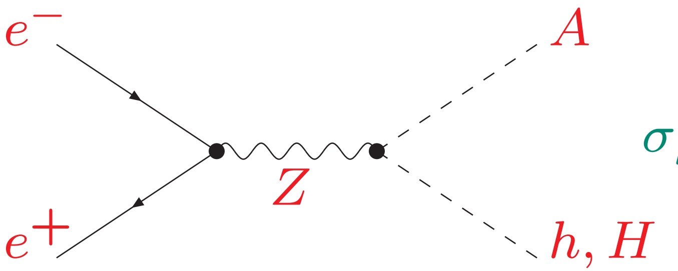
# Search for neutral SUSY Higgs bosons:

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




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

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

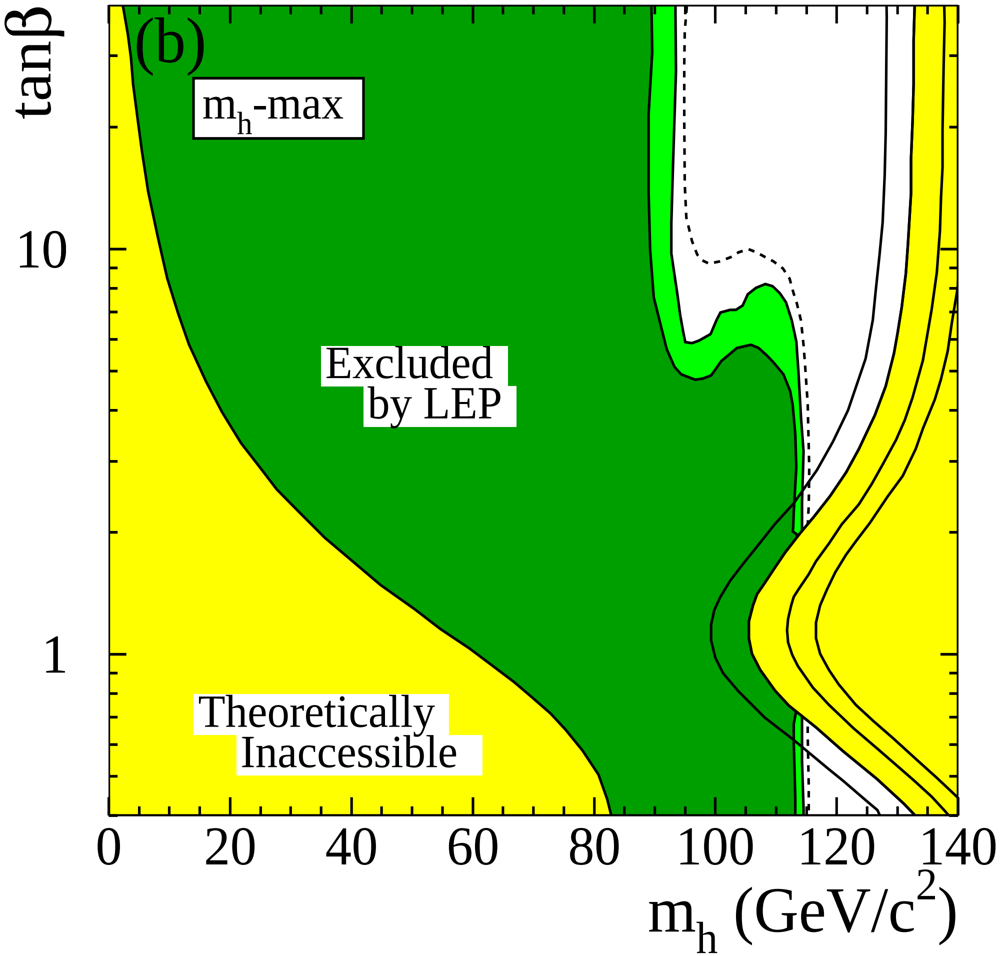



$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

# 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:

$$0.7 < \tan\beta < 2.0$$

Note: this exclusion bound assumes

$m_t$, $M_{\text{SUSY}}$ fixed, $m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV

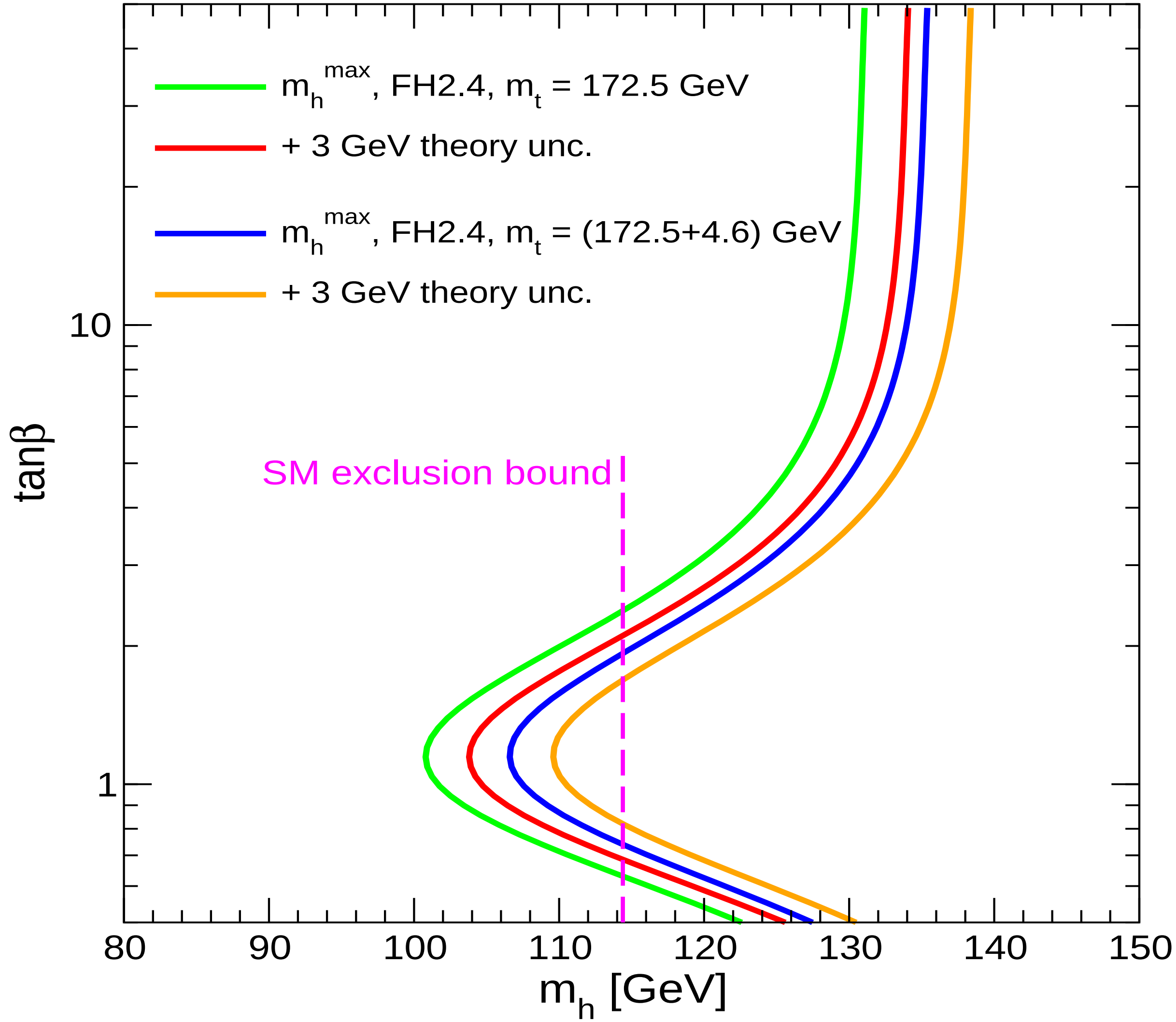
no theoretical uncertainties included

Note: new $m_t$ value: $m_t = 170.9 \pm 1.8$ GeV [*Tevatron EWWG '07*]

parametric uncertainty: $\delta M_h^{\text{para}} \approx \delta m_t$

## Effect of new corrections and $m_t \to m_t + 2\,\sigma_{m_t}$

[S.H., W. Hollik, G. Weiglein '05]



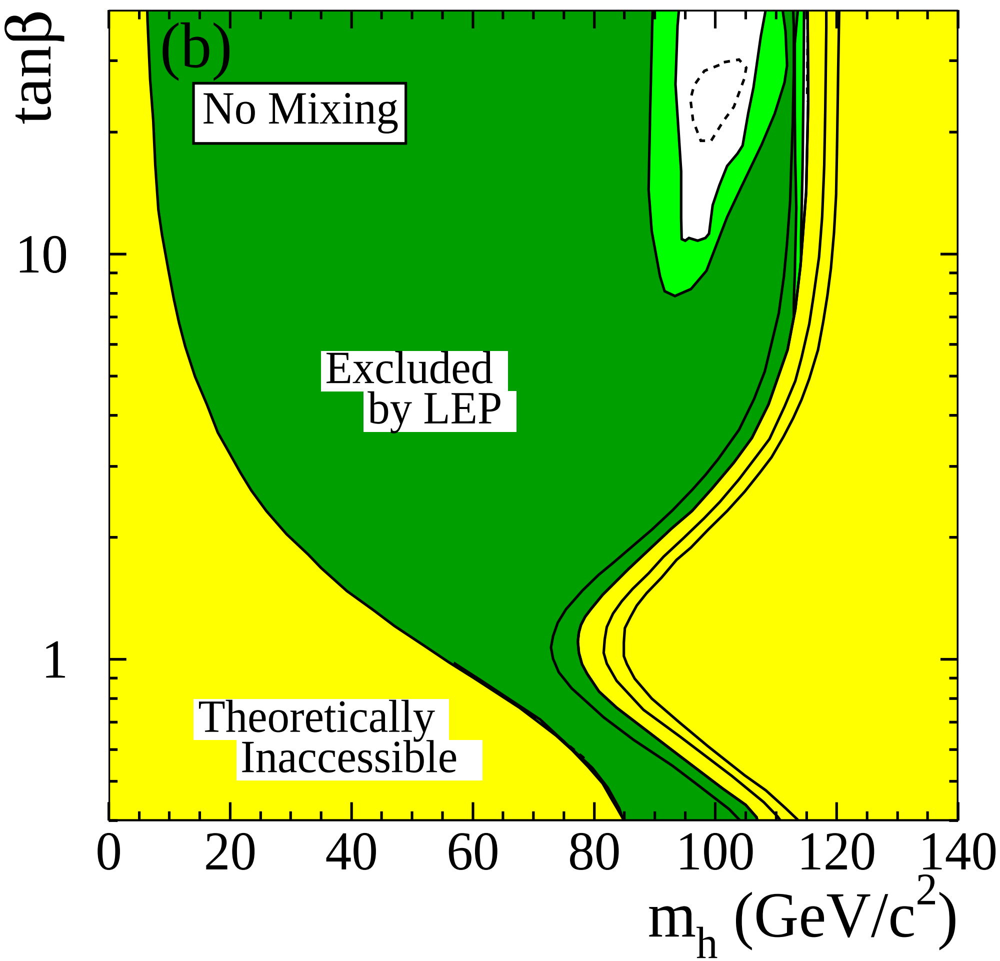

⇒ precise knowledge of $m_t$ important!

⇒ Low $\tan\beta$ LEP exclusion region can vary strongly

# 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, $M_{\rm SUSY} = 1$ TeV):



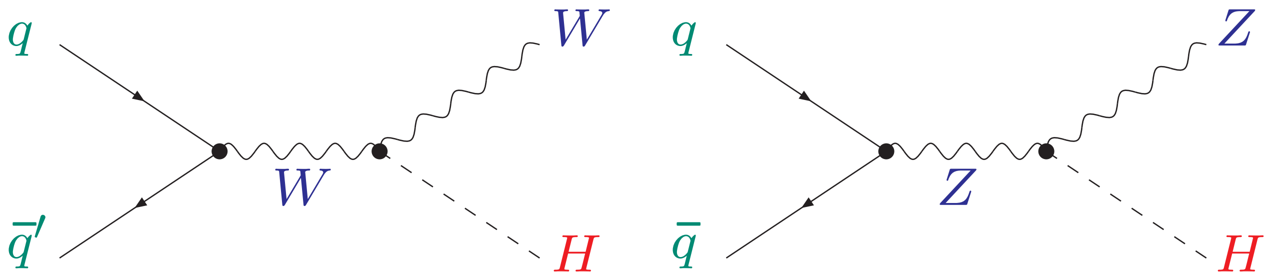

$m_h > 93.6$ GeV
(expected: 96.0 GeV), 95% C.L.

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

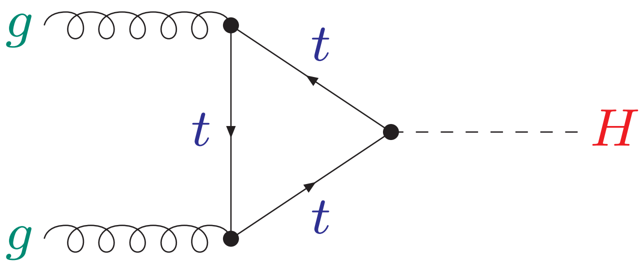
# 1B. Present: Higgs search at the Tevatron

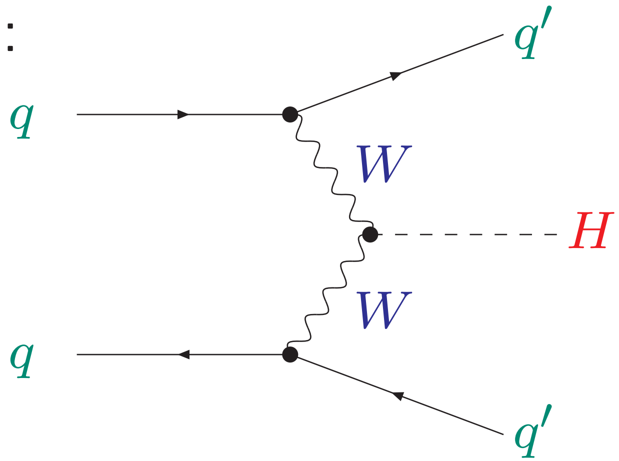
Tevatron: $p\bar{p}$ accelerator: $\rightarrow$ T

Production processes as at LEP:

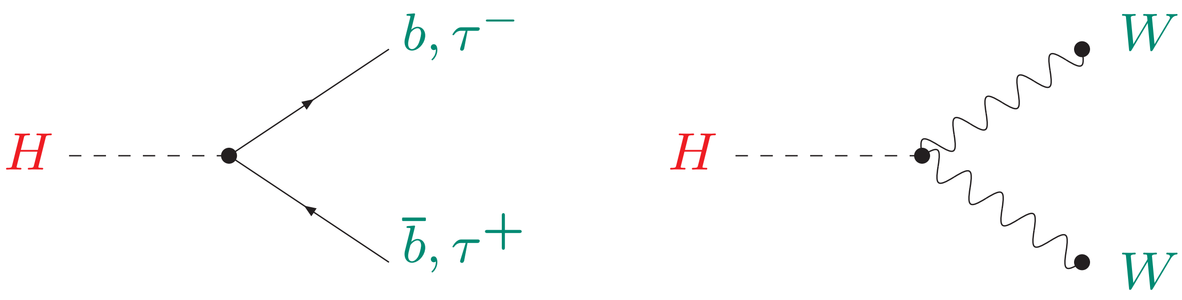



Other important production channels:

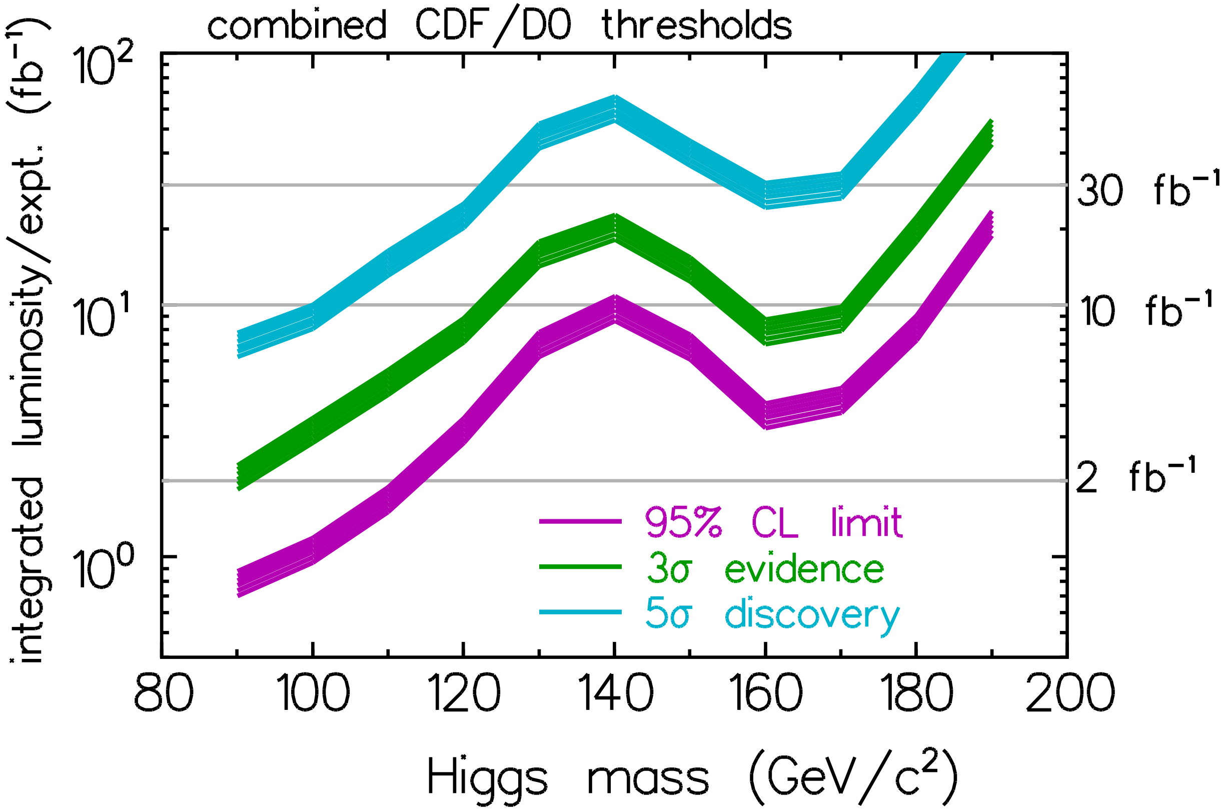



Dominant decays:



# Expectations for Higgs discovery at the Tevatron:




Unfortunately: luminosity problems in the start of RunII

$\Rightarrow$ progress slower than anticipated

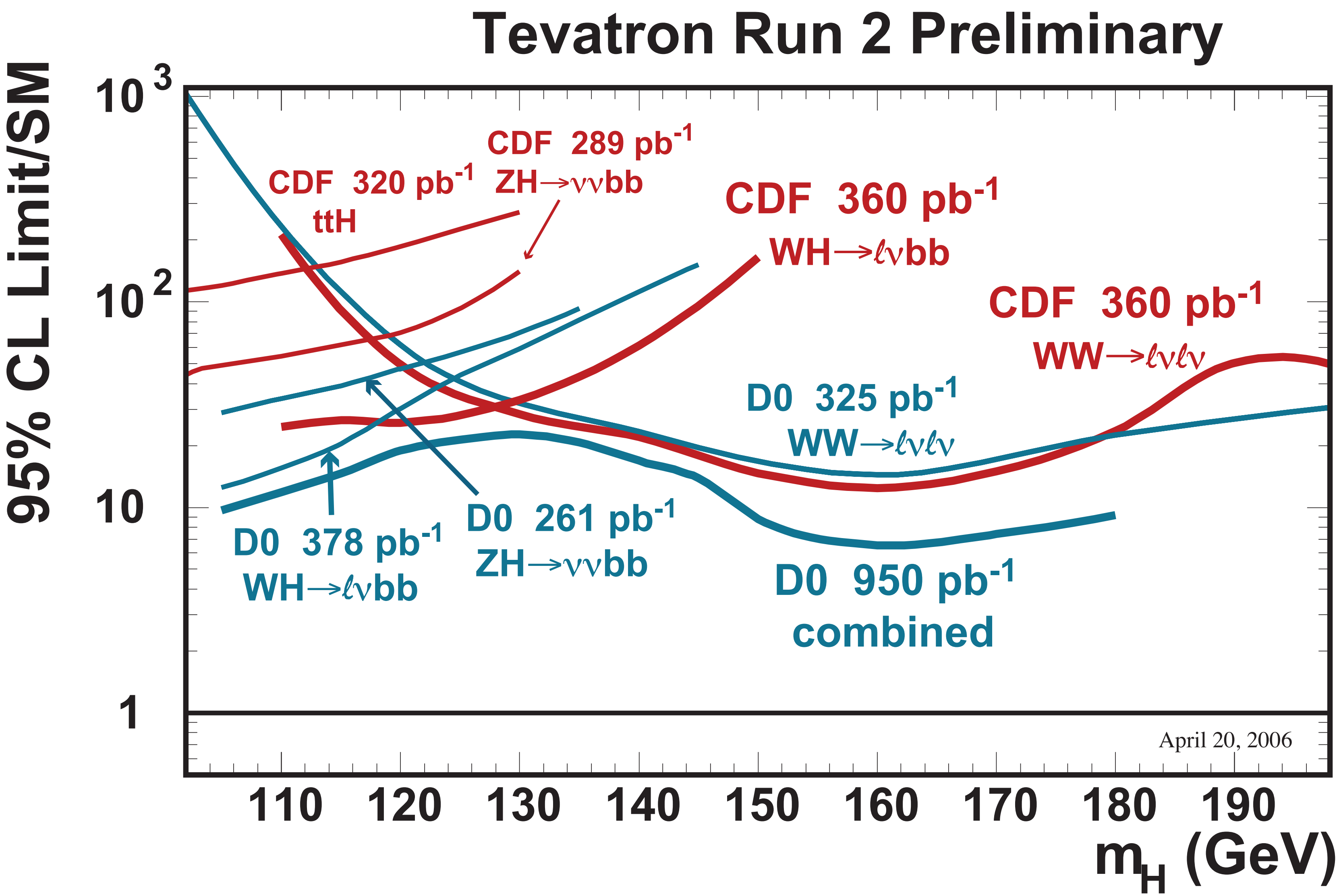
For SM Higgs boson with $M_H \sim 120$ GeV:

$\approx$ 2008/09: sensitivity for 95% C.L. exclusion

$\approx$ 2009: sensitivity for $3\sigma$ evidence
or exclude SM Higgs with $M_H \lesssim 130$ GeV

## Results for various search channels for SM Higgs:

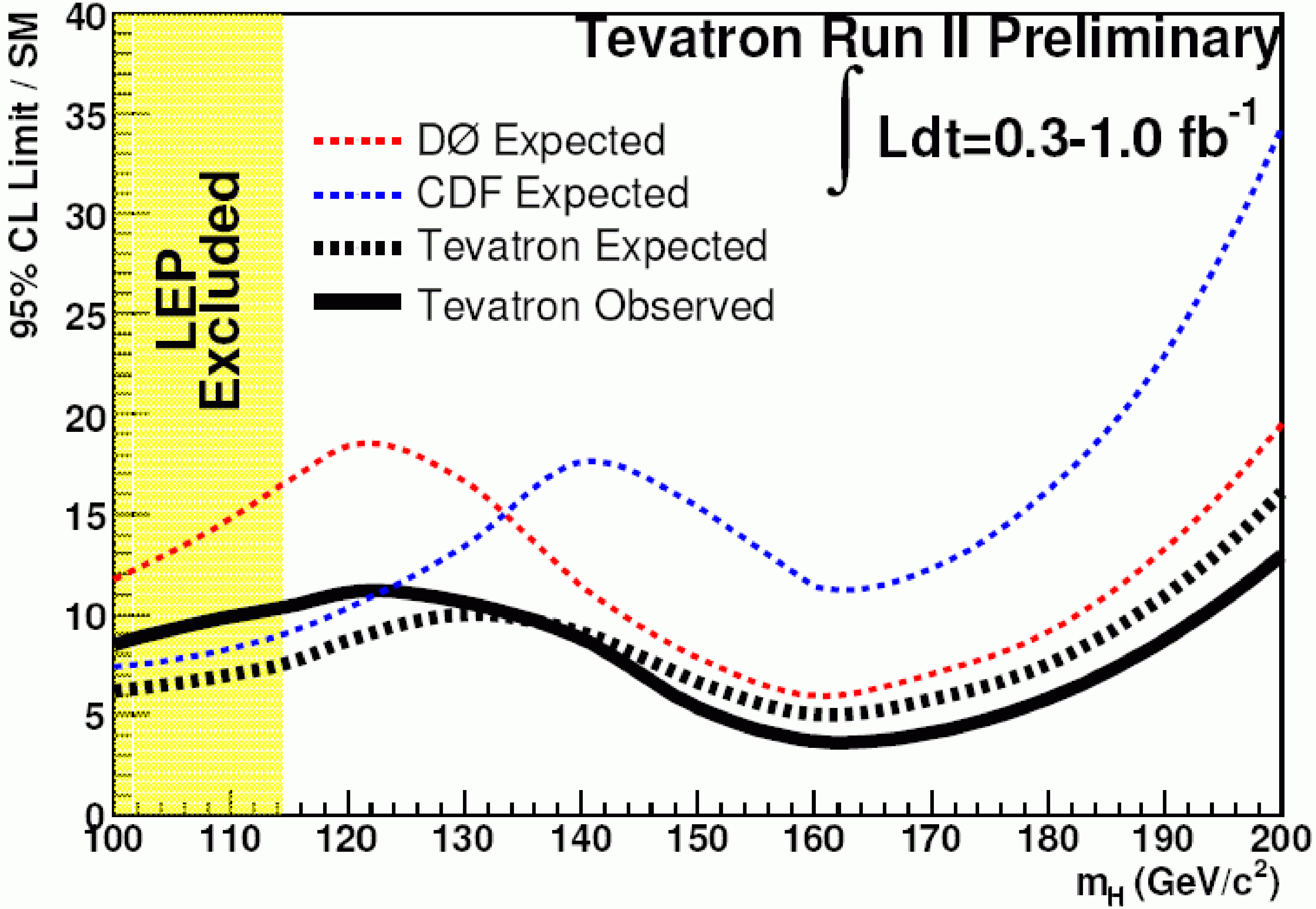
[*CDF, D0 '06*]




Can they close the gap?

## Current status (latest results) of SM Higgs search:

[*CDF, D0 '06*]




Can they close the gap?

## Tevatron MSSM Higgs searches (I): Search for a "SM-like" light Higgs:

Prediction in "simplified" versions of the MSSM:
($m_t^{\text{exp}} = 170.9$ GeV, $\delta m_t^{\text{exp}} = 1.8$ GeV, $M_{\text{SUSY}} \lesssim$ few TeV)
[A. Dedes, S.H., S. Su, G. Weiglein '03] [S.H., W. Hollik, G. Weiglein '04,'05]

| | max. $m_h$ [GeV] | $\delta m_h / \delta m_t$ | for $m_t^{\text{exp}} + 2\delta m_t$ |
|---|---|---|---|
| mSUGRA/CMSSM | 124.5 | 0.65 | 126.9 |
| mGMSB | 118.8 | 0.70 | 121.3 |
| mAMSB | 120.5 | 0.58 | 122.6 |

Exclusion potential of the Tevatron: $M_H^{\text{SM}} \lesssim 130$ GeV

mSUGRA/CMSSM, mGMSB, mAMSB: no suppression of $hVV$ coupling
$\Rightarrow$ SM bound applies

$\Rightarrow$ Tevatron can exclude mSUGRA/CMSSM, mGMSB, mAMSB, ...

$\Rightarrow$ potentially huge impact on search strategies at LHC

# Possible problem in SUSY:

$$h \to b\bar{b}$$

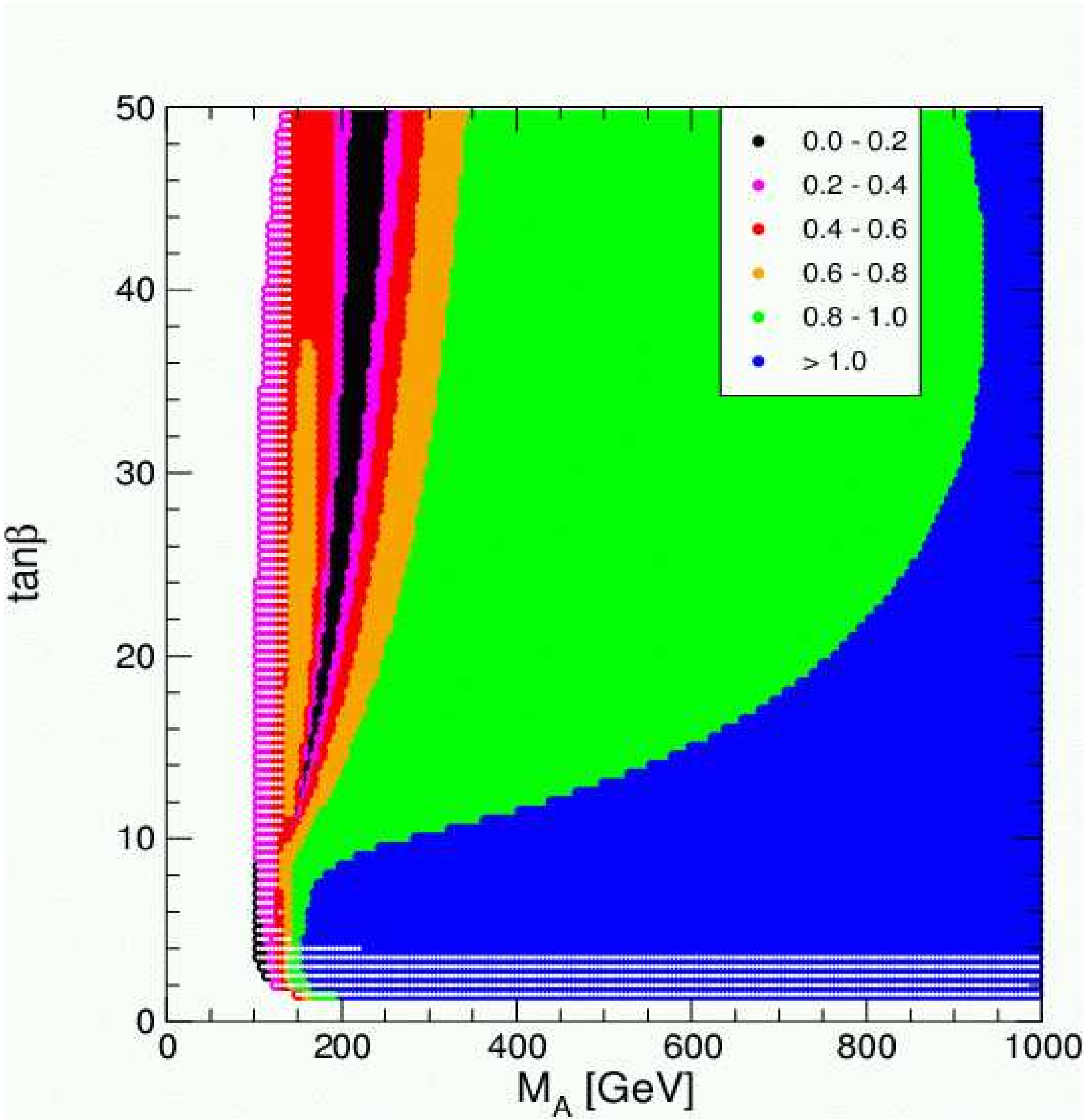
can be strongly suppressed

$\to$ "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 (II): "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:

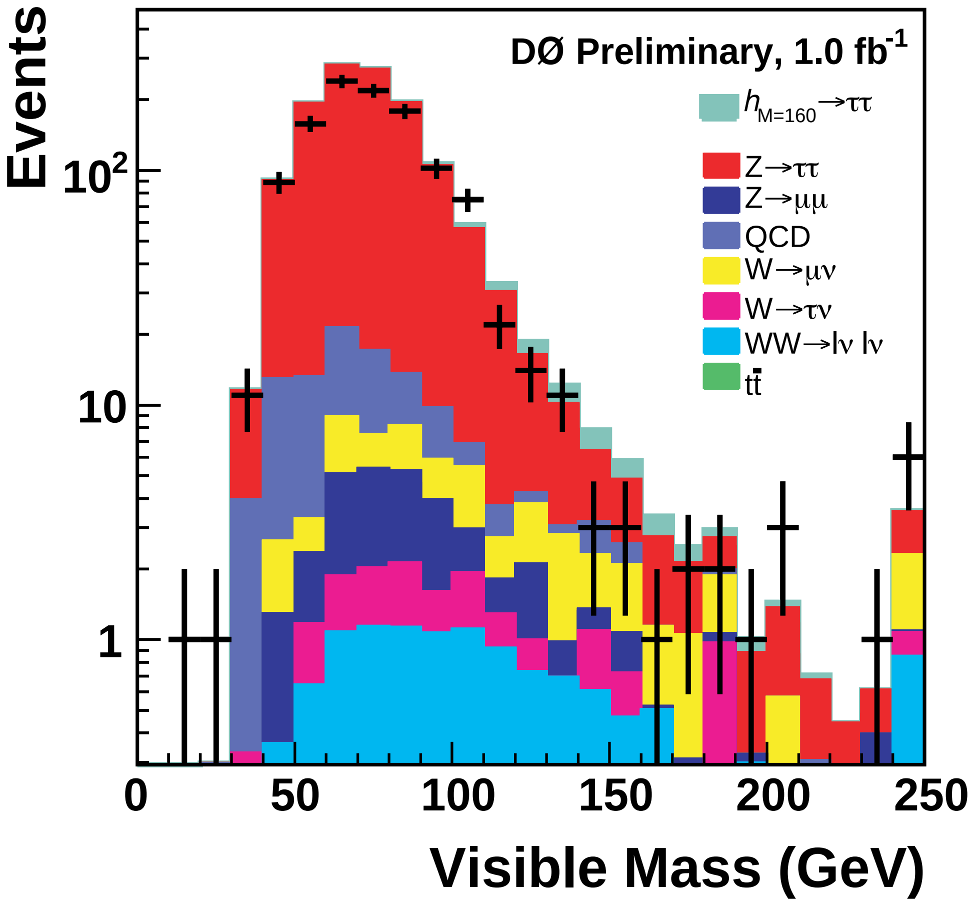
$$\sigma(b\bar{b}A) \times \mathrm{BR}(A \to b\bar{b}) \;\simeq\; \sigma(b\bar{b}A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

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

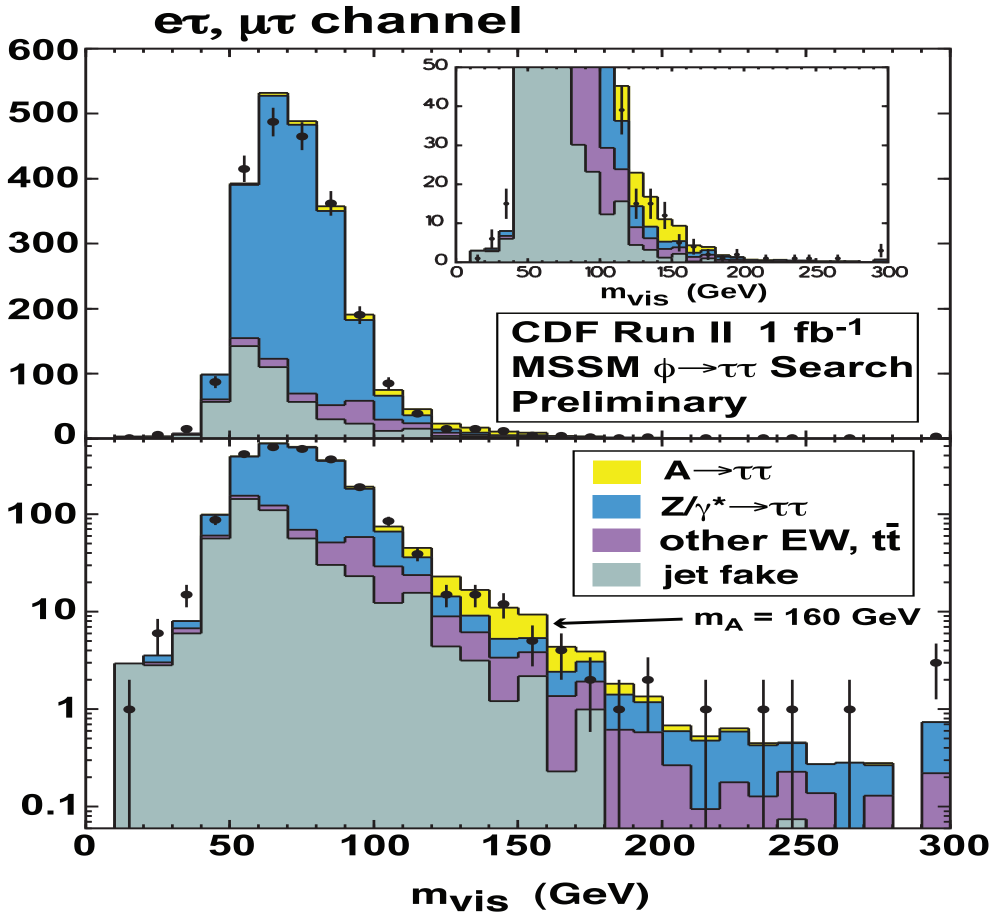
$$\Delta_b = \frac{2\alpha_s}{3\,\pi} m_{\tilde{g}}\,\mu \tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\,\pi} A_t\,\mu \tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

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

## Existing Tevatron analyses: $H/A \to \tau\tau$ (1 fb$^{-1}$):




[D0 '07]




[CDF '07]

⇒ Bounds on the MSSM parameter space for low $M_A$, high $\tan\beta$:

CDF excess? D0 missing events?

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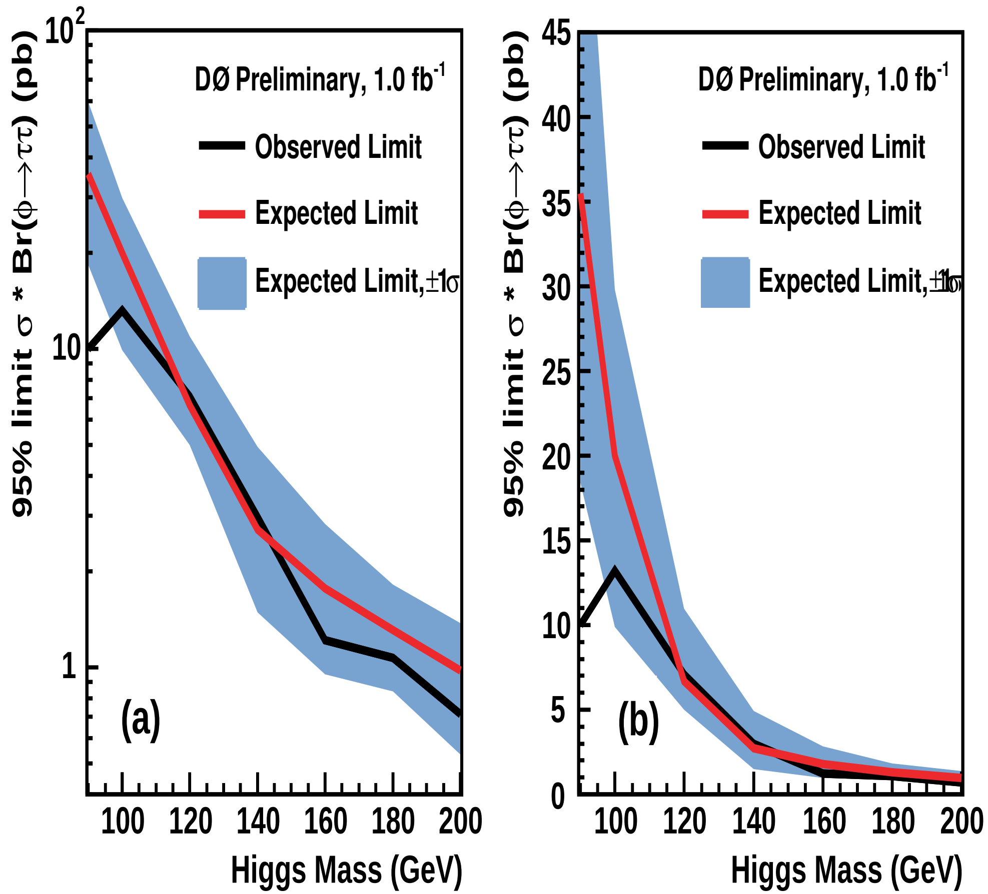
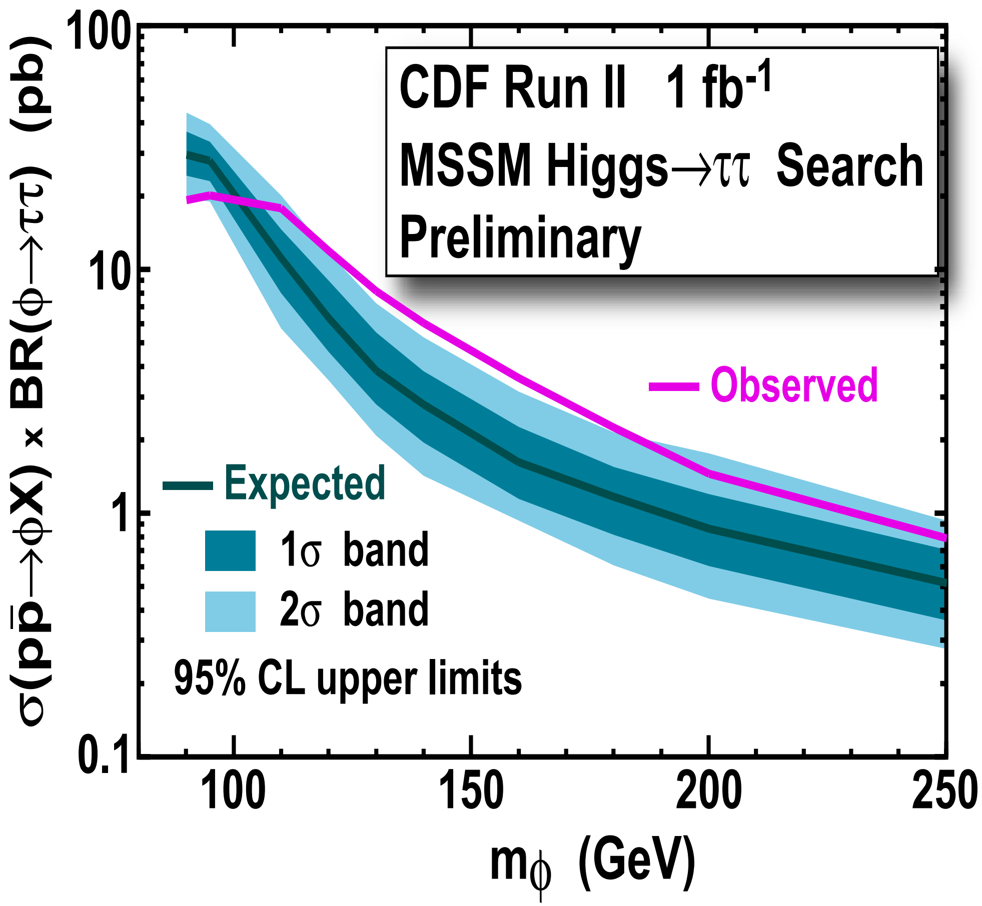



[D0 '07]

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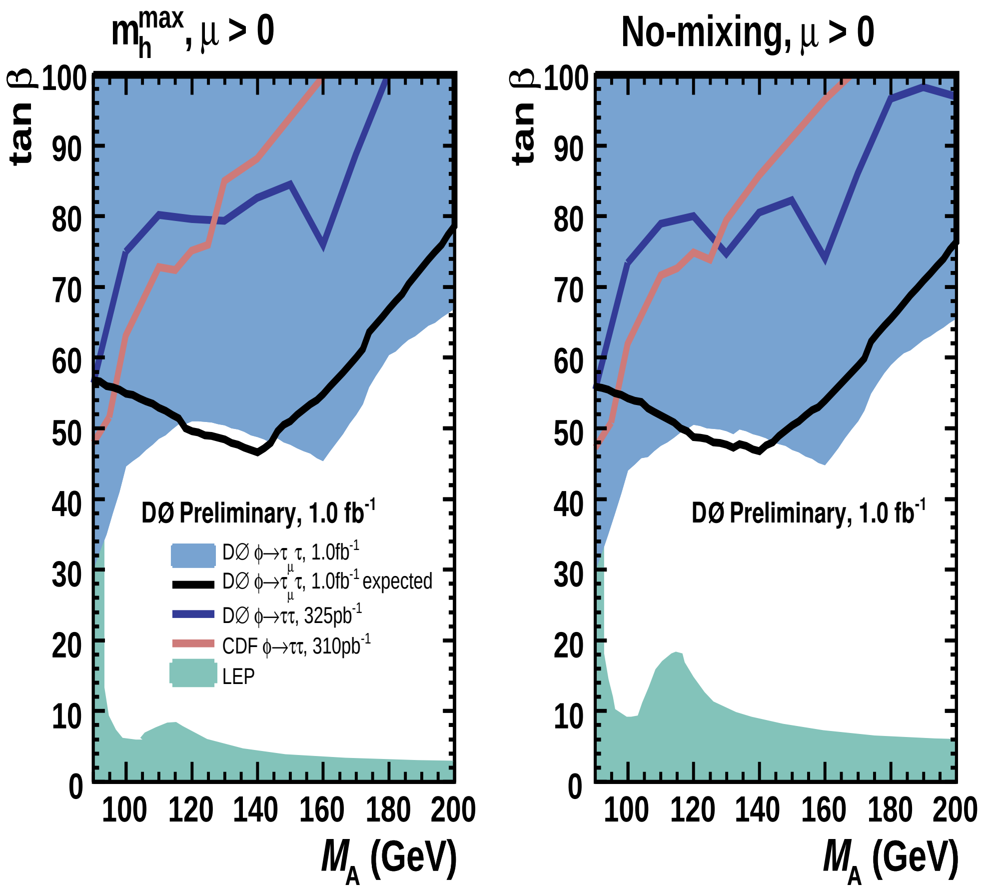
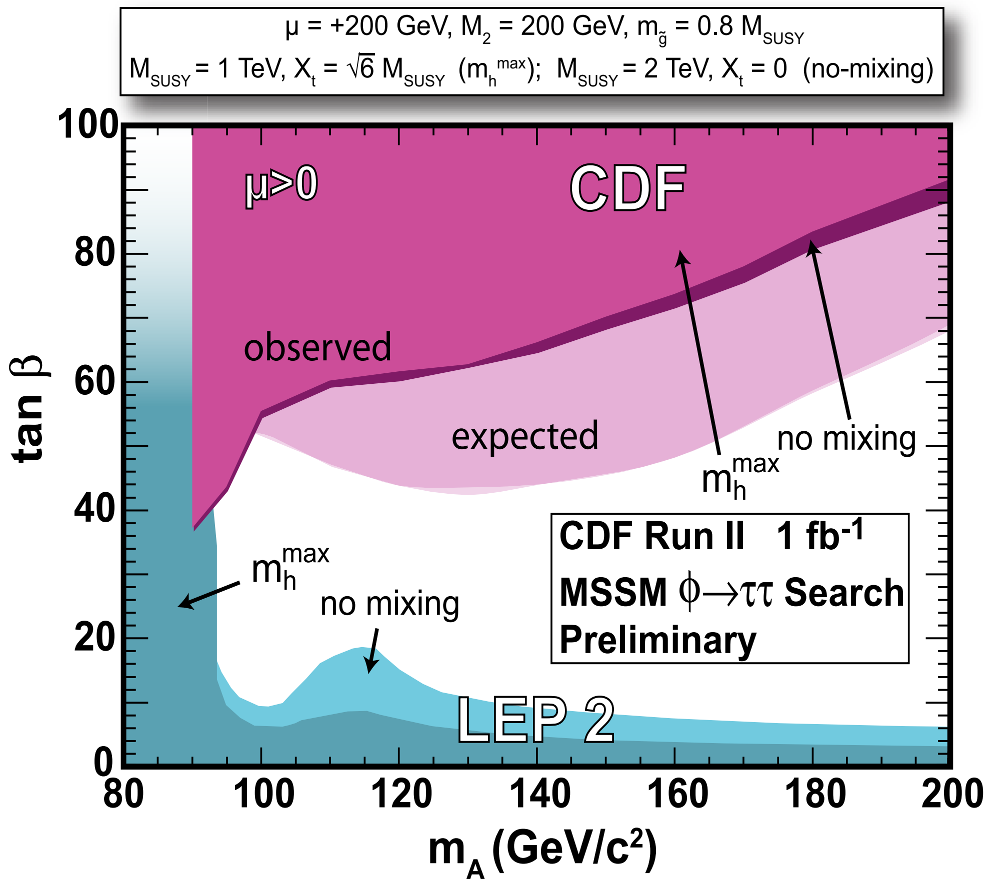



[D0 '07]

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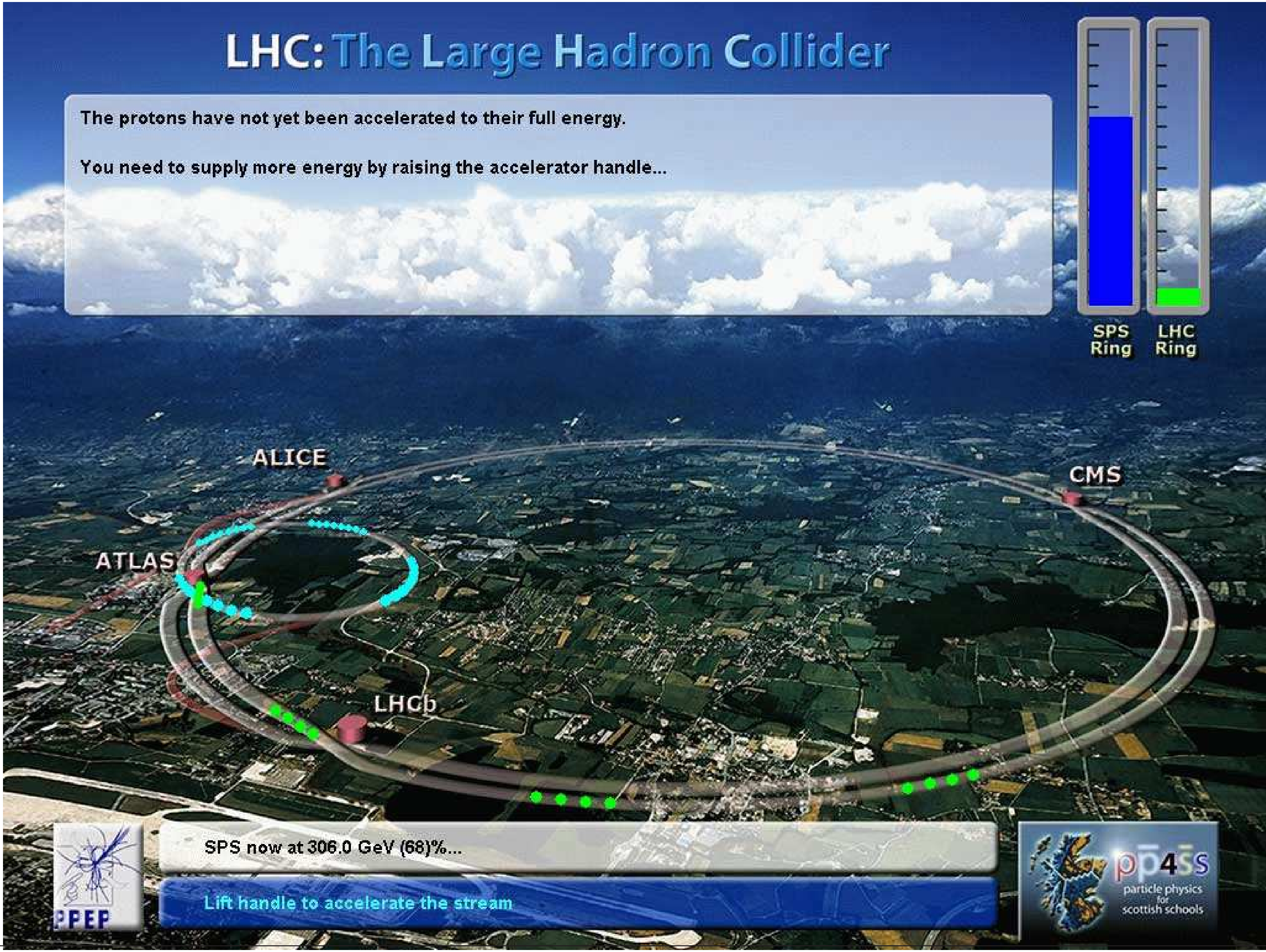
# 1C. Future: The Higgs at the LHC

LHC: $pp$ accelerator: start: fall 2007 $\longrightarrow$ T

The (un)official (optimistic?) LHC timeline:

2007 (11/07): fixing the inner triplets
collisions at $\sqrt{s} = 2 \times 450$ GeV cancelled
2008: 0.1 fb$^{-1}$ – $\mathcal{O}$(few) fb$^{-1}$ (at best) $\Rightarrow$ first physics results?
2009: $\mathcal{O}$(few) fb$^{-1}$ $\Rightarrow$ first physics results?
2010 – 2012: 10 fb$^{-1}$ per year $\Rightarrow$ physics results with "low" luminosity
2013 – ?: 100 fb$^{-1}$ per year $\Rightarrow$ physics results with "high" luminosity
2015 + X (X > 0): upgrade to SLHC?


LHC: The Large Hadron Collider
The protons have not yet been accelerated to their full energy.
You need to supply more energy by raising the accelerator handle...
SPS Ring
LHC Ring
ALICE
CMS
ATLAS
LHCb
SPS now at 306.0 GeV (68)%...
Lift handle to accelerate the stream
PPEP
pp4ss
particle physics for scottish schools

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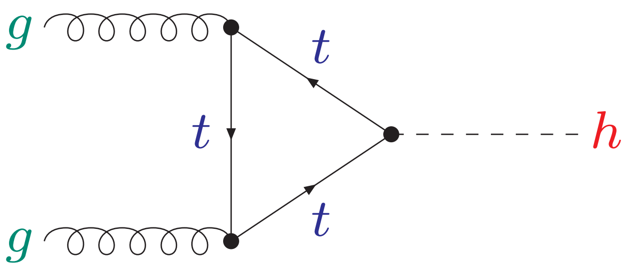
2015 + X (X > 0): upgrade to SLHC?

**YOU live in an exciting time!!!**

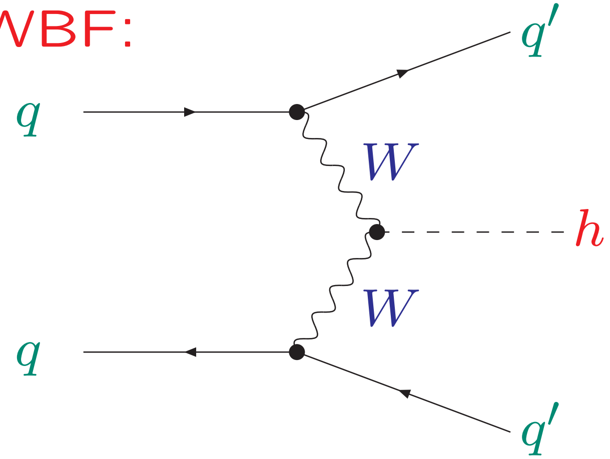
## Examples for Higgs production and decay at the LHC:

Important production channel at the LHC:

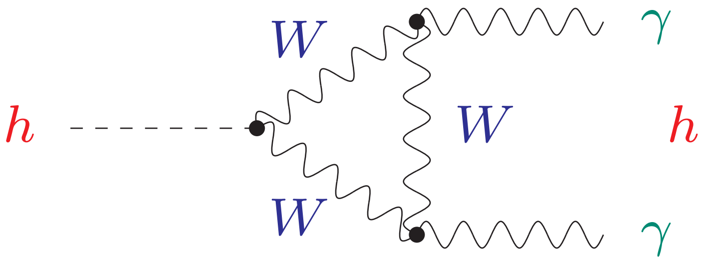
Gluon-Fusion:

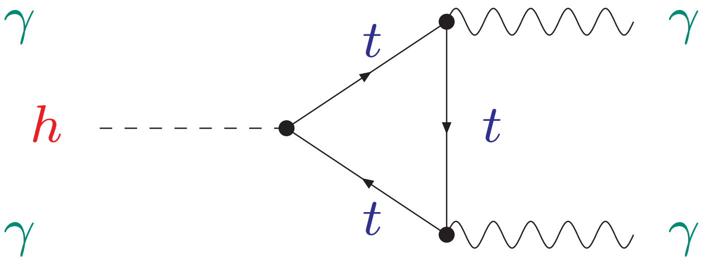



WBF:



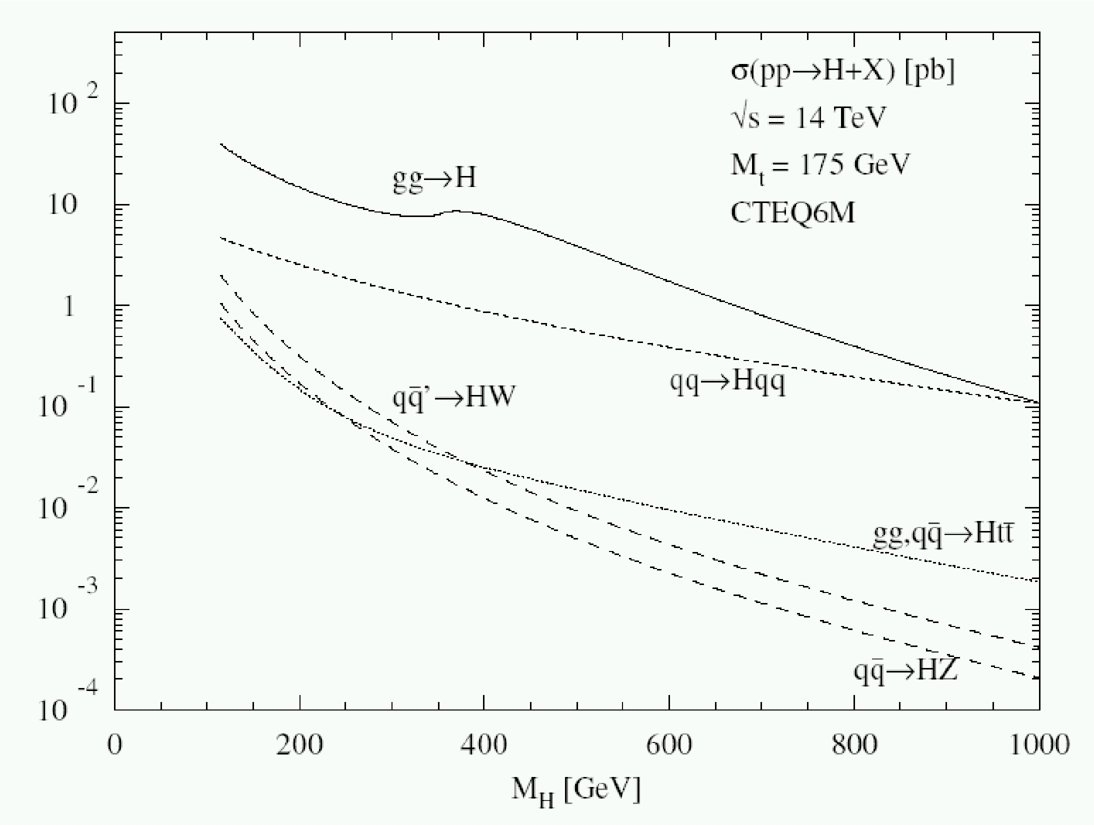

Important decay for Higgs mass measurement:



# Step 1: Discovery of the new particle

## SM Higgs production at the LHC:




gluon fusion: $gg \to H$

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

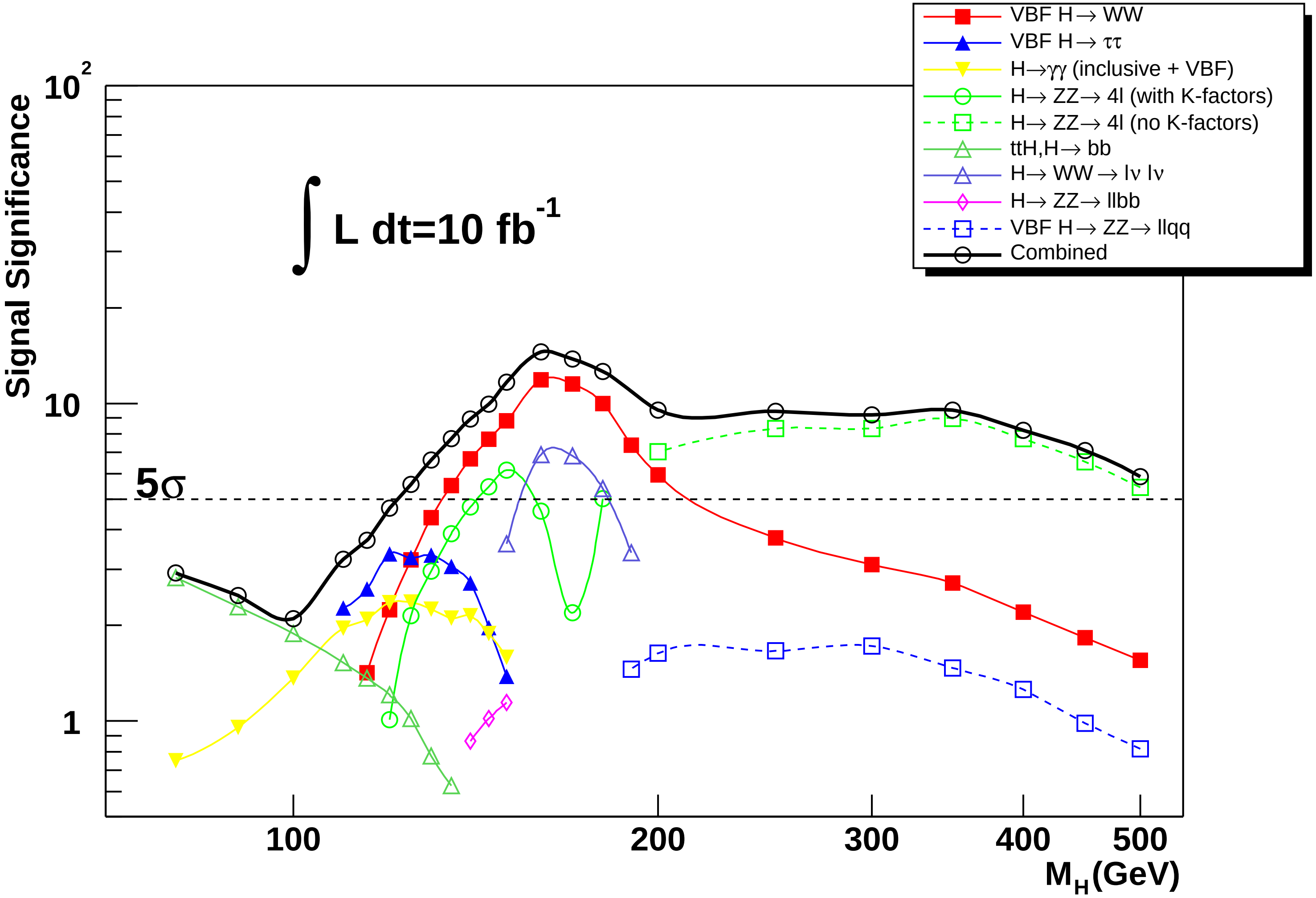
top quark associated
production: $gg, q\bar{q} \to t\bar{t}H$

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

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

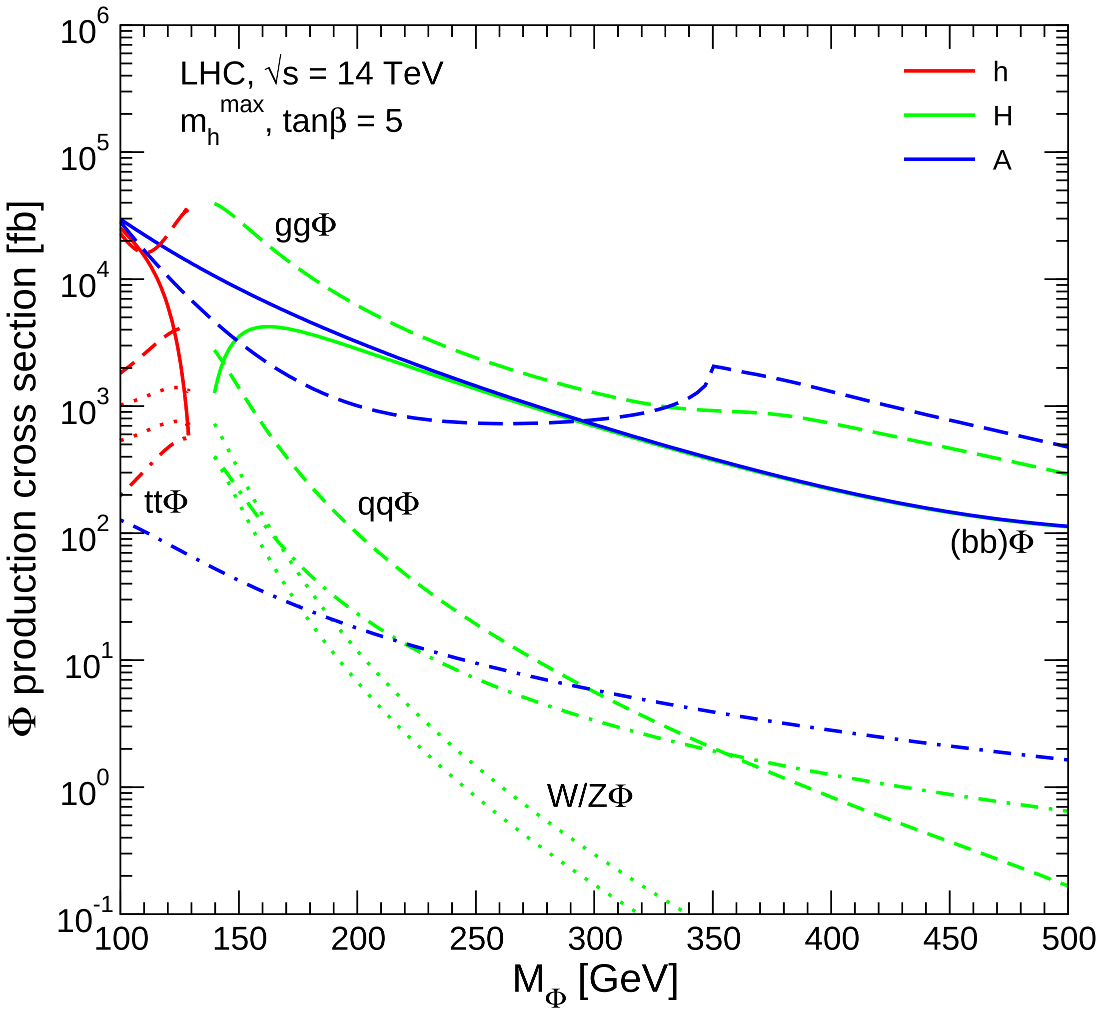
## SM Higgs search at the LHC: ⇒ full parameter space accessible

[*ATLAS '05*]



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

[*T. Hahn, S.H., F. Maltoni, G. Weiglein, S. Willenbrock '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: $q\bar{q}' \to W\phi, Z\phi$

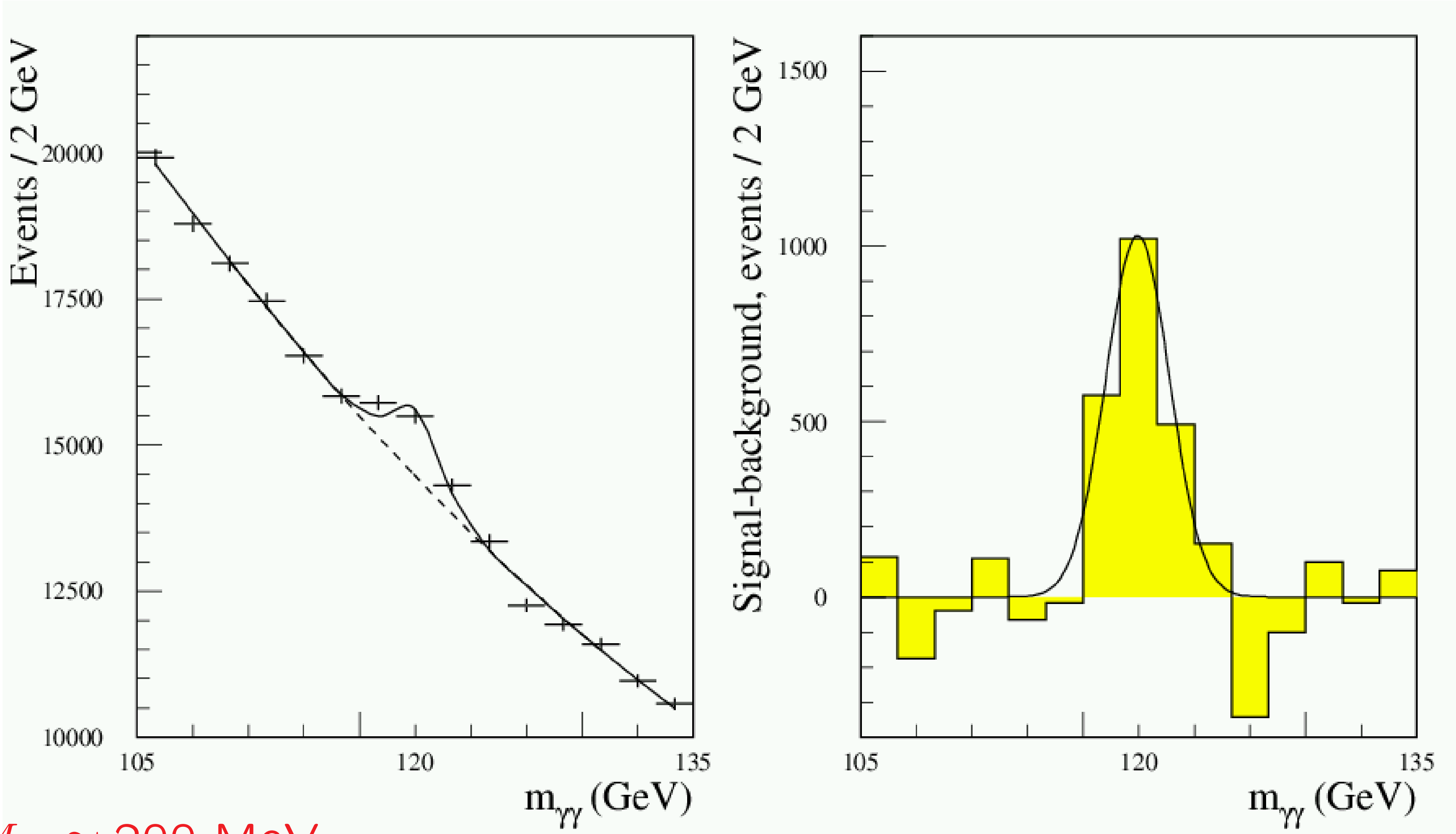
NEW: $b\bar{b}\phi$

Search for the lightest MSSM Higgs at the LHC:

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

## 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

# Possible problem in SUSY:

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

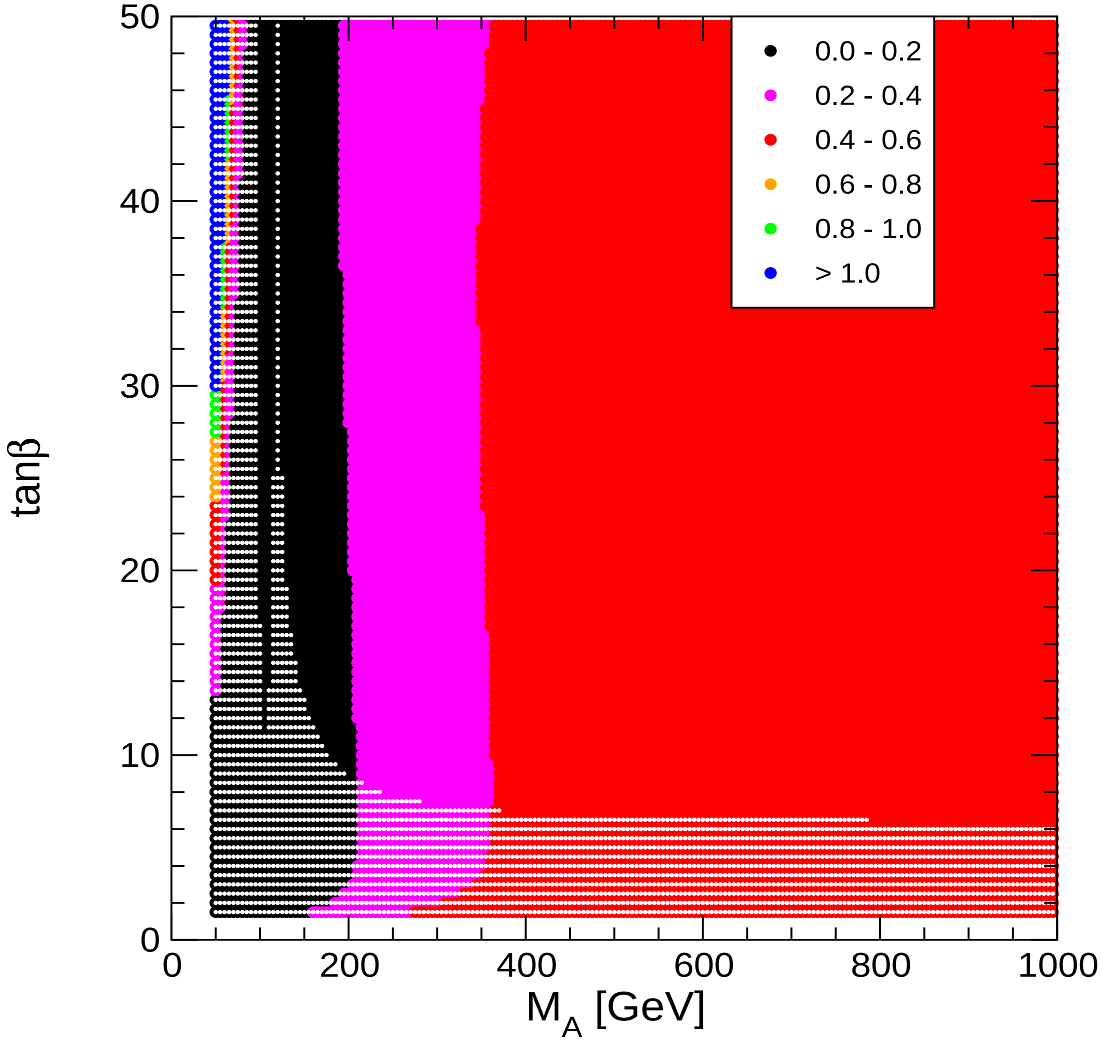
can be strongly suppressed

$\to$ "gluophobic Higgs scenario"

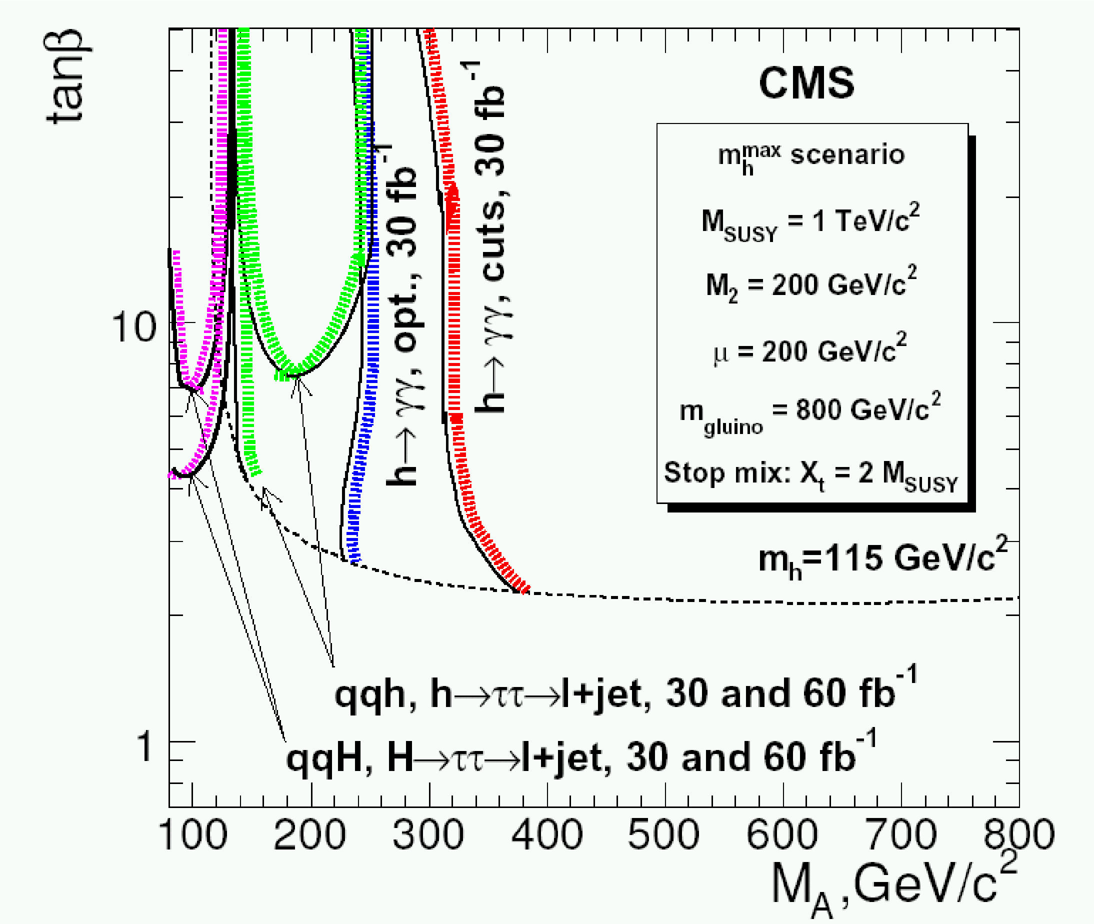
[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

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

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



And even in the "nice" $m_h^{\rm max}$ scenario there might be problems:
[*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

## Step 3, 4: measurement of couplings to gauge bosons and fermions

### Measurements for a SM Higgs (or SM-like MSSM Higgs) at the LHC:

Measurement of $\sigma \times \text{BR}$: "narrow width" approximation:

$$\Rightarrow \sigma(H) \times \text{BR}(H \to xx) \; = \; \sigma(H)^{\text{SM}} \cdot \frac{\Gamma_{\text{prod}}}{\Gamma_{\text{prod}}^{\text{SM}}} \times \frac{\Gamma_{\text{partial}}}{\Gamma_{\text{tot}}}$$

Observation of different channels
⇒ Information about combinations of $\Gamma_b, \Gamma_\tau, \Gamma_W, \Gamma_Z, \Gamma_g, \Gamma_\gamma, Y_t^2$

⇒ Additional theory assumptions necessary for absolute determination of partial widths

Only assumption:

→ consider general multi Higgs-Doublet model
w/o additional Higgs-Singlets
(⇒ includes e.g. MSSM)

⇒ Absolute Determination of $\Gamma_{\text{tot}}$ and Higgs couplings in a global fit
⇒ (nearly) model independent analysis

## Luminosity at the LHC:

- $2 * 30$ fb$^{-1}$: 30 fb$^{-1}$ in each of the two experiments
- $(2*300+2*100)$ fb$^{-1}$: 300 fb$^{-1}$ in each experiment, but only 100 fb$^{-1}$ usable for gauge boson fusion

## Estimate of errors:

### 1.) Statistical errors:

Assumption: SM rates for production and decay in all scenarios

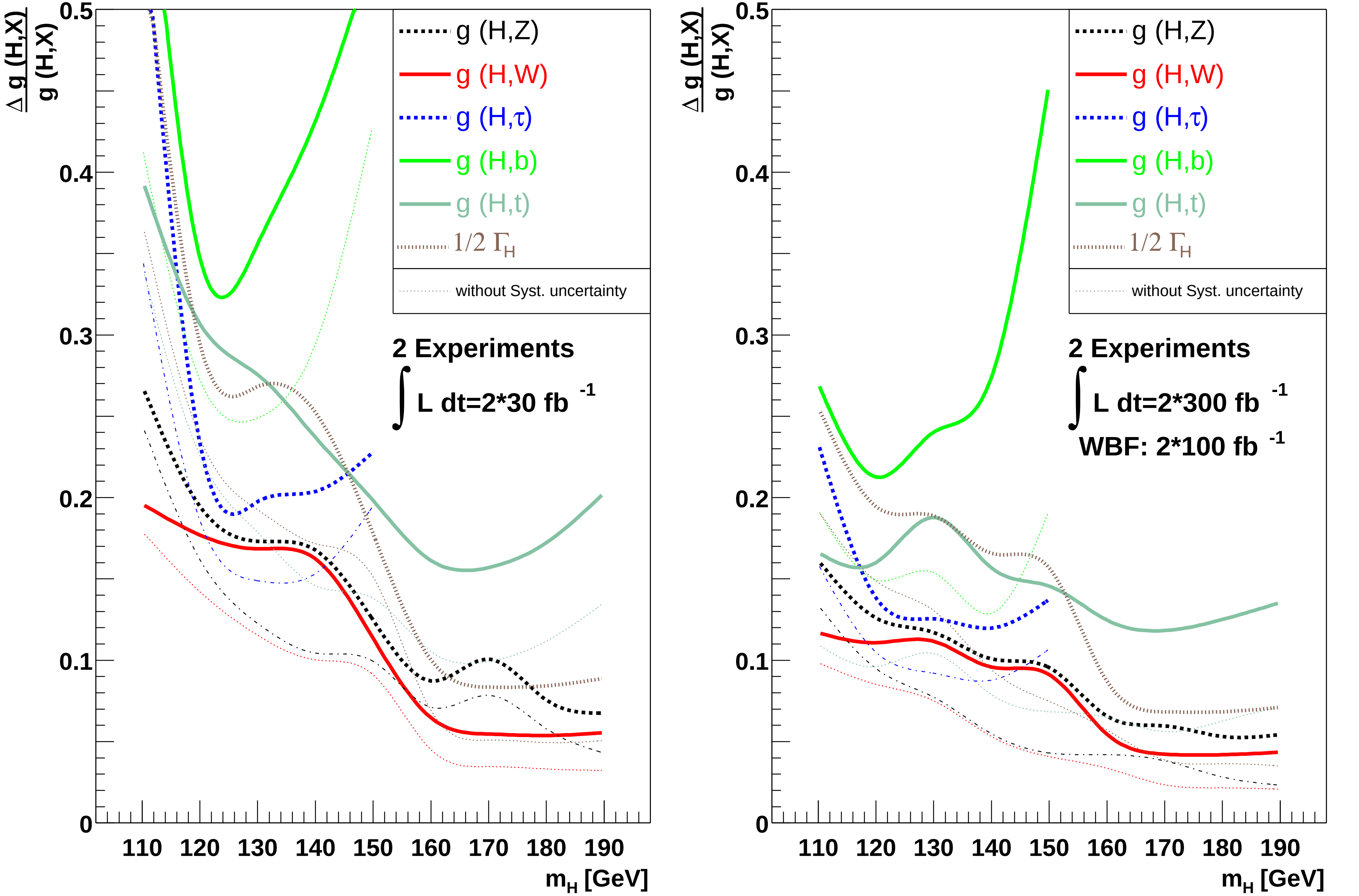
### 2.) Systematic errors:

$\rightarrow$ attempt to include realisticly all possible errors

$\Rightarrow$ "log likelihood" function,
based on statistical and systematic errors

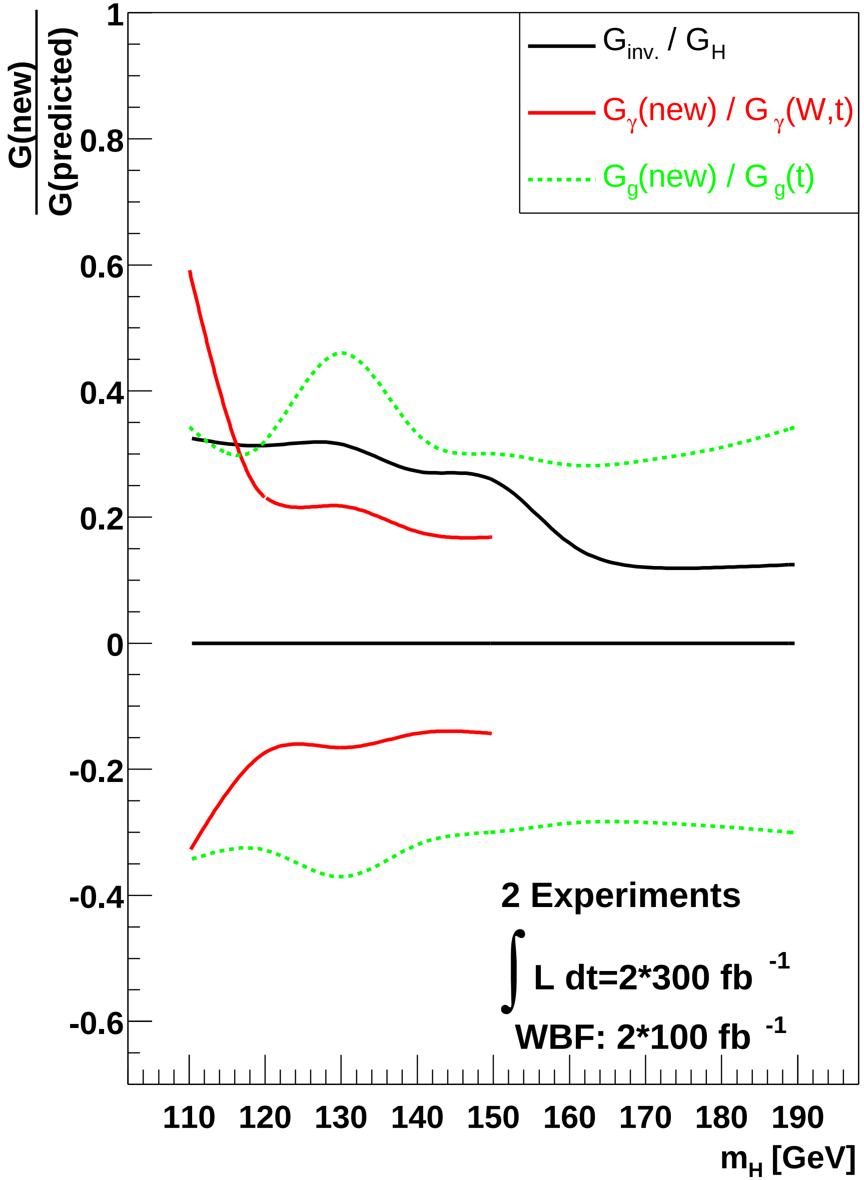
# Relative precision for partial and total Higgs widths: two scenarios

[*M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04*]



# Constraints on extra partial widths:

[M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04]




measurement of SM rates

$\Rightarrow$ constraints on widths:

$(2 * 300 + 2 * 100)$ fb$^{-1}$ scenario:

$\Delta\Gamma_\gamma \leq 0.2 \times \Gamma_\gamma^{\text{SM}}$

$\Delta\Gamma_g \leq 0.4 \times \Gamma_g^{\text{SM}}$

$\Delta\Gamma_{\text{inv}} \leq 0.2 \times \Gamma_{\text{tot}}^{\text{SM}}$

$\Rightarrow$ restrictions on new physics!

## Results:

Absolute determination of Higgs couplings is possible!

Scenario with low luminosity: $2 * 30\ \text{fb}^{-1}$ :

for a light Higgs: results significantly worse in comparison with higher luminosity

Scenario with higher luminosity: $(2 * 300 + 2 * 100)\ \text{fb}^{-1}$ :

– typical precision of 15-25% for $m_H \lesssim 150$ GeV

– 5% accuracy for $HVV$ couplings above $WW$ threshold

Systematic errors contribute about 50% to the total error, especially at high luminosity

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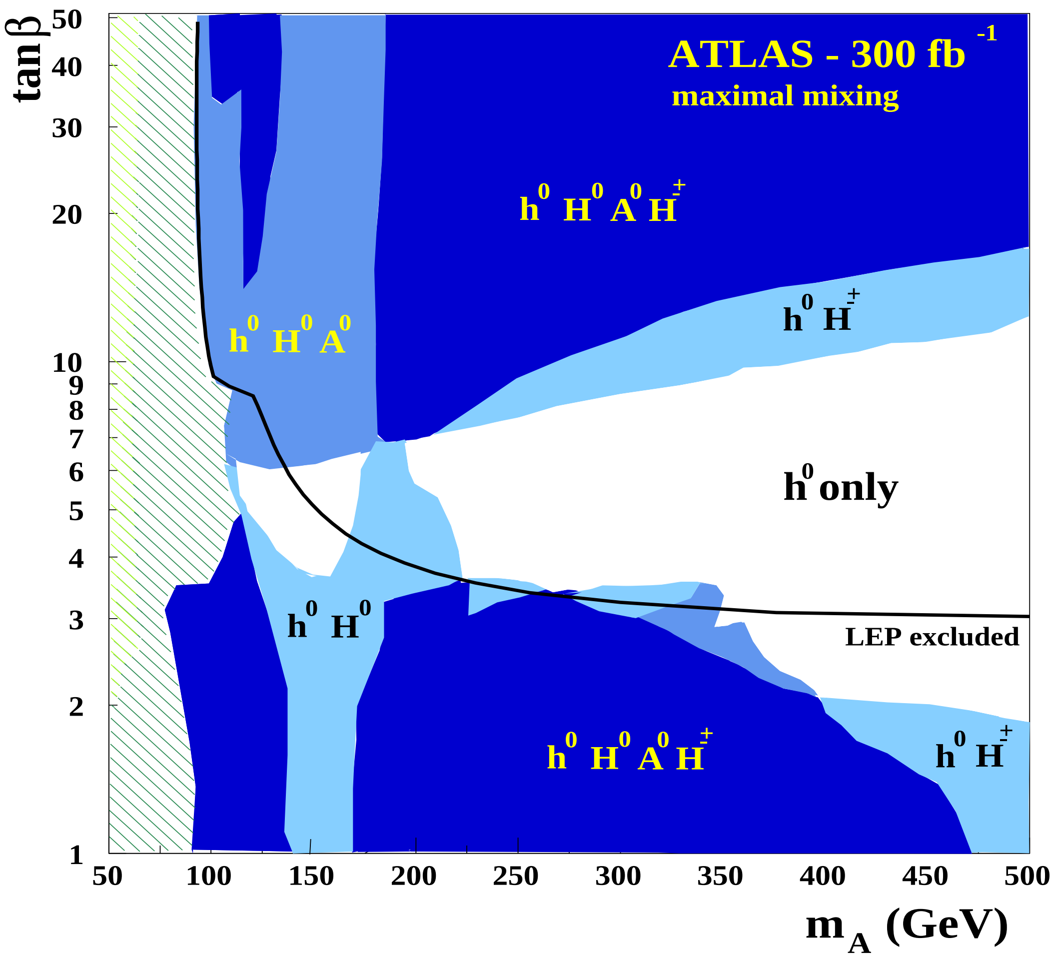
Systematic errors contribute about 50% to the total error, especially at high luminosity

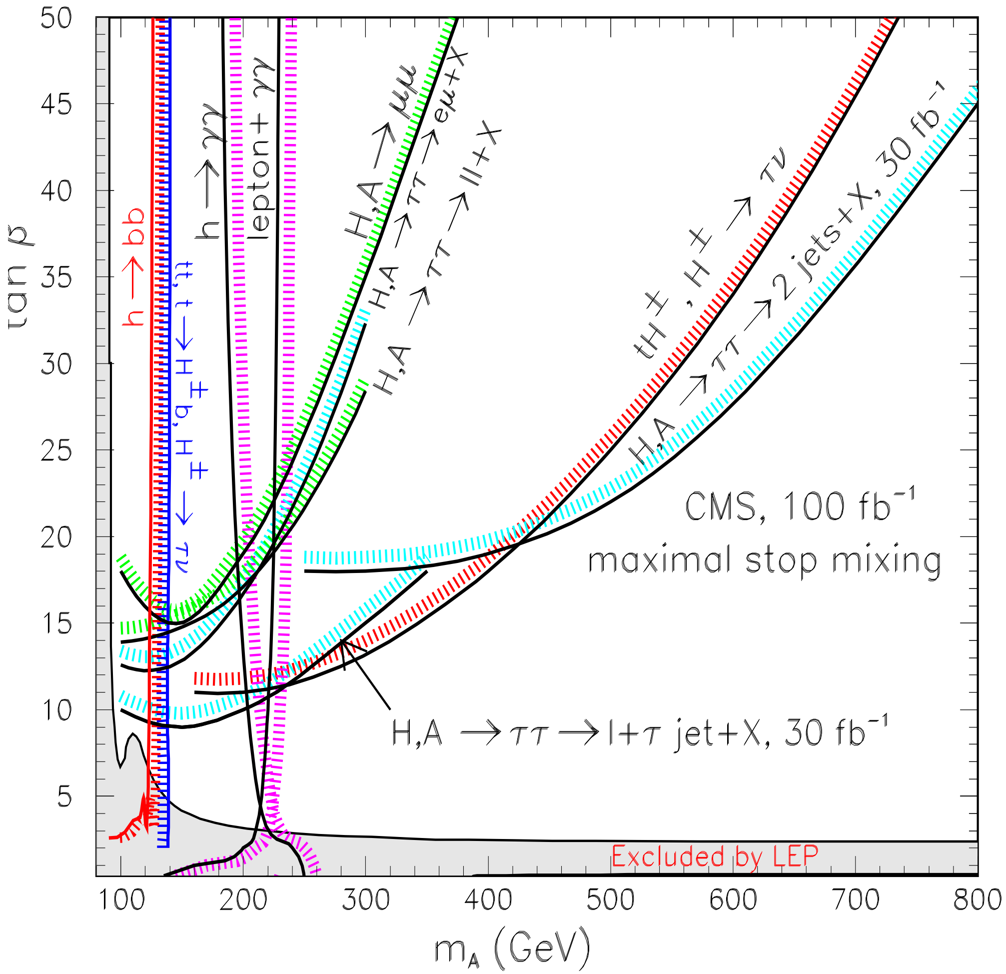
What happens with non-SM rates?

$\Rightarrow$ not analyzed yet . . .

# "Heavy" MSSM Higgs searches:

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




areas where only $h$ is observable ⇒ "LHC wedge"

## Most powerful search modes for heavy MSSM Higgs bosons:

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

Enhancement factors compared to the SM case:

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

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

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

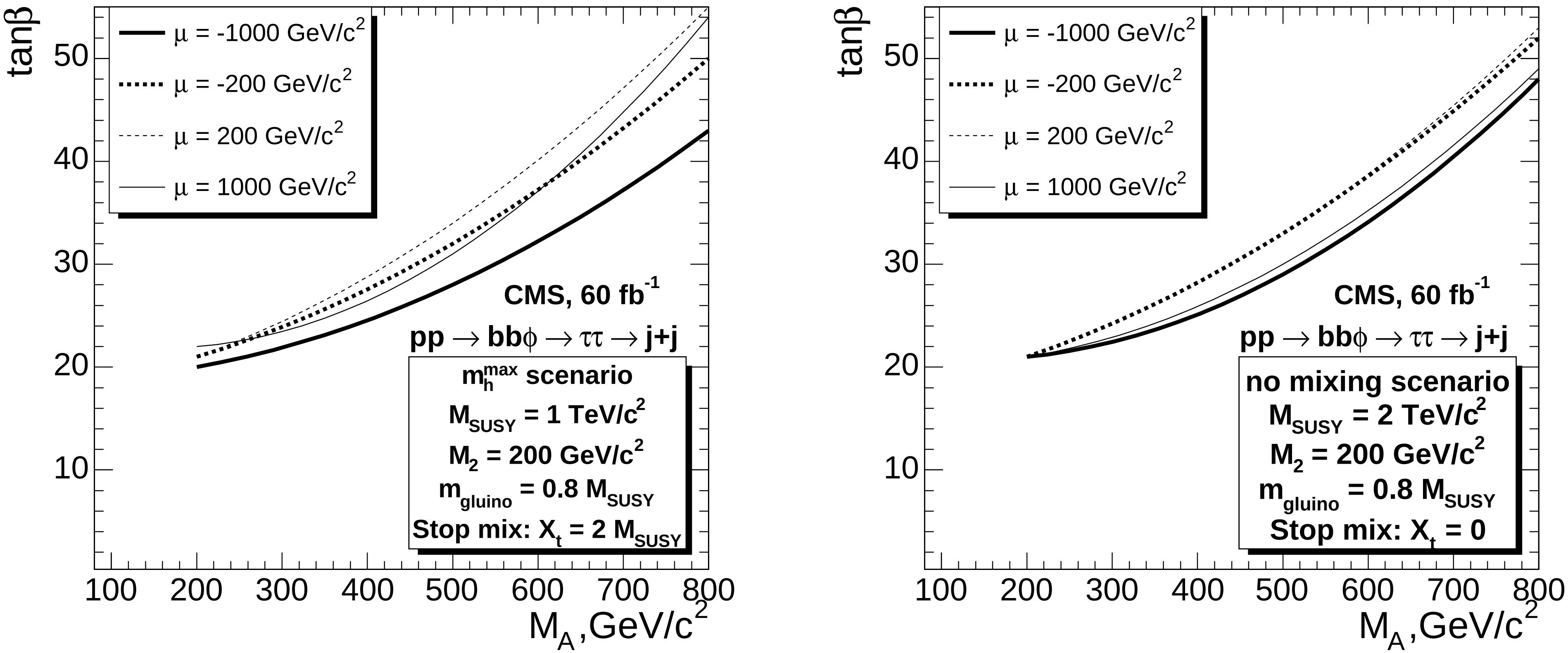
also relevant for $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

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

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

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

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

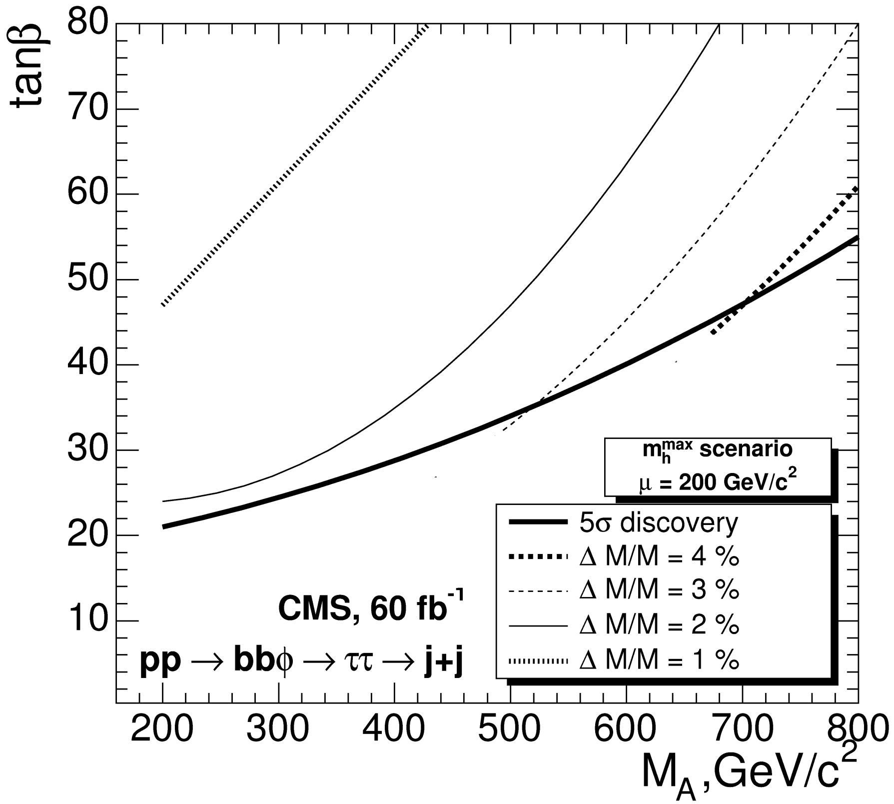


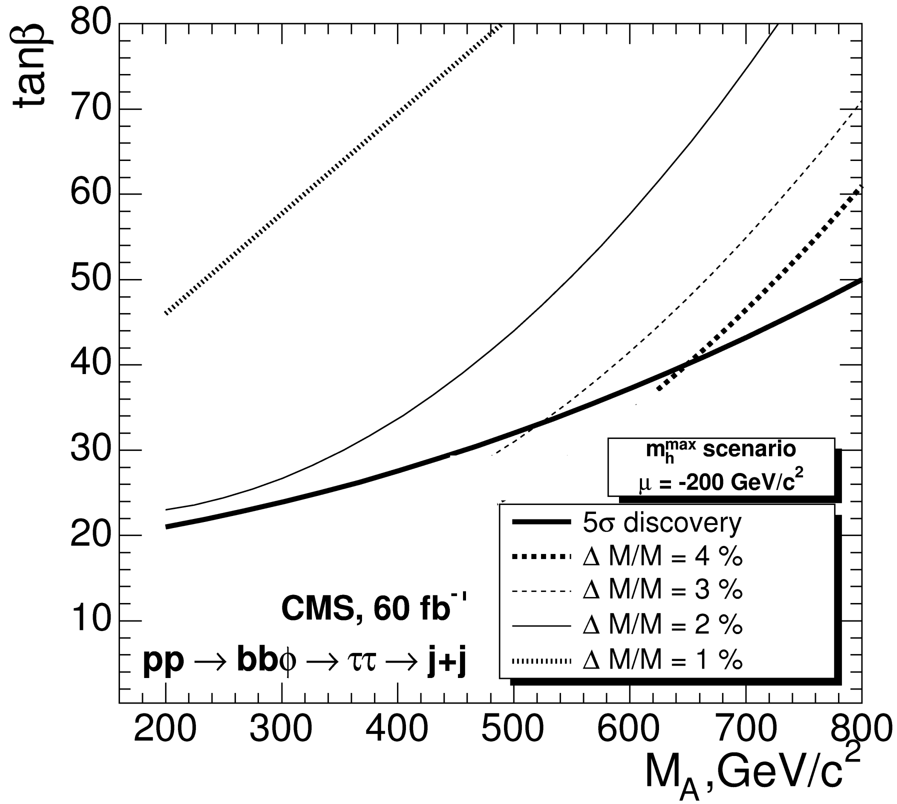

⇒ now based on full CMS simulation

⇒ non-negligible variation with the sign and absolute value of $\mu$
(→ 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*]




⇒ now based on full CMS simulation

⇒ high precision measurement of heavy Higgs boson masses possible

# 2. Discovering SUSY

Two possible ways:

- Search for new SUSY particles

| |
|---|
| new SUSY particles found<br>$\Updownarrow$<br>SM ruled out |

Problem:
SUSY particles are too heavy for todays colliders, only lower limits of $\mathcal{O}(100 \text{ GeV})$.

$\rightarrow$ waiting for Tevatron (2008/09...?)
$\rightarrow$ waiting for LHC (2009/10...? cooling problems...)

- Search for indirect effects of SUSY
  via Precision Observables

$\Rightarrow$ Pietro Slavich's lecture in February

## 2. Discovering SUSY

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 need both: hadron colliders (Tevatron/LHC) and high lumi ILC

## SUSY searches at the Tevatron, Run II:

compared to Run I: $\approx 100\times$ higher luminosity, slightly increased energy ($1.8 \to 2$ TeV)

Limited mass window in which discovery of SUSY particles above Run I is possible

Best prospects for:

– 'Trilepton signal': $\tilde{\chi}_2^0 \tilde{\chi}_1^+ \to \ell^+ \ell^- \tilde{\chi}_1^0 \ell^+ \nu \tilde{\chi}_1^0$

– $\tilde{t}$, $\tilde{b}$, $\tilde{g}$ searches $\to$ T

– SUSY Higgs searches in region of large $\tan\beta$

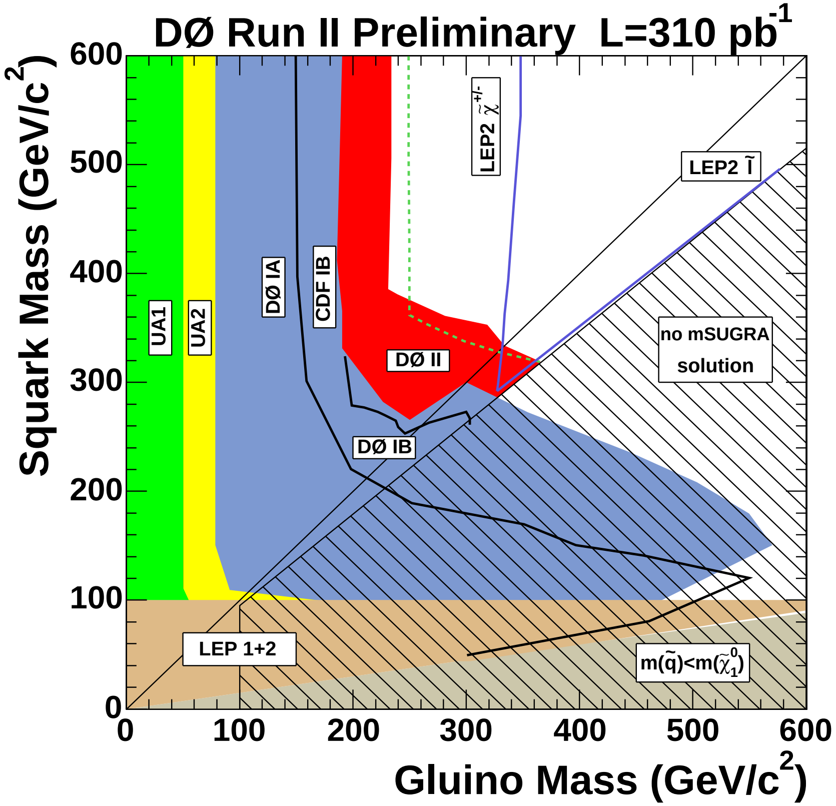
## SUSY searches at the LHC:

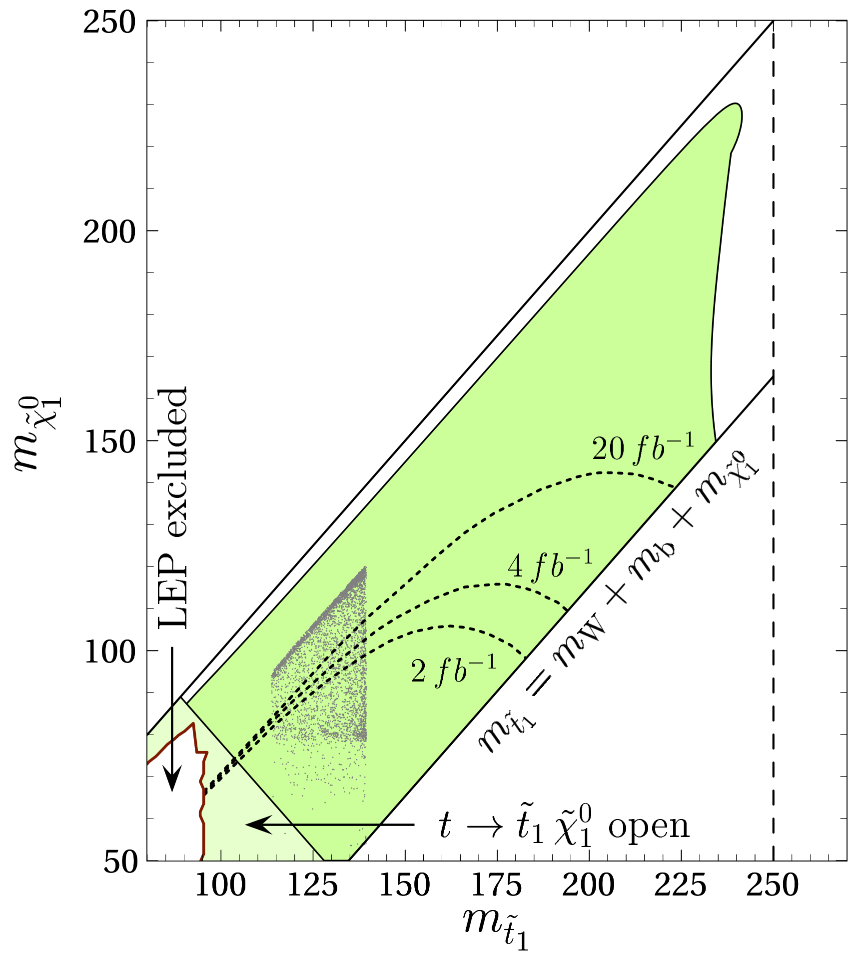
Dominated by production of colored particles: gluino, squarks

Very large mass range in the searches for jets + missing energy

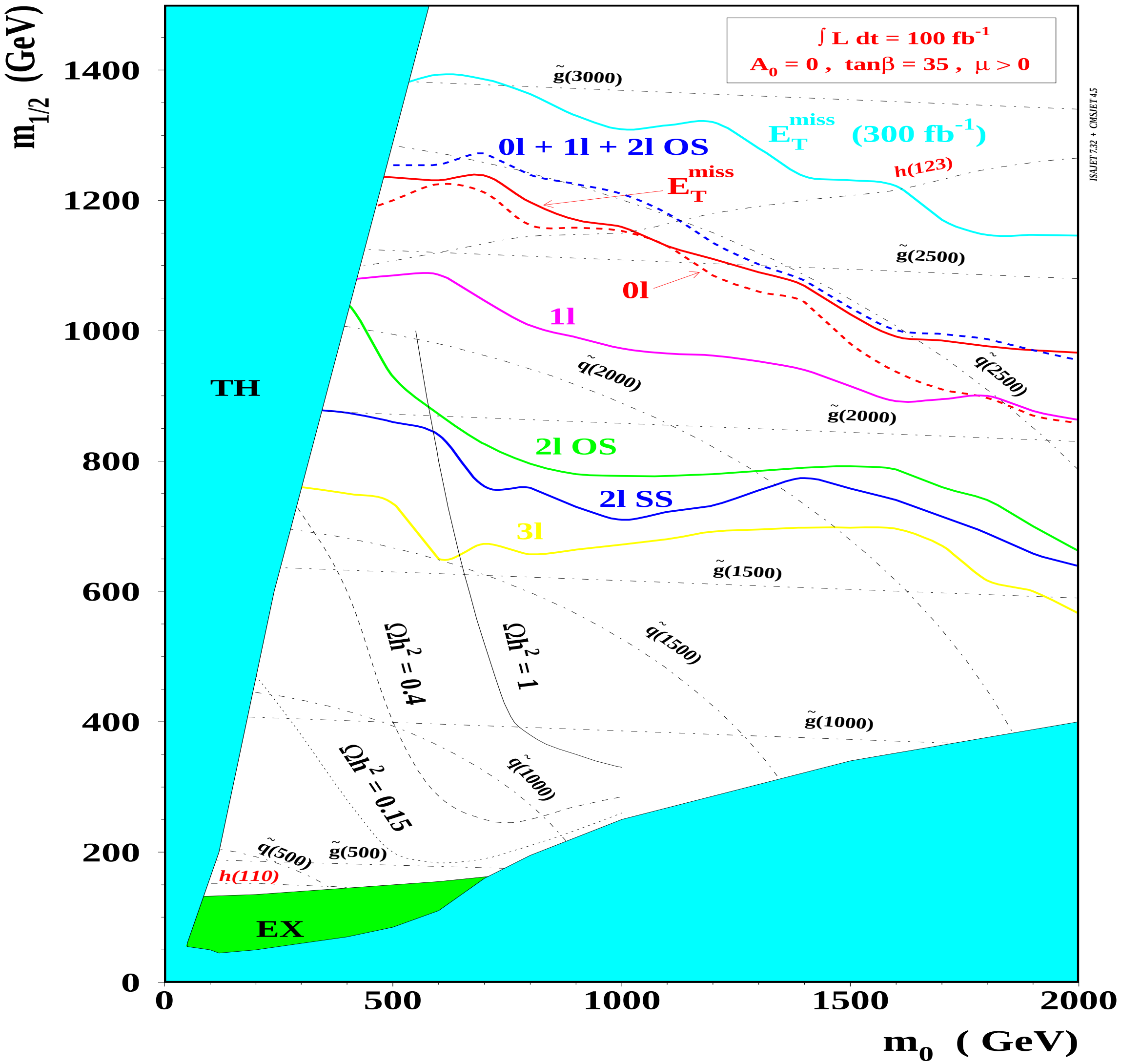
$\Rightarrow$ gluino, squarks accessible up to 2–3 TeV

Search for gluinos, squarks and stops :



Discovery reach contours in $m_0$–$m_{1/2}$ plane (mSUGRA scenario) for various final states with 100 fb$^{-1}$: [*CMS '99*]




⇒ discovery of SUSY particles expected if low-energy SUSY is realized

Production of SUSY particles at the LHC will in general result in complicated final states, e.g.

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

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!**

Searches for MSSM Higgs bosons:

good prospects for detecting light Higgs h

$H/A$ discovery possible in significant part of parameter space

## 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

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

⇒ High luminosity ILC necessary, complementary to hadron machines

## SUSY searches at the ILC:

Clean signatures, small backgrounds

Thresholds for pair production of SUSY particles

⇒ precise determination of mass and spin of SUSY particles, mixing angles, complex phases, . . .

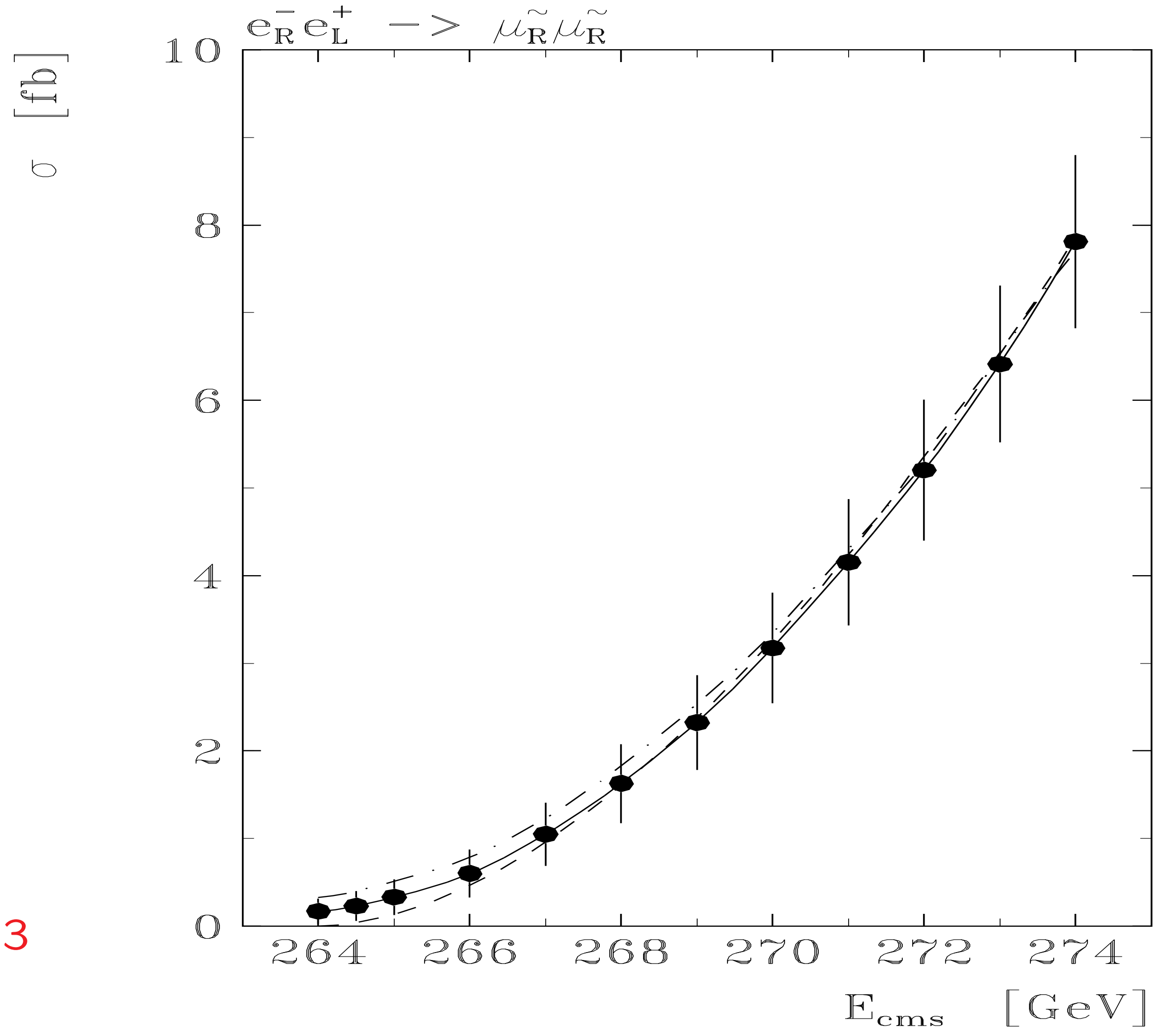
Limited by kinematic reach

Good prospects for production of uncolored particles

⇒ 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*]



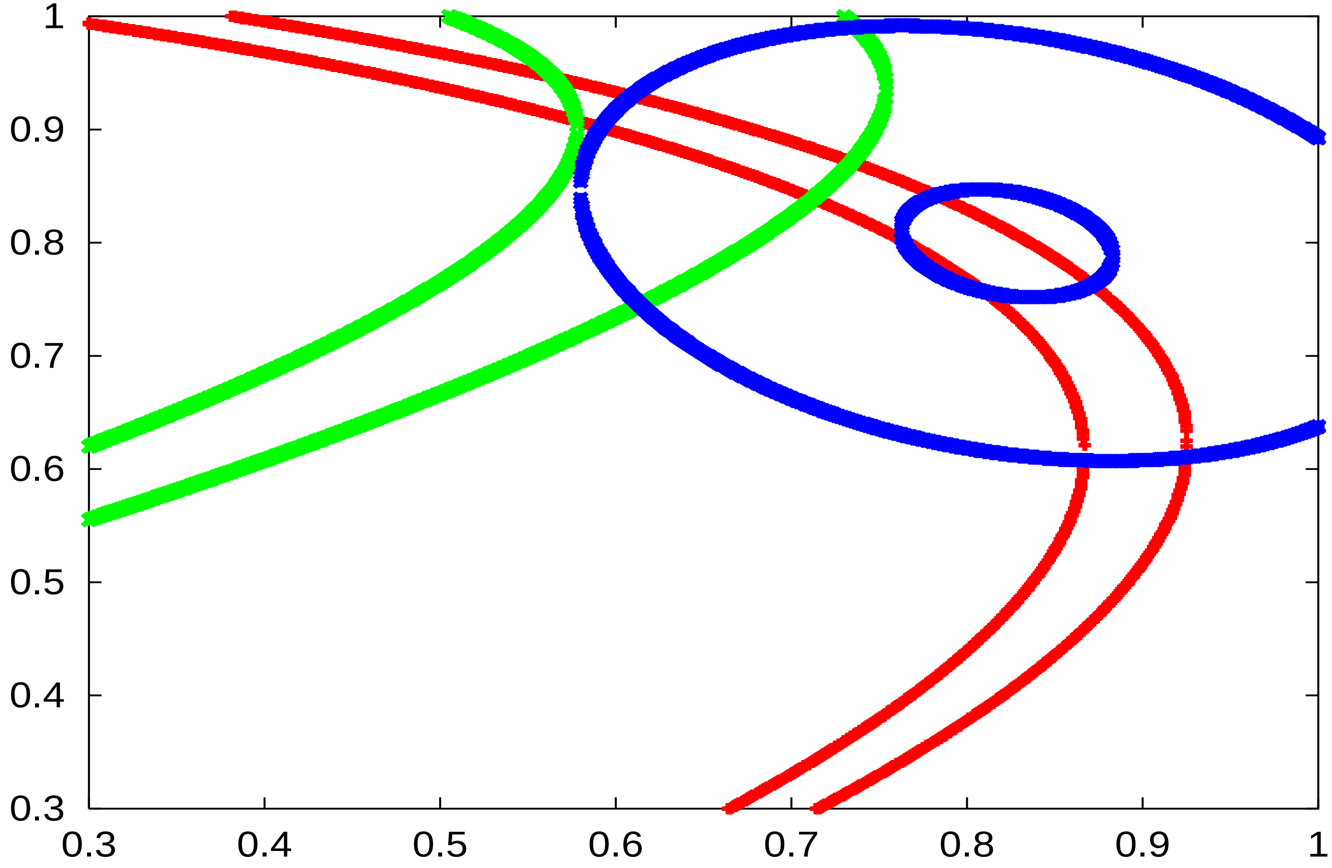

$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

⇒ test of $J = 0$ hypothesis

# Example for SUSY physics at the ILC (II):

Determination of $\phi_R$, $\phi_L$ 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*]

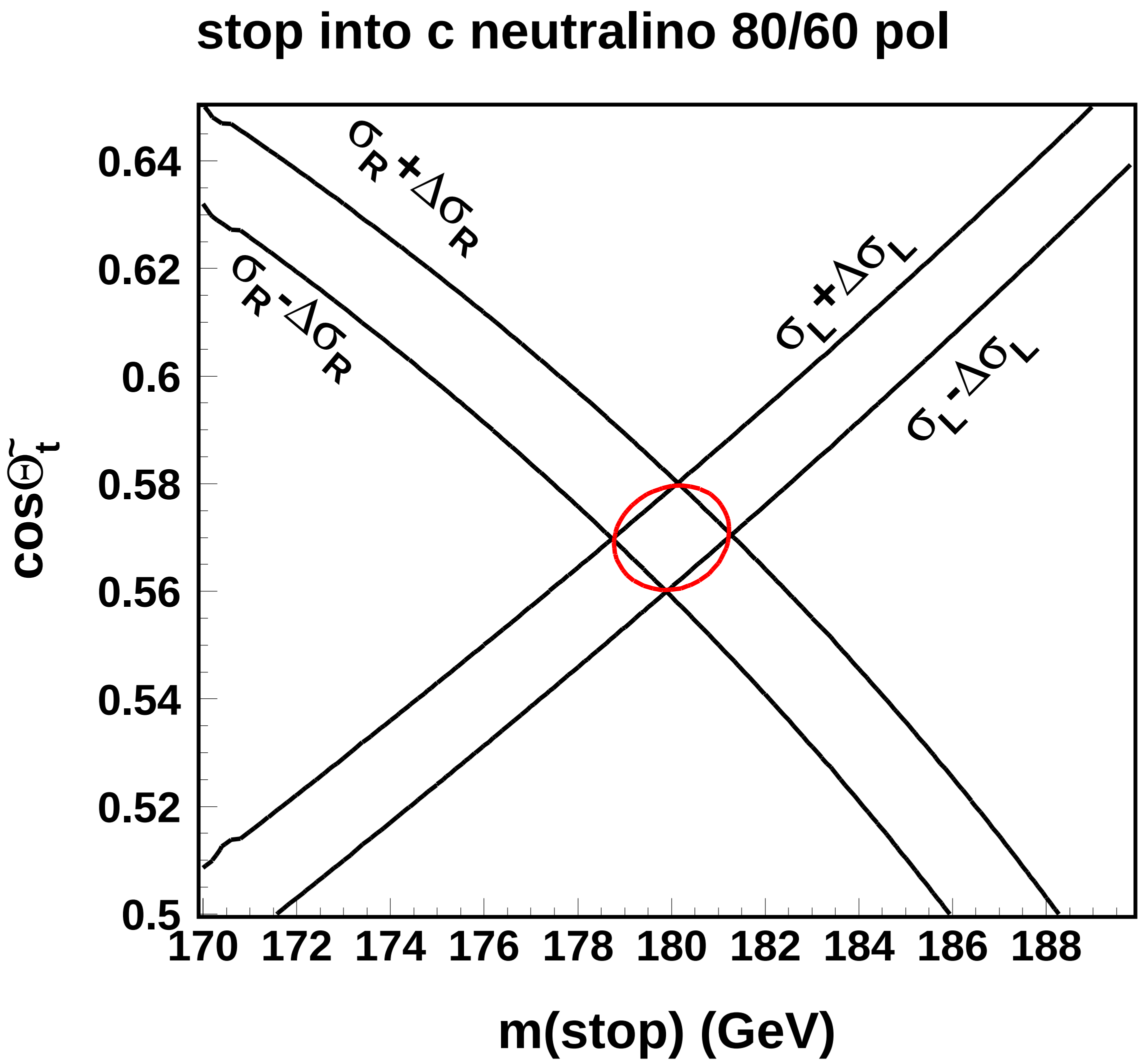



$\Rightarrow \cos 2\phi_L = [0.62, 0.72]$, $\cos 2\phi_R = [0.87, 0.91]$

# 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*]




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

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

# 3. Discovering Cold Dark Matter

## The LSP as a dark matter candidate

Astrophysical data (cosmic microwave background, . . . ) $\Rightarrow$ existence of non-baryonic cold dark matter in the Universe

SUSY with $R$ parity conservation $\Rightarrow$ LSP relic density falls naturally in favored range if $m_{\text{LSP}} \lesssim 1$ TeV

WMAP results (2006 update: no significant change) $\longrightarrow$ T

[*C. Bennet et al. '03*] , [*D. Spergel et al. '03*]

$\Rightarrow$ cold dark matter density:

$$\Omega_{\text{CDM}} h^2 = 0.112 \pm 0.018 \qquad \text{at 95\% C.L.}$$

($h$: normalized Hubble constant)

$\Rightarrow$ Constraints on the SUSY parameter space

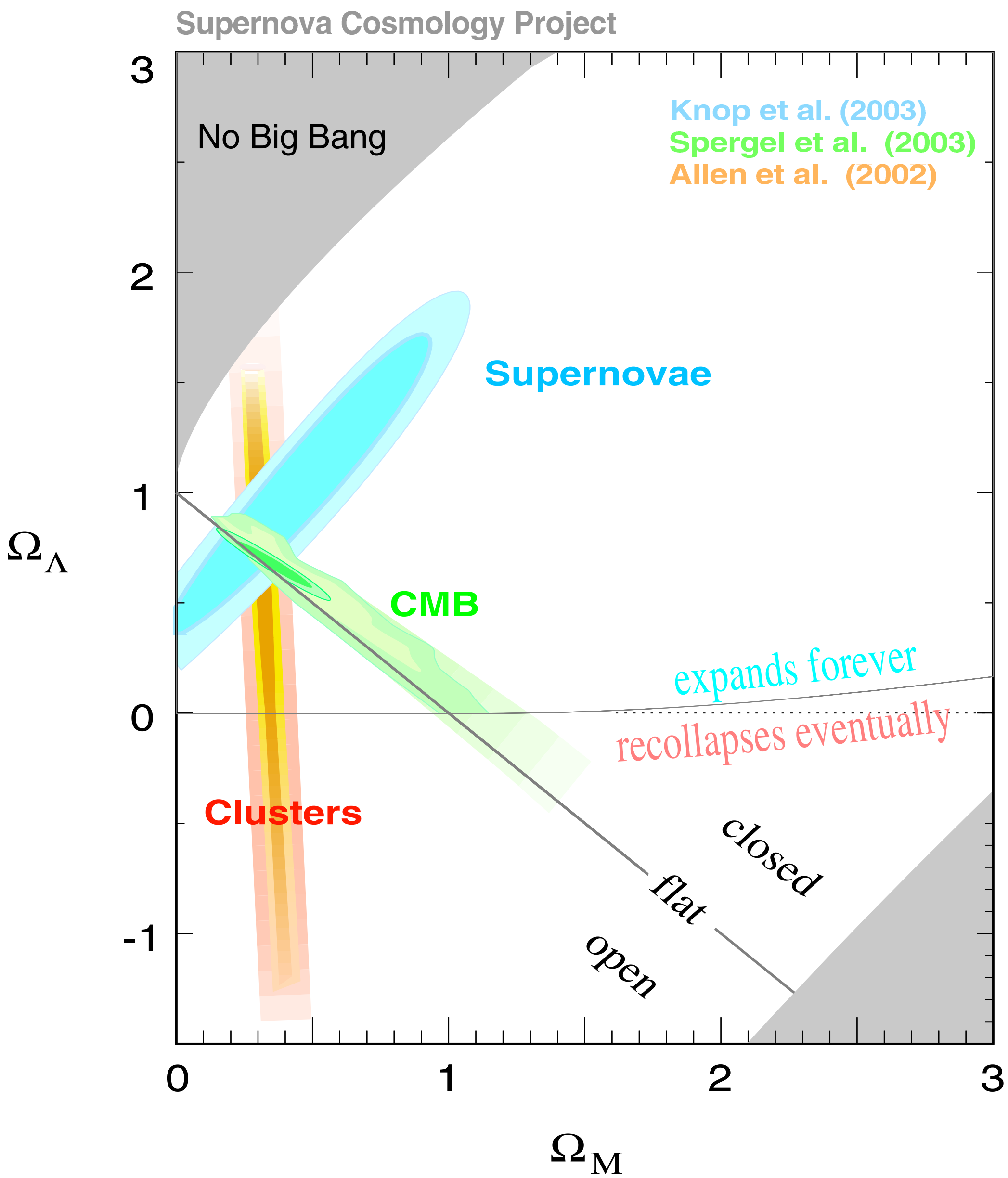
Combination of all existing astrophysical data:

⇒ It all fits together

$$\Omega_{tot} \approx 1$$
$$\Omega_M h^2 = 0.135^{+0.008}_{-0.009}$$
$$\Omega_B h^2 = 0.0224 \pm 0.0009$$
$$\Omega_\chi h^2 = 0.112 \pm 0.018$$
$$\Omega_\Lambda \approx 0.73$$

$\Omega_\chi \Rightarrow$ dark matter

$\Omega_\Lambda \Rightarrow$ dark energy . . .



## dark matter in the CMSSM parameter space:

schematic representation

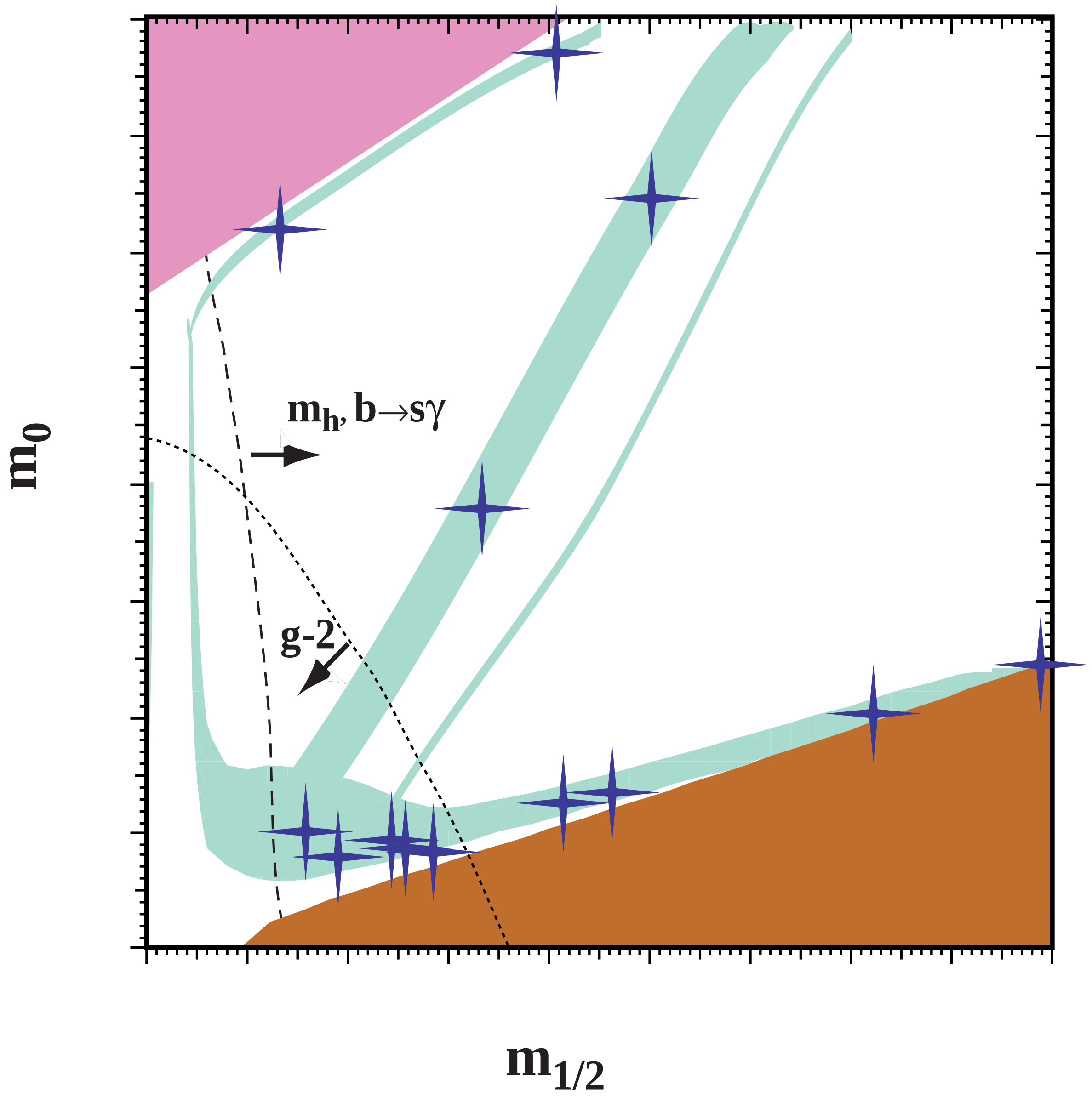
$(0.1 \leq \Omega_\chi h^2 \leq 0.3)$

[*K. Olive et al. '02*]

Despite its simplicity:
CMSSM fulfills all experimental bounds

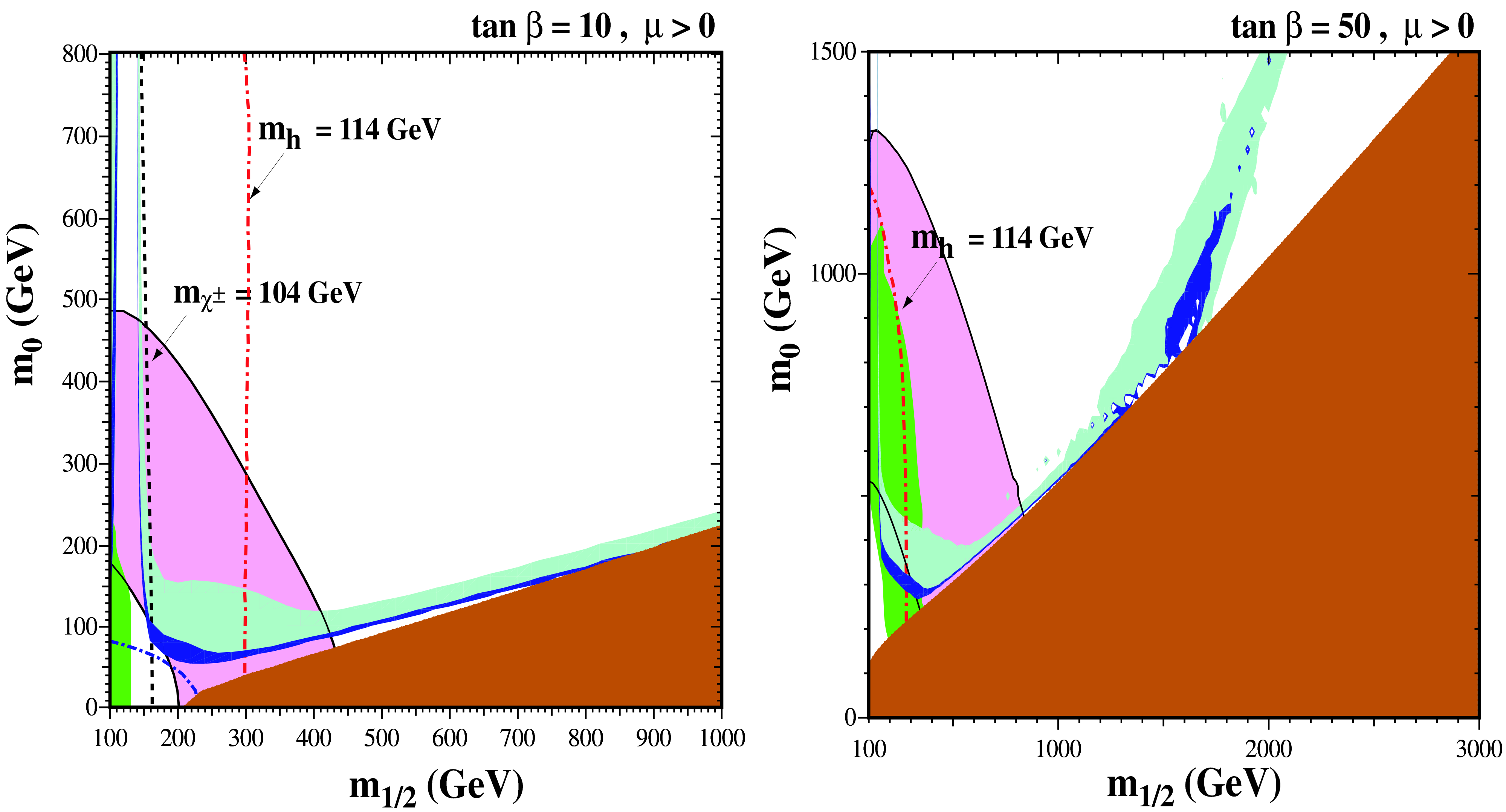
Four mechanisms for "good" $\langle \sigma v \rangle$:

– Bulk
– stau coannihilation
– Higgs pole annihilation
– focus point




Crosses: benchmark points

## Improvement through WMAP: [*K. Olive et al. '03*]




⇒ Strong constraints for the CMSSM parameter space from dark matter measurements

# Direct search for dark matter

Several methods:

(A) Search with earth-based detectors
dark matter scatters with matter in the detector
*[CDMS, CRESST, DAMA, EDELWEISS, GERDA, ZEPLIN, . . . ]*

(B) Search for photons from DM annihilation
*[ARGO, CELESTE, EGRET, GLAST, HEGRA, HESS, MAGIC, VERITAS, . . . ]*

(C) Search for neutrinos from DM annihilation
*[AMANDA, ANTARES, IceCube, . . . ]*

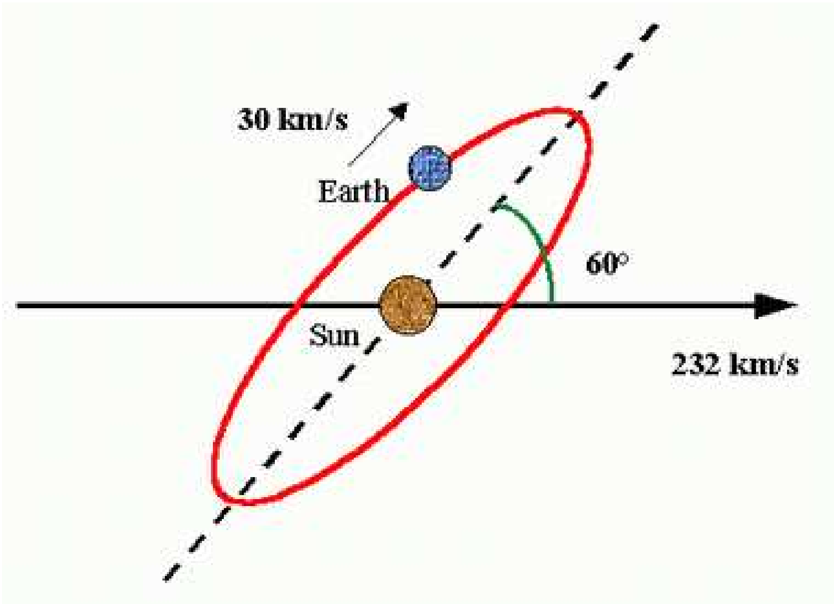
(D) Search for antimatter from DM annihilation
*[AMD, HEAT, . . . ]*

# A) Search with earth-based detectors

⇒ Calculation of cross section for DM matter interaction
⇒ Comparison of calculation with measurement

## Successful measurement with DAMA?

Idea: change of DM wind within the year



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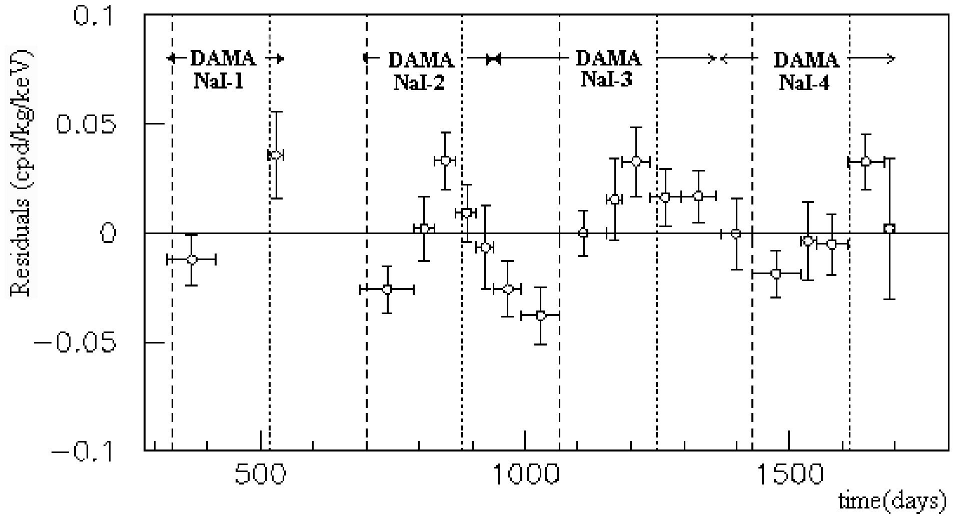
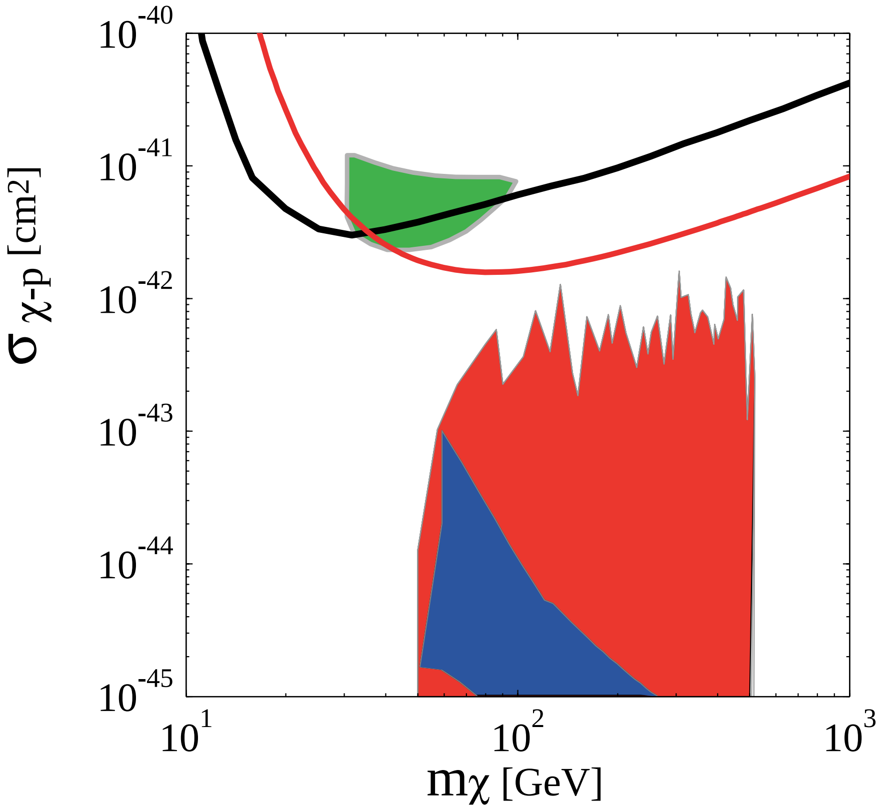



⇒ Change of number of events with a one-year period

# Comparison of DAMA with CDMS'03 and EDELWEISS'03:

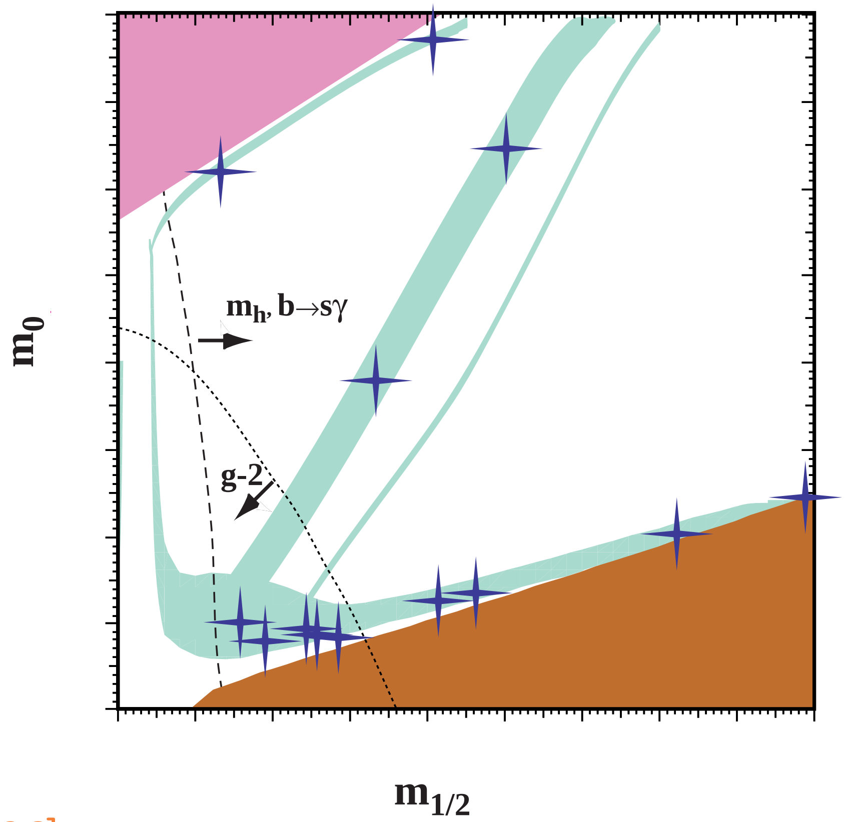



[*K. Olive et al. '03*] (situation in 2006 later)

⇒ DAMA measurement in conflict with other experiments

⇒ CMSSM/SUSY prediction in reach

# Expectations for CMSSM benchmark points:




[*J. Ellis, K. Olive et al. '03*]

⇒ Projection for CDMS/CRESST and GERDA/GENIUS

(higher reach with other future experiments)

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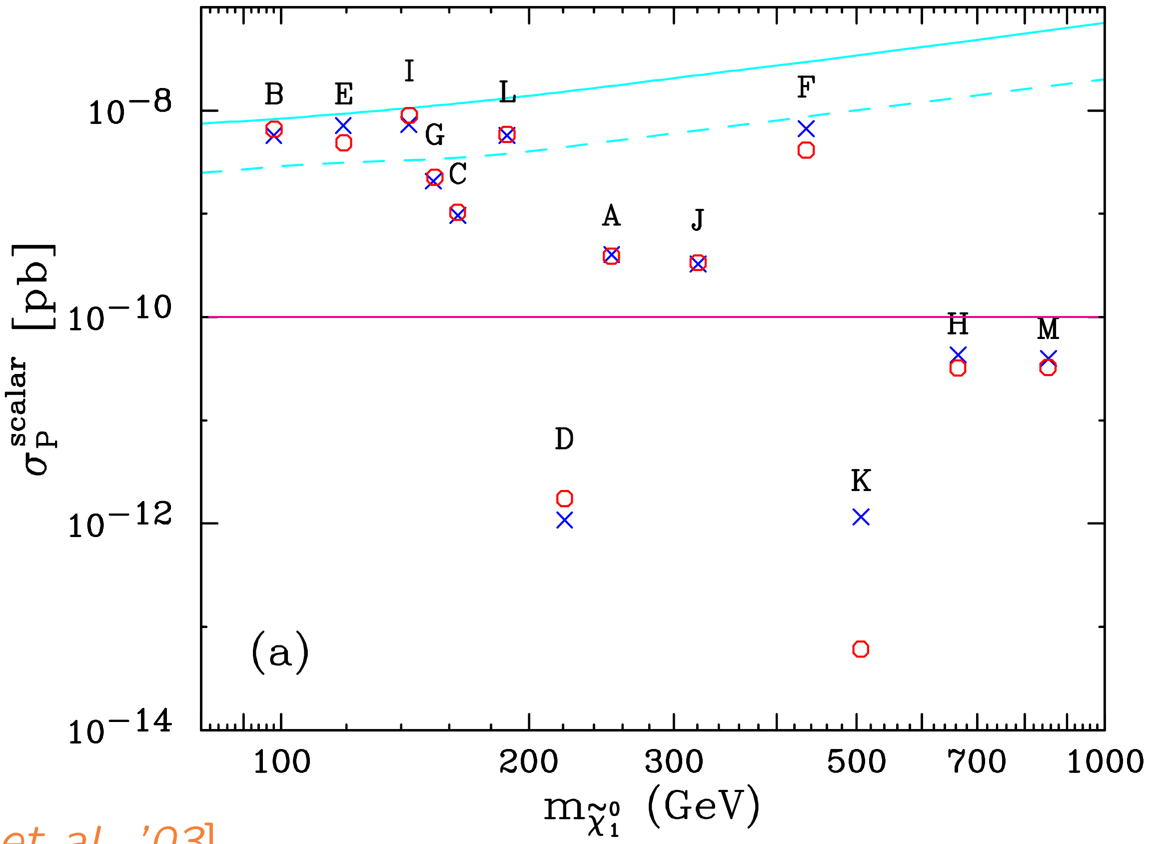



[*J. Ellis, K. Olive et al. '03*]

⇒ Projection for CDMS/CRESST and GERDA/GENIUS

(higher reach with other future experiments)

⇒ Several points can be tested in the near future

# B) Search for photons from DM annihilation: EGRET

DM annihilates (with each other) $\Rightarrow$ excess of photons

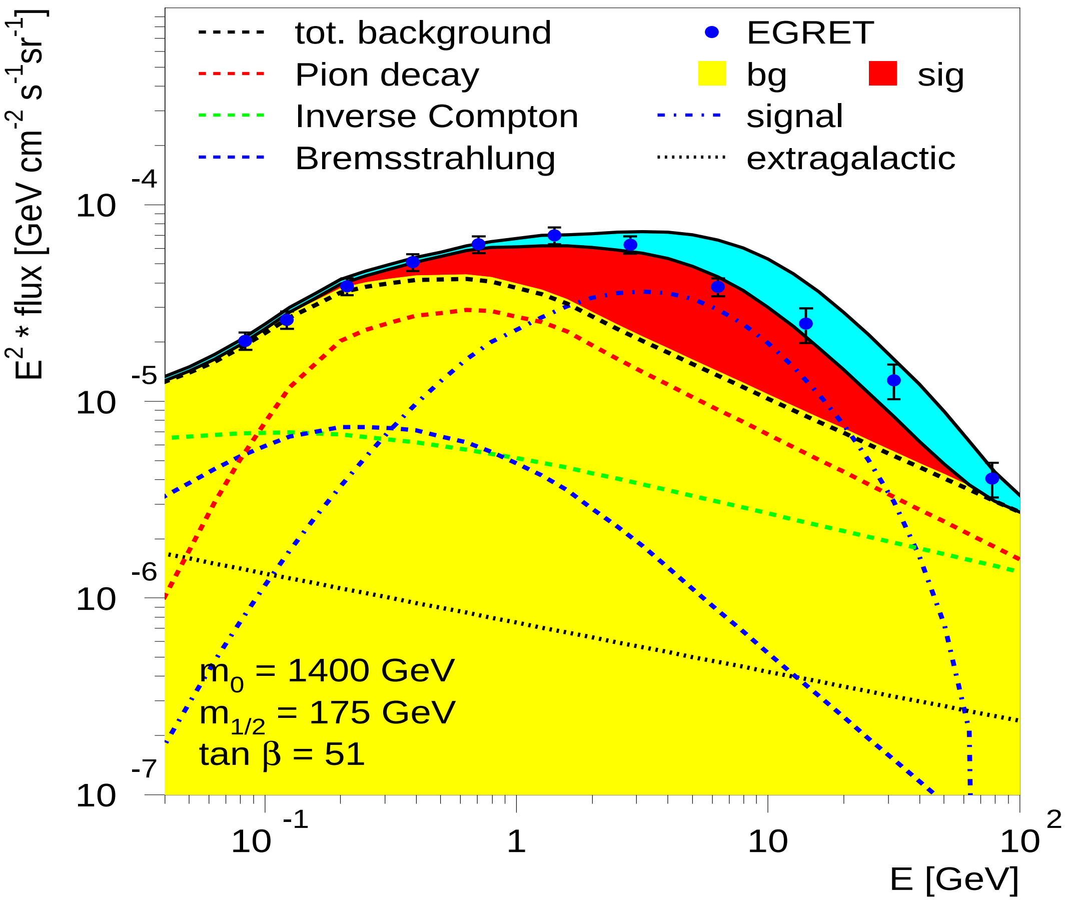
## Excess of photons within our galaxy?

[*de Boer et al. '04*]

Photon excess is fitted with
$\tilde{\chi}$ annihilation (SUSY!)

$\Rightarrow m_{\tilde{\chi}} \approx$ 65 GeV
CMSSM fits!

Background under control?
(extragalactic background ok)



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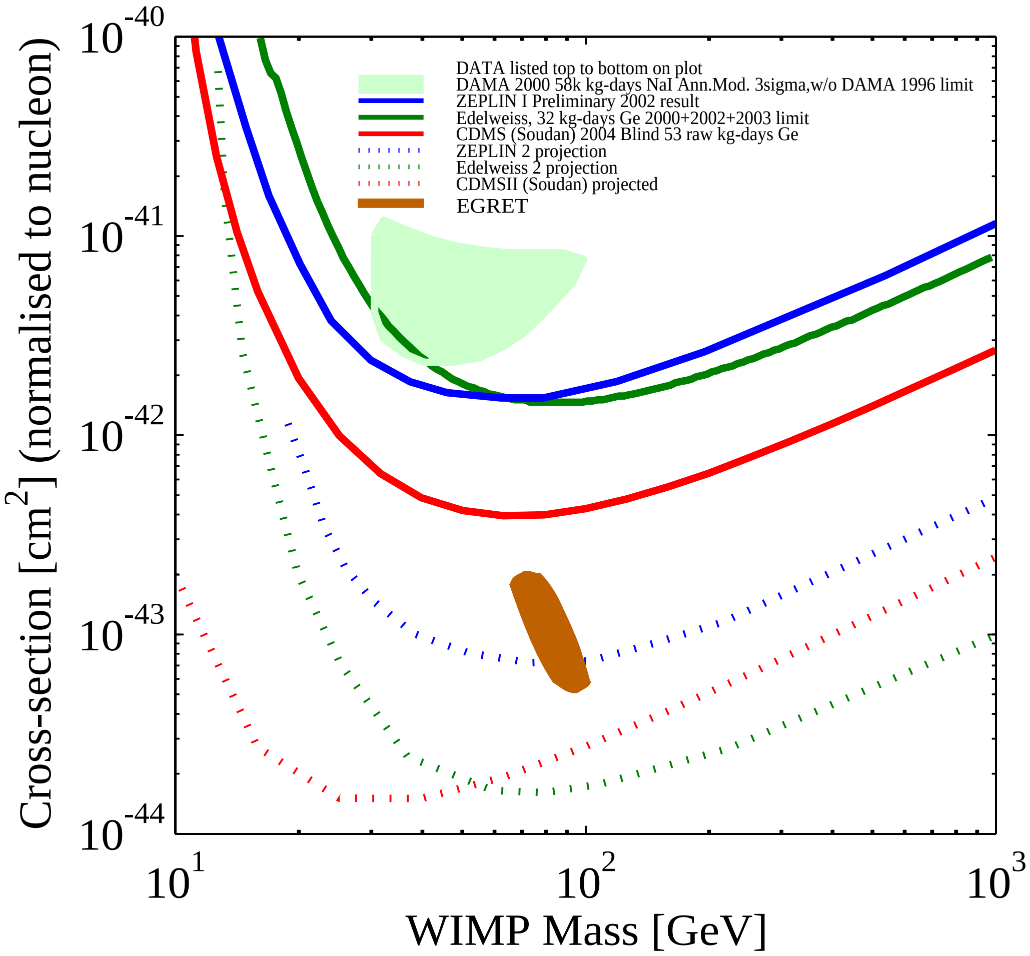

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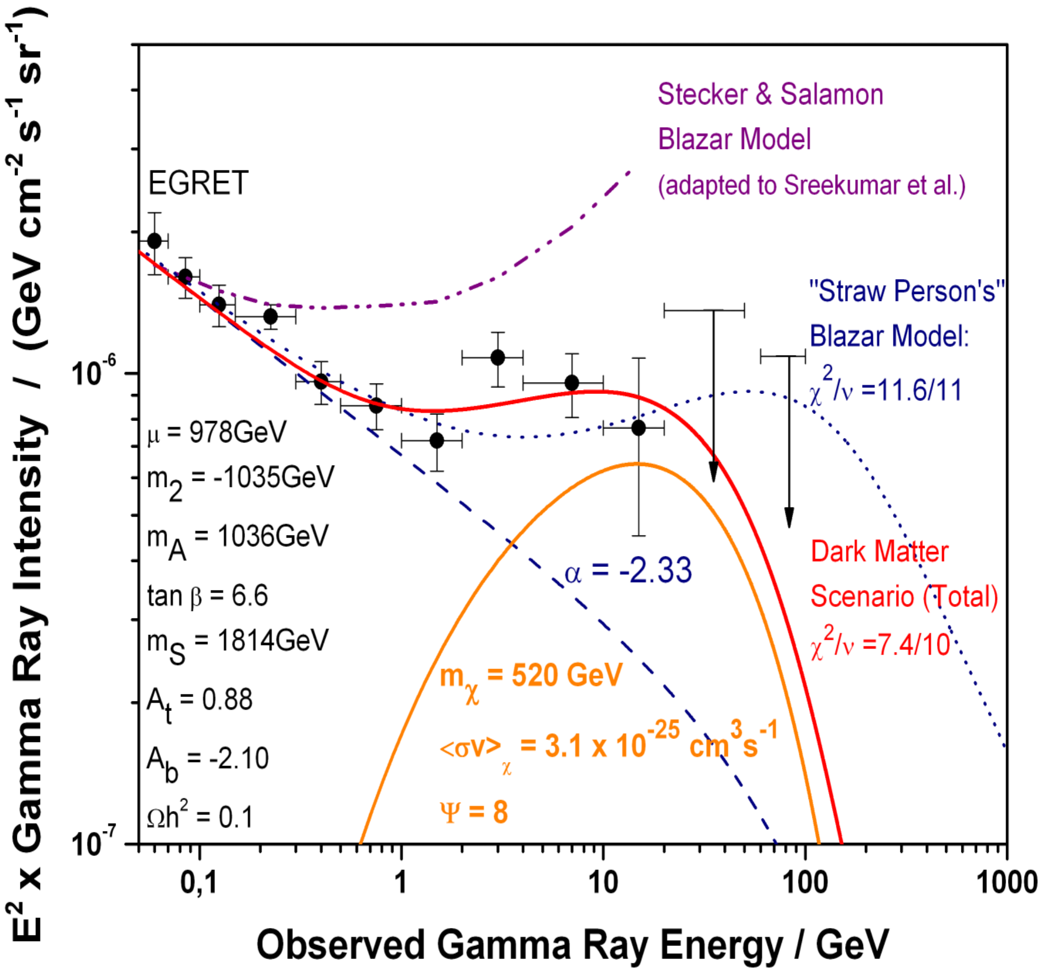
Excess of photons from outside of our galaxy?

[*D. Elsässer, K. Mannheim '05*]

Photon excess is fitted with
$\tilde{\chi}$ annihilation (SUSY!)

$\Rightarrow m_{\tilde{\chi}} \approx 520$ GeV

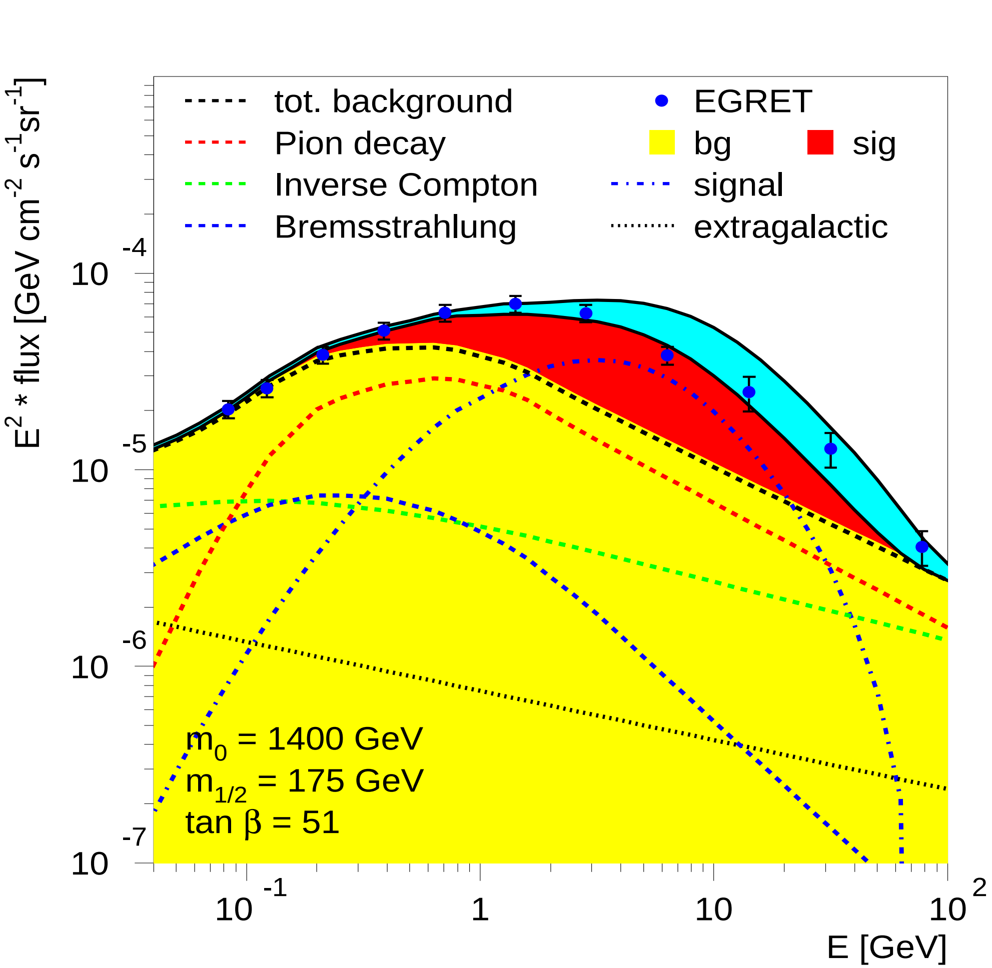
Background under control?
(Excess only in
extragalactic background)

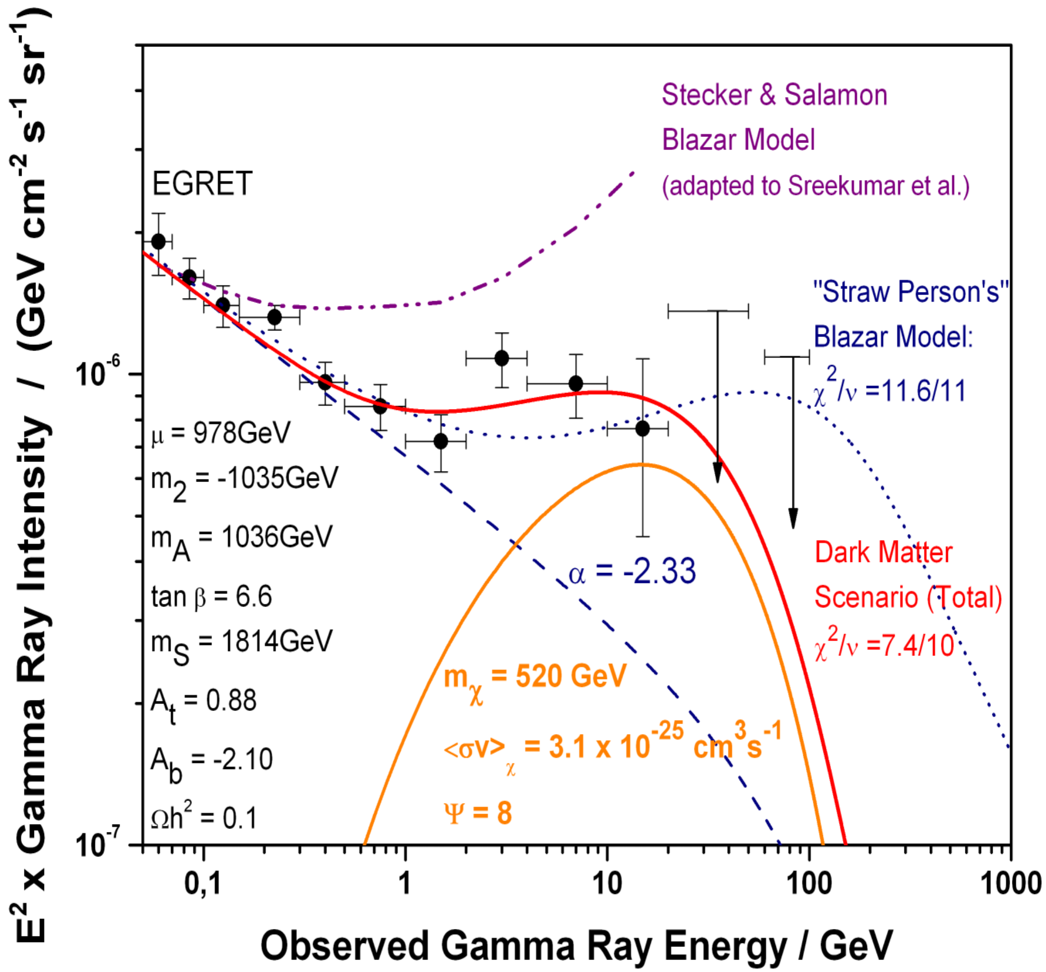


# B) Search for photons from DM annihilation: EGRET

DM annihilates (with each other) ⇒ excess of photons

Excess of photons inside/from outside of our galaxy?



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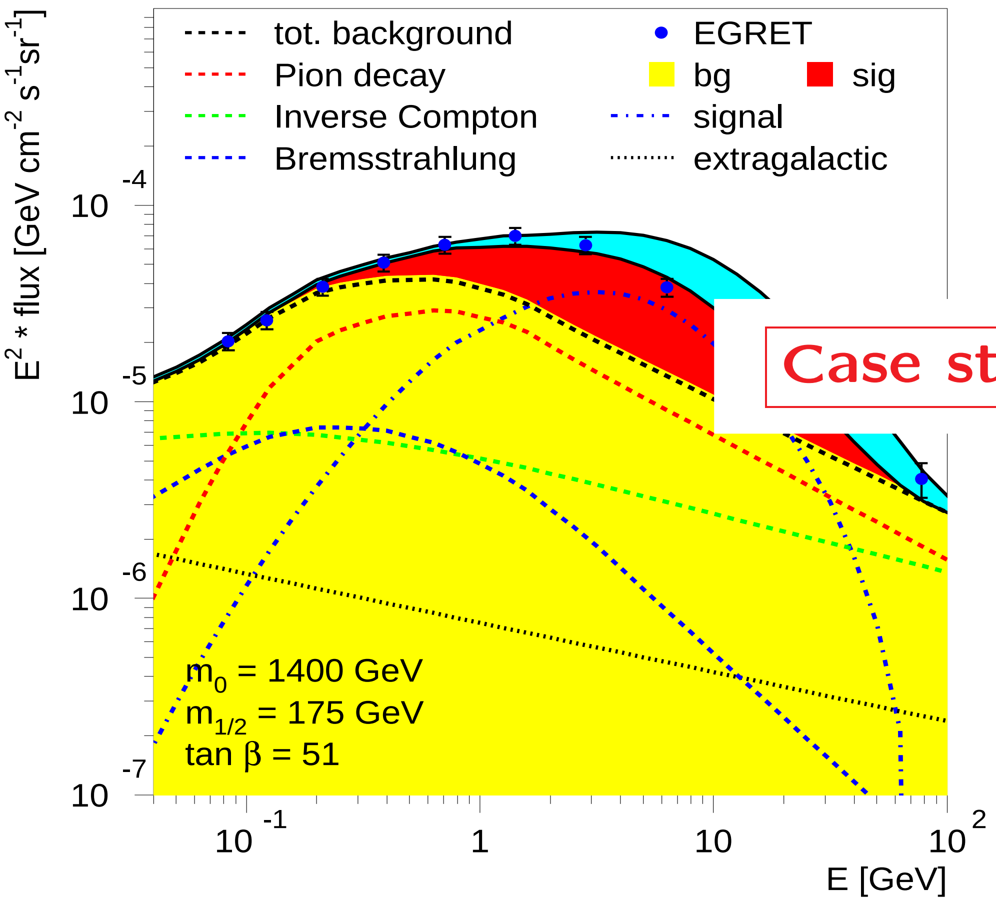


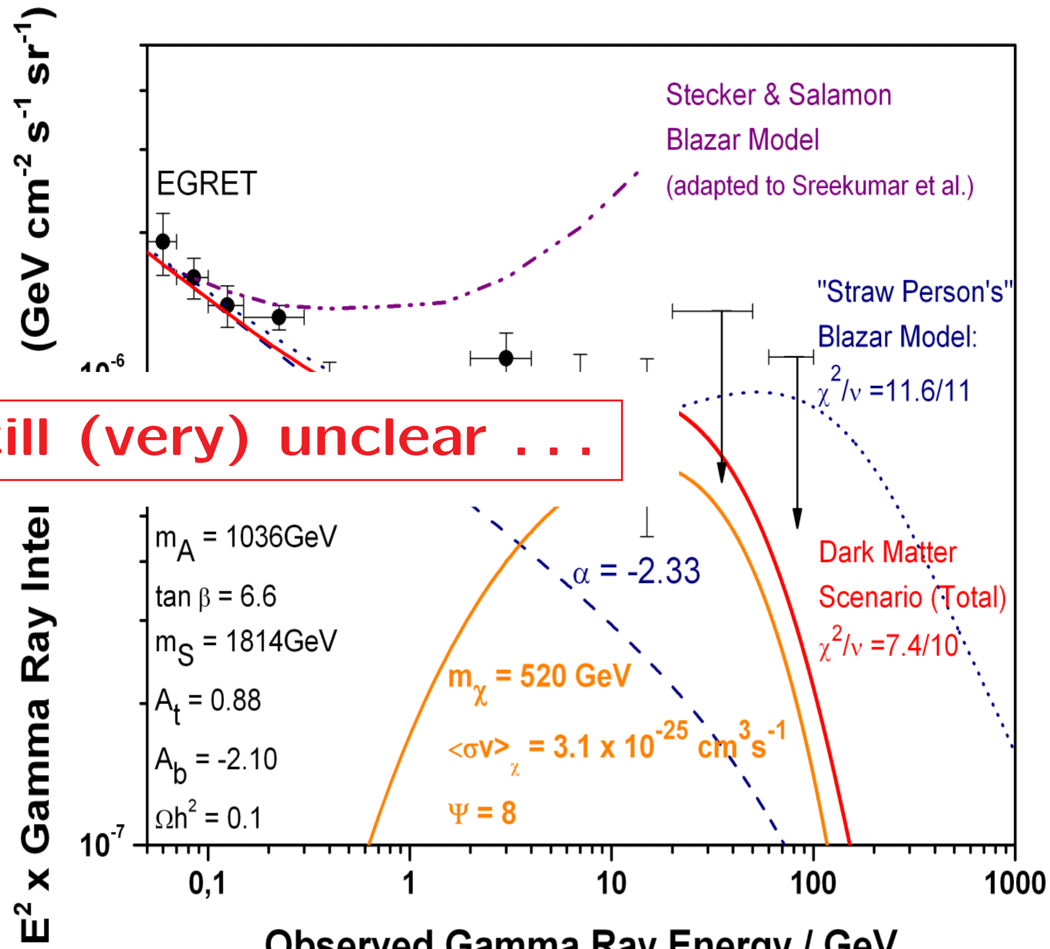


**Case still (very) unclear . . .**

# Outlook

- Low-energy Supersymmetry continues to be our best bet for physics beyond the Standard Model

- Data rules:

  We need experimental information from Tevatron, LHC, ILC,
  $\nu$ experiments, dark matter searches, low-energy experiments, . . .
  to verify / falsify our ideas about electroweak symmetry breaking,
  the Higgs, extensions of the SM, . . .

- The experiments in the next years will bring a decisive test of our ideas about low-energy SUSY and the Higgs

$\Rightarrow$ Very exciting prospects for the coming years

Expect the unexpected!

# 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