Determining tan(beta) at the Photon Collider

Physics at Future Colliders workshop
2005/2006

A.F.Żarnecki
30-11-2005

Outline:
- How to measure tan(beta)
- tau-tau fusion process at the Photon Collider
- First results from experimental study

Theories beyond the Standard Model (SM) that resolve the hierarchy and fine-tuning problems typically involve extensions of its single-doublet Higgs sector to at least a two-doublet Higgs sector (2HDM) [1]. The most attractive such model is the Minimal Supersymmetric Standard Model (MSSM), which contains a constrained two-Higgs-doublet sector [2]. In other cases, the effective theory below some energy scale is equivalent to a 2HDM extension of the SM with no other new physics. Searching for the Higgs particles and studying their properties have high priority for both theoretical and experimental activities in high energy physics.

Among other new parameters in 2HDM and SUSY theories, one is of particular importance: the ratio of the vacuum expectation values of the two Higgs fields, commonly denoted as $\tan\beta = v_2/v_1$. It characterizes the relative fraction that the two Higgs doublets contribute to the electroweak symmetry breaking $v^2 = v_1^2 + v_2^2$, where $v \approx 246$ GeV. The five physical Higgs states couple to the fermions at tree-level [1, 2] as

$$h\bar{t}t : -i\frac{m_t}{v}\frac{\cos\alpha}{\sin\beta} \approx -i\frac{m_t}{v} \qquad h\bar{b}b : i\frac{m_b}{v}\frac{\sin\alpha}{\cos\beta} \approx -i\frac{m_b}{v} \tag{1}$$

$$H\bar{t}t : -i\frac{m_t}{v}\frac{\sin\alpha}{\sin\beta} \approx i\frac{m_t}{v}\cot\beta \qquad H\bar{b}b : -i\frac{m_b}{v}\frac{\cos\alpha}{\cos\beta} \approx -i\frac{m_b}{v}\tan\beta \tag{2}$$

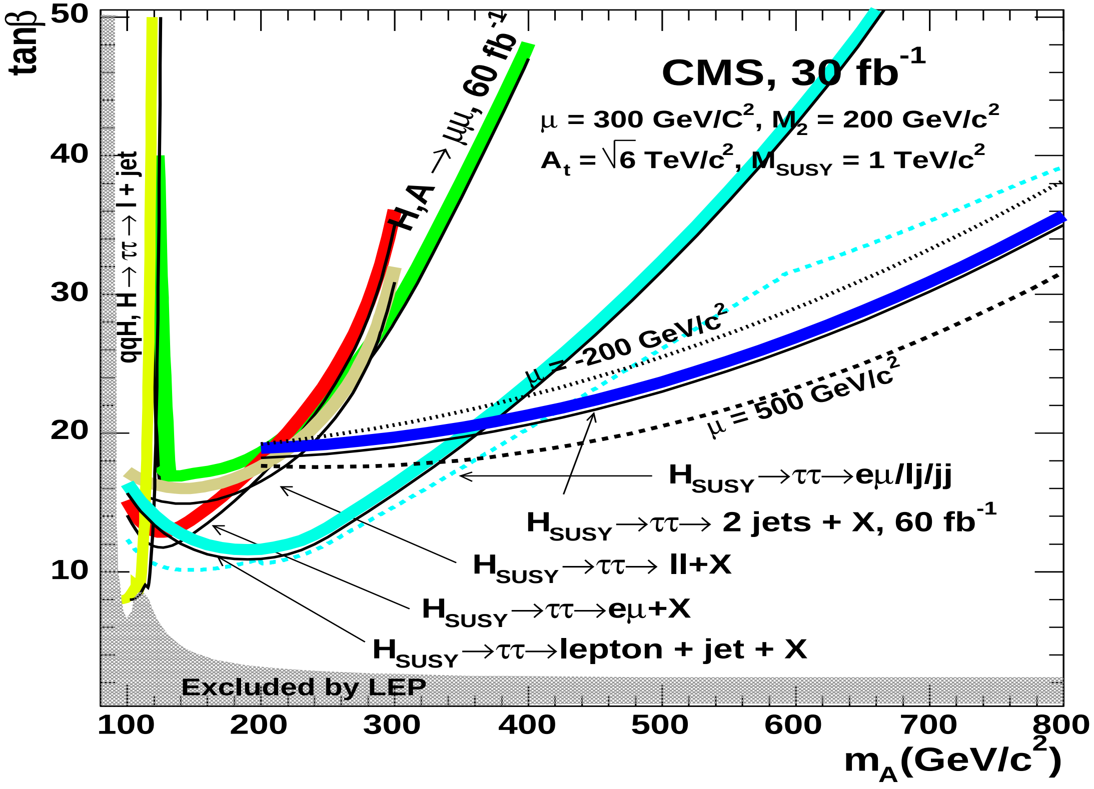
$$A\bar{t}t : -\frac{m_t}{v}\cot\beta\,\gamma_5 \qquad A\bar{b}b : -\frac{m_b}{v}\tan\beta\,\gamma_5 \tag{3}$$

$$H^+\bar{t}b : i\frac{V_{td}}{\sqrt{2}v}[m_b\tan\beta(1+\gamma_5) + m_t\cot\beta(1-\gamma_5)], \tag{4}$$

where α is the mixing angle in the CP-even sector, and the approximation indicates the decoupling limit for $m_A \gg m_Z$ in the MSSM [3, 4], in which the couplings of the light Higgs boson h become SM-like. Eqs. (2)–(4) show that $\tan\beta$ governs the coupling strength of Yukawa interactions between the fermions and the heavy Higgs bosons. In fact, heavy Higgs boson measurements sensitive to their Yukawa couplings are far and away the most *direct* way to probe the structure of the vacuum state of the model as characterized by the ratio of vacuum expectation values that defines $\tan\beta$.

5σ discovery contours

30 fb^{-1} at low luminosity (2×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
max m_h SUSY scenario



$H_{SUSY}\to\tau\tau\to X$ most promising channel for discovering heavy neutral MSSM Higgs boson at large tanβ

Uncertainty of $\tan\beta$ measurement

At large $\tan\beta$ $\sigma \sim \tan^2\beta \times X$, subleading $\tan\beta$ dependence small, can be absorbed into $\tan\beta_{eff}$

$$N_S = \tan^2\beta \times X \times L \times \varepsilon_{sel}$$

$$\tan\beta = \tan\beta_0 \pm \Delta stat \pm \Delta syst$$

Max error:

$$\Delta\tan\beta/\tan\beta = ½(\Delta N_S/N_S + \Delta L/L + \Delta X/X)$$

$$= ½(\mathrm{sqrt}(N_S+N_B)/N_S + \Delta L/L + \Delta X/X)$$

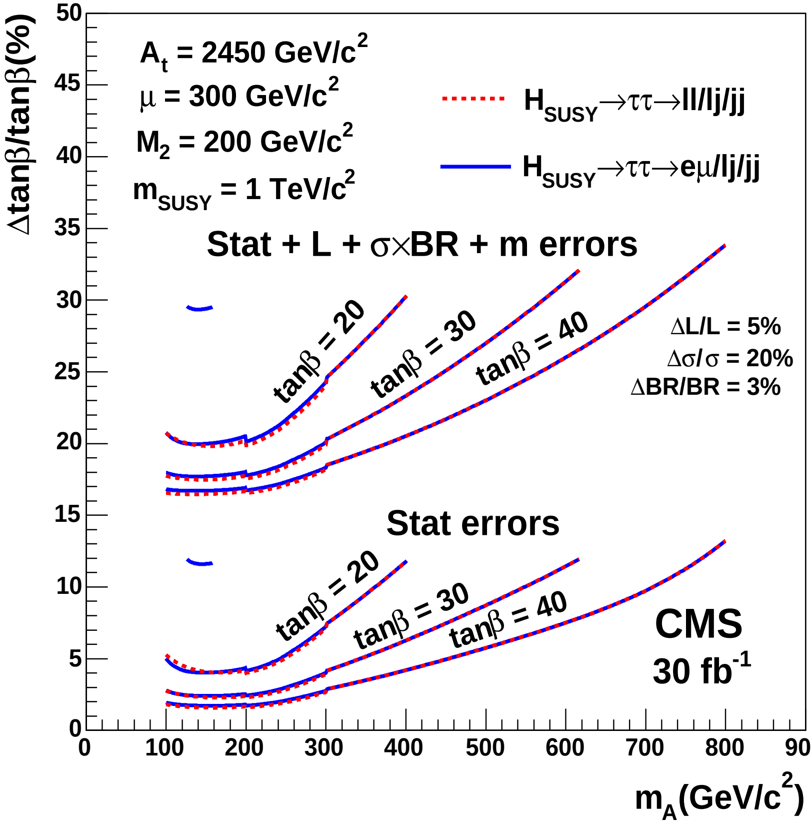
Luminosity error assumed $\Delta L/L \sim 5\%$

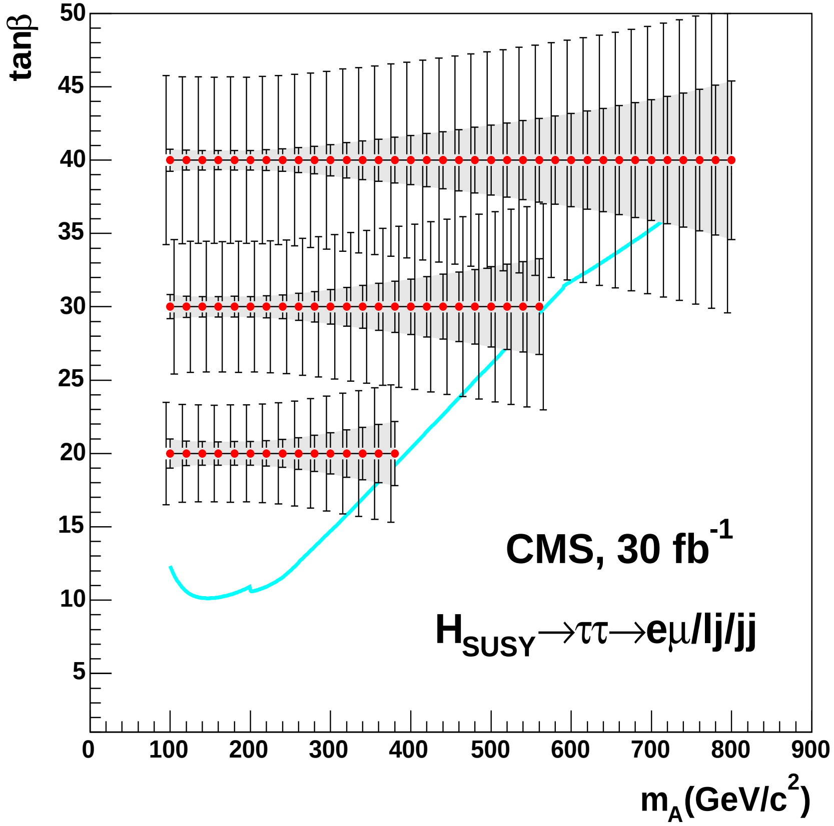
Theoretical error $\Delta\sigma/\sigma \sim 20\%$, $\Delta BR/BR \sim 3\%$

Uncertainties of the background and signal selection efficiency, and the accuracy of the SUSY parameter measurement not yet taken into account. (Uncertainty of the selection (s+b) efficiency expected ~5%)

Uncertainty of tanβ measurement

Small error bars (gray): stat error only
Large error bars: total error



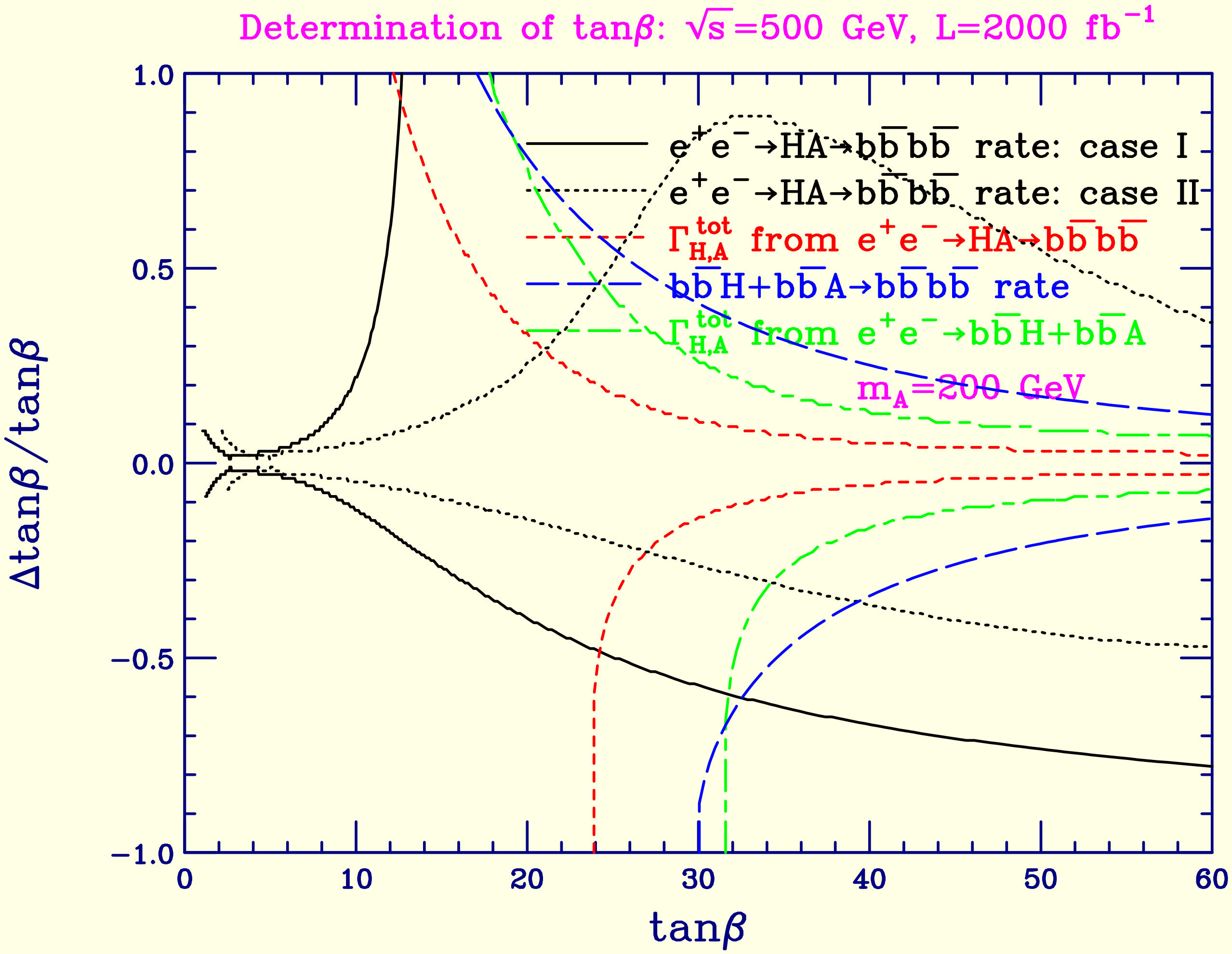


ILC

- Because of background and other issues, an e^+e^- collider with sufficient energy to pair produce non SM-like Higgs bosons, $e^+e^- \to H^0A^0$, is the ideal.
  - At low $\tan\beta$, look at $e^+e^- \to H^0A^0 \to b\overline{b}b\overline{b}$ rate.
    Rate varies as $b\overline{b}b\overline{b}$ branching ratio goes from modest level to being dominant.
    Presence of modest SUSY decays helps in that $b\overline{b}b\overline{b}$ rate varies significantly out to much larger $\tan\beta$ than if no SUSY decays are present.
  - At high $\tan\beta$, look at $\langle\Gamma_{\rm tot}^{H^0}, \Gamma_{\rm tot}^{A^0}\rangle$.
    Recall that the decay widths become dominated at high $\tan\beta$ by $b\overline{b}$ and $\tau^+\tau^-$, growing as $\tan^2\beta$.

- For heavier masses and/or only one light non-SM-like Higgs, $e^+e^- \to b\overline{b}H^0 \to b\overline{b}b\overline{b}$ and/or $e^+e^- \to b\overline{b}A^0 \to b\overline{b}b\overline{b}$ rate(s) do the job at high $\tan\beta$.

  Here, the rates are very sensitive to the $b\overline{b}A^0, b\overline{b}H^0$ Yukawa couplings that are proportional to $\tan\beta$.



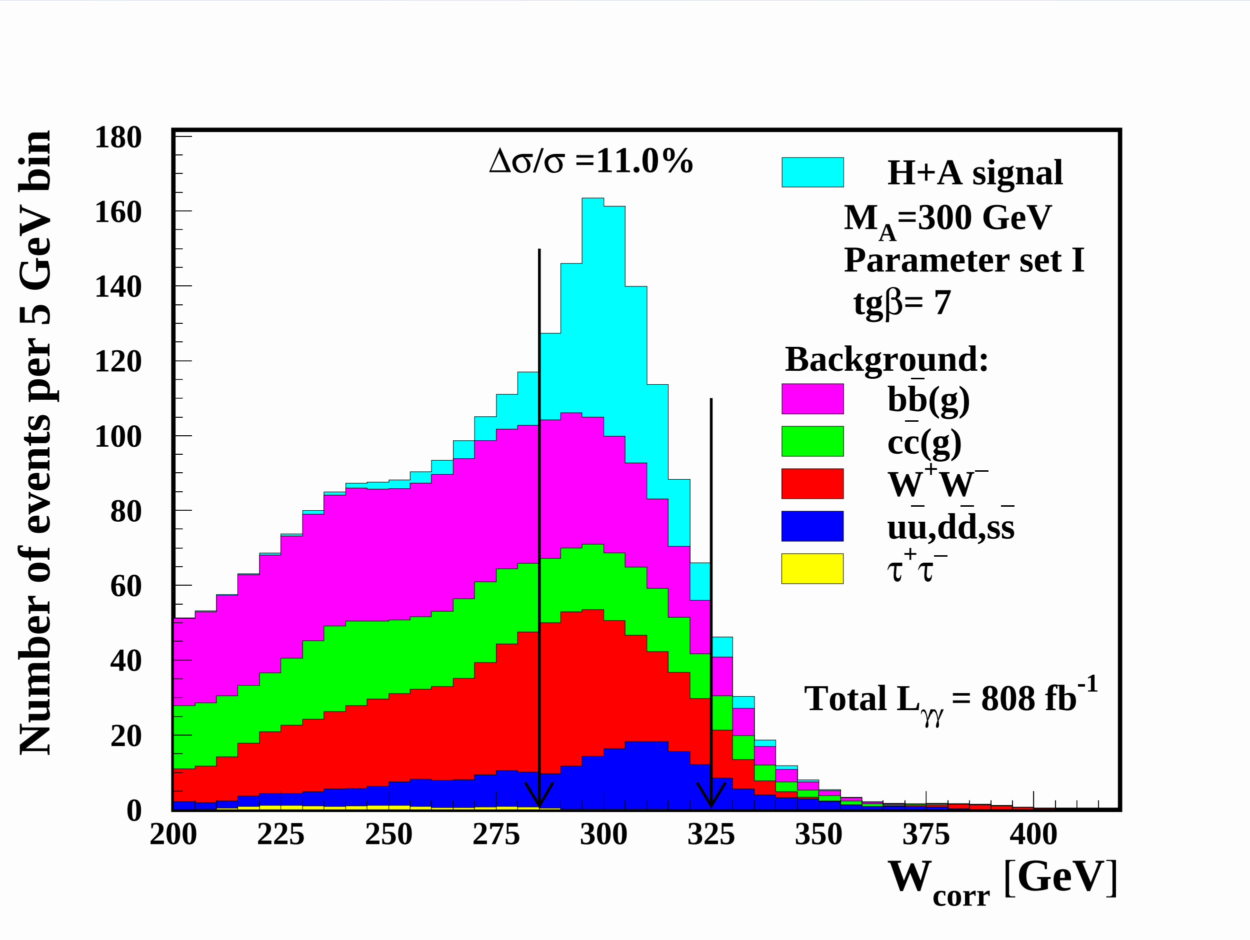
We see significant sensitivity of the $\tan\beta$ errors from $H^0A^0\to b\bar{b}b\bar{b}$ rates to the scenario choice, with the errors worse for scenario (I).

Errors for $\tan\beta$ from the $b\bar{b}H^0+b\bar{b}A^0\to b\bar{b}b\bar{b}$ rate are essentially independent of the scenario choice. Running m_b has big impact on these errors.

All results employ couplings and widths ala HDECAY.

$M_A = 300$ GeV

Final results



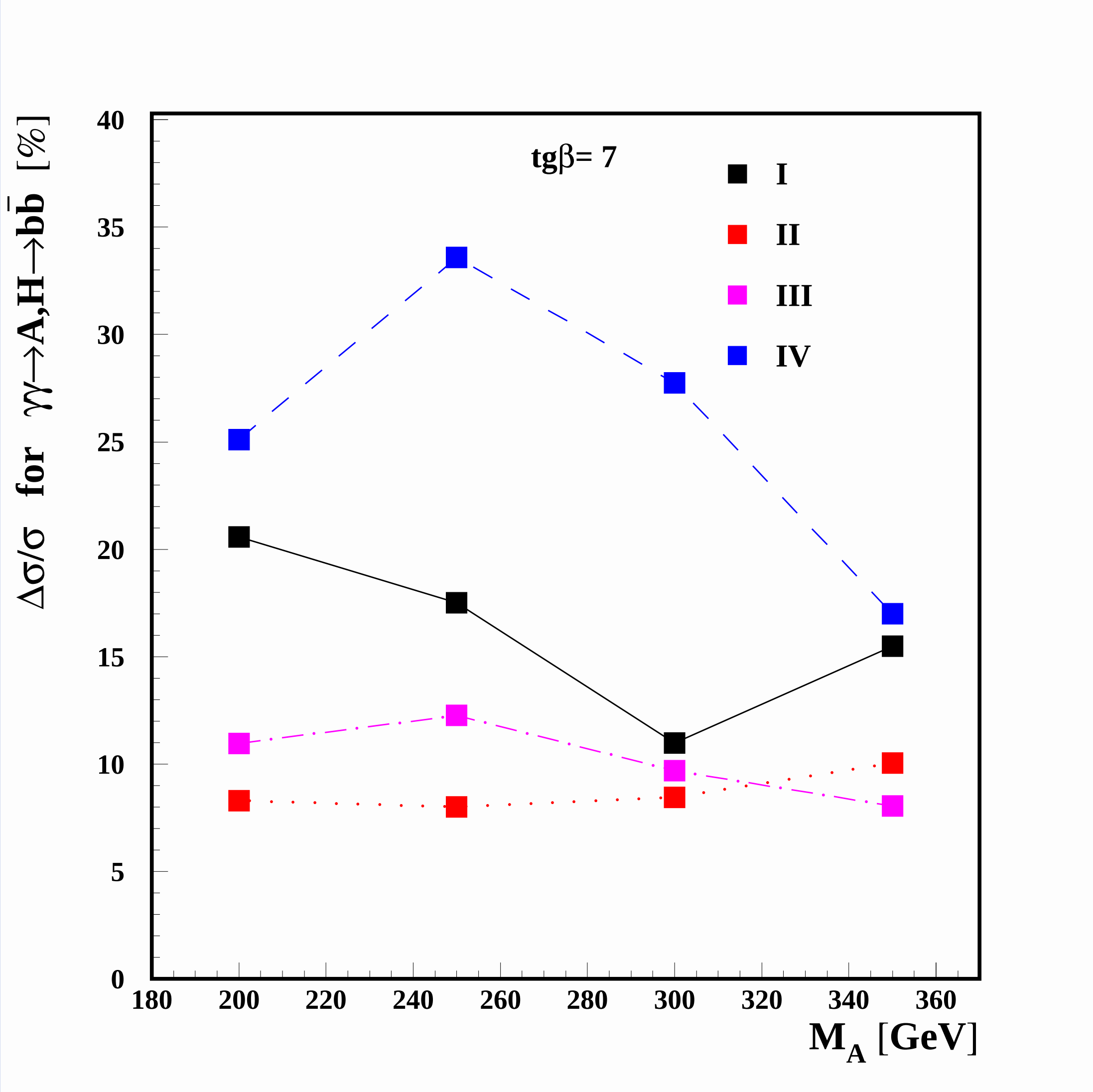
$\gamma\gamma \to hadrons$ (resolved) as a separate contribution – inefficient generation

$\Rightarrow$ we estimate number of events in the mass window

$\gamma\gamma \to q\bar{q}$ $(q = u, d, s)$ (unpolarized cross sec.) is overestimated
but compensates the lack of *resolved* contribution

Precision for $\sigma(\gamma\gamma \to A, H \to b\bar{b})$

$\Delta\sigma(\gamma\gamma \to A, H \to b\bar{b})/\sigma(\gamma\gamma \to A, H \to b\bar{b})$



Symbol	μ [GeV]	$A_{\tilde{f}}$ [GeV]
I	200	1500
II	-150	1500
III	-200	1500
IV	300	2450

Precision

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{\mu_S + \mu_B}}{\mu_S}$$

Testing the SPA project

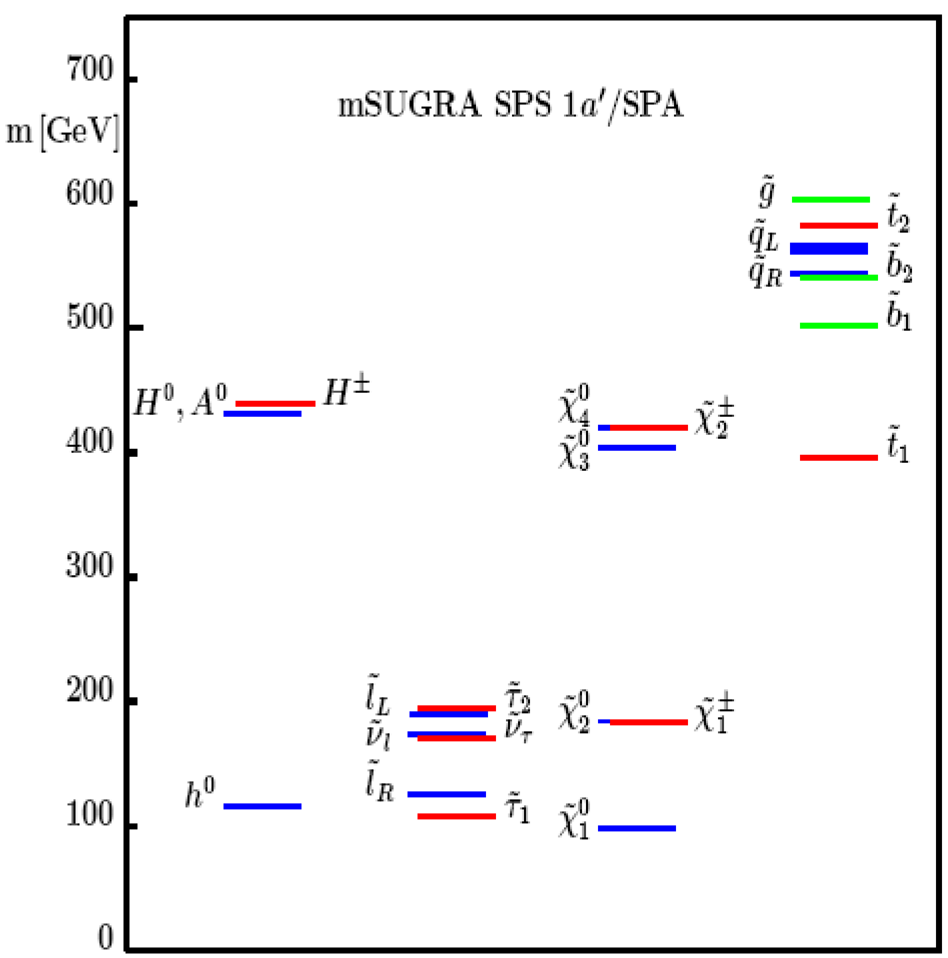
SUPERSYMMETRY PARAMETER ANALYSIS

- SPS1a'- derivative of the SPS1a point

mSUGRA values:

m_0	70 GeV
$m_{1/2}$	250 GeV
A_0	-300 GeV
$\tan\beta$	10
sign μ	$+$

$$BR(b \to s\gamma) = 3.0 \times 10^{-4}$$
$$\Delta[g_\mu - 2]/2 = 33 \times 10^{-10}$$
$$\Omega_{cdm} h^2 = 0.10$$



Susy parameter determination in combined analyses at LHC/LC

K. Desch, J. Kalinowski, G. Moortgat-Pick, M.M. Nojiri and G. Polesello

in Physics Interplay of the LHC and ILC hep-ph/0410364

The neutralino mixing matrix in the $\{\tilde{\gamma}, \tilde{Z}^0, \tilde{H}_1^0, \tilde{H}_2^0\}$ basis is given by

$$\mathcal{M}_N = \begin{pmatrix} M_1 \cos^2_W + M_2 \sin^2_W & (M_2 - M_1) \sin_W \cos_W & 0 & 0 \\ (M_2 - M_1) \sin_W \cos_W & M_1 \sin^2_W + M_2 \cos^2_W & m_Z & 0 \\ 0 & m_Z & \mu \sin 2\beta & -\mu \cos 2\beta \\ 0 & 0 & -\mu \cos 2\beta & -\mu \sin 2\beta \end{pmatrix} \quad (5.44)$$

The neutralino eigenvectors and their masses are obtained with the 4×4 diagonalisation matrix N:

$$N^* \mathcal{M}_N N^\dagger = \tilde{f} diag\{m_{\tilde{\chi}_1^0}, \ldots, m_{\tilde{\chi}_4^0}\} \quad (5.45)$$

LHC

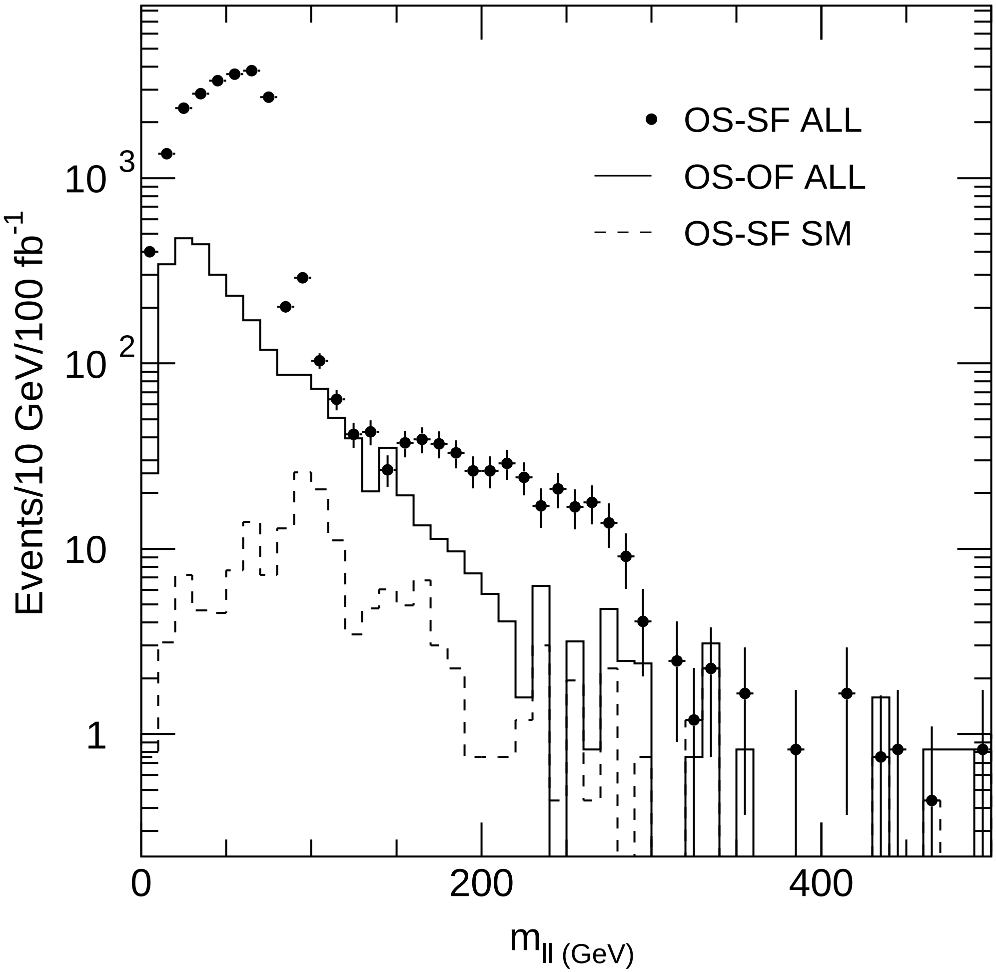


Figure 5.38: *Invariant mass spectrum respectively for: Opposite-Sign Same-Flavour (OS-SF) leptons total (full dots), Opposite-Sign Opposite-Flavour (OS-OF) leptons total (solid line), Opposite-Sign Same-Flavour leptons in the SM (dashed line). The signals of* $\tilde{\chi}^0_2$, $\tilde{\chi}^0_4$ *consist of OS-SF leptons [45].*

b) Joint analysis of the LC and LHC data

SUSY Parameters				Mass Predictions	
M_1	M_2	μ	$\tan\beta$	$m_{\tilde{\chi}^\pm_2}$	$m_{\tilde{\chi}^0_3}$
99.1 ± 0.2	192.7 ± 0.5	352.4 ± 4.5	10.2 ± 0.9	378.5 ± 4.1	358.8 ± 4.1

Table 5.22: *SUSY parameters with 1*σ *errors derived from the analysis of the LC data collected at the first phase of operation and with* $\delta m_{\tilde{\chi}^0_4} = 5.1$ *GeV from the LHC. Shown are also the predictions for the masses of* $\tilde{\chi}^\pm_2$ *and* $\tilde{\chi}^0_3$.

Methods to determine $\tan\beta$ for large values beyond $\tan\beta = 10$

(a) charginos / neutralinos	$\Rightarrow$ $\cos 2\beta$ slope $\sim 1/\tan^3\beta$ insensitive	Choi et al
(b) τ polarization etc	$\Rightarrow$ $\sim 10\%$	Boos et al
(c) $bbH/A, H/A$ widths etc	$\Rightarrow$ LHC/$300 fb^{-1}$: 12 to 4%	Gunion et al
	$\Rightarrow$ LC/$2,000 fb^{-1}$: 5 to 3% at $M_A = 200$GeV	
(d) LHC sim $H/A \to \tau\tau$	$\Rightarrow$ $30 fb^{-1}$ $\sim 20\%$	Kinnunen et al
(e) $\gamma\gamma \to H/A \to b\bar{b}$	$\Rightarrow$ ~ 4 to 10% [estimate]	see: Niezurawski et al and Velasco et al

Additional methods strongly required for precision analysis of $\tan\beta$

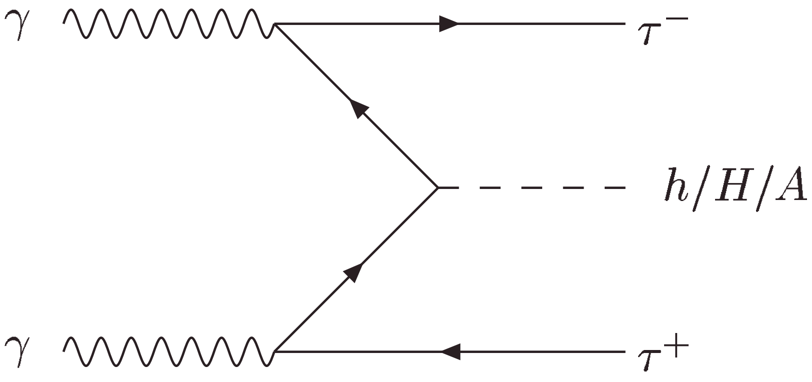
Determining $\tan\beta$ in $\tau\tau$ Fusion to SUSY Higgs Bosons at a Photon Collider

S.Y.Choi, J.Kalinowski, J.S.Lee, M.M.Mühlleitner, M.Spira,
P.M.Zerwas

hep-ph/0404119

New method: Tauon fusion of Higgs $h/H/A/$ at $\gamma\gamma$ collider:

$$\gamma\gamma \to (\tau^+\tau^-)(\tau^+\tau^-) \to \tau^+\tau^- + h/H/A$$



couplings: for large $\tan\beta$

$$\begin{array}{lll} A\tau\tau = \tan\beta, \ H\tau\tau \simeq \tan\beta & \text{for } A, H & \text{heavy} \\ h\tau\tau \simeq \tan\beta & A & \text{light} \end{array}$$

Higgs decays: $h/H/A \to bb$ at 90% level $\Rightarrow$ SPS1b

SIGNAL: in equivalent-particle approximation

$$\sigma_{\gamma\gamma} \approx 2 \int dx_1 D_{\tau/\gamma}(x_1) \int dx_2 D_{\tau/\gamma}(x_2) \times \hat{\sigma}[\tau\tau \to \Phi; \hat{s} = x_1 x_2 s]$$

fusion coss-section:

$$\hat{\sigma}[\tau\tau \to \Phi; \hat{s}] \approx \frac{\pi m_\tau^2}{2v^2} \tan^2\beta \, \frac{m_\Phi \Gamma_\Phi/\pi}{(\hat{s}-m_\Phi^2)^2 + m_\Phi^2 \Gamma_\Phi^2}$$

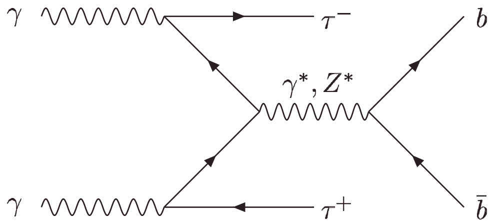
splitting function $\gamma \to \tau$:

$$D_{\tau/\gamma}(x) = \frac{\alpha}{2\pi}[x^2 + (1-x)^2] \log\left(\frac{m_\Phi^2}{m_\tau^2}\right)$$

$\gamma\gamma$ cross section [narrow-width approximation]:

$$\sigma_{\gamma\gamma} \approx \frac{\pi m_\tau^2}{2v^2 s} \tan^2\beta \times 2 \int_\tau^1 \frac{dx}{x} D_{\tau/\gamma}(x) D_{\tau/\gamma}(\tau/x) \quad \text{with} \quad \tau = M_\Phi^2/s$$

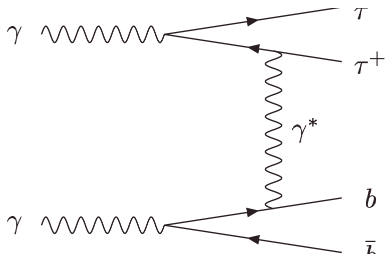
BKGDs: annihilation: $\tau^+\tau^- \to b\bar{b}$ and $b\bar{b} \to \tau^+\tau^-$ via γ, Z:



suppressed $\sim g^2$, except: $M_{bb} \sim M_Z$

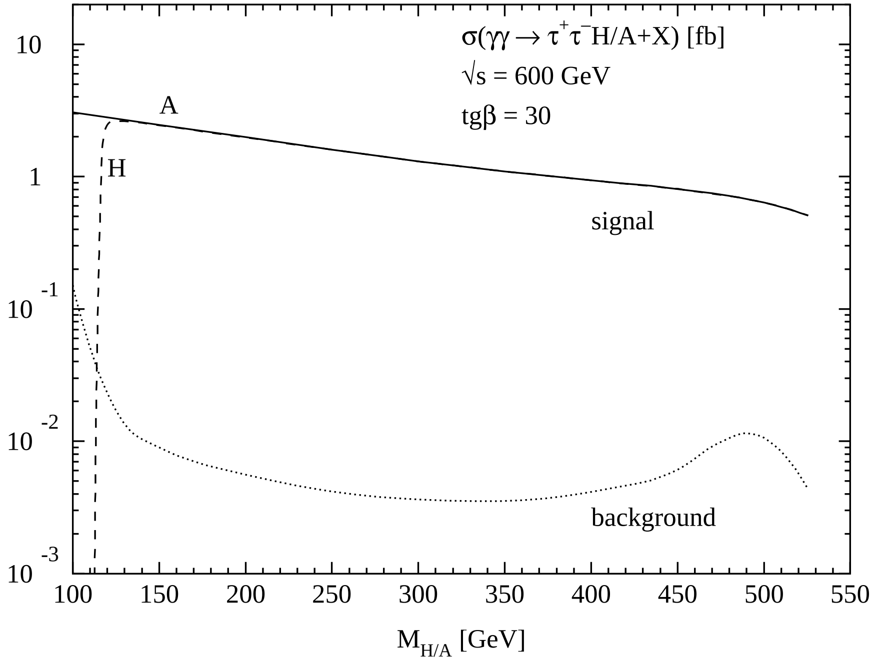
$M_{\tau\tau} \sim M_Z$

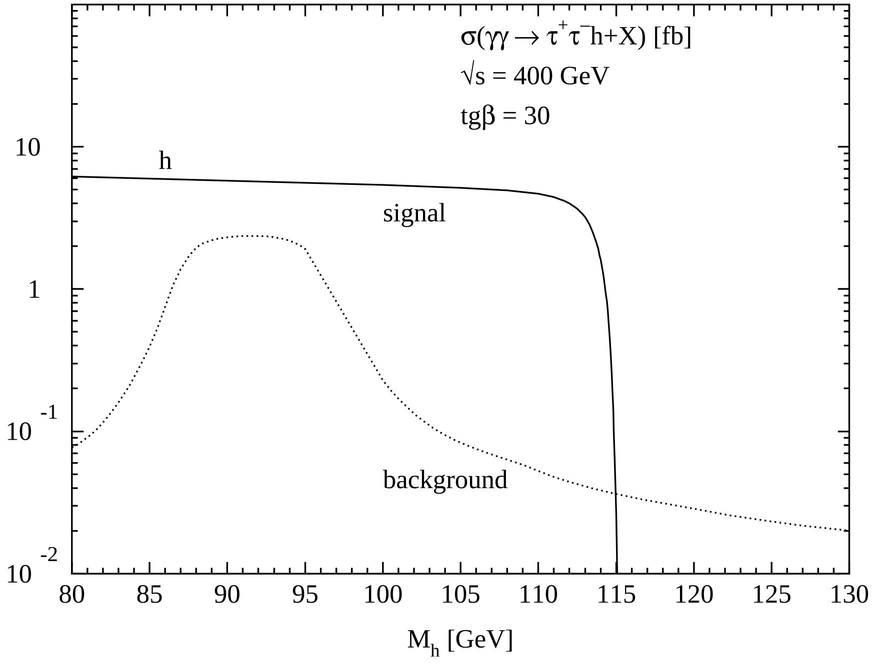
diffractive: $\gamma\gamma \to (\tau\tau)(bb)$:



suppr. by event topology: $\tau\tau$ small inv mass / same direction

bb ditto / close to γ axes


σ(γγ → τ⁺τ⁻H/A+X) [fb]
√s = 600 GeV
tgβ = 30
A
H
signal
background
10
1
10 -1
10 -2
10 -3
100
150
200
250
300
350
400
450
500
550
M_H/A [GeV]


σ(γγ → τ⁺τ⁻h+X) [fb]
√s = 400 GeV
tgβ = 30
h
signal
background
10
1
10 -1
10 -2
80
85
90
95
100
105
110
115
120
125
130
M_h [GeV]

ANALYSIS:

signal: including Higgs-bremsstrahlung off external legs

$$\gamma\gamma \to \tau\tau + h/H/A[\to bb]$$

bkgds: all non-Higgs 4-particle final states in $\gamma\gamma \to (\tau\tau)(bb)$

calculated by means of CompHEP

cuts: $M_{bb} = M_\Phi \pm \Delta$ with $\Delta = max[\Gamma_\Phi/2, \Delta_{ex}] \to \Delta_{ex} = 0.05 \times M_\Phi$

τ polar angle $\geq$ 130 mrad [shielding: dead mask]

τ energy $\geq$ 5 GeV

τ^+ and τ^- in opposite directions along beam axis

efficiencies: $\epsilon_{bb} \sim 0.7$ and $\epsilon_{\tau\tau} \sim 0.5 \to \epsilon \sim 0.35$

RESULTS: $E_{e^-e^-} = 800/500$ GeV $\Rightarrow$ $E_{\gamma\gamma} = 600/400$ GeV

$\mathcal{L} = 200/100\ \text{fb}^{-1}$

(a) Cross sections $h/H/A$: for $\tan\beta = 10$ to 50

$\sigma(H/A) = 3$ to 1 fb for $M_{A/H} = 100$ to 500 GeV at $\tan\beta = 30$

$\sigma(h) = 5$ fb for $M_h = 110$ GeV at $\tan\beta = 30$

(b) Errors ⇐ matching and improving on alternative methods:

	$E_{\gamma\gamma} = 400$ GeV, $\mathcal{L} = 100\ \text{fb}^{-1}$			$E_{\gamma\gamma} = 600$ GeV, $\mathcal{L} = 200\ \text{fb}^{-1}$				
M_{Higgs} [GeV]	$A \oplus h$ 100	$A \oplus H$ 200	300	$A \oplus h$ 100	$A \oplus H$ 200	300	400	500
$\tan\beta$	I	II	III	IV	V	VI	VII	VIII
10	8.4%	10.7%	13.9%	8.0%	9.0%	11.2%	13.2%	16.5%
30	2.6%	3.5%	4.6%	2.4%	3.0%	3.7%	4.4%	5.3%
50	1.5%	2.1%	2.7%	1.5%	1.8%	2.2%	2.6%	3.2%

SUMMARY:

$$\boxed{\begin{array}{c}\Delta\tan\beta \simeq 0.9 \text{ to } 1.3 \text{ uniform in } \tan\beta \\ \text{for all } M_A \text{ up to kin. limit}\end{array}}$$

Results are encouraging enough to start experimental simulations including detector effects, overlaying events, optimized cuts, etc.

First Results from an Experimental Study of $\tan\beta$ Measurement in $\tau\tau$ Fusion Process

J. Brodowska
with A.F. Żarnecki and P. Nieżurawski
Warsaw University

Outline

- Motivation
- Generator level results
- Detector level results

Event generation

Signal events $\gamma\gamma \rightarrow \tau\tau h \rightarrow \tau\tau b\bar{b}$
and background events $\gamma\gamma \rightarrow \tau\tau b\bar{b}$ (excluding h exchange)
were generated using CompHEP 33.23 (A.Pukhov et al. hep-ph/9908288)

Realistic luminosity spectra for Photon Collier was included with CompAZ
(A.F.Zarnecki, Acta Phys.Polon. B34 (2003) 2741)

Photon polarization was taken into account.

For $\sqrt{s_{ee}} = 500$ GeV, integrated luminosity expected after one year is 1000 fb^{-1}

About 130 fb^{-1} in the high energy peak ($W_{\gamma\gamma} > 300$ GeV)

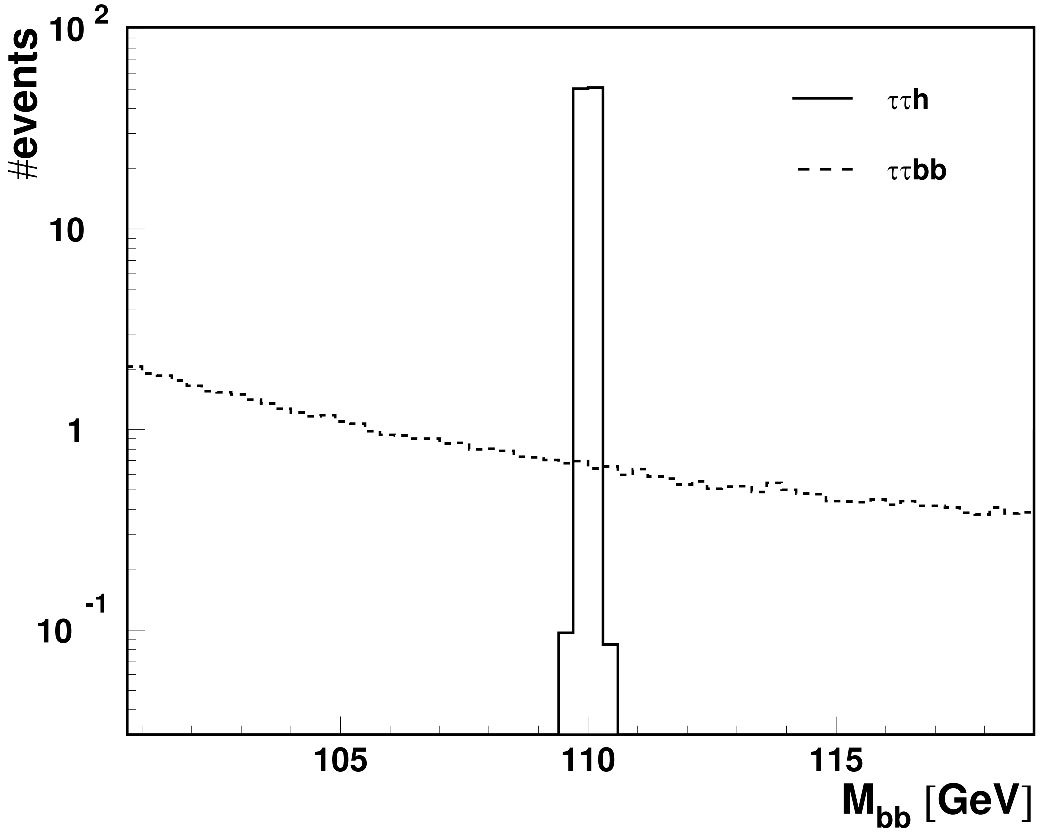
Cuts imposed on generator level:

- $b\bar{b}$ invariant mass $80 < M_{bb} < 150$ GeV
- For both τ: energy $E_{\tau} > 5$ GeV
- For all particles: production angle $|\cos\theta| < 0.99156$ (130 mrad)

Generator level results

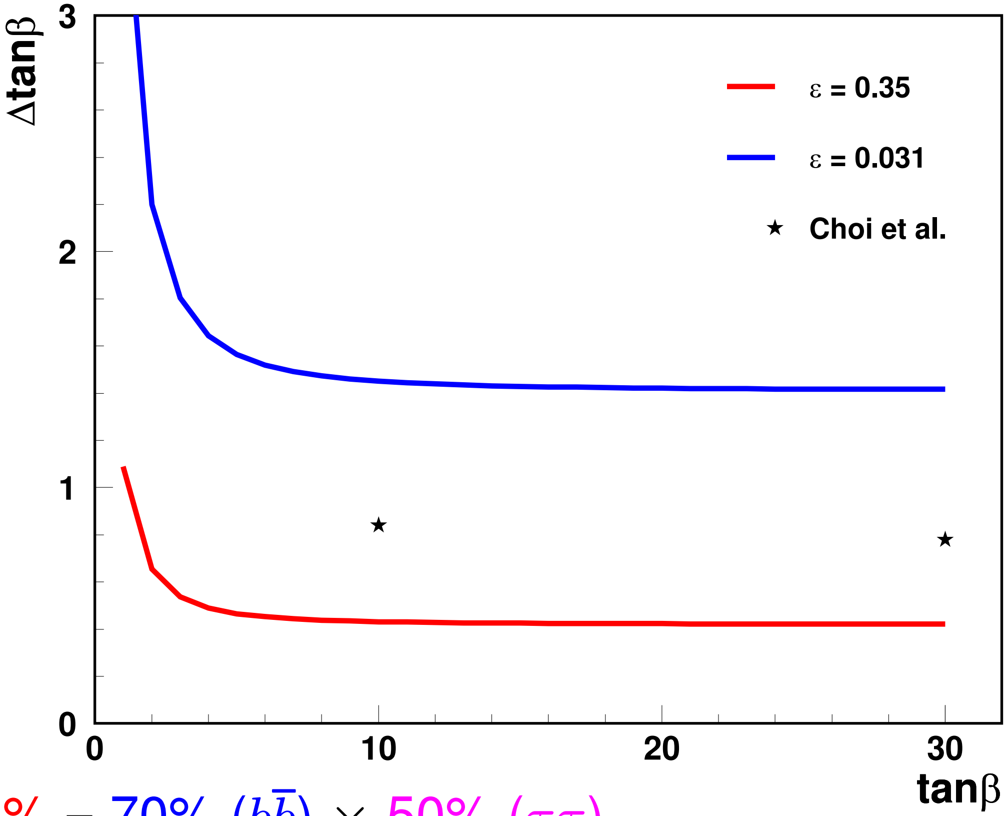
Invariant mass distribution on generator level

$M_h = 110$ GeV, $\tan\beta = 5$



Generator level results

From number of events reconstructed in the ±5 GeV mass window:



Cross section for M_h =110 GeV and $\tan\beta = 30$

$$\sigma(\gamma\gamma \rightarrow \tau\tau h \rightarrow \tau\tau b\bar{b}) \approx 3.6 fb$$

about 25% lower than or monochromatic beam, but total luminosity is an order of magnitude higher !

35% = 70% ($b\bar{b}$) × 50% ($\tau\tau$)

3.1% = 70% ($b\bar{b}$) × 70% ($\tau\tau$) $\times BR^2(\tau \rightarrow l\nu\bar{\nu})$

Experimental analysis

The analysis follows the approach developed in $\gamma\gamma \to h \to b\bar{b}$ analysis.

$\Rightarrow$ for details see: P.Niezurawski, hep-ph/0503295.

Experimental details taken into account:

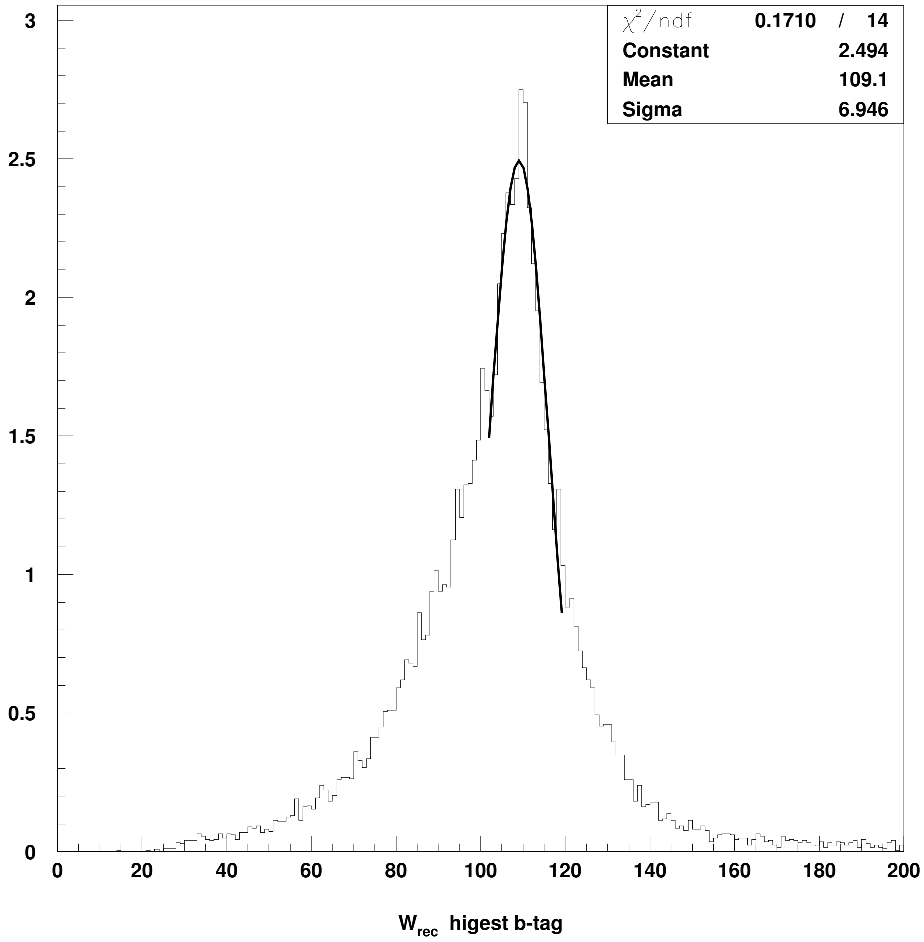
- crab-wise crossing of the beams, $\theta_c =$ 34 mrad
- primary vertex distribution
- overlaying events $\gamma\gamma \to hadrons$ (OE)
  generated with PYTHIA using realistic $\gamma\gamma$-luminosity spectrum (V. Telnov)

- Description of detector performance: Simdet 4.01
- ZVTOP-B-HADRON-TAGGER package used for b-tagging
- Jets reconstructed using Durham algorithm

Event selection

Reconstructed invariant mass of two b-tagged jets (M_h= 110 GeV, $\tan\beta = 10$)

Tag value $P_b > 0.6$ and $|cos\theta_j| < 0.75$



Selection efficiency $\sim$ 20% only !

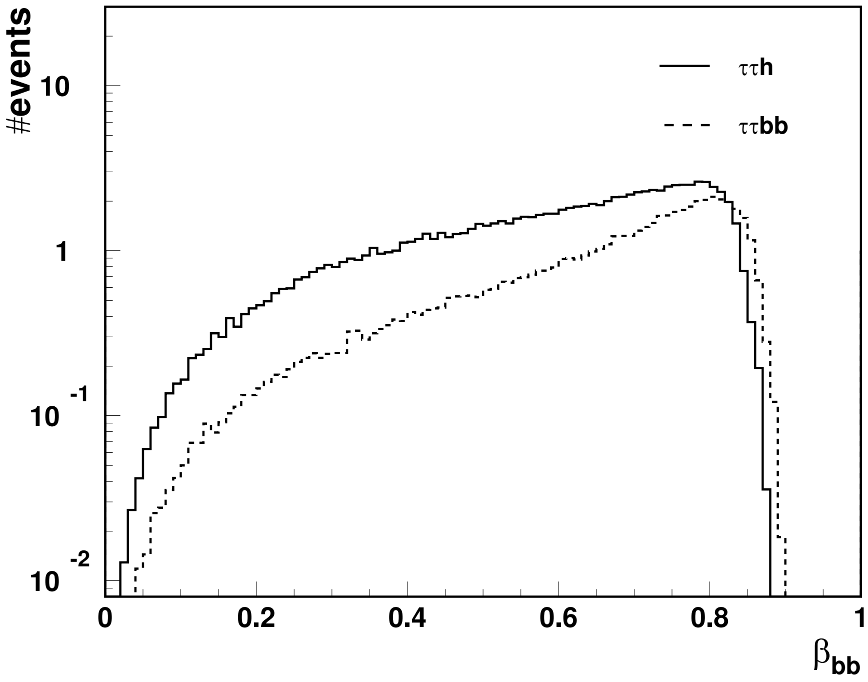
Mainly due to large boost of $b\bar{b}$ system

Mass resolution affected by

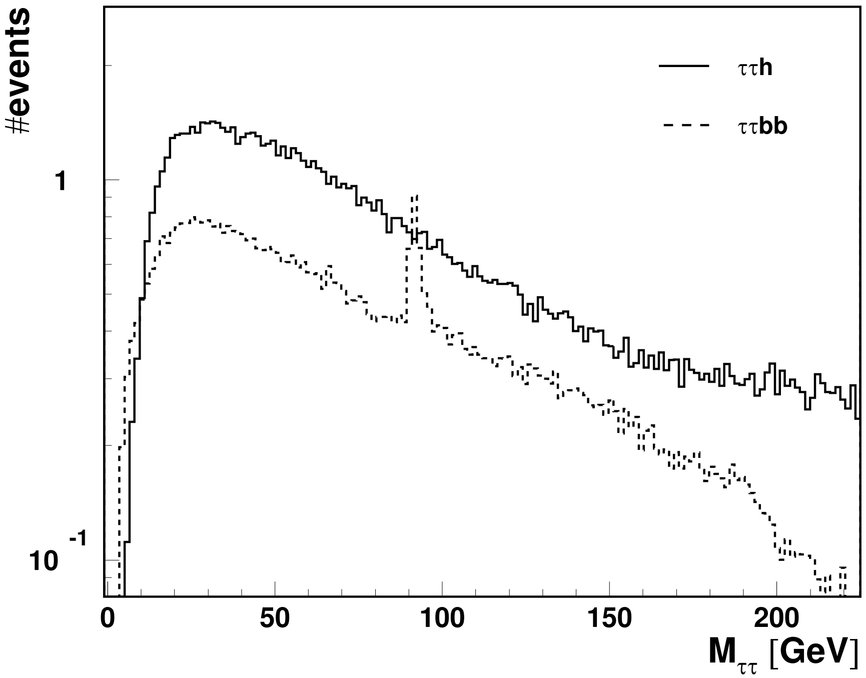
- boost of $b\bar{b}$ system
- overlying events
  (2 per bunch crossing, on average)
- escaping neutrinos
  from semi-leptonic b decays

Generator level results

Boost of $b\bar{b}$ system



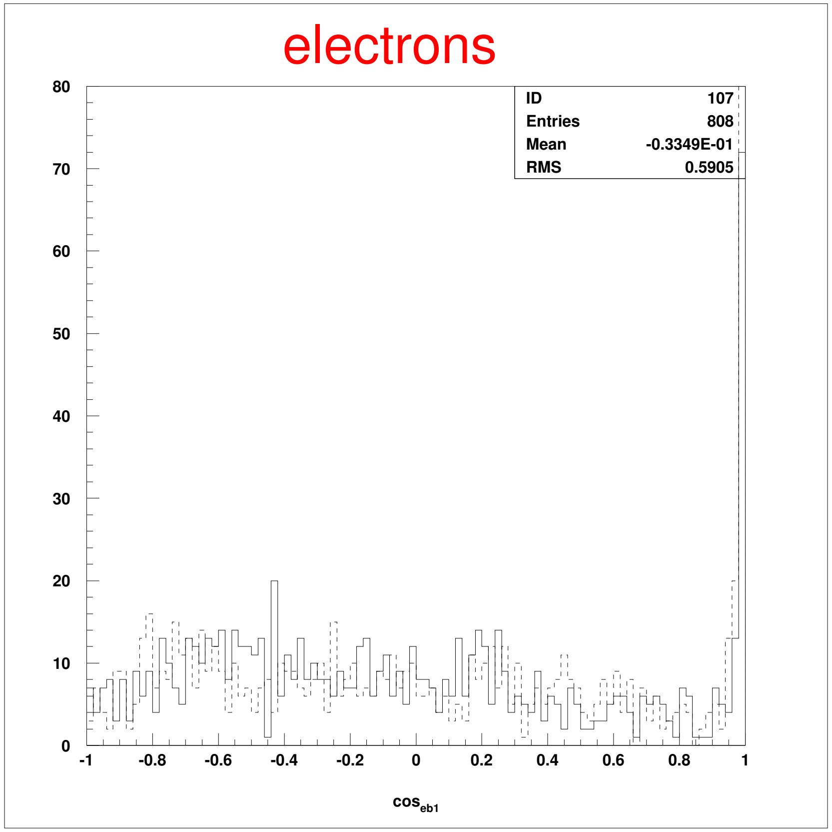
Invariant mass of $\tau^+\tau^-$ pair

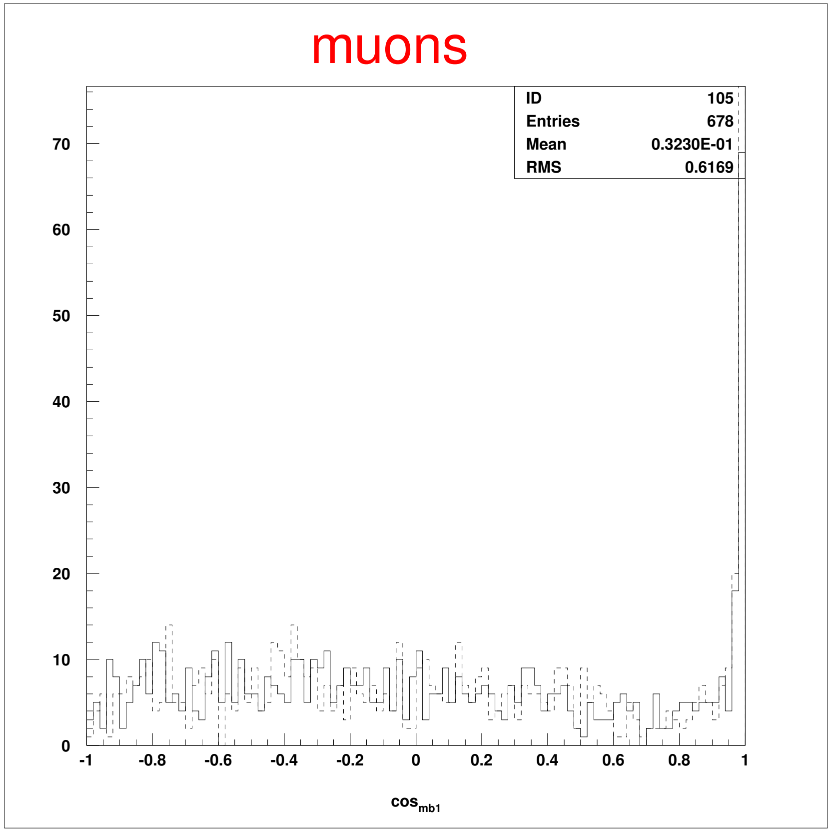


Event selection

Semi-leptonic b decays can be identified by reconstructing leptons in b-tagged jets.

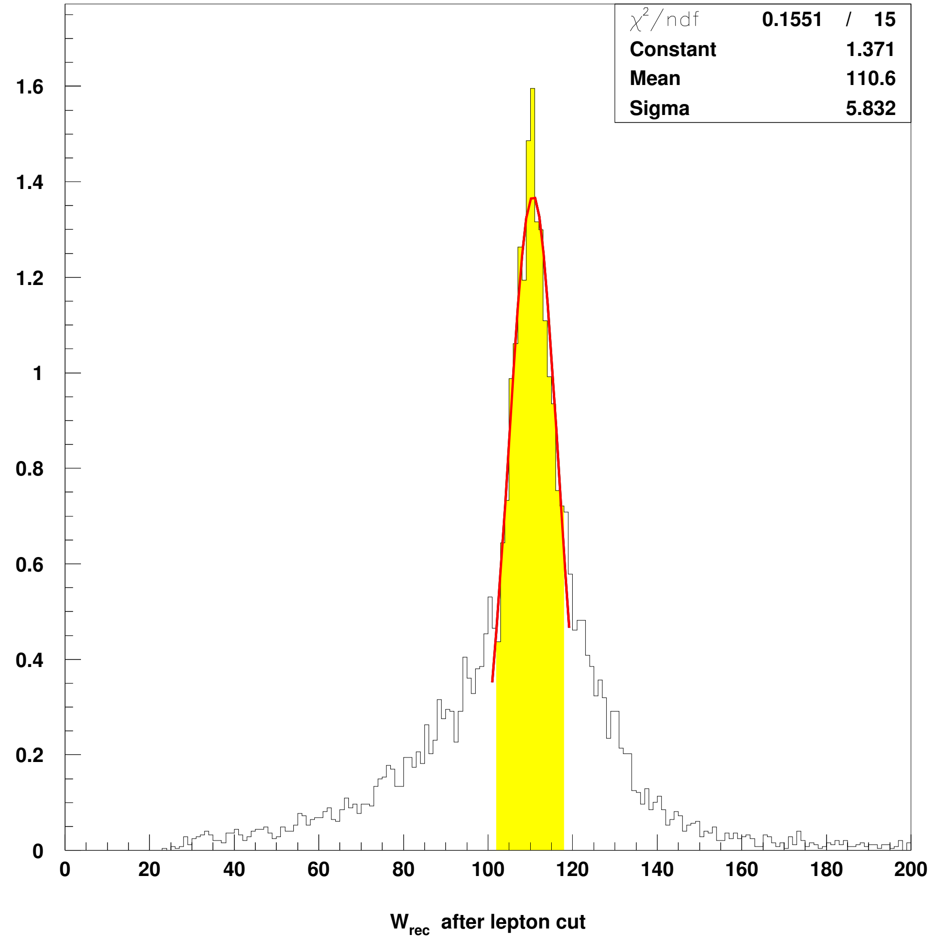
Cosine of the angle between reconstructed lepton and b-jet:





Event selection

Reconstructed invariant mass for two b-tagged jets: $P_b > 0.6$ and $|cos\theta_j| < 0.75$, after additional requirement $\cos\theta_{lb} < 0.9$: selection efficiency down to $\sim$ 10% !

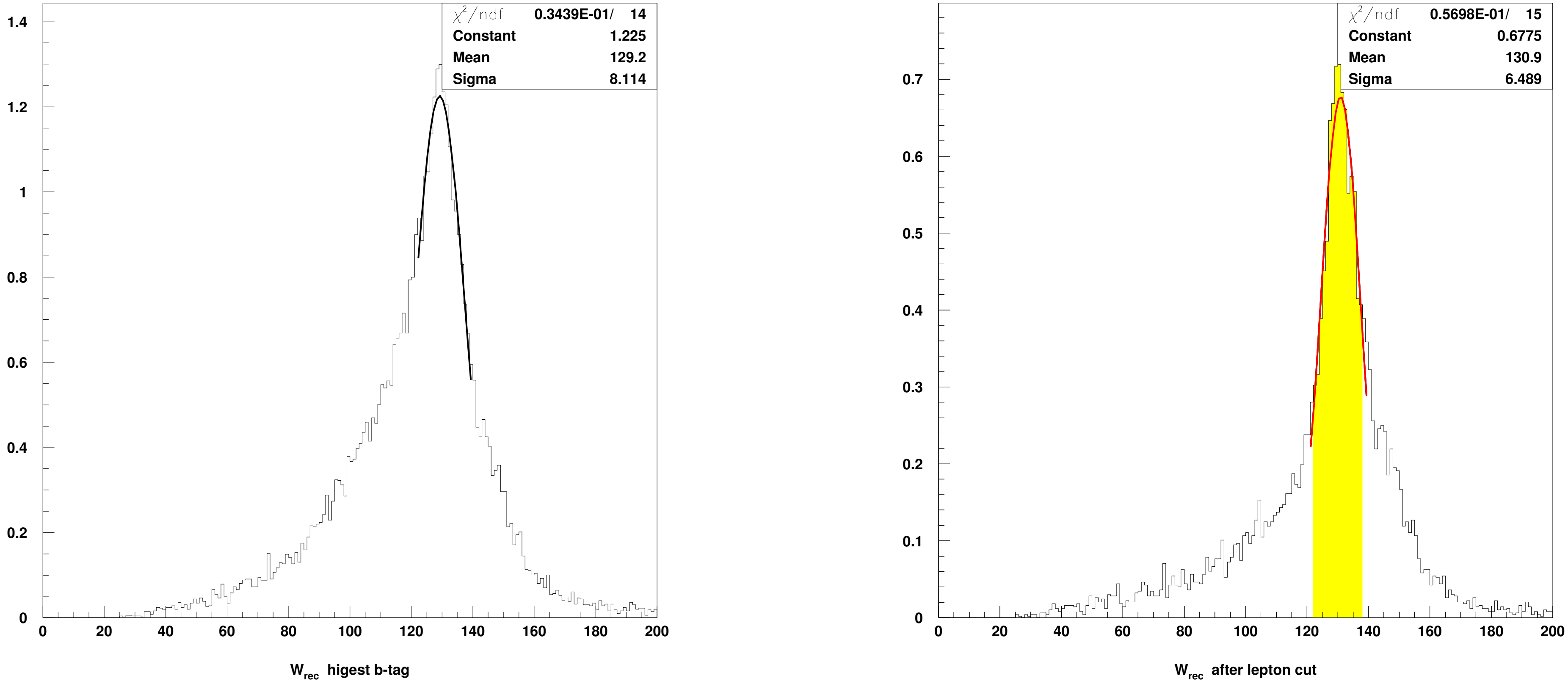


Detector level results

Reconstructed invariant mass of two b-tagged jets for signal events (M_h= 130 GeV)

without lepton cut

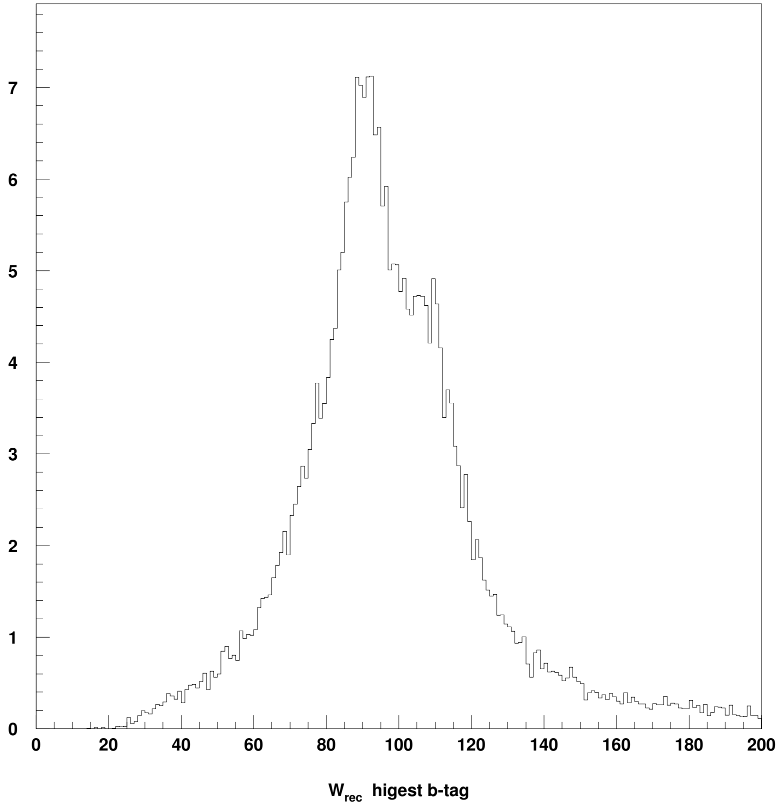
with lepton cut



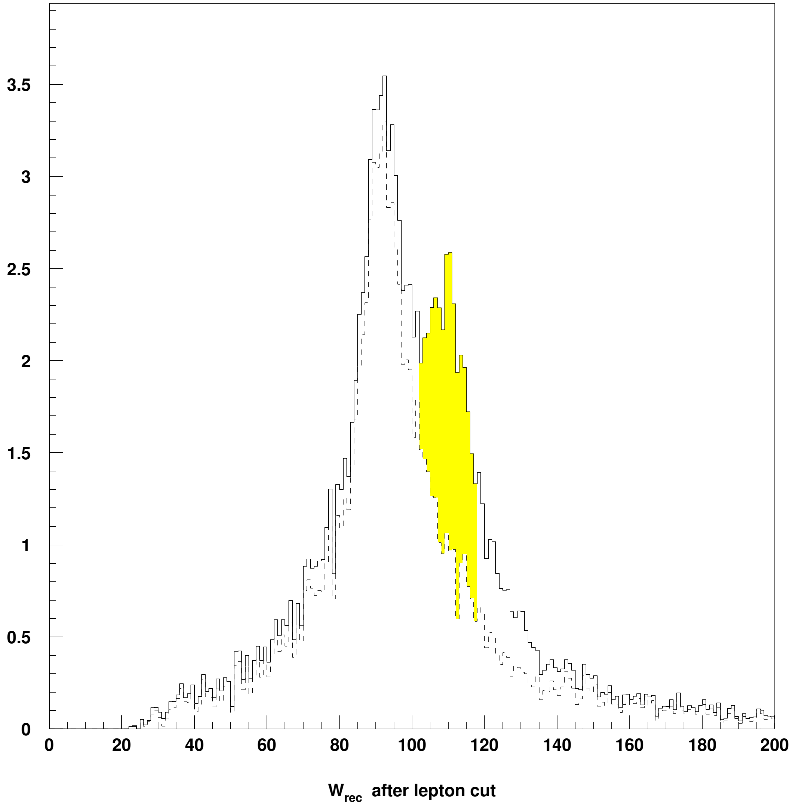
Detector level results

Reconstructed invariant mass distribution for two b-tagged jets, for signal (M_h=110 GeV, $\tan\beta = 10$) and background events

without lepton cut



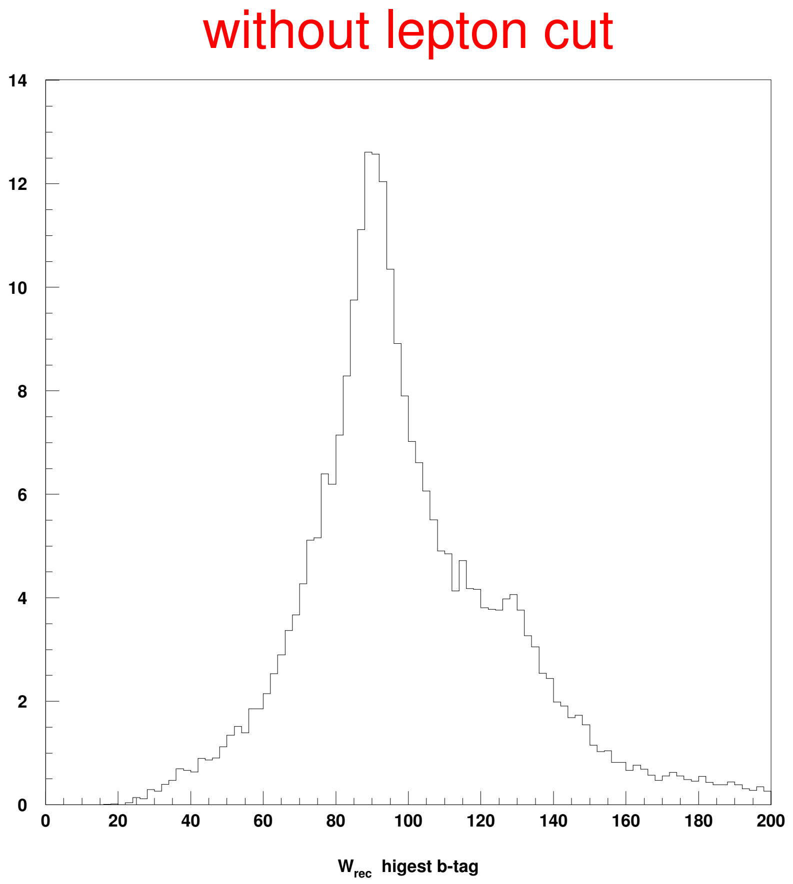
with lepton cut

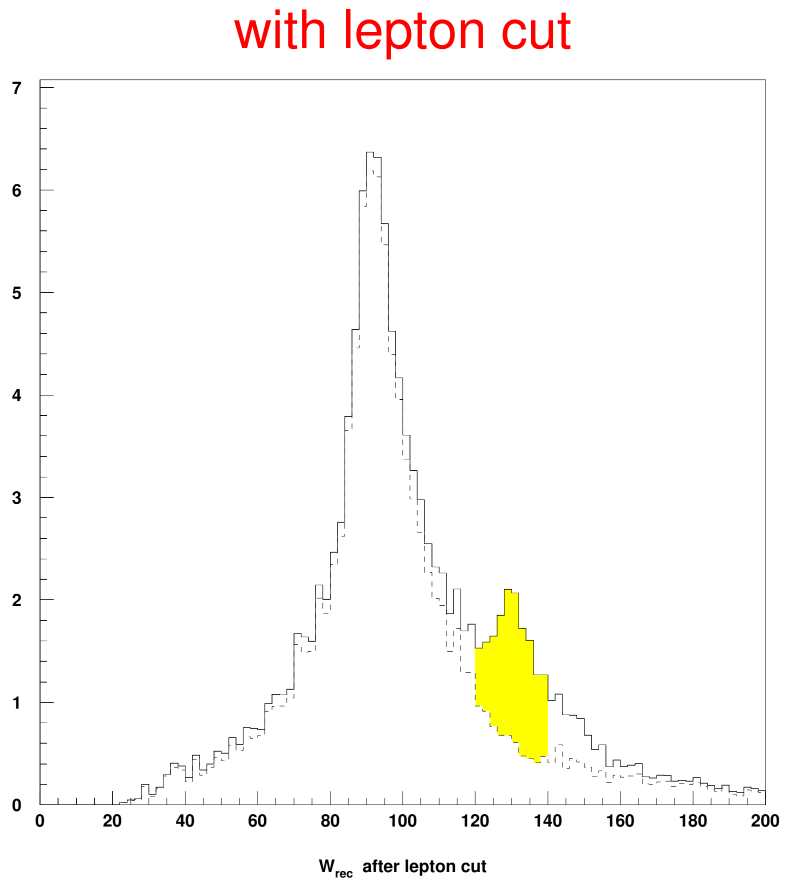


⇒ cut against semi-leptonic b decays allows to separate h and Z° peaks

Detector level results

Reconstructed invariant mass of two b-tagged jets
for signal and background events (M_h= 130 GeV)


without lepton cut

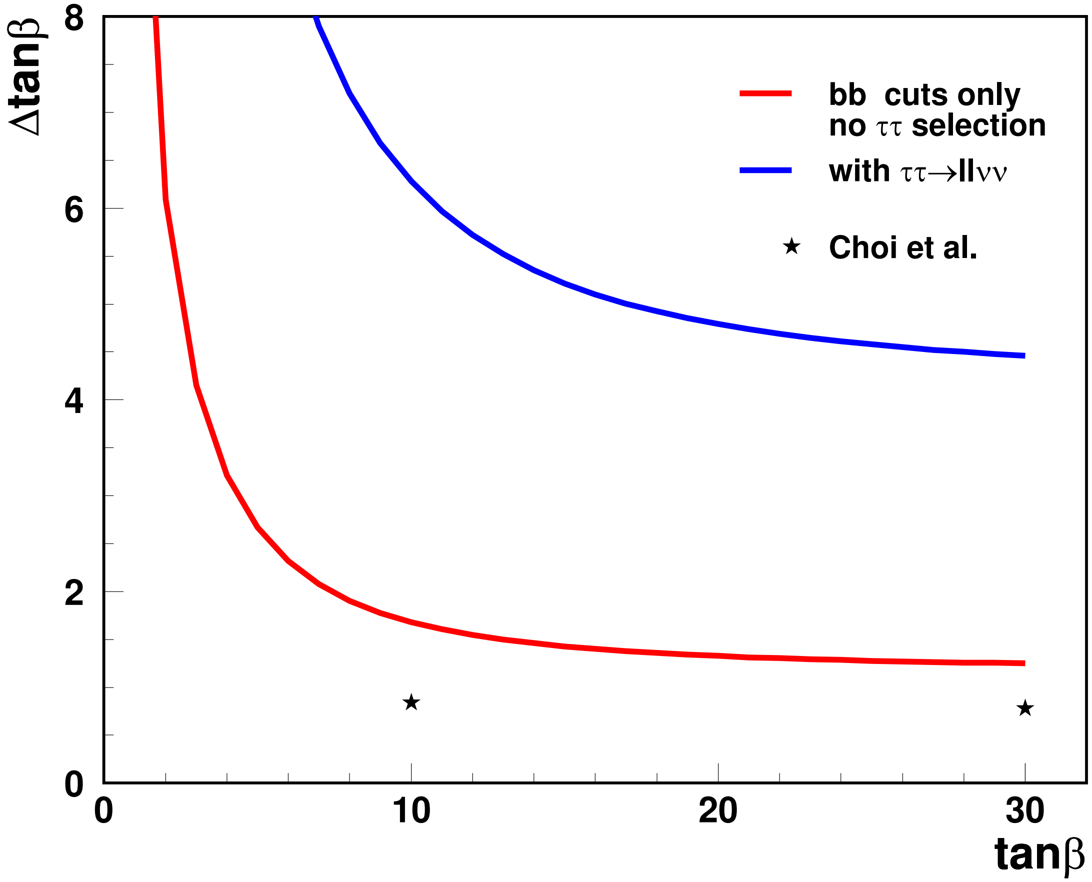

with lepton cut

Detector level results

Expected precision of $\tan\beta$ determination:

after b selection cuts only and after tagging of leptonic τ decays

using ±10 GeV mass window

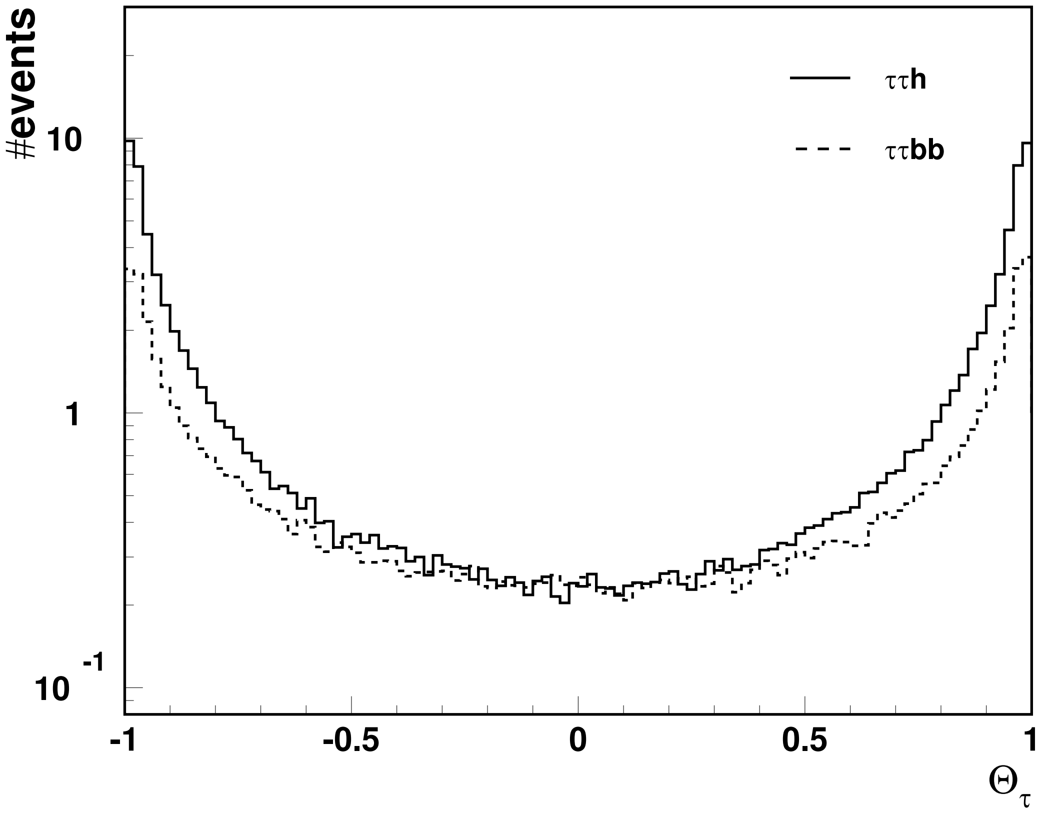


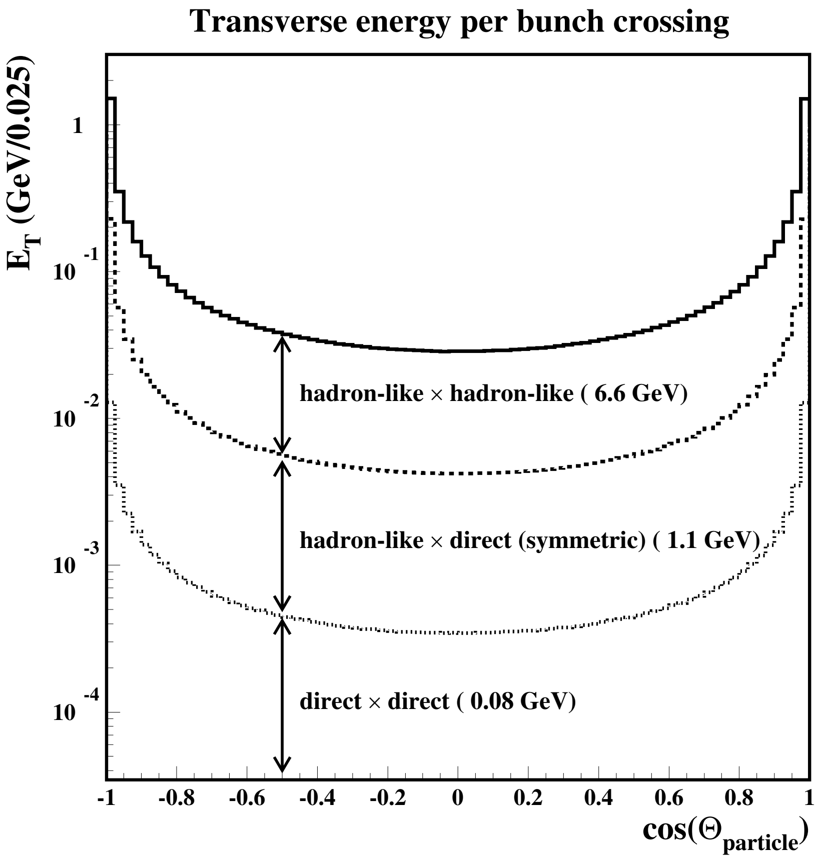
τ identification

Angular distributions of:

signal and background τ

hadrons from OE





Identification of hadronic τ decays can be very difficult...

Conclusions

First experimental study of $\gamma\gamma \rightarrow \tau\tau h$ process

Preliminary results not very promising, but:

- No $b\bar{b}$ selection optimization (!)
- Simple mass window approach
- No τ identification algorithm (hadronic decays)

  $\Rightarrow$ room for improvements

- No reducible background simulation

  e.g. $\gamma\gamma \rightarrow b\bar{b}$ with OE

  $\Rightarrow$ is it possible to reconstruct hadronic τ decays in the forward region?