Physics at a $\gamma\gamma$-Collider

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Fermilab *Line Drive* Series

1. General Remarks
2. Higgs!
3. Photon Structure
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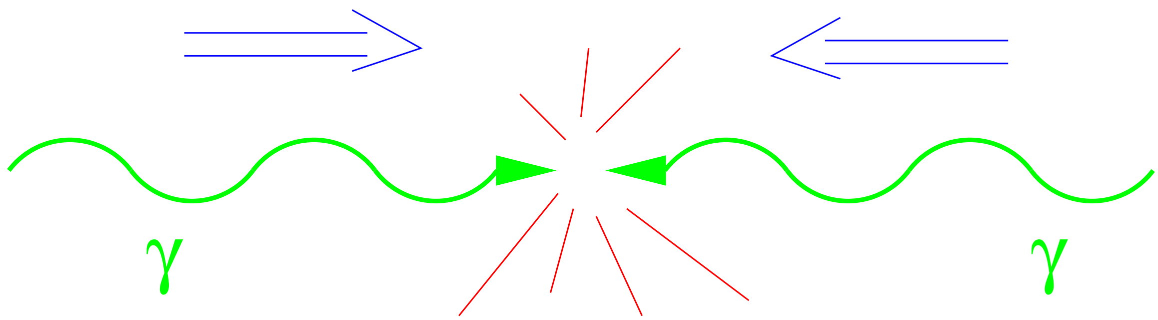
General Points



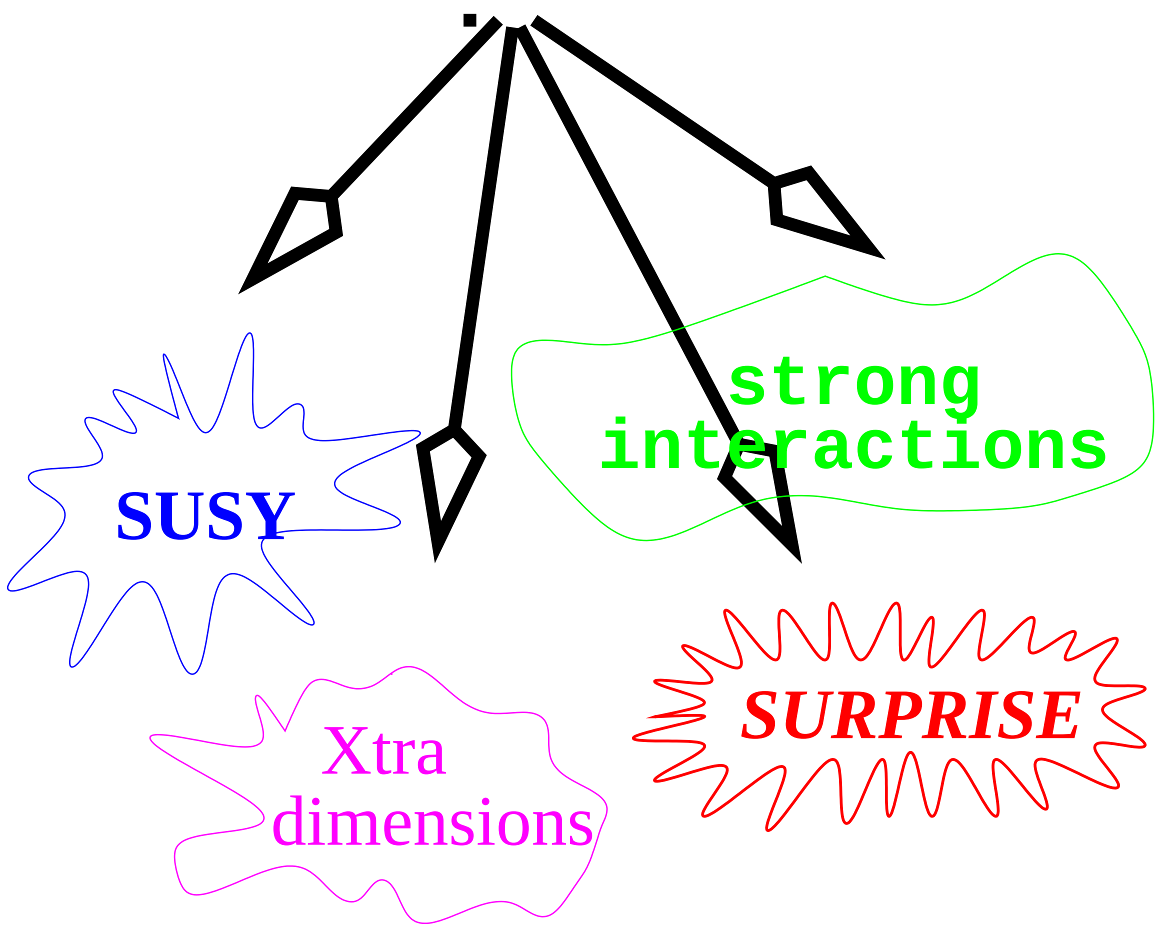
- Photons give access to $J = 0, 2$ final states.
  emphasis is on diboson rather than difermion production, in contrast to e^+e^- machines.
- Pair-production of charged particles is large and theoretically unambiguous for colorless particles.
- Photons are 'clean' in terms of quantum numbers.
  - the initial state is neutral wrt many qn's
  - it is possible to prepare initial states of specific CP
- Since photons couple only to electric charge, production of neutral particles such as Z and h proceeds through loops.
  Loops are good because new higher mass charged particles can circulate, and sensitivity is not masked by a large SM tree level contribution.

- A $\gamma\gamma$-Collider is not only complimentary to e^+e^-, it is probably essential to understanding the Higgs sector.
  - CP violations
  - production of higher mass states $\rightarrow \alpha, \beta$.
- Preparing the photon beam is experimentally challenging.
  The cost comes in a broad energy distribution.
  (better than protons, inferior to electrons)
  Consequently, measurement capabilities must be estimated with simulations.
- A $\gamma\gamma$-Collider is an experimental challenge – can we afford
- The photon is a complicated probe, due to its hadronic structure. Background estimates will need to be tied to the data, not unlike hadronic machines.

Directions...

What are the directions for our understanding?

→ verify EWSB in the simplest sense ←



caveat: I am going to frame this discussion in terms of SM Higgs, 2HDM and MSSM. This does not mean that I am unaware of the possibility that no fundamental scalar field is resposible for EW symmetry breaking. However, focussing on the Higgs paradigm allows a concrete evaluation of the potential of a $\gamma\gamma$-Collider for physics, and ultimately, form comparisons to other possibilities such as an e^+e^- collider.

I will not answer the question: What good is a $\gamma\gamma$-Collider if none of the current theoretical prejudice is correct?

Scenario: only a light CP-even Higgs is found at a hadron collider. Then for a 500 GeV e^+e^- machine, the point will be to deduce the parameters of the MSSM in order to predict the masses of the heavier Higgs states, and thus know what $\sqrt{S}$ to run at in the second stage.

How can a $\gamma\gamma$-Collider help this effort?

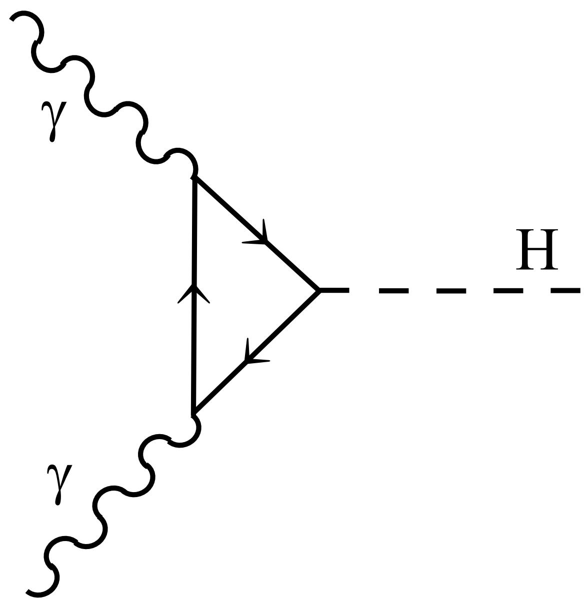
What do we want to know?

- total width, and $\Gamma_{\gamma\gamma}$
- mass
- Yukawa couplings, for top at least
- Higgs potential
- CP quantum numbers

Higgs production at a $\gamma\gamma$-Collider

But that's Crazy!?! There's no tree-level $\gamma\gamma h$ coupling...

Exactly. This is a **virtue**. New Physics (N.P.) will not be *masked* by large tree-level contributions.



The effective coupling is still large enough to be comparable to other colliders:

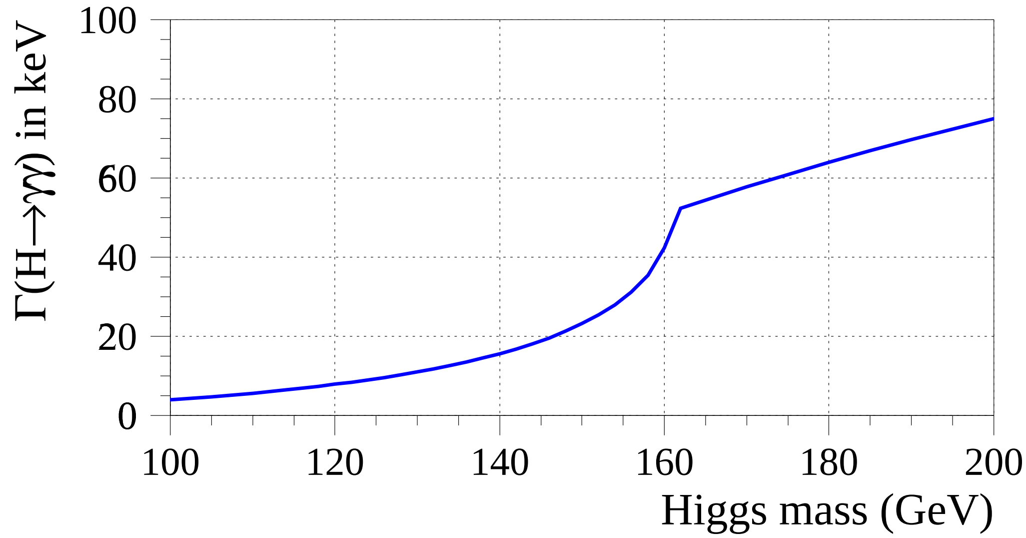
- associated production (e^+e^- and pp) are higher order
- $\mu^+\mu^-$ suffers from Yukawa suppression.

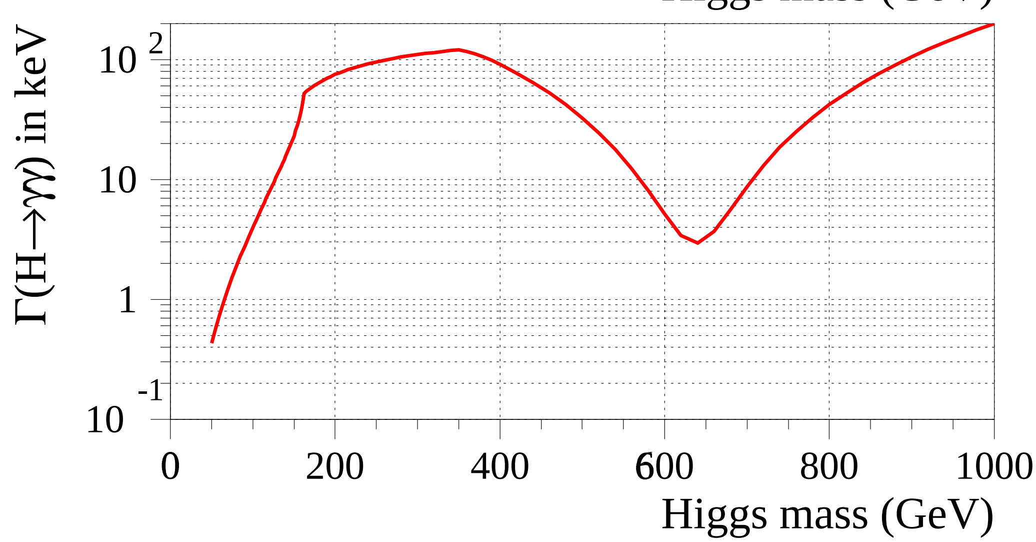
The main question is about: $\Gamma_{\gamma\gamma}$.

The main contributions come from W and t.
Unfortunately, they interfere destructively (key for SUSY...)

- is the W loop resonant?
- is the t loop resonant?

$\Longrightarrow$ $\Gamma_{\gamma\gamma}$ is a strong function of m_h:





Isolating a Higgs signal

Not so easy, not so hard...

A complete event simulation by Sölder-Rembold & Jikia

signal = two b-quark jets

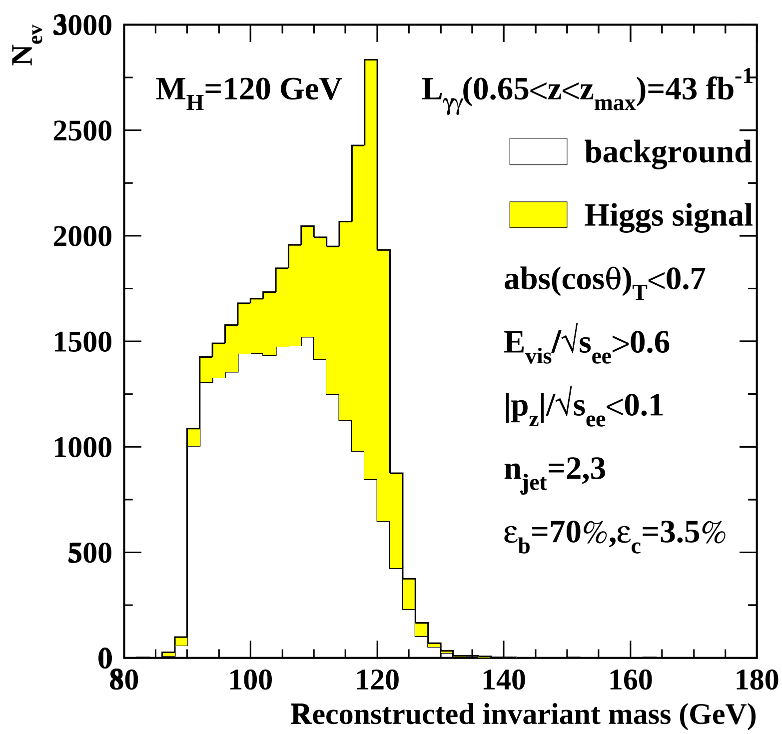
background = continuum b production

(Note: good charm rejection is needed for decent b-efficiency.)

photons of the same helicity $\Longrightarrow$ suppress continuum $b\bar{b}$

Problem: this does not suppress the $b\bar{b}g$ final state!

Nonetheless it is *still* possible to isolate a good signal for the Higgs, using intelligent kinematic cuts: hep-ph/0101056



Higgs Width

The mass peak ($m_h = 120$ GeV), gives a 2% measure of

$$\{\Gamma(h \to \gamma\gamma) \times BR(h \to b\bar{b})\}$$

given 40 fb^{-1}of 'hard' $\gamma\gamma$ collisions.

Taking $BR(h \to b\bar{b})$ and $BR(h \to \gamma\gamma)$ from elsewhere,

$$\Gamma_{\text{tot}} = \frac{\{\Gamma_{\gamma\gamma} \times BR(h \to b\bar{b})\}}{\{BR(h \to \gamma\gamma)\} \times \{BR(h \to b\bar{b})\}}$$

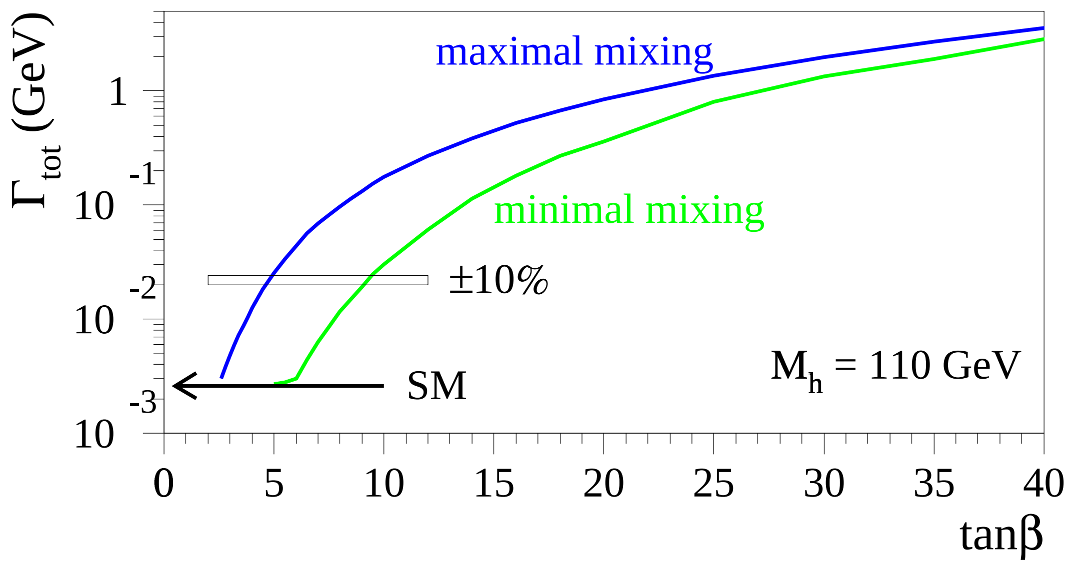
measured to 10–15%. (Melles, Ohgaki: similar conclusions)

This is often proposed as *the* way to get Γ_{tot} is based on $\Gamma_{\gamma\gamma}$. This would be a model-independent result.

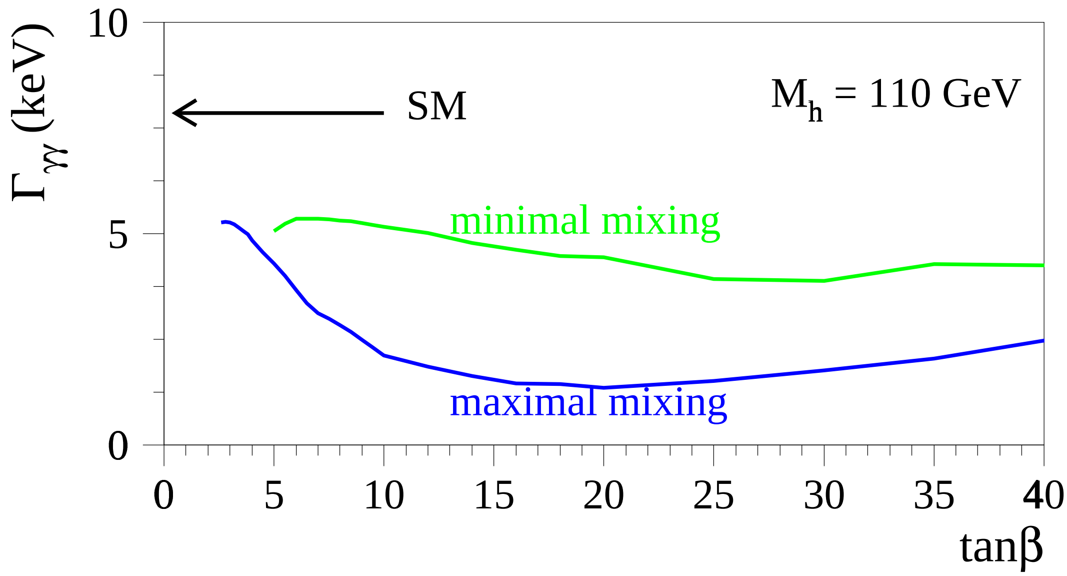
[Snowmass 1996, Gunion et al. hep-ph/9703330]

(NB: For other possibilitues, see Ohgaki's scan method...)

The total width is an obvious window on N.P. In the MSSM, $\Gamma_{\rm tot}$ varies wildly wrt $\Gamma_{\rm tot}^{\rm SM}$ due to enhancement and suppression of different SM modes.



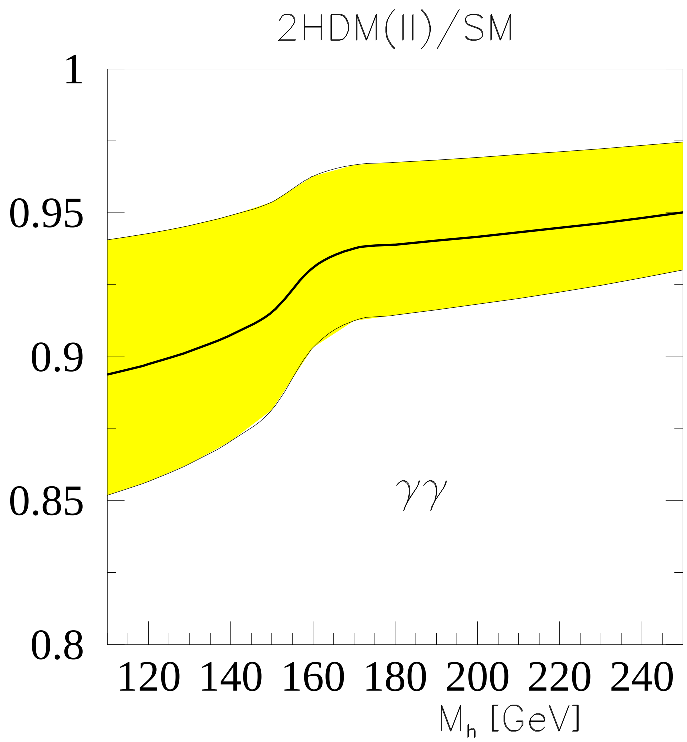
The partial width $\Gamma_{\gamma\gamma}$ varies less.



Calculations done using HDECAY.

Γ(**Higgs $\rightarrow$ photons**)

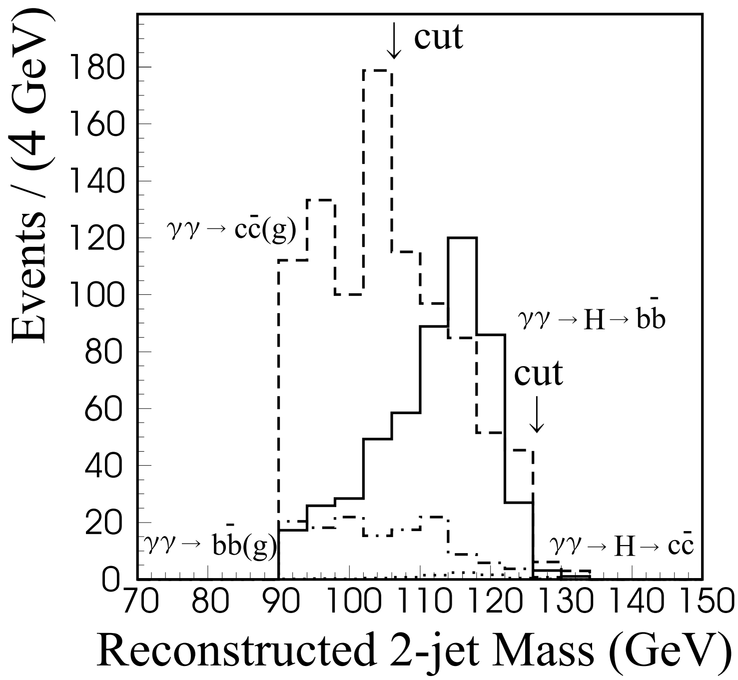
Telnov has drawn a nice analogy with $\Gamma^{Z}_{\nu\bar{\nu}}$ at LEP, which counted the number of light neutrino species. (What if the answer had been **'4'**...)



[Krawczyk et al. hep-ph/0101229]

On this basis alone, it will be possible to distinguish minimal SM and generic 2HDM...

Ohgaki performed simulations and concluded that a 6% measurement was possible for 10 fb^{-1}. [hep-ph/9703301]



Söldner-Rembold reports 2% for 43 fb^{-1}.

Melles focusses on theoretical uncertainties and quotes a precision of 1–2%, for one year's running. [hep-ph/0008125]

This is one of the main justifications for a $\gamma\gamma$-Collider.

Side comment:

$\Gamma_{\gamma\gamma}$ is particularly powerful when combined with $\Gamma_{Z\gamma}$ from an $e\gamma$-collider, and Γ_{gg} from e^+e^-.

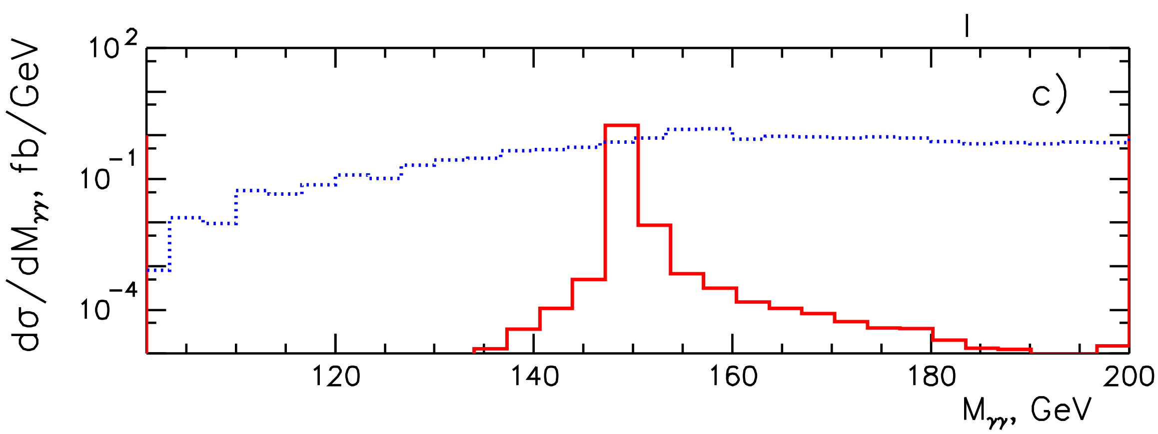
What about H→WW ?

The W^+W^- channel dominates for $m_h > 140$ GeV, but the huge continuum production of W^+W^- makes this exceptionally difficult.

$$\sigma(\gamma\gamma \to W^+W^-) \sim 81 \text{ pb}$$

Nonetheless, a measurement for $m_h < 160$ GeV looks quite feasible.

[Boos et al. hep-ph/9801359]

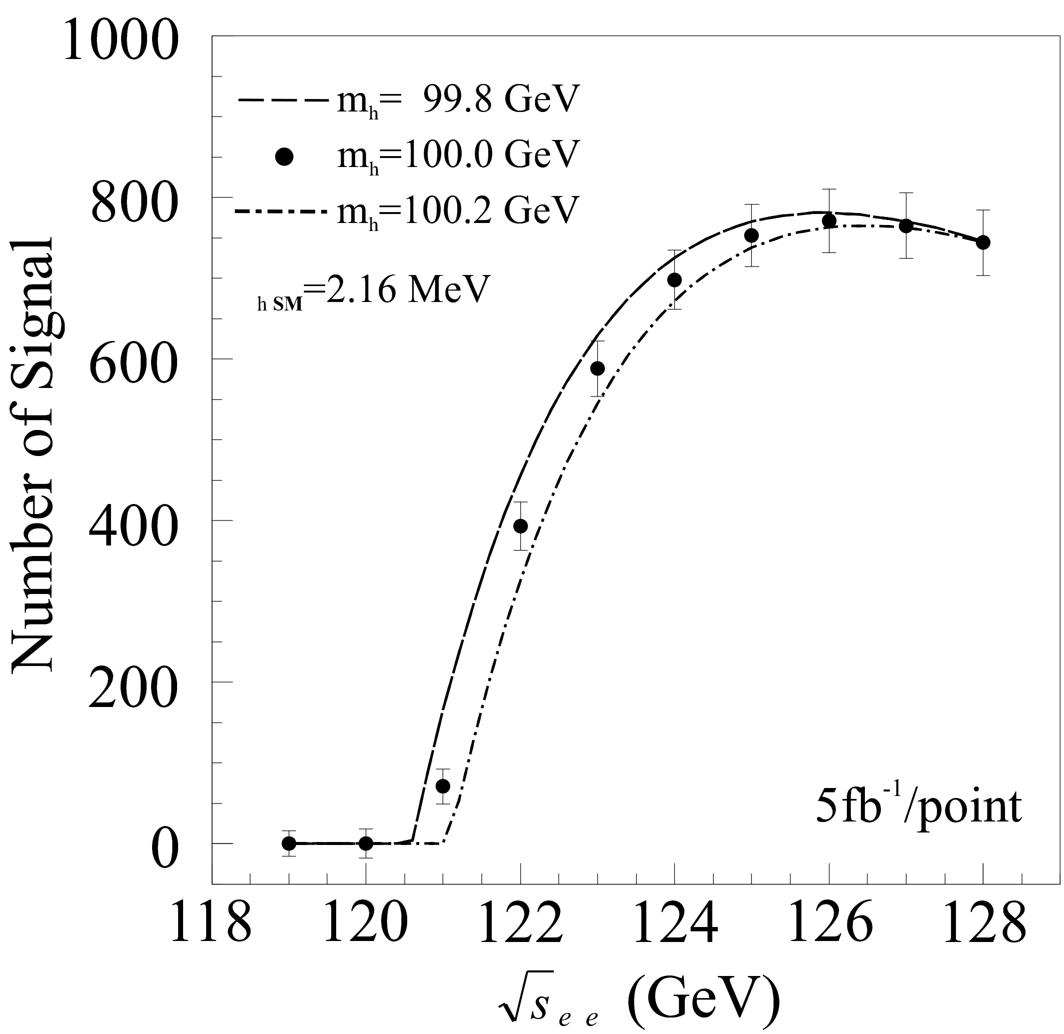


Much more work is needed here.

Higgs mass

Take advantage of the sharp edge of the photon spectrum to pin down the Higgs mass.

$\Longrightarrow \Delta m_h = 110$ MeV for 50 fb^{-1}



The same data would give $\frac{\Delta\Gamma_{\rm tot}}{\Gamma_{\rm tot}} = 6\%$.

[Ohgaki, hep-ph/0002083]

Higgs mass

Why is a good measurement of m_h important?

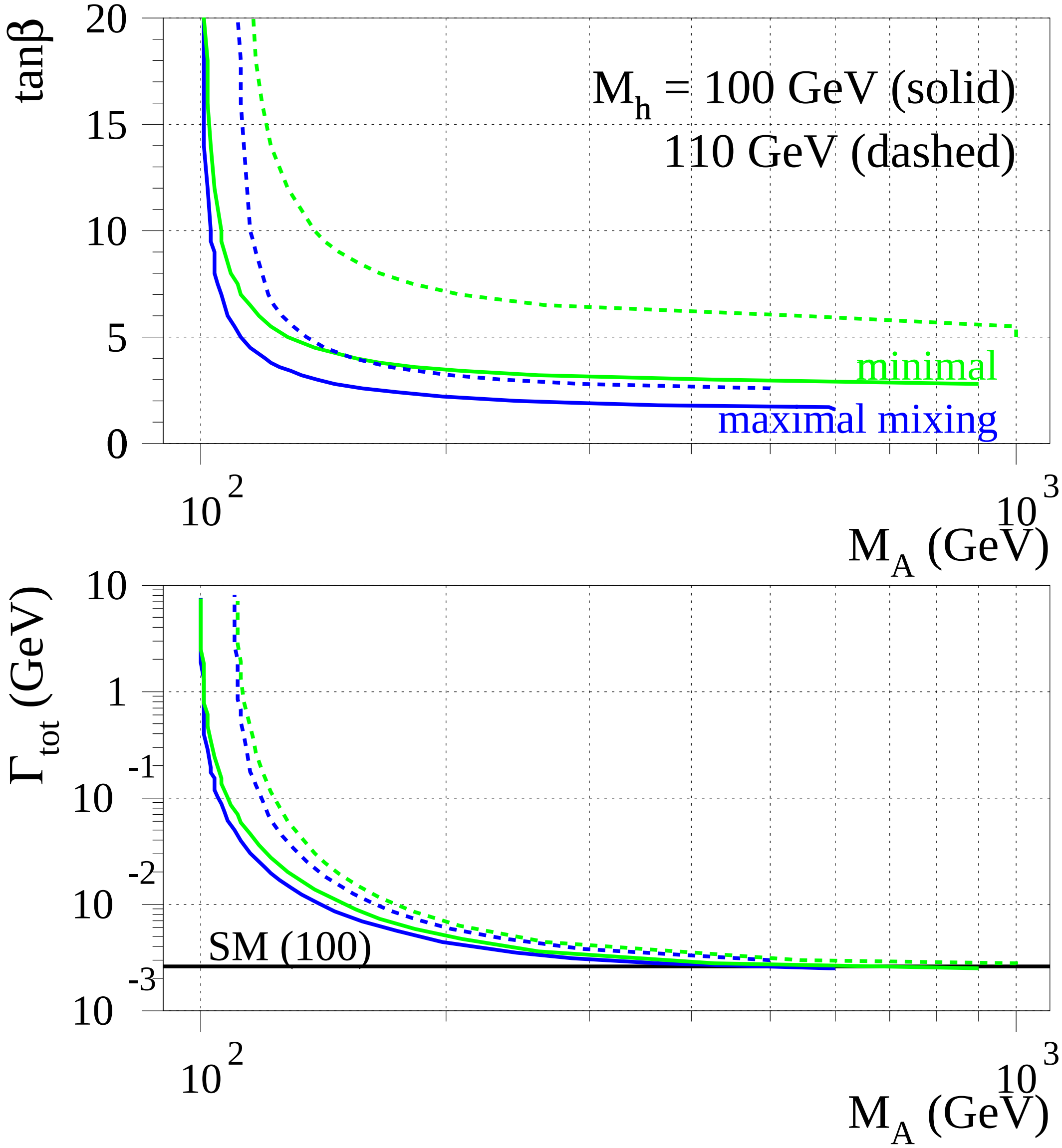
New Physics enters in the radiative corrections to the mass.

For example, we had an indirect indication of the top quark mass through radiative corrections to the Z mass; and now we are exploiting the same data to derive a range for the Higgs mass.

Another example: consider the MSSM.
Currently, since the tree-level upper bound on m_h is M_Z while the lower limit from direct searches is about 95 GeV, we already know that at least 25% of the mass comes through radiative corrections.

The main parameters that enter are m_A, $\tan\beta$ and the stop mixing quantity X_t.

A measurement of the mass limits $\tan\beta$ and m_A to a narrow crescent. The thickness of this crescent corresponds to different stop mixing possiblities.



Another measurement, such as the total width, will independently constrain m_A and $\tan\beta$.

Higgs Coupling to Top Quarks

The increase of Higgs coupling with mass is an essential prediction of the theory. We need to test it!!!

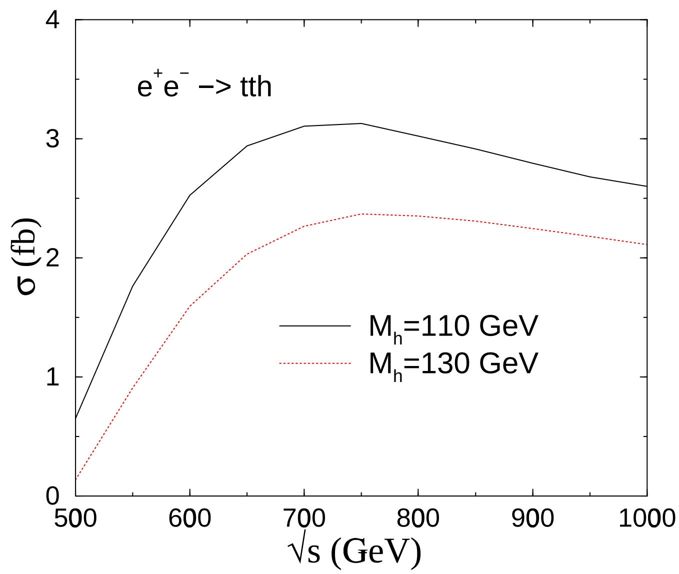
The top quark is unbelievably heavy, and there are moderately heavy bottom quarks and tau leptons. We should check that the cross sections for

$$\gamma\gamma \to f\bar{f}h$$

proceeds basically as m_f^2.

(For 2HDM's, there will be factors complicating the relation of top versus bottom and tau.)

e^+e^- example:



[Dawson hep-ph/0101079]

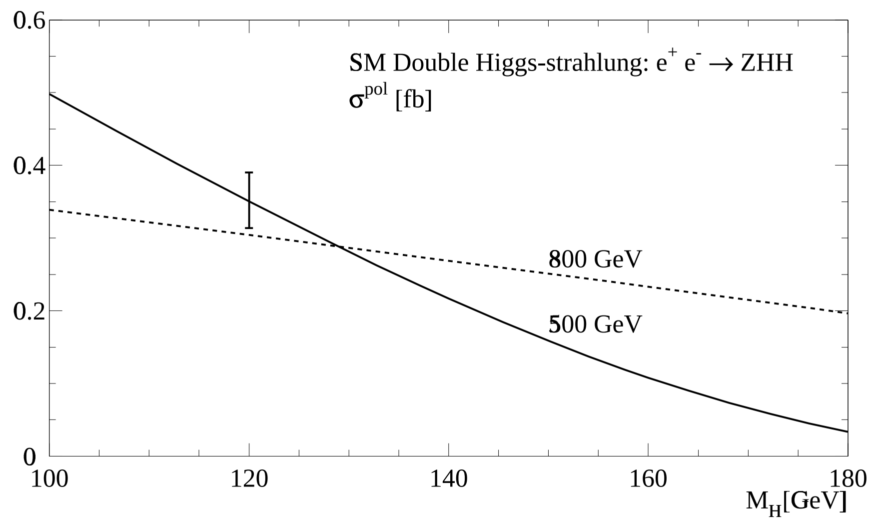
Higgs self-coupling

An essential part of the Higgs mechanism. (Otherwise, no minimum!)

What can the $\gamma\gamma$-Collider do?

Cross sections are quite small, (the trilinear part is ~ 0.2 fb) as they are for e^+e^- LC's.

e^+e^- example: Mühlleitner hep-ph/0101262



But... backgrounds are probably easier to deal with.

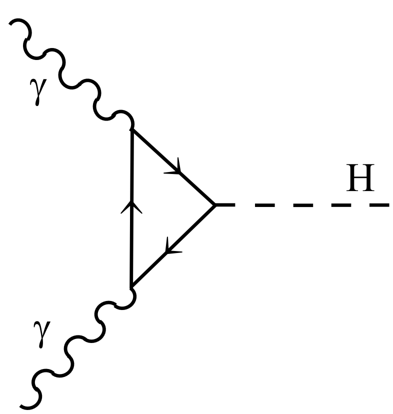
higgs, Higgs and more A-Higgs'ing

In a general 2HDM, there are h, H, A and $H^{\pm}$. Masses and mixings are not related. (In the MSSM, they *are* related.)

Unless the single doublet model is correct, understanding the Higgs mechanism means measuring four masses as well as α and $\tan\beta$ (assuming to CPV).

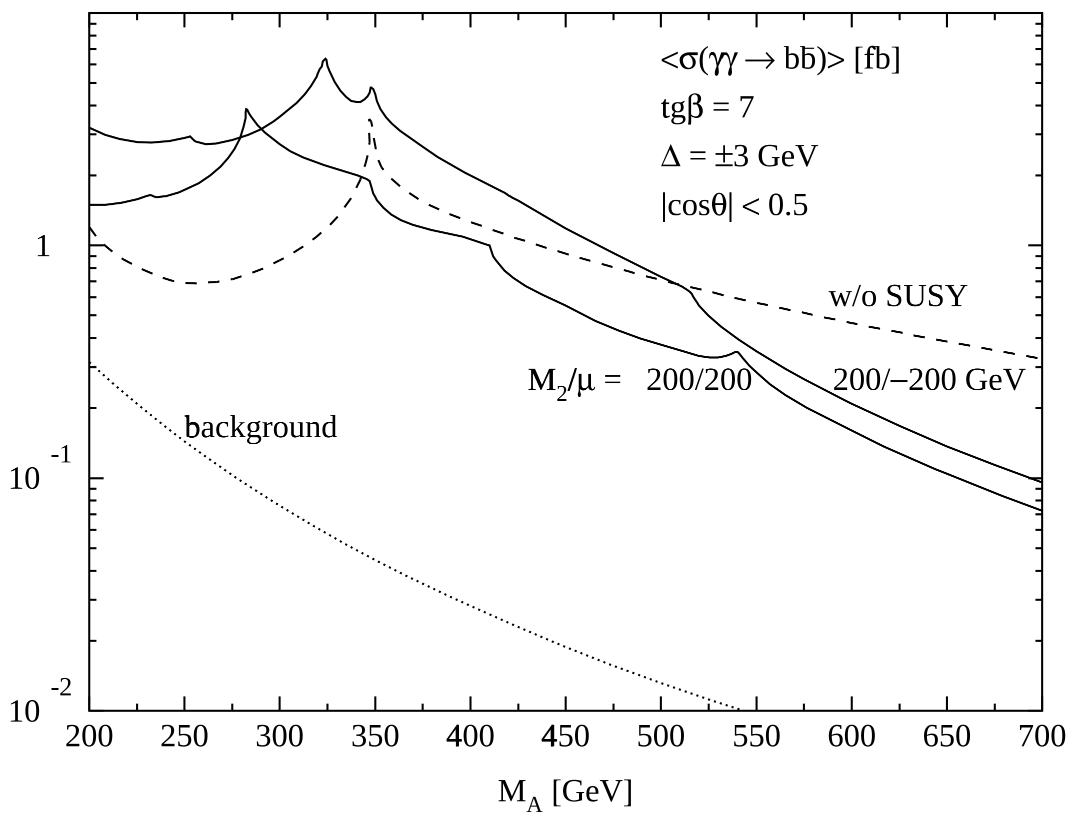
It turns out that H and A may be very difficult or even impossible to observe at future e^+e^- and pp colliders, due to suppression of couplings to vector bosons.

The $\gamma\gamma$/top+W+whatever loop saves the day.



H and A

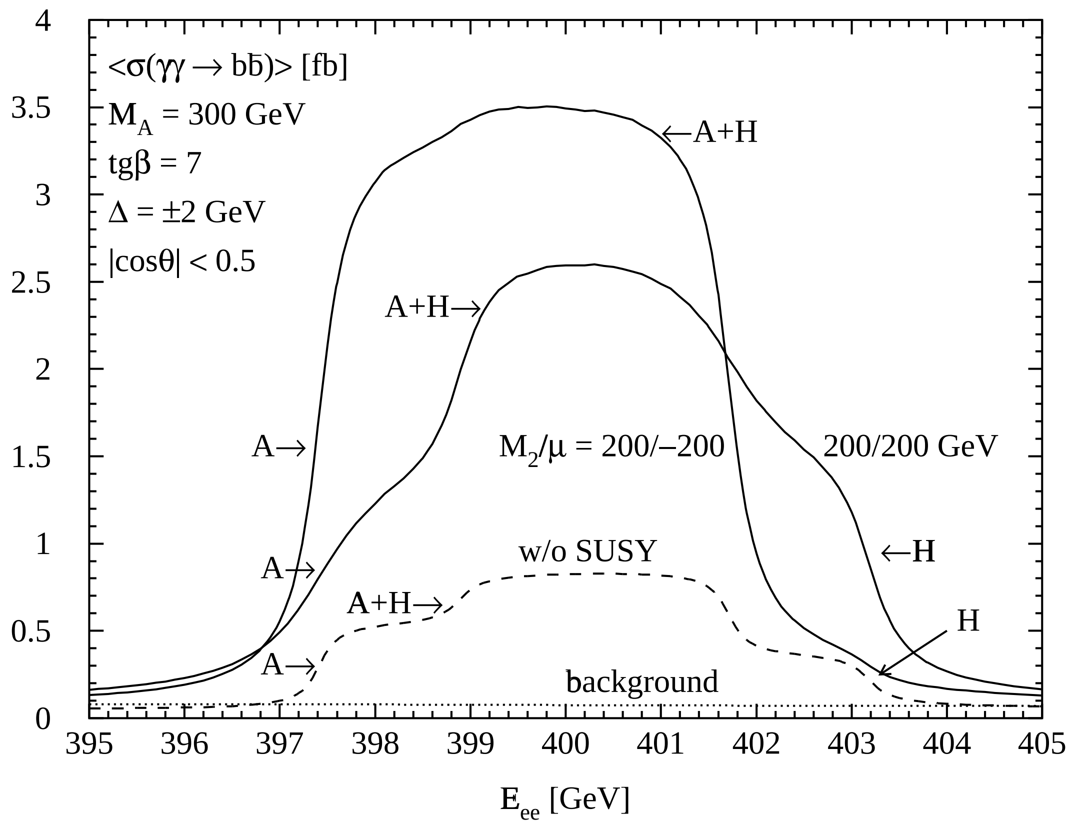
Cross sections are quite small, but not impossibly so. (For SM, quite large, but there's a lot of suppression in MSSM to W's and top when $\sin(\beta - \alpha) \approx 1$.)



Precision measurements are unlikely, but observation and reasonable mass measurements seem possible.

[Mühlleitner hep-ph/0101083]

Decay modes to SUSY can have a major impact...



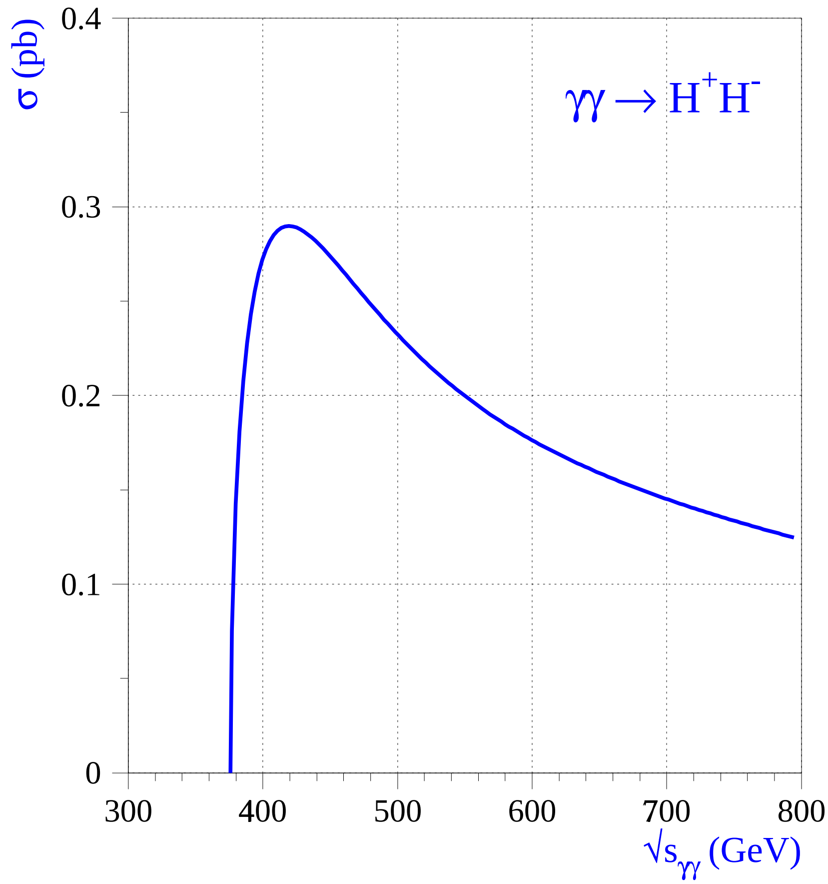
Interesting point: $m_H \gtrsim m_A$, and channels interfere b/c $\Gamma_H, \Gamma_A \gtrsim m_H - m_A$.

question: is this lineshape sensitive to CP mixing?

$\mathbf{H^{\pm}}$

For sufficiently large $\sqrt{s_{\gamma\gamma}}$, cross sections are moderate.

The sharp turn-on (not available to e^+e^- machines due to phase space suppression), could allow a good measurement of the mass.



[CompHEP, hep-ph/9908288]

→ measure major decay modes. (either mainly $\tau\nu$+$c\bar{s}$, or SUSY decays such as $\tilde{\chi}^{\pm}\tilde{\chi}^{0}$ in addition. Would reveal a lot about the MSSM.)

CP Violation in the Higgs Sector

CP Violation is the great enigma of high energy physics.

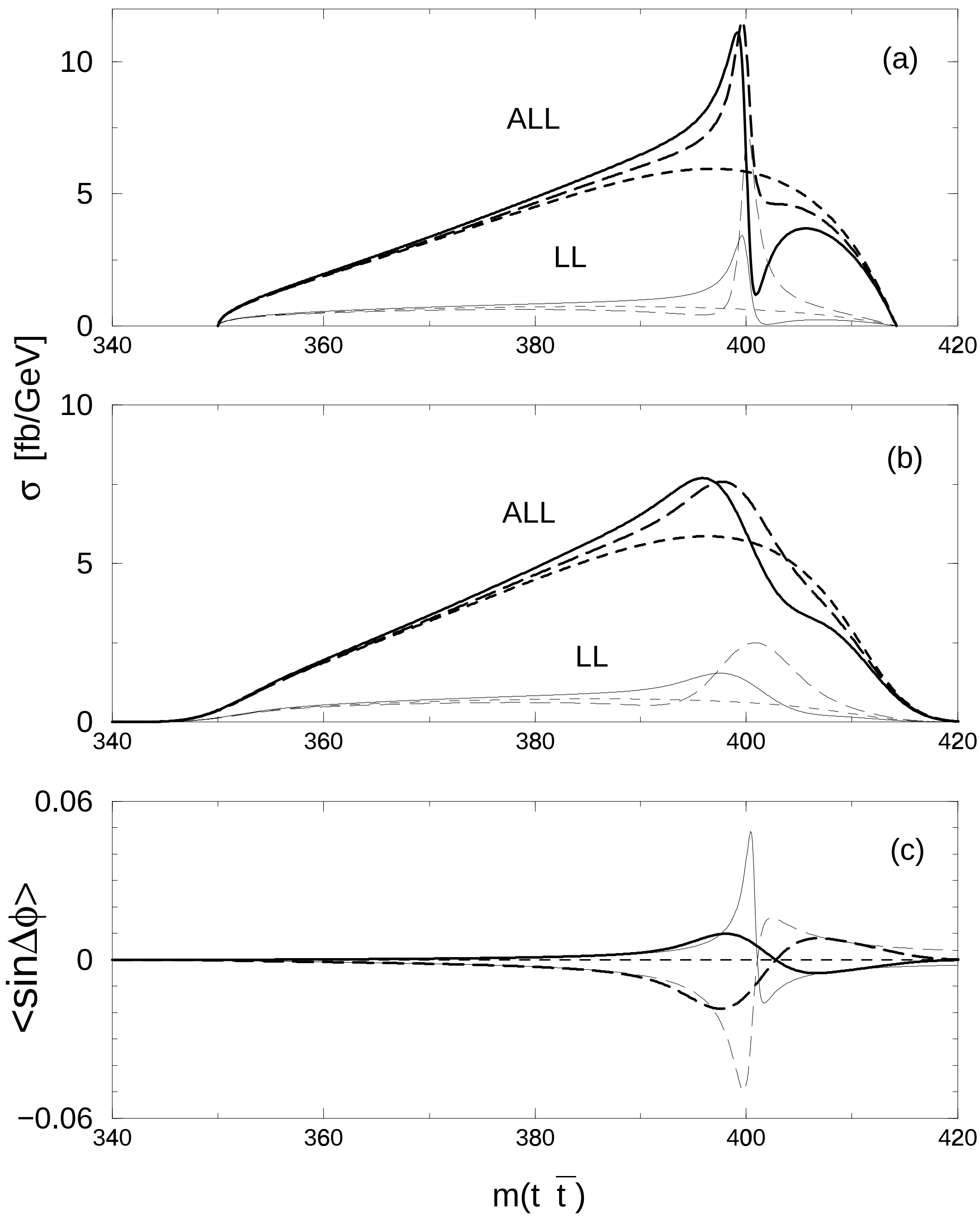
In the MSSM, CP violation in the Higgs sector comes through radiative corrections, with stop loops playing the main role. This effective CPV can be large, and has a major impact on the phenomenology.

The best place to study CP violation in the Higgs sector is at a $\gamma\gamma$-Collider – in fact, this is a unique capability.

The technique exploits linear polarization of photon beams. These define a CP-even or CP-odd state depending on whether the polarization vectors are parallel or perpendicular.

$$\begin{aligned} \mathbf{CP}-\text{even} &: \quad \vec{\epsilon}_1 \cdot \vec{\epsilon}_2 \\ \mathbf{CP}-\text{odd} &: \quad (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \vec{k} \end{aligned}$$

$\gamma\gamma \to t\bar{t}$: Exploit the interference between continuum and resonant higgs production.



[Hagiwara, Asakawa hep-ph/0011360]

We cannot say that we understand EWSB until the entire Higgs sector has been elucidated – i.e., measured.

Given the additional mixing among the higgs bosons that occurs when CP is broken, studies of all three Higgs bosons are needed before we can say we understand anything.

Those Pesky Photons

A $\gamma\gamma$-Collider is an excellent place to study the hadronic struction of the photon, and its interactions.

Some people may ask: *What is the point of all this?*

There are two answers:

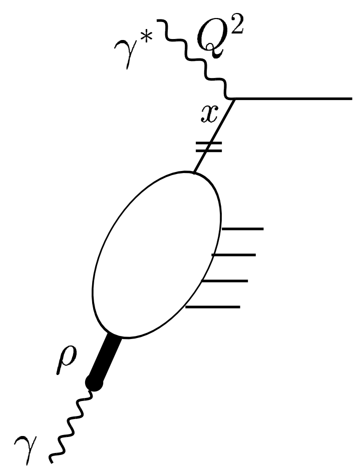
1: These 'resolved photon' processes pose large 'SM' backgrounds to Higgs and other N.P. studies. We must understand them at an experimental level.

2: The theory is **'pliable.'** An understanding of this physics will come from the interplay of measurements and models. There are controversies and competing schools of thought.

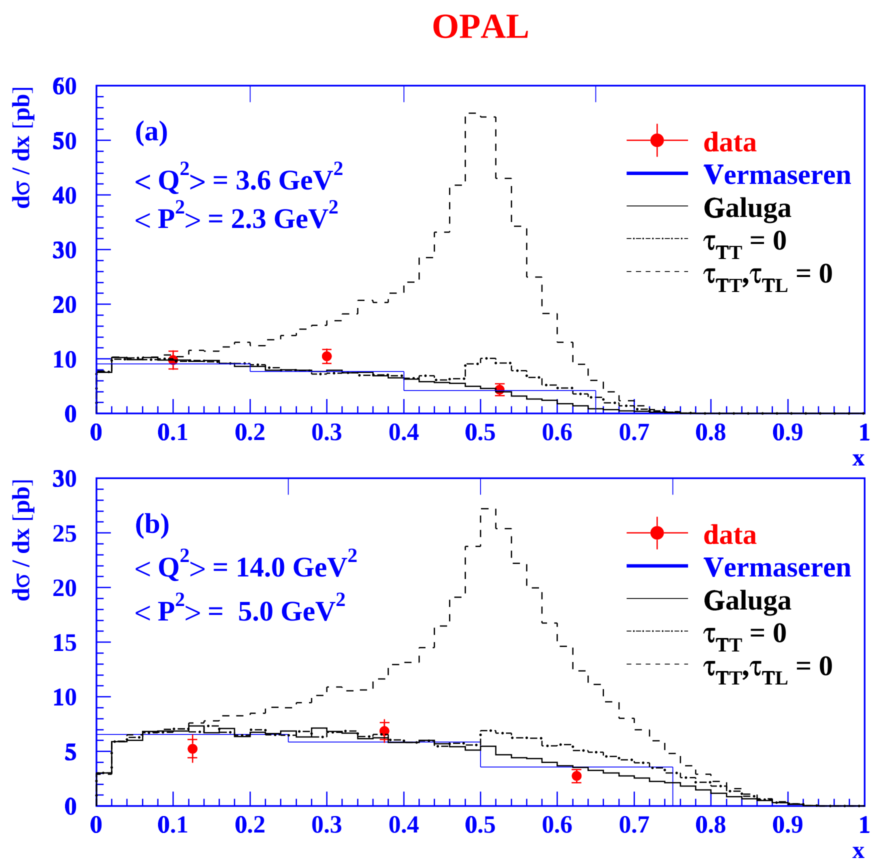
(For some people, that's already enough of a motivation...)

Look for experimental surprises, and new channels of investigation such as heavy quark production, or spin-dependent struction functions g_1^γ, which have a deep connection with strong and electromagentic gauge anomalies, and chiral QCD.

[Krawczyk hep-ph/0012179] Apparently, the physical ρ^0 regularizes the real photon.



Even the *leptonic* structure of virtual photons is hard to understand: large interference terms...



The other Gauge Bosons

The high energy cross section for $\gamma\gamma \to W^+W^-$ is 81 pb.

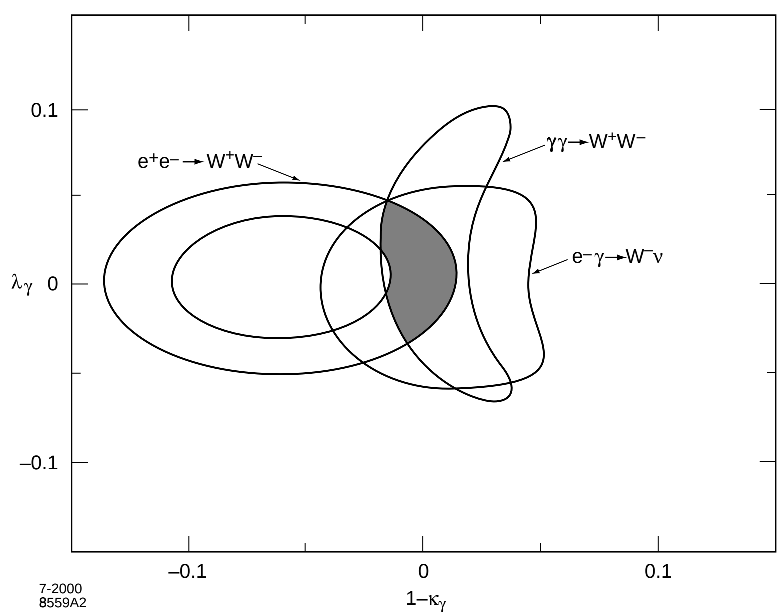
– more than $10\times$ cross section for e^+e^-

This means O(10 million) W bosons per year!!!

a great place for studies of **anomalous couplings**

- you can control the beam polarization
- there are many sensitive observables
- W decay allows extraction of off-diagonal elements

These limits complement those from e^+e^- (and $e\gamma$).

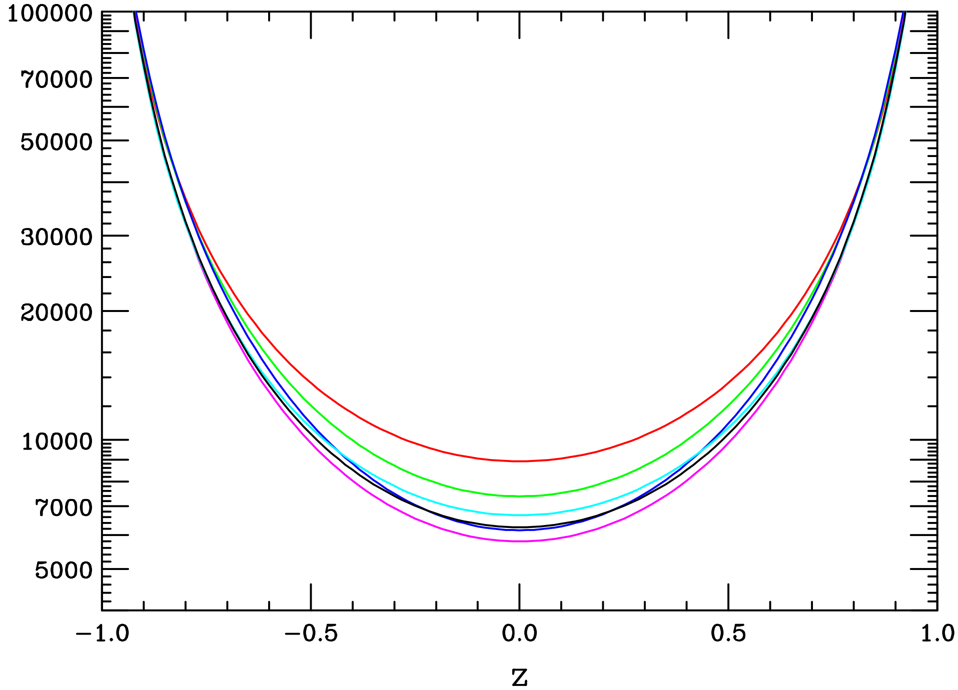


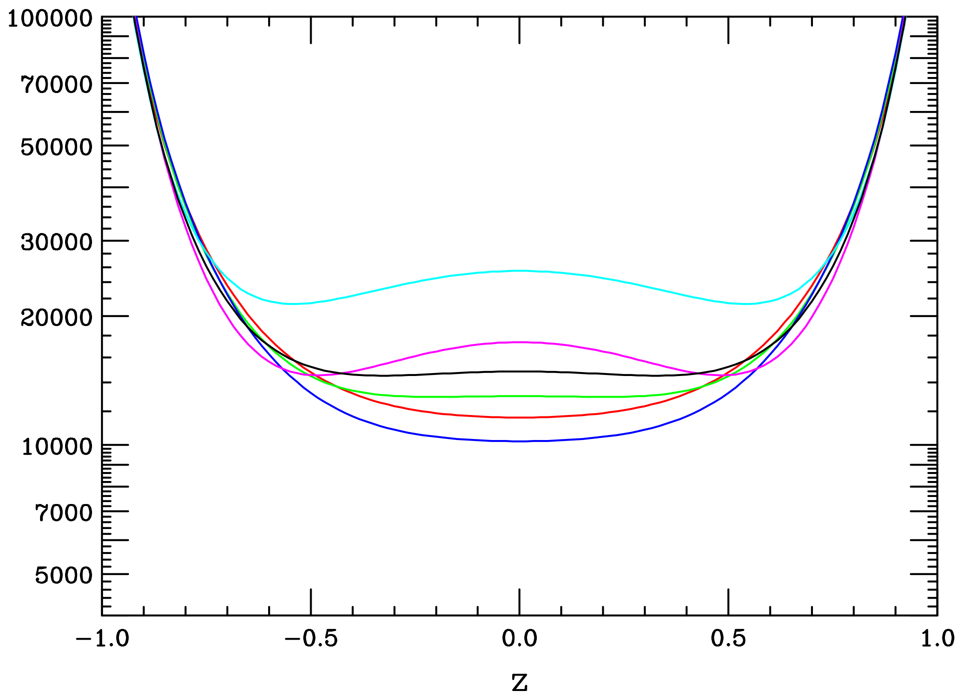
[Choi and Schrempp, 1991]

modern limits typ. $\Delta\kappa$, $\Delta\lambda \sim 10^{-3}$

Extra Dimensions

Rizzo has found out that $\gamma\gamma \to W^+W^-$ is the most sensitive channel for finding extra dimensions.





SUSY and other Exotica

Photons couple directly to charge...

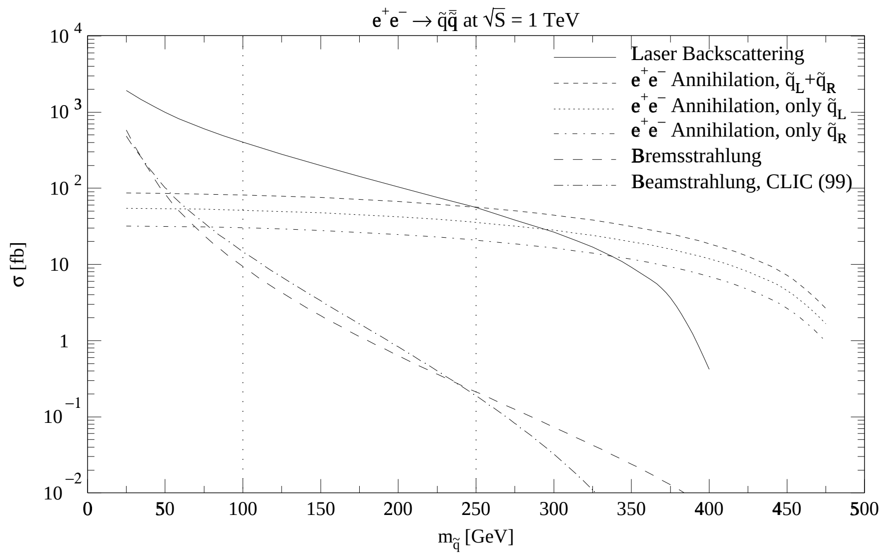
When pairs of particles are produced in e^+e^- annihilations, both the photon and the Z are involved, so the overall strength of the interaction depends on charge and weak isospin. Messy.

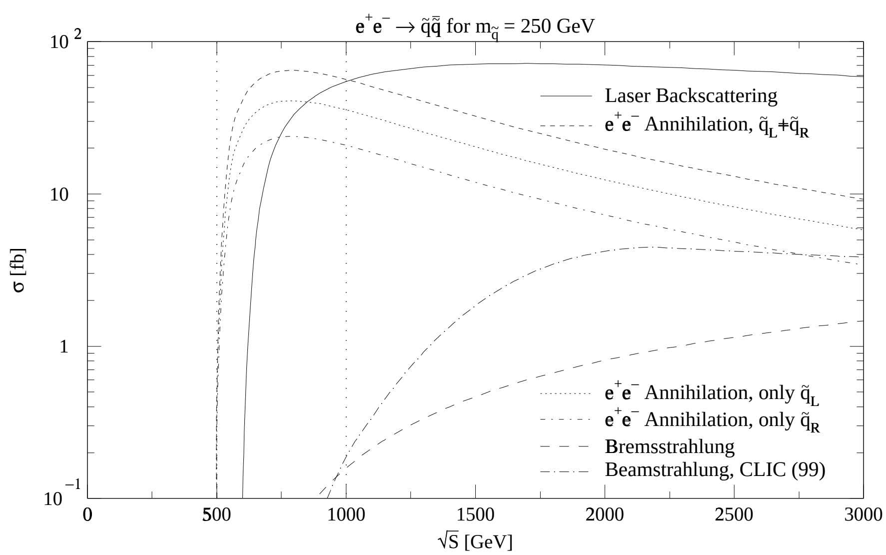
By building a $\gamma\gamma$-Collider you are effectively removing the Z from the picture, so production cross sections are unambiguous.

Another advantage of $\gamma\gamma$-Colliders is kinematic: the production of scalar pairs at threshold is *not suppressed*, affording the possibility of a good mass measurement.

Furthermore, production cross sections are large relative to e^+e^- machines (although reach is not as great).

[Klasen, hep-ph/0008081]





Klasen has recognized the possibility of gluino production through resolved photon processes – it could be viable...

Machine Scenarios

The physics will drive the operation of a $\gamma\gamma$-Collider to varying scenarios (also true for an e^+e^- machine).

These still need to be worked out. But some features of the physics program are becoming obvious:

- low-energy
  h-factory: runnning "on the higgs peak"
  Measure m_h, $\sigma_{\gamma\gamma}$, BR's, $\Gamma_{\rm tot}$, CP properties...
  This may involve an energy scan.
- medium energy
  top properties and top Yukawa coupling, precision gauge boson measurements, anomalous couplings
- broad energy spectrum to find H & A.
  measure H,A masses and main decay modes
  exotics and extra dimensions
  Higgs self-couplings?

Concluding Remarks

Most of the physics that we want to do to understand the EW sector can be done at a $\gamma\gamma$-Collider(or perhaps a series of them).

Some of this physics can also be done at electron and proton machines.

But there are at least three areas in which a $\gamma\gamma$-Collider would play a **crucial role**:

1. Extraction of CP quantum numbers.
   The use of polarized photon beams is an extremely powerful physics tool which is unavailable at electron and proton machines.

2. Production of heavier Higgs states.
   The gamma triangle is more robust that the tree-level couplings of Higgs to vector bosons.

3. $\Gamma_{\gamma\gamma}$, the two-photon partial width.
   This will give a simple and powerful distinction between the SM and 2HDM (such the MSSM) with a light SM-like Higgs.

If precision studies of the electroweak sector (Higgs, W, Z, superpartners, etc.) at an e^+e^- machine are the way to see exiting new physics at high energy scales, then perhaps a high energy $\gamma\gamma$-Collider will provide the binoculars you need to see clearly.