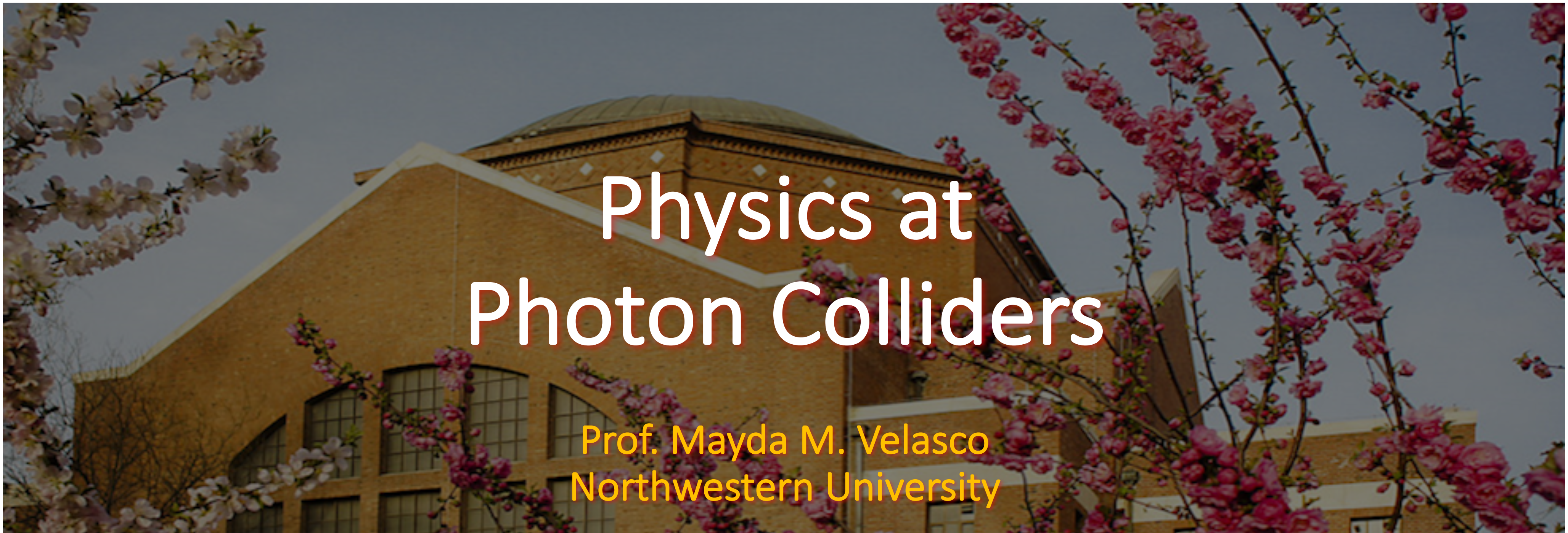


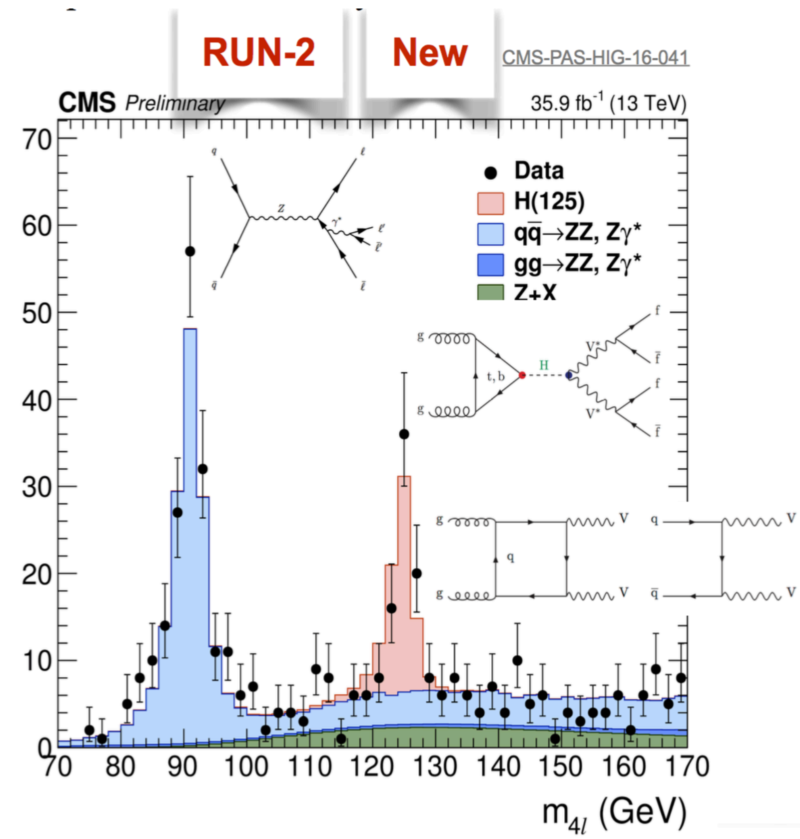
Physics at Photon Colliders

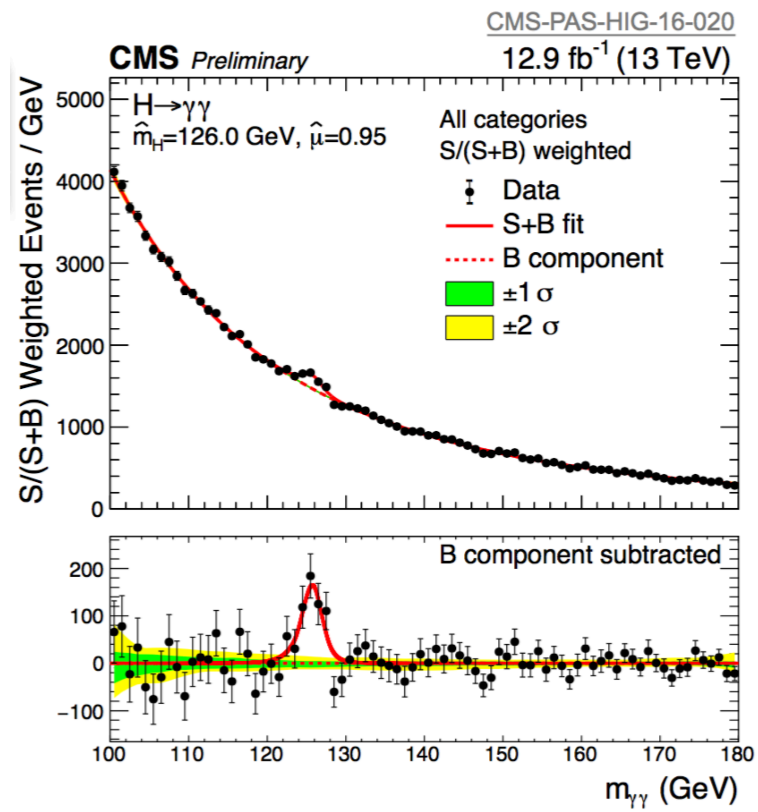
Prof. Mayda M. Velasco
Northwestern University

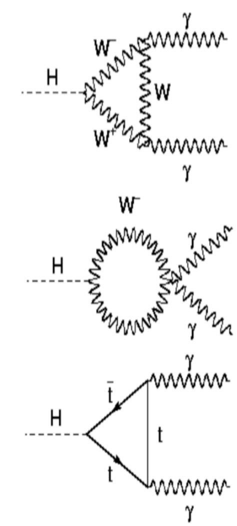
ICFA Mini-Workshop on Future gamma-gamma Collider

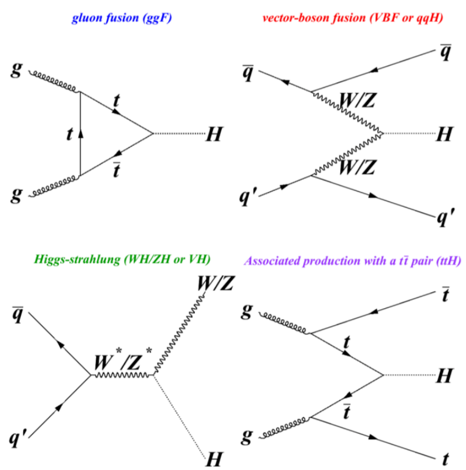
April 23-26, 2017 Tsinghua University Beijing China

Higgs Boson discovered in 2012 at the LHC using 8 TeV data and is still there at 13 TeV ☺

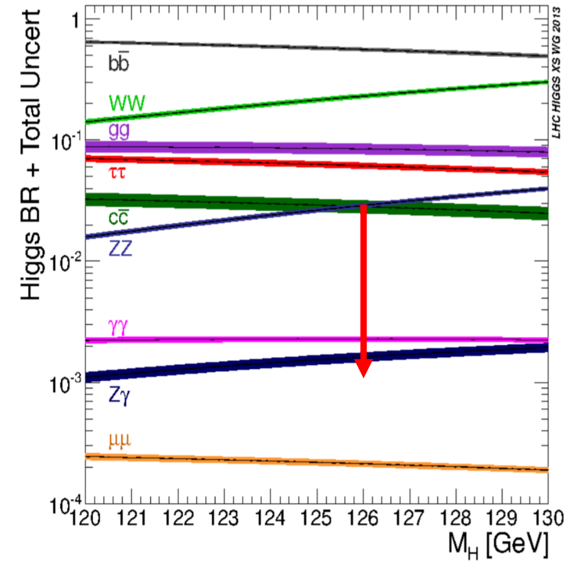


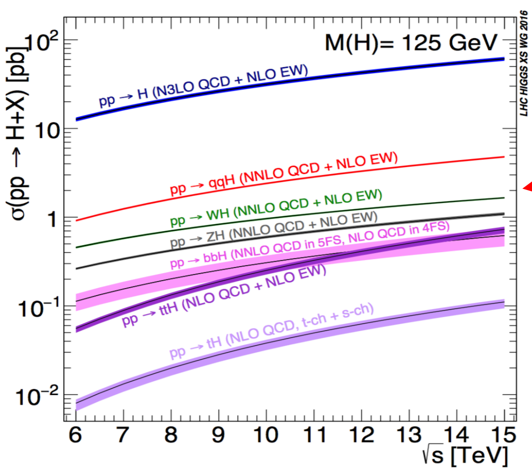


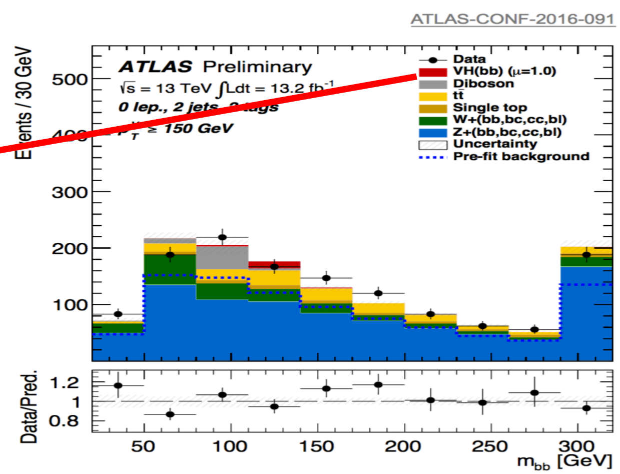




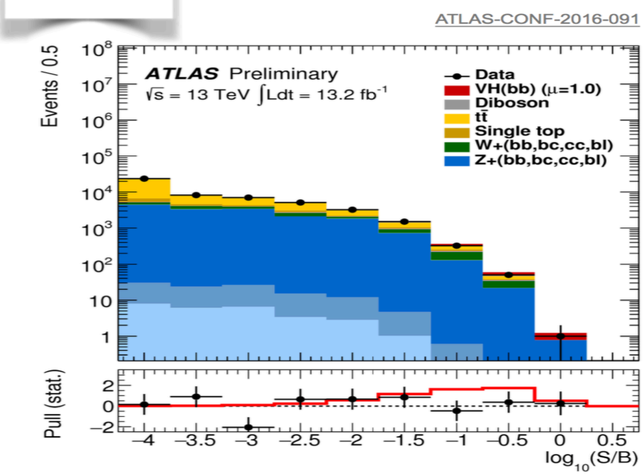
- @LHC the Higgs is better detected in rare decays like γγ and ZZ→4L
  - Reflecting the power of Signal/Power
- Sensitivity of Higgs to fermions (g_F) comes from the gg to H production and dominated by the top quark
- See example for H to bb ➔ we need to do this elsewhere like @γγC





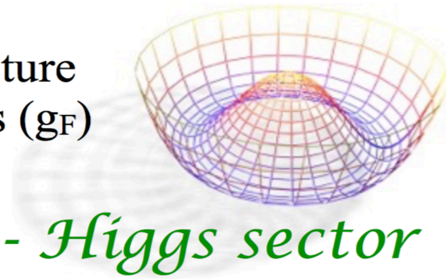


RUN-2



The discovery of Higgs Boson has created as many questions as it has answer

K. Cranmer

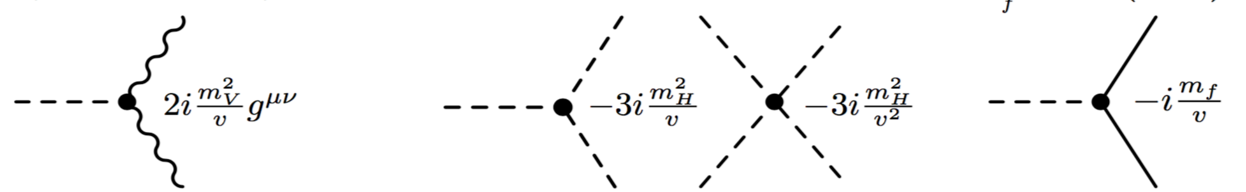


1. Higgs boson mass (M_H) & decay width (Γ_H)
2. Higgs boson quantum numbers J^{PC} and tensor structure
3. Higgs couplings to gauge bosons (g_V) and fermions (g_F)
4. Higgs potential - Higgs self-coupling (λ)

The Standard Model Lagrangian - Higgs sector

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons	Higgs self-couplings	Couplings to fermions
$[m_W^2 W^{\mu +} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0] \cdot (1 + \frac{h}{v})^2$	$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$	$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$

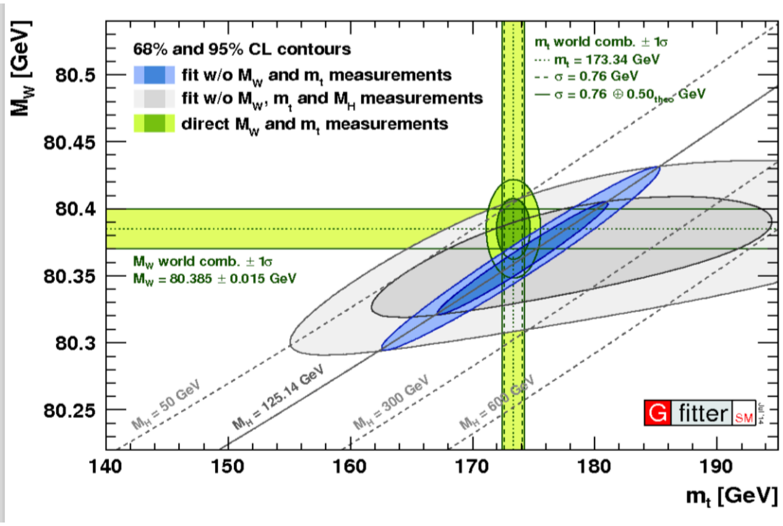


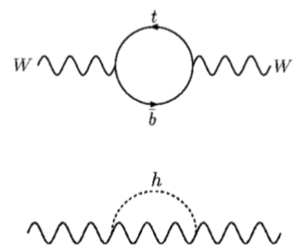
$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \ (v = \text{vacuum expectation value, } 246\,\text{GeV})$$

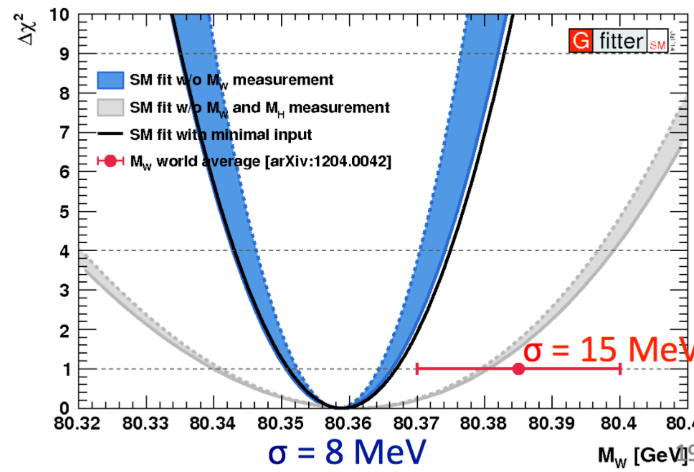
Are (1)-(3) measured precise enough @ LHC to be sensitive the relevant PBSM?

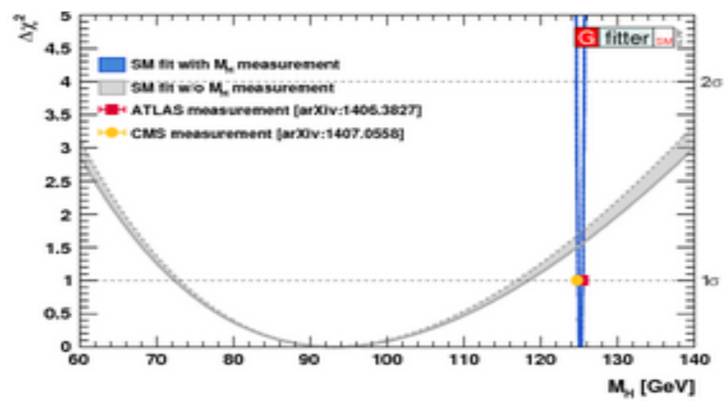
(4) What is the exact shape of the Higgs potential?

Examples of the M_H measurements/predictions before and after discovery









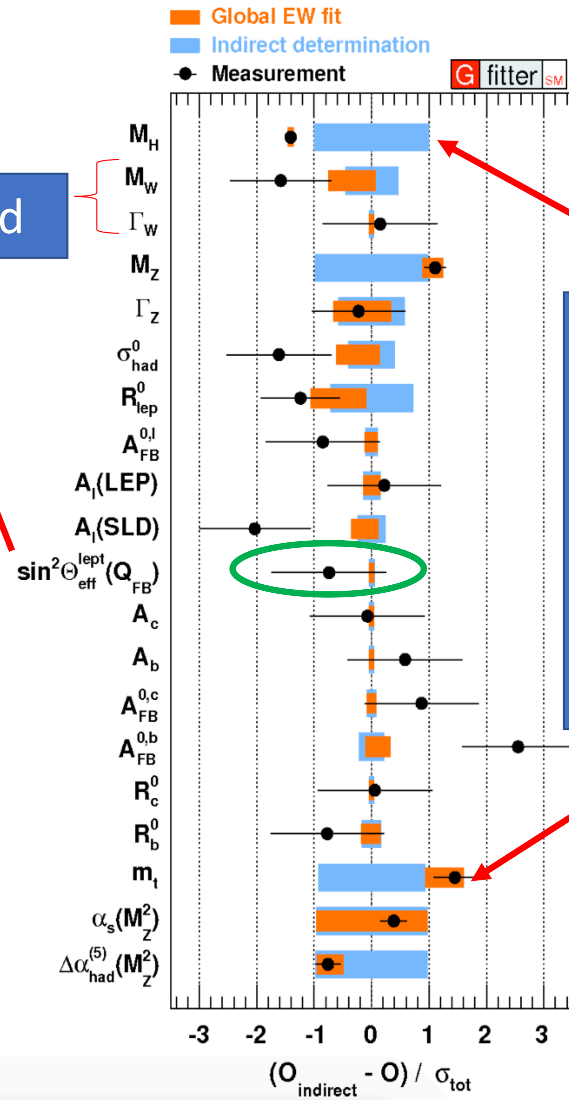
- Combination of precise measurements of m_W, m_{top}, m_H provides critical test of SM if $\sigma(m_W) \lesssim 6$ MeV
- Huge challenge at LHC
- Recent ATLAS result: $\sigma(m_W) = 19$ MeV
- m_W measurement is the bottleneck, where the experimental uncertainty is worse than the theoretical one

➔ We need to do this elsewhere like @γγC

LHC Data making clear the need for future machines

Poorly measured

- Discovered the Higgs Boson @125 GeV
- Excluded Physics Beyond the Standard Model (PBSM) at relatively low masses:
  - < few TeV in many models
- Need to include Precision Electroweak measurements to have sensitivity to PBSM not accessible direct at the LHC



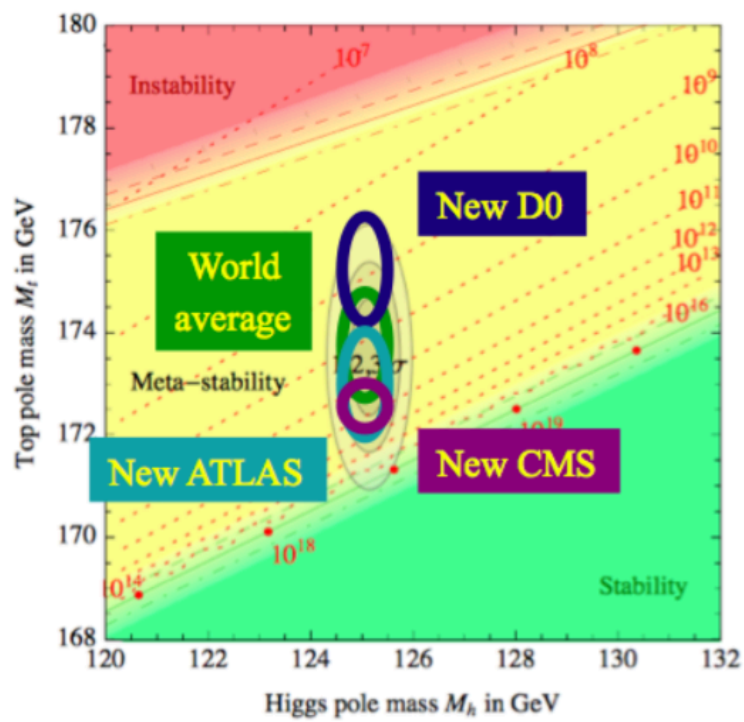
Pointing to Physics Beyond Standard Model of Particle Physics?

Already signs from new physics in the Higgs data by comparing M_{top} with M_H?

- Dashed lines: Calculation of the regions of the (m_H, m_{top}) plane where the electroweak vacuum is stable, metastable or unstable, and yields the following estimate of the "tipping point" Λ_I, where λ goes negative

- The final result is an estimate:
  - $\log_{10} (\Lambda_I /\mathrm{GeV}) = 9.4 \pm 1.1$

indicating to some experts that we are (probably) doomed, unless some new physics intervenes.



Based on what we have learned at the LHC

1. E_{ee}=160 GeV or $E_{\gamma\gamma} = M_H$
   - We need a "low" energy $\gamma\gamma$C to study the Higgs in more detailed
   - Branching ratios not accessible with precisions at the the LHC (i.e. $H \rightarrow bb$) and precision measurements of those that loop induced (i.e. $H \rightarrow \gamma\gamma$)
   - Look for new physics in the Higgs sector:
     - CP admixture
     - Flavor violating decays like $H \rightarrow e\mu$, $\mu\tau$ and $e\tau$
     - Dark sector H → dark photons → fermions
   - Precise measurements of W properties (m_W, Γ_W and W Branching fraction) using $e^- \gamma \rightarrow W\nu$
   - Precise measurements of $\sin^2\theta_W$ from $e^-e^- \rightarrow e^-e^-$
2. $E_{\gamma\gamma}$ above 2 x M_W to 2 x M_H, that is 200 to 300 GeV

First steps: as discussed in the past,
$\gamma\gamma$C as Higgs Factory and associated e^-e^-C and $e^-\gamma$C

See talk from
Ziheng Chen

e^-e^-C

Running of $\sin^2\theta_W$

$e^-e^- \rightarrow e^-e^-$

$\gamma\gamma$C

Higgs CP Mixing and Violations

$e^-\gamma$C

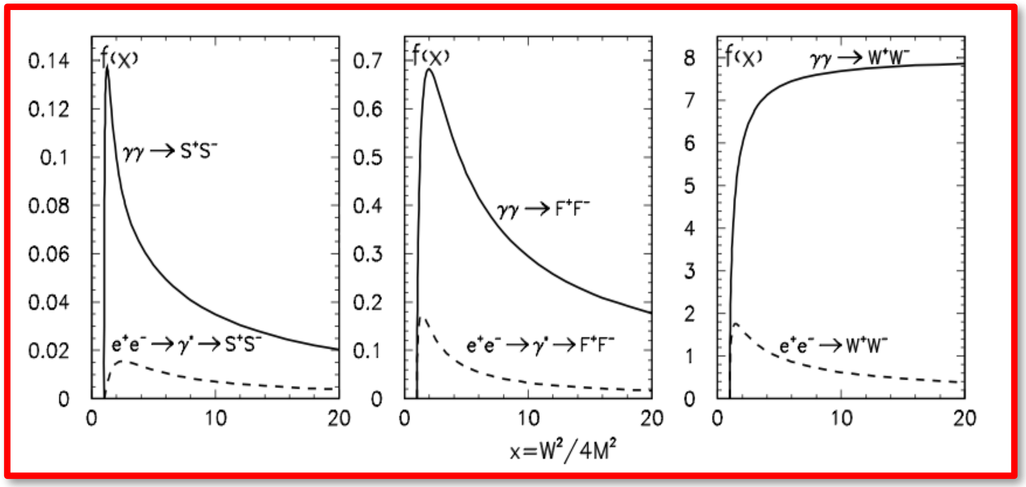
M_W & Γ_W $e^-\gamma \rightarrow W\nu$

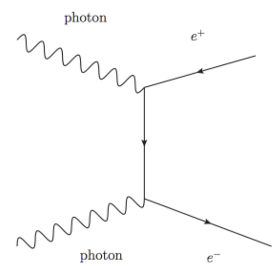
and γ-Structure

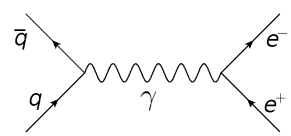
- Well defined CP-states, with *linearly* $(\lambda = 0)$ polarized γ's
  $\Rightarrow (\gamma_\| \parallel \gamma_\|) \quad \Rightarrow$ CP-even
  $\Rightarrow (\gamma_\| \perp \gamma_\|) \quad \Rightarrow$ CP-odd

What is special about $\gamma\gamma$C ?

- **#1: Higher sensitivity due to higher cross sections**

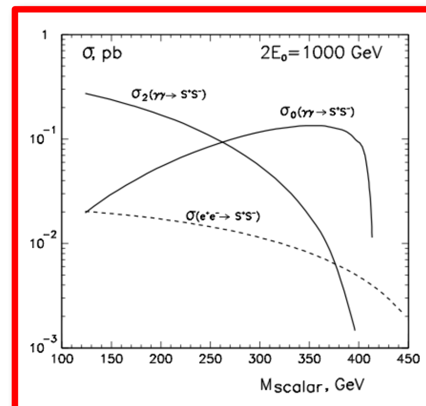






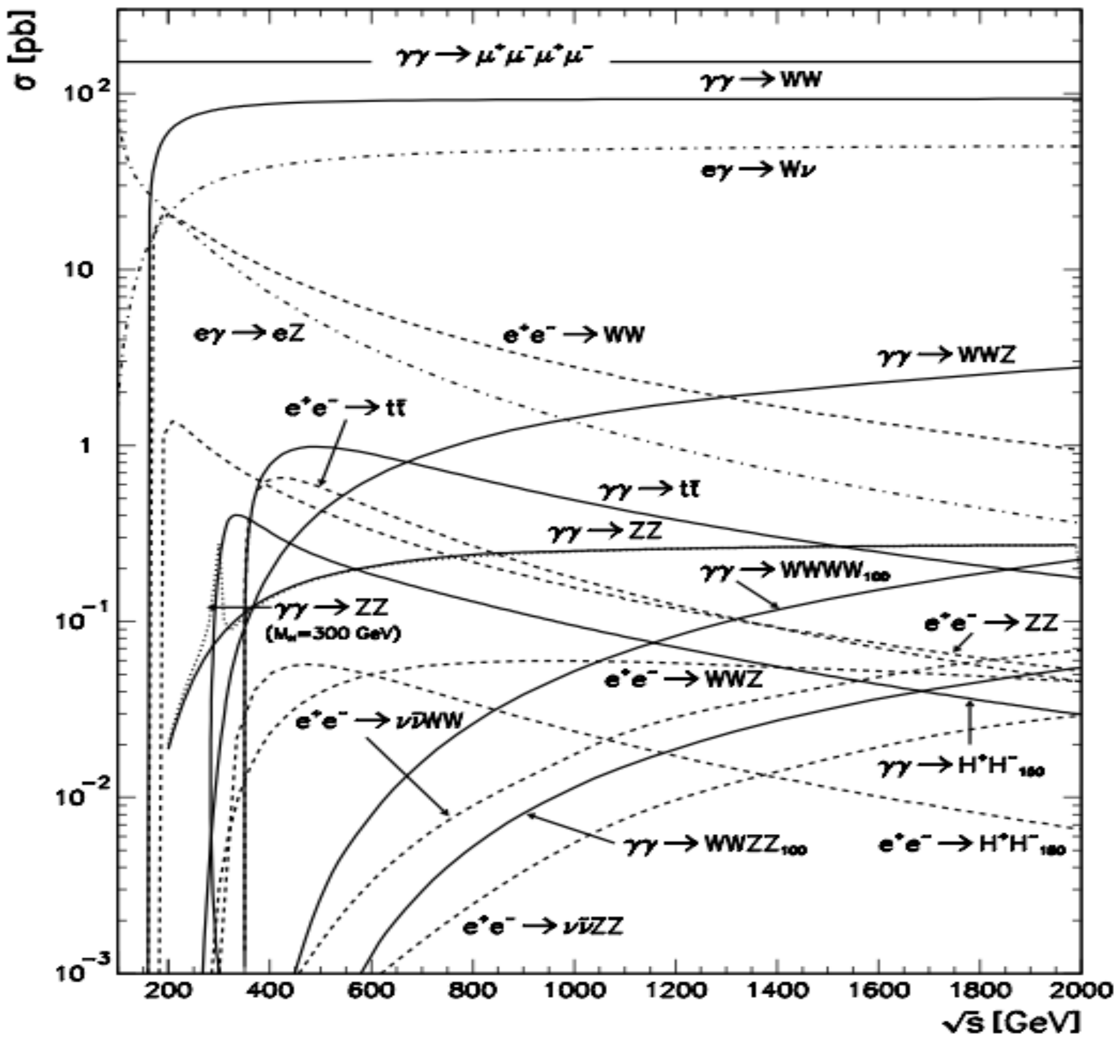
W = invariant mass (c.m.s. energy of colliding beams)

M = mass of scalar (S) or fermion (F)



and ability to manipulate the photon beam polarization to produce J_z of $\gamma\gamma$ system is = 0 or 2

Example of Standard Model Processes



What is special about γγC ?

- **#2: Unique role in understanding CP structure due to the possibility of having linearly polarized beams that allow us to have:**

- Well defined CP-states, with *linearly* ($\lambda = 0$) polarized γ's
  $\Rightarrow (\gamma_{\|} \parallel \gamma_{\|}) \Rightarrow$ CP-even
  $\Rightarrow (\gamma_{\|} \perp \gamma_{\|}) \Rightarrow$ CP-odd

- **Change polarization of *circularly polarized* photon beams ($\lambda = \pm 1$) as needed to measure asymmetries for J_Z=0 produced from:**

λ_1, λ_2 = (+, +) and λ_1, λ_2 = (-, -)

What is special about γγC ?

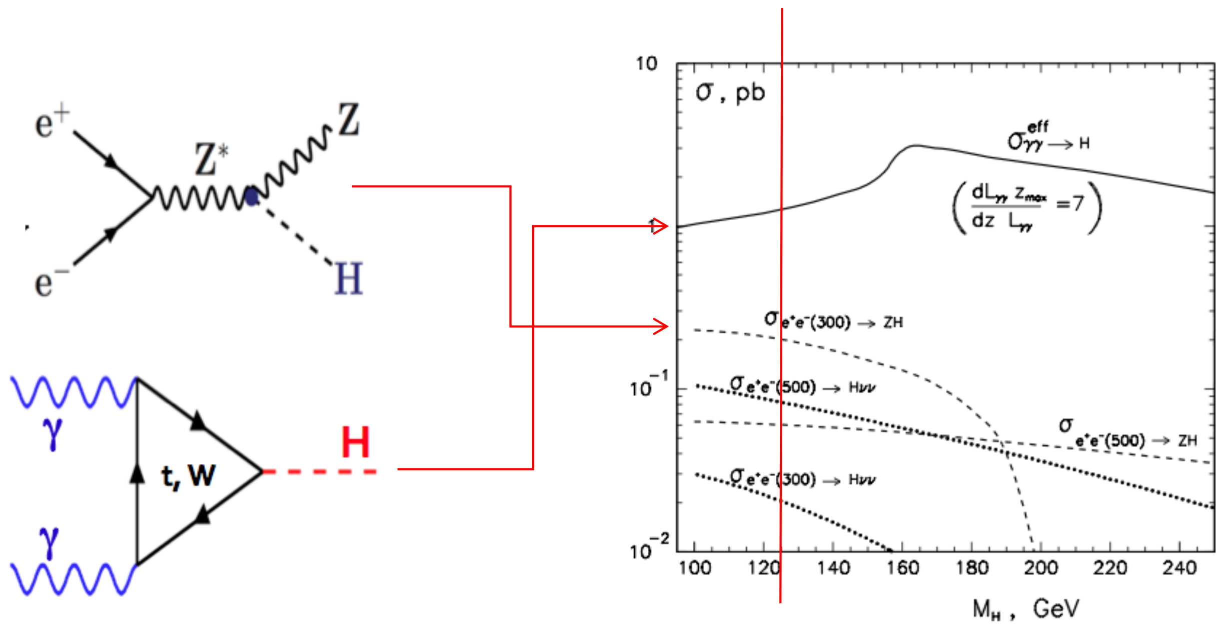
- **#2: Unique role in understanding CP structure due to the possibility of having linearly polarized beams that allow us to have:**

- Well defined CP-states, with *linearly* $(\lambda = 0)$ polarized γ's
$\Rightarrow (\gamma_{\|} \ \| \ \gamma_{\|}) \quad \Rightarrow \quad$ CP-even
$\Rightarrow (\gamma_{\|} \ \perp \ \gamma_{\|}) \quad \Rightarrow \quad$ CP-odd

We are still searching for the source of matter anti-matter asymmetry observed for visible matter in our universe;
➔therefore looking for new sources of CP is crucial !

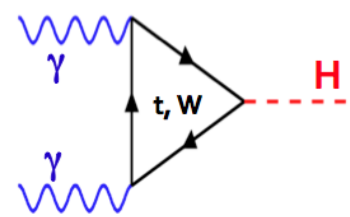
What is special about γγC ?

- **#3: Special role in understanding Higgs mechanism due to larger cross sections and the fact that Higgs is produced as an resonance:**



Physics Motivation of $\gamma\gamma$C Higgs factory

- **Important measurements that can only be done with high precision at the $\gamma\gamma$C assuming at least 10,000/year**
  - **$\Gamma_{\gamma\gamma}$ to 2% (Model independent)**
    - **Results in a 13% on Γ_{Total}**
    - **Results in a Y_{tt} of 4%**
  - **Measure CP mixing and violation to better than 1%**
  - **At higher energies Higgs self coupling: λ_{hhh} to a few %**



$\Gamma_{\gamma\gamma}$
proportional to
$\Gamma_{Fermions}$ - $\Gamma_{Vectors}$ - $\Gamma_{Scalars}$
in the loop

Practical motivation of $\gamma\gamma$C Higgs factory

- **Development of compact $\gamma\gamma$C starting from e^-e^- :**
  - **Based on already existing accelerator technology**
  - **Polarized and low energy e^- beam: E_e = 80 GeV and (λ_e= 80%)**
  - **Cost of building and operation is lower than other machines (excluding laser… to be discussed here)**

- **Required laser technology is becoming available**

Designs that will produce $\geq$10K Higgs/year (10^7s)

- **HFiTT:** **Higgs Factory in Tevatron Tunnel (Fermilab specific)**
- **SILC:** **SLC-ILC-Style $\gamma\gamma$ Higgs Factory (SLAC specific)**
- **SAPPHiRE:** **Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons (Can be built elsewhere)**
- **CLICHÉ :** **CLIC Higgs Experiment**
- **Plus designed to come out of this meeting**

- **Detector and beam environment not more difficult than what we are experiencing at the LHC**

➔ 3 machines in 1: e^-e^-, $e^-\gamma$, $\gamma\gamma$

Just for reference: Primary Parameters

Parameter	HFiTT	Sapphire	SILC	CLICHE
cms e-e- Energy	160 GeV	160 GeV	160 GeV	160 Gev
Peak $\gamma\gamma$ Energy	126 GeV	128 GeV	130 GeV	128 GeV
Bunch charge	2e10	1e10	5e10	4e9
Bunches/train	1	1	1000	1690
Rep. rate	47.7 kHz	200 kHz	10 Hz	100 Hz
Power per beam	12.2 MW	25 MW	7 MW	9.6 MW
L_ee	3.2e34	2e34	1e34	4e34
L_gg ($E\gamma\gamma$ > 0.6 Ecms)	5e33	3.5e33	2e33	3.5e33
CP from IP	1.2 mm	1 mm	4 mm	1 mm
Laser pulse energy	5 J	4 J	1.2 J	2 J

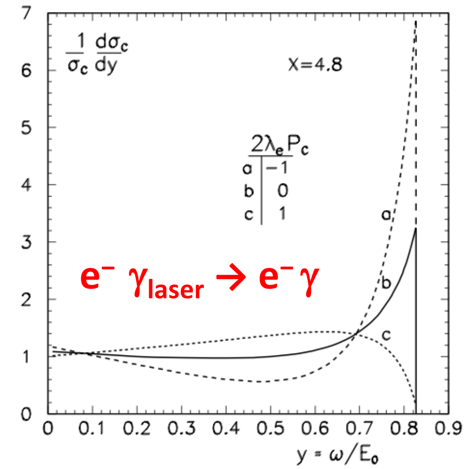
35-50 $fb^{-1}s^{-1}$

Total electric power		< = 100 MW

γ_{laser}: In all designs a laser pulses of a several *Joules* with a λ~350nm (3.53 eV) for E_{e-} ~ 80 GeV

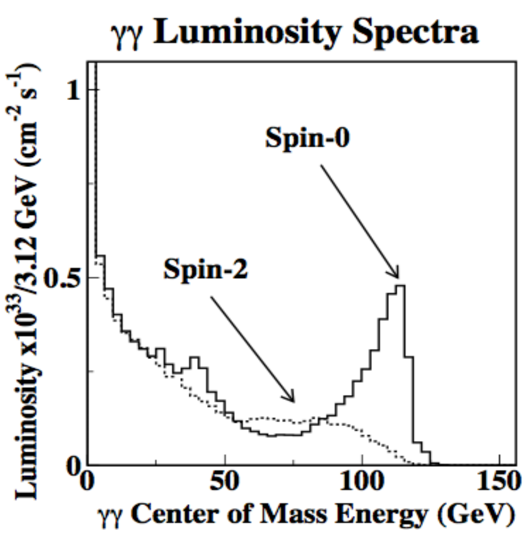
Idea of γγC Based on Compton Backscattering (see Telnov's talk)

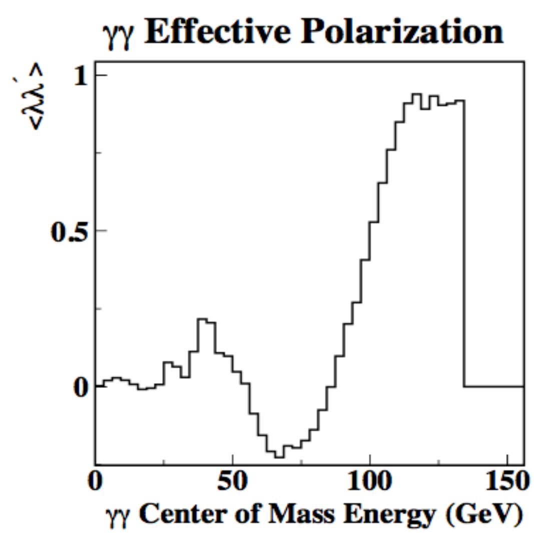
With circularly polarized γ_{laser} ($P_C = \pm 1$) & polarized e- ($\lambda_e = \mp 1$)



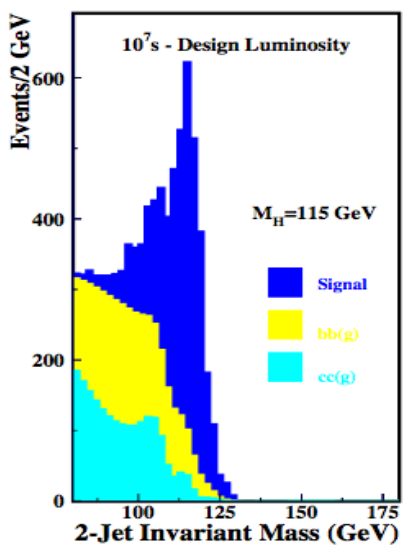
Example:
γγC Optimized as a Higgs Factory

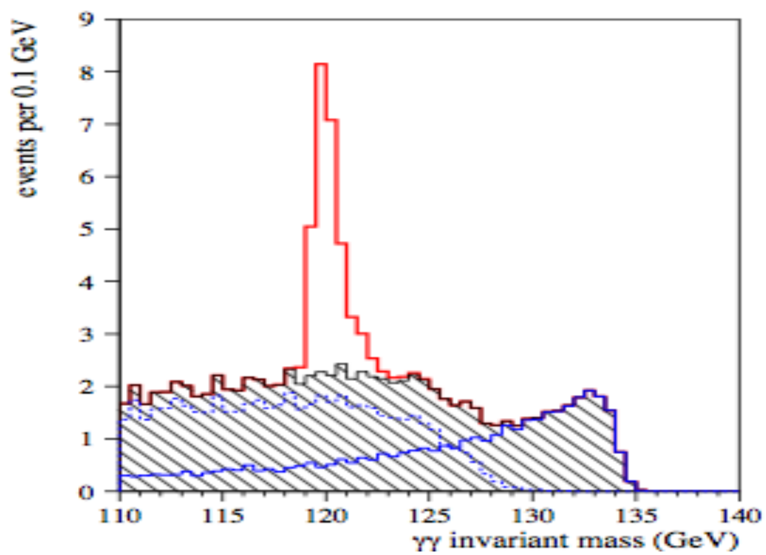
$\sigma(\gamma\gamma \rightarrow H) > 200$ fb





$h^0 \longrightarrow b\bar{b}$ and $h^0 \longrightarrow \gamma\gamma$ hep-ex/0110056





2% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \rightarrow b\bar{b})\}$ within a year!

21% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \rightarrow \gamma\gamma)\}$ within a year!

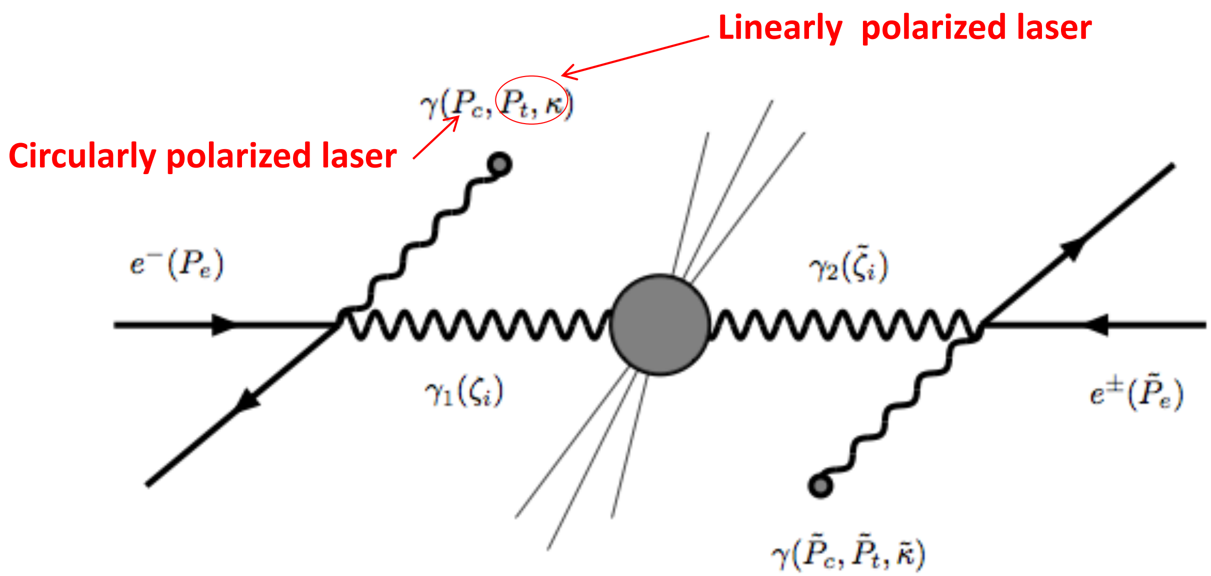
150 MeV mass measurement in 0.5 year!

γγC Higgs-factory

Table 1: Precision of measurements to be performed at HFiTT after 5 years of data taking

Measurement	**Precision after 5 years of operation**	**Comment**
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to \bar{b}b)$	0.01	
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to WW^*)$	0.03	Leptonic decays only
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to \gamma\gamma)$	0.12	
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to ZZ^*)$	0.06	One Leptonic and one hadronic decay
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to Z\gamma)$	0.20	Leptonic and hadronic decays for Z
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to \tau^+\tau^-)$	-	Work in progress
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to \bar{c}c)$	-	Work in progress
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to gg)$	-	Work in progress
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to \mu^+\mu^-)$	0.38	
$\Gamma_{\gamma\gamma}$	0.02	Using $\mathrm{Br}(h \to \bar{b}b)$ as input
Γ_{total}	0.13	Using $\mathrm{Br}(h \to \bar{b}b)$ as input
H_{tt} Yukawa coupling	0.04	Indirect from $\Gamma_{\gamma\gamma}$
Mass measurement	60 MeV	From $h \to \gamma\gamma$
CP Asymmetry using $h \to \bar{b}b$	<0.01	
CP Asymmetry using $h \to WW^*$	0.04	

γγC Higgs-factory to Study CP Violation in Detail



ζ_2 is the degree of circular polarization

(ζ_3, ζ_1) are the degrees of linear polarization

$\gamma\gamma$ Ideal To Measure CP Mixing and Violation

(ζ_3, ζ_1) are the degrees of linear polarization

ζ_2 is the degree of circular polarization

<u>In s-channel production of Higgs:</u>

$$\overline{|\mathcal{M}^{H_i}|^2} = \overline{|\mathcal{M}^{H_i}|_0^2} \left\{ [1 + \zeta_2 \tilde{\zeta}_2] + \mathcal{A}_1 \left[\zeta_2 + \tilde{\zeta}_2\right] + \mathcal{A}_2 \left[\zeta_1 \tilde{\zeta}_3 + \zeta_3 \tilde{\zeta}_1\right] - \mathcal{A}_3 \left[\zeta_1 \tilde{\zeta}_1 - \zeta_3 \tilde{\zeta}_3\right] \right\}$$

== 0 if CP is conserved

== +1 (-1) for CP is conserved for A CP-Even (CP-Odd) Higgs

If $\mathcal{A}_1 \neq 0$, $\mathcal{A}_2 \neq 0$ and/or $|\mathcal{A}_3| < 1$, the Higgs is a mixture of CP-Even and CP-Odd states

Possible to search for CP violation in $\gamma\gamma \rightarrow H \rightarrow$ fermions without having to measure their polarization

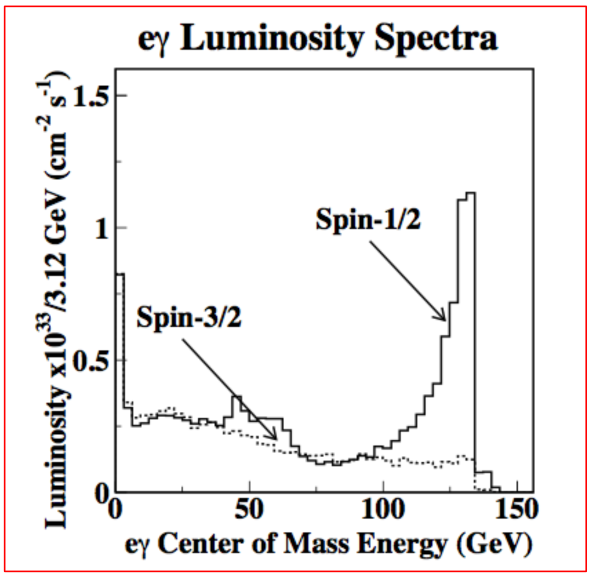
In bb, a ≤1% asymmetry can be measure with 100 fb^{-1} that is, in 1/2 years

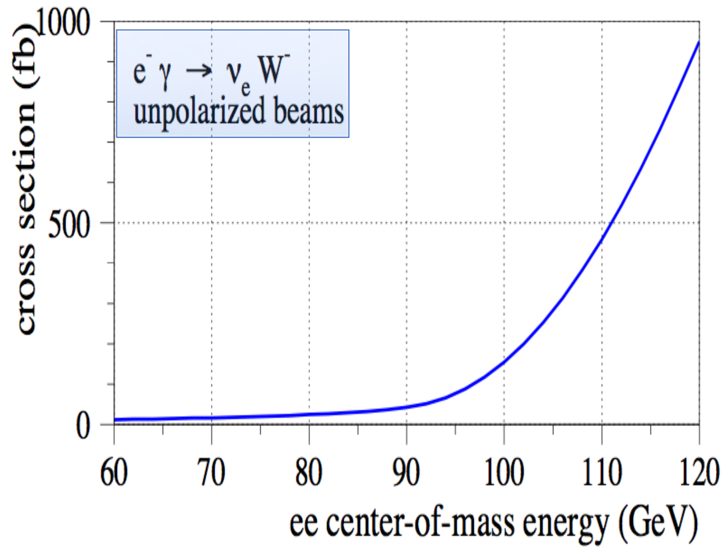
arXiv:0705.1089v2

Only with $\gamma\gamma$C

M_W from $e^- \gamma \rightarrow W^- \nu$

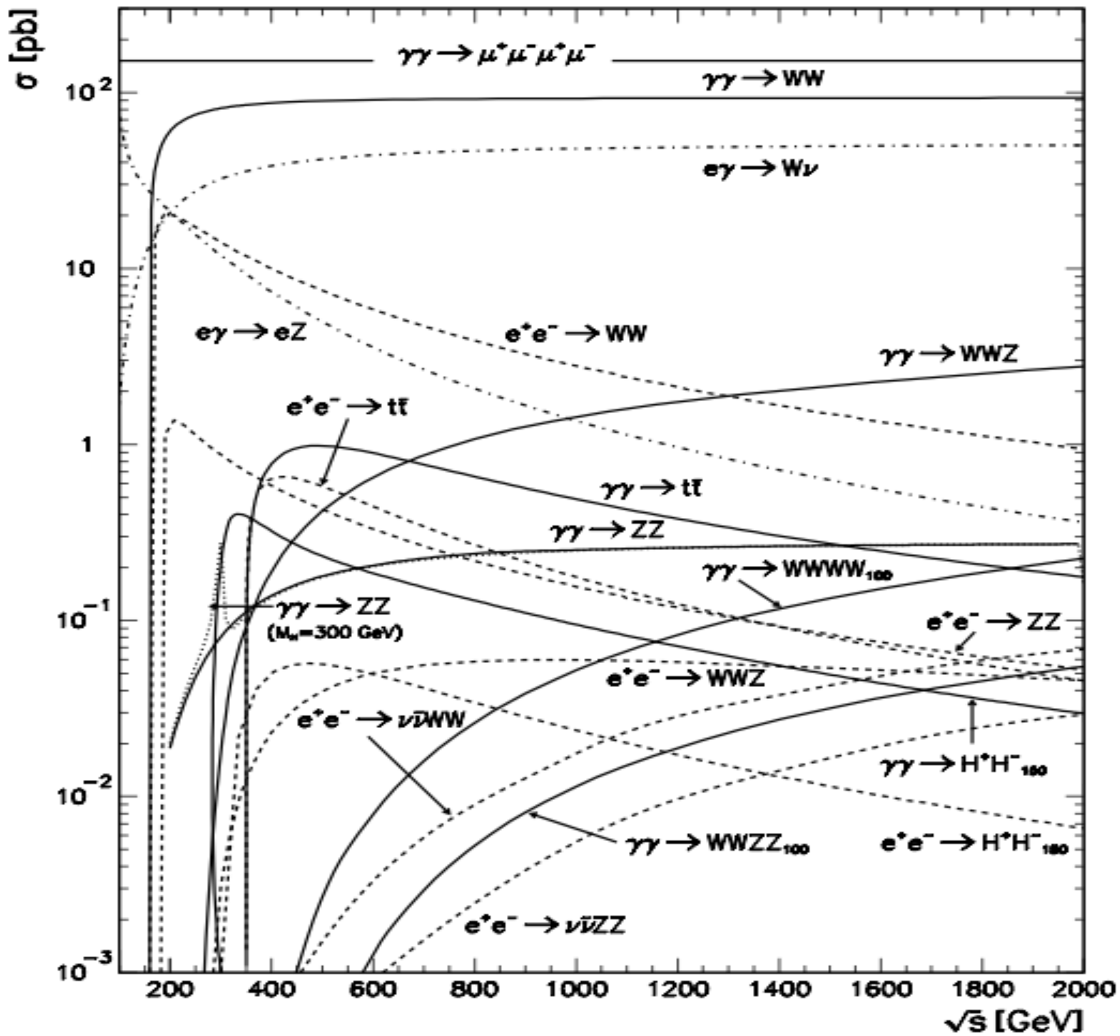
Mass measurement from W → hadron events scan can provide a error < 5 MeV





$e^- \gamma \rightarrow W^- \nu$ vs
$\gamma \gamma \rightarrow W^+ W^-$

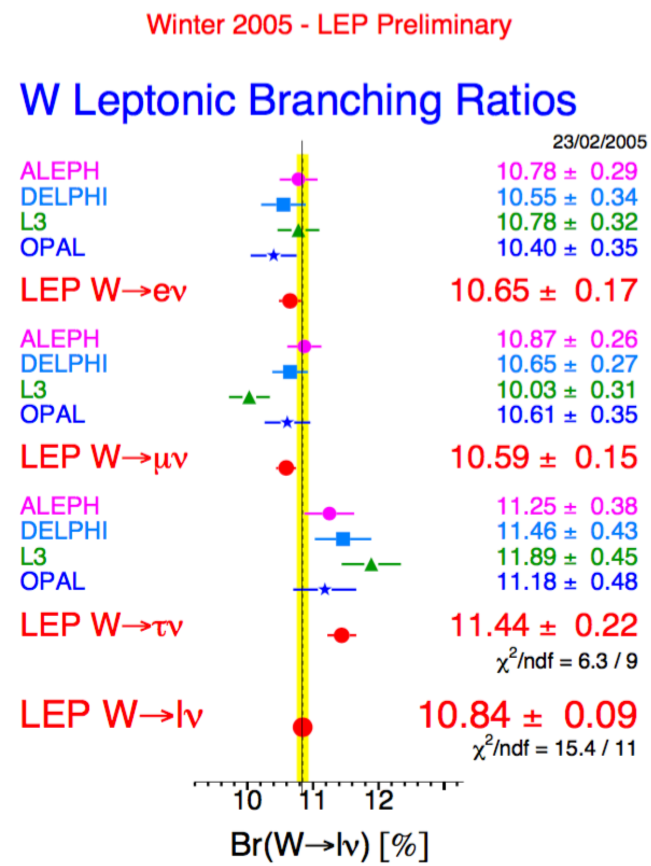
Mass measurement
and width might be event
better to work at
$\gamma\gamma \rightarrow$ WW threshold

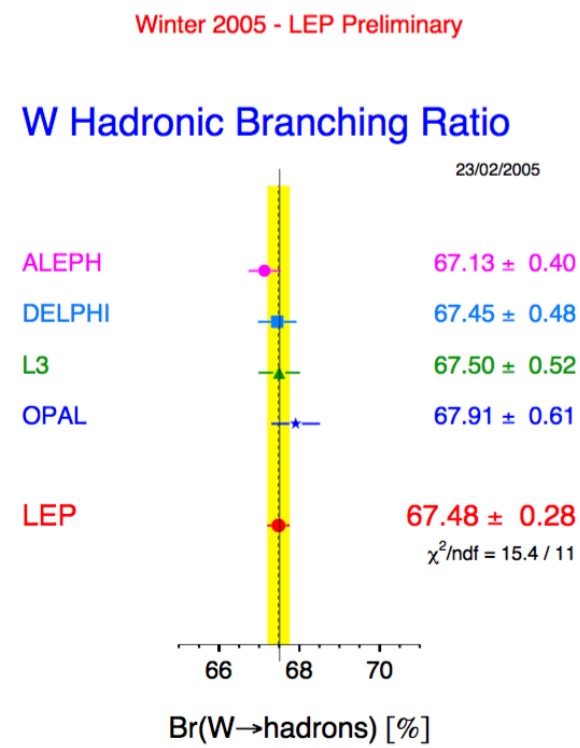


Comment: Interests in W branching fraction to improve tests of lepton unversality

- Lepton universality tested at 1% level

- *τ BR ~2.7 σ larger than e/μ*

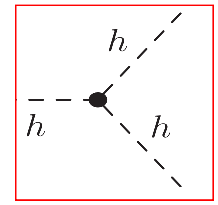




q/ l universality at 0.6%

Higher center of mass

- **Upgrade: Increase energy of the e- beam from 80 GeV to 150 GeV to measure Higgs self coupling**



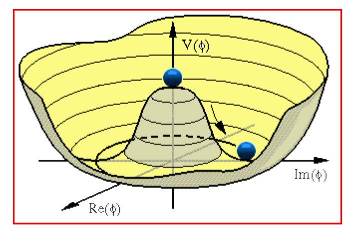
- **The Higgs self couplings measurements one of key topics for the future -- ILC (30%) and LHC (20%) cannot do the full job:**

  - only way to reconstruct the Higgs potential:

$$\lambda_{SM} = \sqrt{\frac{\eta}{2}} m_H$$

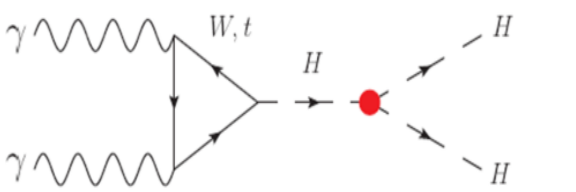
$$V_H = \mu^2 \Phi^+ \Phi + \eta(\Phi^+ \Phi)^2 \;\rightarrow\; \frac{1}{2} m_H^2 h^2 + \sqrt{\frac{\eta}{2}} m_H h^3 + \frac{\eta}{4} h^4 \text{ with :}$$

$$m_H^2 = \eta v^2 / 2 \text{ and } v^2 = -\mu^2 / \eta$$



[1]**Presented by Tor Raubenheimer** *ICFA Higgs Factory Workshop November 14th, 2012*

Higgs Self-Coupling

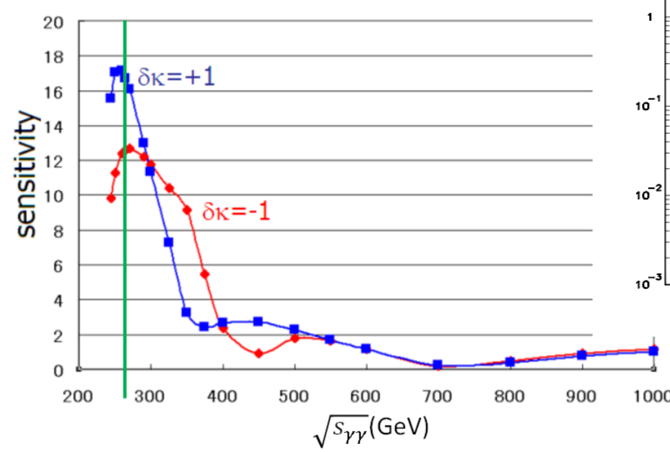


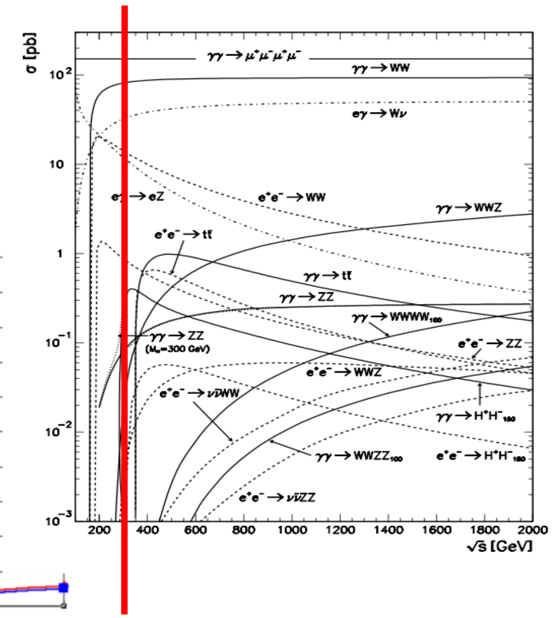
Final goal: Study of Higgs self-coupling

$$\lambda = \lambda^{SM}(1 + \delta\kappa)$$

Self-coupling constant in the SM

Parameter of deviation from the SM





A $\gamma\gamma$ Collider with a center of mass around 300 GeV and ILC characteristics, will produce 80 events in bbbb channel for a 120 GeV Higgs

Possible to suppress background and have large significance after 5 years of data taking

S.Kawada.. et.al, Phys. Rev. D 85, 113009 (2012)

$$S_{Ideal} = \frac{N_{Sg}}{\sqrt{N_{total}}} = 4.9$$

Disclaimer

- Many of these results are old.
- Better simulation and detector designs available
- If a new “official” design comes out of this meeting, I recommend that we repeat and expand these studies

$\gamma\gamma$C Summary

- The Higgs factory $\gamma\gamma$C Physics program is
  - Complementary to other programs (LHC & e-e+)
    - $\Gamma_{\gamma\gamma}$ to 2% (Model independent)
      - Results in a 13% on Γ_{Total}
      - Results in a Y_{tt} of 4%
  - AND nevertheless unique:
    - Precise measurements of CP-admixture < 1% in Higgs
- More physics topics that go well beyond Higgs
  - Other examples: τ factories including g-2
    - $e^- e^- \rightarrow e^- e^- \tau^+ \tau^-$, $e\gamma \rightarrow W\nu \rightarrow \tau \nu \nu$, $\gamma\gamma \rightarrow \tau \tau \gamma$
    - [$\sigma(\gamma \gamma \rightarrow \tau \tau \gamma) > 100$ pb]
- $e^- e^- \rightarrow e^- e^-$ and $e\gamma \rightarrow W\nu$ also important

BACKUP

More Primary Parameters

Parameter	HFiTT	Sapphire	SILC	CLICHE
ε_x / ε_y [μm]	10/0.03	5 / 0.5	6 / 5	1.4 / 0.05
β_x / β_y at IP [mm]	4.5/5.3	5 / 0.1	0.5 / 0.5	2 / 0.02
σ_x / σ_y at IP [nm]	535/32	400 / 18	140 / 125	138 / 2.6