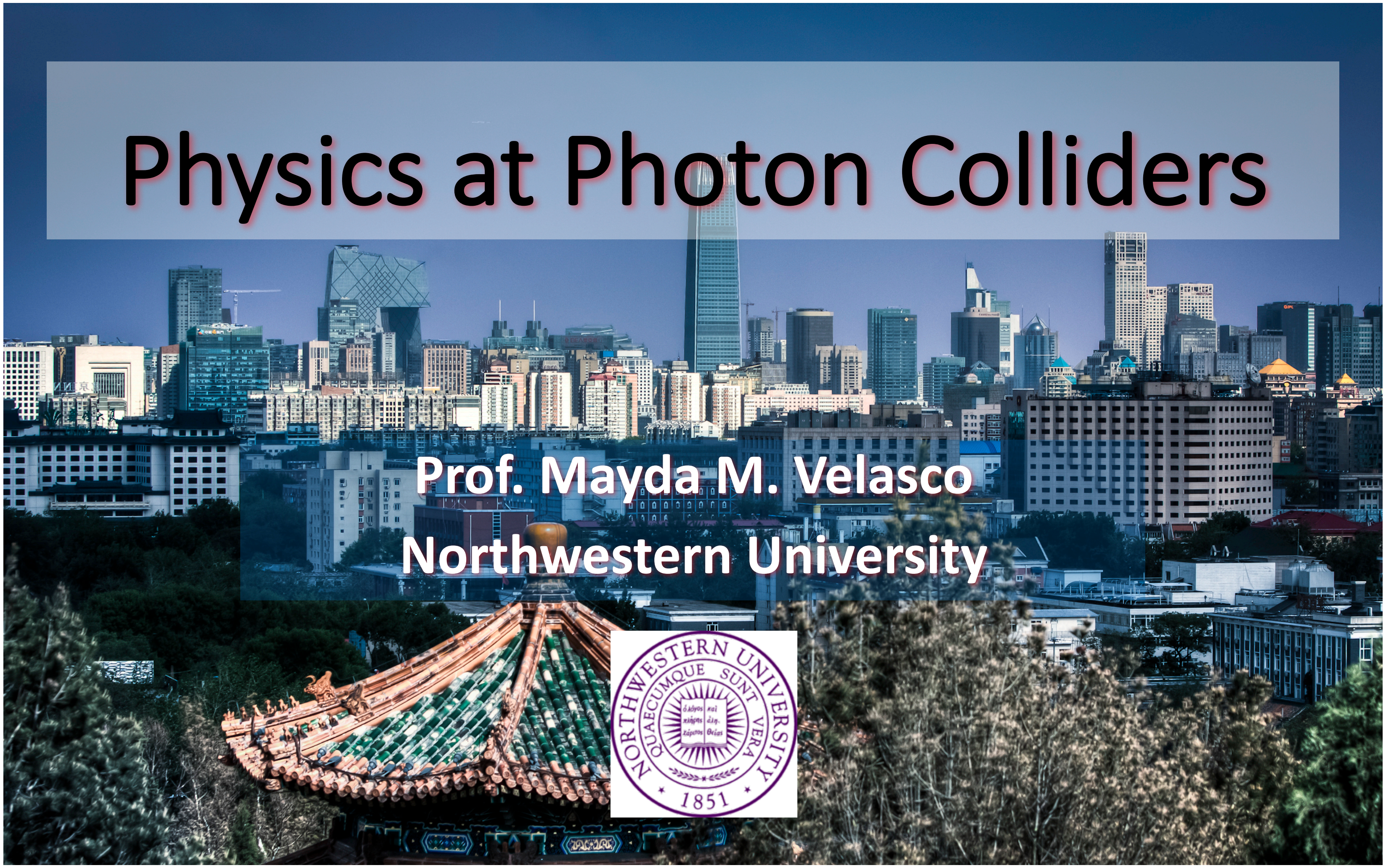
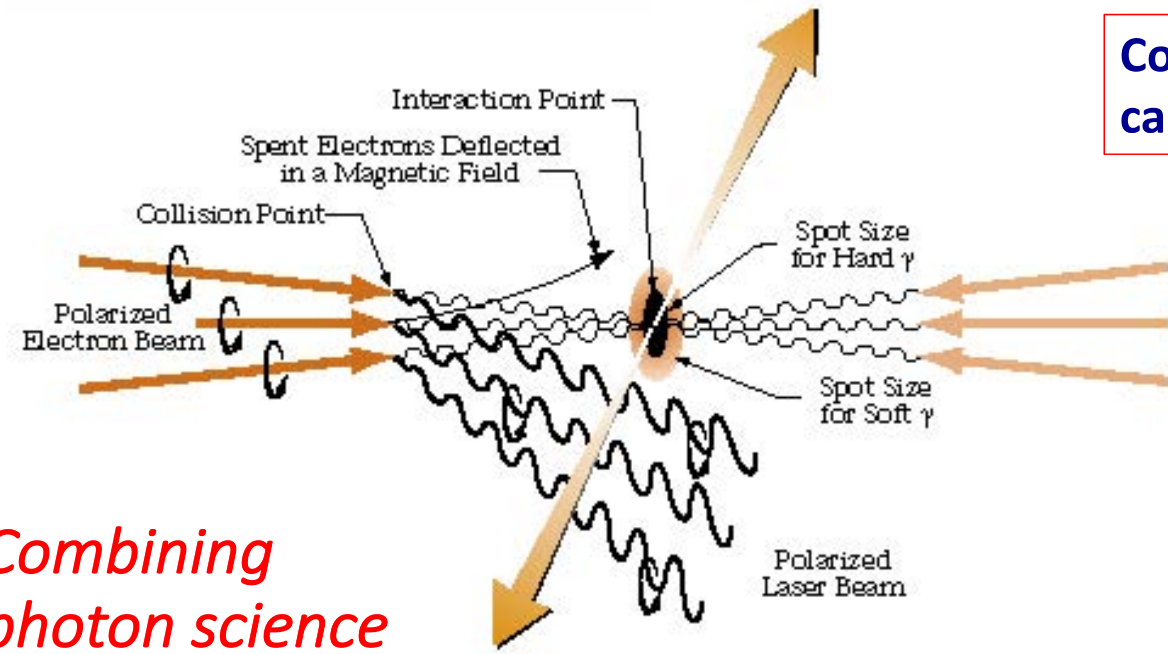


Physics at Photon Colliders

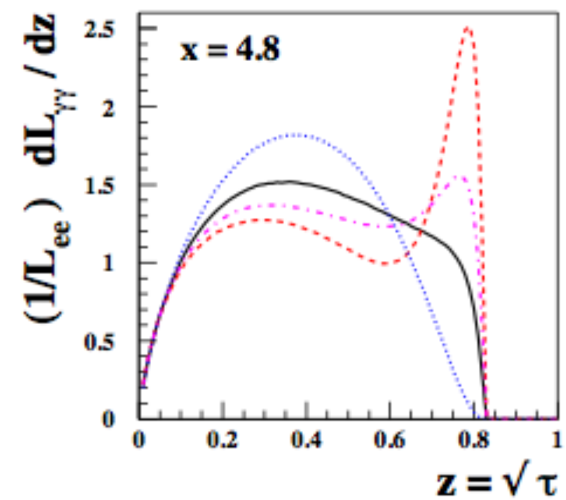
Prof. Mayda M. Velasco
Northwestern University

China CMS group visit **April 26, 2017**

Basics: γγ collider based on e^-e^-



Compton scattering: $e^- \gamma_{laser} \rightarrow e^- \gamma$
can transfer 80% of e- energy to γ

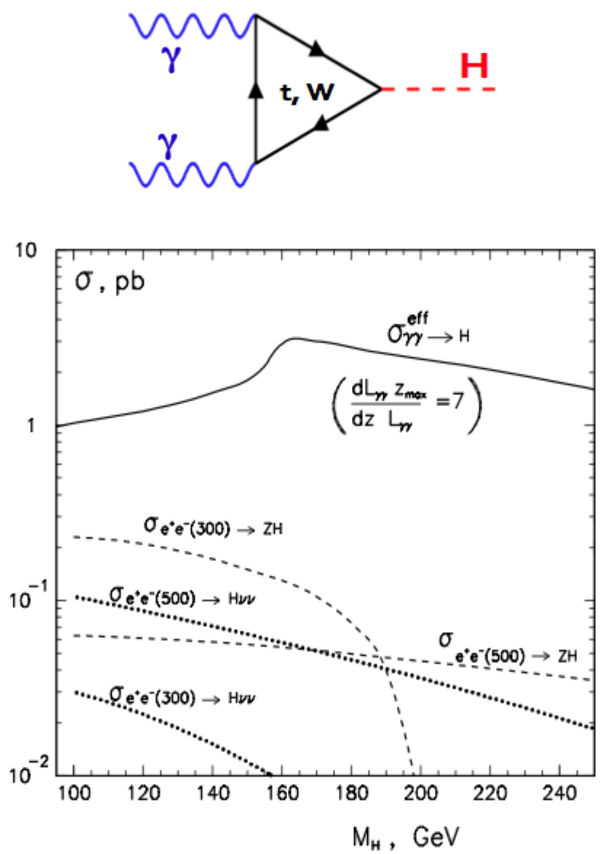


Combining photon science & particle physics!

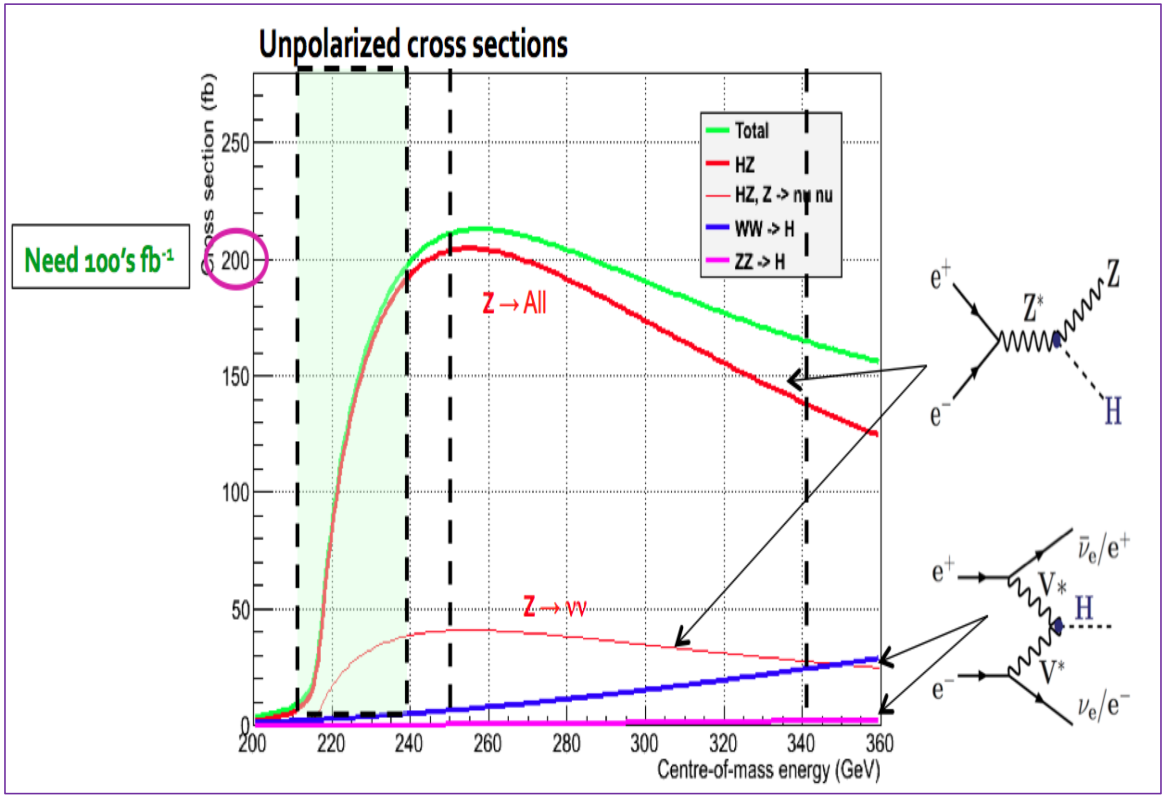
$$\omega_m = \frac{x}{x+1}E_0; \quad x \approx \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3\left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\omega_0}{eV}\right],$$

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

Expected cross sections in $\gamma\gamma$C and e+e-



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



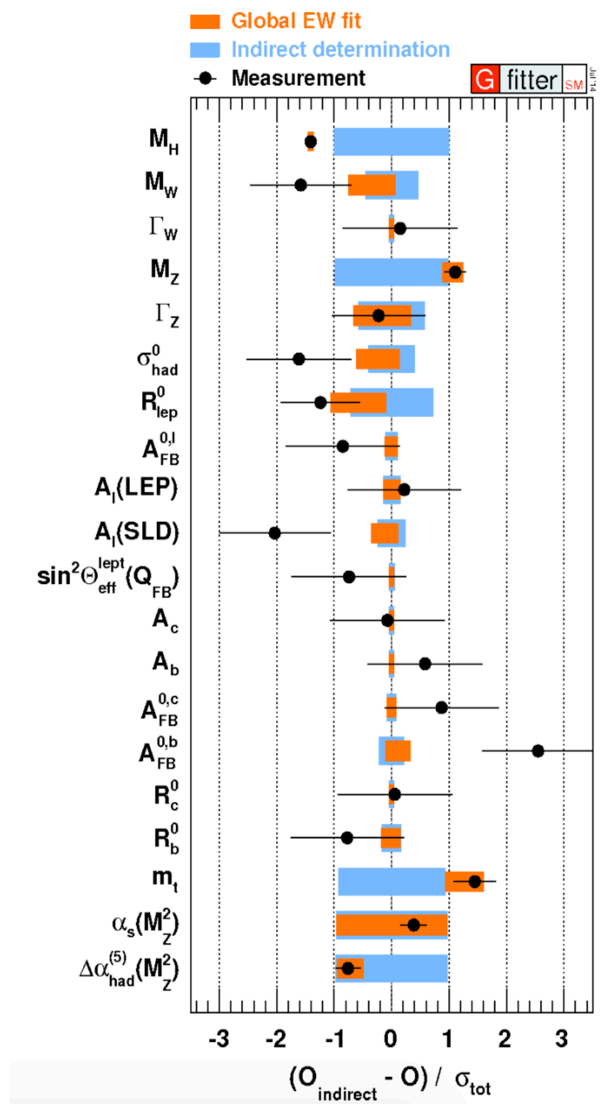
General plan for this talk:

- What have we learn from the LHC and other experiments?
- Where are the opportunities to search for physics beyond the standard model?
- How they compare with $\gamma\gamma$ colliders?
  - Low energy machines $2m_\tau < E_{\gamma\gamma} < 2m_b$
  - Higgs factories $E_{\gamma\gamma} < m_h$

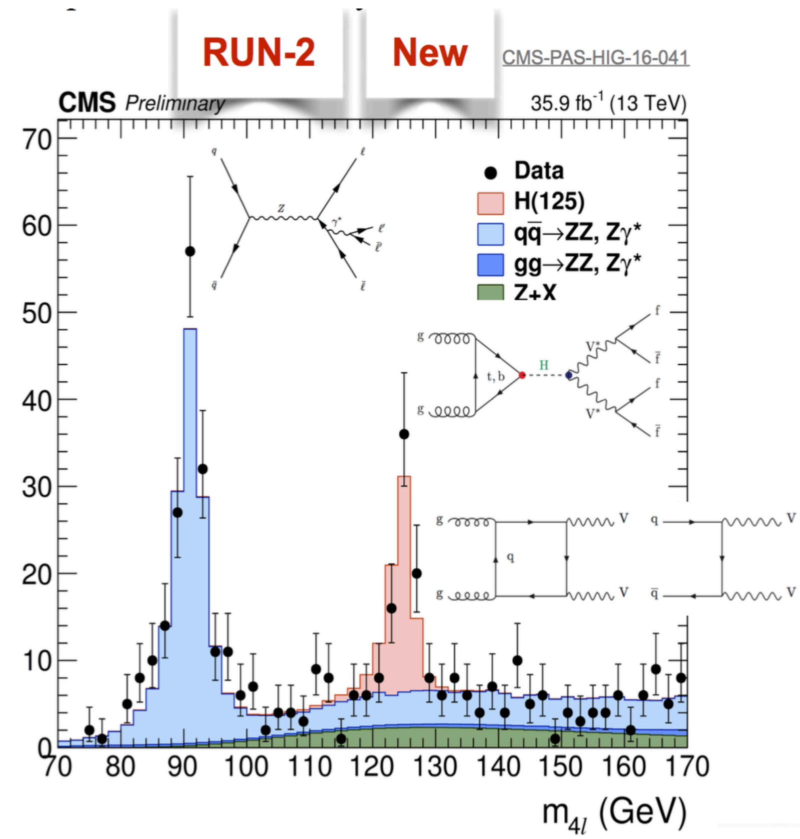
- Other details of alternative machines like e-e-, e-γ and $\gamma\gamma$?

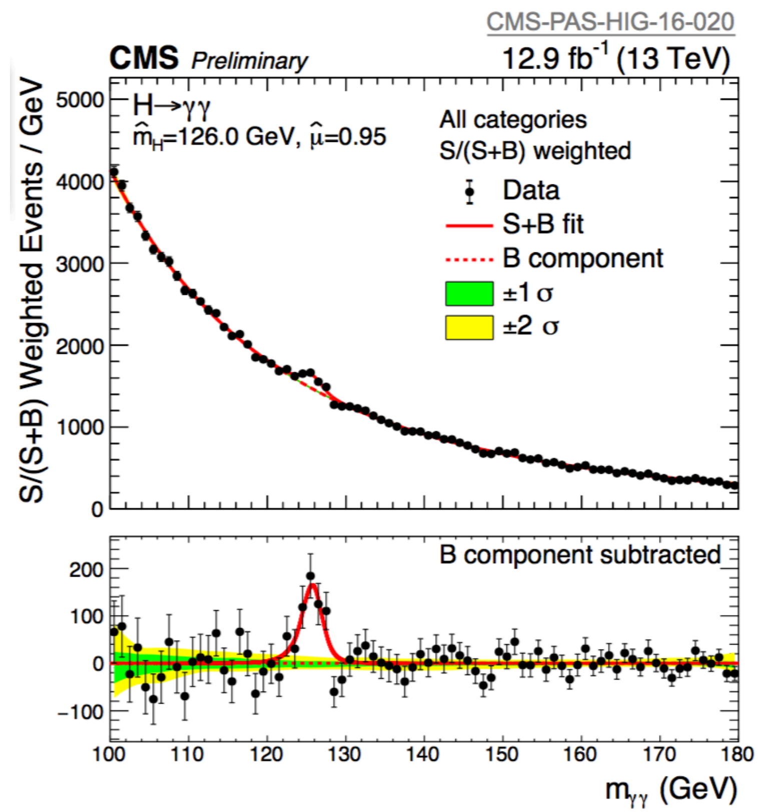
LHC Data making clear the need for future machines

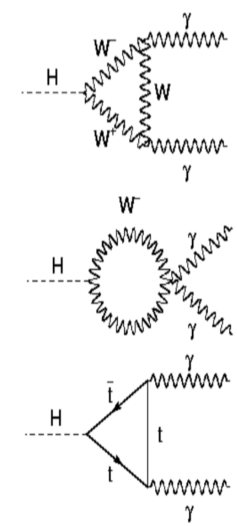
- Discovered the Higgs Boson @125 GeV
- Excluded Physics Beyond the Standard Model (PBSM) at relatively low masses:
  - < few TeV in many models
- Need to include Precision Electroweak measurements to have sensitivity to PBSM not accessible direct at the LHC

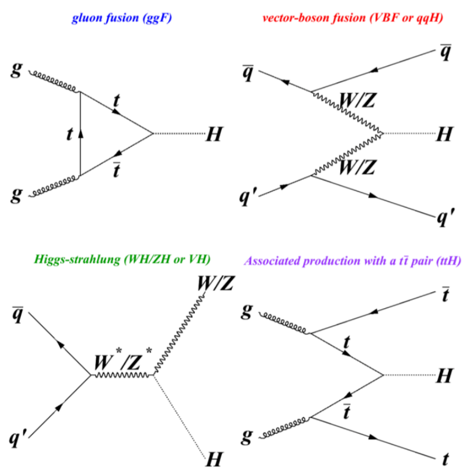


Higgs Boson discovered in 2012 at the LHC using 8 TeV data and is still there at 13 TeV ☺

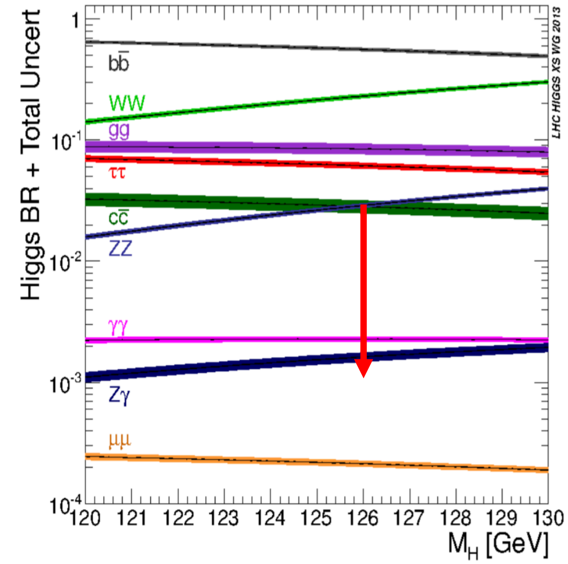


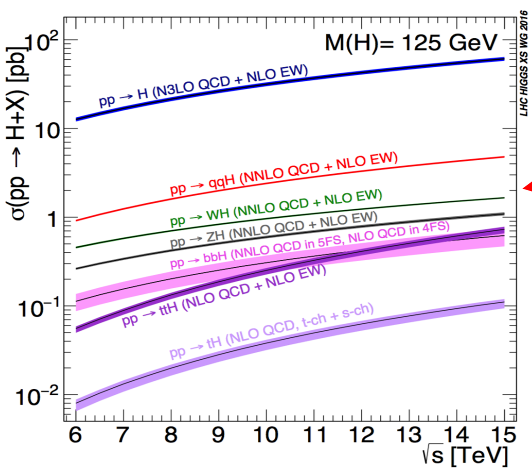


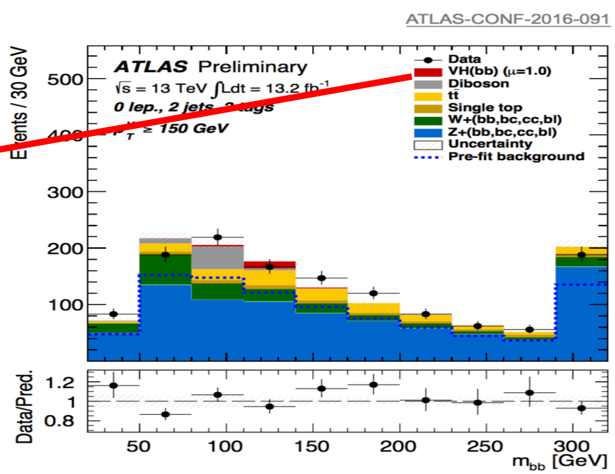




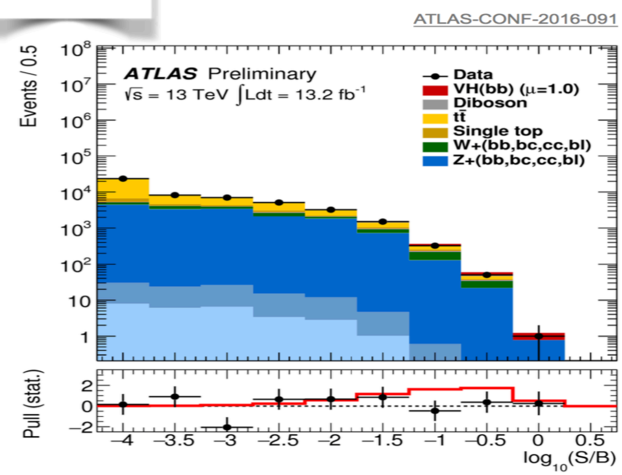
- @LHC the Higgs is better detected in rare decays like γγ and ZZ→4L
  - Reflecting the power of Signal/Power
- Sensitivity of Higgs to fermions (g_F) comes from the gg to H production and dominated by the top quark
- See example for H to bb ➔ we need to do this elsewhere like @γγC



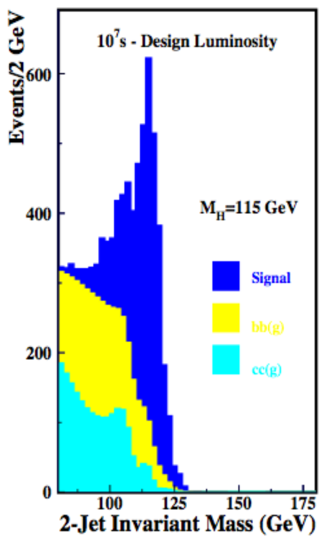


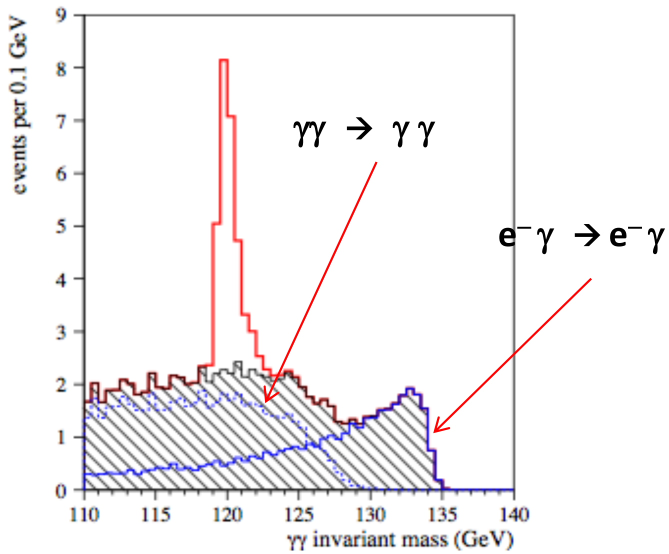


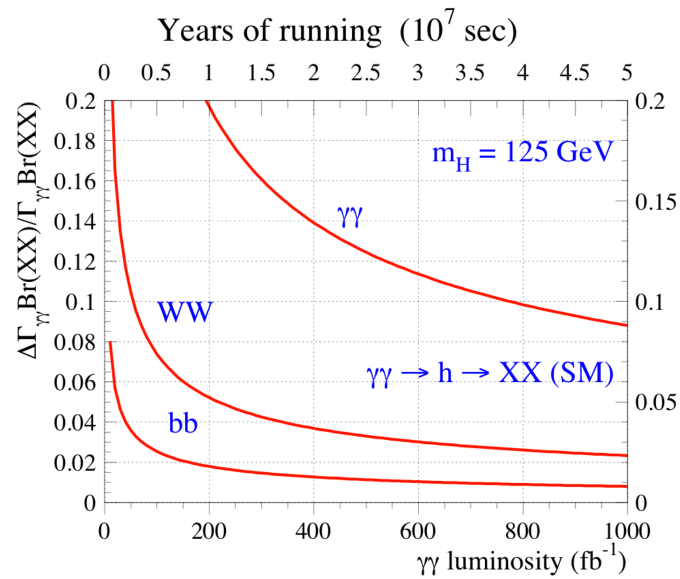
RUN-2



H to bb & γγ at a γγ collider after 1 & 5 years







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! Schmitt, Stenz & Velasco

$\Delta\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma}$ = **30% at ILC after 5 years**

NEW **M(4l) from CMS with 39.5 fb at 13 TeV**

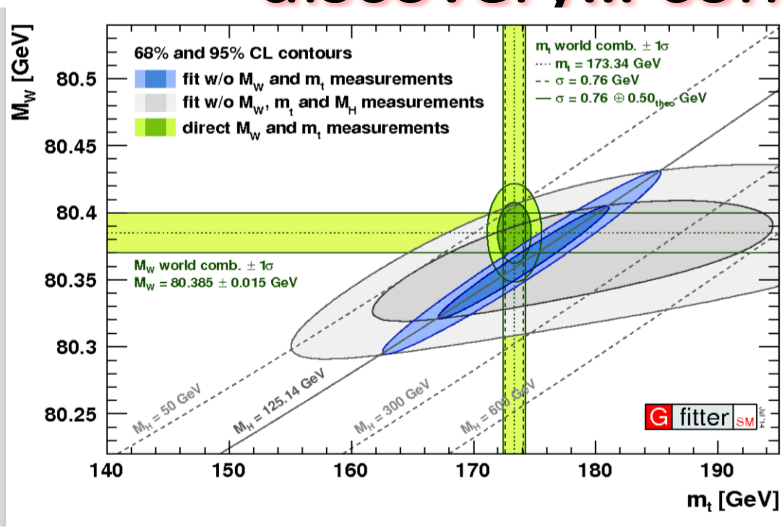
$$m_H = 125.26 \pm 0.20\,(\text{stat.}) \pm 0.08\,(\text{syst.})\ \text{GeV}$$

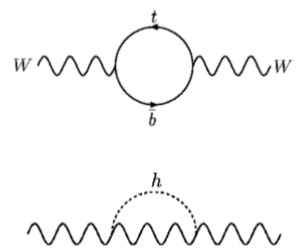
Putting things in perspective…

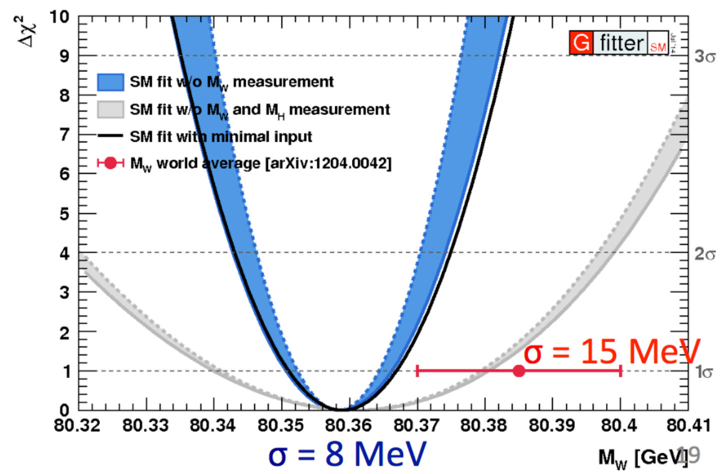
Should we work hard to get the Higgs mass more precise

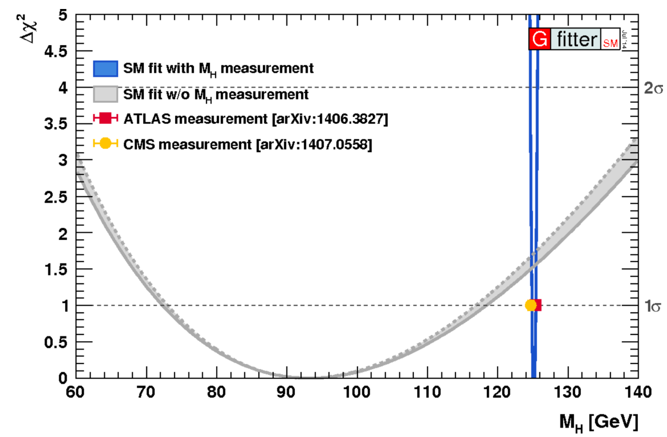
Of course if it comes for free we take it

M_H measurements/predictions before and after discovery… conclusion work on W-mass







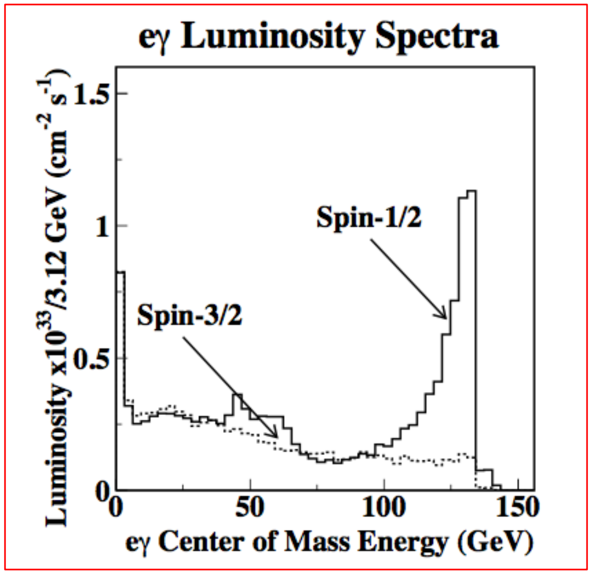


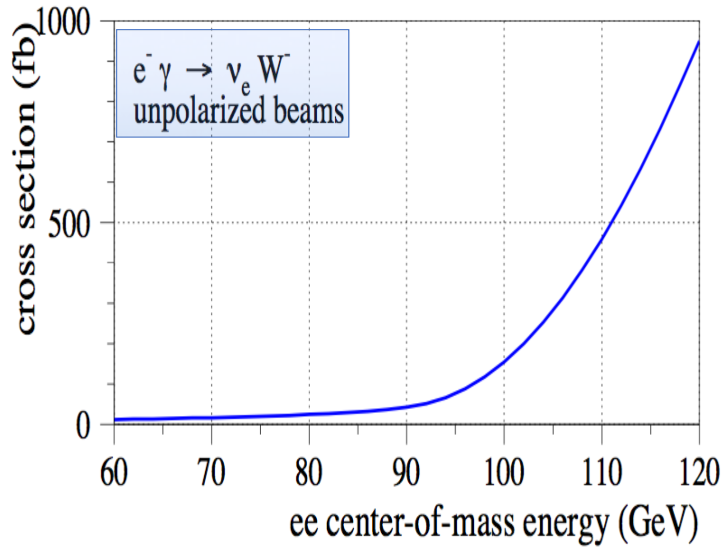
- Combination of precise measurements of m_W, m_{top}, m_H provides critical test of SM if $\sigma(m_W) \lesssim 6$ MeV
- Huge challenge at LHC
- Recent ATLAS result: $\sigma(m_W)$ = 19 MeV
- m_W measurement is the bottleneck, where the experimental uncertainty is worse than the theoretical one
  ➔ We need to do this elsewhere like @γγC or e+e-

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

(e+e- needs to run at the WW threshold)

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



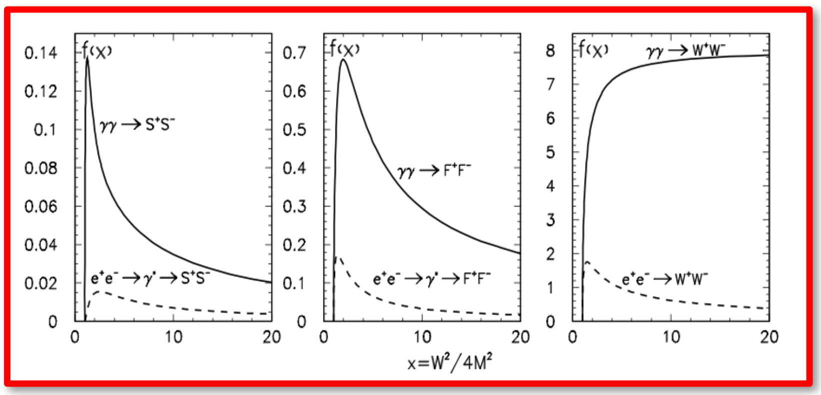


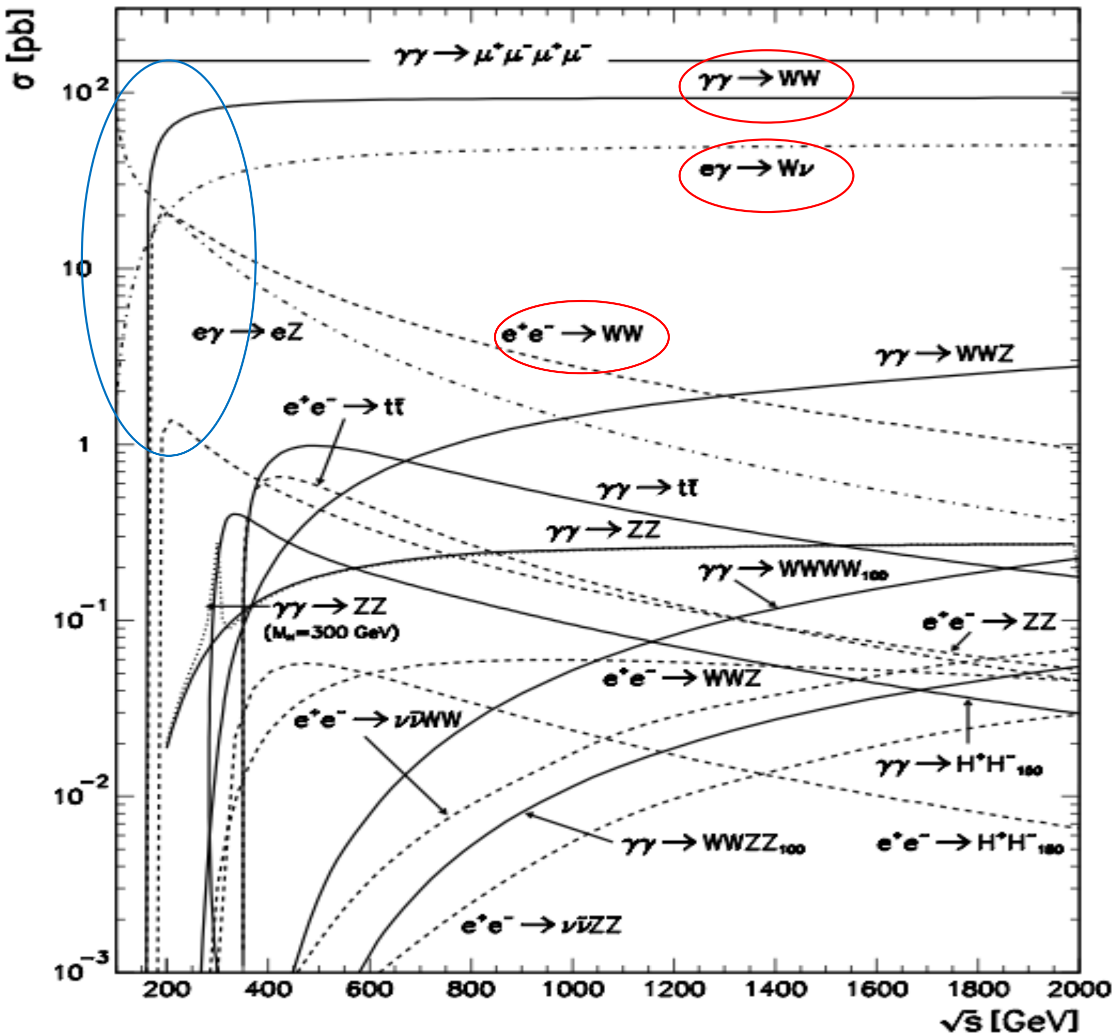
$e^-\gamma \rightarrow W^-\nu$

$\gamma\gamma \rightarrow W^+W^-$

$e^+e^- \rightarrow W^+W^-$

Mass measurement and width might be better to work at WW thresholds



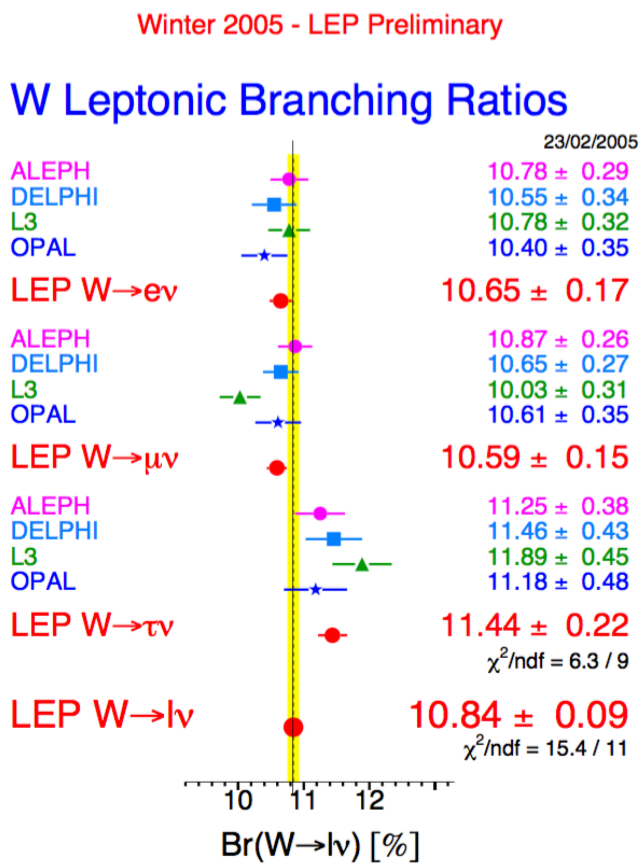


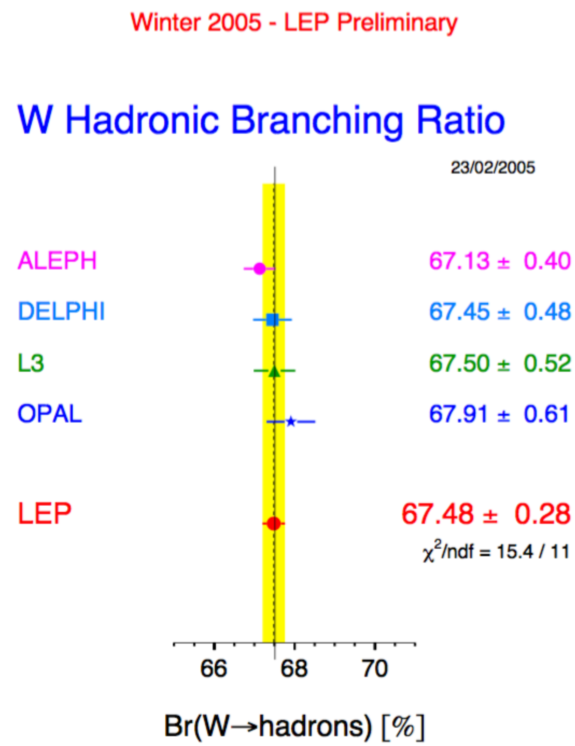
Comment: Interests in W branching fraction to improve tests of lepton universality

- Lepton universality tested at 1% level

- *τ BR ~2.7 σ larger than e/μ*

How well could we measure the ratio of BR of the W at the LHC including the tau?





q/ l universality at 0.6%

How to get widths of Higgs: Γ_{total} & $\Gamma_{\gamma\gamma}$ at $\gamma\gamma$ collider ?

Only with $\gamma\gamma C$

- The event rate of $\gamma\gamma \to h \to b\bar{b}$ is proportional to:

$$\{\Gamma(h^0 \to \gamma\gamma) \times BR(h^0 \to b\bar{b})\}$$

Assuming that we know $\Delta Br(h \to bb)$ ~2%

Therefore with $BR(h^0 \to b\bar{b})$ from elsewhere we can get $\Gamma(h^0 \to \gamma\gamma)$

%2 Measurement of $\Gamma_{\gamma\gamma}$

→4% constraint in ttH Yukawa coupling (y_{tt})

- Similarly,

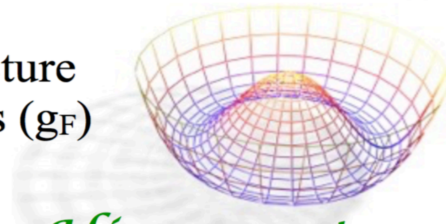
$$\Gamma_{\text{total}} = \frac{\{\Gamma_{\gamma\gamma} \times \mathcal{B}r(H \to \bar{b}b)\}}{\{\mathcal{B}r(H \to \gamma\gamma)\} \times \{\mathcal{B}r(H \to \bar{b}b)\}}$$

Therefore combining $b\bar{b}$ and $\gamma\gamma$ modes will give us Γ_{Total} in a model independent way.

%10 Measurement of Γ_{Total}

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

K. Cranmer

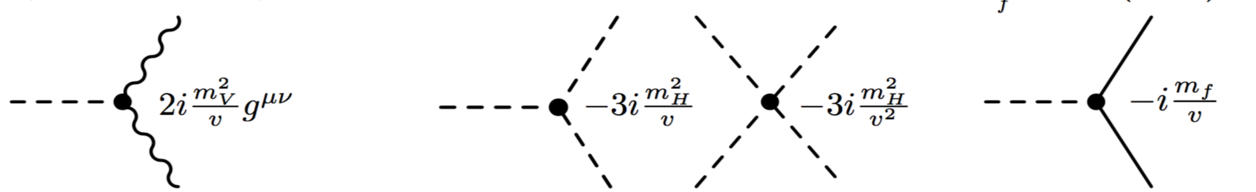


1. Higgs boson mass (M_H) & decay width (Γ_H)
2. Higgs boson quantum numbers J^{PC} and tensor structure
3. Higgs couplings to gauge bosons (g_V) and fermions (g_F)
4. Higgs potential - Higgs self-coupling (λ)

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
$[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0] \cdot (1 + \frac{h}{v})^2$	$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$	$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$



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

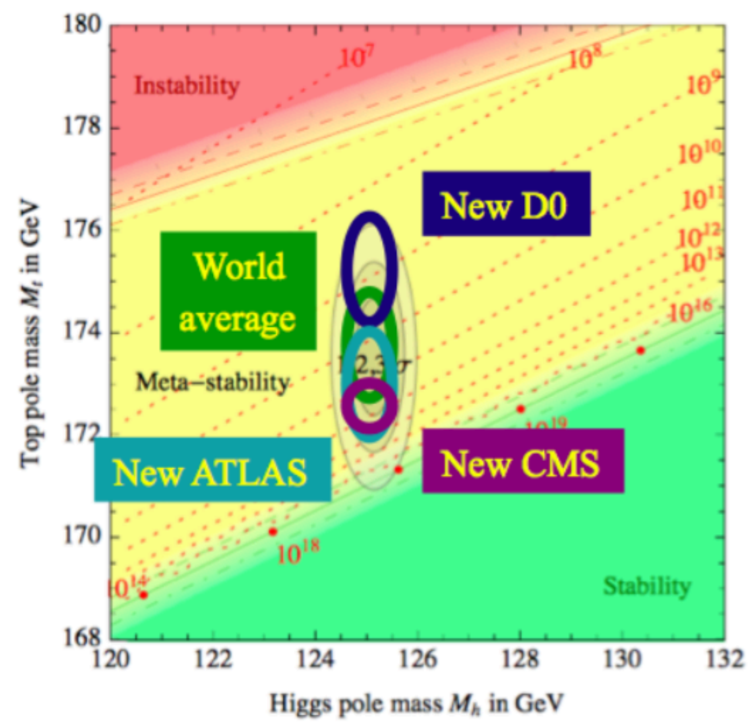
Are (1)-(3) measured precise enough @ LHC to be sensitive the relevant PBSM?

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

Already signs from new physics in the Higgs data by comparing M_{top} with M_H due to the shape of the Higgs potential?

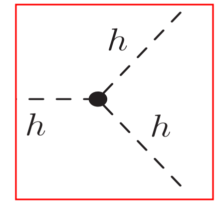
- Dashed lines: Calculation of the regions of the (m_H, m_{top}) plane where the electroweak vacuum is stable, metastable or unstable, and yields the following estimate of the "tipping point" Λ_I, where λ goes negative
- The final result is an estimate:
  - $\log_{10}(\Lambda_I / \text{GeV}) = 9.4 \pm 1.1$

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



Higher center of mass

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



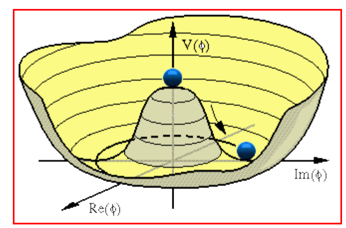
- **The Higgs self couplings measurements one of key topics for the future -- ILC (30%) and LHC (20%) cannot do the full job:**

  - only way to reconstruct the Higgs potential:

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

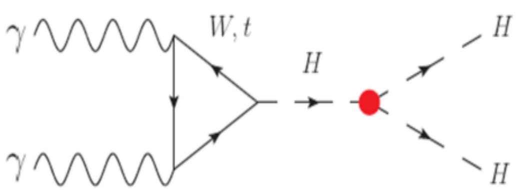
$$V_H = \mu^2 \Phi^+ \Phi + \eta (\Phi^+ \Phi)^2 \quad \rightarrow \quad \frac{1}{2} m_H^2 h^2 + \sqrt{\frac{\eta}{2}} m_H h^3 + \frac{\eta}{4} h^4 \text{ with :}$$

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



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

Higgs Self-Coupling

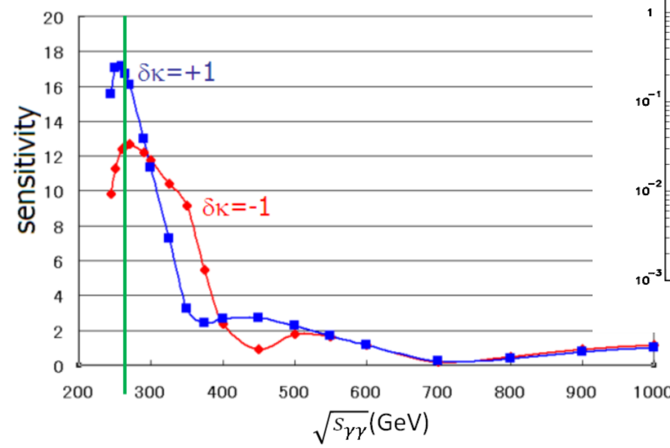


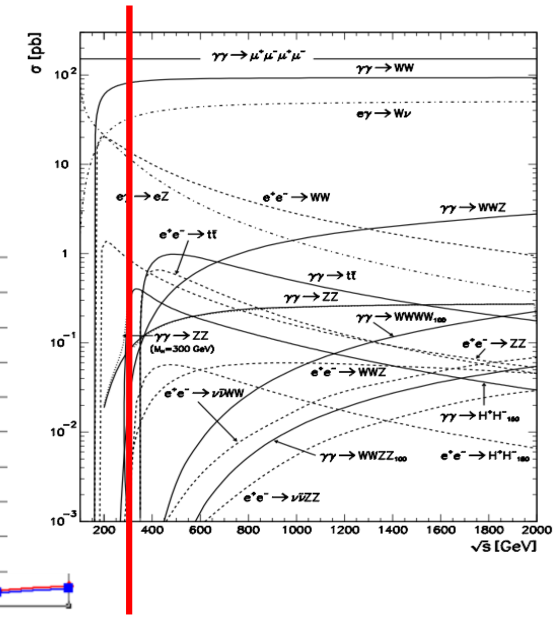
Final goal: Study of Higgs self-coupling

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

Self-coupling constant in the SM

Parameter of deviation from the SM





A γγ 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)

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

e^-e^-C

Running of $\sin^2\theta_W$

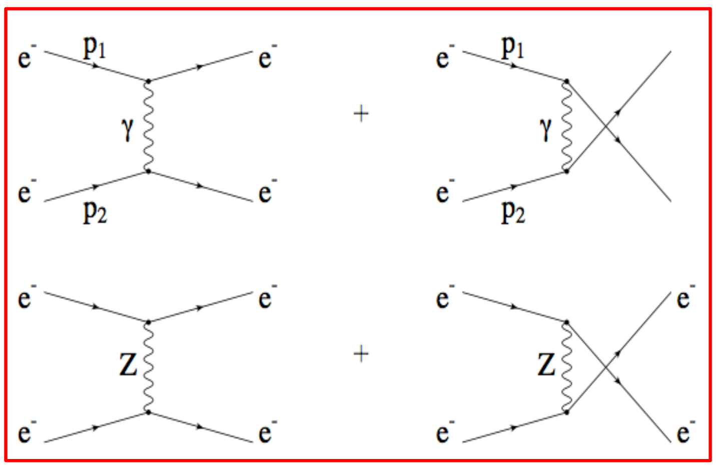
$e^-e^- \rightarrow e^-e^-$

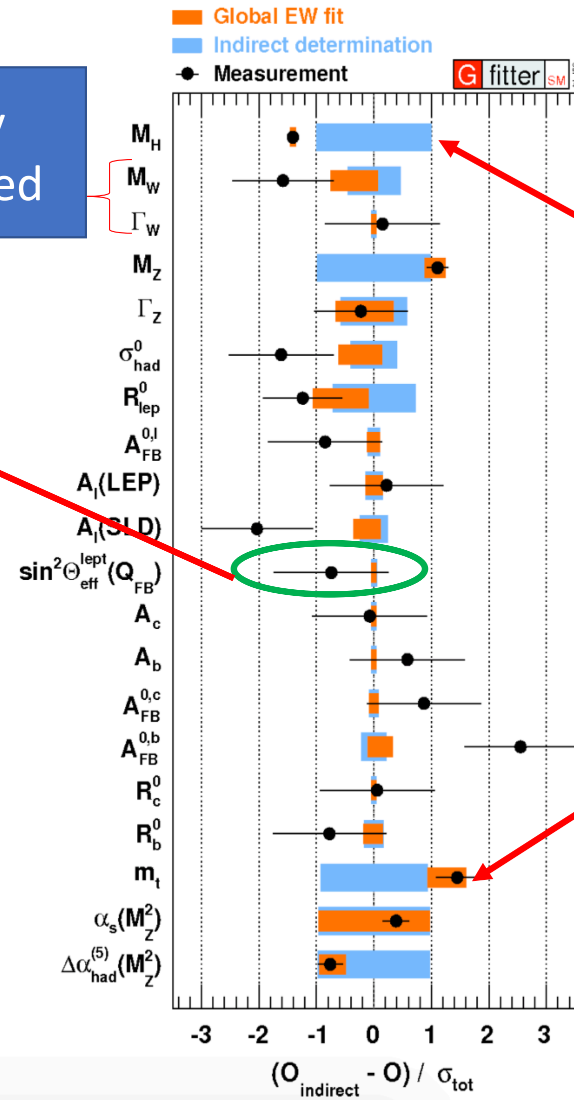
Moller scattering

Poorly measured

Pointing to Physics Beyond Standard Model of Particle Physics?

ee geometric luminosity: $\mathcal{L}_{ee} = 2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$





V-A structure of weak interaction gives rise to L-R parity violation in Moller scattering

$$\mathfrak{L} = eA_\mu \bar{\psi}\gamma^\mu \psi - gZ_\mu \bar{\psi}\gamma^\mu (c_V + c_A\gamma_5)\psi$$

$$\frac{d\sigma}{dcos\theta} = \frac{2\pi\alpha^2}{s} \times$$

$I \backslash F$	RR	RL	LR	LL
RR	$\frac{s^4}{u^2t^2} + \beta\frac{4s^3}{ut}c_{RR}$	0	0	0
RL	0	$\frac{u^2}{t^2} - \beta\frac{2u^2}{t}c_{RL}$	$\frac{t^2}{u^2} - \beta\frac{2t^2}{u}c_{RL}$	0
LR	0	$\frac{t^2}{u^2} - \beta\frac{2t^2}{u}c_{RL}$	$\frac{u^2}{t^2} - \beta\frac{2u^2}{t}c_{RL}$	0
LL	0	0	0	$\frac{s^4}{u^2t^2} + \beta\frac{4s^3}{ut}c_{LL}$

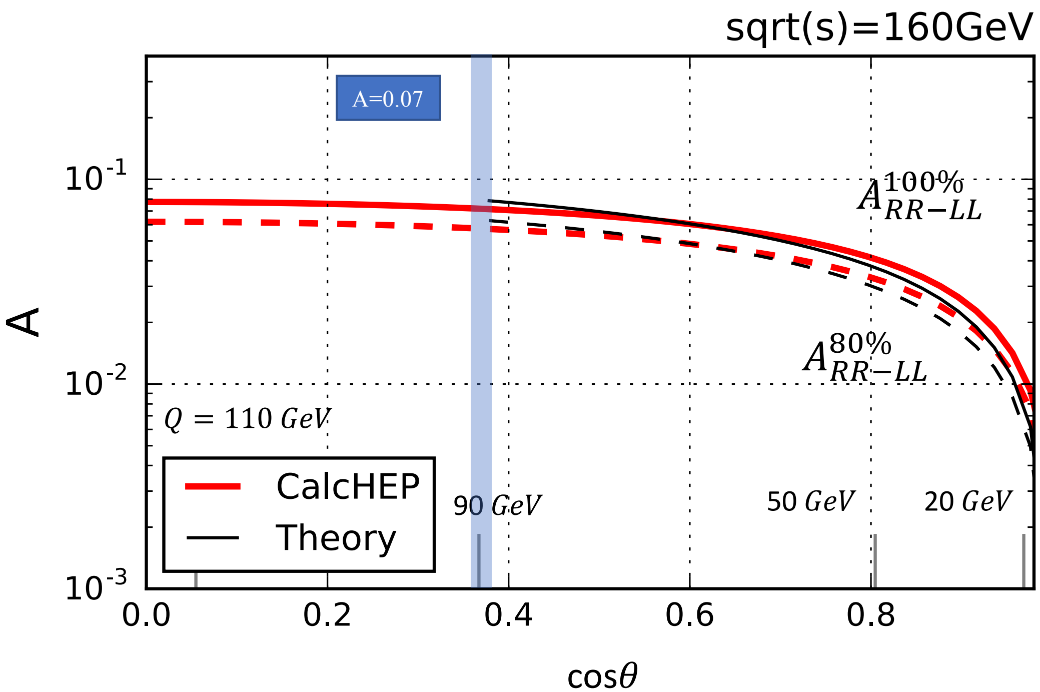
σ_R, σ_L → A_{R-L}

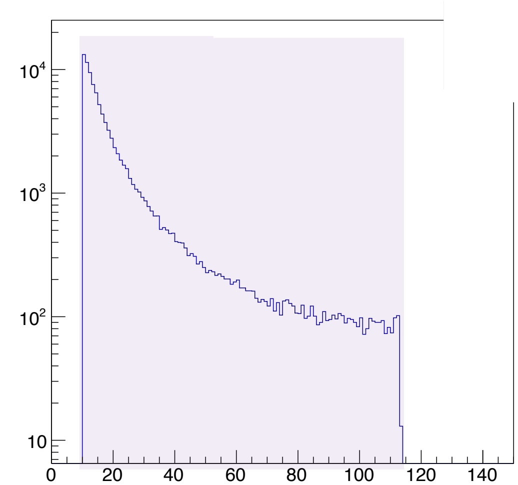
σ_{RR}, σ_{LL} → A_{RR-LL}

By measuring the L-R parity violation in Moller scattering, one can precisely measure the electroweak mixing angle $sin^2(\theta_W)$

$$A_{R-L} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = \frac{s}{\sqrt{2}\pi}\frac{G_F}{\alpha} \cdot \left[\frac{s^2ut}{u^4 + t^4 + s^4}\right] \cdot (4sin^2\theta_W - 1)$$

$$A_{RR-LL} = \frac{\sigma_{RR} - \sigma_{LL}}{\sigma_{RR} + \sigma_{LL}} = \frac{sG_F}{\sqrt{2}\pi\alpha}\left[\frac{ut}{s^2}\right](4sin^2\theta_w - 1)$$





Q = E$_{cm}$ sqrt{ ½ (1-cos θ)}
θ = scattering angle

Scattering angle > 5 degree

$\sigma_{RR+LL} = 1.2{\times}10^7$ fb

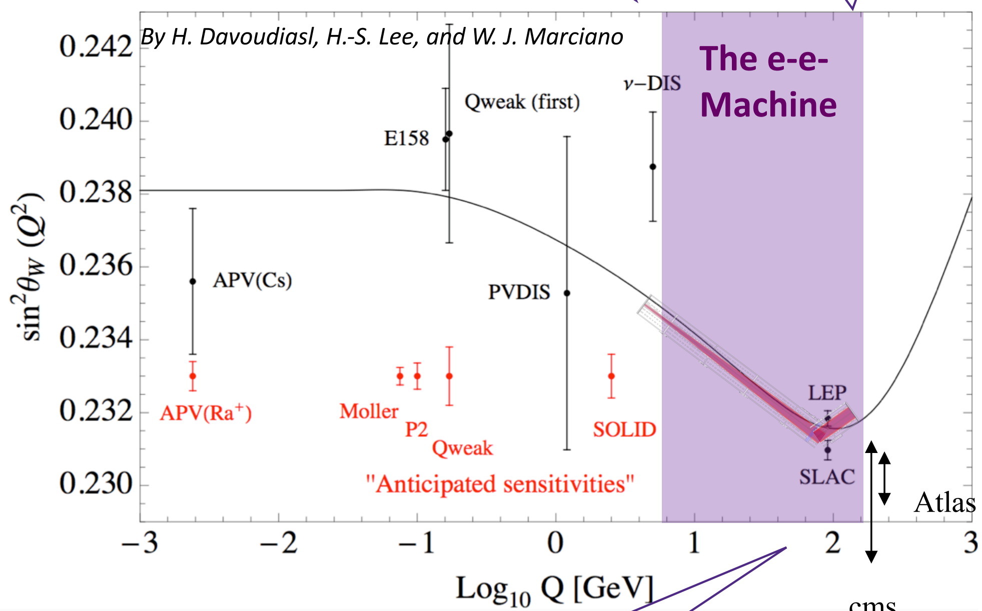
$\sigma^{80\%}_{RR-LL} = 4.8{\times}10^4$ fb

$\sigma_{RR-LL} = 8.0{\times}10^4$ fb

Standard Model

Q = 7 GeV
|η| = 3.1
5 degree

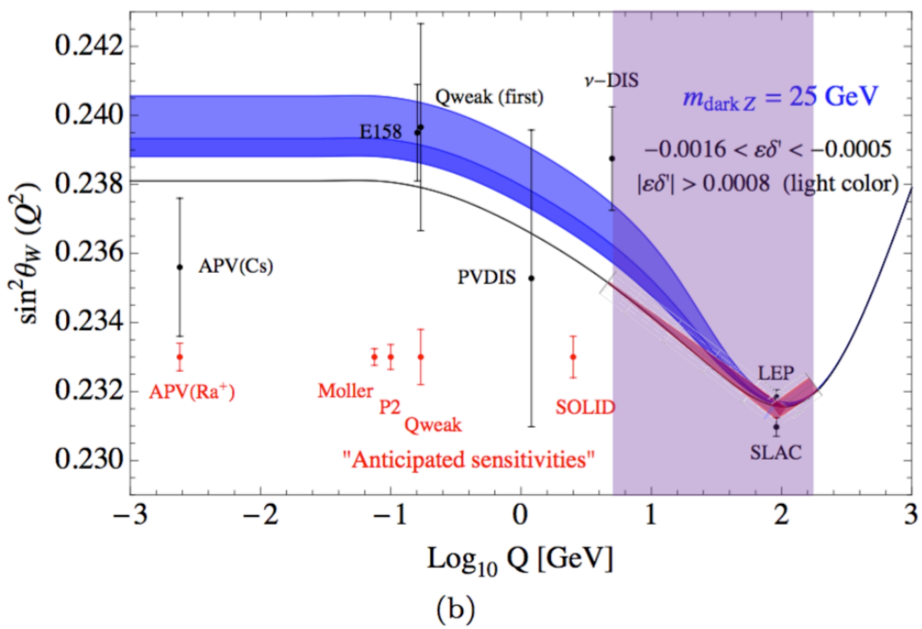
Q = 112 GeV
|η| = 0



LEP A_{FB} 0.23193(29)
SLAC A_{RL} 0.23070(26)
3-sigma deviates ?

Good Average
Ex 0.23125(15)
Th 0.23124(12)
Constrain New physics

Beyond Standard Model – Dark Z – Motivated in the muon g-2 anomaly



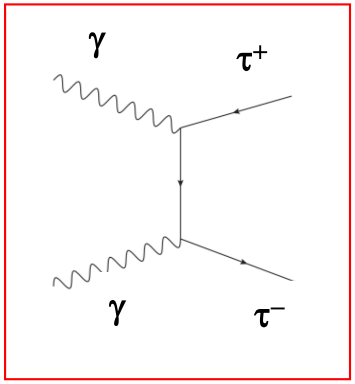
Blue -- 1-sigma region indicated by experiments.

Dark Blue -- constrain allowed region in Z' model 1-sigma region of experiments.

Black line -- SM prediction

Physics in low energy $\gamma\gamma C$:
g-2 of the tau lepton a few more things…

Proposal for $\gamma\gamma$ collider at the $\tau\tau$ threshold



$3.6\ \text{GeV} < E_{\gamma\gamma} < 8\ \text{GeV}$

Or $2m_\tau < E_{\gamma\gamma} < 2m_b$

Away from bb thresholds to avoid contamination from B to τ decays

Indirect search for new physics

1. First precise measurement of the g-2 of the τ (a_τ)
   - $\tau\tau\gamma$ vertex
2. Improve g-2 of the μ (a_μ) *
   - Hadronic decays of the τ like τ to $\nu_\tau\pi^\pm\pi^0$

Direct search for new physics

3. Search for lepton flavor violation (i.e. $\tau \rightarrow \mu\gamma$, $\mu\mu\mu$, etc.) *
4. Search for CP and T -Violation in τ measured from dipole moment and rate, angular and polarization asymmetries from τ decays

** Topics part of the Intensity Frontier program in the USA*

QED: Electromagnetic and Weak Dipole Moments

- Electromagnetic coupling of spin-1/2 charged lepton to the virtual photon involves 3 form factors:

$$\mathcal{M}_{\ell\bar{\ell}\gamma^*} = e\, Q_\ell\, \varepsilon_\mu(q)\, \bar{u}_\ell(\vec{p}\,')\left[F_1(q^2)\,\gamma^\mu + i\,\frac{F_2(q^2)}{2m_\ell}\,\sigma^{\mu\nu}q_\nu + \frac{F_3(q^2)}{2m_\ell}\,\sigma^{\mu\nu}\gamma_5\, q_\nu\right] u_\ell(\vec{p})$$

$$F_1(0) = 1$$

Charge conservation

$$\mu_\ell \equiv \frac{e}{2m_\ell}\frac{g_\ell^\gamma}{2} = \frac{e}{2m_\ell}\left[1 + F_2(0)\right]$$

Magnetic moment

$$d_\ell^\gamma = \frac{e}{2m_\ell}F_3(0)$$

Dipole moment

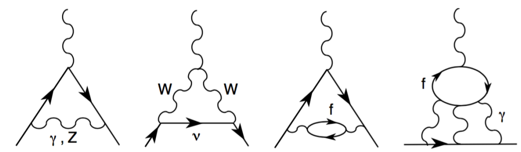
- $F_i(q^2)$ sensitive to a possible lepton substructure
- d^γ good probe of CP and T violation

➔ Polarization useful for these measurement

The τ anomalous magnetic and dipole moment have an enhanced sensitivity to new physics because of the large τ mass

Anomaly in the μ (g-2) is well know, however g-2 of the τ is basically unknown

$$a_\ell \equiv (g_\ell^\gamma - 2)/2$$



μ

$$
\begin{aligned}
10^{10} \times a_\mu^{th} &= 11\,658\,471.895\,1 \pm 0.008\,0 && \text{QED} \\
&+ \;\; 15.4 \pm 0.1 && \text{EW} \\
&+ 696.4 \pm 4.6 && \text{hvp}^{LO} \quad (701.5 \pm 4.7)_\tau \quad (692.3 \pm 4.2)_{e^+e^-} \\
&- \;\; 9.8 \pm 0.1 && \text{hvp}^{NLO} \\
&+ \;\; 10.5 \pm 2.6 && \text{lbl} \\
&= 11\,659\,184.4 \pm 5.3 && (11\,659\,189.5 \pm 5.4)_\tau \quad (11\,659\,180.3 \pm 4.9)_{e^+e^-}
\end{aligned}
$$

τ

$$
\begin{aligned}
10^{8} \times a_\tau^{th} &= 117\,324 \pm 2 && \text{QED} \\
&+ \;\; 47.4 \pm 0.5 && \text{EW} \\
&+ 337.5 \pm 3.7 && \text{hvp}^{LO} \\
&+ \;\; 7.6 \pm 0.2 && \text{hvp}^{NLO} \\
&+ \;\; 5 \pm 3 && \text{lbl} \\
&= 117\,721 \pm 5\,.
\end{aligned}
$$

$$
\begin{aligned}
a_e &= (1\,159\,652\,180.73 \pm 0.28) \times 10^{-12}\,, \\
a_\mu &= (11\,659\,208.9 \pm 6.3) \times 10^{-10}\,.
\end{aligned}
$$

$$-0.052 < a_\tau < 0.013$$

From Weizsacker Williams radiation events

$\sigma(e^+e^- \to e^+e^-\tau^+\tau^-)$ at $\sqrt{s}$ between 183 and 208 GeV at LEP2

Last comments on $\gamma\gamma$C

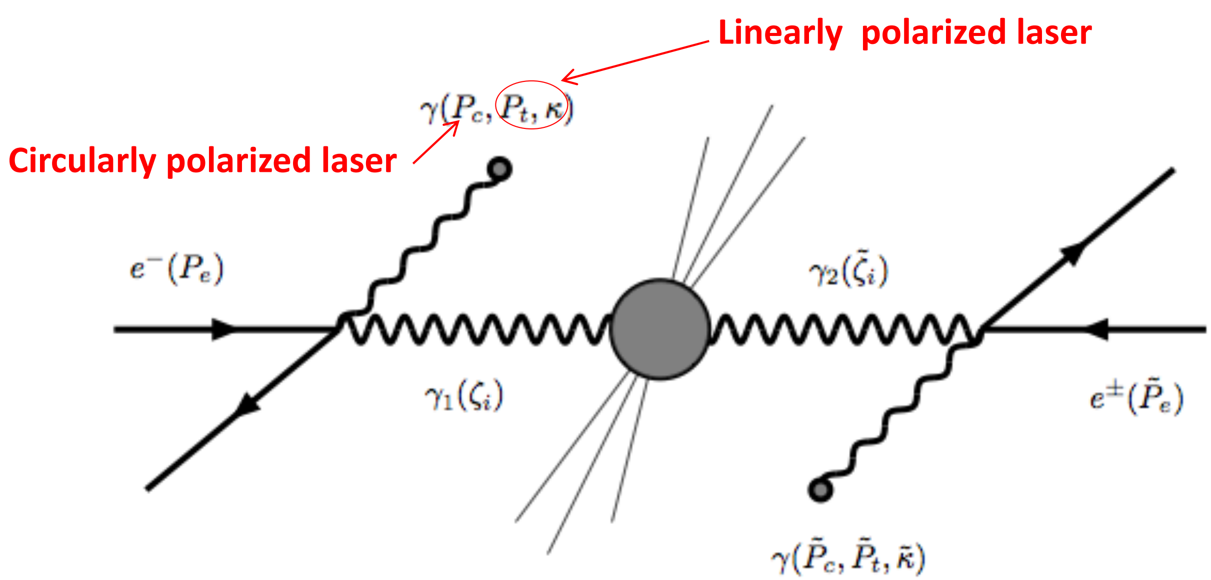
What is special really about $\gamma\gamma$C ?

- **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
$\Rightarrow (\gamma_{\parallel} \parallel \gamma_{\parallel}) \Rightarrow$ CP-even
$\Rightarrow (\gamma_{\parallel} \perp \gamma_{\parallel}) \Rightarrow$ 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 !

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

In s-channel production of Higgs:

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

== 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

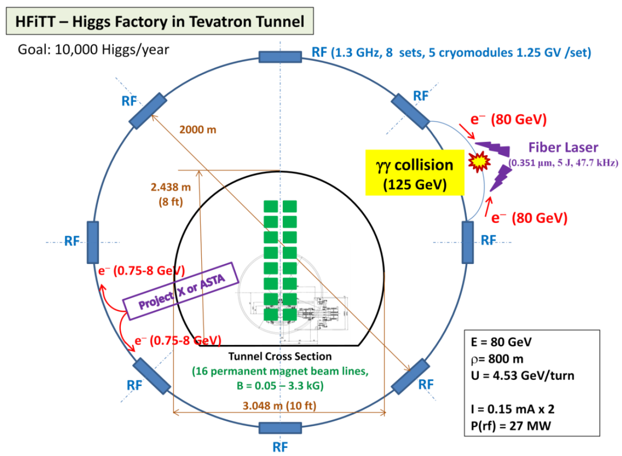
→ In bb, a ≤1% asymmetry can be measure with 100 fb^{-1} that is, in 1/2 years

Only with γγC

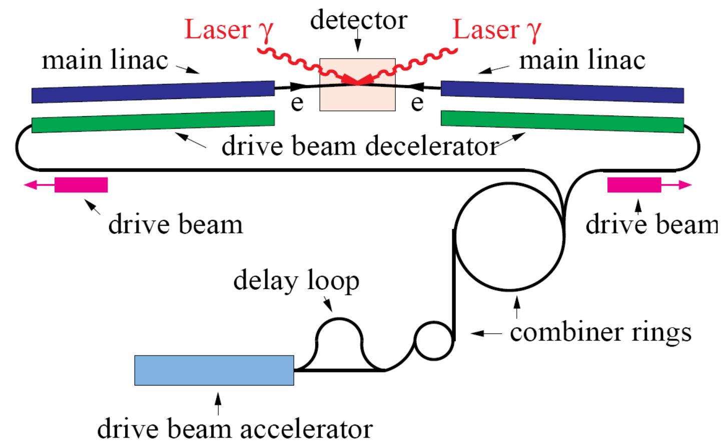
arXiv:0705.1089v2

γγC Proposals

HFiTT

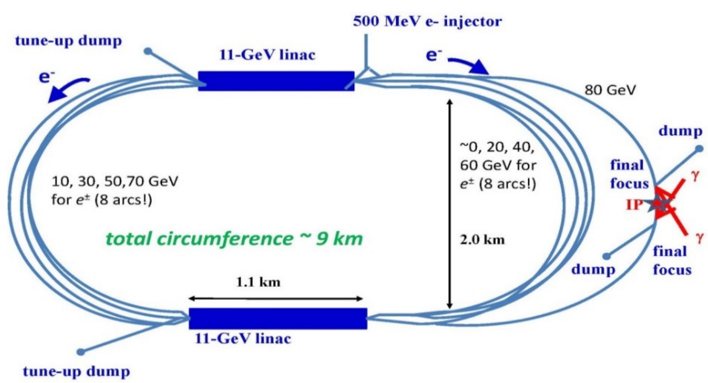


CLIC based

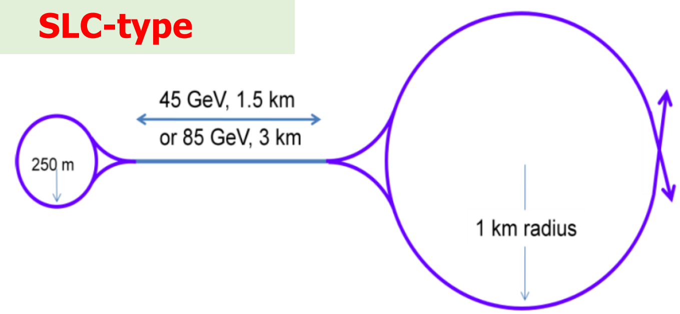


➔ 3 machines in 1: e⁻e⁻ , e⁻ γ, γ γ

SAPPHiRE



SLC-type



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

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

Summary

Plenty of fun ahead of us…