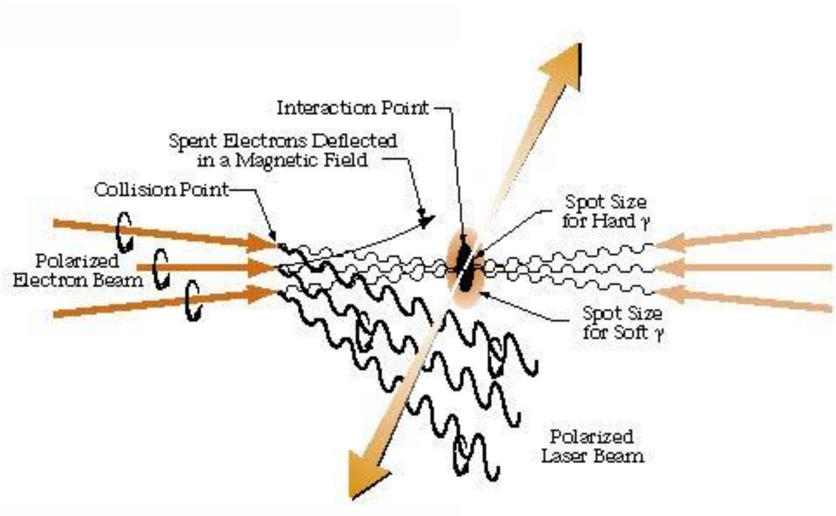
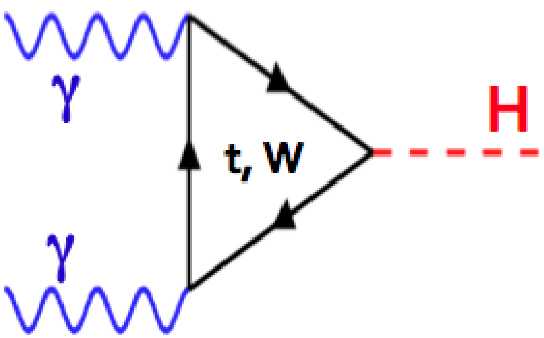
Photon-Photon Colliders (γγC)





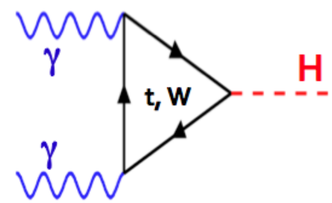
Mayda M. Velasco

Northwestern University

Higgs and Beyond -- June 5-9, 2013 -- Japan

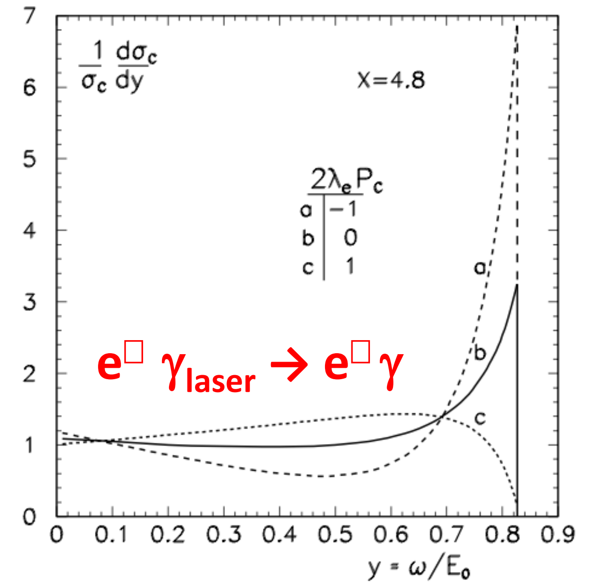
Full understanding of the Higgs boson and EWSM

- Will benefit not only the
  - LHC
  - e^+e^- colliders with $M_Z \leq E_{cm} \leq$ top-pair threshold
- But also a $\gamma\gamma$C Higgs factory
  - $\Gamma_{\gamma\gamma}$ to 2% (Model independent)
    - Results in a 13% on Γ_{Total}
    - Results in a Y_{tt} of 4%
  - Measure CP mixing to better than 1%
  - At higher energies: λ_{hhh} to a few %



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

Idea of γγC Based on Compton Backscattering *NOT* New

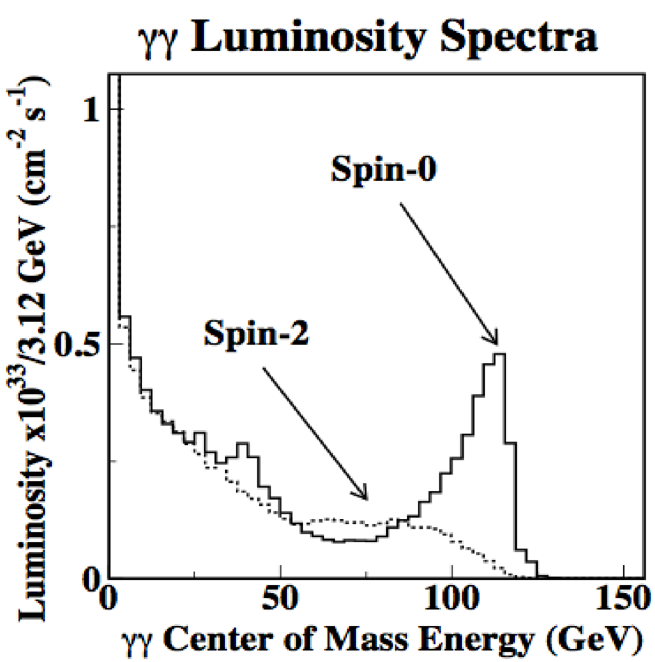


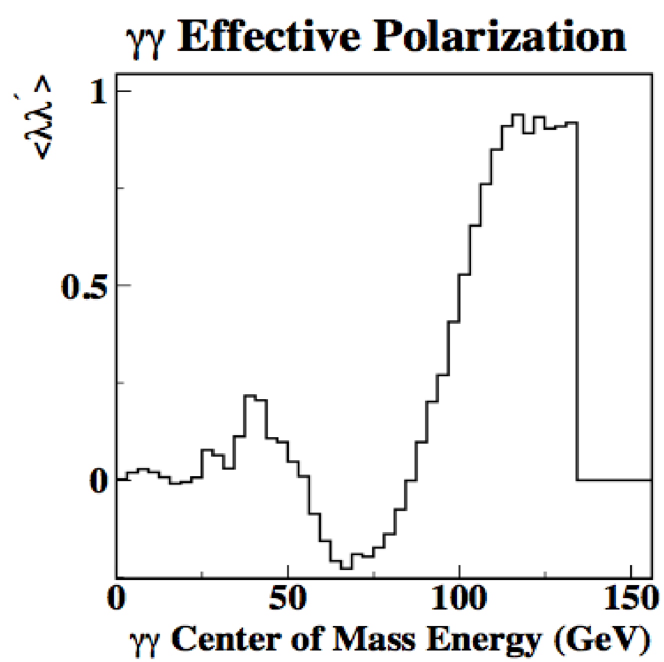
$\sigma(\gamma\gamma \rightarrow H) > 200$ fb

- Well defined $J = 0, 2$ final states,

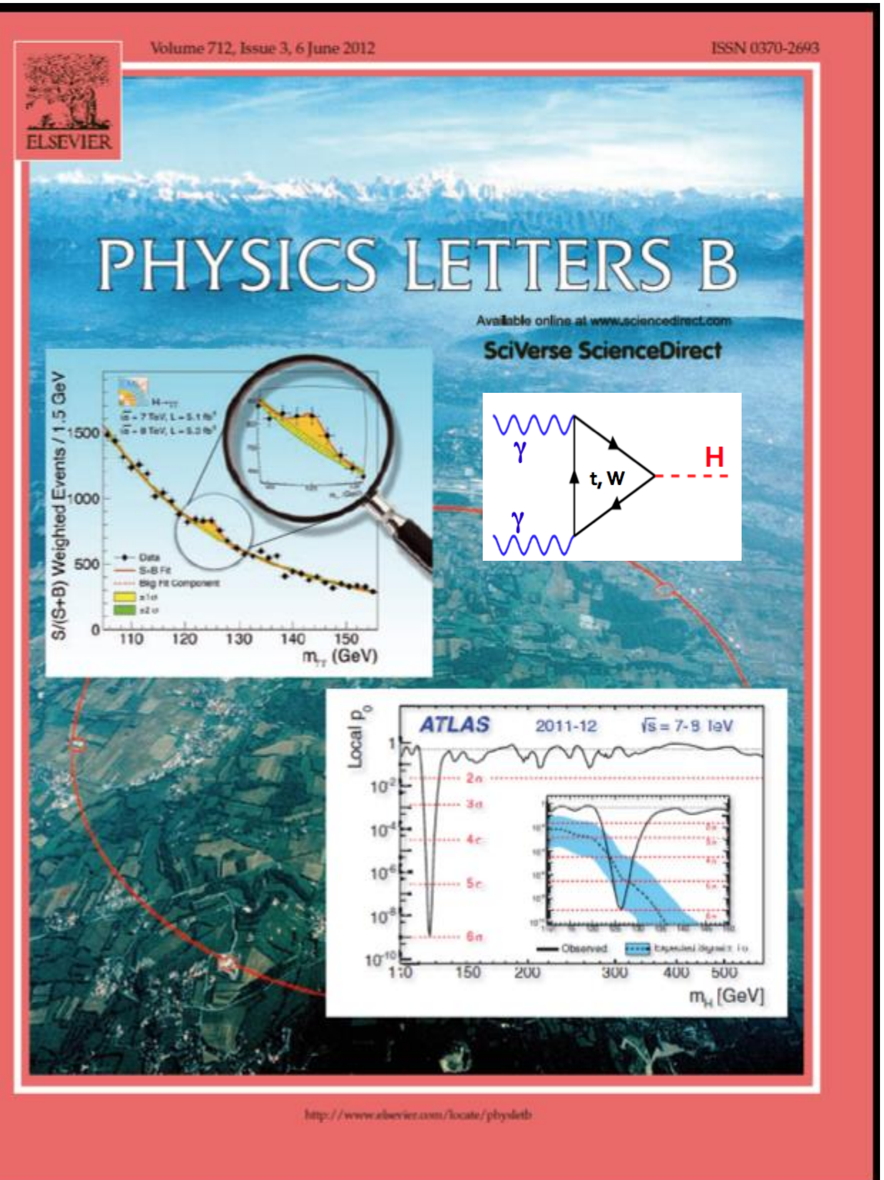
With circularly polarized γ_{laser} ($P_C = \pm 1$) & polarized e- ($\lambda_e = \mp 1$)

Example: Optimized as a Higgs Factory





What is “New” ? (I)



Higgs Discovery in July 2012

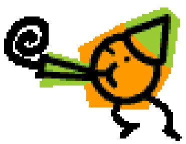
Higgs relatively light

M_H~125 GeV

E_{ee}~160 GeV enough to produce $\gamma\gamma \rightarrow H$

What is "New" ? (II)

- 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%
  - Independent of e^+e^- program
  - "Low" cost



- Required laser technology is becoming available and affordable. Two options:

  - Fiber based laser (ICAN)
  - High power laser developed for fusion program (LLNL)

3 New Designs that will Produce 10K Higgs/year

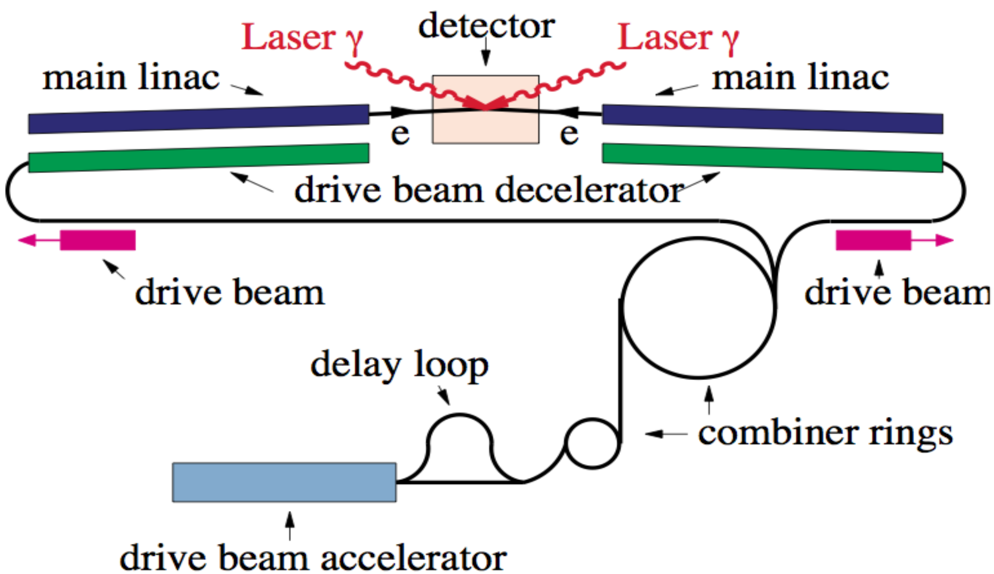
- **HFiTT:** Higgs Factory in Tevatron Tunnel
  - Fermilab specific
- **SILC:** SLC-ILC-Style $\gamma\gamma$ Higgs Factory
  - SLAC specific
- **SAPPHiRE:** Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons
  - Developed at CERN, but can be built elsewhere

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

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

Earlier e-e- based γγC design

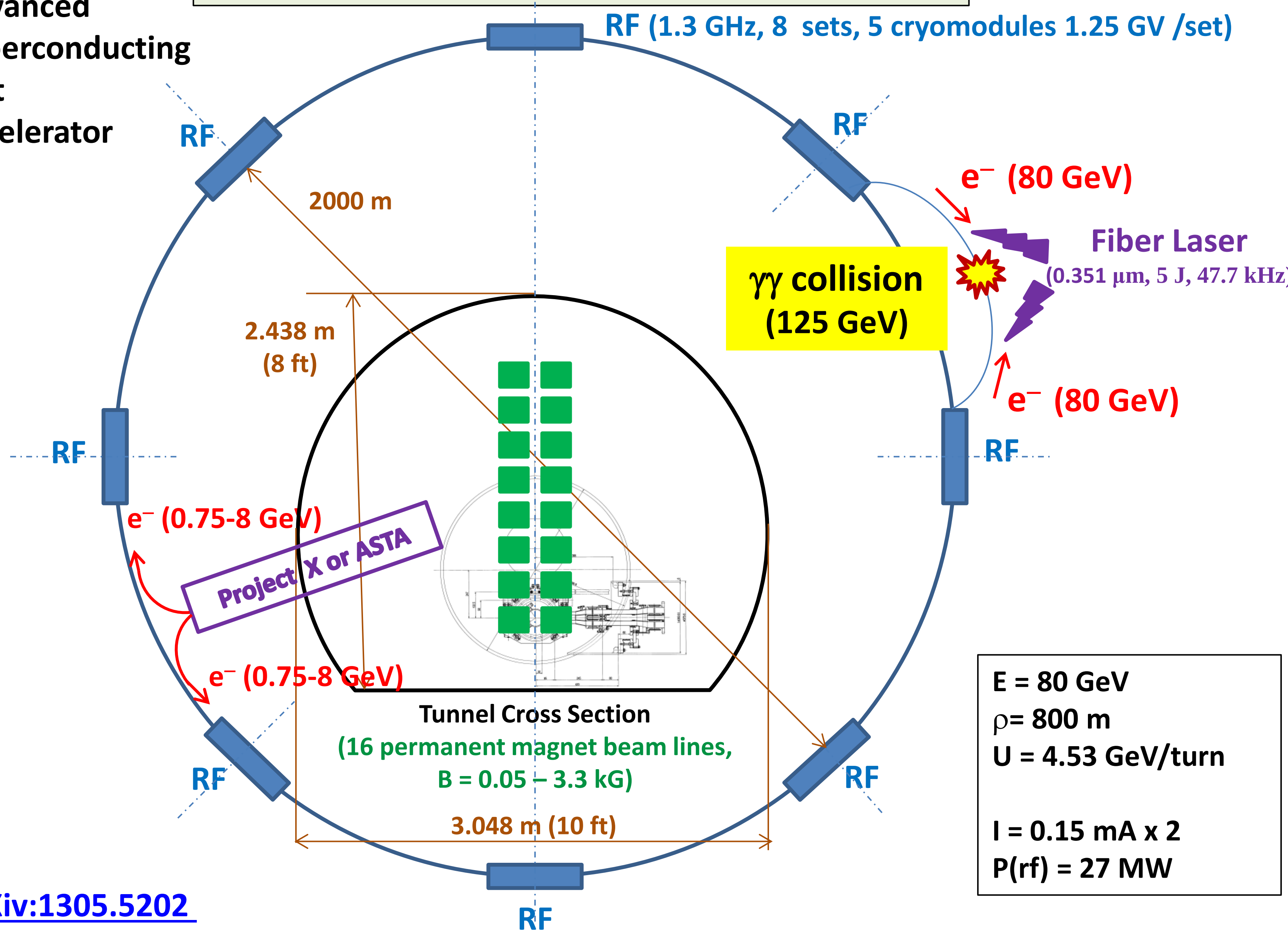
- CLICHÉ : CLIC Higgs Experiment
- From SNOWMASS 2001 – hep-ex/0110056



- Aggressive design with > 20k Higgs / year
- Design to be revised to take into account latest knowledge of the CLIC team

HFiTT – Latest Design

ASTA =
Advanced
Superconducting
Test
Accelerator



arXiv:1305.5202

Cost estimate for HFiTT

Fermilab-TM-2558-APC

HFiTT – Higgs Factory in Tevatron Tunnel (Rev. 1)

Weiren Chou[1], Gerard Mourou[2], Nikolay Solyak[1], Toshiki Tajima[3], Mayda Velasco[4]

[1] Fermilab, USA
[2] École Polytechnique, France
[3] University of California at Irvine, USA
[4] Northwestern University, USA

May 20, 2013

White Paper for the 2013 US HEP Community Summer Study (Snowmass2013)

Cost Consideration

This proposal is at an early stage and it is premature to discuss about its total cost. However, it will be useful to provide cost references for major systems based on the ILC study and Recycler experience.

- 40 cryomodules. Cost – \$2-3 million each according to the ILC cost estimate. (As a comparison, the ILC would need ~1,700 cryomodules.)
- 27 MW of RF power. Assuming 50% efficiency, one needs 54 MW of wall power for RF. Cost – \$5 million per MW according to the ILC cost estimate.
- 25 MW of wall power for cryogenics. Cost – about 2/3 of the ILC cryogenics.
- 16 permanent magnet beam lines. Cost reference – the Recycler permanent magnet total cost was \$3.2 million.
- 2×240 kW laser system. Assuming wall plug efficiency of 30%, compressor efficiency of 50%, diode price of €10/W and the rule of thumb that "3 times the diode cost equals the cost of the full system," the laser system will cost ~€50M, or \$65 million.
- Civil – the Tevatron tunnel, CDF and DZero experimental halls, service buildings and utilities can be reused to minimize the civil cost.

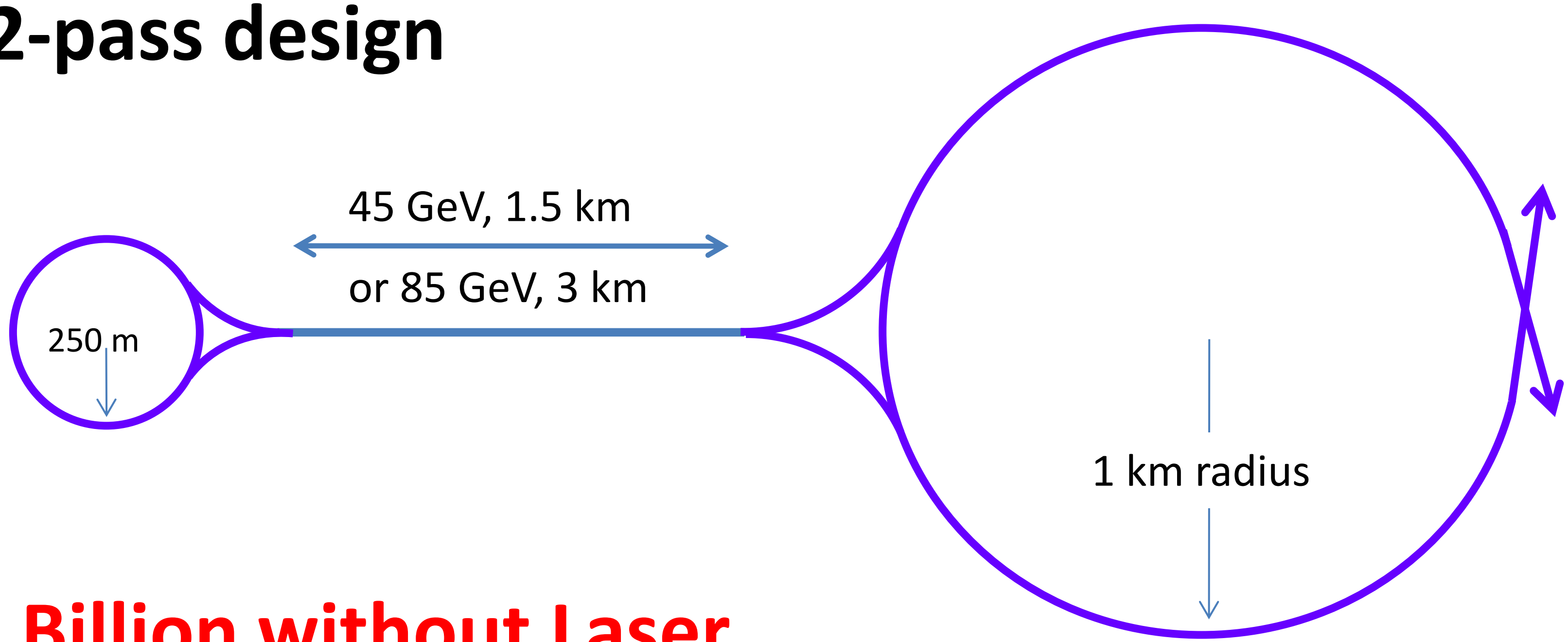
< 1Billion USD

With Laser design by ICAN collaborators and based on Fiber laser

SILC – Presented by Tor Raubenheimer

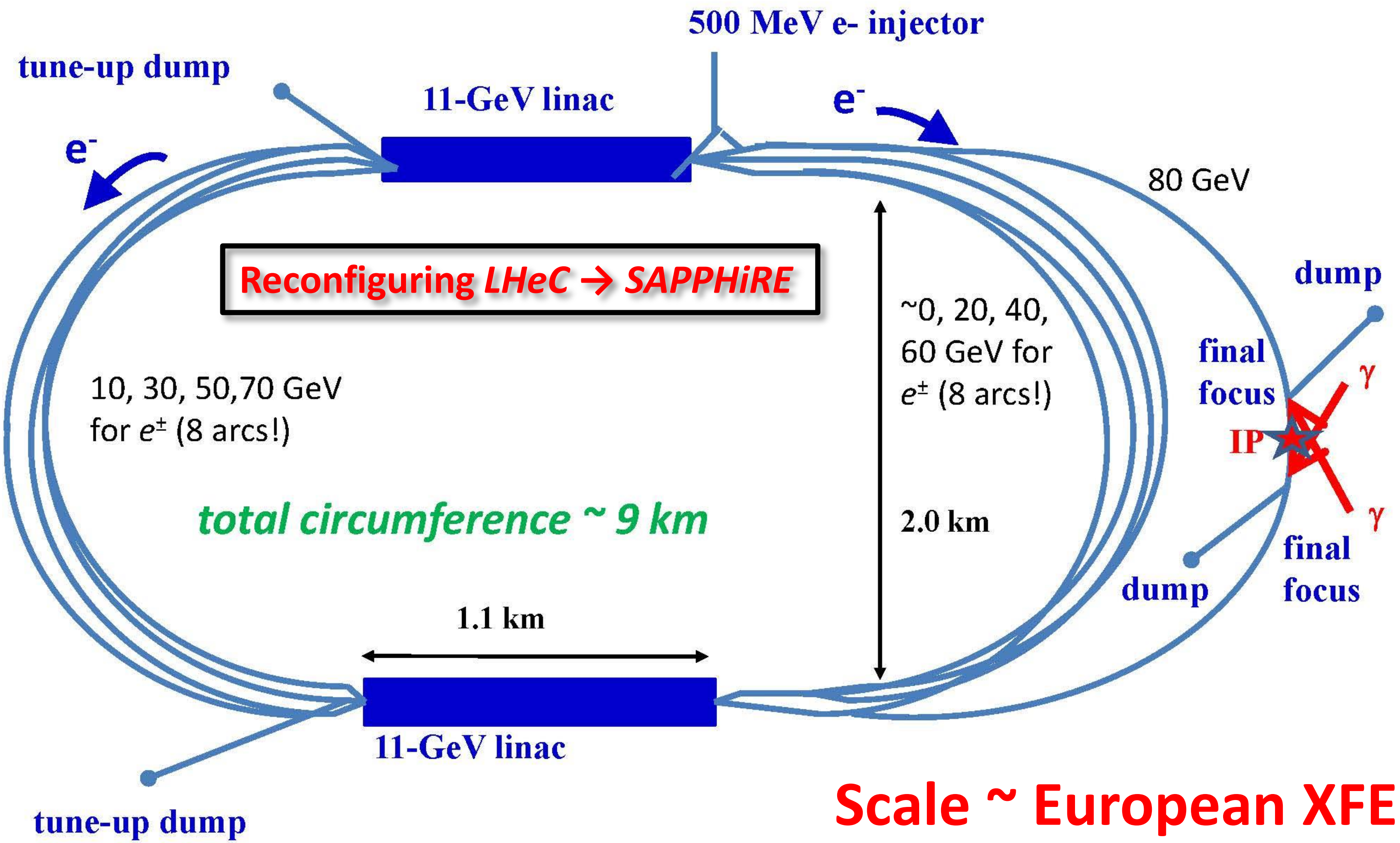
ICFA Higgs Factory Workshop November 14th, 2012

➔2-pass design



1.6 Billion without Laser

SAPPHiRE – Presented in 2012 at European Strategy Meeting arXiv:1208.2827



Energy lost	3.89 GeV

Scale ~ European XFEL

~ 1 Billion

Primary Parameters

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

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

These $\gamma\gamma$C designs need Flat Polarized e- bunches with low emittance

Flat beams

- Design parameters are within the present state of the art (e.g. the LCLS photo-injector routinely achieves 1.2 μm emittance at 1 nC charge)

Required R&D for 1nC polarized e- bunches with 1 μm emittance already in progress:

- Low-emittance DC guns @
  - MIT-Bates, Cornell, SACLA,JAEA,KEK, etc
- Polarized SRF guns @
  - FZD, BNL, etc

➔ For more details see Frank Zimmermann:

HF2012 – FNAL (16 Nov 2012)

Option #1:
Fiber Lasers -- Significant breakthrough

Gerard Mourou et al., *"The future is fiber accelerators," Nature Photonics, vol 7, p.258 (April 2013).*

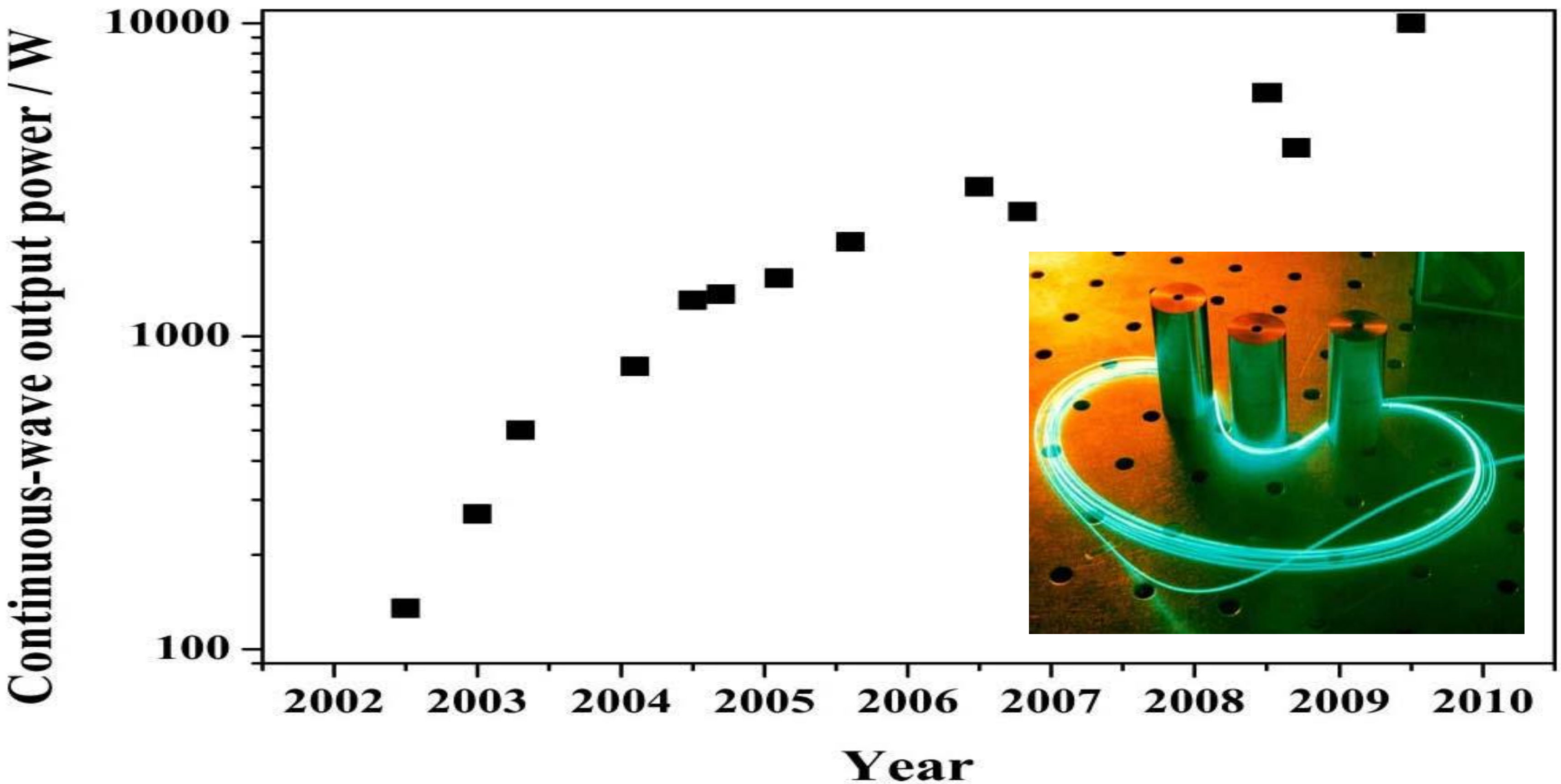
ICAN – International Coherent Amplification Network – will finish design a single-stage laser system by July. Aiming at >10 J per pulse and >10 kHz with 100-200 fs pulses.

Figure 2: Principle of a coherent amplifier network (CAN) based on fiber laser technology. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of 10 kHz (7). [3]

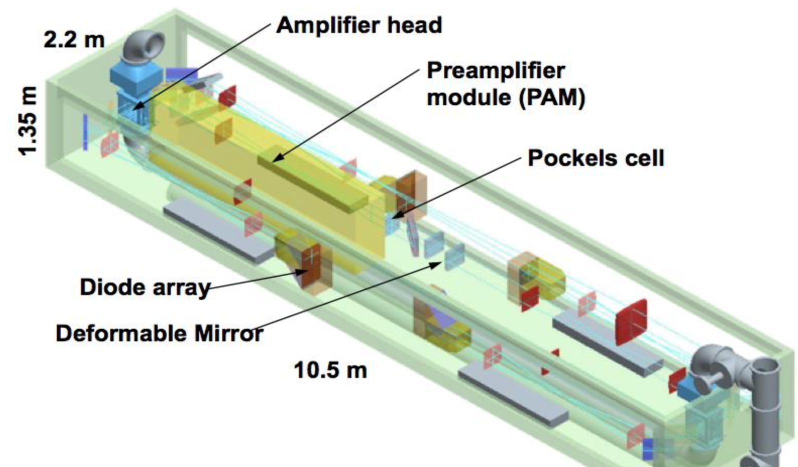
Example: HFiTT needs 5 J at ~40kHz!

Side comment: Fiber lasers should continue to get better ☺

Power evolution of cw double-clad fiber lasers



Option #2: The high peak & high average power lasers needed are also available from → LIFE: Laser Initiated Fusion Energy



LIFE beam line :
- Pulses at 16 Hz
- 8.125 kJ / pulse
- 130 kW average power
- ns pulse width

LIFE based options for SAPPHIRE-like $\gamma\gamma$C

J. Gronberg (LLNL)

Single pass system would have MW average power

➔ 10 LIFE beam lines running at 20kHz, each with 100kW average power and interleave pulses to create 200kHz

- Advantages:
  - Easier control of photon beam polarization
  - Eliminate issues with recirculating cavities
- Disadvantages:
  - Higher capital cost and energy requirements

Recirculating cavity would have 10kW average power

➔ 1 LIFE beam line at 200kHz, 0.05J/pulse & 10 kW average power

- Advantages:
  - Minimized capital cost and small power requirement
- Disadvantages:
  - Phase matching required
  - Cavity capital cost and operation
  - Reduced polarization control

Motivation for $\gamma\gamma$C as Higgs Factory and Associated e^-e^-C and $e^-\gamma$C

e^-e^-C

Running of $\sin^2\theta_W$

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

$e^-\gamma$C

γ- Structure and M_W

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

$\gamma\gamma$C

Higgs CP Mixing and Violations

- 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

1^{st} "run": e^-e^- mode

- Commission e-e- and understand e- beam polarization
- $L_{ee} = 2 \times 10^{34}\ cm^{-2} s^{-1}$ ➔ 10^7 sec per year: 200,000 pb^{-1}

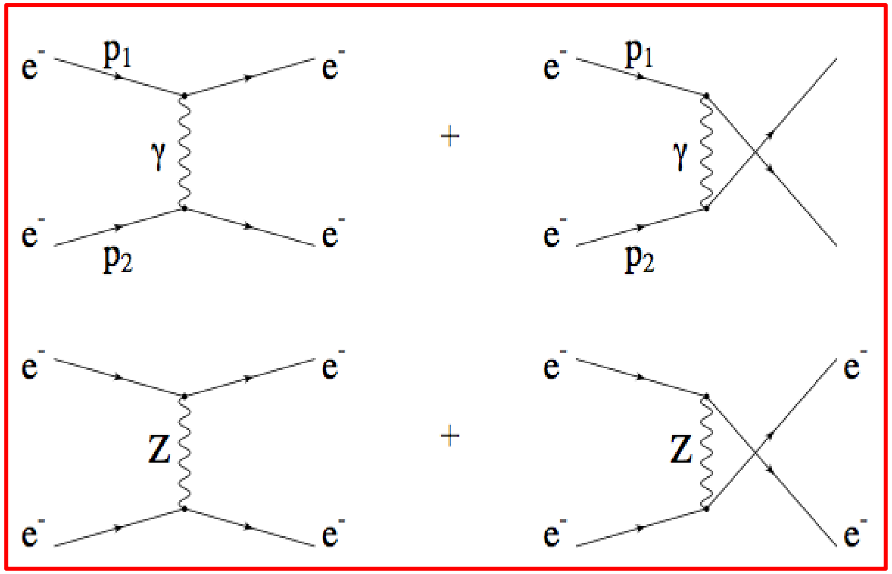
➔ Moller scattering e- e- → e- e-
  – E_{cm} = 160 GeV ; Scatt. angle > 5° ; P_T > 10 GeV for outgoing e-

$P_{1e} \times P_{2e} = 0$ → $\sigma = 2981$ pb

$P_{1e} \times P_{2e} = -1$ → $\sigma = 3237$ pb

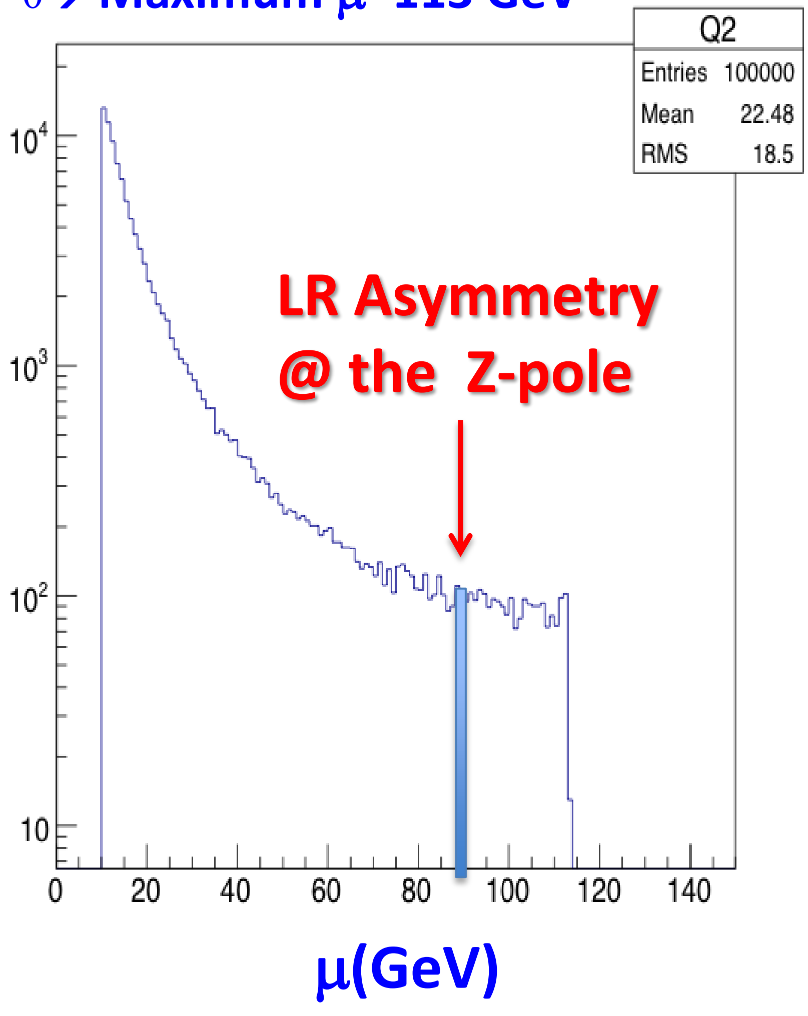
$P_{1e} \times P_{2e} = +1$ → $\sigma = 2728$ pb

➔ $N_{ev} \sim 6 \times 10^8$ / year



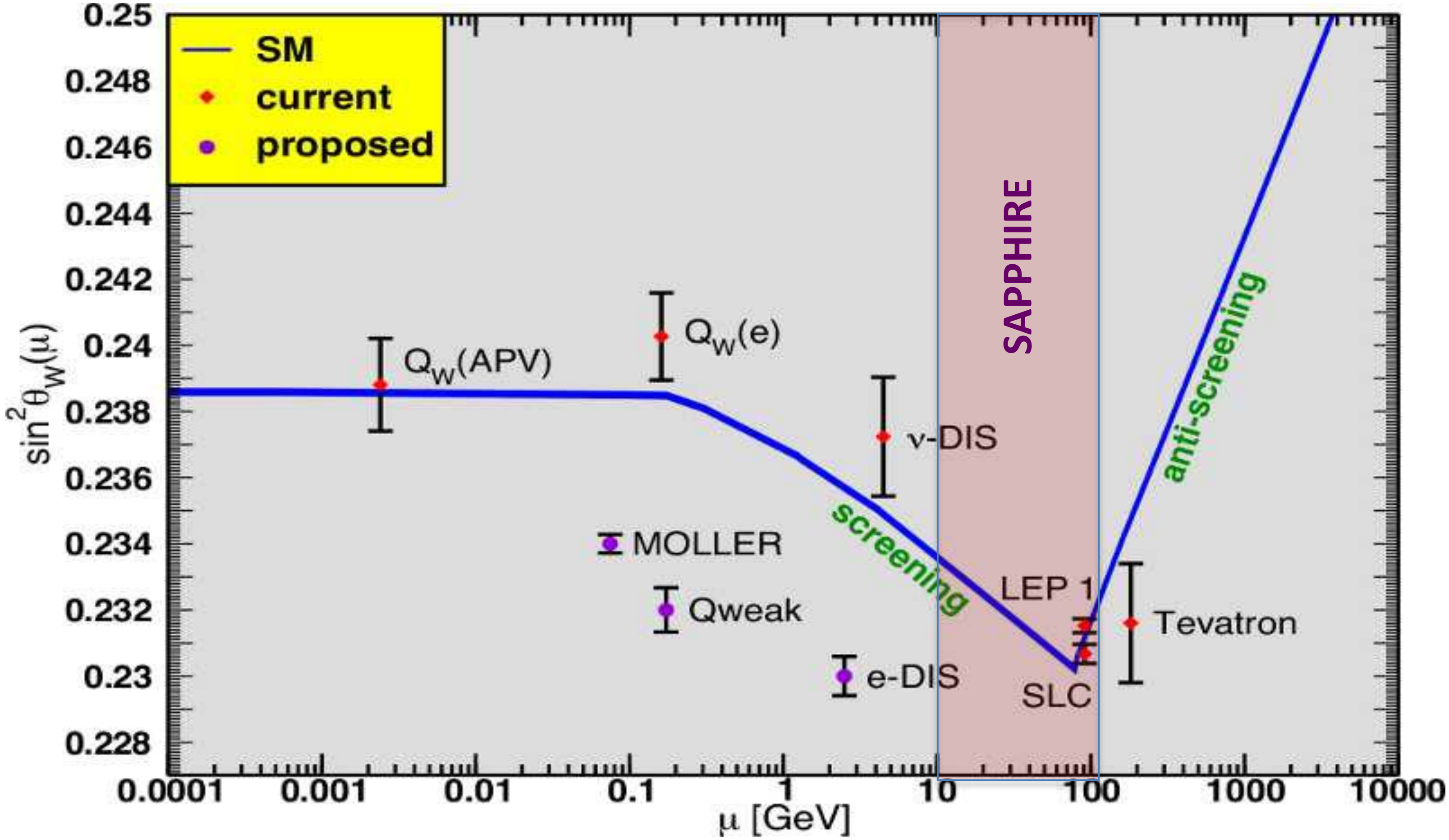
Precision on $\sin^2 \theta_W$ at SAPPHIRE

$\mu = E_{cm}$ sqrt{ ½ (1-cos θ)}
θ = scattering angle
θ→ Maximum μ~113 GeV



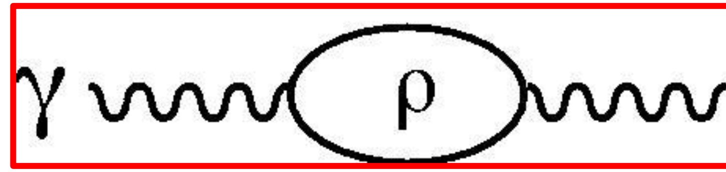
- Like SLAC-SLC (& LEP) at M_Z
  - A_{LR} based on 150K event
  - $\delta A_{LR} \sim 0.003$
  - $\delta \sin^2 \theta_W \sim 0.0003$
- SAPPHiRE at highest μ
  - A_{LR} based on 10^6 event
  - $\delta A_{LR} \sim 0.001$
  - $\delta \sin^2 \theta_W \sim 0.0004$
- In addition to precise measurement of running down to 10 GeV

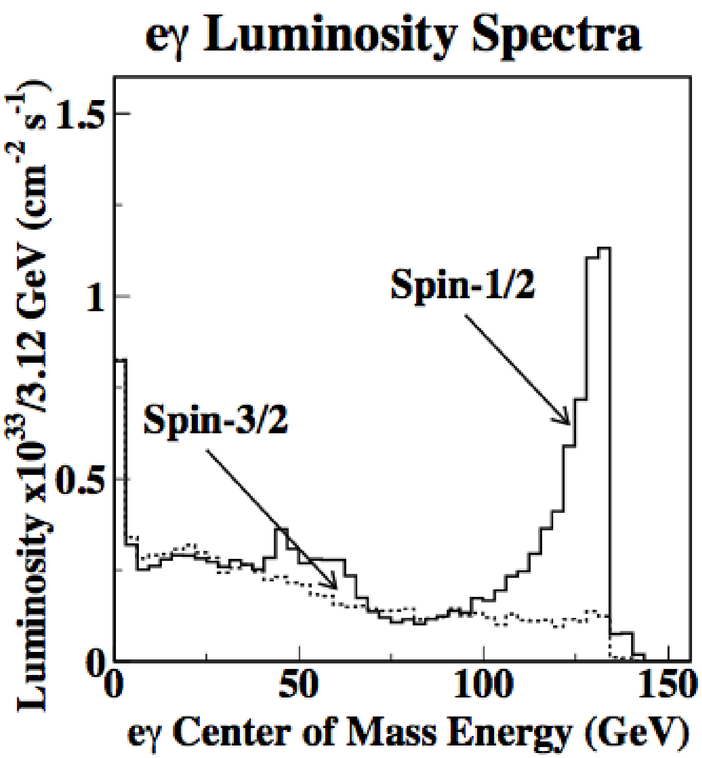
e^-e^-: Moller Scattering to measure running of $\sin^2\theta_W$



➔ Complements future lower energy programs

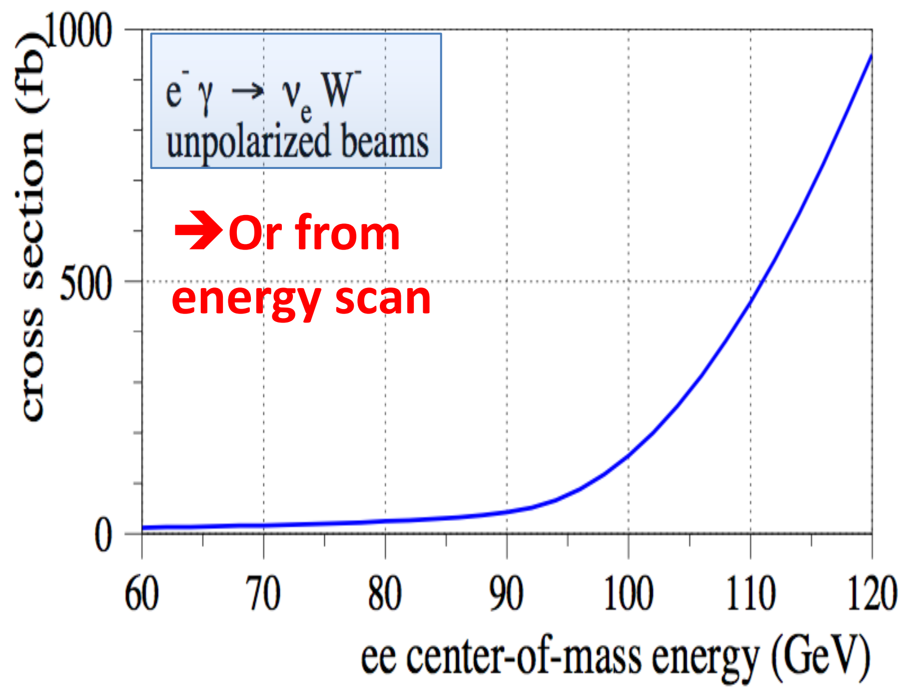
2nd "run": $e^-\gamma$ M_W from $e^-\gamma \rightarrow W^-\nu$ and photon structure





M_W measurement from $W \rightarrow$ hadron events

- Commission e-γ collisions
- Understand γ beam spectrum & polarization



3rd "run" : γγC Higgs-factory

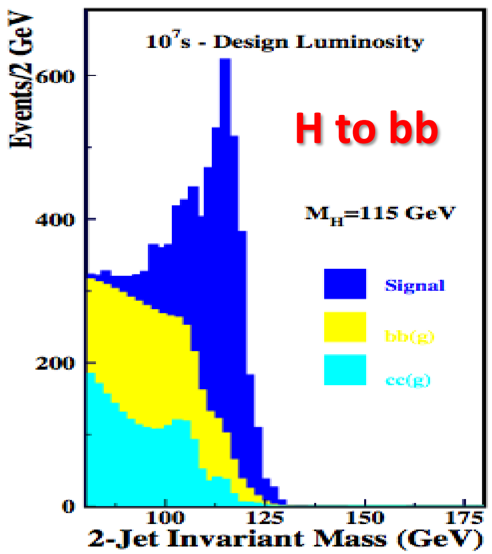
Table 1: Precision of measurements to be performed at HFiTT after 5 years of data taking

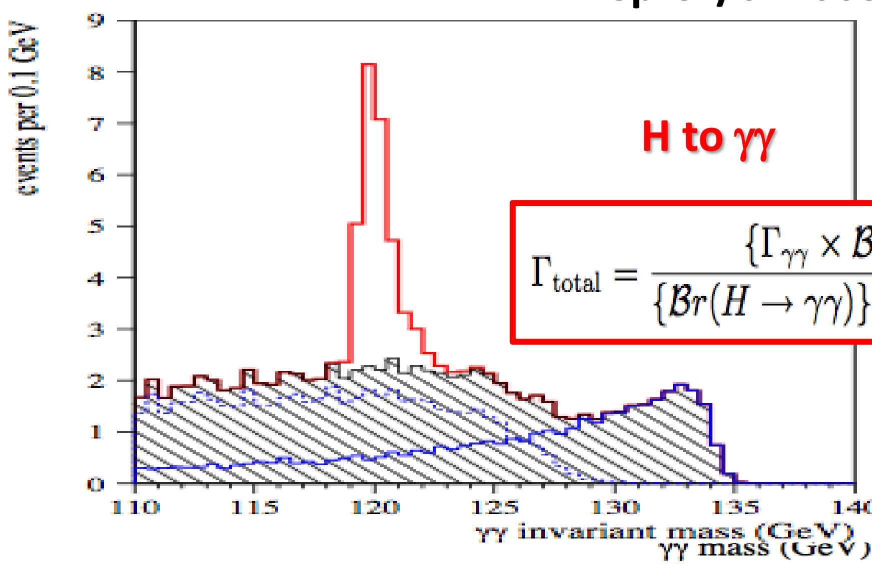
Measurement	Precision after 5 years of operation	Comment
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to \bar{b}b)$	0.01	
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to WW^*)$	0.03	Leptonic decays only
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to \gamma\gamma)$	0.12	
$\Gamma_{\gamma\gamma} \times \mathrm{Br}(h \to ZZ^*)$	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 a good option for the USA

Physics capabilities complementary to those of the LHC and future e+e- collider

hep-ex/0110056





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

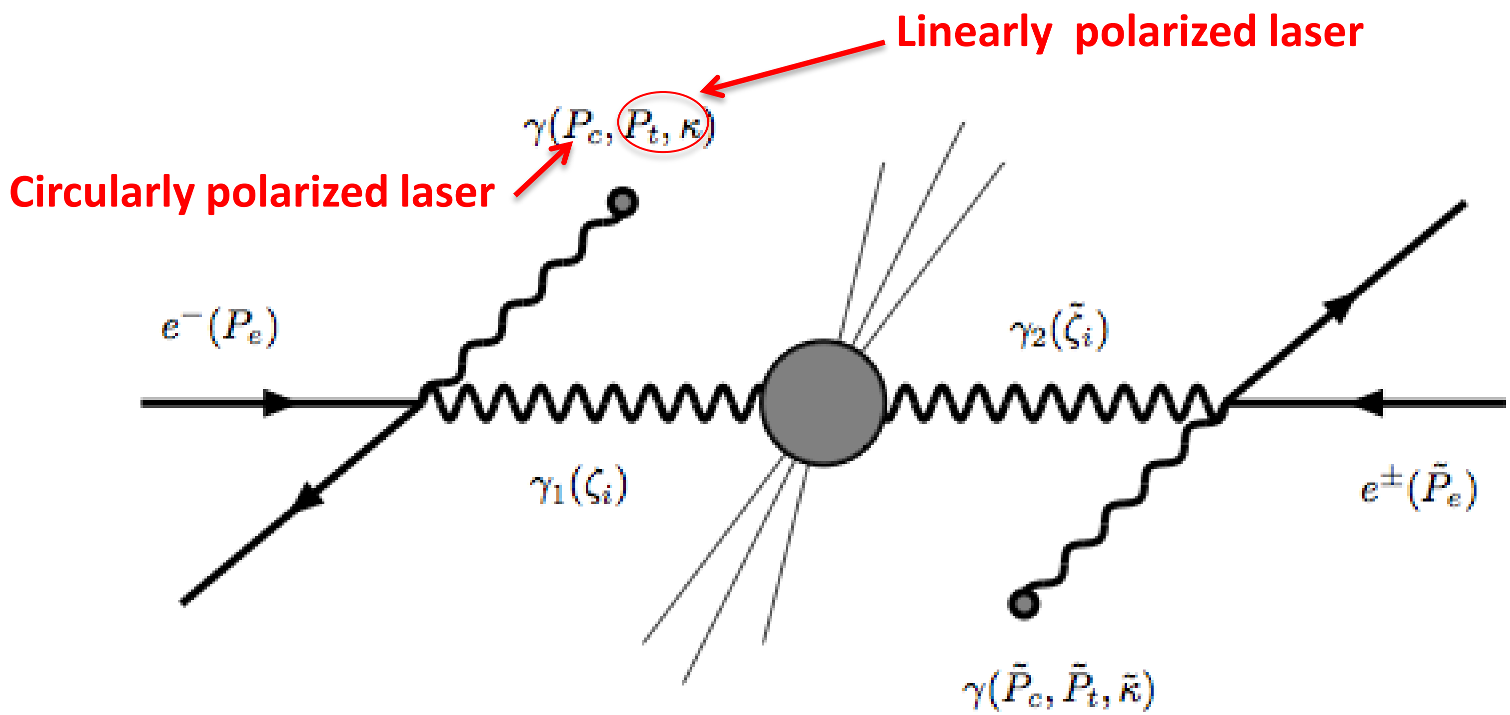
2% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to b\bar{b})\}$ within a year!

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

Similar performance for H to bb predicted by other studies:

S.Soldner-Rembold, P.Niezurawski, Rosca, etc…

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

γγ Ideal To Measure CP Mixing and Violation

ζ_2 is the degree of circular polarization

(ζ_3, ζ_1) are the degrees of linear polarization

Only with $\gamma\gamma C$

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

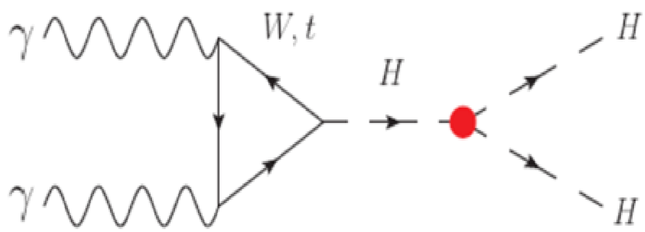
→ If $\mathcal{A}_1 \neq 0$, $\mathcal{A}_2 \neq 0$ and/or $|\mathcal{A}_3| < 1$, the Higgs is a mixture of CP-Even and CP-Odd states

→ Possible to search for CP violation in $\gamma\gamma \to H \to$ 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

JS Lee arXiv:0705.1089v2

Higgs Self-Coupling

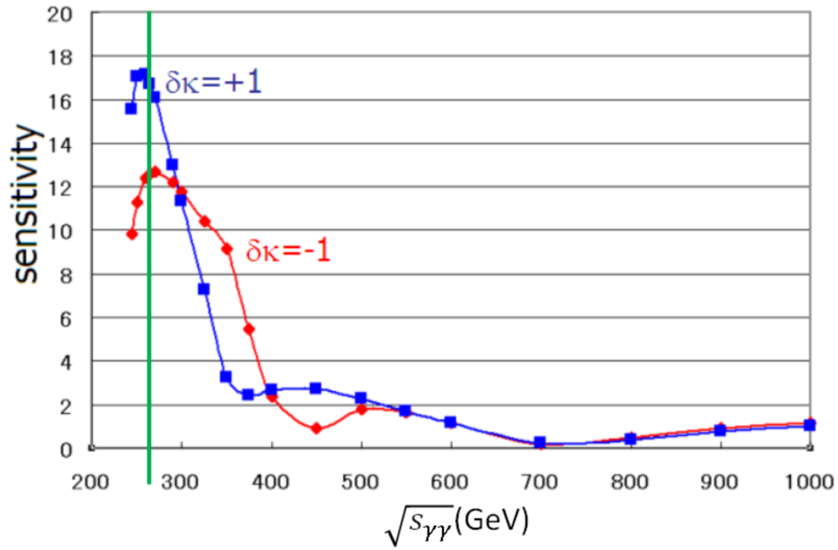


Final goal: Study of Higgs self-coupling

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

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

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

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

$\gamma\gamma$C Summary (I)

- 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
  - Already mention: Running of $\sin^2\theta_W$ in $e^-e^- \rightarrow e^-e^-$
  - 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]
    - Exotic: e-e- → W^-W^- to search for Majorana neutrino

$\gamma\gamma$C Summary (II)

- $\gamma\gamma$C is an interesting option that is starting to look more realistic:
  - Laser technology needed to generate γ – beam becoming a reality
    - Notice that this involves a new scientific community that would like to be an active collaborator, like the ICAN laser group. That will increase the technology transfer capability of this machine.
  - Various designs available that are:
    - Cost effective (<1 Billion)
    - Take advantage of exciting technology and infrastructure

Therefore, we might be able to build and operate SAPPHIRE and HFiTT like machines in parallel to the more ambitious e+e- program. Increasing the possibility of answering some our questions within our lifetime ☺