Higgs factories based on Photon Colliders

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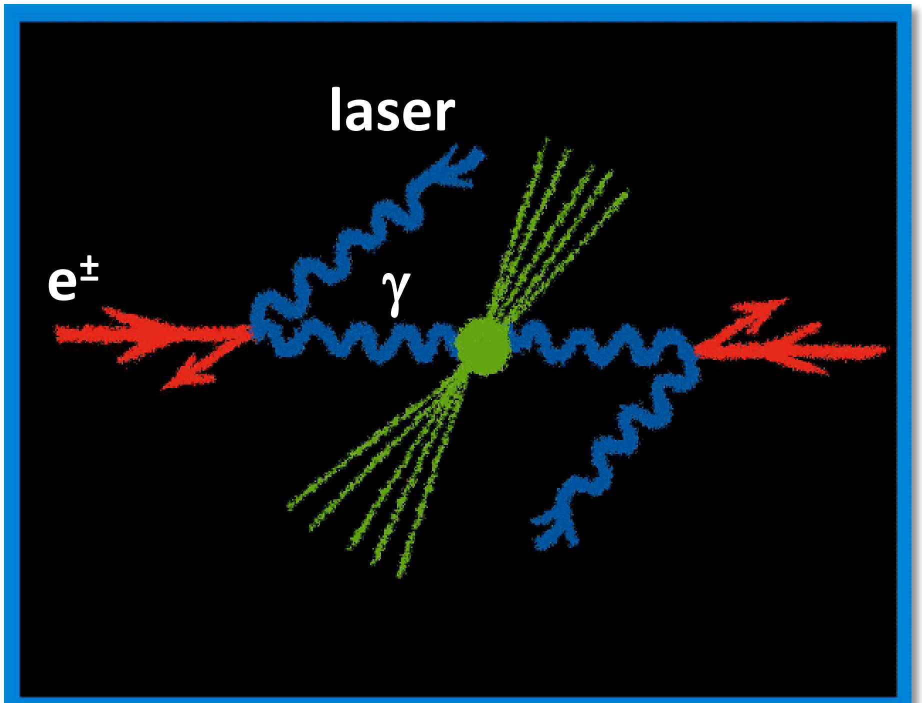
Northwestern University

Excited to be here… Because

- ICAN success in producing high power lasers will allow us to build a <u>new type</u> of high-energy particle collider:

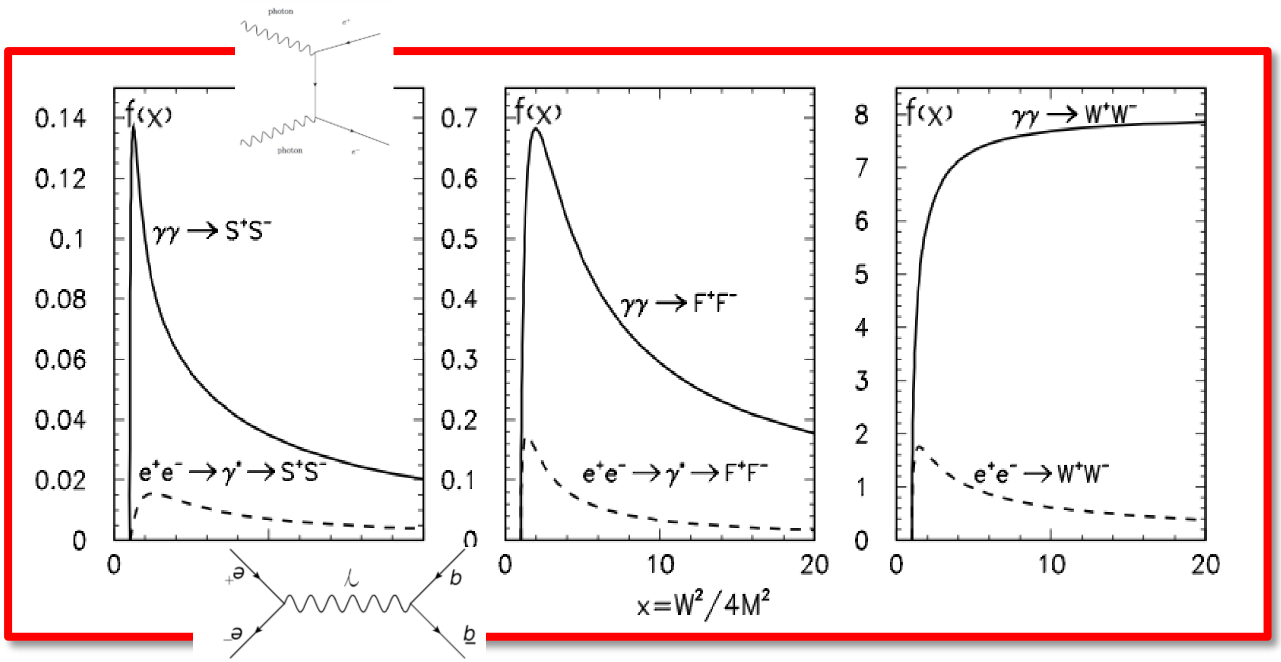


30 years old concept from Ginsburg et. al.
So far, limited the laser requirements:
- 5 Joules
- 10 to 10^2 kHz
- 0.3 to 1 μm

➔ **Photon-Photon colliders (γγC)**

What is special about γγC ?

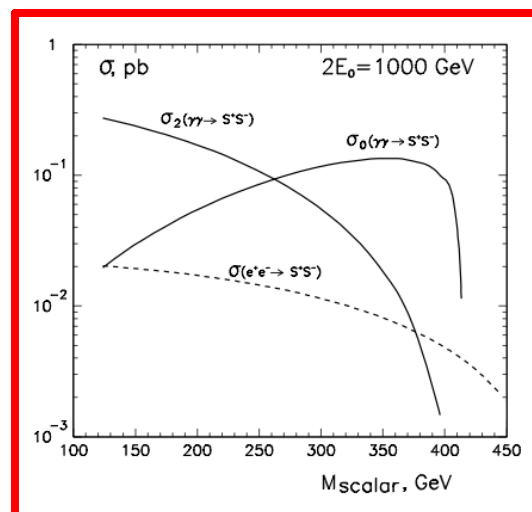
- **#1: Higher sensitivity to particle physics beyond the standard model due to higher cross sections**



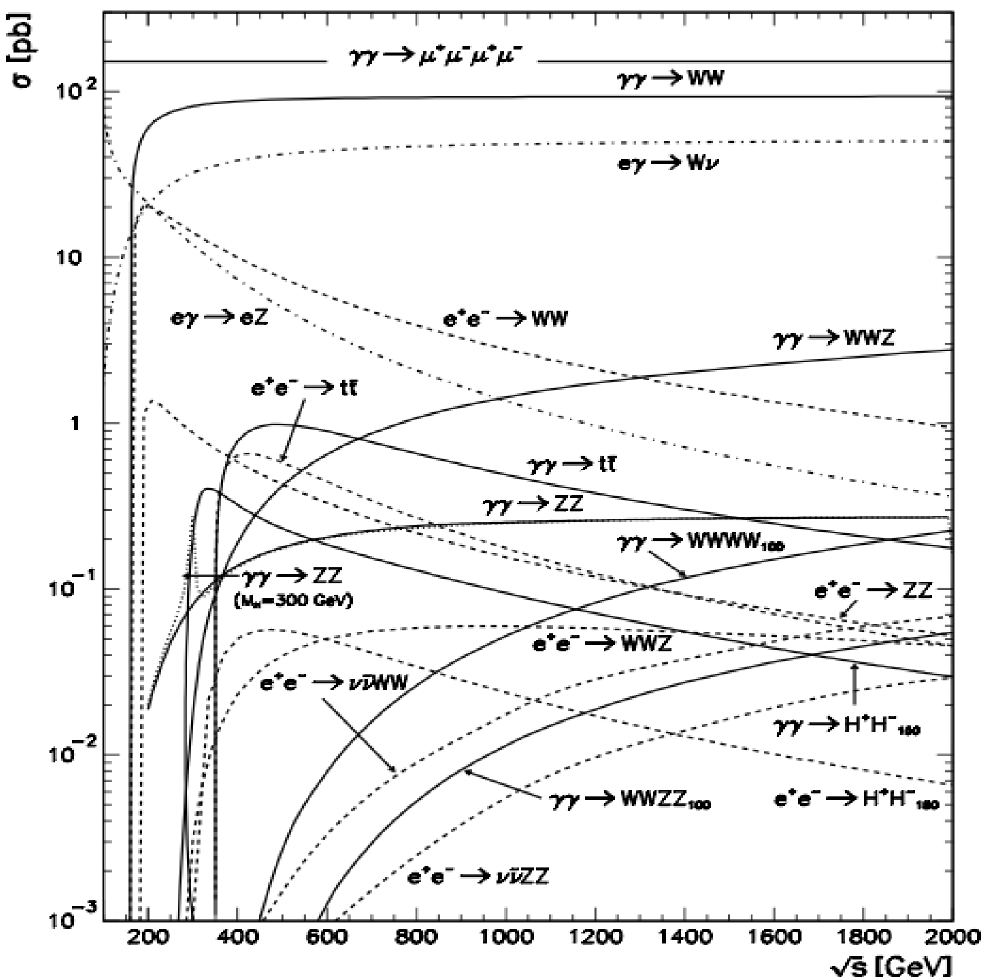
W = invariant mass (c.m.s. energy of Colliding beams)

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

and ability to manipulate the photon beam polarization to produce J of γγ system is = 0 or 2



Example of Standard Model Processes



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

- **#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

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

$$\lambda_1, \lambda_2 = (+,+) \quad \text{and} \quad \lambda_1, \lambda_2 = (-,-)$$

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

- #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

  $\Rightarrow (\gamma_{\parallel} \parallel \gamma_{\parallel}) \quad \Rightarrow \quad$ CP-even

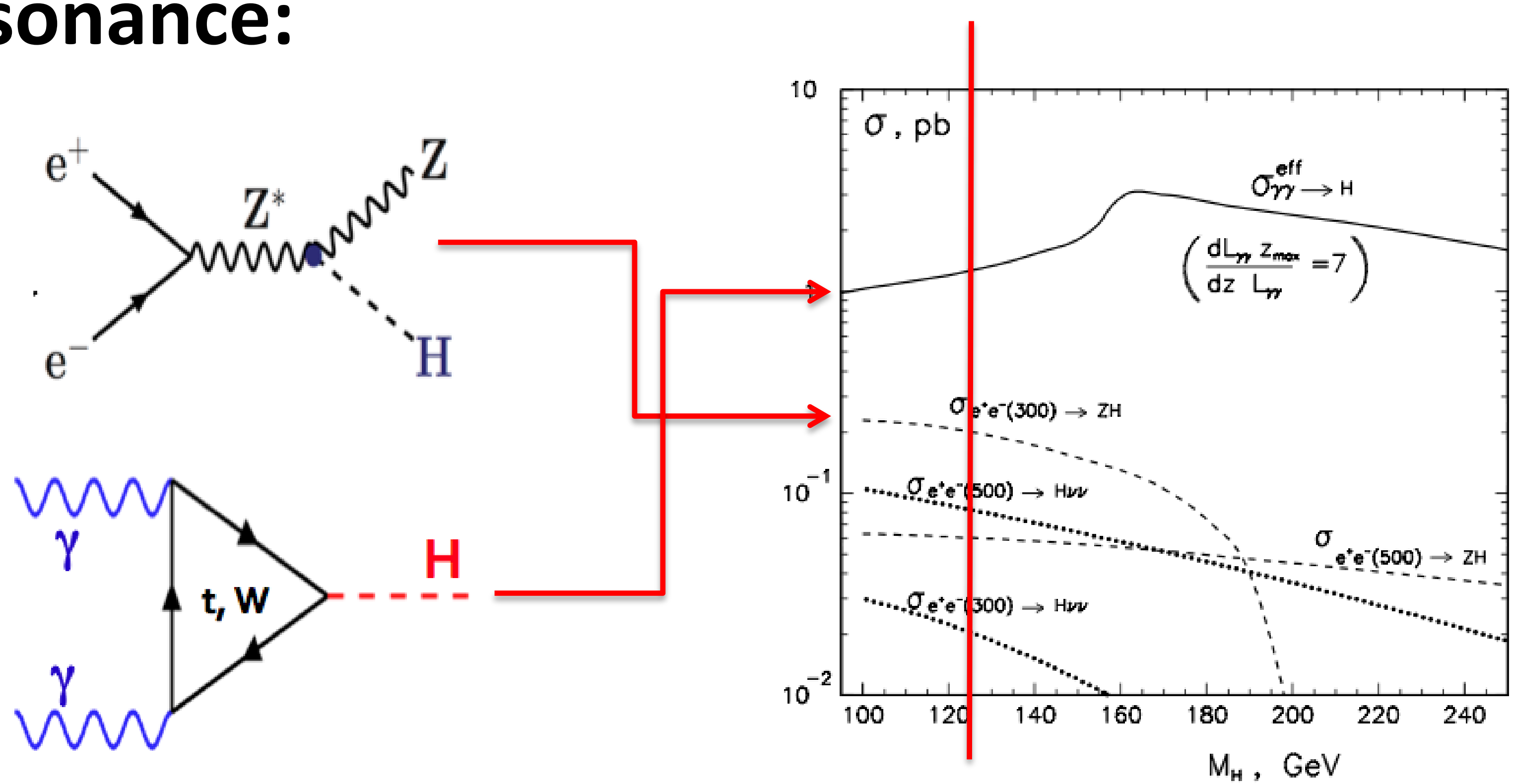
  $\Rightarrow (\gamma_{\parallel} \perp \gamma_{\parallel}) \quad \Rightarrow \quad$ CP-odd

Still looking for the source of matter anti-matter asymmetry observed for visible matter in our universe; therefore looking for new sources of ~~CP~~

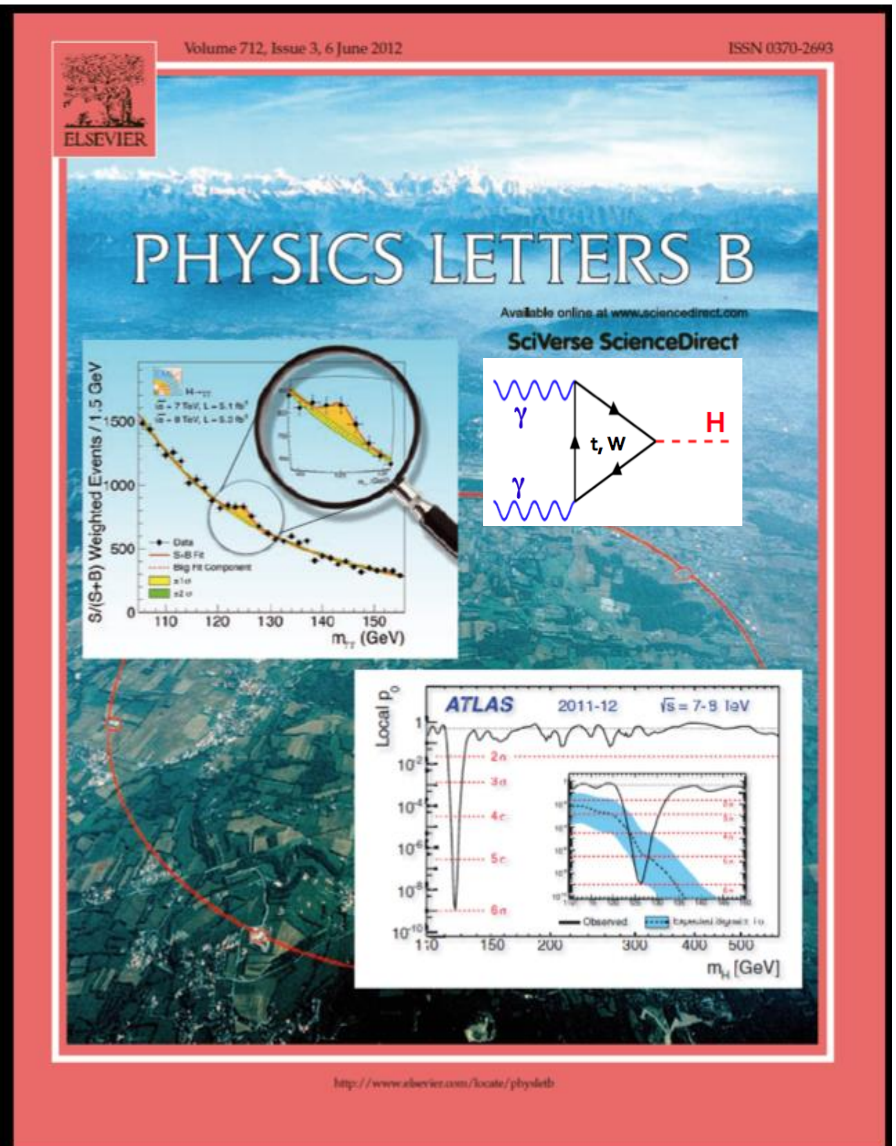
$\lambda_1, \lambda_2 = (+, +)$ **and** $\lambda_1, \lambda_2 = (-, -)$

What is special about γγC ?

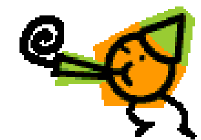
- **#3: Special role in understanding Higgs mechanism due to larger cross sections and the fact that Higgs is produced as an resonance:**



Combined all of these and we get γγC as Higgs factory… Just in time ☺



Higgs Discovery in July 2012

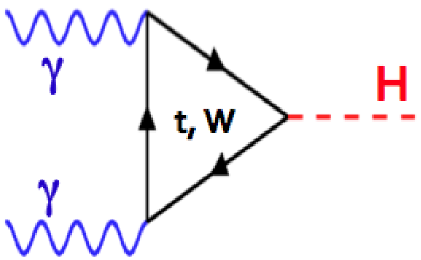


Higgs relatively light M_H~125 GeV

E_{ee}~160 GeV enough to produce γγ→H

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

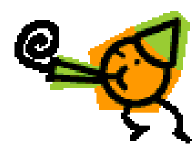
- Important measurements that can only be done with high precision at the $\gamma\gamma$C
  - $\Gamma_{\gamma\gamma}$ to 2% (Model independent)
    - Results in a 13% on Γ_{Total}
    - Results in a Y_{tt} of 4%
  - Measure CP mixing and violation to better than 1%
  - At higher energies Higgs self coupling: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



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

Technical 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%)
  - Independent of ILC or CLIC
  - "Low" cost



- Required laser technology is becoming available:
  - Fiber based laser (ICAN) and it is affordable
  - A completely new community to collaborate with

3 New Designs that will Produce 10K Higgs/year

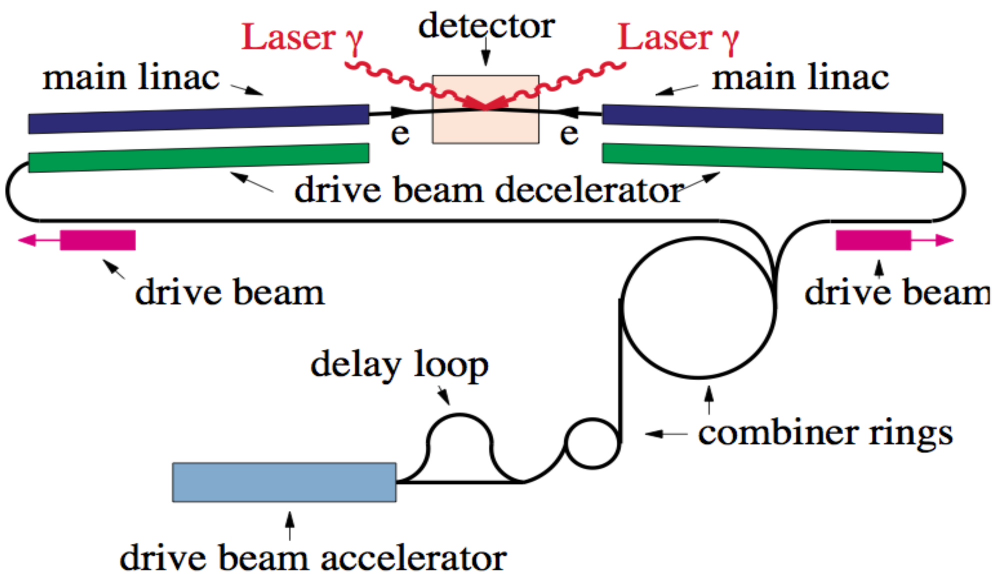
- **HFiTT:** **Higgs Factory in Tevatron Tunnel**
  - **Fermilab specific**
- **SILC:** **SLC-ILC-Style $\gamma\gamma$ Higgs Factory**
  - **SLAC specific**
- **SAPPHiRE:** **Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons**
  - **Developed at CERN, but can be built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

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

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

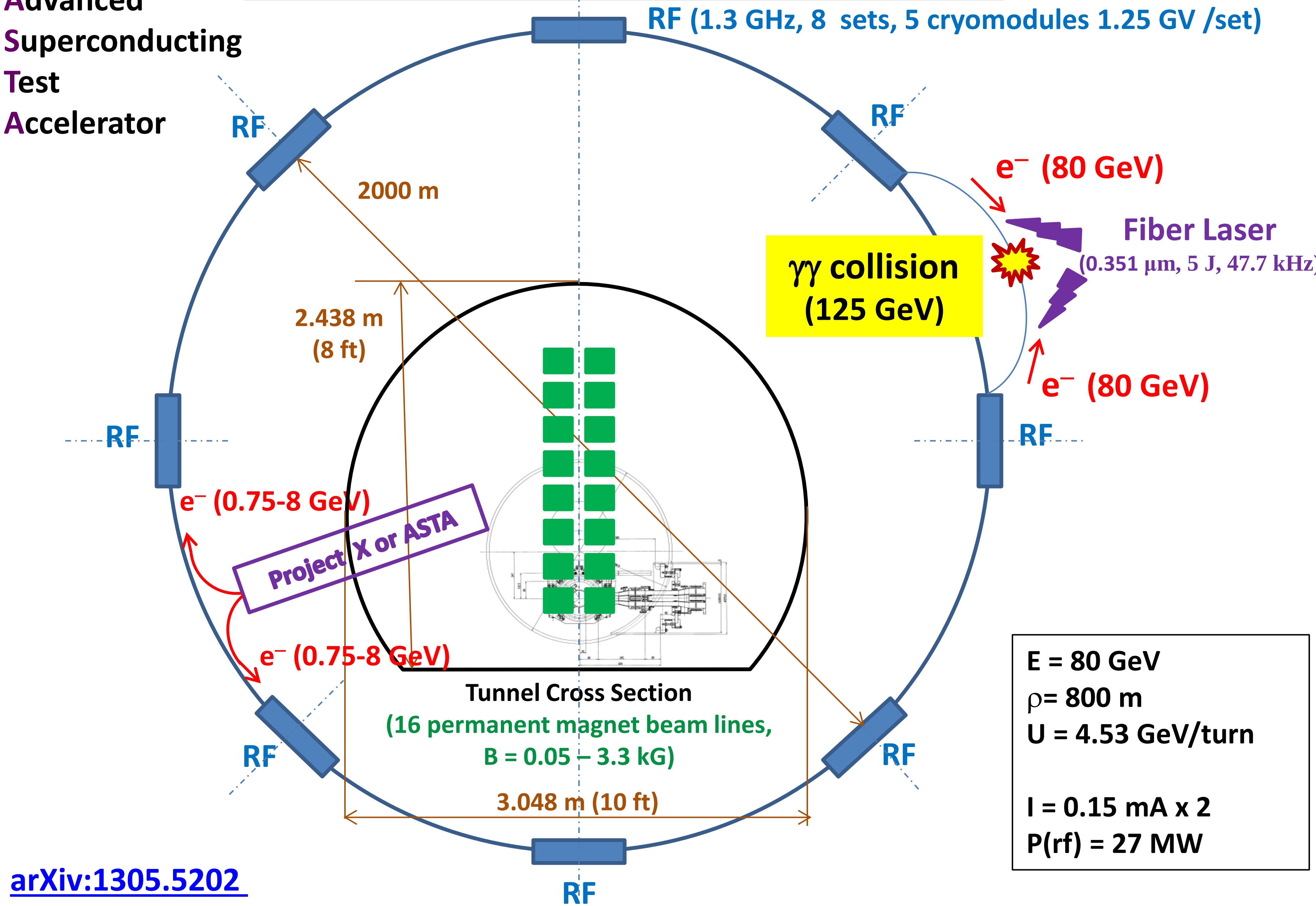
Earlier e-e- based γγC design

- 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



E = 80 GeV
ρ= 800 m
U = 4.53 GeV/turn

I = 0.15 mA x 2
P(rf) = 27 MW

arXiv:1305.5202

Cost estimate for HFiTT

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

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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.

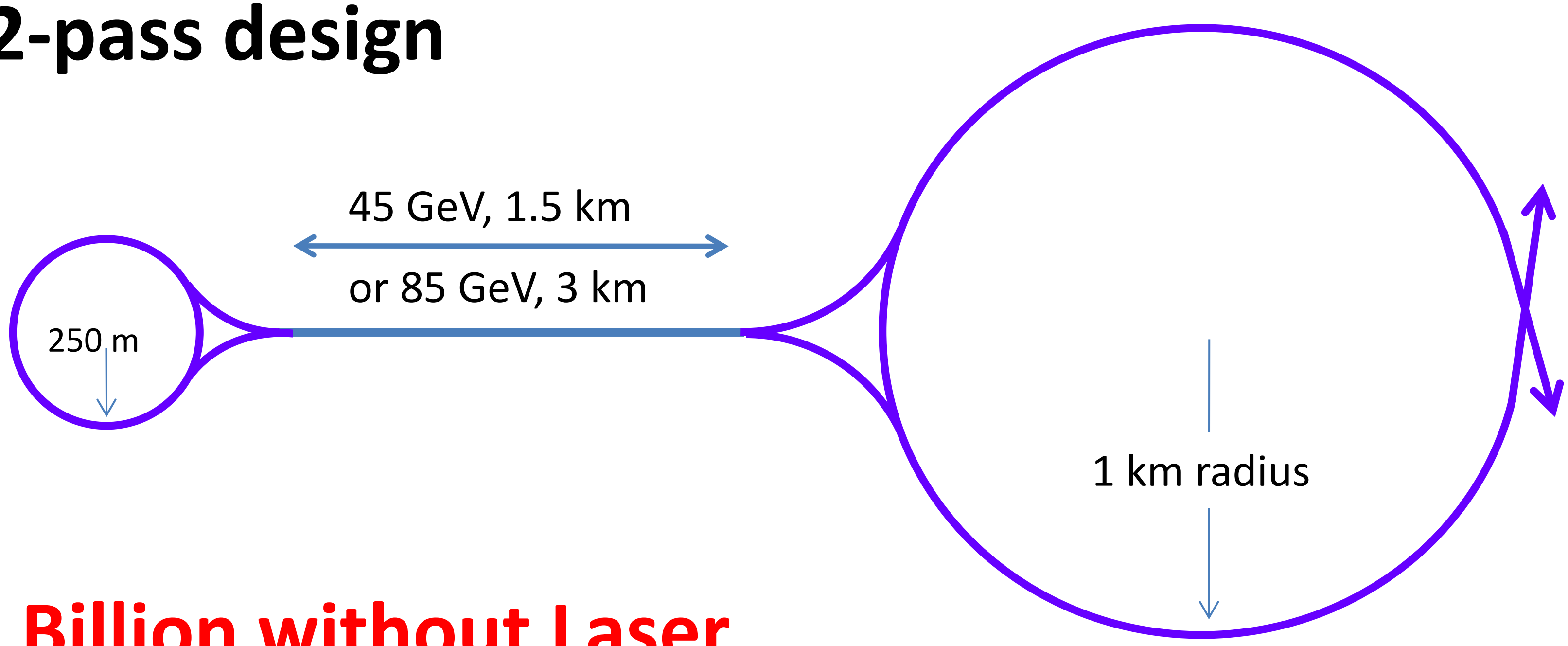
< 1Billion USD

With Laser design by ICAN collaborators and based on Fiber laser

SILC – Presented by Tor Raubenheimer

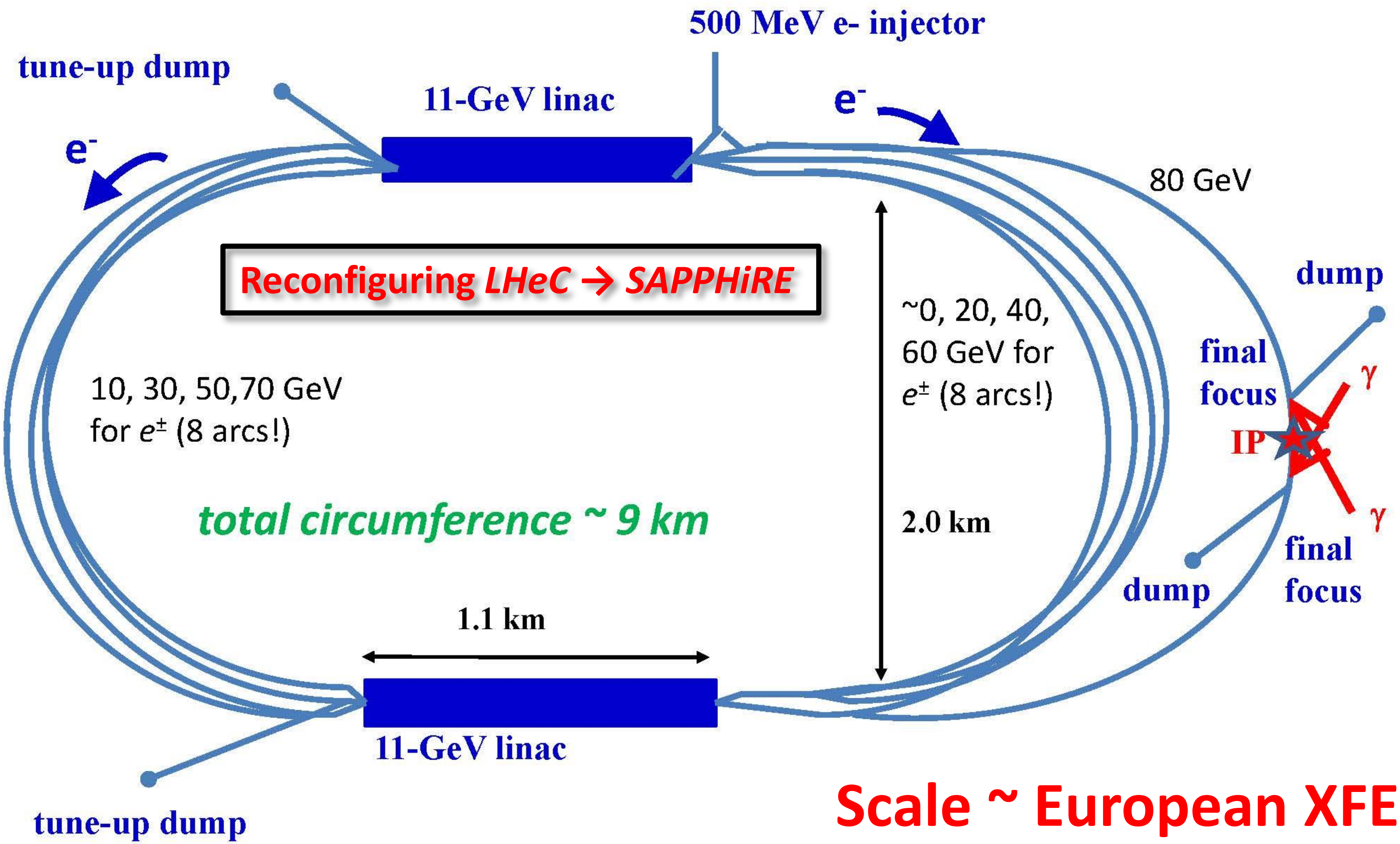
ICFA Higgs Factory Workshop November 14th, 2012

➔2-pass design



1.6 Billion without Laser

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



Scale ~ European XFEL

~ 1 Billion

Energy lost	3.89 GeV

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

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:

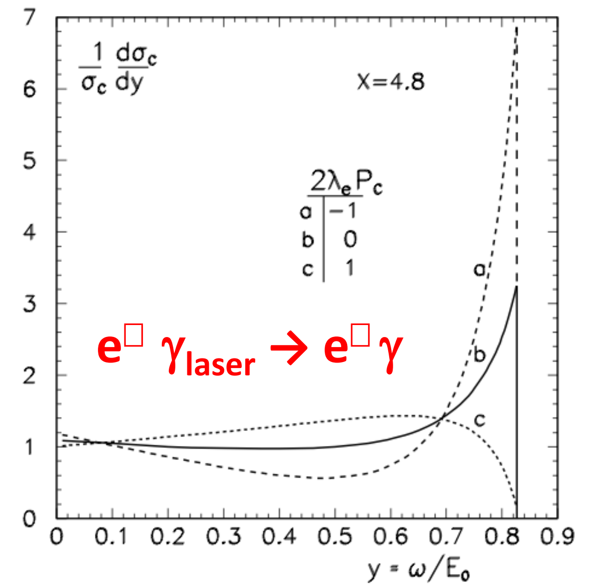
- Low-emittance DC guns @
  - MIT-Bates, Cornell, SACLA,JAEA,KEK, etc
- Polarized SRF guns @
  - FZD, BNL, etc

➔ For more details see Frank Zimmermann:

HF2012 – FNAL (16 Nov 2012)

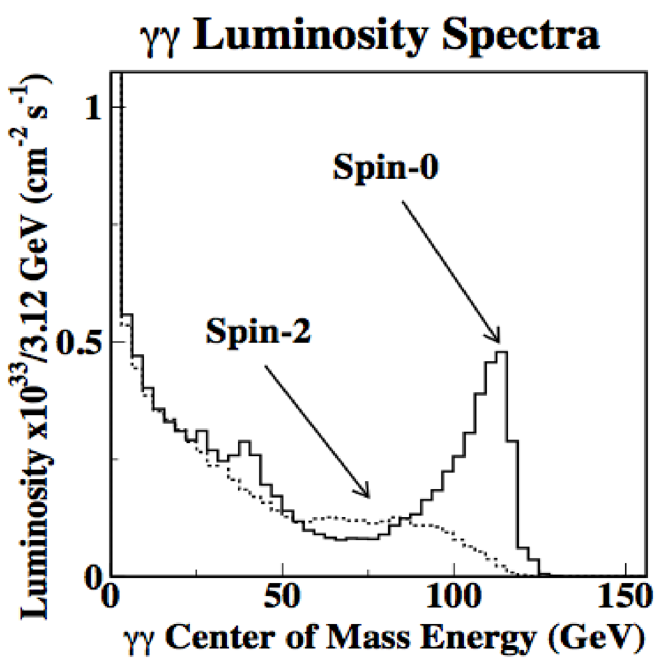
Idea of γγC Based on Compton Backscattering

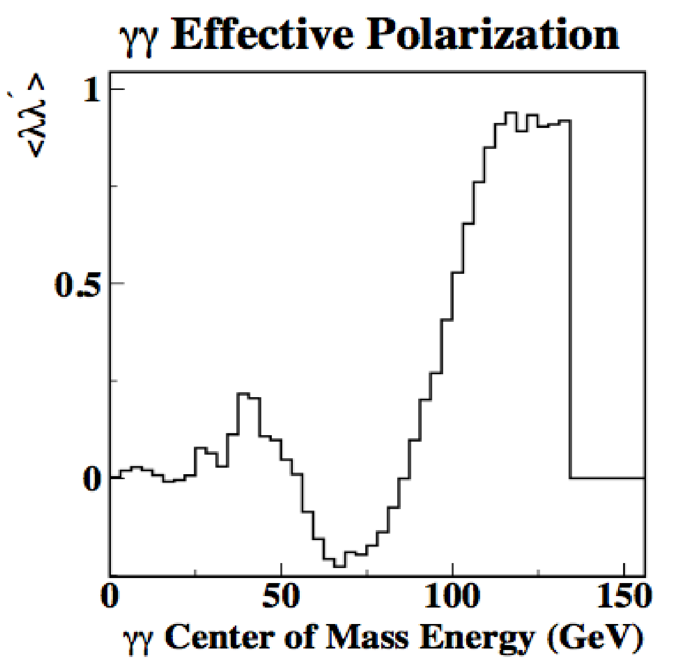
With circularly polarized γ_{laser} ($P_C = \pm 1$) & polarized e- ($\lambda_e = \mp 1$)



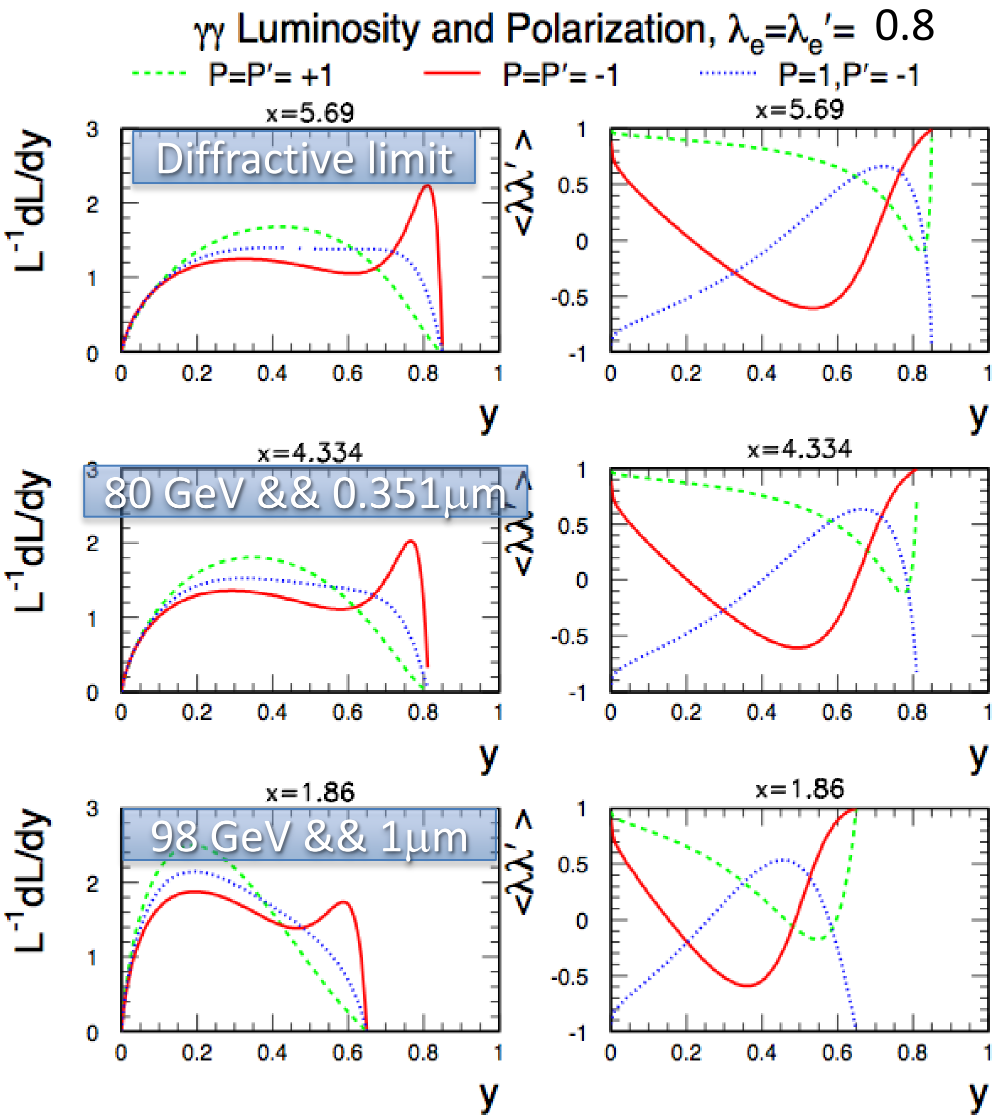
σ(γγ → H) >200 fb

Example: Optimized as a Higgs Factory





Compton Laser Backscattering Facts



$$E_e + w_o \rightarrow E_{e'} + E_\gamma$$

$$x_{max} = \frac{4E_e w_o}{m_e^2}$$

$$E_\gamma = \frac{x}{x+1} E_e$$

$$y_{max} = \frac{E_\gamma}{E_e}$$

For e- energies below 100 GeV it is better to use:

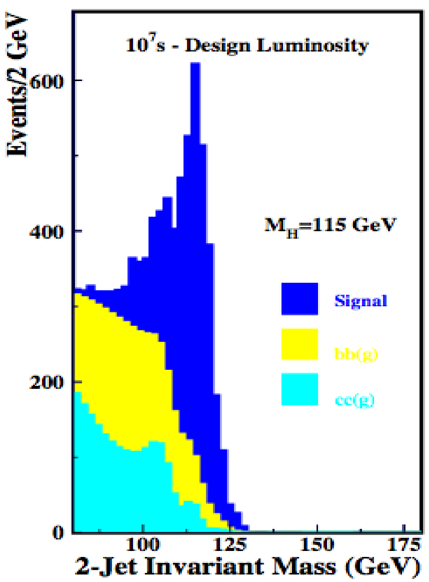
$$w_o = 3.53\ eV$$

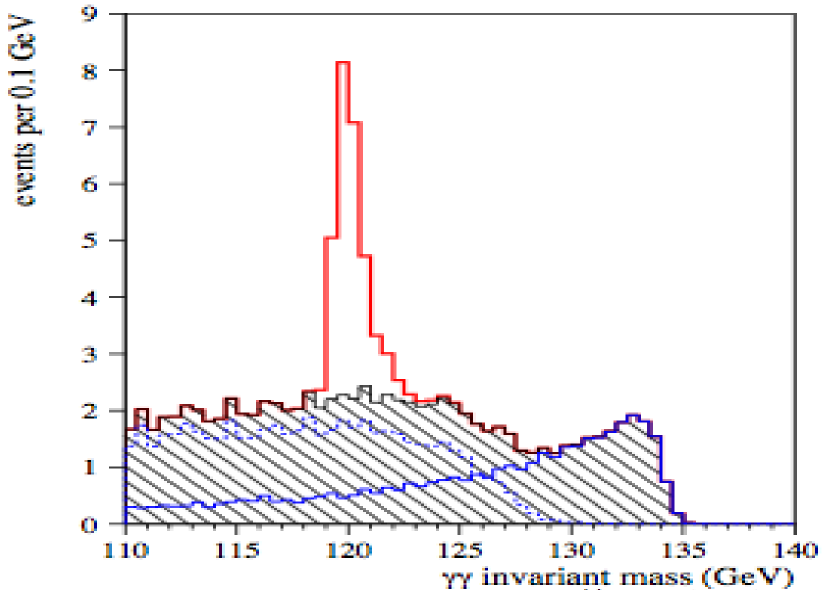
$$= 0.351 \mu m\ laser$$

$$x = 15.3 \left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\omega_0}{\mathrm{eV}}\right] = 19 \left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\mu m}{\lambda}\right]$$

γγC a good complement with existing and future programs

- **Physics capabilities complementary to LHC 2022 or future ILC because γγC will provide:**





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!

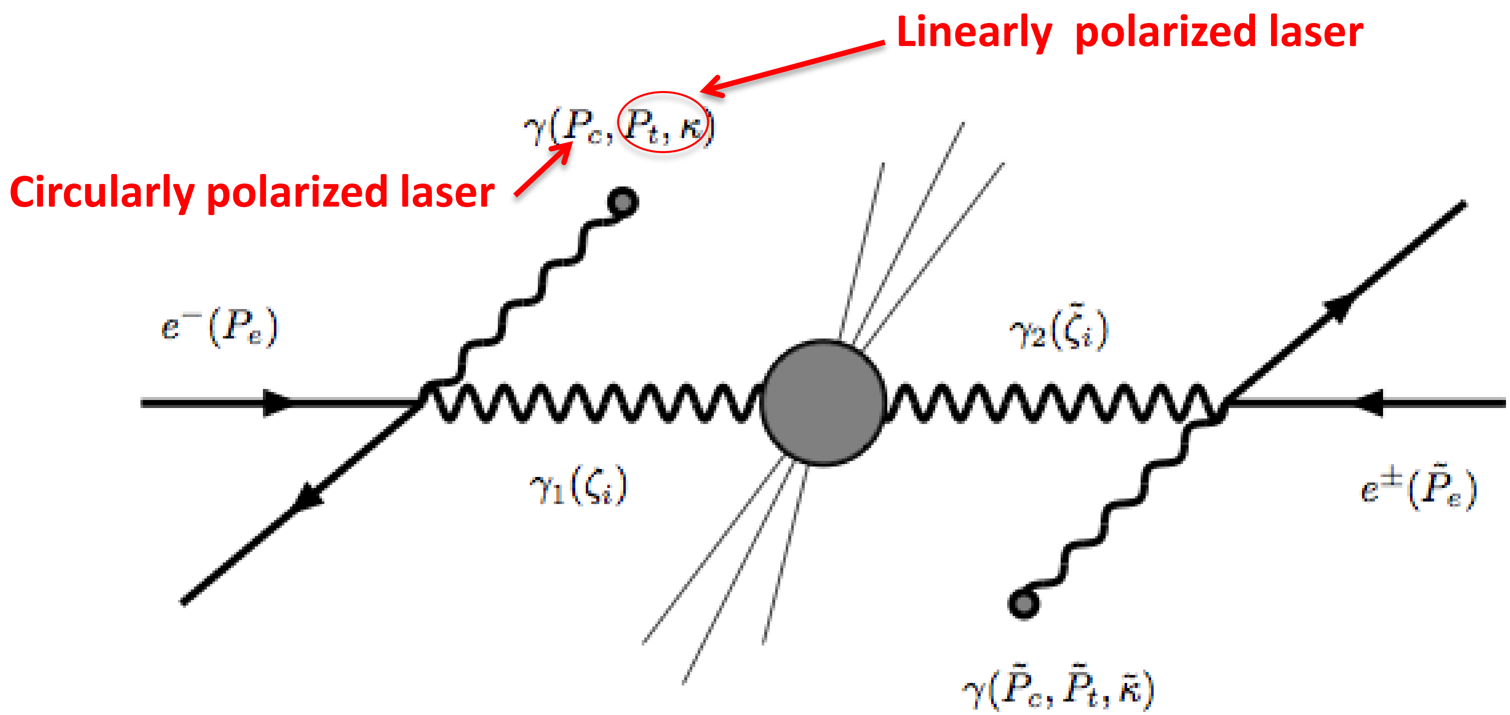
150 MeV mass measurement in 0.5 year!

$\gamma\gamma$C 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_2 is the degree of circular polarization

(ζ_3, ζ_1) are the degrees of linear polarization

Only with $\gamma\gamma$C

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

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

$\mathcal{A}_1$, $\mathcal{A}_2$: == 0 if CP is conserved

$\mathcal{A}_3$: == +1 (-1) for CP is conserved for A CP-Even (CP-Odd) Higgs

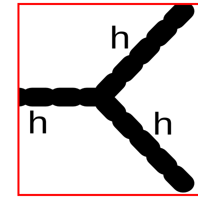
→ If $\mathcal{A}_1 \neq 0$, $\mathcal{A}_2 \neq 0$ and/or $|\mathcal{A}_3| < 1$, the Higgs is a mixture of CP-Even and CP-Odd states

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

Next generation also needs laser…

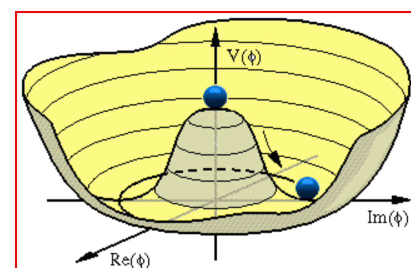


- **Upgrade: Increase energy of the e- beam from 80 GeV to 150 GeV *plasma afterburners (PWFA)*[1] to measure Higgs self coupling**

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

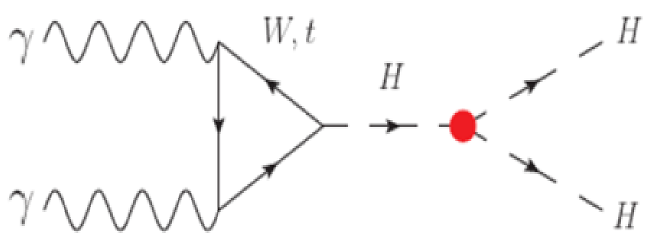
$$l_{SM} = \sqrt{\frac{h}{2}} m_H$$

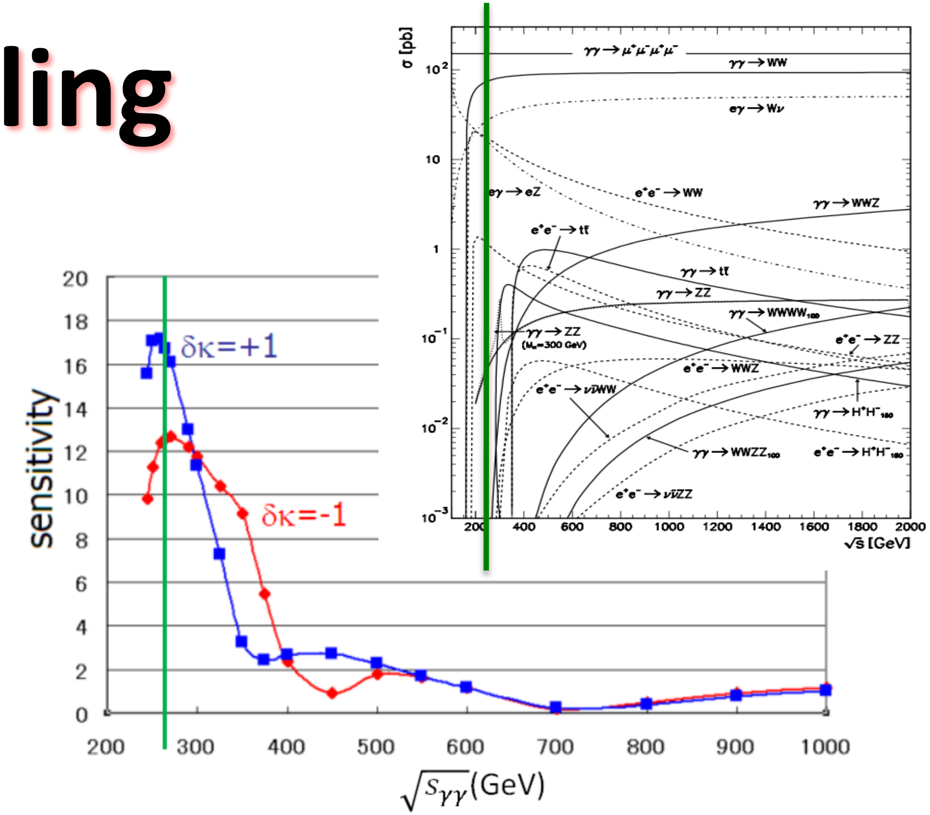
- only way to reconstruct the Higgs potential:



[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

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

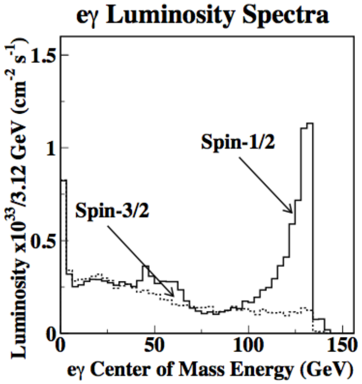
S.Kawada.. et.al, Phys. Rev. D 85, 113009 (2012)

$\gamma\gamma$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
  - 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]



γγC Summary (II)

- γγC is an interesting option that is starting to look more realistic thanks to the ICAN prospects:
  - Laser technology needed to generate γ – beam becoming a reality: Single shot with 5J and 47.7kHz (No cavity ☺) *Laura Corner talk*

Could Optical Fibre Lasers be the Future of Accelerators?

→ YES!

  - Various designs available that are:
    - Cost effective (<1 Billion)
    - Take advantage of exciting technology and infrastructure

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

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