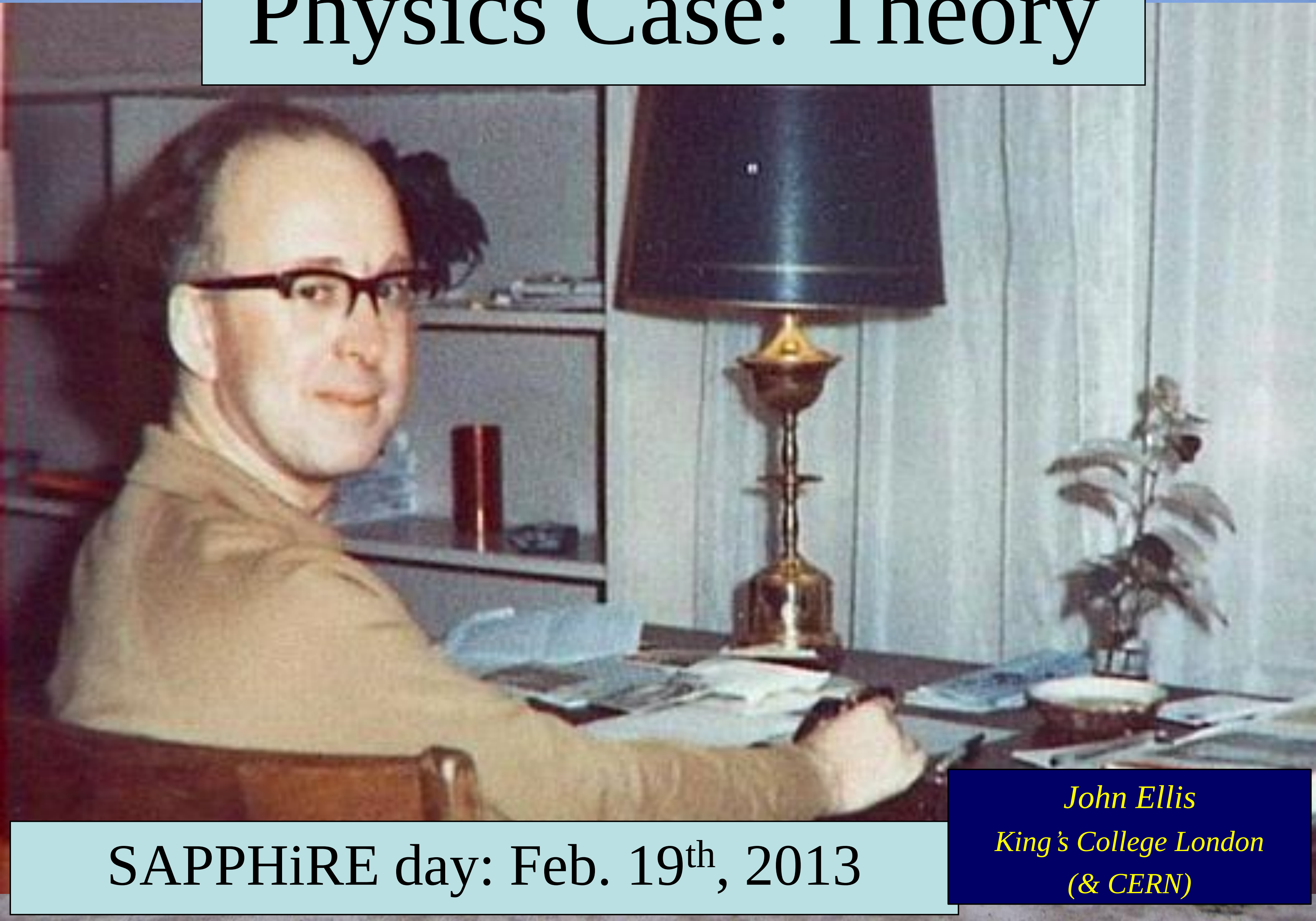
Physics Case: Theory

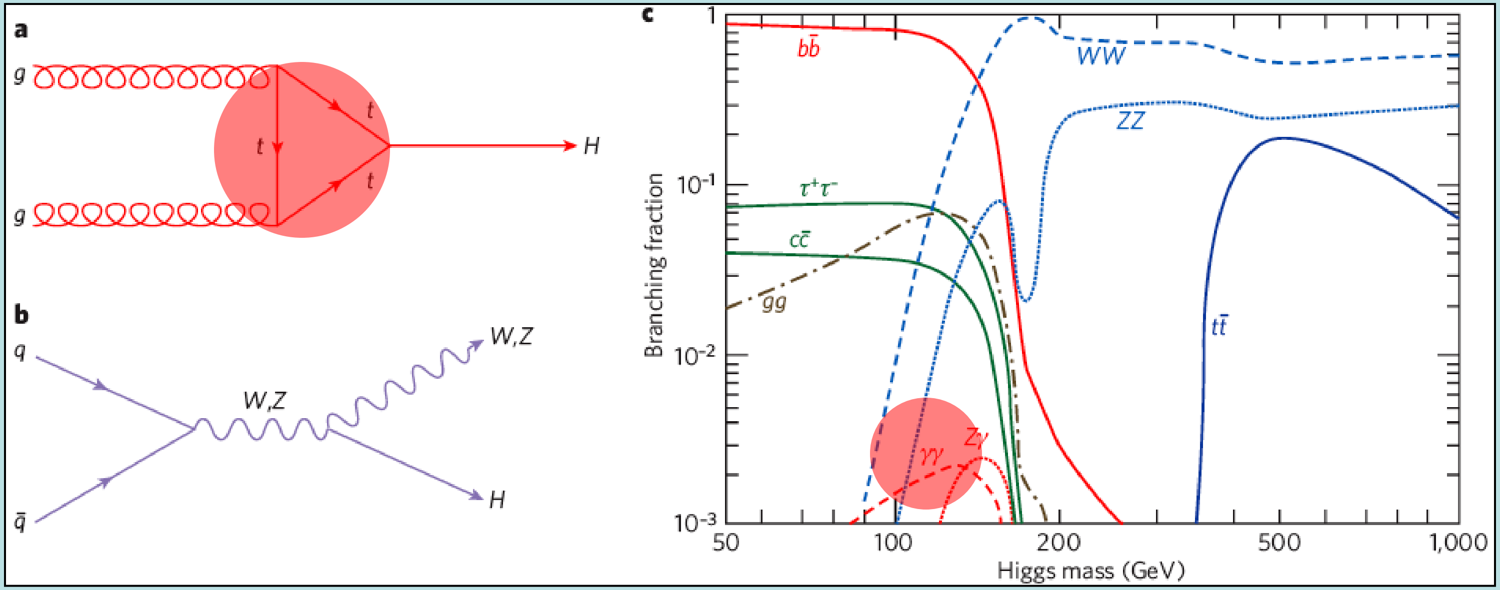


SAPPHiRE day: Feb. 19th, 2013

John Ellis
King's College London
(& CERN)

Higgs Decay Branching Ratios

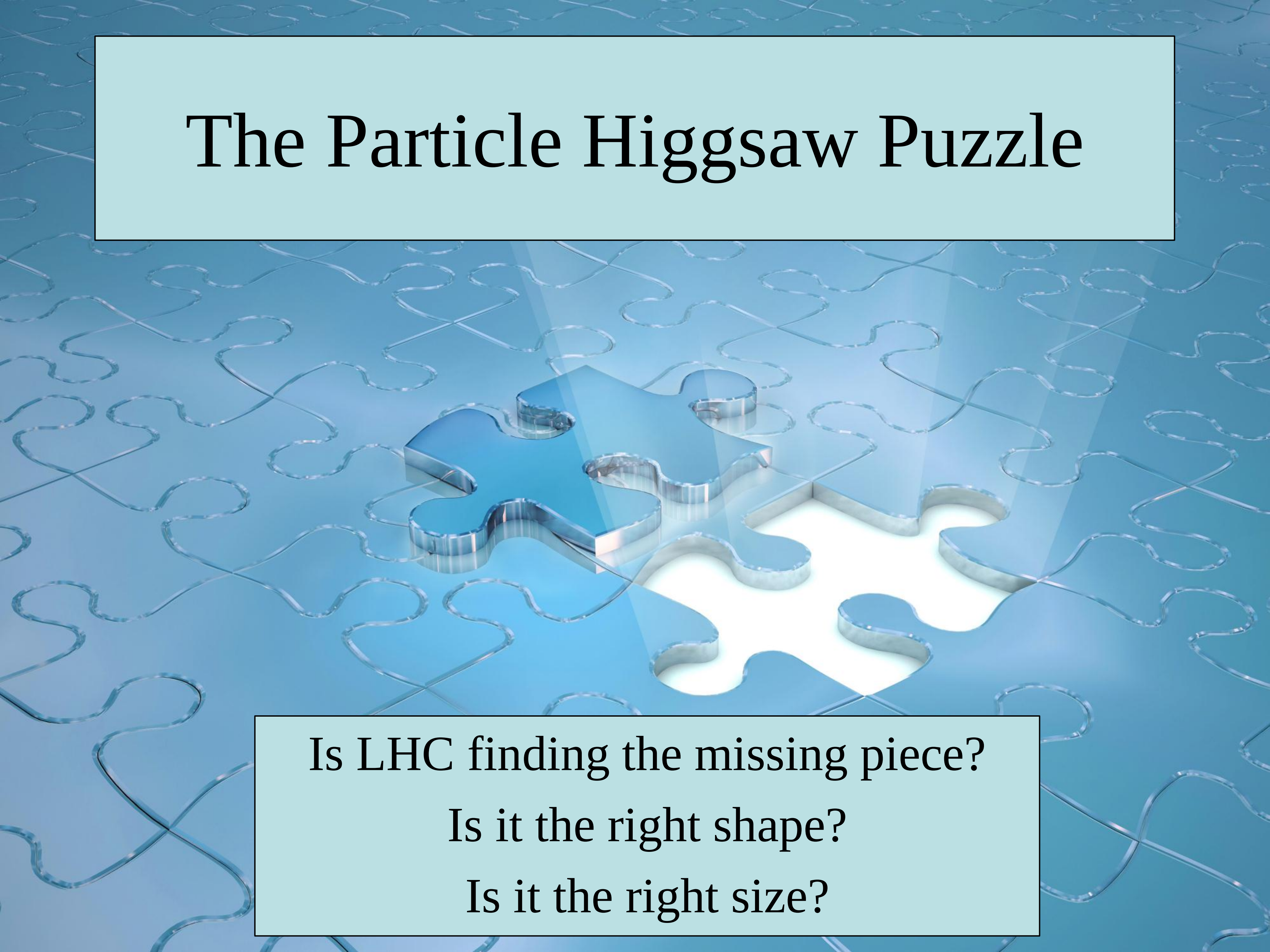
- Couplings proportional to masses (?)



- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if $M_h \sim 125$ GeV

The Particle Higgsaw Puzzle



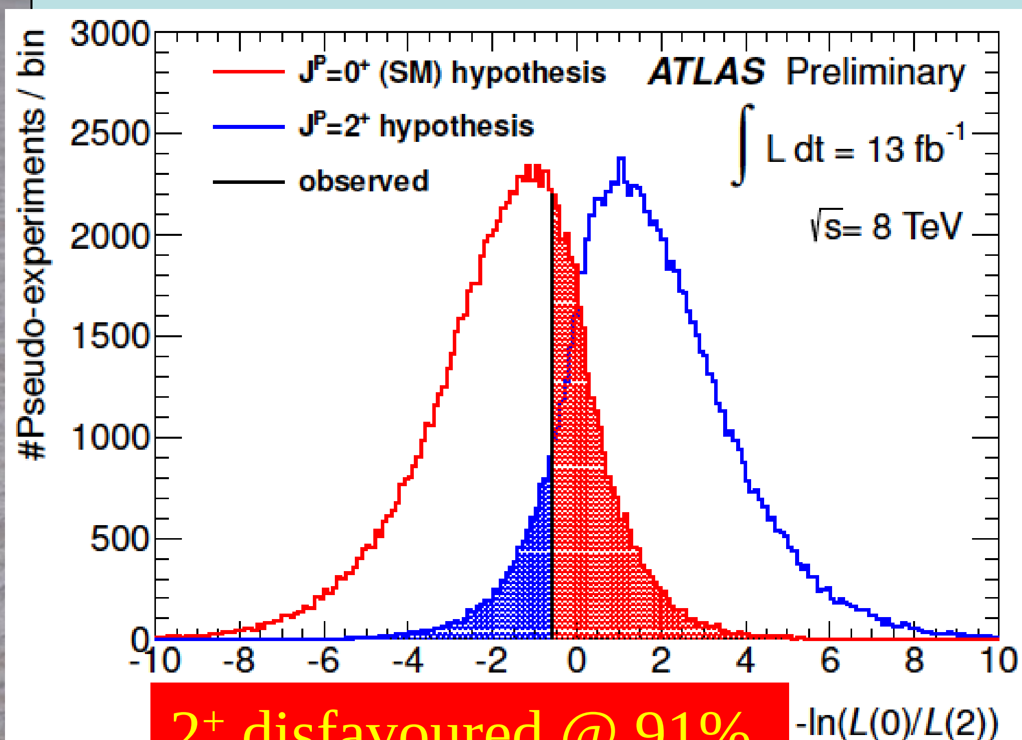
Is LHC finding the missing piece?

Is it the right shape?

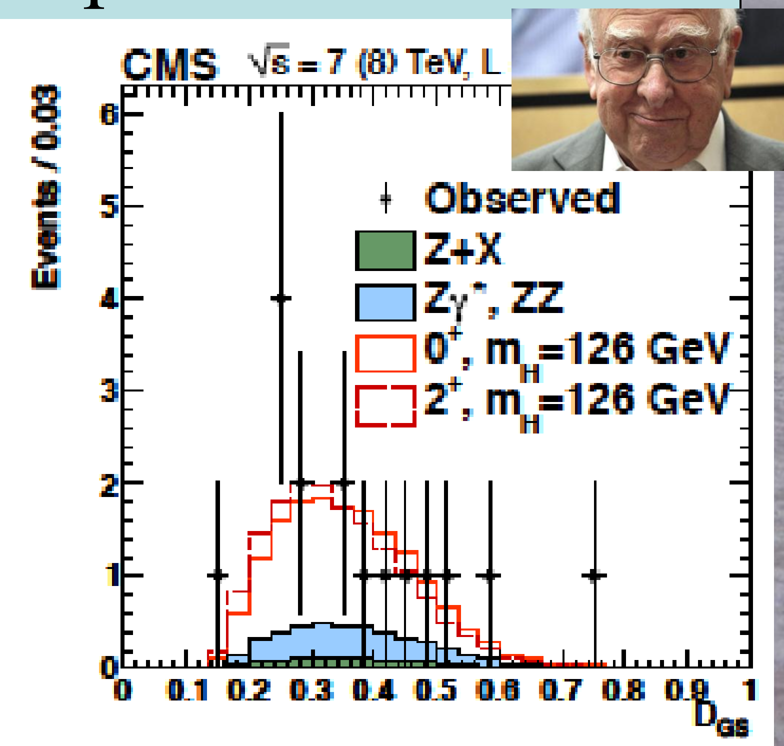
Is it the right size?

The 'Higgs' probably does not have Spin Two

- ATLAS γγ analysis prefers spin 0 over 2^+



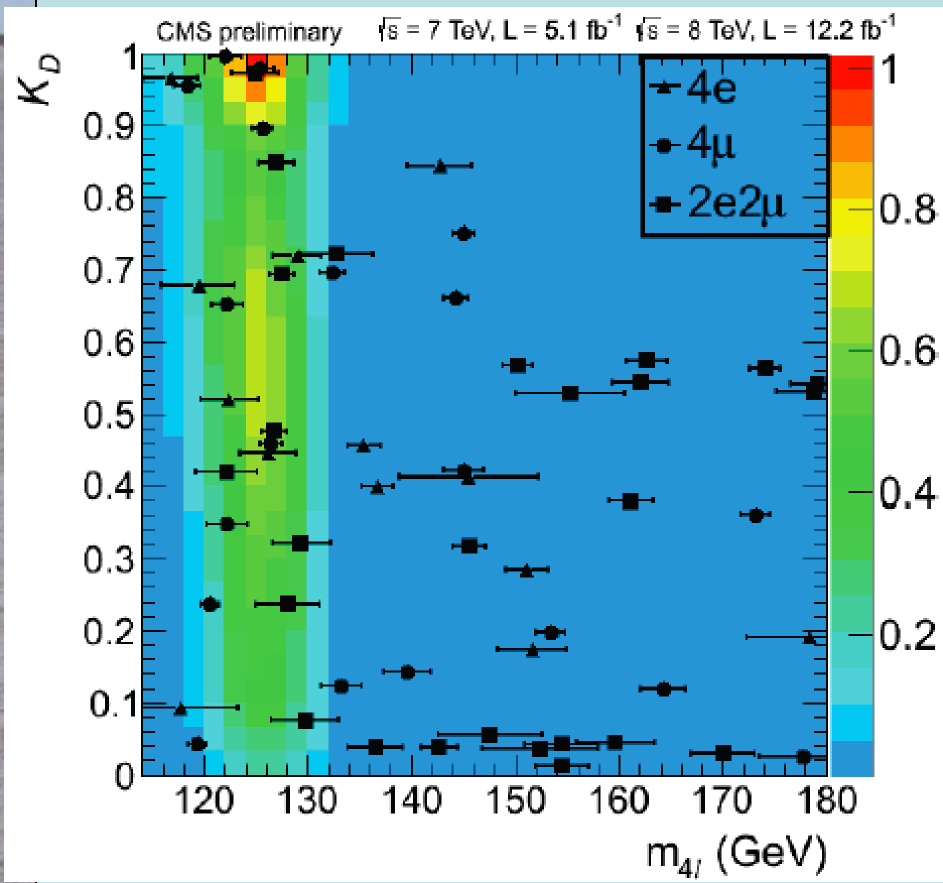
2^+ disfavoured @ 91%

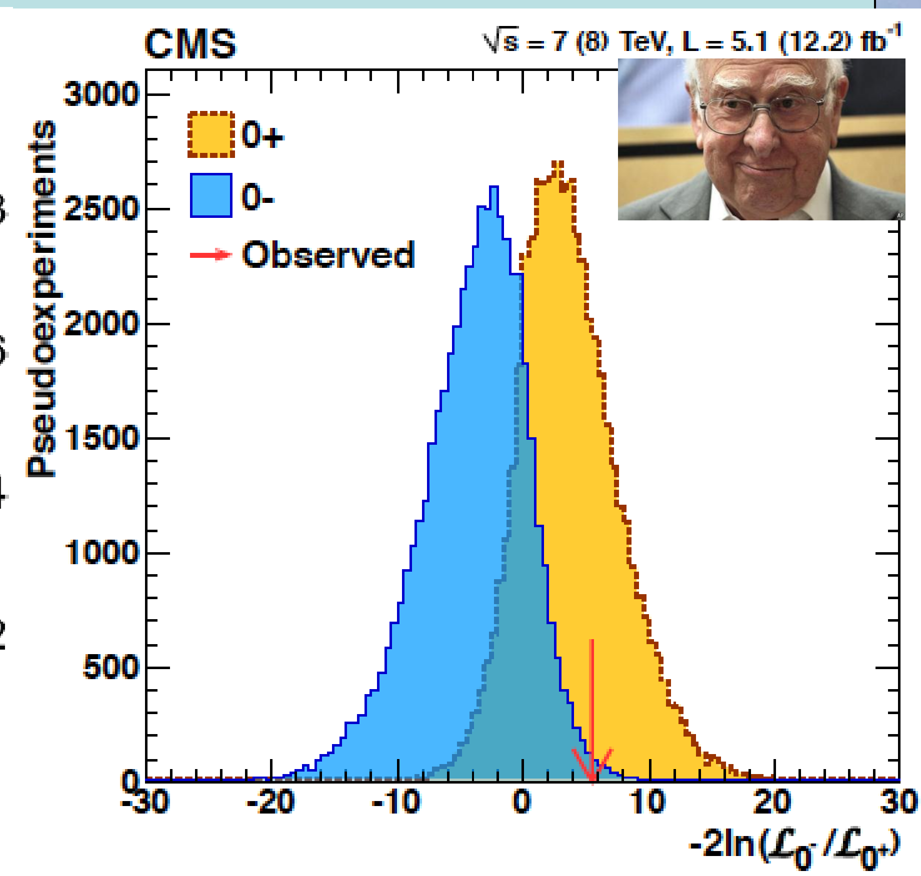


- No discrimination from CMS ZZ* analysis

The ‘Higgs’ probably has Parity +

- Kinematic distribution of ZZ* final state





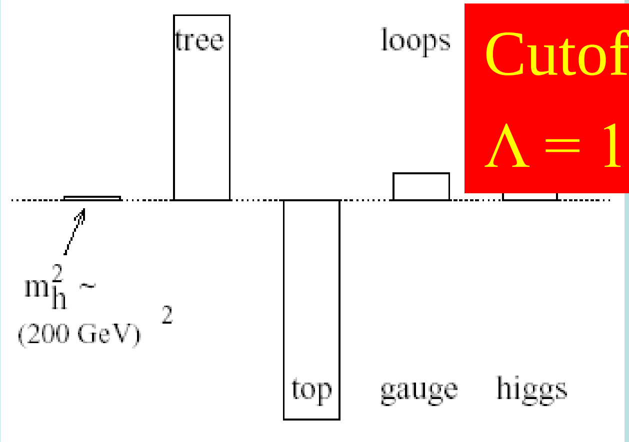
- 0^- disfavoured @ 97% level

Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- Quantum loop problems



Cutoff

$\Lambda = 10$ TeV

Cut-off $\Lambda \sim 1$ TeV with

Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed $m_t > 200$ GeV

New technicolour force?

- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

General Analysis of 'unHiggs' Models

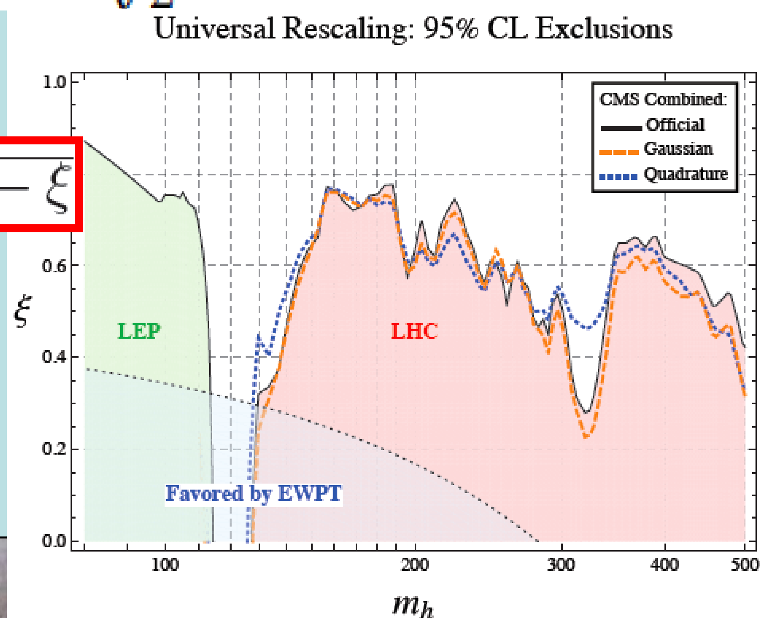
- Parametrization of effective Lagrangian:

$$\mathcal{L}^{(2)} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \cdots\right)$$

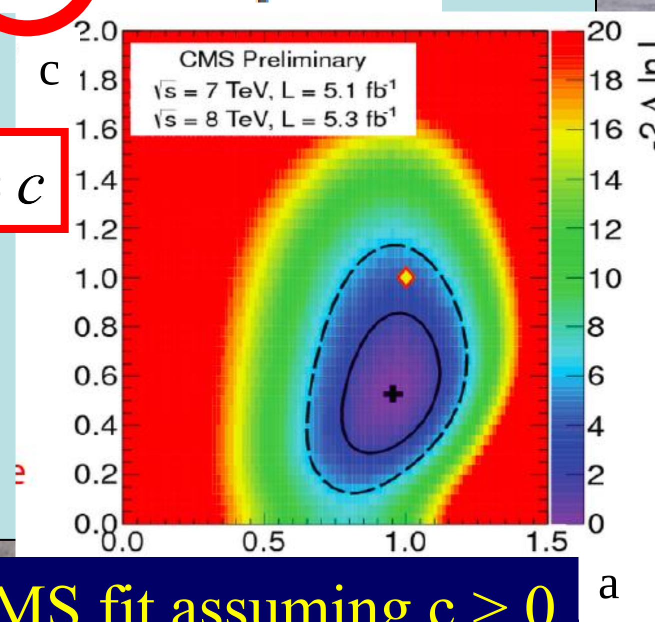
$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}_L^{(i)}, \bar{d}_L^{(i)}\right)\Sigma\left(u_R^{(i)}, 0\right)^T\left(1 + c_u\,\frac{h}{v} + c_{2u}\,\frac{h^2}{v^2} + \cdots\right)$$

- Fits

$a = c = \sqrt{1-\xi}$



$a \neq c$



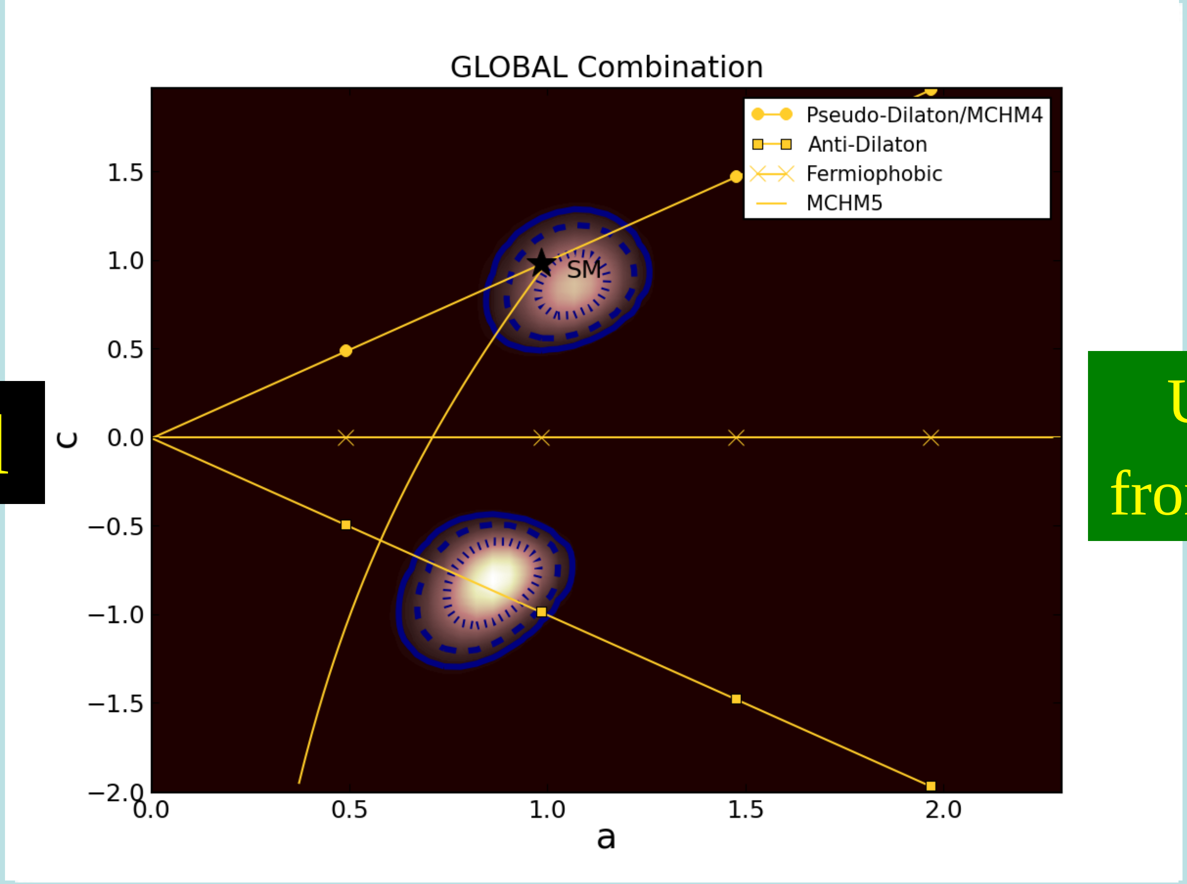
CMS fit assuming c > 0

Azatov, Contino, Galloway: arXiv:1202.3415

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*

Global 0



Update from Kyoto

- Standard Model: $a = c = 1$

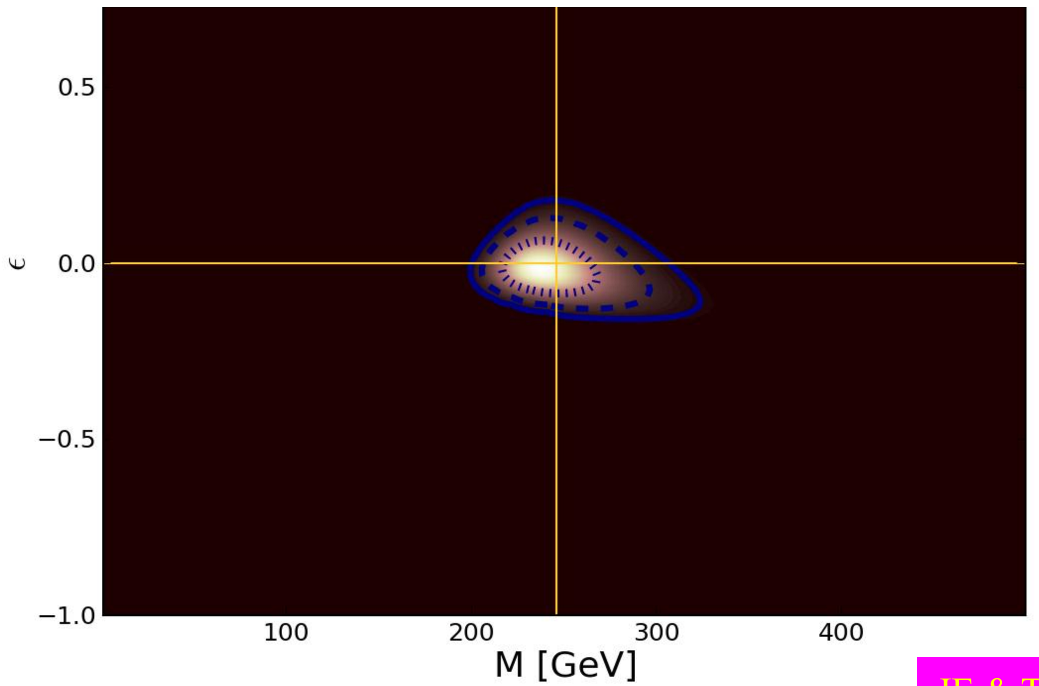
JE & Tevong You, arXiv:1207.1693

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

Global fit



Update from Kyoto

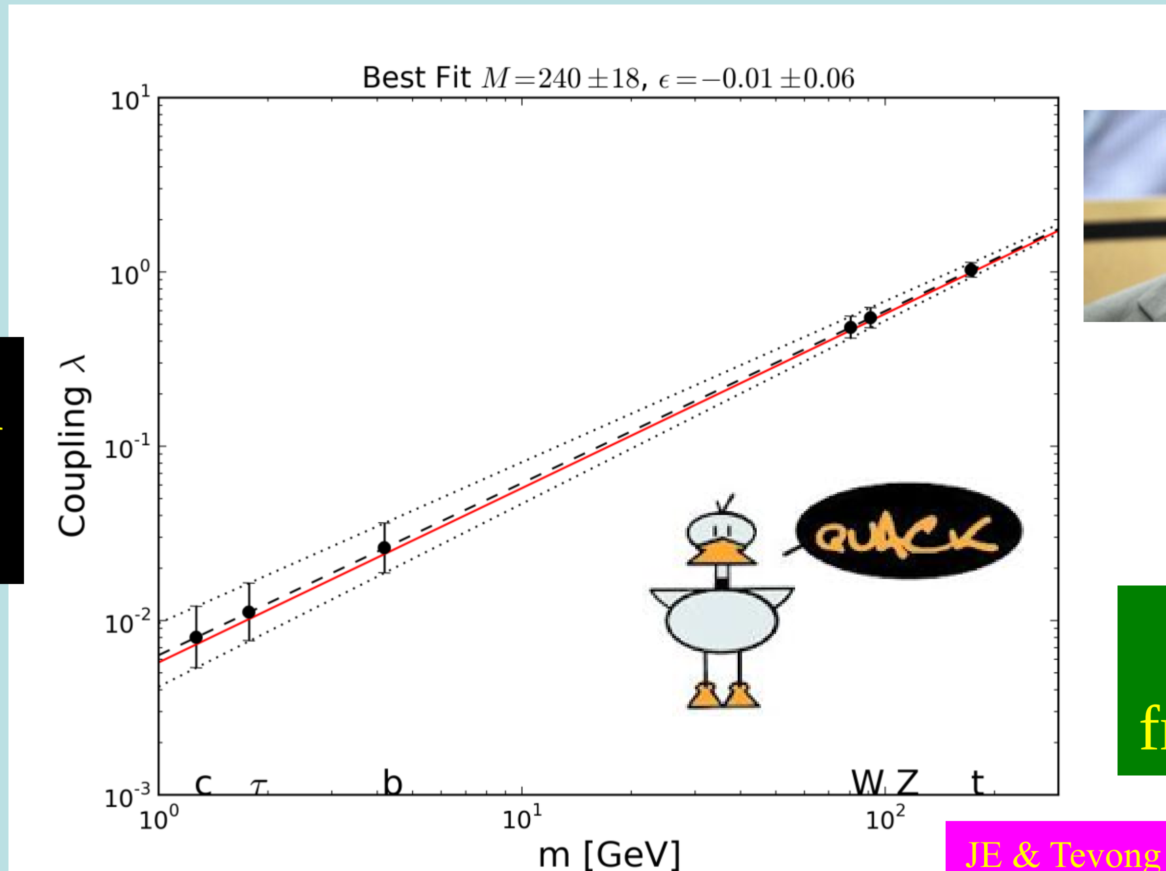
JE & Tevong You, arXiv:1207.1693

- Standard Model Higgs: ε = 0, M = v

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

Global fit



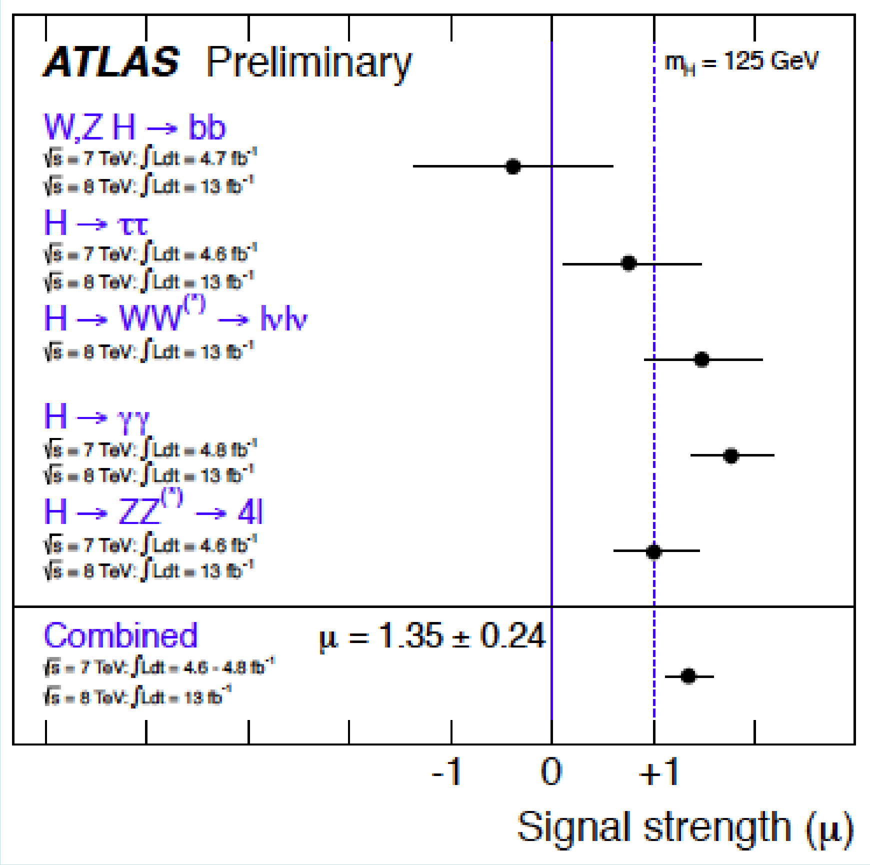
Update from Kyoto

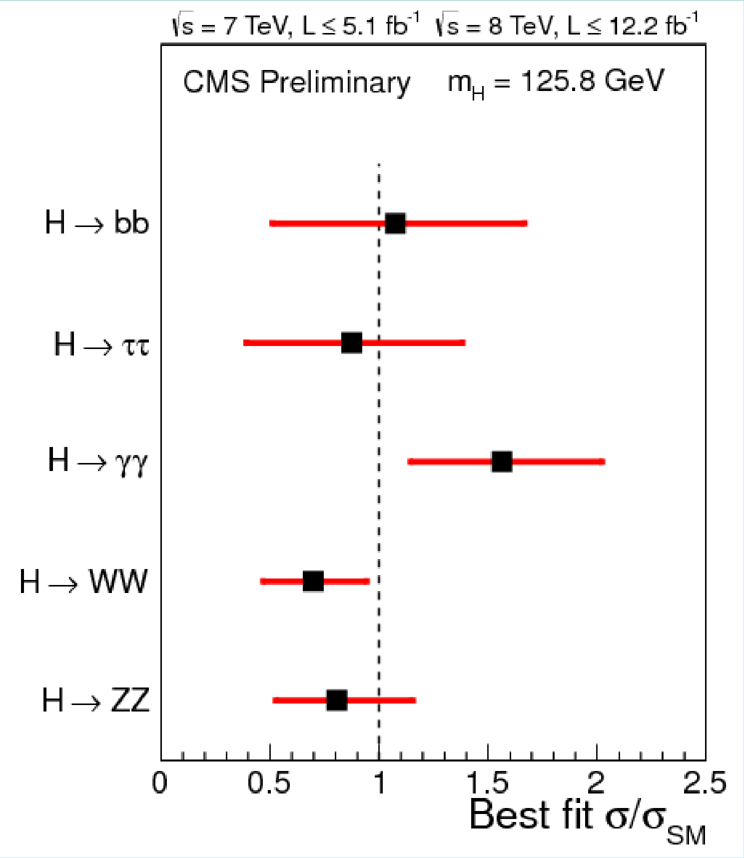
JE & Tevong You, arXiv:1207.1693

- **Red line = SM**, dashed line = best fit

Loop Corrections ?

- Both ATLAS and CMS see excess in γγ ?





- Loop diagrams > Standard Model?

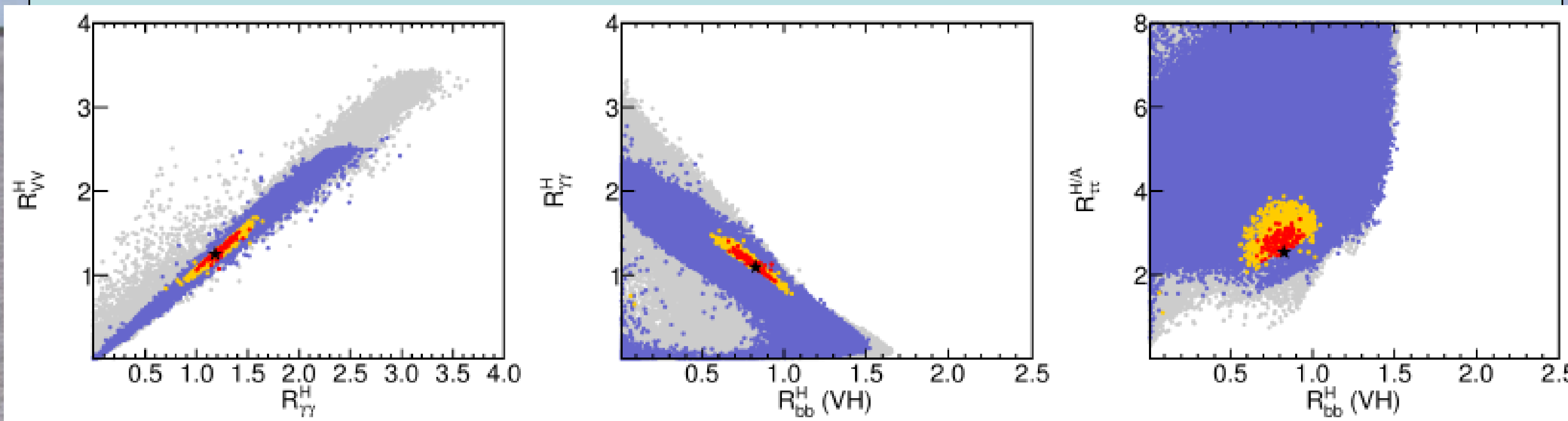
New Physics in Loops in γγ?

- Dominated by top and W in Standard Model
- Loops may be most sensitive to new physics
- Contributions to γγ decay amplitude from all massive **charged** particles
- *Cf* , contributions to gluon-gluon amplitude from all massive **coloured** particles
- Expect coloured particles to be lighter than uncoloured
- Higgs decay mode least unlikely to reveal new physics?

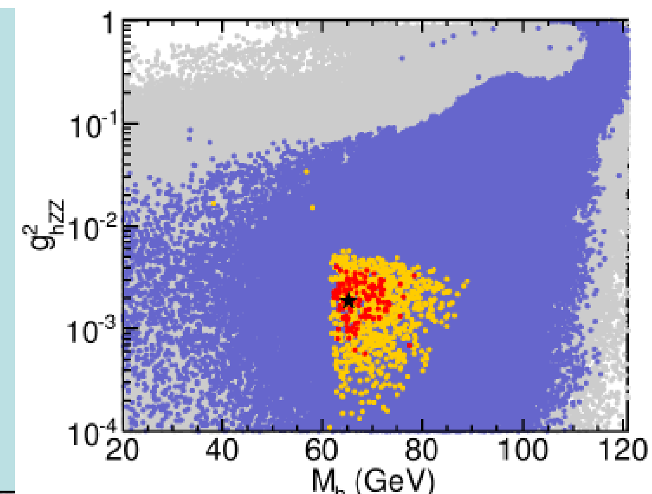
Exotic Supersymmetric Interpretation?

Bechtle et al: arXiv:1301.2345

- As heavier supersymmetric Higgs boson?



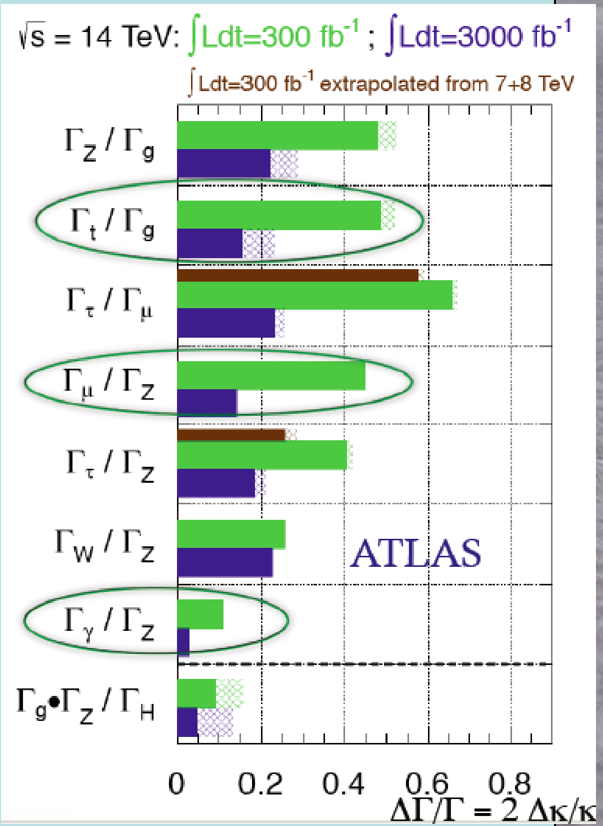
- Couplings have significant deviations from Standard Model
- Lighter Higgs @ 60 to 70 GeV overlooked at LEP, LHC?



What Next: A Higgs Factory?

To study the 'Higgs' in detail:

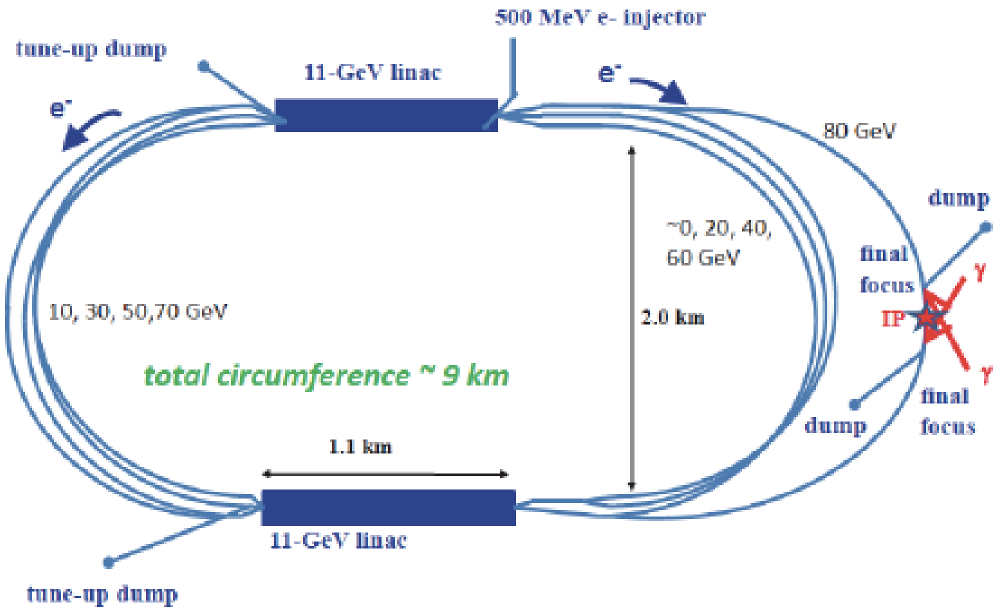
- The LHC
  - Rethink LHC upgrades in this perspective?
- A linear collider?
  - ILC up to 500 GeV
  - CLIC up to 3 TeV
    (Larger cross section at higher energies)
- A circular e+e- collider: LEP3, …
  - A photon-photon collider: SAPPHiRE
- A muon collider



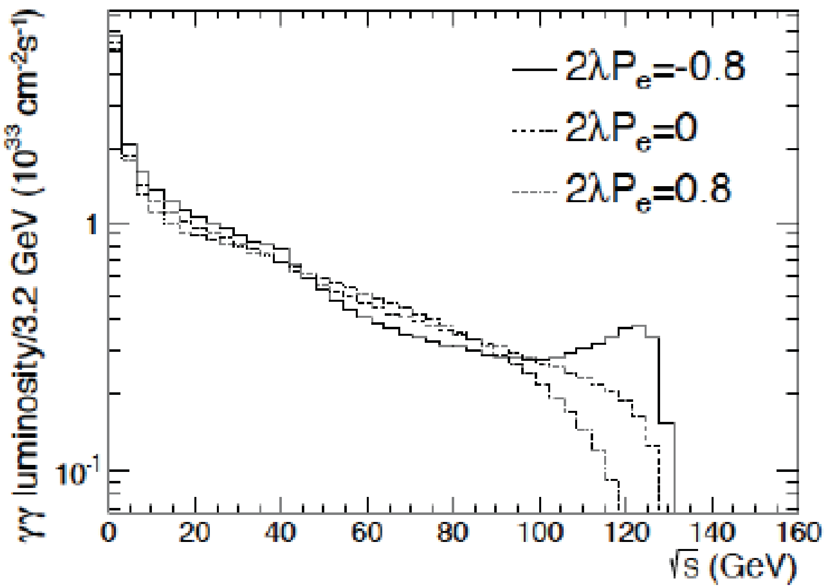
e^+e^- Collider Summary

Accelerator →Physical quantity ↓	LHC $300fb^{-1}$ /exp	HL-LHC $3000fb^{-1}$ /exp	ILC (250) 250 fb^{-1}	ILC (250+350+1000)	LEP3 240 4 IP	TLEP 240 +350 4 IP
Approx. date	2021	2030	2035	2045	2035	2035
N_H	1.7 x 10^7	1.7 x 10^8	5 10^4 ZH	(10^5 ZH) (1.4 10^5 Hvv)	4 10^5ZH	2 10^6 ZH
m_H (MeV)	100	50	35	35	26	7
$\Delta\Gamma_H/\Gamma_H$	--	--	10%	3%	4%	1.3%
$\Delta\Gamma_{inv}/\Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	0.35%	0.15%
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	3.4%	1.4%
$\Delta g_{Hgg}/g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	2.2%	0.7%
$\Delta g_{Hww}/g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	1.5%	0.25%
$\Delta g_{HZZ}/g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	0.65%	0.2%
$\Delta g_{HHH}/g_{HHH}$	--	< 30% (2 exp.)	--	~30%	--	--
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<30	<10	--	--	14%	7%

Photon-Photon Colliders



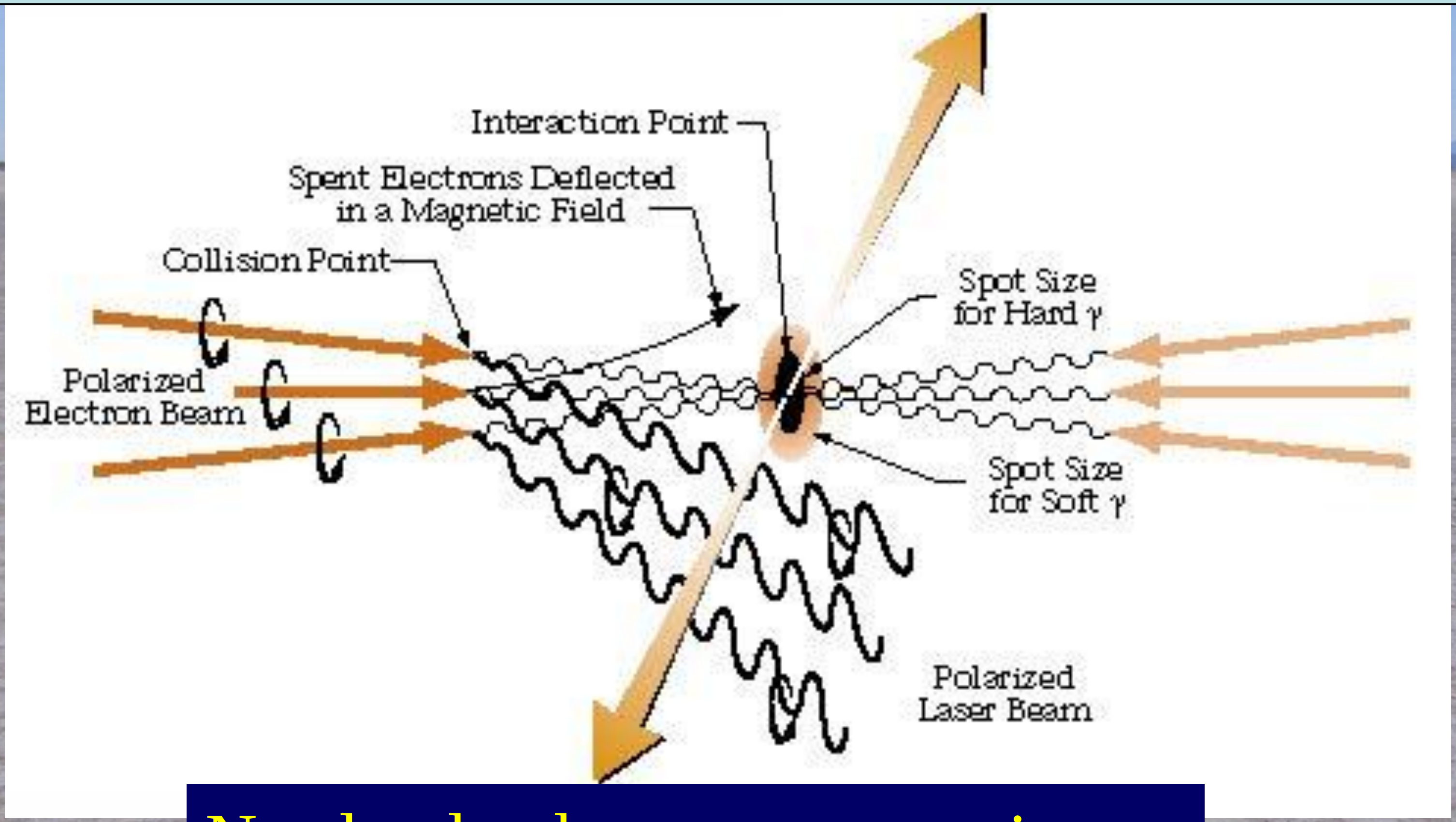
γ γ luminosity as function of √s for different polarization of laser photons (λ) and electrons (P_e)



- Photon-photon collisions at √s = 125 GeV for γ γ ➔H (s-channel)
- E.g., SAPPHiRE:
- Pair of recirculating linacs similar in design to those proposed for the LHeC
  - E_{beam} = 80 GeV
- Laser back-scatter system peak power 6 x 10^{21} Wm^{-2}
  - Needs R&D!
- γ γ Luminosity ~0.3 x 10^{34} $cm^{-2}s^{-1}$ for √s ≈ 125 GeV
- Some advantages over e^+e^- for Higgs
  - Lower beam energy
  - Do not need positron source

Bogacz, JE et al: arXiv:1208.2827

The γγ Collider Concept

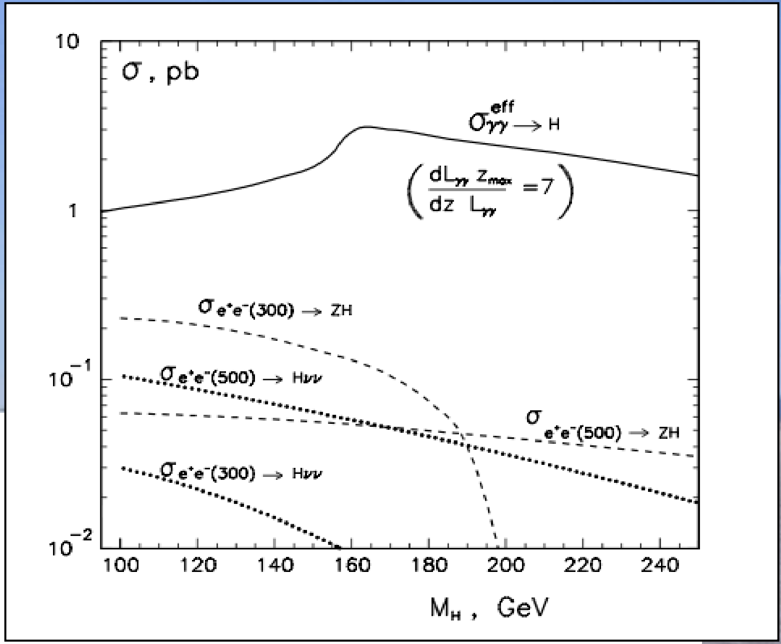


Need only electrons, no positrons

Need less E_{CM} than e+e- collider

BUT need powerful laser system

Good Features of $\gamma\gamma$ Colliders



- Large cross section
  $\Rightarrow$ Neutral Higgs ($Y = h_{SM}, H, A$)

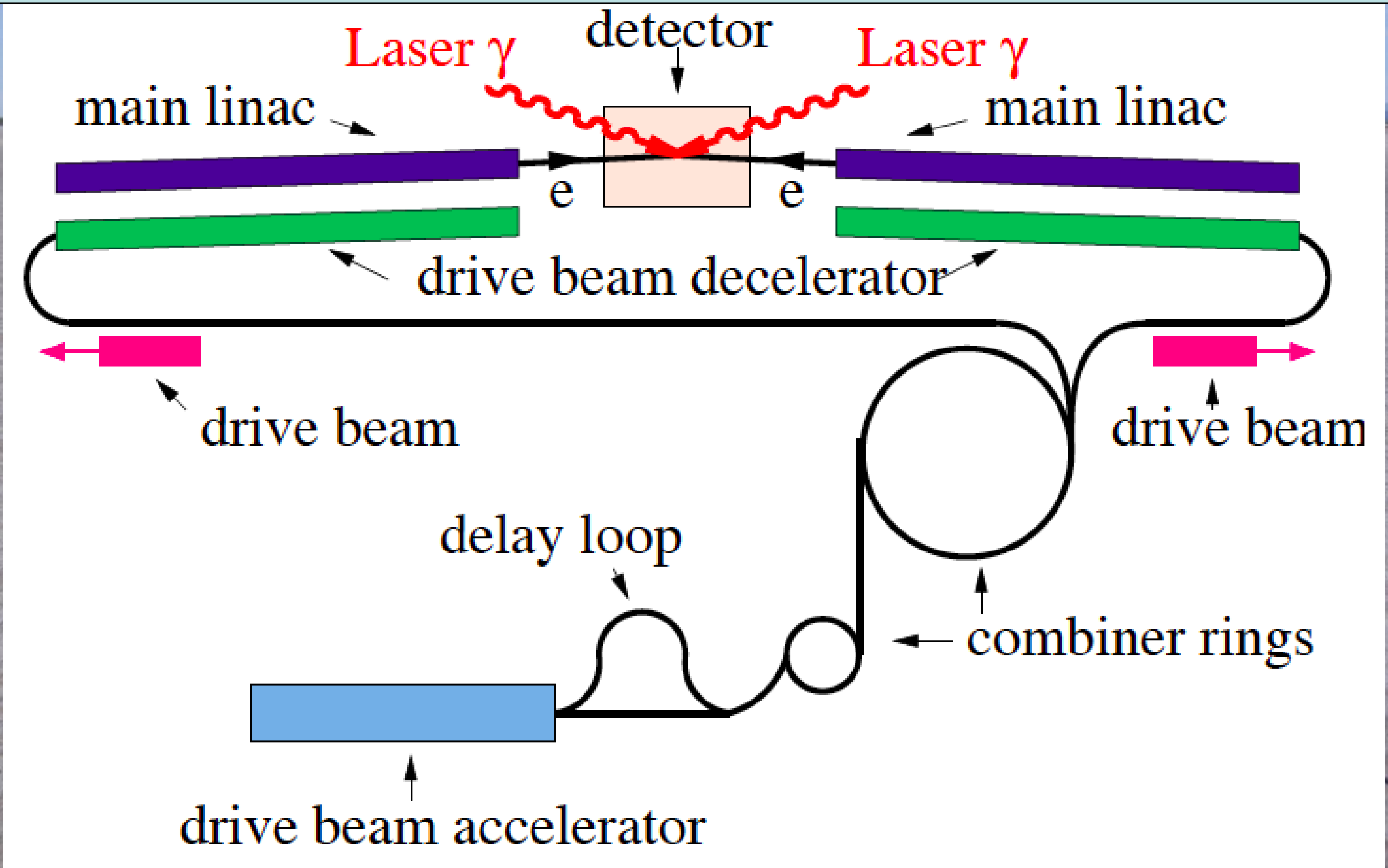
$$\sigma(\gamma\gamma \to Y \to XX') \propto \Gamma^{Y}_{\gamma\gamma} Br(Y \to XX')(1 + \lambda_1\lambda_2)$$

  $\Rightarrow$ Charged Higgs $H^{\pm}$:

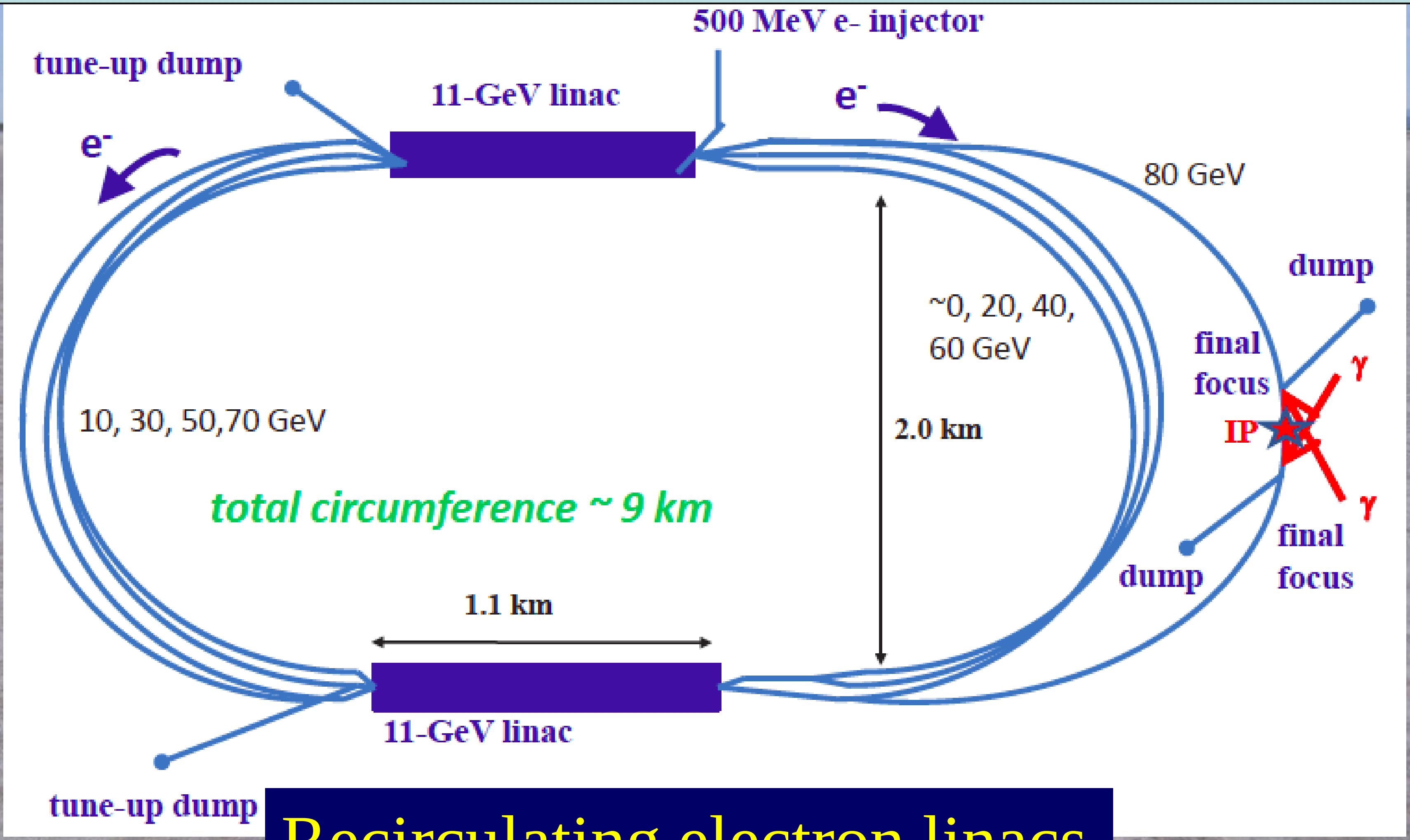
$$\sigma(\gamma\gamma \to H^+H^-) \geq 10\sigma(e^+e^- \to H^+H^-) \quad L_{\gamma\gamma}^{E_{\gamma\gamma}\geq 0.6E_{e^+e^-}} = \frac{L_{e^+e^-}}{3}$$

- 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

γγ Collider based on CLIC-1: CLICHE

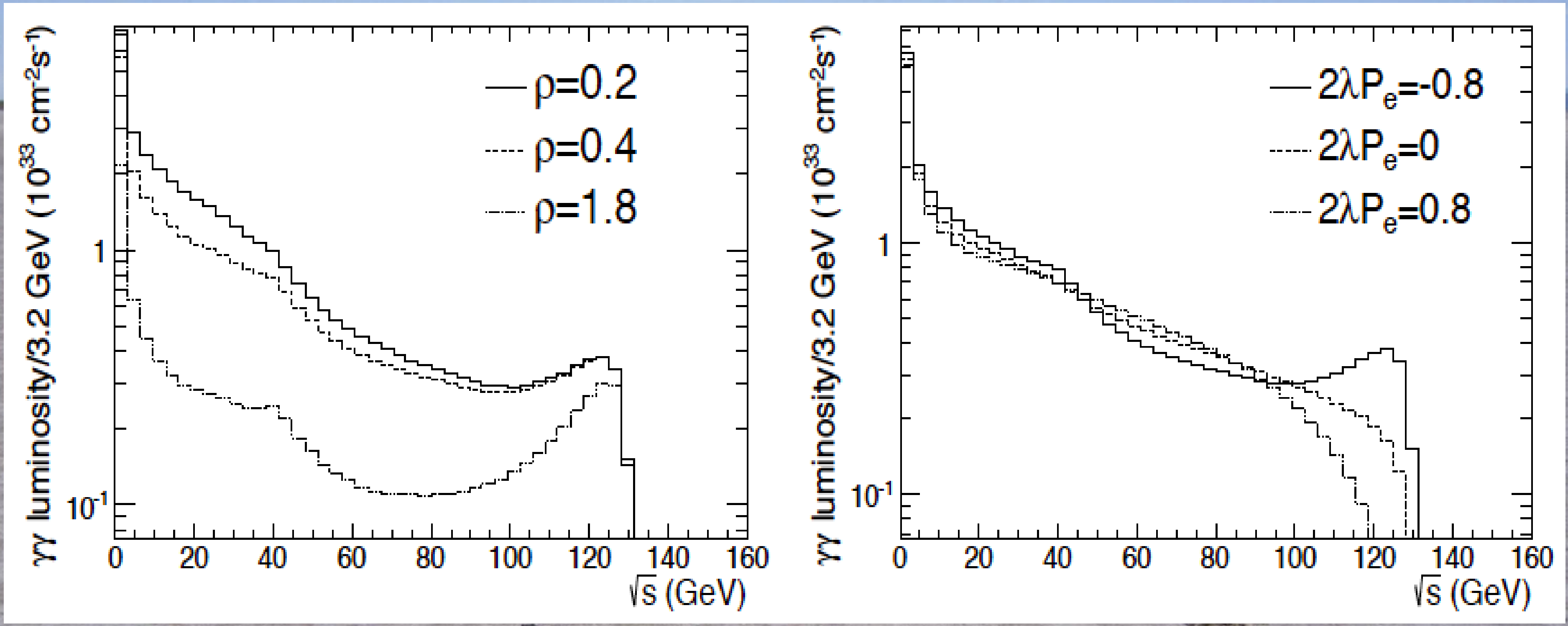


SAPPHiRE γγ Collider Concept



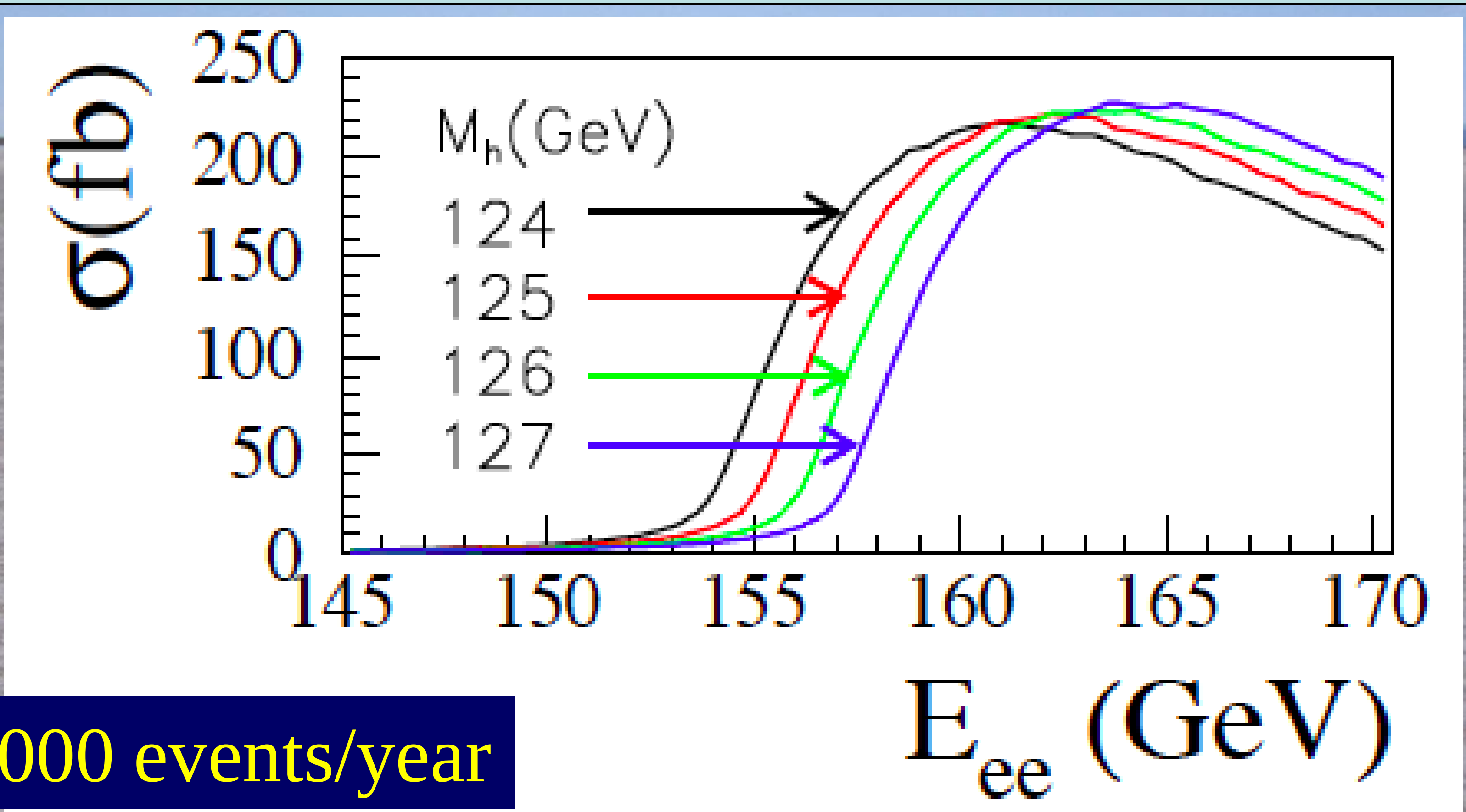
Recirculating electron linacs

Luminosity Spectra and Polarization



- Rate ~ 20,000 Higgs per year
- Polarization invaluable diagnostic tool

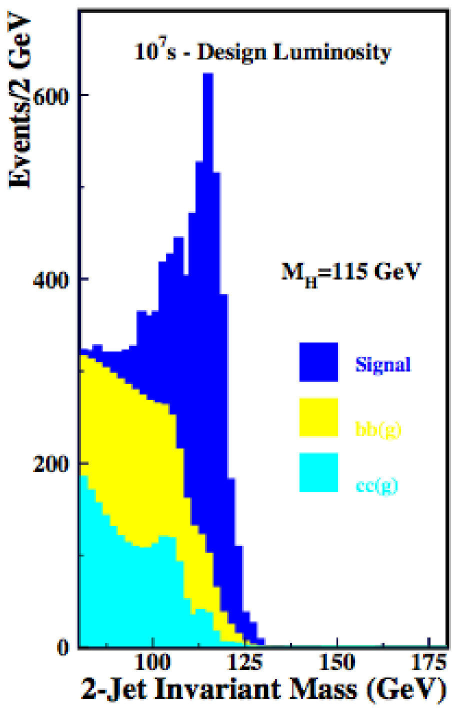
Higgs Excitation Function

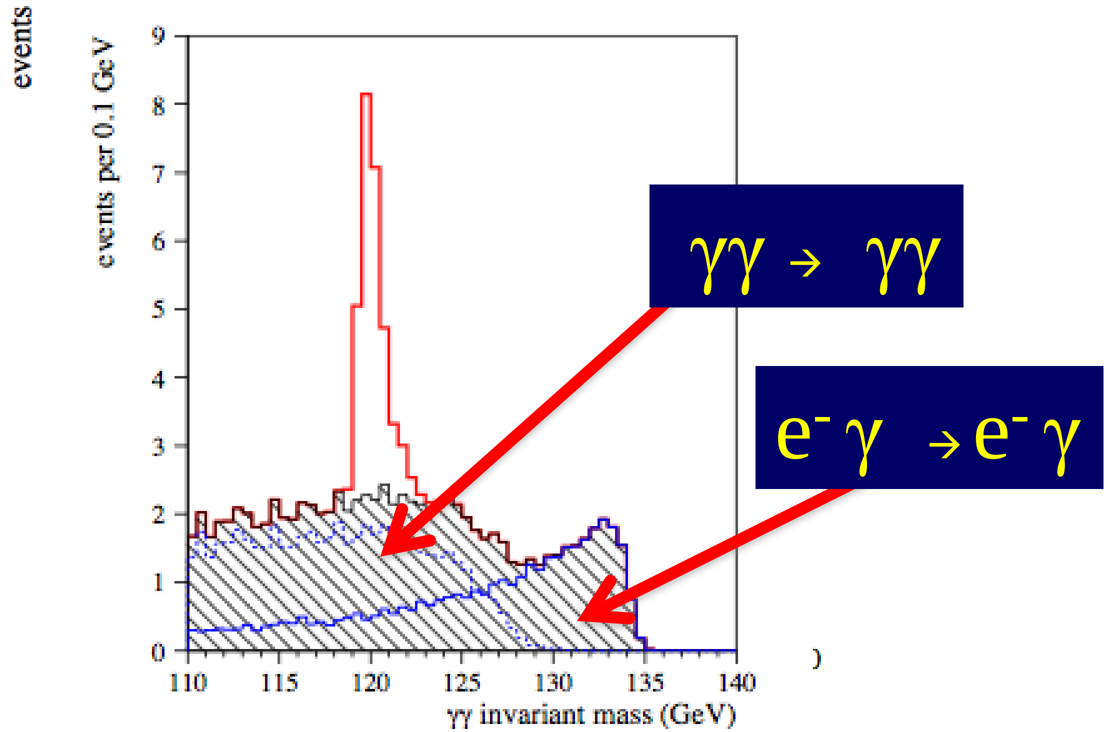


20,000 events/year

decay mode	raw events/year	S/B	ϵ_{sel}	$\mathcal{BR}$	$\Delta\Gamma_{\gamma\gamma}\mathcal{BR}/\Gamma_{\gamma\gamma}\mathcal{BR}$
$\bar{b}b$	11540	4.5	0.30	57.7%	2%
W^+W^-	4300	1.3	0.29	21.5%	5%
$\gamma\gamma$	45	—	0.70	0.23%	8%

Signals for H → bbbar, γγ

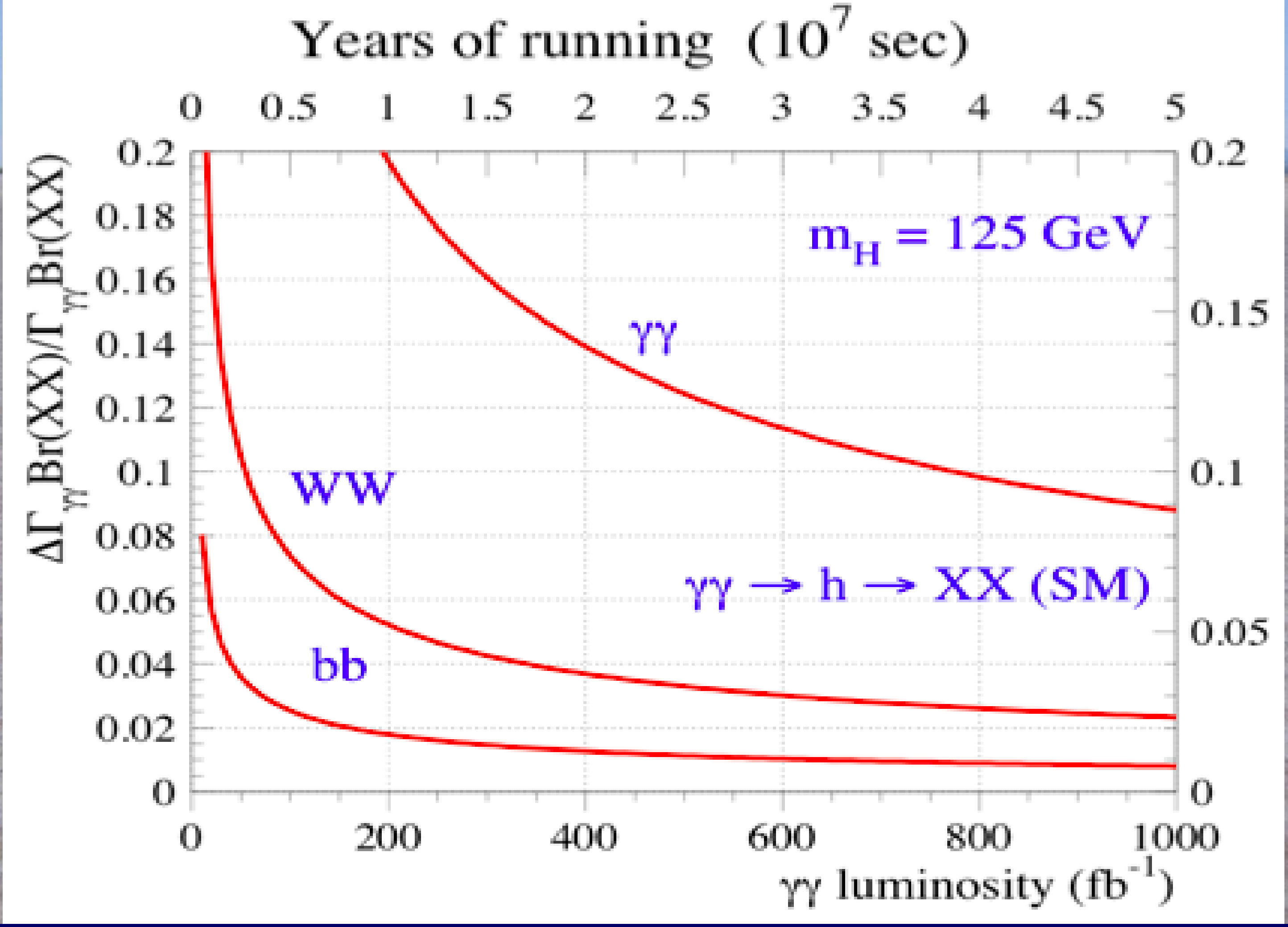




2% measurement of $\Gamma_{\gamma\gamma}$ × BR(H → bb) within a year

21% measurement of $\Gamma_{\gamma\gamma}$ × BR(H → γγ) within a year

Measurements of Higgs Decays

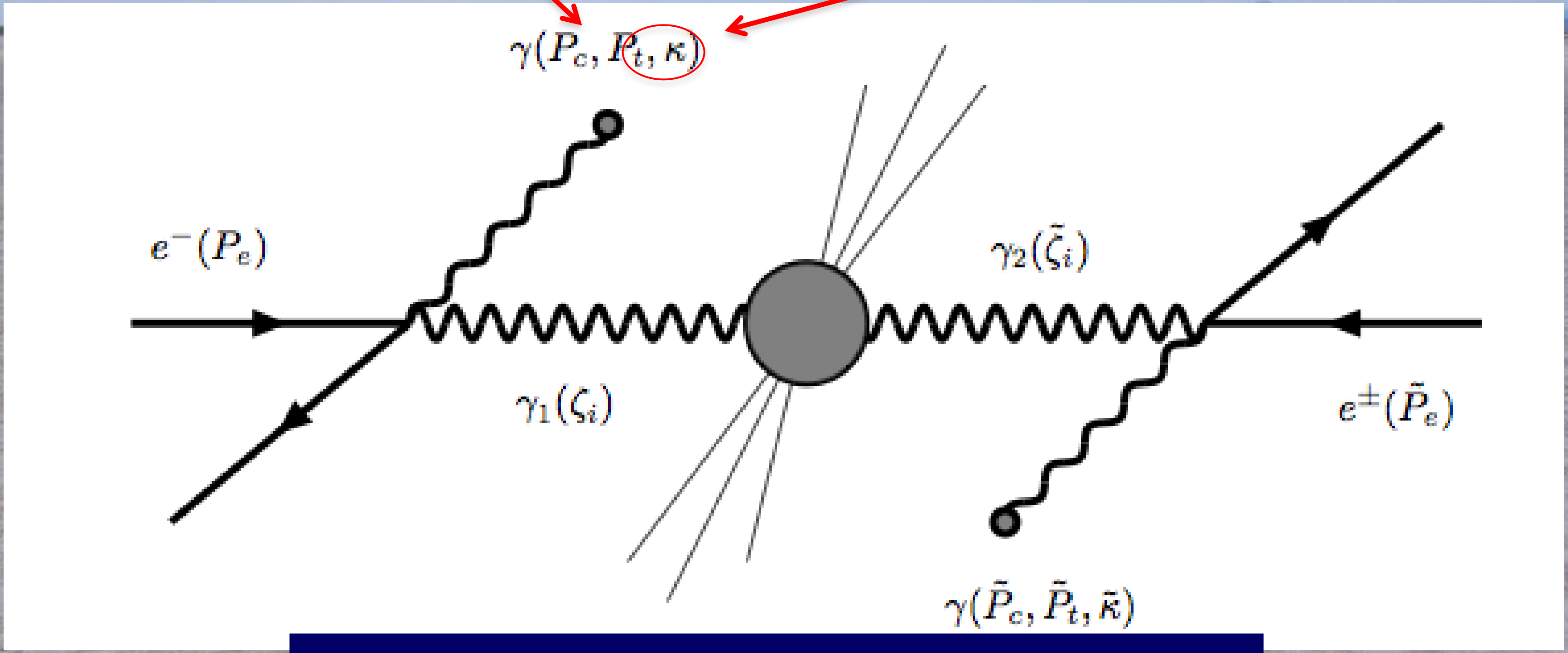


Cf, $\Delta\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma}$ = 10% at ILC (250 + 350 + 1000)

γγ Ideal to Search for CP Violation

Circularly polarized laser

Linearly polarized laser



Circular polarization ζ_2

Linear polarization states $\zeta_{1,3}$

Unique to a γγ Collider

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

Adjustable initial state:
Circular polarization ζ_2
Linear polarization states $\zeta_{1,3}$

= 0 if CP conserved

±1 if CP conserved for CP-even (-odd) Higgs

- If $A_1 \neq 0$, $A_2 \neq 0$ and/or $|A_3| < 1$, Higgs is CP mixture
- Possible to search for CP violation in γγ → H → fermions without measuring their polarization
- 1% asymmetry in bb can be measured with 100 fb^{-1}

Minimal Flavour Violation (MFV) & Maximal CP Violation (MCP)

- MFV: All squark mixing due to CKM matrix
  - Universal scalar masses at high scale for sparticles with same quantum numbers
- Parametrization:

$$M_{1,2,3}\,, \quad M^2_{H_{u,d}}\,, \qquad \widetilde{\mathbf{M}}^2_{Q,L,U,D,E} \;=\; \widetilde{M}^2_{Q,L,U,D,E}\,\mathbf{1}_3\,, \qquad \mathbf{A}_{u,d,e} \;=\; A_{u,d,e}\,\mathbf{1}_3$$

- Maximally CP-violating MFV (MCPMFV) model has 19 parameters, of which 6 violate CP:

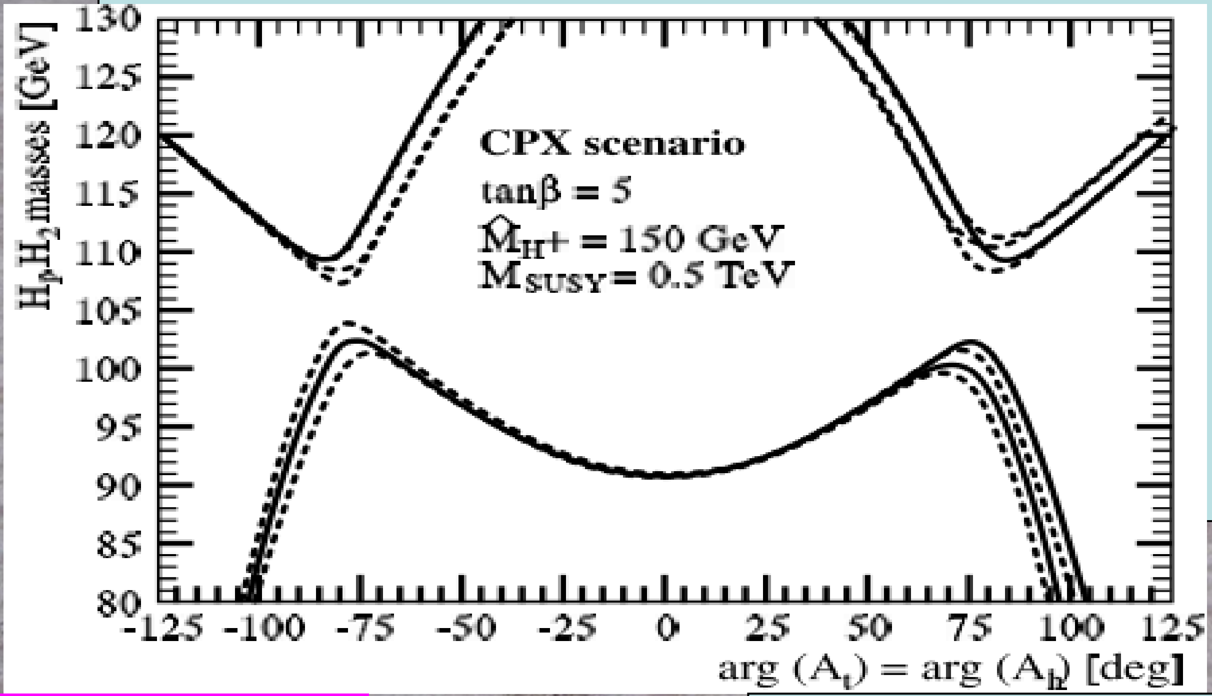
$$\mathrm{Im}\,M_{1,2,3} \text{ and } \mathrm{Im}\,A_{u,d,e}$$

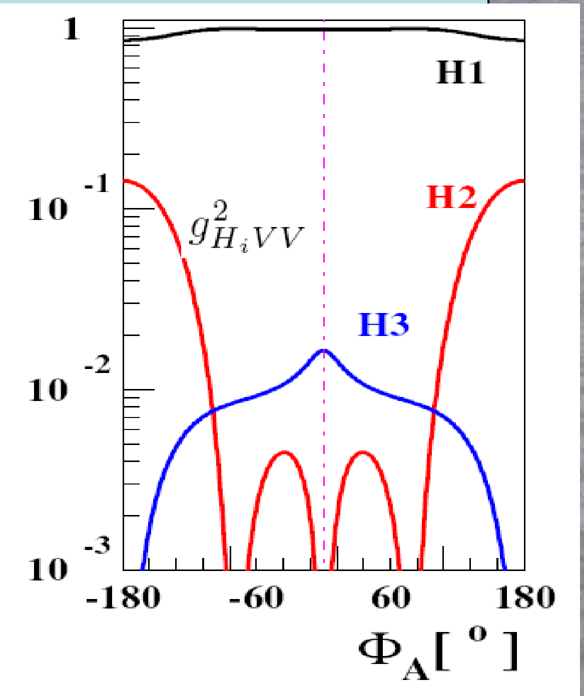
- Often assume universal ImM_a, ImA_f, but non-universality compatible with MFV: **MCPMFV**

•JE, Lee & Pilaftsi

Complexification of CMSSM

- Loop-induced mixing:
  - (h, H, A) → (H_1, H_2, H_3) with indefinite CP
- Effects on masses, couplings



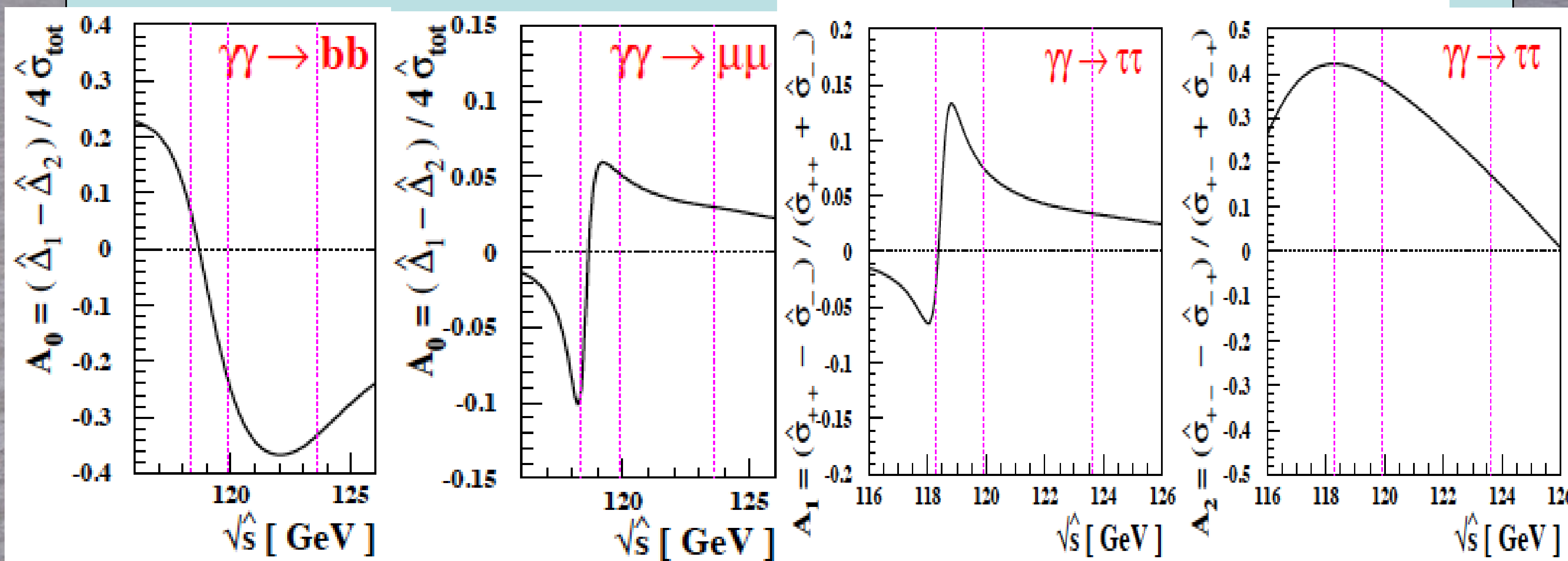


JE + Lee + Pilaftsis

Beware: Out-of-date model parameters!

CP-Violating Asymmetries?

- Final-state fermion, initial-state γ polarizations yield 2 asymmetries: $\hat{\Delta}_1 \equiv \hat{\sigma}_{++} - \hat{\sigma}_{--}\,, \quad \hat{\Delta}_2 \equiv \hat{\sigma}_{+-} - \hat{\sigma}_{-+}$

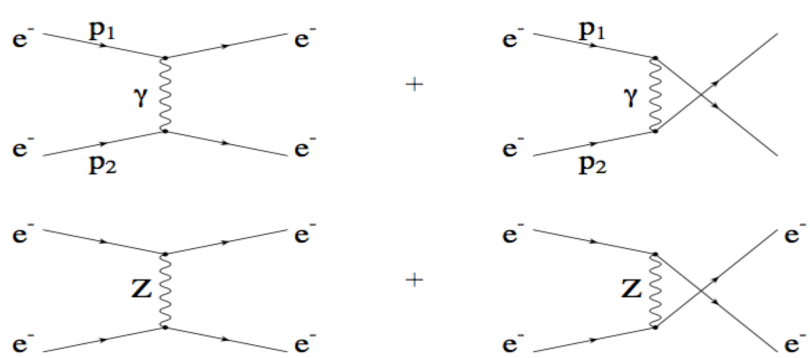


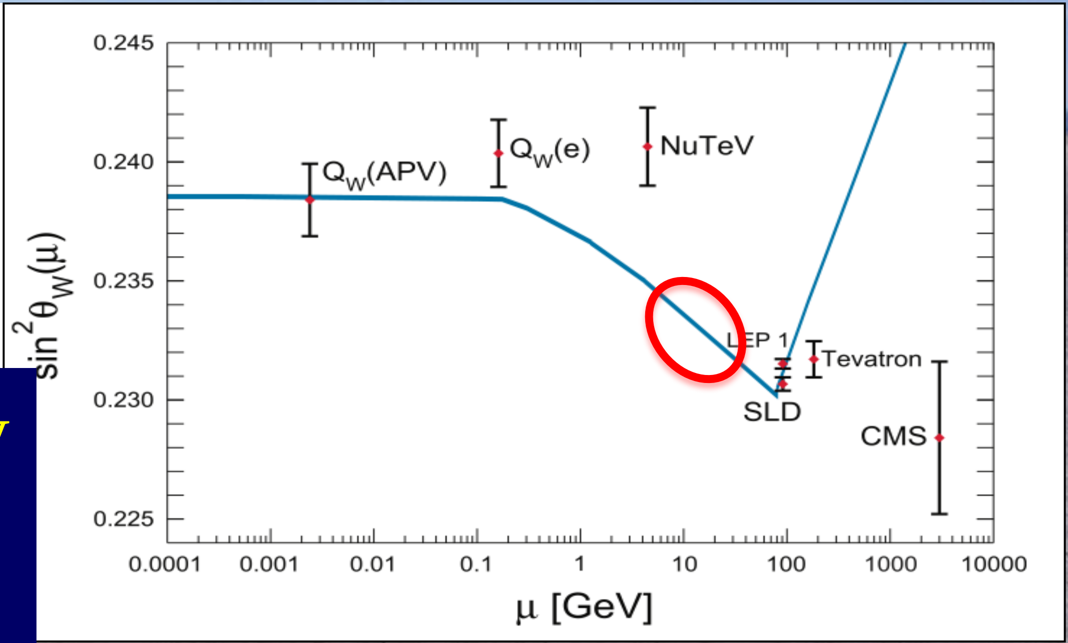
- One measurable in bbbar, $\mu^+\mu^-$; two in $\tau^+\tau^-$

JE + Lee + Pilaftsis: hep-ph/0411379

Beware: Out-of-date model parameters!

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





Polarization asymmetry

$$A_{\rm LR}^{(2)} \equiv \frac{d\sigma_{\rm LL} - d\sigma_{\rm RR}}{d\sigma_{\rm LL} + d\sigma_{\rm RR}}$$

$$\frac{N_{\rm LL} - N_{\rm RR}}{N_{\rm LL} + N_{\rm RR}} = P_{\rm eff} A_{\rm LR}^{(2)}(y) \left(\frac{1}{1 + \frac{1-P_1P_2}{1+P_1P_2} \frac{\sigma_{\rm LR}+\sigma_{\rm RL}}{\sigma_{\rm LL}+\sigma_{\rm RR}}} \right)$$

$$P_{\rm eff} = \frac{P_1 + P_2}{1 + P_1P_2}.$$

> mbarn

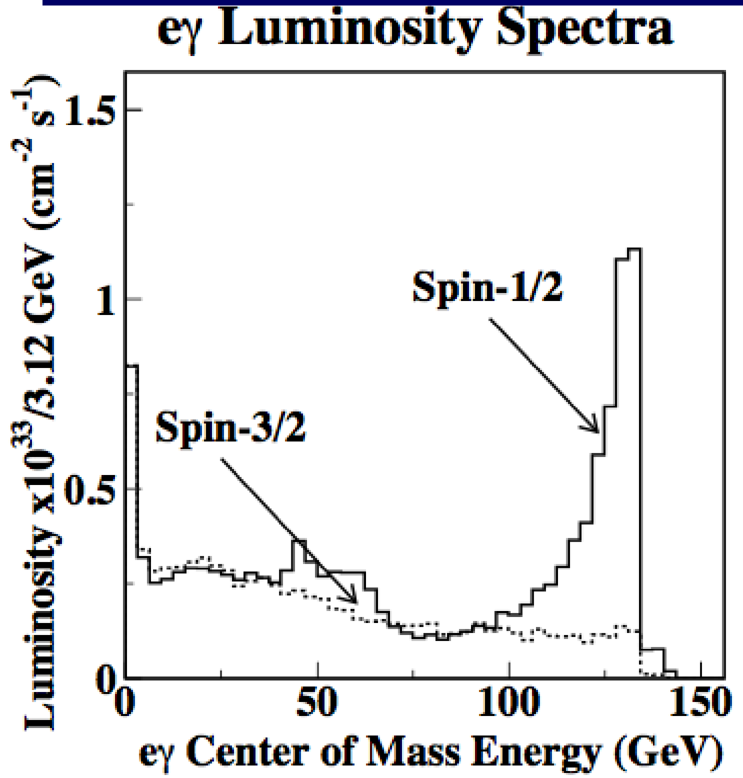
$$y = \frac{1-\cos\theta}{2}, \qquad 0 \le \theta \le \pi$$

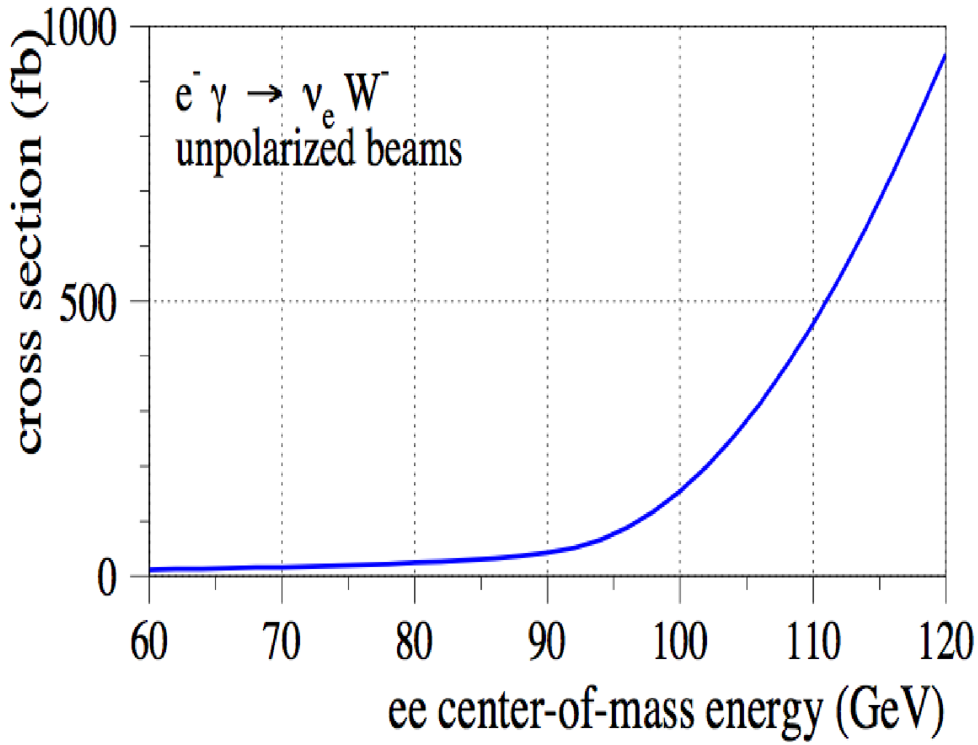
Complementary to low-energy and LEP measurements

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

Luminosity spectra in
$e^- \gamma$ olarization states

Mass measurement from
W → hadron events …





… or from energy scan

Summary

- Do not assume that the X(126) is (very close to) a Standard Model Higgs boson

  "Do not sell the (Standard Model) bearskin until you have caught the (Standard Model) bear"

  "It is not over until the fat lady sings"

- A $\gamma\gamma$ collider would offer unique insights
- Could it be built?
- If so, how quickly could it be built?

How to get Widths, Γ_{tot} & $\Gamma_{\gamma\gamma}$?

•Only with γγC

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

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

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

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

•*Assuming*

•*we know*

ΔBr(h→

→4% constrain

•Yukawa coupli

- Similarly,

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

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

•%10 Measurement of Γ_{Total}

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

Ex. of physics program relevant to our understanding of Higgs that will be accessible with SAPPHIRE

- e^-e^- ---> $\sin^2\theta_W$ (running)
- $e^-\gamma$ ---> M_W
- $\gamma\gamma$ to H
  - $\Gamma_{\gamma\gamma}$ → g_{ttH}
  - Γ_{Total}
  - – CP mixing and violation in a model independent way from both g_{Hff} and g_{HVV}