Photon Collider

Higgs Physics and Supersymmetry

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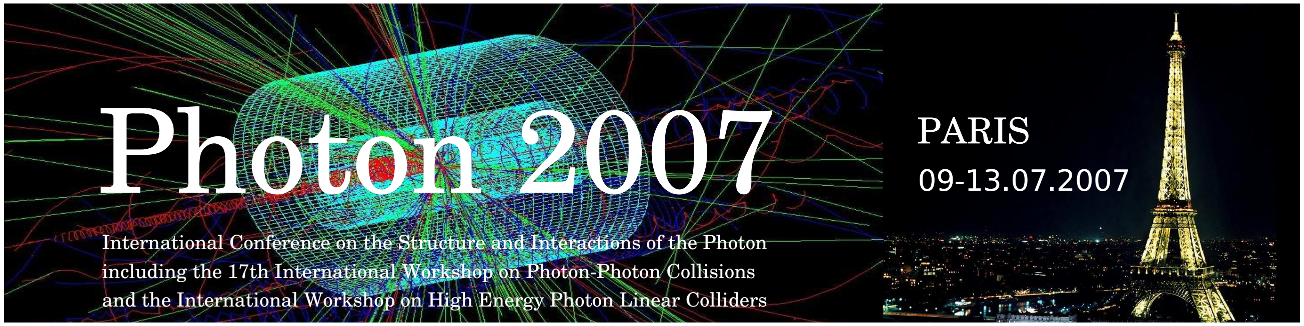
(CERN/LAPTH)

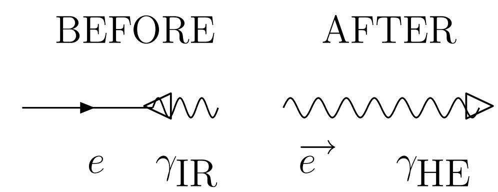
Photon 2007

9.7-13.7.2007, Sorbonne, Paris



The $\mathcal{P}$hoton $\mathcal{C}$ollider $\mathcal{P}$rinciple

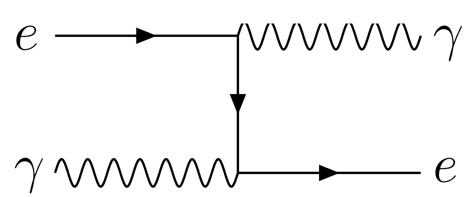
Linear Collider conversion of $e^{\pm}$ energy to γ energy by
Compton backscattering of laser light



Pioneers: I.F. Ginzburg, G.L. Kotkin, V.G. Serbo, V.I. Telnov

Pizma ZhETF 34 (1981) 514; JETP Lett. 34 (1982) 491;
Nucl. Instr. Meth. 47 (1983) 205; (+ Panfil) ibid. A219 (1984) 5

Compton scattering



$$A_u \sim \frac{1}{(u-m_e^2)} \sim \frac{1}{(1+\beta_e \cos\theta)} \quad \text{[backwards]}$$

$\mathcal{P}$hoton $\mathcal{E}$nergy

Spectrum: $F(y) = \frac{1}{1-y} + (1-y) - 4r(1-r) + 2\lambda_e P_c xr(1-2r)(2-y)$

with $y = E_\gamma/E_e$ and $r = y/(1-y)x$

Max Energy: $E_\gamma^{max} = \frac{1}{1+x^{-1}} E_e$ with $x = 4E_e\omega_\gamma/m_e^2$ $[\leq 4.8]$

Typical: $E_e = 250$ GeV

$\omega_\gamma = 1.17$ eV $\Rightarrow$ $\boxed{E_\gamma^{max} = 0.82 E_e}$

Polarization: $2\lambda_e P_c = -1$ sharpens spectrum [e^- source preferable]

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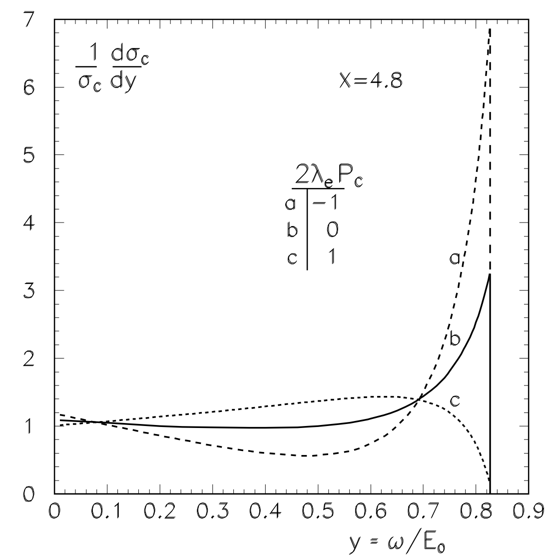

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Circular γ polarization: $\lambda_\gamma \to -P_c$ near maximum

Linear γ polarization: $l_\gamma \to +P_l/[1 + (x^2+1)/2x]$ near maximum

$\mathcal{P}$hoton $\mathcal{E}$nergy

Spectrum: $F(y) = \frac{1}{1-y} + (1-y) - 4r(1-r) + 2\lambda_e P_c x r(1-2r)(2-y)$

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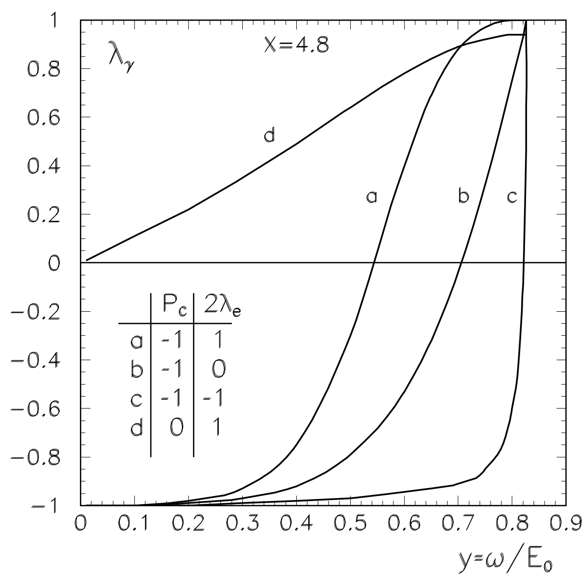
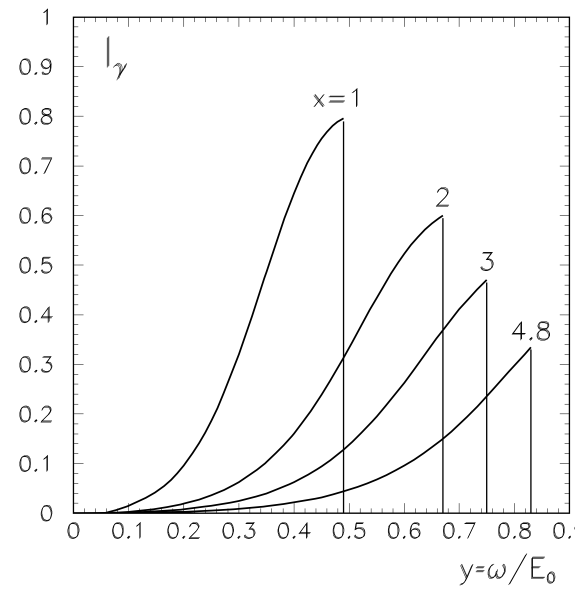
Circular Pol



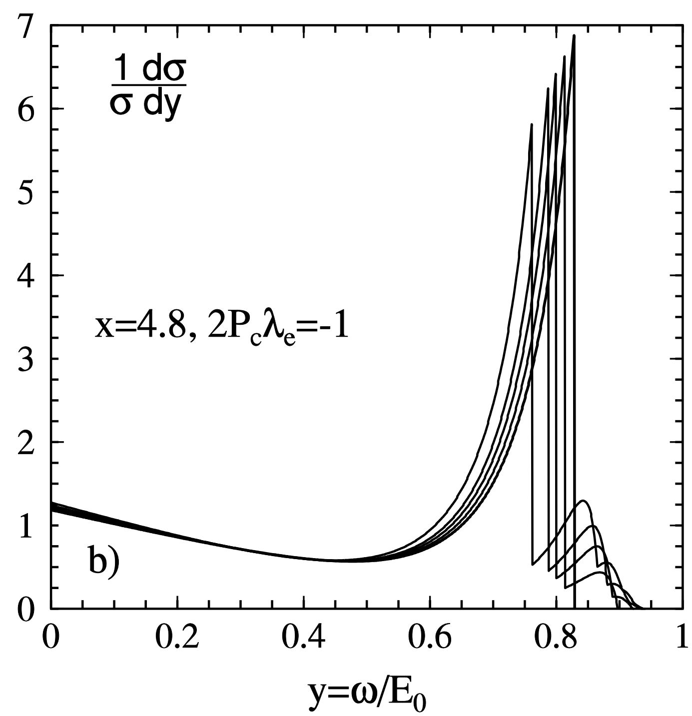
Linear Pol

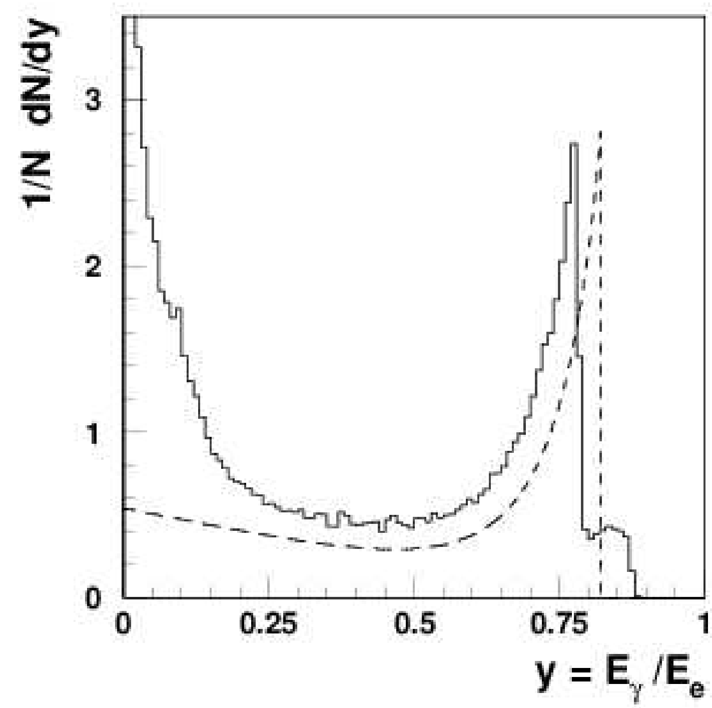


$\mathcal{L}$uminosities

Nonlinear Effects Maximal E_γ reduced // add. higher harmonics $\Rightarrow$

Simulation: Telnov,Zarnecki

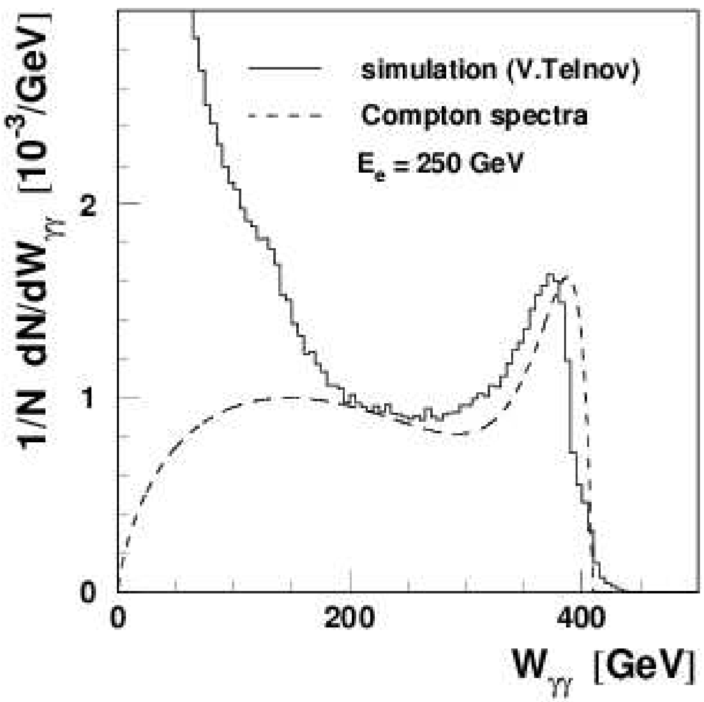




$\mathcal{L}$uminosities

$e\gamma$ luminosity: $$d\mathcal{L}/dm^2_{e\gamma} = F(y = m^2_{e\gamma})$$ $m_{e\gamma} = M_{e\gamma}/\sqrt{s}$

$\gamma\gamma$ luminosity: $$d\mathcal{L}/dm^2_{\gamma\gamma} = \int_{m^2_{\gamma\gamma}}^1 \frac{dy}{y} F(y) F(m^2_{\gamma\gamma}/y)$$ $m_{\gamma\gamma} = M_{\gamma\gamma}/\sqrt{s}$



$\mathcal{LC}$: $P_- = 0.85$ / $P_c = -1$

$\sqrt{s}_{ee}$ [GeV]	500	800
$m_{e\gamma} \geq 0.8 m^{max}_{e\gamma}$	0.9	1.3
$m_{\gamma\gamma} \geq 0.8 m^{max}_{\gamma\gamma}$	1.1	1.7
e^+e^-	3.4	5.8

$$\mathcal{L}_{\gamma\gamma}(\geq 0.8) \sim \frac{1}{3}\mathcal{L}_{ee}$$ $[10^{34}\ \text{cm}^{-2}\text{s}^{-1}]$

$\gamma\gamma$ $\mathcal{C}$ross $\mathcal{S}$ections

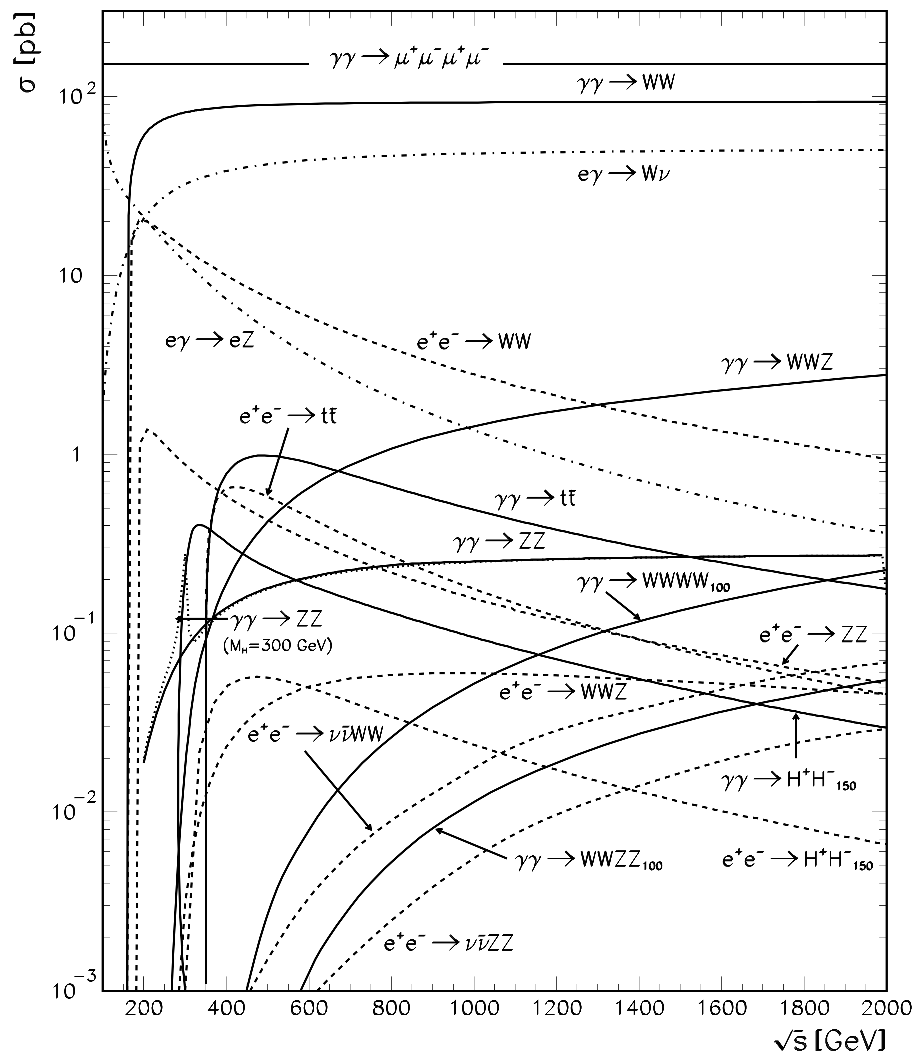
Cross secs: $\gamma\gamma \sim 3$ to $10 \times e^+e^-$

Examples: $t, W^\pm, H^\pm, \tilde{e}, \tilde{\chi}^\pm, ...$

Large Size: 10 to 10^5 fb $\Rightarrow$

10^3 to 10^7 events

for $\mathcal{L} = 100$ fb^{-1}



$\mathcal{H}$iggs and $\mathcal{SUSY}$ $\mathcal{P}$hysics at a $\mathcal{P}$hoton $\mathcal{C}$ollider

Exploration of EWSB among central exp tasks of future colliders.

Higgs mechanism strongly supported by EW precision analyes.

Large variety of models incorporating different realizations of Higgs mechanism still possible $\longrightarrow$

- Supersymmetric theories
- CP violating Higgs bosons
- Extra dimensions ...

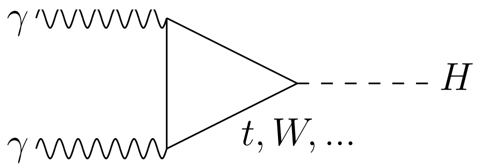
Photon Collider: high-energy photons/high luminosity/high degree of polarization $\longrightarrow$
unique possibilities to uncover the underlying structure.

Higgs physics and SUSY:

- $\Gamma_{H\gamma\gamma}$ in $\gamma\gamma \to H$ sensitive to high scales
- Heavy H/A production where not accessible elsewhere
- Alternative method for $\tan\beta$ determination
- Unique possibilities to test CP-violation
- Extend mass reach of slepton production

$\mathcal{L}$ight $\mathcal{H}$iggs in $\gamma\gamma$ $\mathcal{C}$ollisions

Higgs productions in $\gamma\gamma$ collisions: via loops



Cross section: $\sigma_{\gamma\gamma} \sim \Gamma_{\gamma\gamma}\, d\mathcal{L}/dm^2_{\gamma\gamma}(M_H^2)$

- sharp onset for polarised beams
- equal γ helicities $\rightsquigarrow$ enhance signal & suppress background

Measurement of $\Gamma_{\gamma\gamma}(H)$: ≤ 140 GeV: $H \to bb$

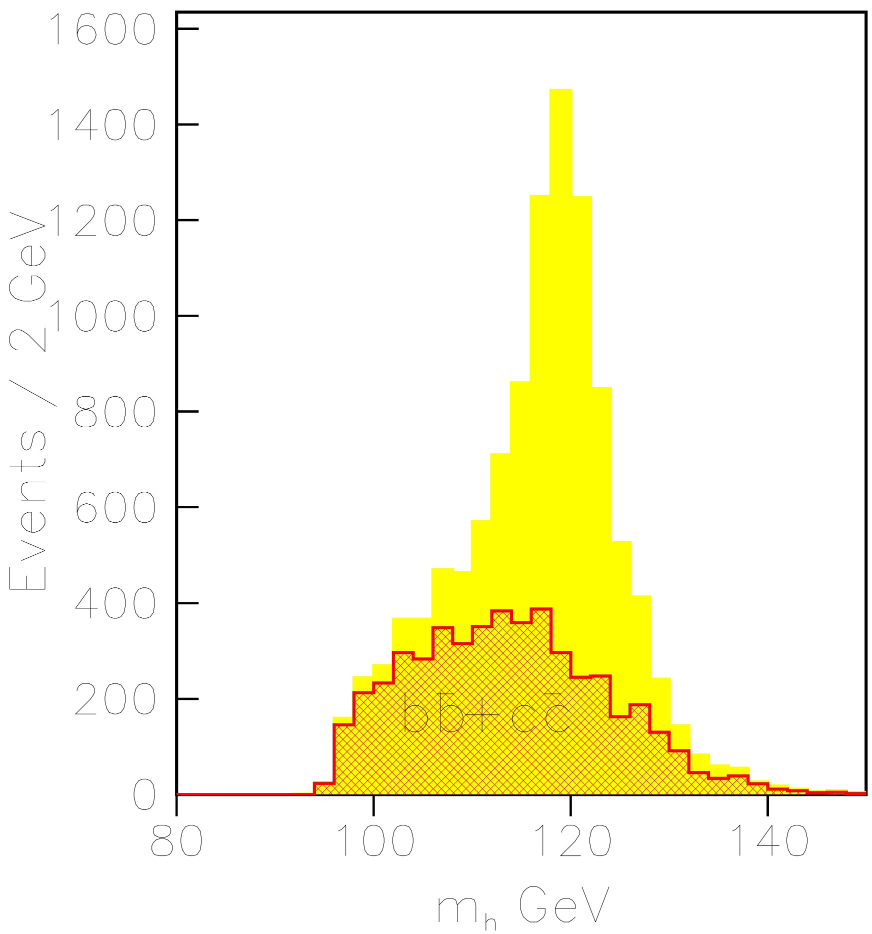
error: $\delta\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma} \approx 1.7$ %

lifetime: $\tau_H = BR_{\gamma\gamma}/\Gamma_{\gamma\gamma} \sim 15$ %

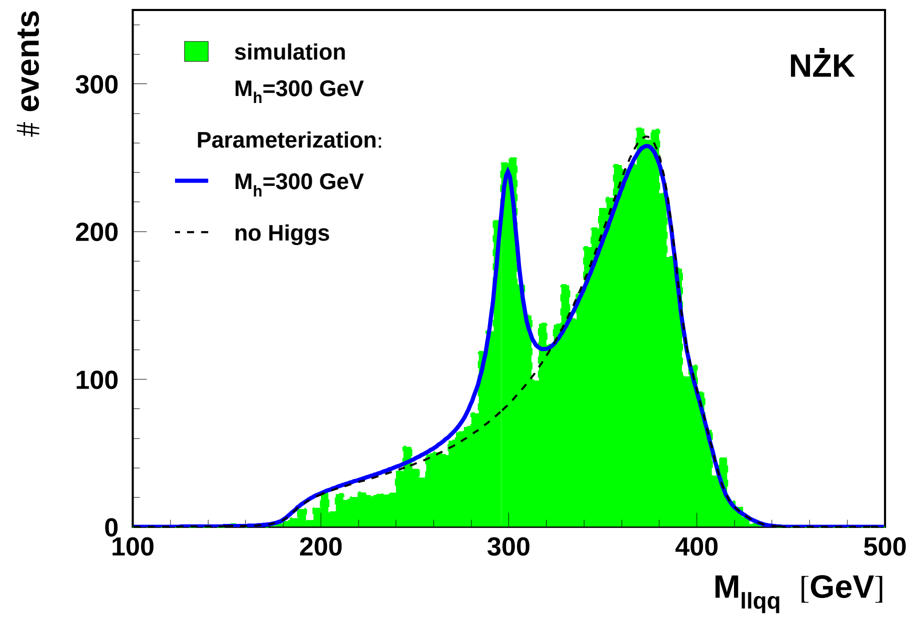
≥ 140 GeV: $H \to ZZ$

$\mathcal{L}$ight $\mathcal{H}$iggs in $\gamma\gamma$ $\mathcal{C}$ollisions

$H \longrightarrow bb$ [Mönig,Sekaric]



$H \longrightarrow ZZ$ [Niezurawski,Zarnecki,Krawczyk]

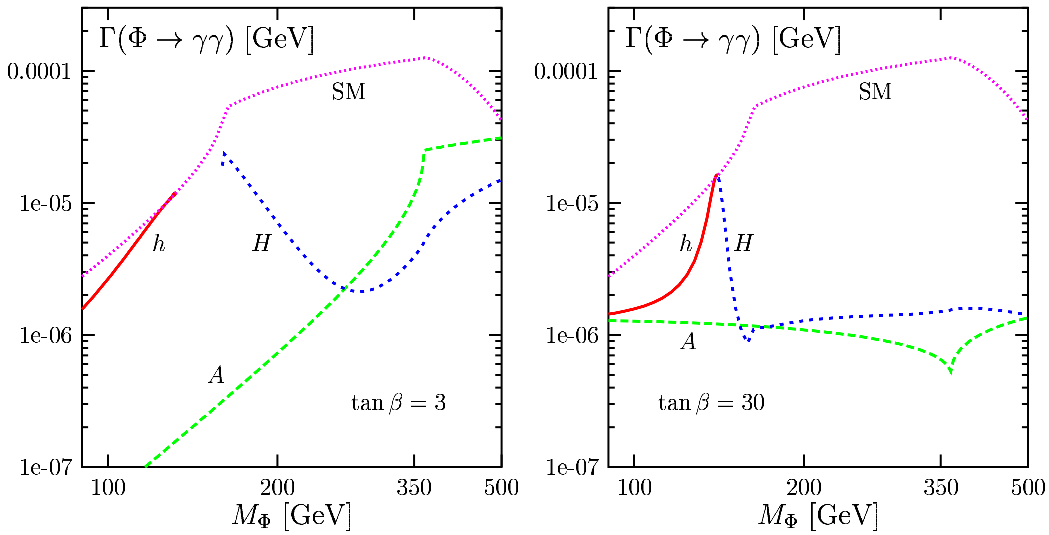


$\mathcal{S}$ensitivity of $\Gamma_{\gamma\gamma}$ to $\mathcal{P}$hysics beyond the $\mathcal{SM}$

$\Gamma_{\gamma\gamma}$ sensitivity to:

a) SUSY loop contributions

Djouadi



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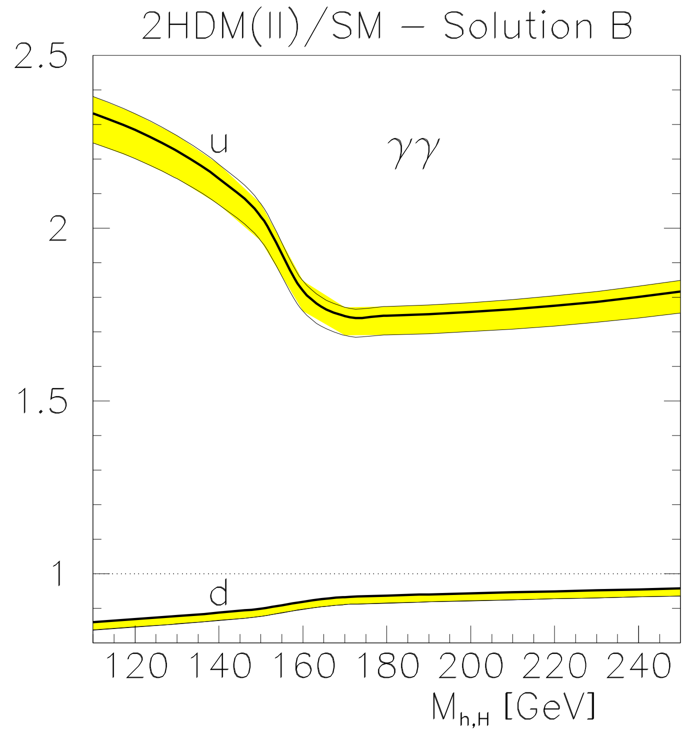
b) $H^\pm$ loop in general 2HDM

Ginzburg,Krawczyk,Osland



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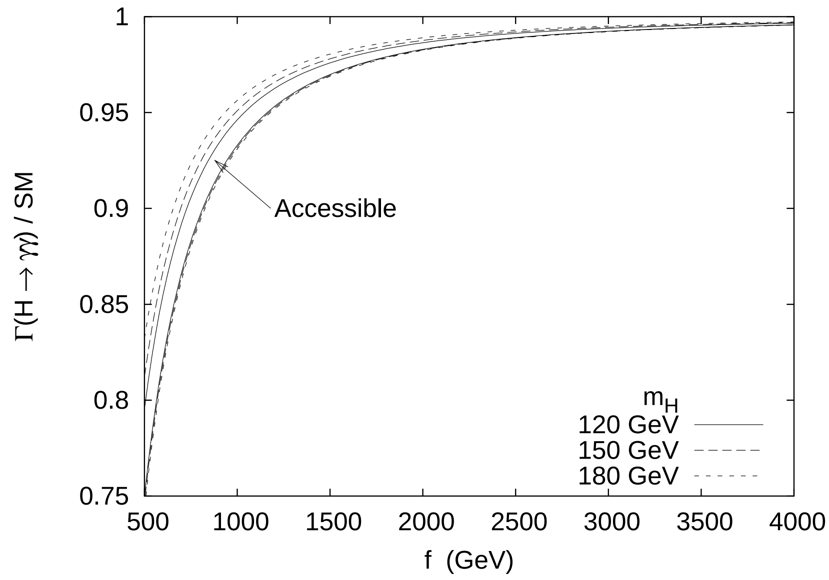
Djouadi

b) $H^{\pm}$ loop in general 2HDM

Ginzburg,Krawczyk,Osland

c) Little Higgs dof's $\sim$ sev. TeV

Logan



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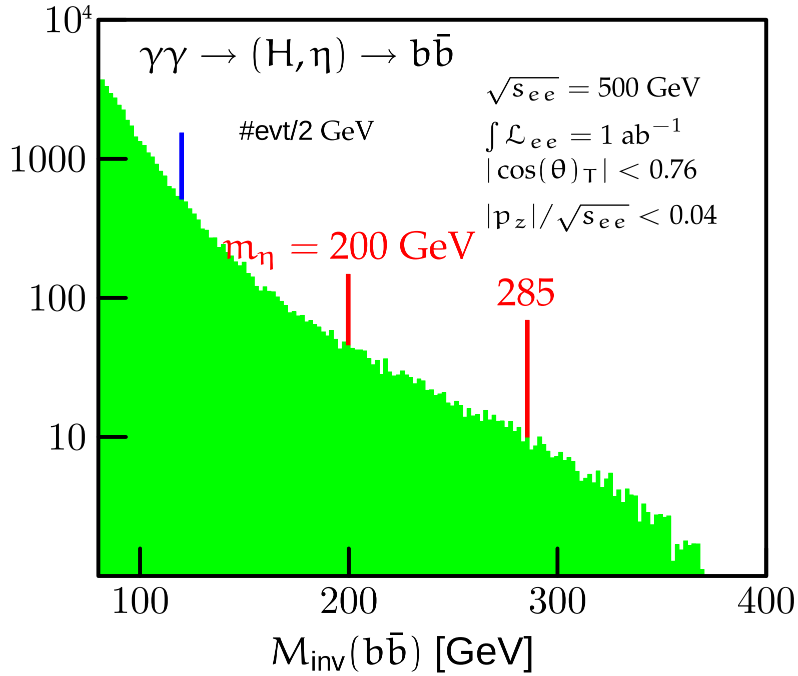
Ginzburg,Krawczyk,Osland

c) Little Higgs [width/pseudoscalar]

Kilian,Rainwater,Reuter



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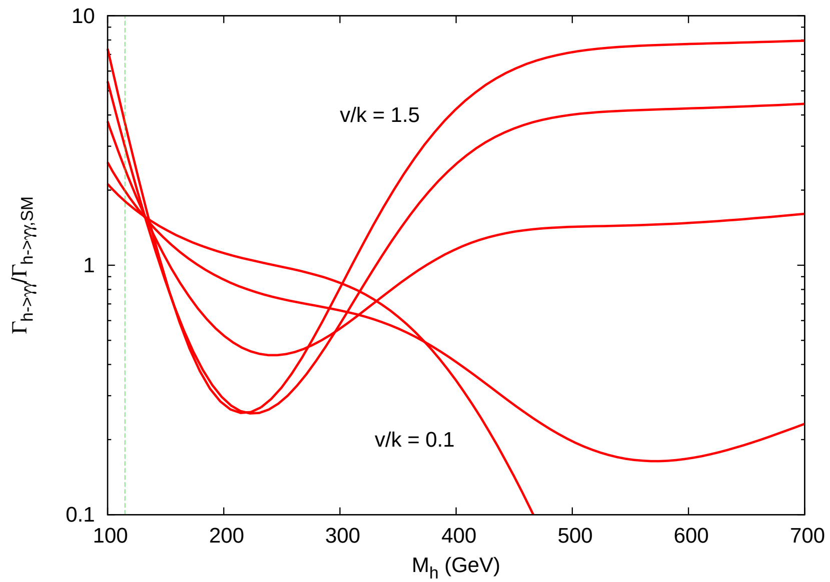
Ginzburg,Krawczyk,Osland

c) Little Higgs [width/pseudoscalar]

d) KK in extra-space dimensions

Lillie



$\mathcal{B}$eyond $\mathcal{SM}$: $\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\stackrel{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-

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Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;...

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Decoupling limit:

$M_A \sim M_H \sim M_{H^\pm} \gg v$

$M_h \rightarrow$ max. value, $\tan\beta$ fixed; h becomes SM-like

Beyond SM: MSSM Higgs Sector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\stackrel{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-

Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
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Decoupling limit:

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Modified couplings with respect to the SM: (decoupling limit Gunion,Haber)

Φ	$g_{\Phi u\bar{u}}$	$g_{\phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \rightarrow 1$	$-s_\alpha/c_\beta \rightarrow 1$	$s_{\beta-\alpha} \rightarrow 1$
H	$s_\alpha/s_\beta \rightarrow 1/\text{tg}\beta$	$c_\alpha/c_\beta \rightarrow \text{tg}\beta$	$c_{\beta-\alpha} \rightarrow 0$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

$\tan\beta \uparrow \Rightarrow g_{\Phi uu} \downarrow$

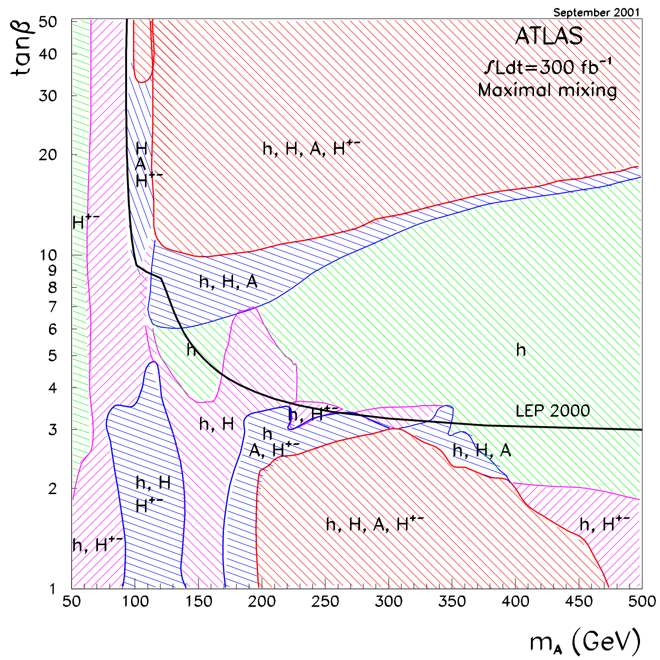
$g_{\Phi dd} \uparrow$

$g^{MSSM}_{\Phi VV} \lesssim g^{SM}_{\Phi VV}$

$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction in $\gamma\gamma$ $\mathcal{C}$ollisions

Krämer,MM,Spira,Zerwas, Phys.Lett.B508(2001)311-316

▷ Search for H, A at the **LHC**:



Higgs particles H, A with masses $M_{H/A} \gtrsim 200$ GeV and centered around $\tan\beta \sim 7$ may escape discovery at the LHC

▷ At e^+e^- **linear colliders:** Production of H, A with masses $M_{H,A} \lesssim 0.5\sqrt{s_{ee}}$

▷ Alternative: Search for H, A at **future $\gamma\gamma$ colliders**

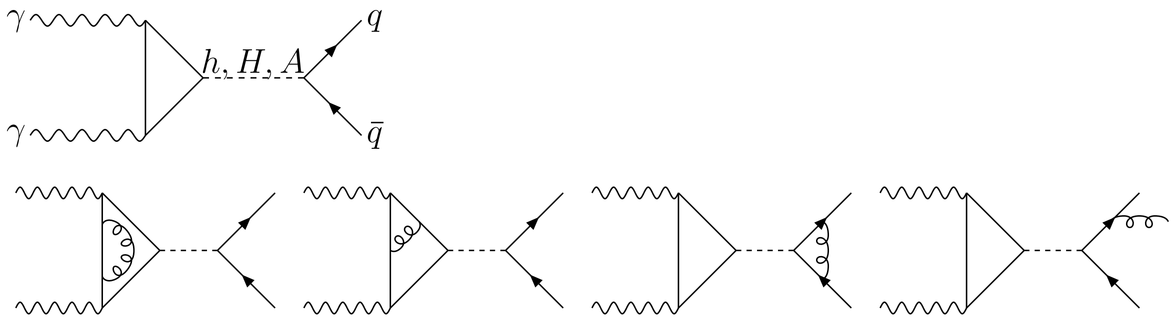
H, A can be produced with masses up to $M_{H,A} \lesssim 0.8\sqrt{s_{ee}}$

$\mathcal{M}$ost promising: $\gamma\gamma \to b\bar{b}$

Signal process

LO

NLO



Spira, Djouadi, Graudenz, Zerwas
Melnikov, Yakovlev
Inoue et al.
Braaten, Leveille
Drees, Hikasa; ...

$$\frac{d\sigma_{\rm LO}^{++/--}}{d\cos\theta} = \frac{N_c G_F^2 \alpha^2 \beta m_q^2}{128\pi^3}\left[g_{hqq}^2 \beta^2 |\mathcal{G}_h|^2 + g_{Hqq}^2 \beta^2 |\mathcal{G}_H|^2 + g_{Aqq}^2 |\mathcal{G}_A|^2 + 2 g_{hqq} g_{Hqq} \beta^2 {\rm Re}(\mathcal{G}_h \mathcal{G}_H)\right]$$

$$\frac{d\sigma_{\rm LO}^{+-/-+}}{d\cos\theta} = 0$$

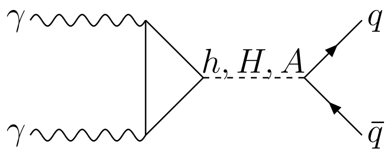
$$\mathcal{G}_\Phi = \mathcal{M}_\Phi/(1 - m_\Phi^2/s + i m_\Phi \Gamma_\Phi/s) \qquad \Phi = h, H, A \qquad \mathcal{M}_\Phi : \ \gamma\gamma\Phi - \text{form factor}$$

$$\beta = (1 - 4m_q^2/s)^{1/2}$$

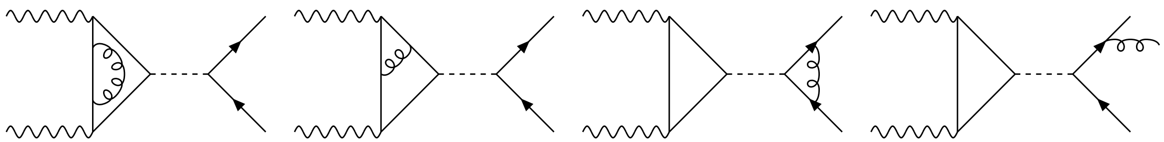
$\mathcal{M}$ost promising: $\gamma\gamma \to b\bar{b}$

Signal process

LO



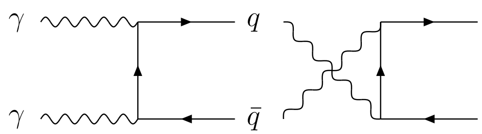
NLO



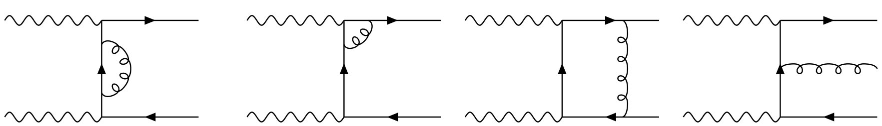
Spira, Djouadi, Graudenz, Zerwas
Melnikov, Yakovlev
Inoue et al.
Braaten, Leveille
Drees, Hikasa;...

Background process

LO



NLO



Jikia, Tkabladze
Kamal, Merebashvili, Conogouris

Interference process

NLO corrections have been calculated

$\mathcal{P}$rocess $\gamma\gamma \to b\bar{b}$ - $\mathcal{A}$nalysis

∘ Restriction to 2-jet final states (including resummation Fadin,Khoze,Martin Melles,Stirling) ⇝ enhance S/B

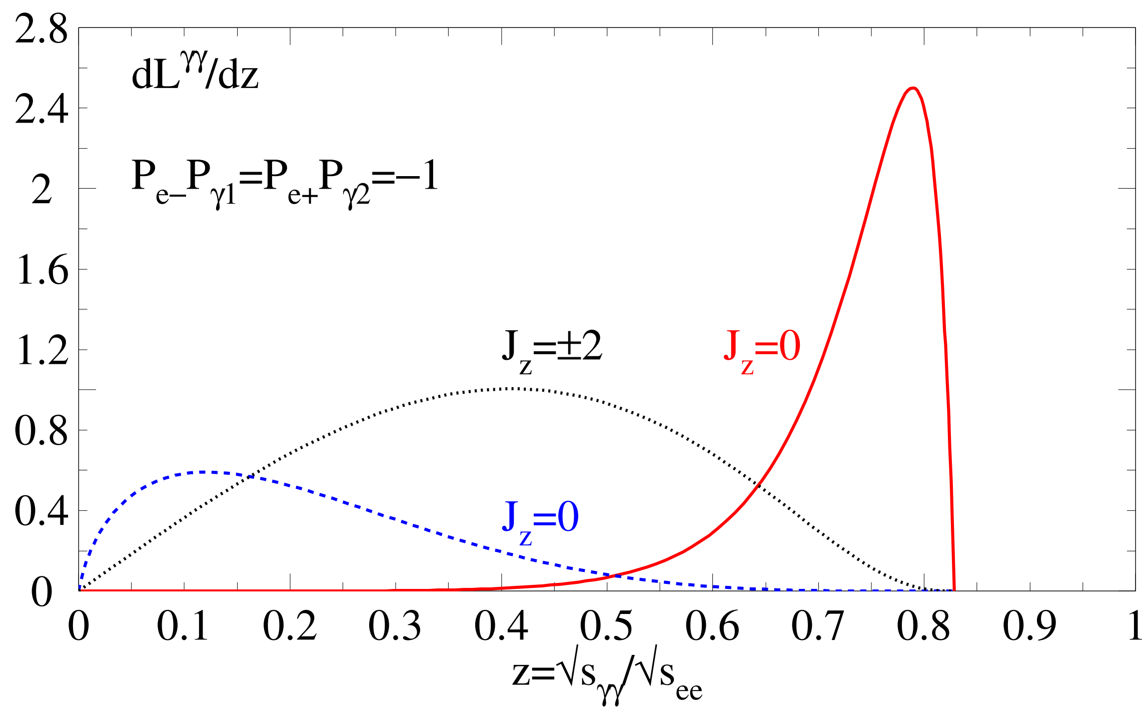
∘ Polarisation of $e^{\pm}$ and laser beams ⇝ enhance S/B
[For leading order with realistic photon spectra see also Gunion et al.]

∘ Cut in scattering angle of the b quark $|\cos\theta| < 0.5$ ⇝ enhance S/B

$\gamma\gamma$ luminosity $d\mathcal{L}^{\gamma\gamma}/dz$ Ginzburg et al. Kühn et al.

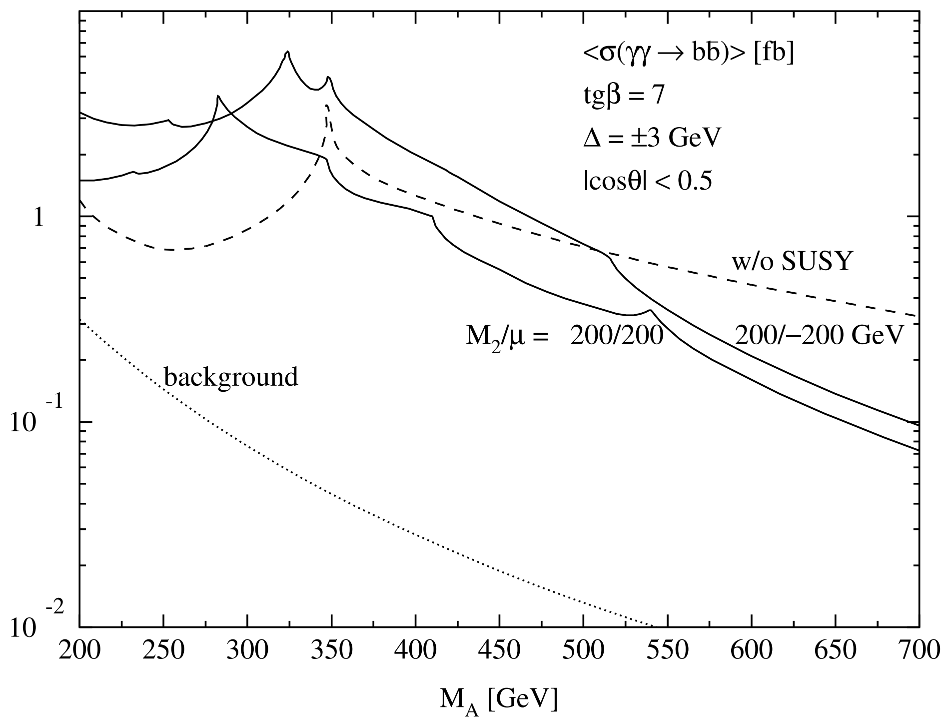
"P": pol.; $\sqrt{s_{ee}} = 500$ GeV

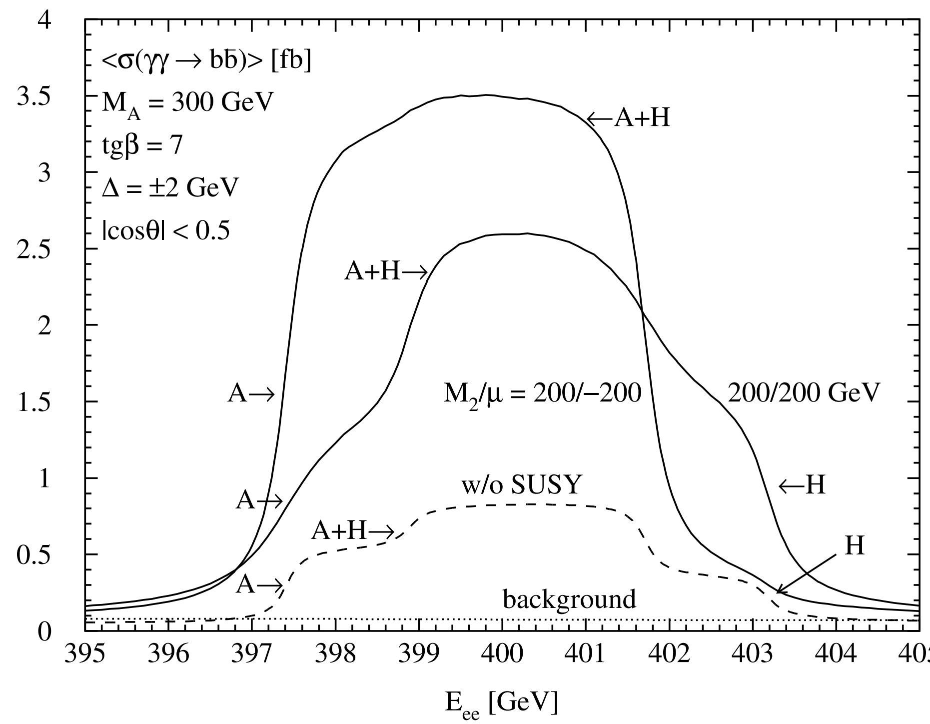
For this helicity combination:
$d\mathcal{L}^{\gamma\gamma}/dz$ max. for $J_z = 0$
peaked towards high energies



$\mathcal{R}$esult $e^+e^- \to \gamma\gamma \to b\bar{b}$

Krämer,MM,Spira,Zerwas





Resonant H/A production in $\gamma\gamma$ collisions $+$bgk

Threshold scans for H/A production to disentangle H/A

$\mathcal{A}$nalysis $\gamma\gamma \to H/A \to b\bar{b}$

P.Nieżurawski, A.F.Żarnecki, M.Krawczyk

Parameter Sets: $\tan\beta = 7$, $\mu = \pm 200$ GeV, $M_2 = 200$ GeV, $M_{\tilde{f}} = 1$ TeV, $A_{\tilde{f}} = 1.5$ TeV $(I,\, III)$
$\mu = -150$ GeV (II), $\mu = 300$ GeV, $A_{\tilde{f}} = 2450$ GeV (IV)

Analysis:

- ◦ $\gamma\gamma$ spectrum: COMPAZ Żarnecki
- ◦ Signal: HDECAY,PYTHIA
- ◦ Background:
  - NLO $\gamma\gamma \to Q\bar{Q}(g)$ for Q=c,b Jikia,Söldner-Rembold
  - $\gamma\gamma \to W^+W^-$ PYTHIA; Bélanger,Boudjema
  - $\gamma\gamma \to q\bar{q}$ for $q = u, d, s$ PYTHIA
  - $\gamma\gamma \to \tau^+\tau^-$ PYTHIA
- ◦ Overlaying events $\gamma\gamma \to had$ (PYTHIA) with realistic $\gamma\gamma$ luminosity spectrum V.Telnov
- ◦ Beam crossing angle, primary vertex distribution
- ◦ b-tagging ZVTOP-B-HADRON-TAGGER/Hansen et al.; Kuhl,Harder
- ◦ Parton Shower (not for $Q\bar{Q}(g)$) PYTHIA
- ◦ Fragmentation PYTHIA
- ◦ Detector Performance SIMDET/Pohl,Schreiber

$\mathcal{A}$nalysis $\gamma\gamma \to H/A \to b\bar{b}$

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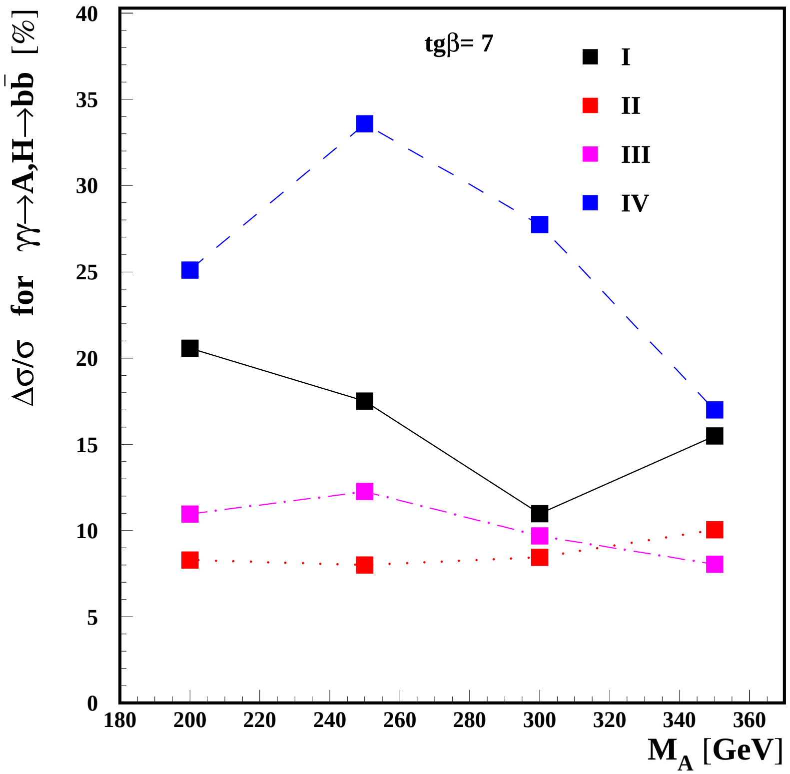

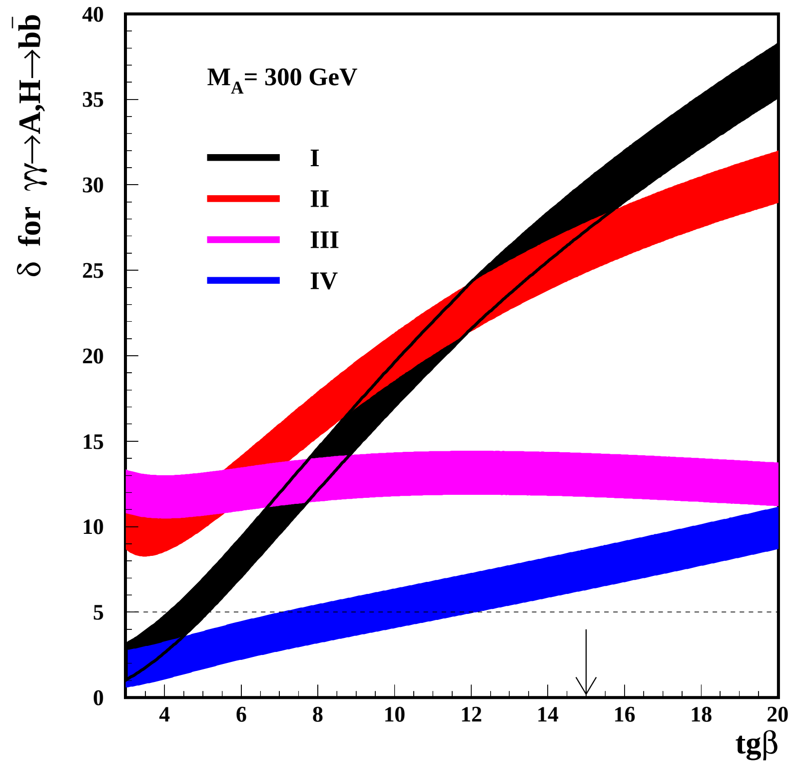

Precision

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{N_S+N_B}}{N_S}$$

Symbol	μ [GeV]	$A_{\tilde{f}}$ [GeV]
I	200	1500
II	-150	1500
III	-200	1500
IV	300	2450

Significance

$$\delta = \frac{N_S}{\sqrt{N_B}} \pm \sqrt{1 + \frac{N_S}{N_B}}$$

$\tau\tau$ $\mathcal{F}$usion to $\mathcal{SUSY}$ $\mathcal{H}$iggs $\mathcal{B}$osons at a $\mathcal{P}$hoton $\mathcal{C}$ollider

Choi,Kalinowski,Lee,MM,Spira,Zerwas, Phys.Lett.B606(2005)164

- **Motivation:** $\delta \tan\beta / \tan\beta \sim 10$ % at e^+e^-/pp colliders Choi et al.;Boos et al.;Gunion et al.;Kinnunen et al. Nieżurawski et al.;Velasco et al.

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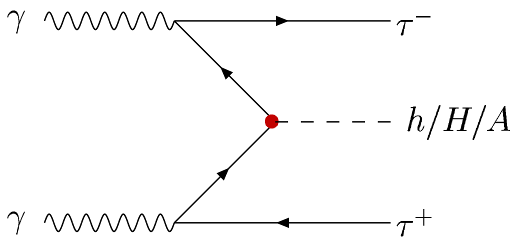
- **$\tau\tau$ Fusion to h, H, A at a $\gamma\gamma$ Collider: Signal**



Couplings: for large $\tan\beta$

$A\tau\tau = \tan\beta$, $H\tau\tau \approx \tan\beta$	heavy H/A
$h\tau\tau \approx \tan\beta$	light A

Higgs decays: $h/H/A \to b\bar{b}$ at 90% (SPS1b)

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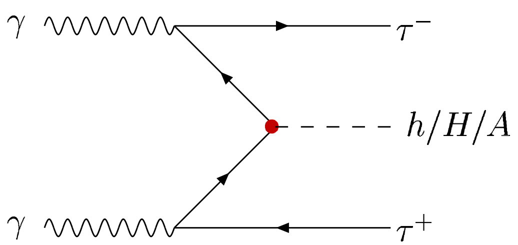

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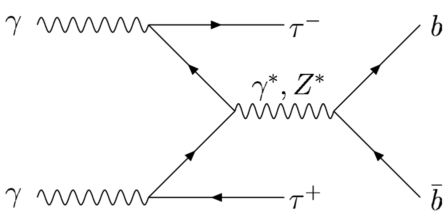
- **Bkg - Annihilation: $\tau^+\tau^- \to b\bar{b}$ and $b\bar{b} \to \tau^+\tau^-$ via γ, Z**



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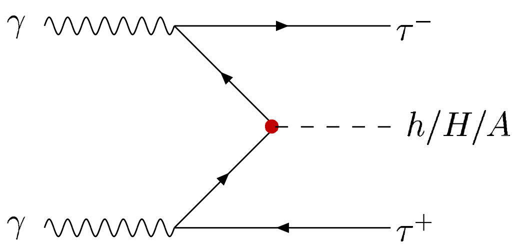

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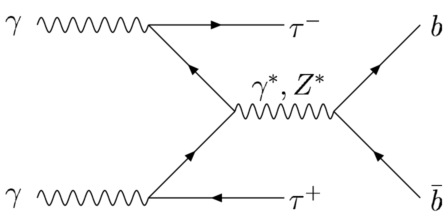

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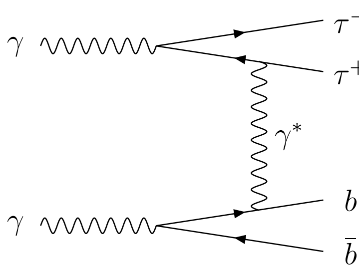
- **Bkg - diffractive: $\gamma\gamma \to (\tau\tau)(bb)$**



suppressed by event topology:

$\tau\tau$ small invariant mass/same direction

bb dito/close to γ axes

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Choi,Kalinowski,Lee,MM,Spira,Zerwas, Phys.Lett.B606(2005)164

Analysis: Full set of signal and bkg diagrams ($\rightarrow$ CompHEP Boos,Pukhov,...)

Cuts: $M_{bb} = M_\Phi \pm \Delta$ with $\Delta = \text{max}[\Gamma_\phi/2, \Delta_{\text{ex}}] \rightarrow \Delta_{\text{ex}} = 0.05 M_\Phi$

τ polar angle	≥ 130 mrad [shielding: dead mask]
τ energy	≥ 5 GeV
τ^+ and τ^-	assumed in opposite directions

Efficiencies: $\epsilon_{bb} \sim 0.7$ and $\epsilon_{\tau\tau} \sim 0.5 \rightsquigarrow \epsilon \sim 0.35$

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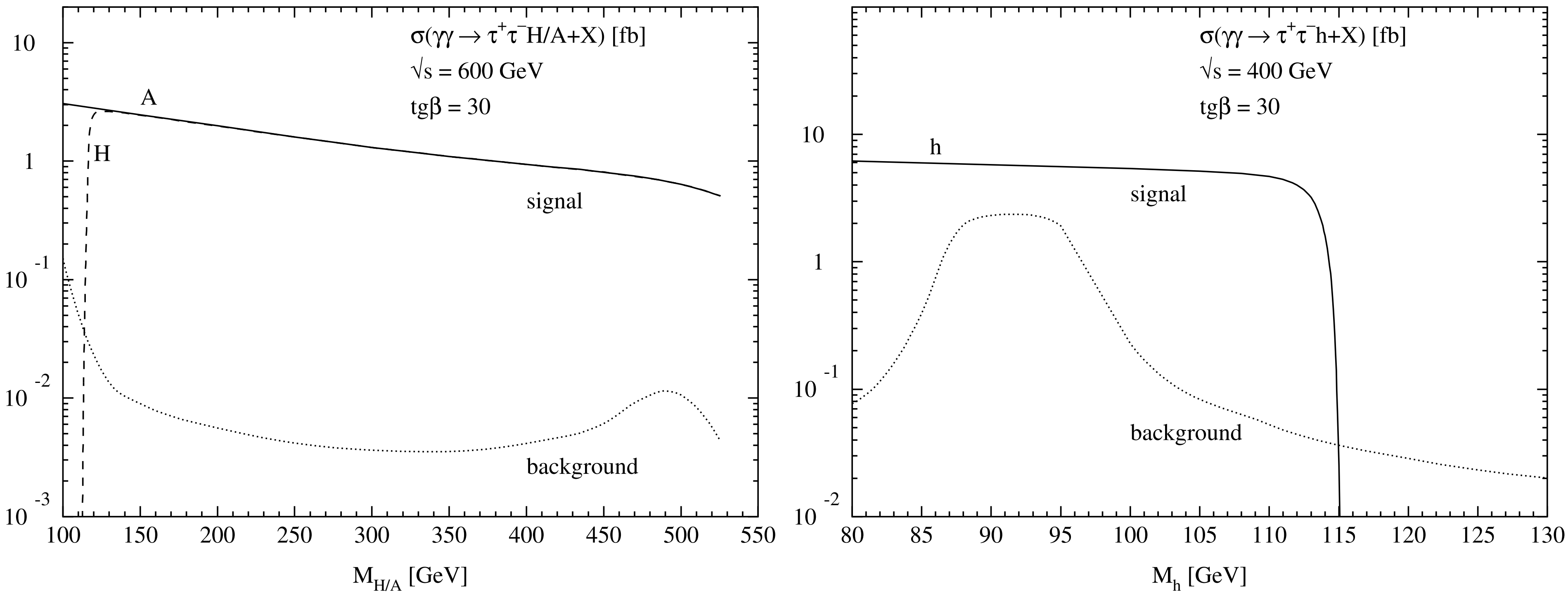
$E_{e^\pm e^-} = 800/500$ GeV $\Rightarrow E_{\gamma\gamma} = 600/400$ GeV, $\mathcal{L} = 200/100$ fb^{-1}



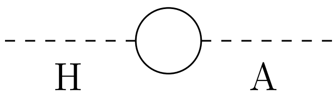
- $\Delta \tan\beta \approx 0.9$-$1.3$ uniformly for $\tan\beta \gtrsim 10$

$\mathcal{CP}$ violation in the $\mathcal{SUSY}$ $\mathcal{H}$iggs sector

∘ **MSSM Born level:** no CP violation

∘ **CP violation induced by loops** $\sim$ trilinear coupling

Choi ea;Asakawa ea;Godbole ea;Lee ea



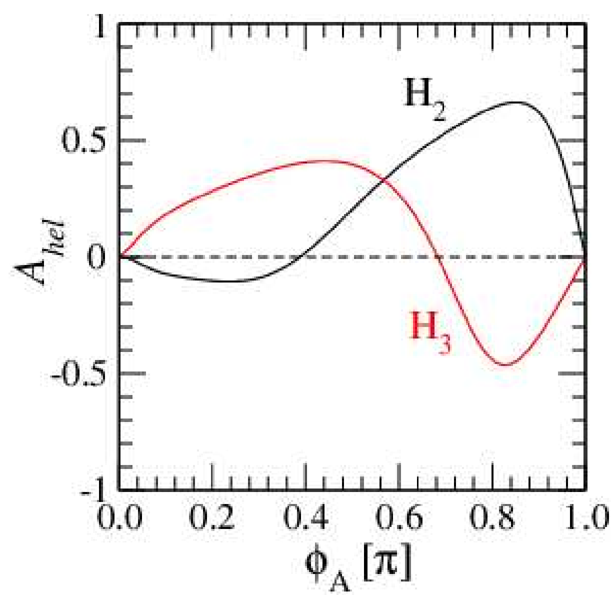
decoupling regime: $M_A \approx M_H$

mixing: $\frac{1}{2}\tan 2\theta = \frac{\Delta^2_{HA}}{M_H^2 - M_A^2 - i[M_H\Gamma_H - M_A\Gamma_A]}$

$\Rightarrow$ $\gamma\gamma$ LR asymmetry

$$A_{LR} = \frac{\sigma_{++} - \sigma_{--}}{\sigma_{++} + \sigma_{--}}$$

Choi ea



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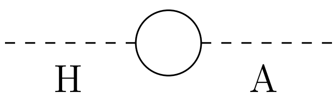

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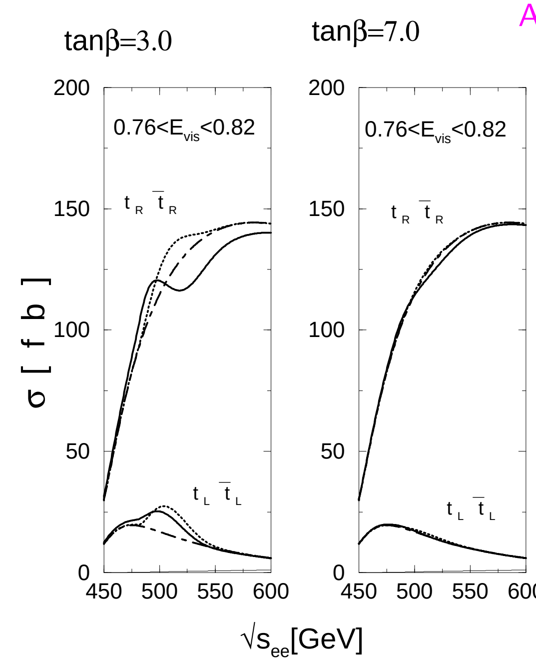
$\Rightarrow$ top/τ polarisation

$$A_{LR} = \frac{\sigma_{RR} - \sigma_{LL}}{\sigma_{RR} + \sigma_{LL}}$$

Asakawa ea



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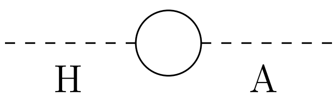

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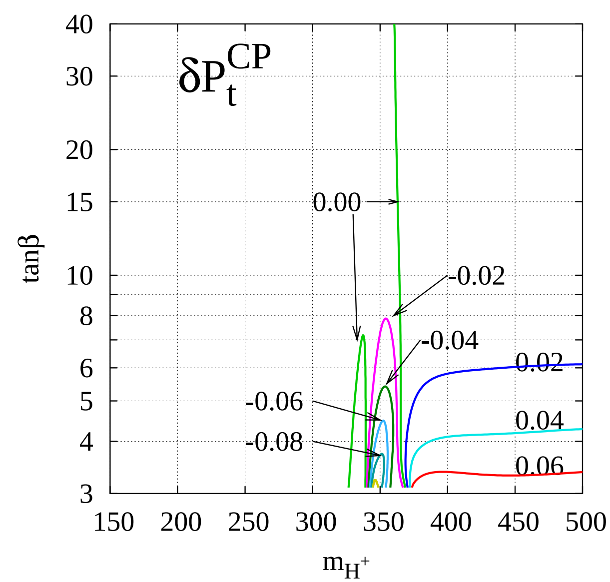
$\Rightarrow$ top/τ polarisation

$$\delta P_t^{\text{CP}} = P_t^{++} + P_t^{--}$$

($\rightarrow$ talk by R.K.Singh)

Godbole ea



$\mathcal{S}$upersymmetry

◦ **Selectron production:** $e^+e^- \to \tilde{e}\tilde{e}$ $\tilde{m} \le \frac{1}{2}\sqrt{s}$

extended channel: $e\gamma \to \tilde{e}\tilde{\chi}^0$ $\tilde{m} \le \sqrt{s} - \tilde{m}_\chi$ [$i.g.$ larger than $\frac{1}{2}\sqrt{s}$] Datta, Djouadi,MM

◦ **Sneutrino production:** $e^+e^- \to \tilde{\nu}\tilde{\nu}$ invisible for light $\tilde{\nu}$ [$c.f.$ SPS1a']

exploit $\tilde{\chi}^\pm$ decays in pairs: $\tilde{\chi}_1^\pm \to l^\pm \tilde{\nu}_l$ / difficult bkgs

Alternative channel: $e\gamma \to \tilde{\nu}_e \tilde{\chi}_1^\pm$

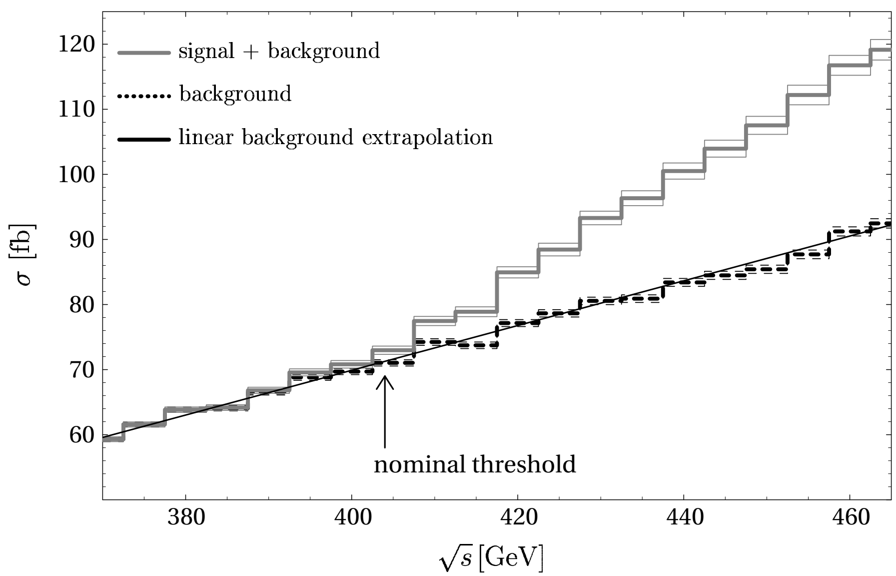
$\to \tilde{\nu}_e \tilde{\nu}_\mu \mu$

$\sigma \sim \beta$: sharp onset $\Rightarrow$

threshold scan: $\sqrt{s_{\gamma\gamma}} \ge m_{\tilde{\mu}} + m_{\tilde{\chi}}$

$m_{\tilde{\nu}_e} = 169.8 \pm 3.2$ GeV

Freitas,Porod,Zerwas



$\mathcal{C}$onclusions

Photon Collider: high energy / high luminosity / high degree of polarisation

$\mathcal{O}$ffers not only experimental instrument to address
a variety of physics problems in and beyond the SM, but also

$\mathcal{U}$nique $\mathcal{P}$ossibilities
in the Higgs sector and slepton sector of SUSY theories

- ◦ Unique access to heavy Higgs particles
- ◦ Unique access to heavy selectrons and $\tilde{\nu}_e$
- ◦ Determine $\Gamma(H \to \gamma\gamma)$ at high precision
- ◦ Test CP-violation
- ◦ Alternative for $\tan\beta$ determination