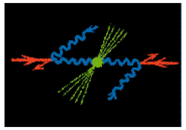
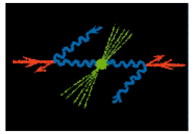
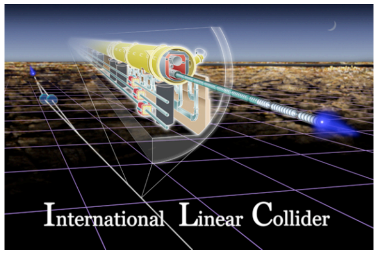


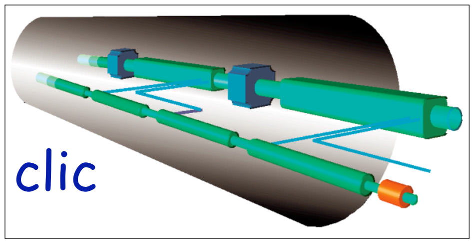


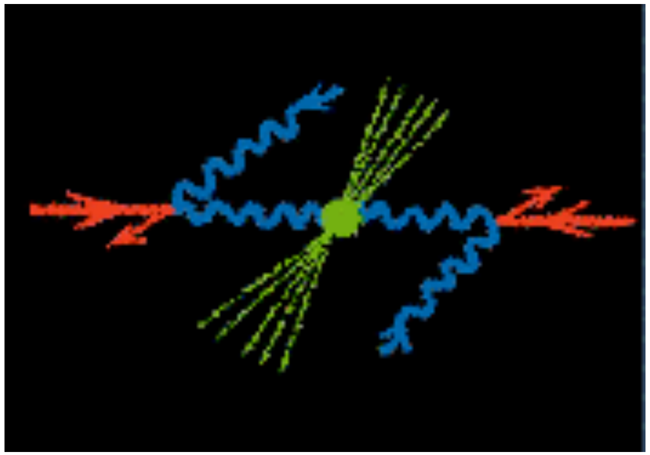
Physics at a Photon Collider

A.De Roeck

CERN/Antwerp University





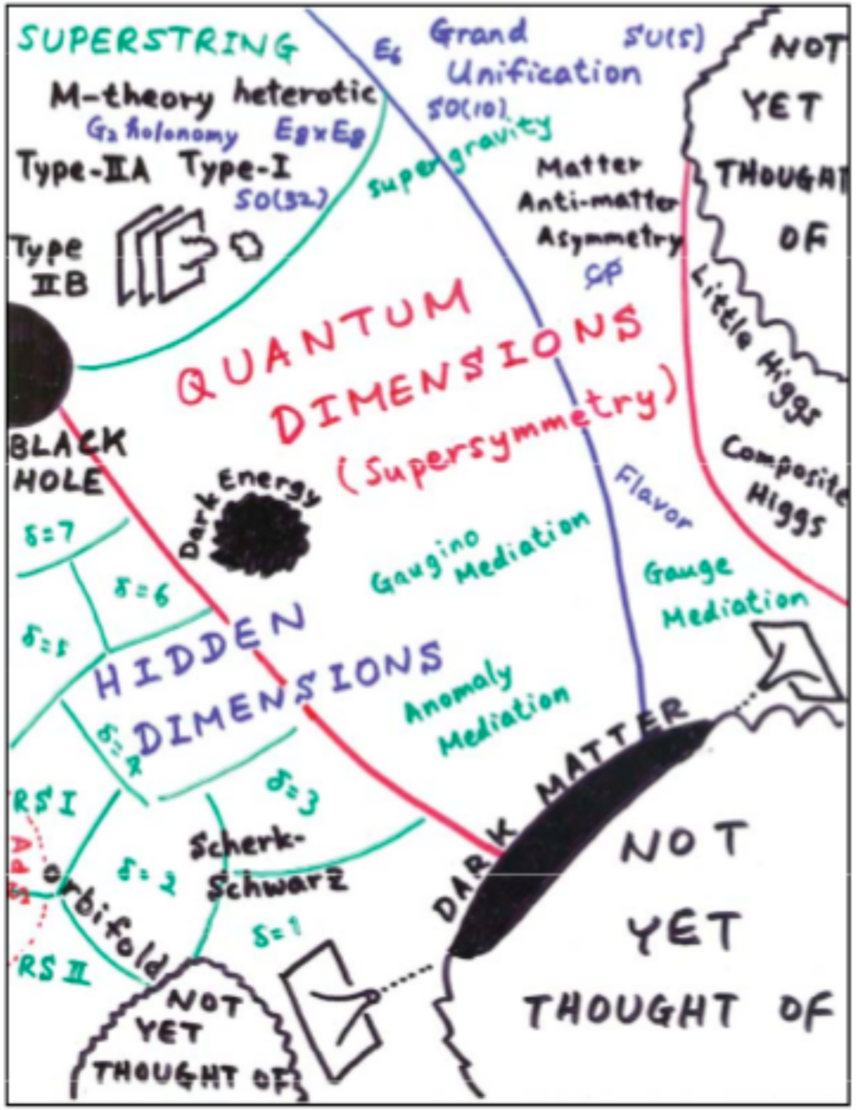


Contents

- Introduction: experimental aspects of gamma-gamma collider
  - Machine and detector issues, kinematics, luminosity spectra
- Short review on the physics (⇒ more from Maria and Lia)
  - QCD studies: photon structure
  - Higgs production at a photon collider:
  - Supersymmetry,
  - W-boson interactions, Extra Dimension, Top Quark…

Further reading: B. Badelek et al., TESLA TDR part VI appendix
E. Boos et al., hep-ph/0103090
Proceedings of the ECFA/DESY '01-'03 workshop.
hep-ph/0308103, hep-ph/0311138/hep-ph/0307175 80 83
PLC05 proceedings, LCWS07 and Photon2007 proceedings

Theorist Summary of New Physics

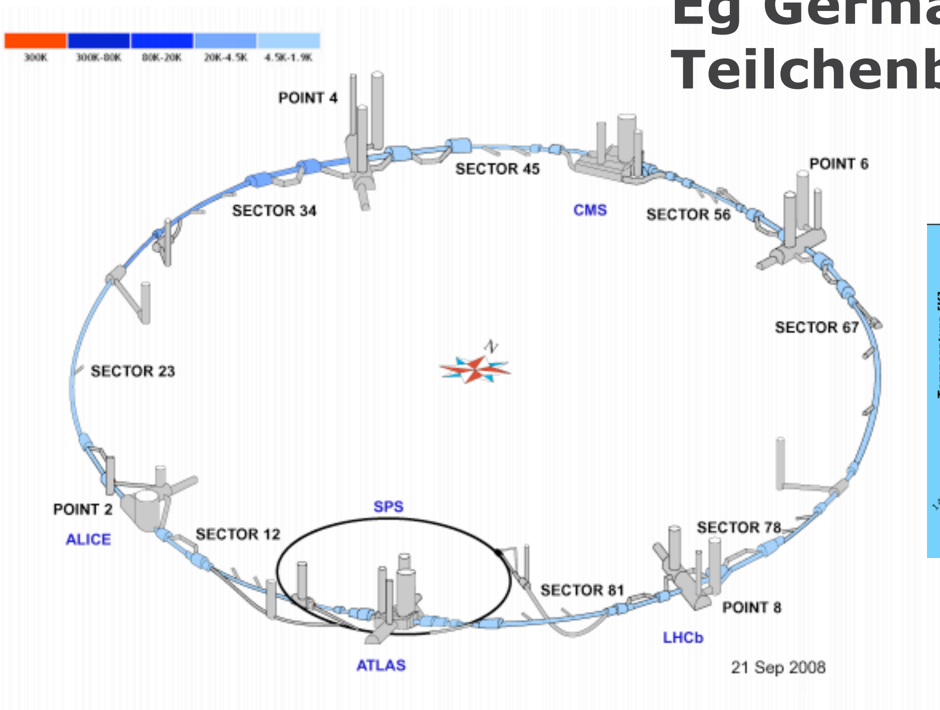


H. Maruyama

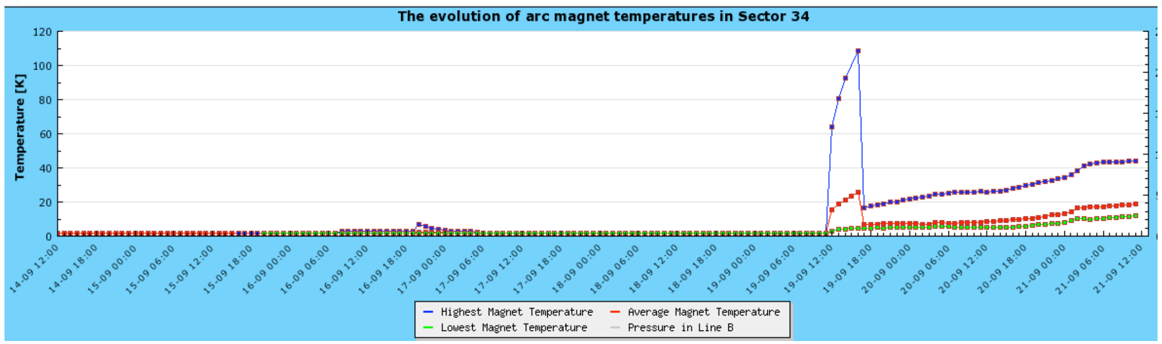
Only data can help to give clarity….

The LHC is our next Hope !

- Great startup on 10/9!
- …Serious problem on 19/9 (> 2 months to fix)
- So, a bit more patience will be required.
- But LHC will come on strongly in 2009

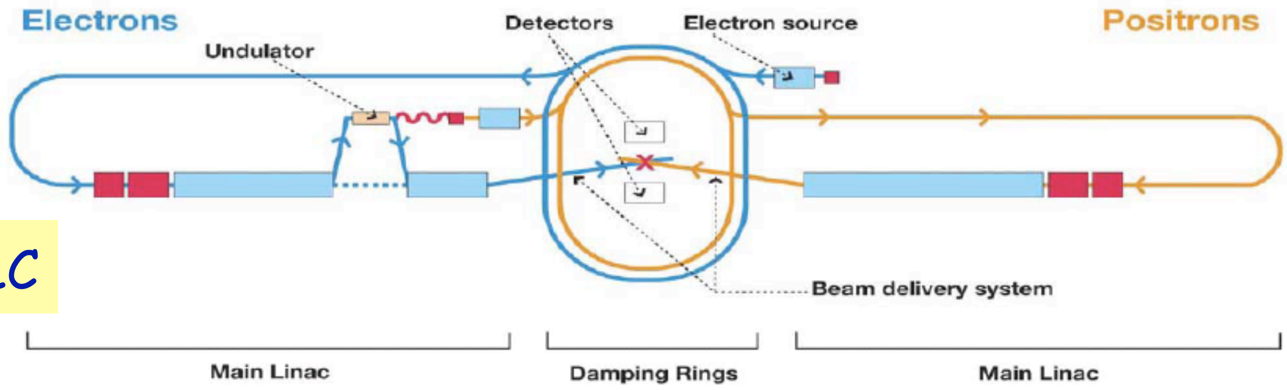


Eg German press:
Teilchenbeschleuniger ist schon kaputt



Linear Colliders

ILC



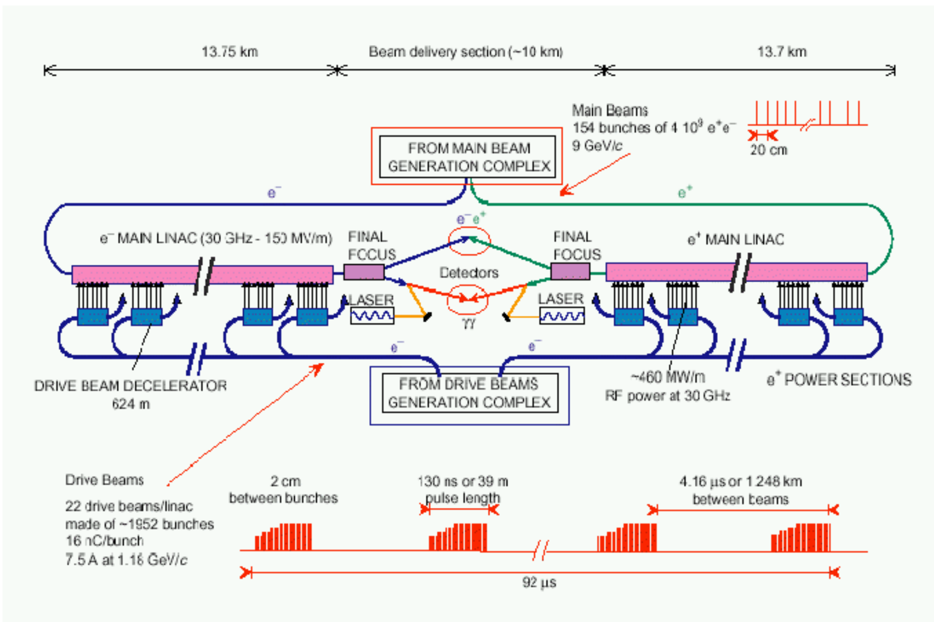
Luminosity

~ $2 \bullet 10^{34}$ $cm^{-2}s^{-1}$

$\sqrt{s}$=500-1000 GeV

~31 km (500 GeV)

CLIC



Luminosity

~ $6 \bullet 10^{34}$ $cm^{-2}s^{-1}$

$\sqrt{s}$=3000 GeV

~41 km (3000 GeV)

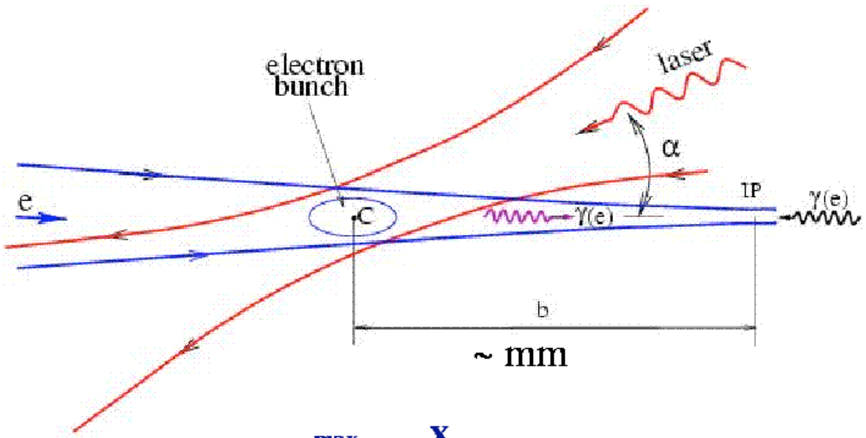
Both can have a
Photon Linear Collider mode

Two-photon interactions

Two ways to have two photon interactions at linear colliders

- Weizacker-Williams spectrum from electron beams, similar to LEP
- Convert electron beams into photon beams by Compton backscattering of laser photons ⇒ high energy γγ & high luminosity

Luminosity Spectrum of a Photon Collider



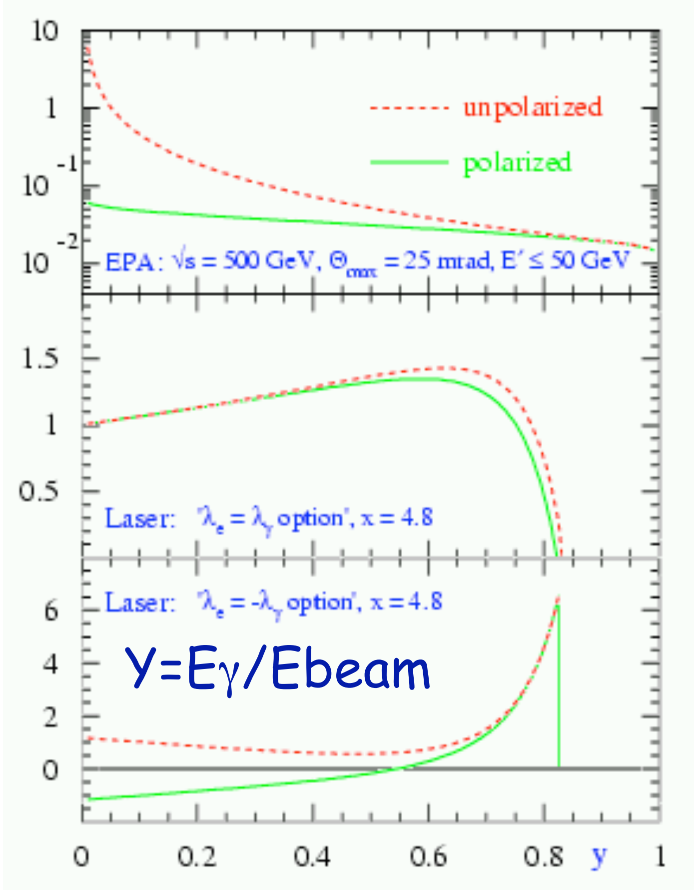
$$E_\gamma^{max} = \frac{x}{x+1} E_e$$

$$x = \frac{4 E_\gamma^0 E_e}{m_e}$$

$$E_e = 250\,GeV; E_\gamma^0 = 1.17\,eV (\lambda = 1.06\,\mu m) \Rightarrow$$

$$x = 4.5 \wedge E_\gamma^{max} = 0.82\,E_e$$

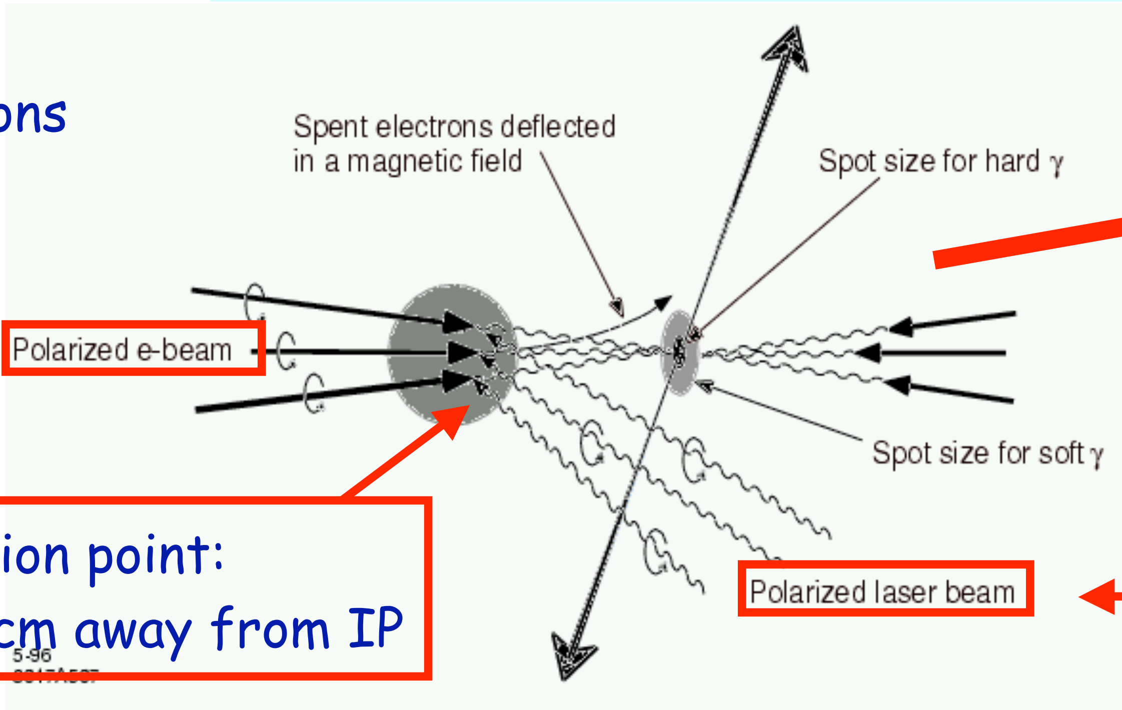
V.Telnov et al.

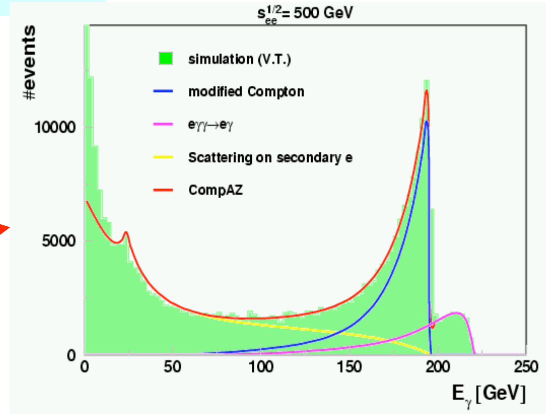


A Photon Collider

convert electron beams into photon beams

$\gamma\gamma$ or $e\gamma$ interactions





Conversion point:
1 mm-1 cm away from IP

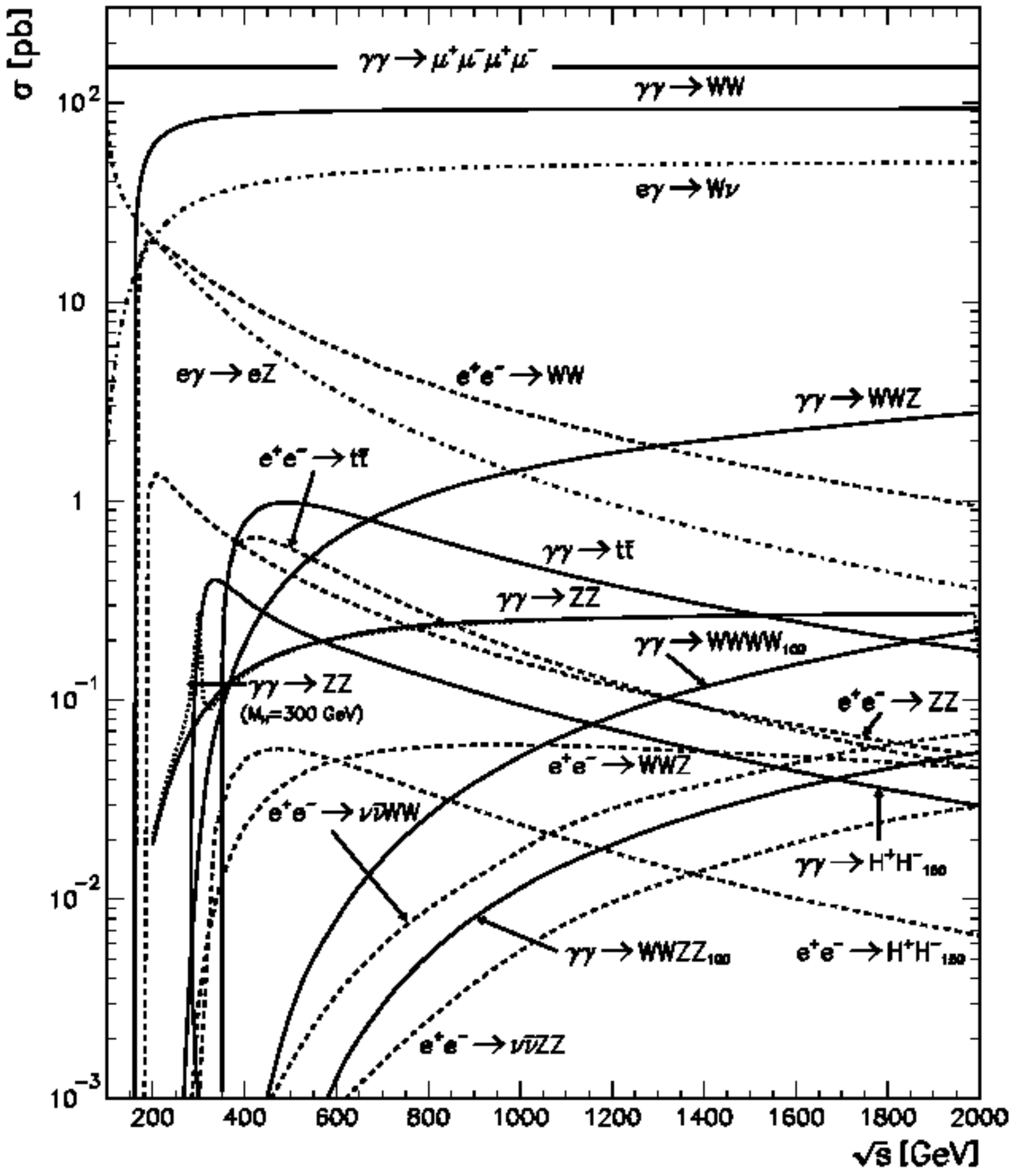
Shoot photons from a laser onto the electron beam

Compton backscattering on low energy (eV) laser photons

- Needs crossing angle (to avoid background from disrupted beams)
- Needs second/different interaction point (lasers, optics)
- Needs only e- beams (no positrons)
  ⇒ higher polarization (electrons 80% vs positrons 40-60%)

Physics at a $\gamma\gamma$ and $e\gamma$ collider --General--

Cross sections for γγ processes



Historically:

The Photon Linear Collider (PLC)

Ginzburg, Kotkin, Serbo, Telnov, Pizma ZhETF 34 514 (1981),JETP Lett. 34 491 (1982)

where the basic ideas have been elaborated

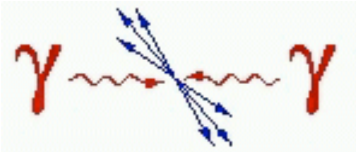
Since then:

- Over 1000 papers on physics issues of a PC
- Taken up seriously in LC studies R&D (slowly) progressing

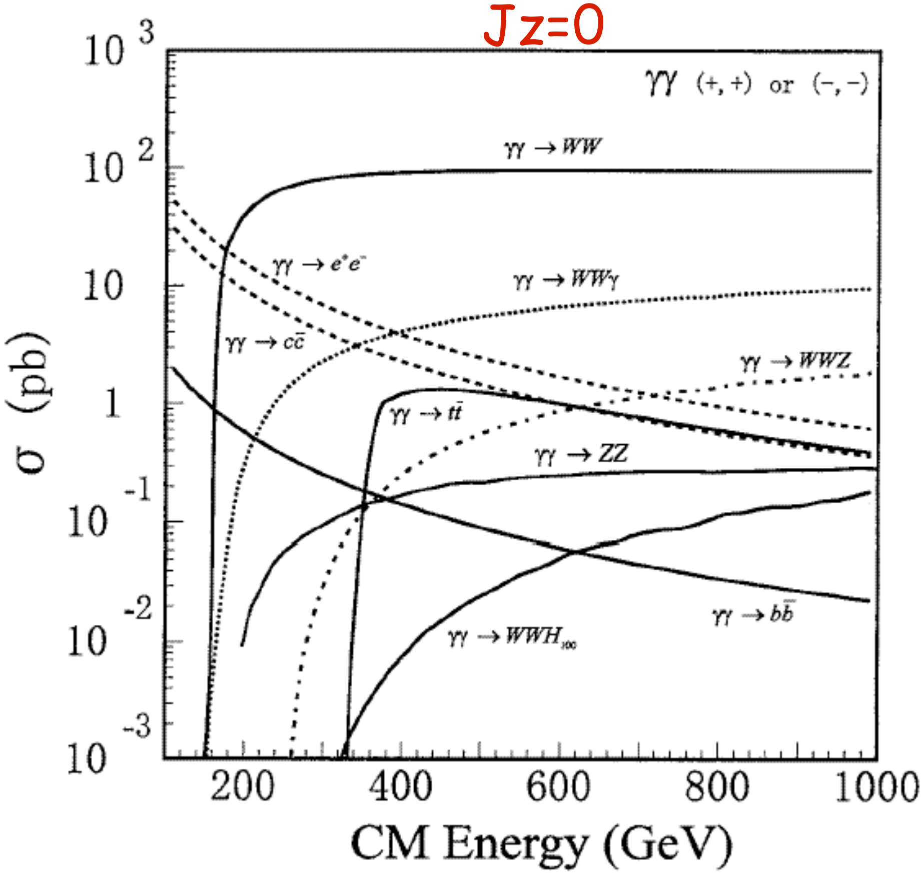
PLC part of LC roadmap
considered as possible upgrade for a Linear Collider (Jeju 2002)

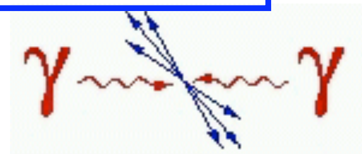
Cross sections

At PC: one can control the photon helicities

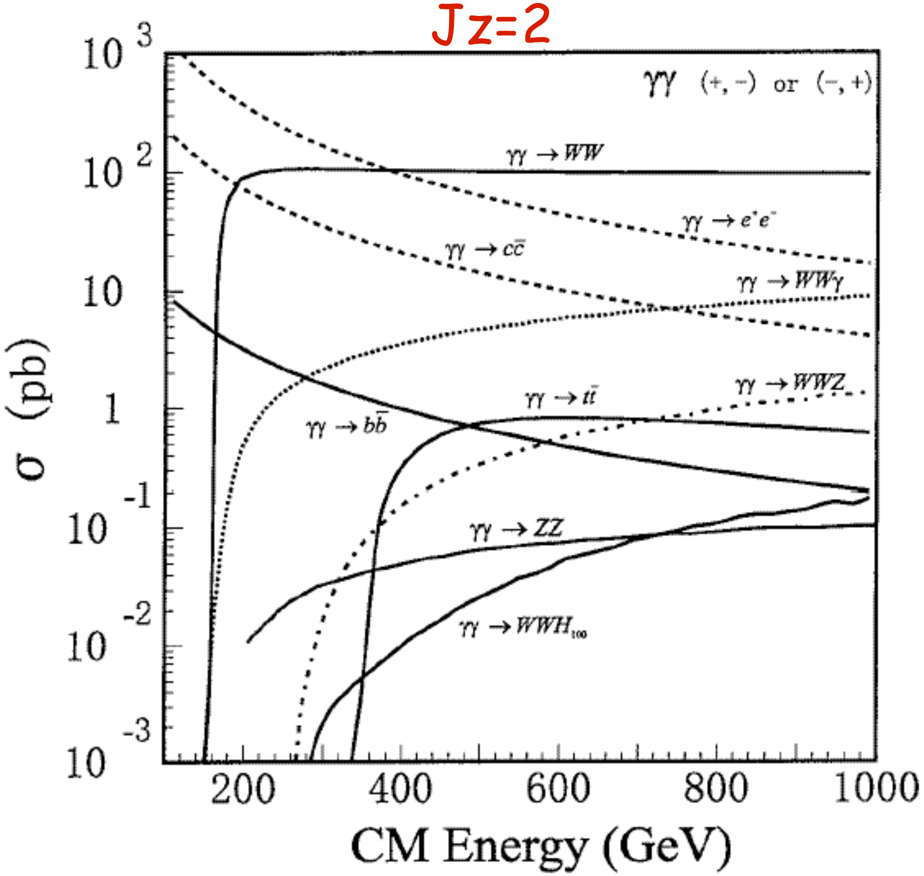


Jz=0



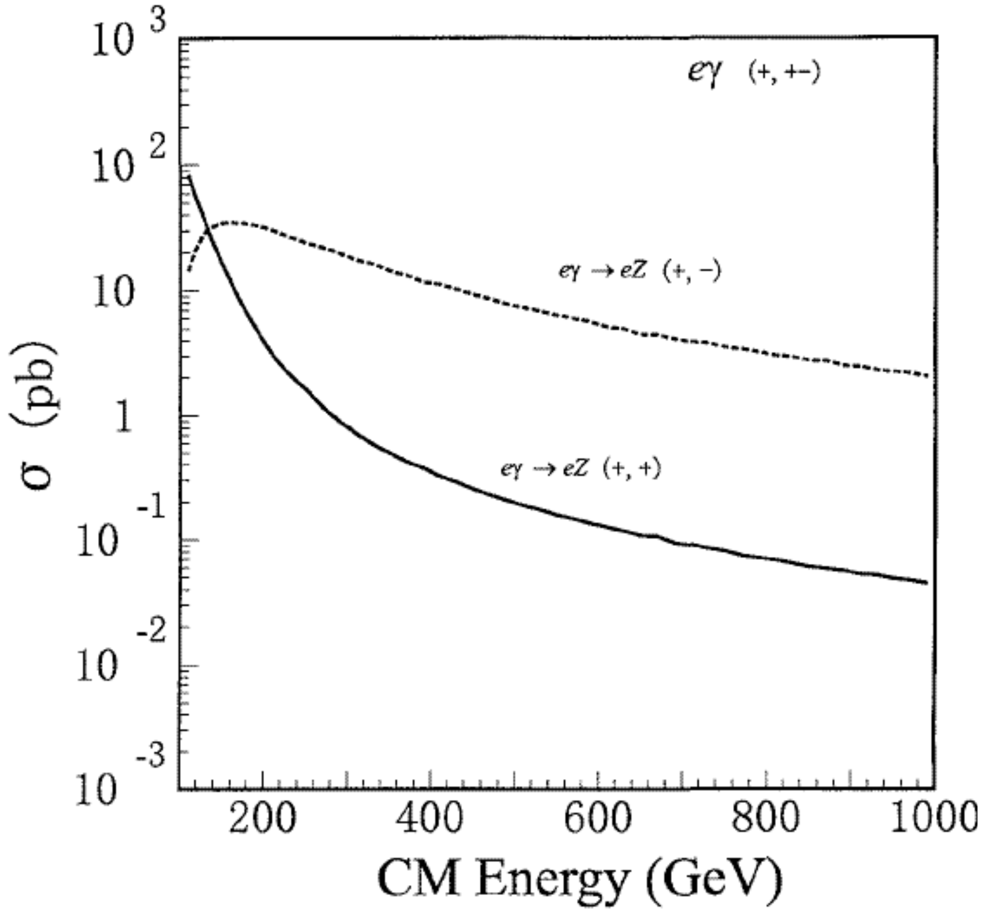


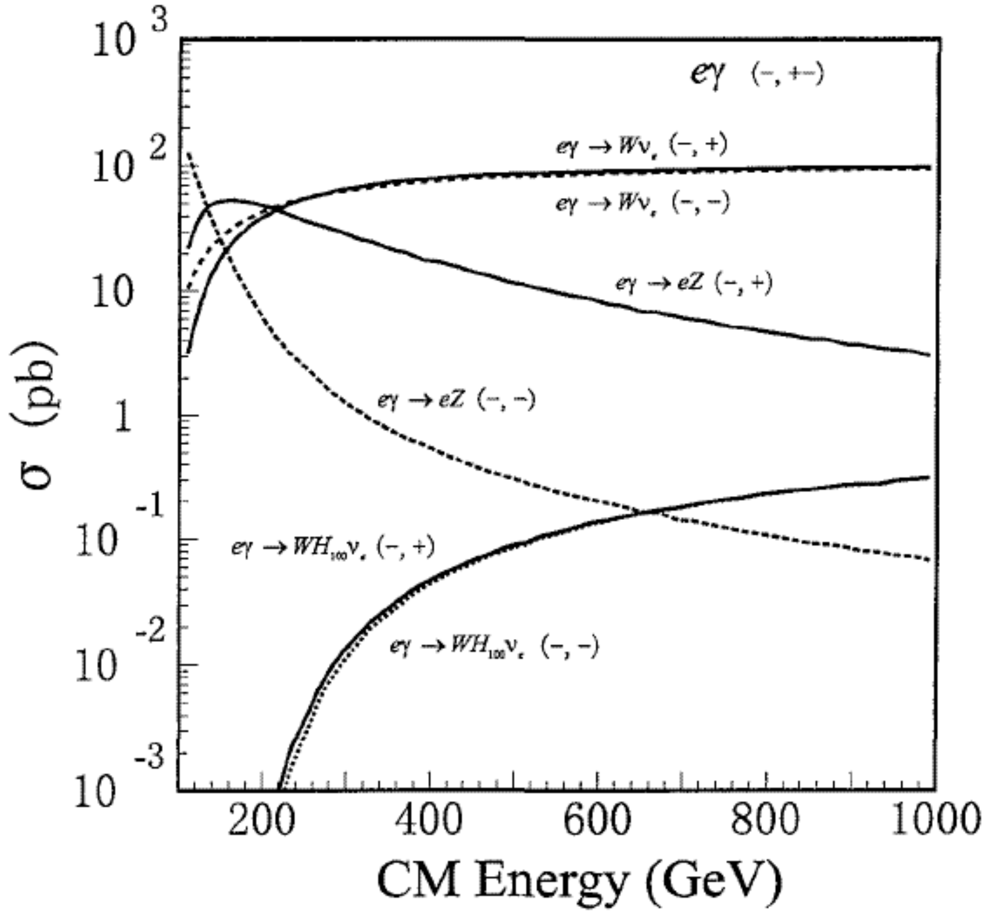
Jz=2



Cross sections

eγ cross sections





Note: get eγ by 1) switching of 1 laser side 2)using eγ background in γγ collisions

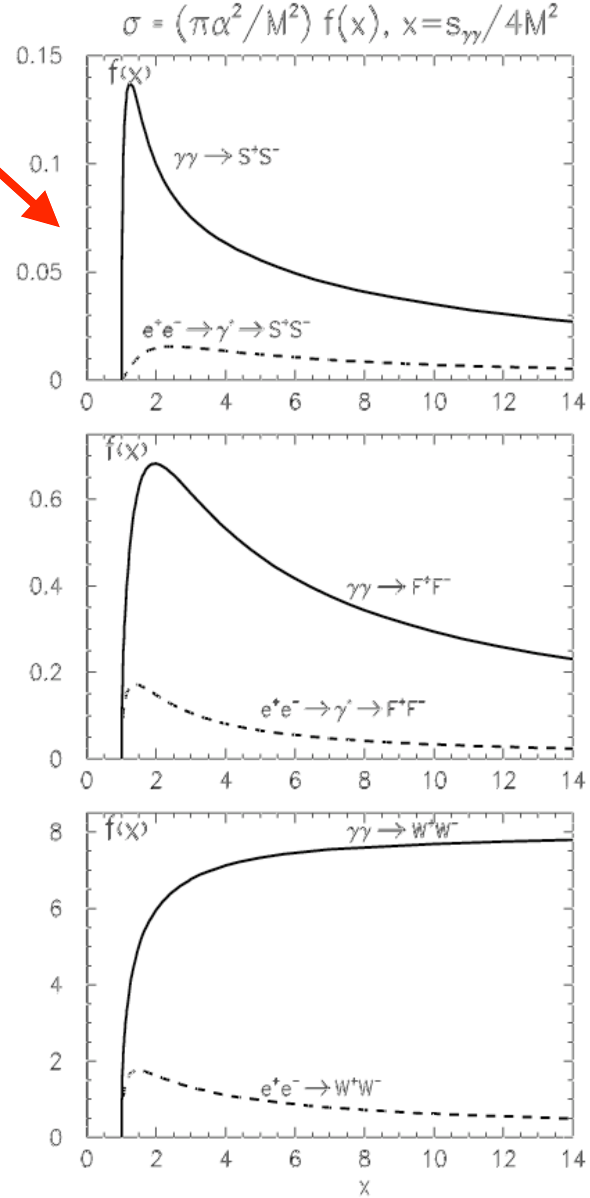
Advantages of γγ and eγ

Higher cross sections for charged particles

- Different J^{PC} state than in e+e-
- Higgs can be s-channel produced
- Higher mass reach in some channels
- Pure QED interaction (in e+e- also Z exchange)
- Higher polarization of initial state (>80%/beam)
- CP analysis opportunities (linear γ polarization…)

⇒ Physics Menu … as for an e+e- collider

- Higgs
- Supersymmetry
- Alternative theories (extra dimensions, etc.)
- EW: e.g. Triple Gauge couplings, QCD, Top,…



Golden Processes for a Photon Collider

Reaction	Remarks	
$\gamma\gamma \to H, h \to bb$	SM/MSSM Higgs, $M_{H,h} < 160$ GeV	Higgs
$\gamma\gamma \to H \to WW(^*)$	SM Higgs, 140$< M_H <$ 190 GeV	
$\gamma\gamma \to H \to ZZ(^*)$	SM Higgs, 180$< M_H <$ 350 GeV	
$\gamma\gamma \to H \to \gamma\gamma$	SM Higgs, 120$< M_H <$ 160 GeV	
$\gamma\gamma \to H \to t\bar{t}$	SM Higgs, $M_H > 350$ GeV	
$\gamma\gamma \to H, A \to bb$	MSSM heavy Higgs, interm. $\tan\beta$	
$\gamma\gamma \to \tilde{f}\bar{\tilde{f}},\ \tilde{\chi}_i^+\tilde{\chi}_i^-$	large cross sections	SUSY
$\gamma\gamma \to \tilde{g}\tilde{g}$	measurable cross sections	
$\gamma\gamma \to H^+H^-$	large cross sections	
$\gamma\gamma \to S[\tilde{t}\bar{\tilde{t}}]$	$\tilde{t}\bar{\tilde{t}}$ stoponium	
$e\gamma \to \tilde{e}^-\tilde{\chi}_1^0$	$M_{\tilde{e}^-} < 0.9 \times 2E_0 - M_{\tilde{\chi}_1^0}$	
$\gamma\gamma \to \gamma\gamma$	non-commutative theories	EDs,...
$e\gamma \to eG$	extra dimensions	
$\gamma\gamma \to \phi$	Radions	
$e\gamma \to \tilde{e}\tilde{G}$	superlight gravitions	
$\gamma\gamma \to W^+W^-$	anom. W inter., extra dimensions	Trilin. coupl.
$e\gamma \to W^-\nu_e$	anom.W couplings	
$\gamma\gamma \to 4W/(Z)$	WW scatt., quartic anom. W,Z	
$\gamma\gamma \to t\bar{t}$	anomalous top quark interactions	Top
$e\gamma \to \bar{t}b\nu_e$	anomalous Wtb coupling	
$\gamma\gamma \to$ hadrons	total $\gamma\gamma$ cross section	QCD
$e\gamma \to e^-X, \nu_e X$	NC and CC structure functions	
$\gamma g \to q\bar{q},\ c\bar{c}$	gluon in the photon	
$\gamma\gamma \to J/\psi\, J/\psi$	QCD Pomeron	

Boos et al.,
hep-ph/0103090

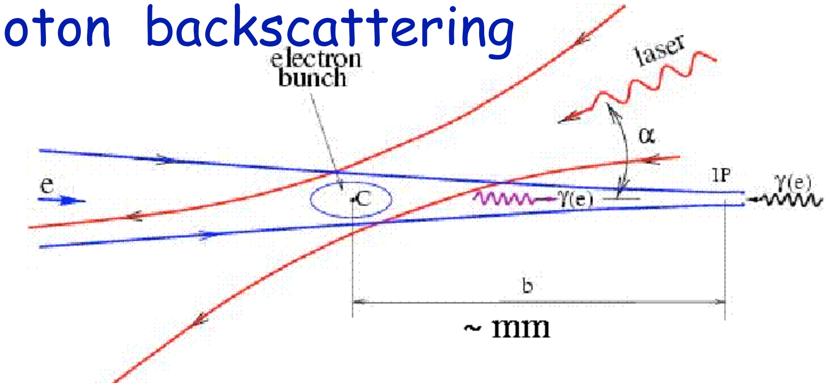
ADR (ECFA/DESY)
hep-ph/0311138

Luminosity spectra

Kinematics & Photon spectra

V. Telnov/TESLA TDR

Photon backscattering



First experiments (30-35 years ago)

$k = N_\gamma / N_e \sim 10^{-7}$

(k = # electrons that interacts with a γ)

Photon collider needs k~1

⇒Needs laser with flash energy~ 1-5 J

(e.g. solid state lasers)

Energy of the scattered photon ω depends on the photon scattering angle θ

$$\omega = \frac{\omega_m}{1+(\vartheta/\vartheta_0)^2}, \quad \omega_m = \frac{x}{x+1}E_0, \quad \vartheta_0 = \frac{mc^2}{E_0}\sqrt{x+1},$$

$$x = \frac{4E_0\omega_0}{m^2c^4}cos^2\alpha_0/2 \simeq 15.3\left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\omega_0}{\mathrm{eV}}\right] = 19\left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\mu m}{\lambda}\right]$$

ω_m is the maximum energy of the photon

Example: $E_0 = 250\,\mathrm{GeV},\ \omega_0 = 1.17\mathrm{eV}\ (\lambda = 1.06\,\mu\mathrm{m})$

$\Rightarrow x = 4.5$ and $\omega_m/E_0 = 0.82$.

Compton Cross Section

The energy spectrum of the scattered photons is defined by the Compton cross section

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{dy} = \frac{2\sigma_0}{x\sigma_c}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) + 2\lambda_e P_c r x(1-2r)(2-y)\right]$$

$$y = \omega/E_0, \qquad r = \frac{y}{(1-y)x}, \quad \sigma_0 = \pi r_e^2 = \pi\left(\frac{e^2}{mc^2}\right)^2 = 2.5\cdot 10^{-25}\,\mathrm{cm}^2$$

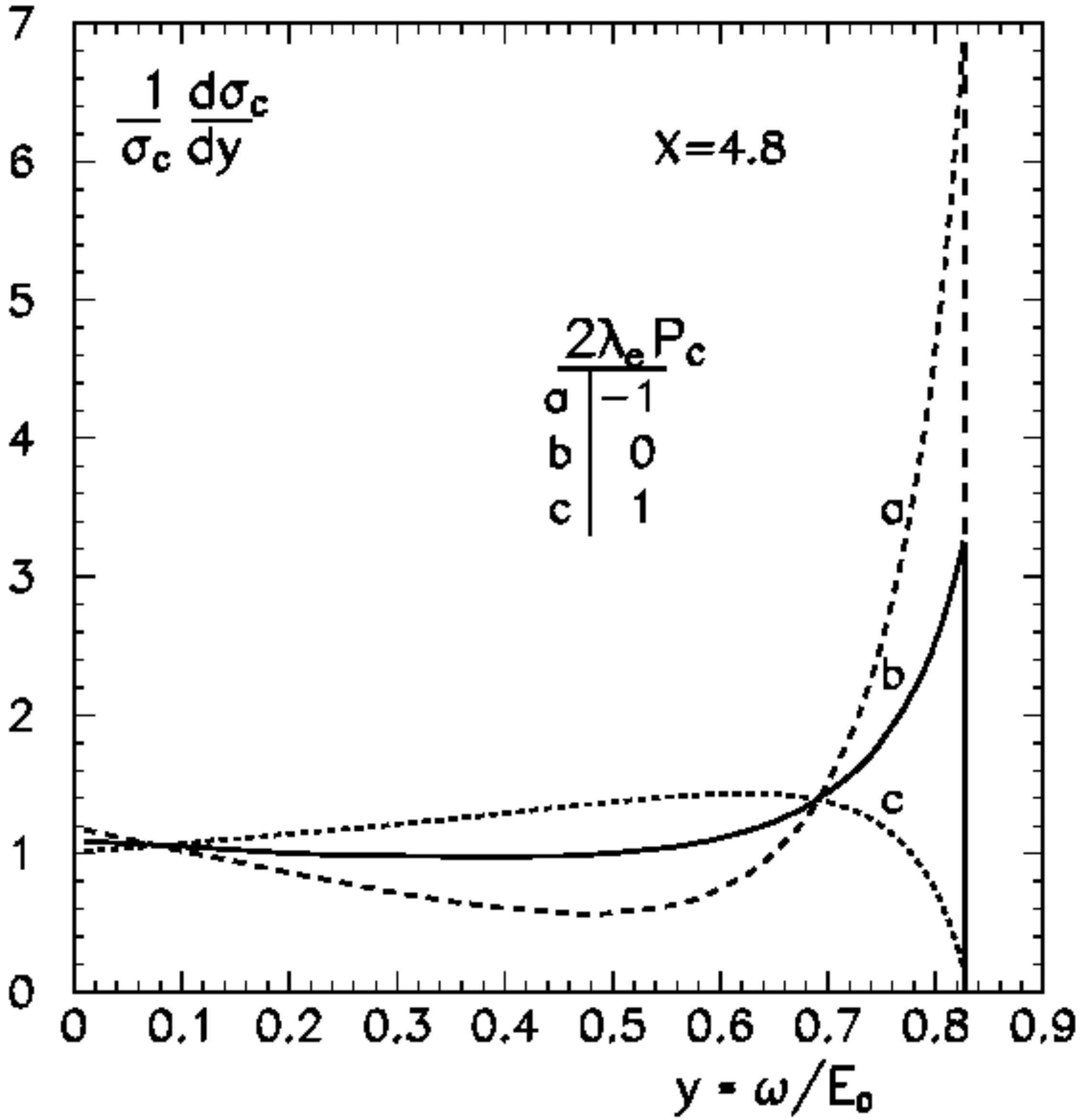
Where λ_e is the (mean) electron helicity and P_c that of the laser photon

Total cross section $\sigma_c \;=\; \sigma_c^0 \;+\; 2\lambda_e P_c\,\sigma_c^1\,,$

$$\sigma_c^0 \;=\; \frac{2\sigma_0}{x}\left[\left(1-\frac{4}{x}-\frac{8}{x^2}\right)\ln(x+1)+\frac{1}{2}+\frac{8}{x}-\frac{1}{2(x+1)^2}\right],$$

$$\sigma_c^1 \;=\; \frac{2\sigma_0}{x}\left[\left(1+\frac{2}{x}\right)\ln(x+1)-\frac{5}{2}+\frac{1}{x+1}-\frac{1}{2(x+1)^2}\right].$$

Spectrum of the Compton scattered photons



$$\Delta\omega_{1/2} \approx \omega_m/(x+2)$$

$\approx$ 10-15%

Spectrum of the scattered photon strongly peaked at high energy (80%E_0 for x~ 4.5)

Higher x: stronger peak and higher ω_m

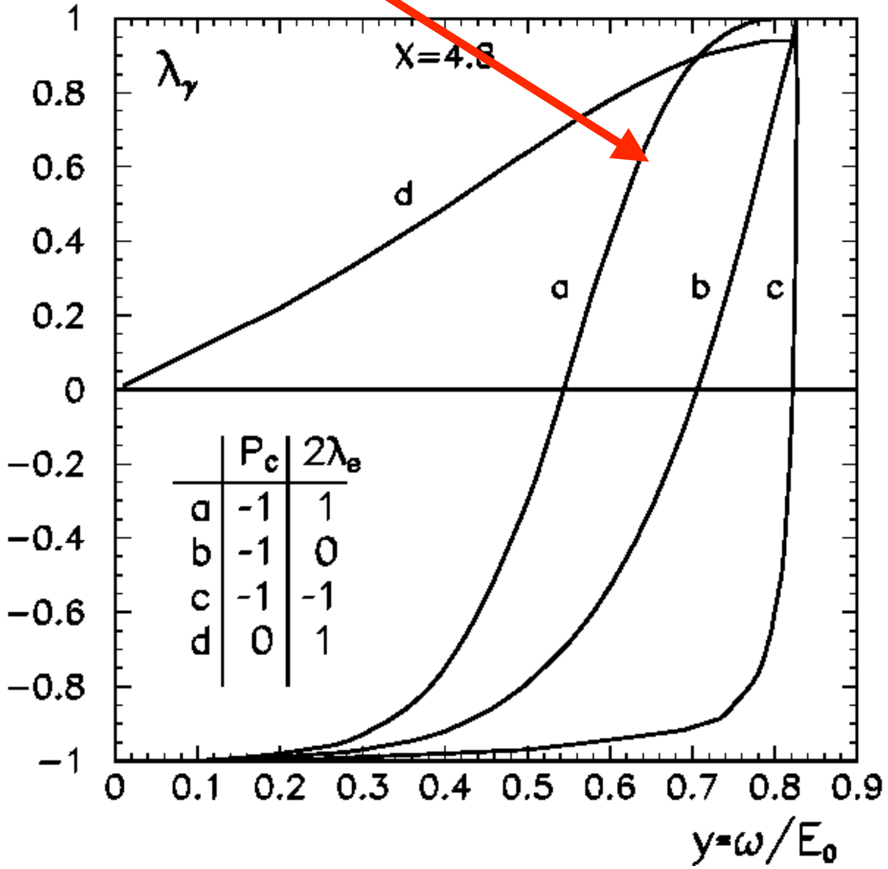
But x limited to ~ 4.8 due to e+e- pair creation

Polarization of the photons

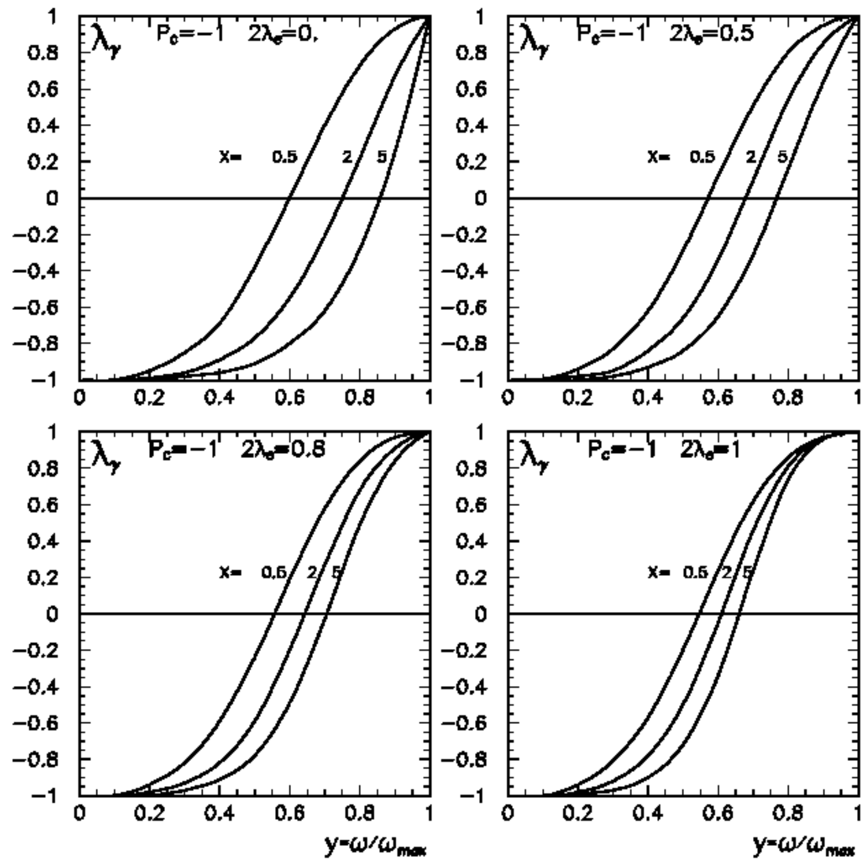
The averaged helicity of the photons after Compton Scattering

$$\langle \lambda_\gamma \rangle = \frac{-P_c(2r-1)[(1-y)^{-1}+1-y]+2\lambda_e xr[1+(1-y)(2r-1)^2]}{(1-y)^{-1}+1-y-4r(1-r)-2\lambda_e P_c xr(2-y)(2r-1)}$$

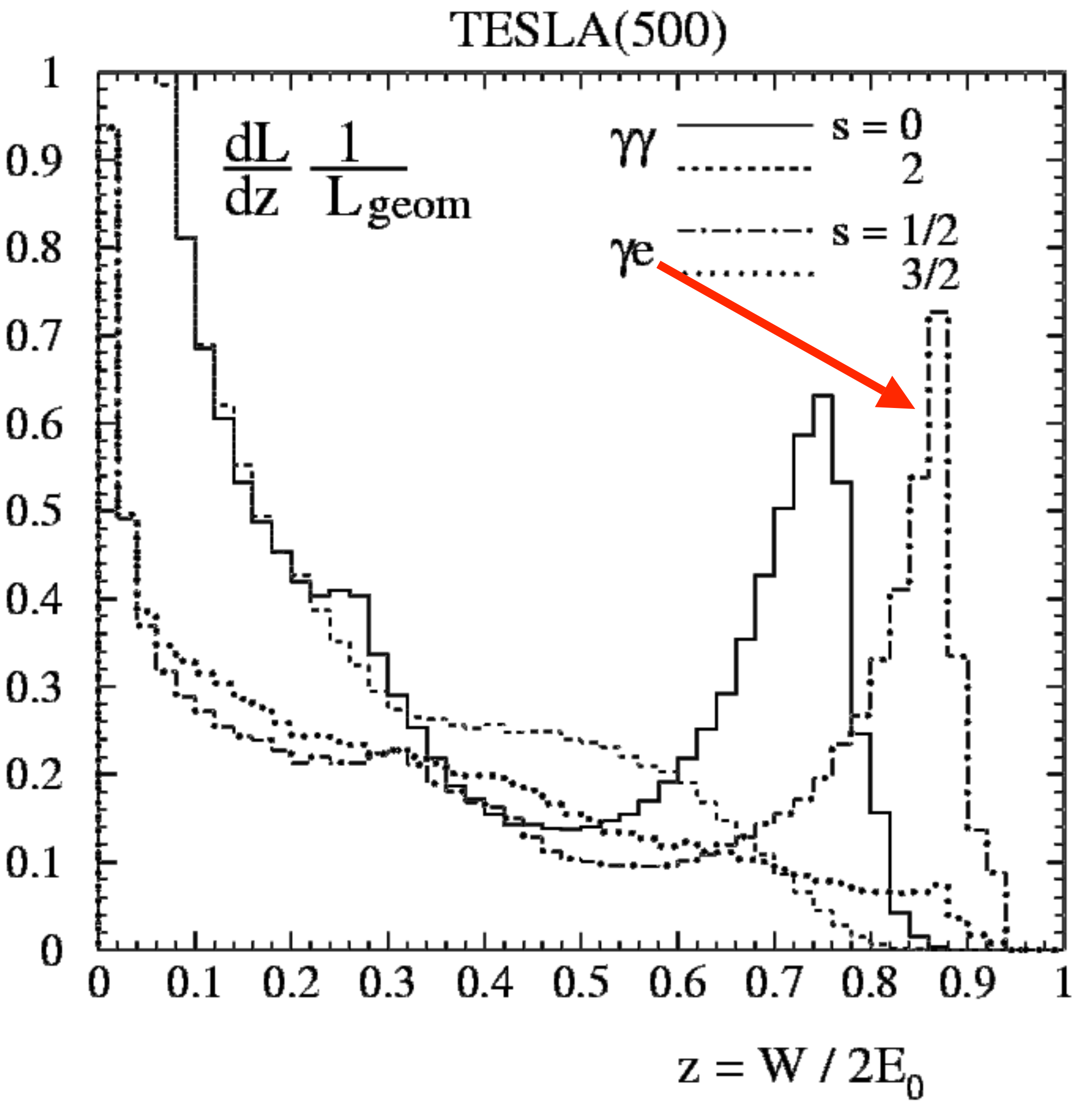
High degree of polarization in the peak



	P_c	$2\lambda_e$
a	-1	1
b	-1	0
c	-1	-1
d	0	1



γγ and eγ luminosities



Not all electrons converted

⇒A γγ collider gives also γe luminosity

Luminosity

$L_{\gamma\gamma} \approx 0.2\ L_{e+e-}$

(but could be larger)

Degree of linear polarization

If the laser light has linear polarization then the high energy photons are polarised in the same direction

$$\langle l_\gamma \rangle = \frac{2r^2\ P_l}{(1-y)^{-1} + 1 - y - 4r(1-r) - 2\lambda_e P_c x r (2-y)(2r-1)}\ .$$

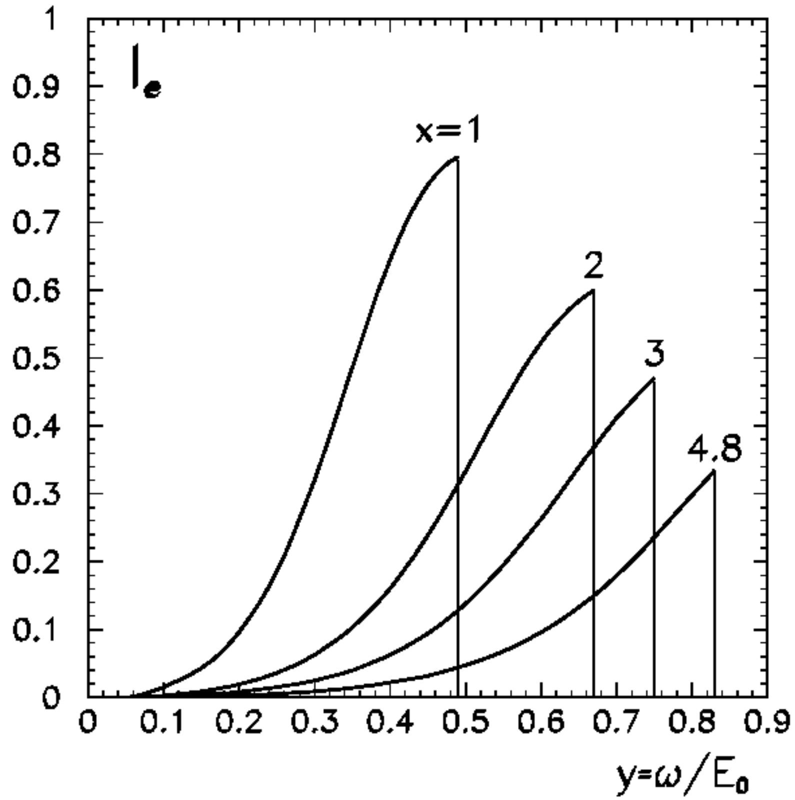
At $y = y_m$ the degree of linear polarization is

$$l_\gamma = \frac{2}{1 + x + (1+x)^{-1}}$$

l_γ	x
0.334	4.8
0.6	2
0.8	1

Sensitivity goes as l_γ^2

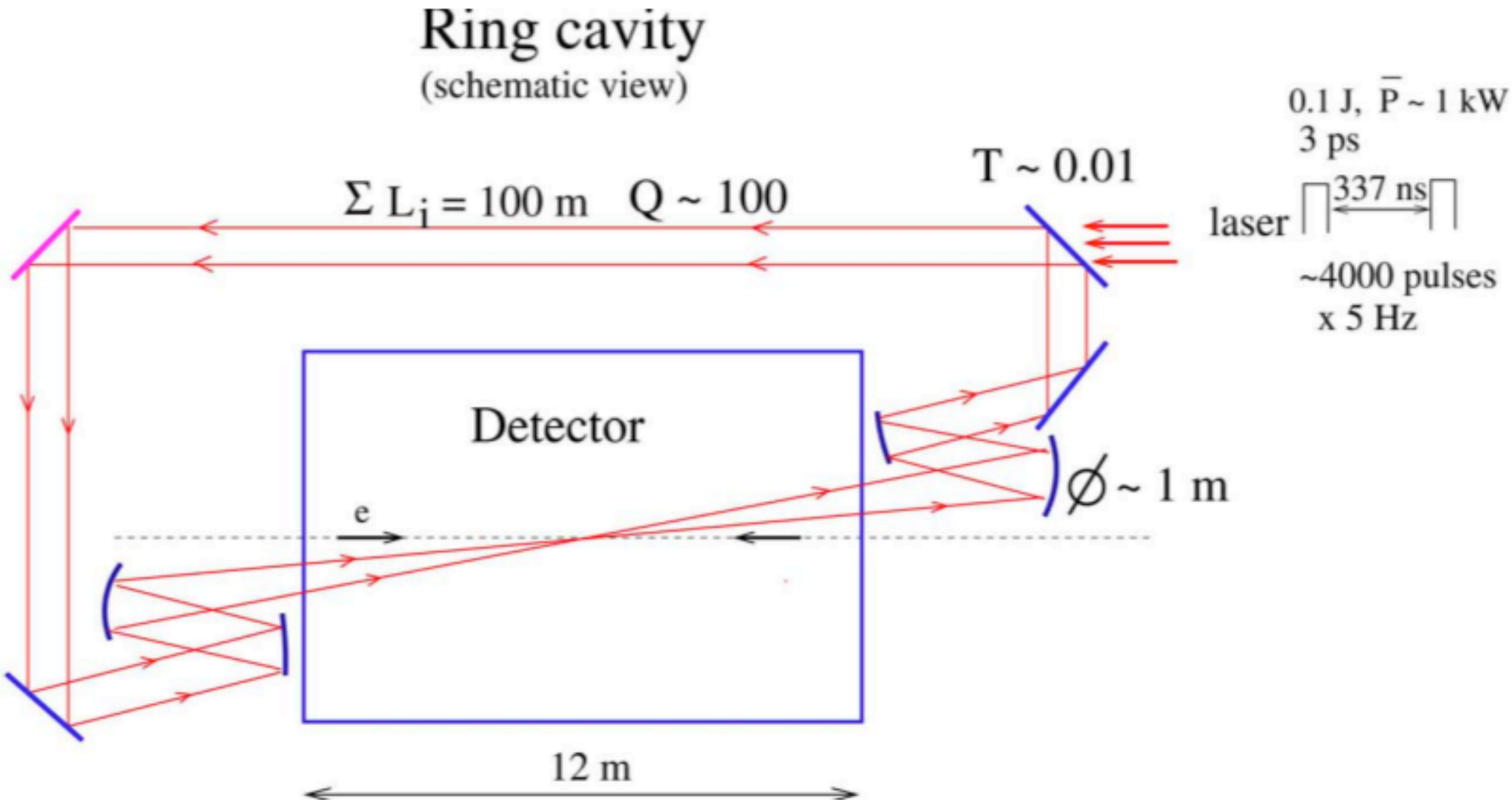
⇒ 3 time more signal at x=2 comp. X=4.8



Important for CP measurements of e.g the Higgs Boson

Interaction Region and Detector

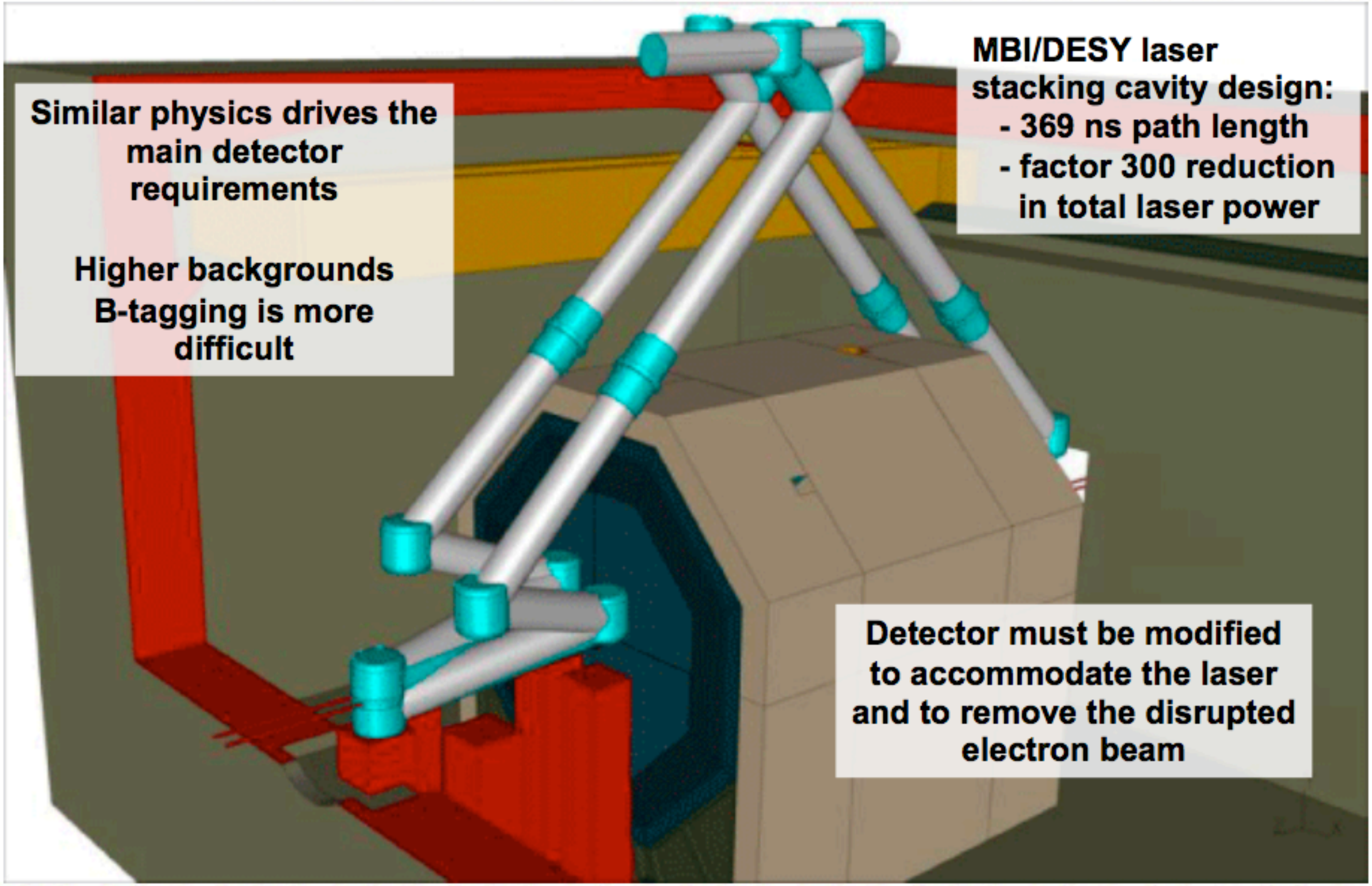
Lasers & Optical Cavity



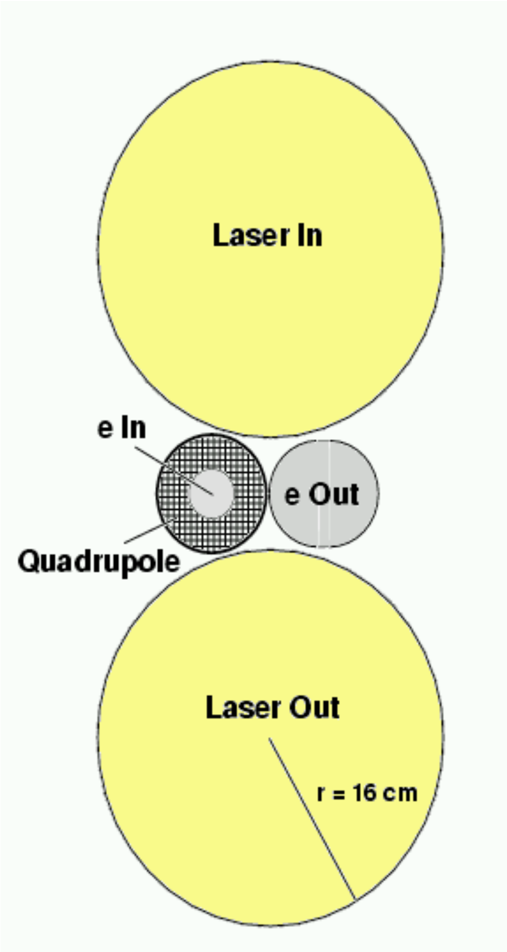
Use lasers with 0.1J Flash energy/bx, ~ 1 ps flash, recycle ~ 200-300 times

⇒ Technically feasible today !

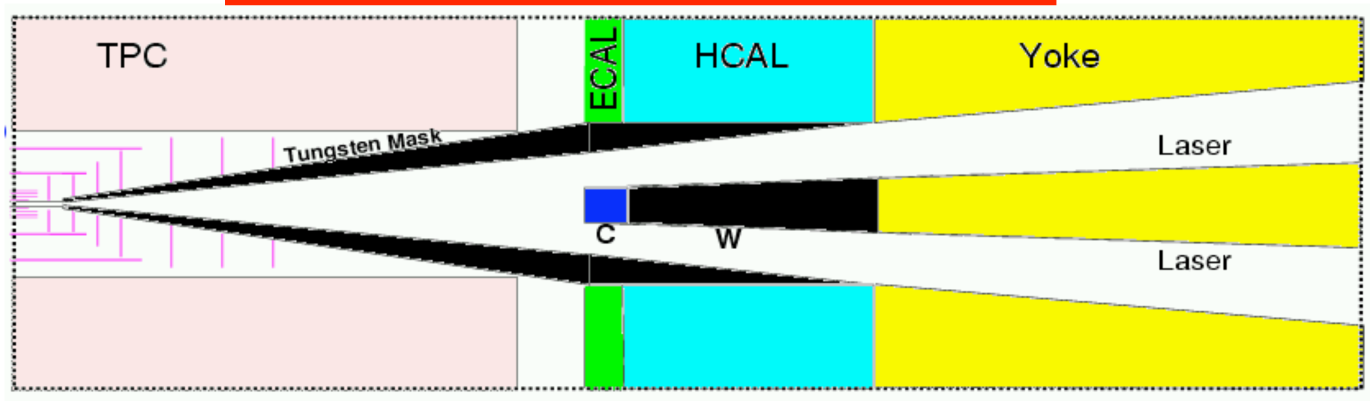
Photon Linear Collider



Interaction region



Mask and laser optical paths

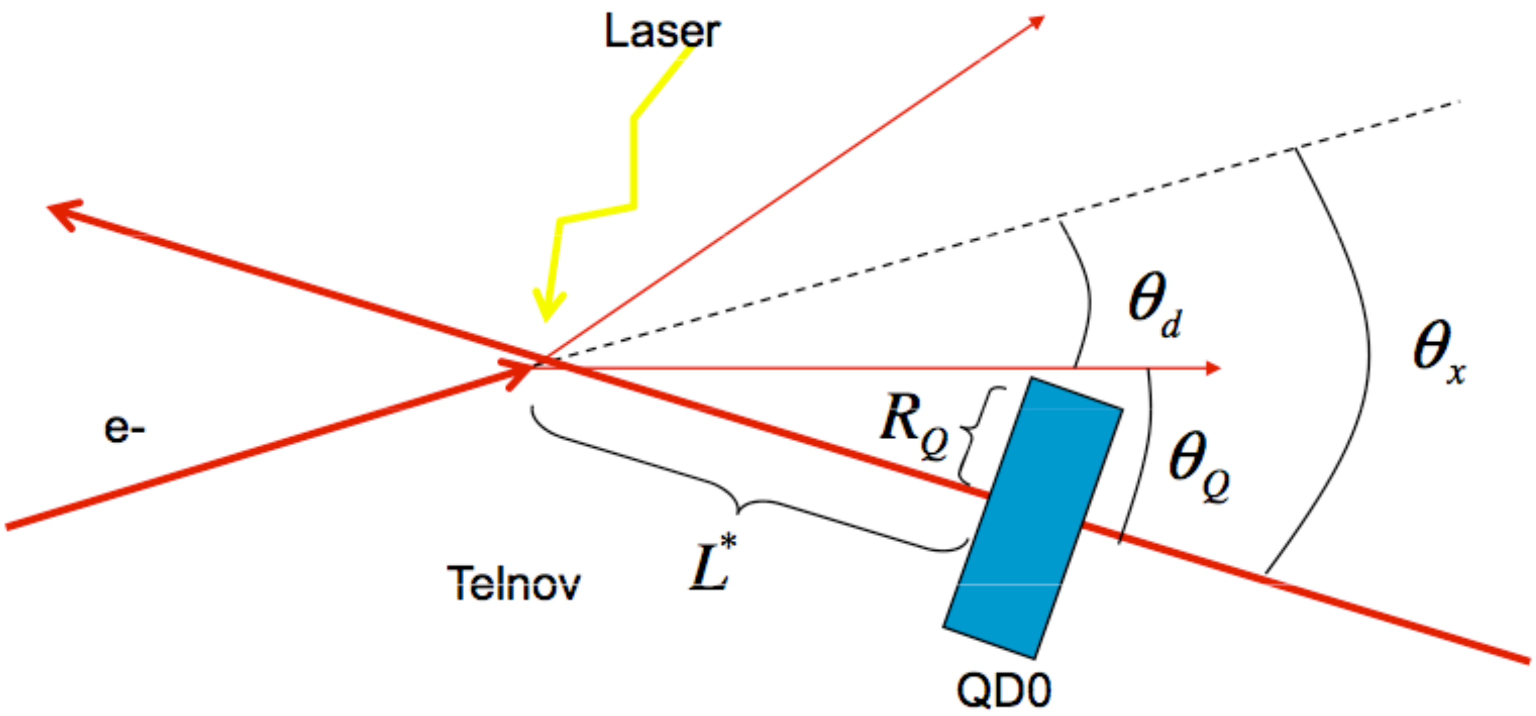


Under control

Backgrounds

- Low energy electrons
- Incoherent e+e- pairs
- $\gamma\gamma\rightarrow$hadrons (overlaid events)
- X-rays
- Neutron background

The Photon Linear collider must have a 25 mr crossing angle



T. Takahashi

- Physical overlap between the extraction line and the final focus quad sets the minimum crossing angle

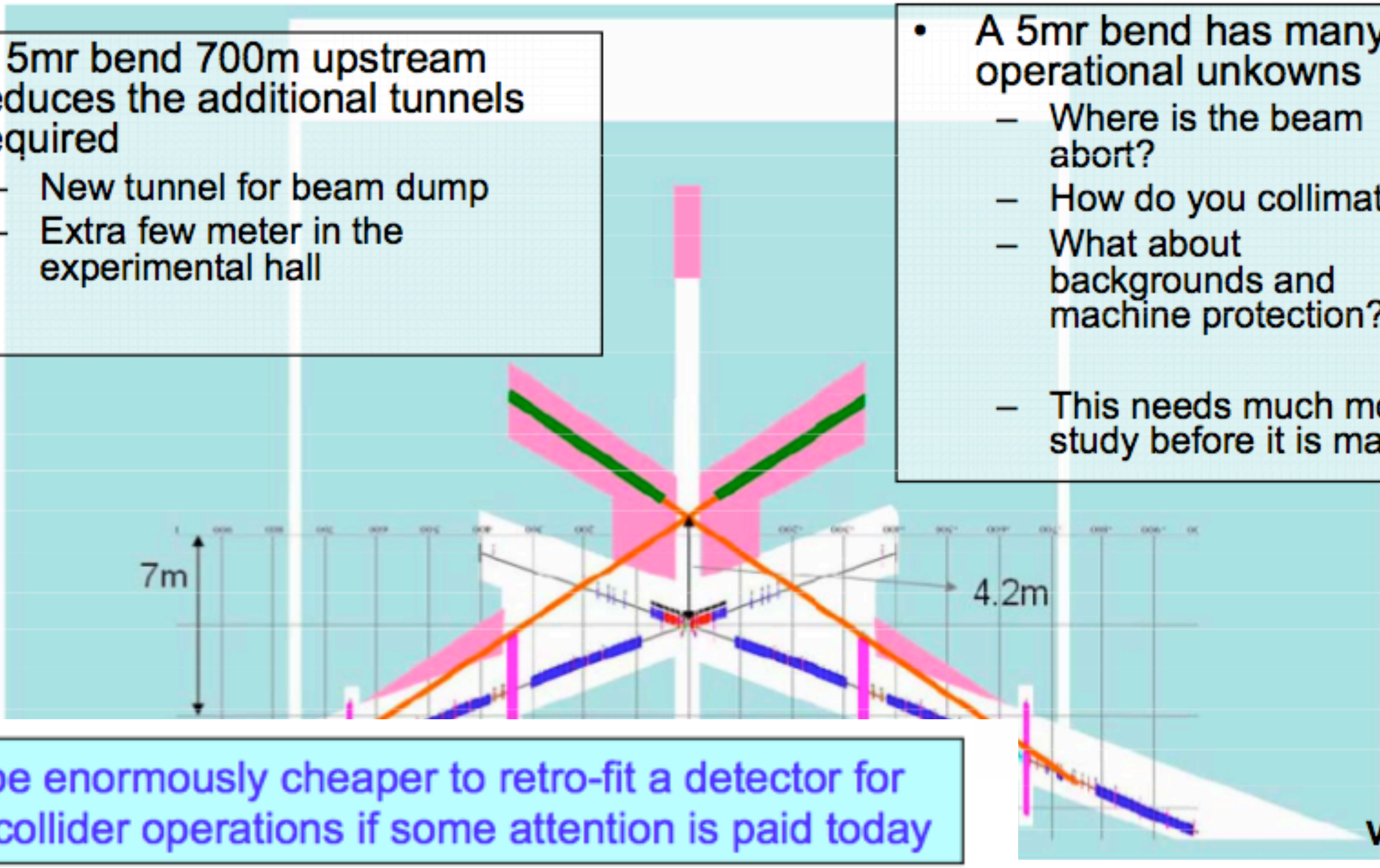
Bend at 700m has cheaper conventional facilities but has operational issues

14mr => 25mr

A.Seryi, LCWS06

- A 5mr bend 700m upstream reduces the additional tunnels required
  - New tunnel for beam dump
  - Extra few meter in the experimental hall

- A 5mr bend has many operational unkowns
  - Where is the beam abort?
  - How do you collimate?
  - What about backgrounds and machine protection?
  - This needs much more study before it is mature



It will be enormously cheaper to retro-fit a detector for photon collider operations if some attention is paid today

V. Telnov

Physics Processes

QCD

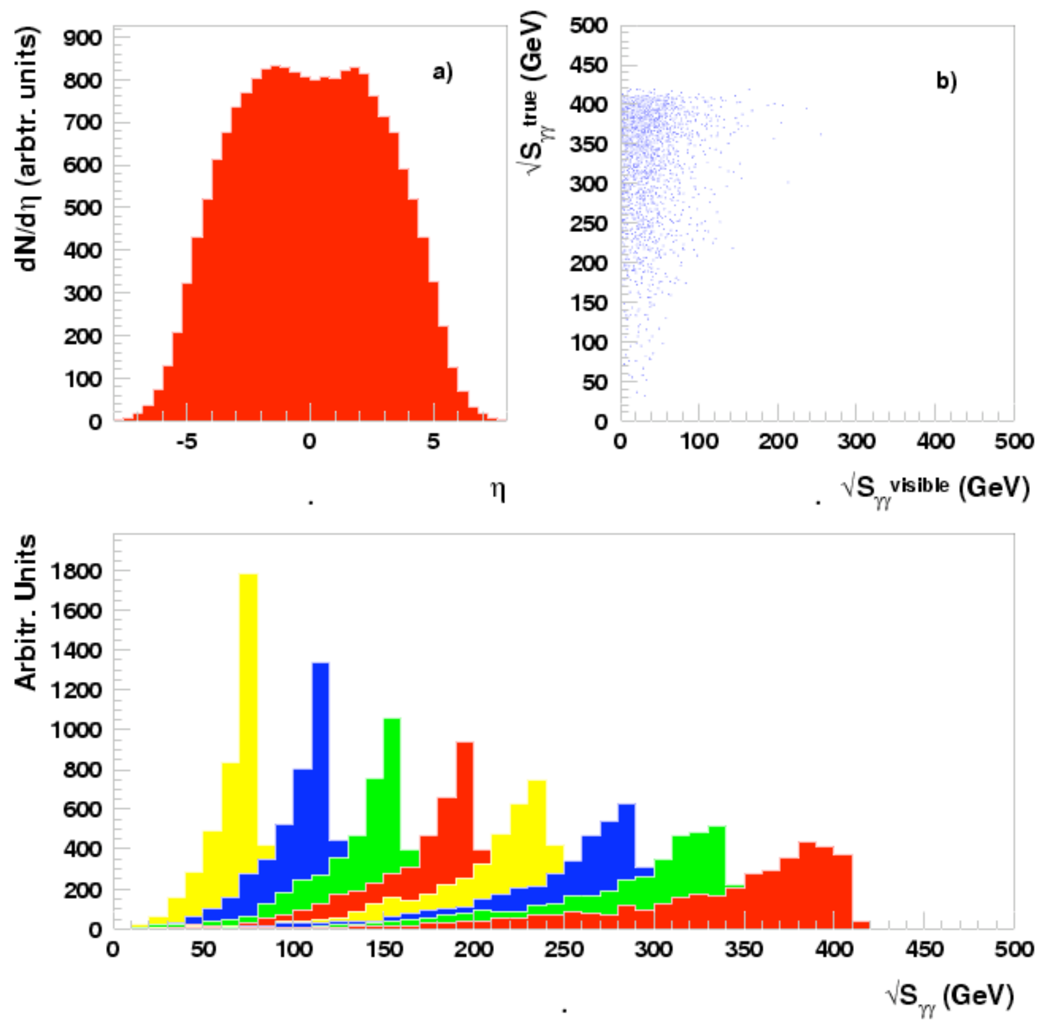
Higgs

EW

SUSY

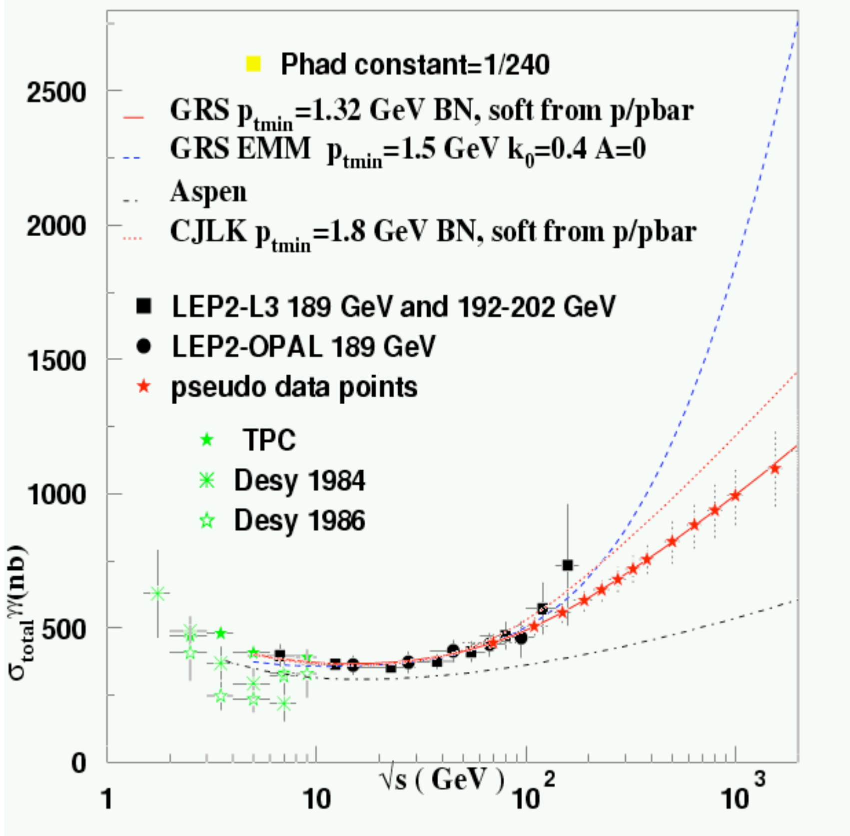
Alternatives

Total Cross Section



Fixed $x = 4.8 \longrightarrow$ change laser energy

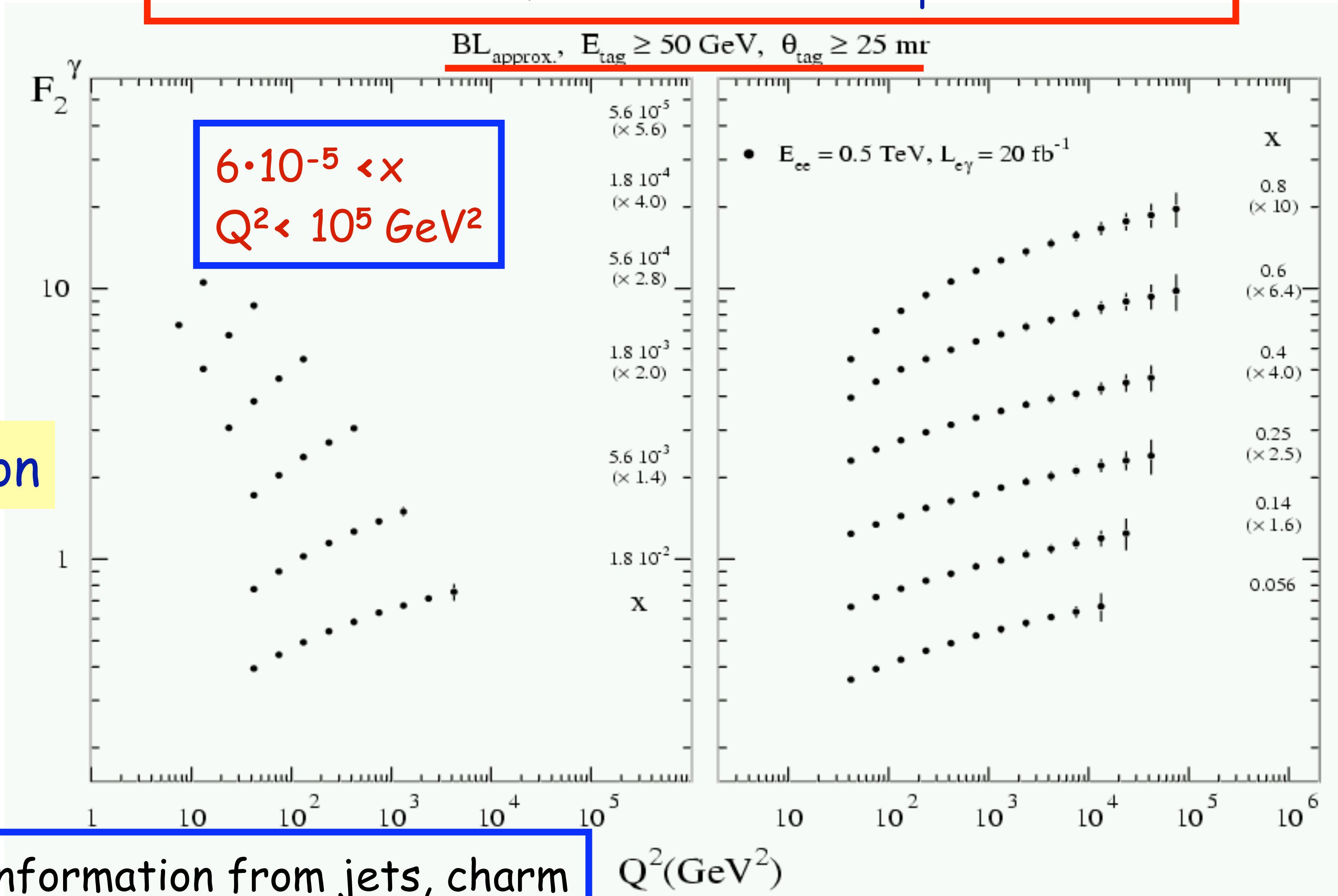
Pancheri, Grau, Godbole, ADR



Detector level study:
Can measure $\sigma(\gamma\gamma)_{tot}$ to 7-15%
at several energies

QCD

Photon structure function reach at a photon collider



$6 \cdot 10^{-5} < x$

$Q^2 < 10^5$ GeV^2

Vogt & ADR

$e\gamma$ option

Also information from jets, charm

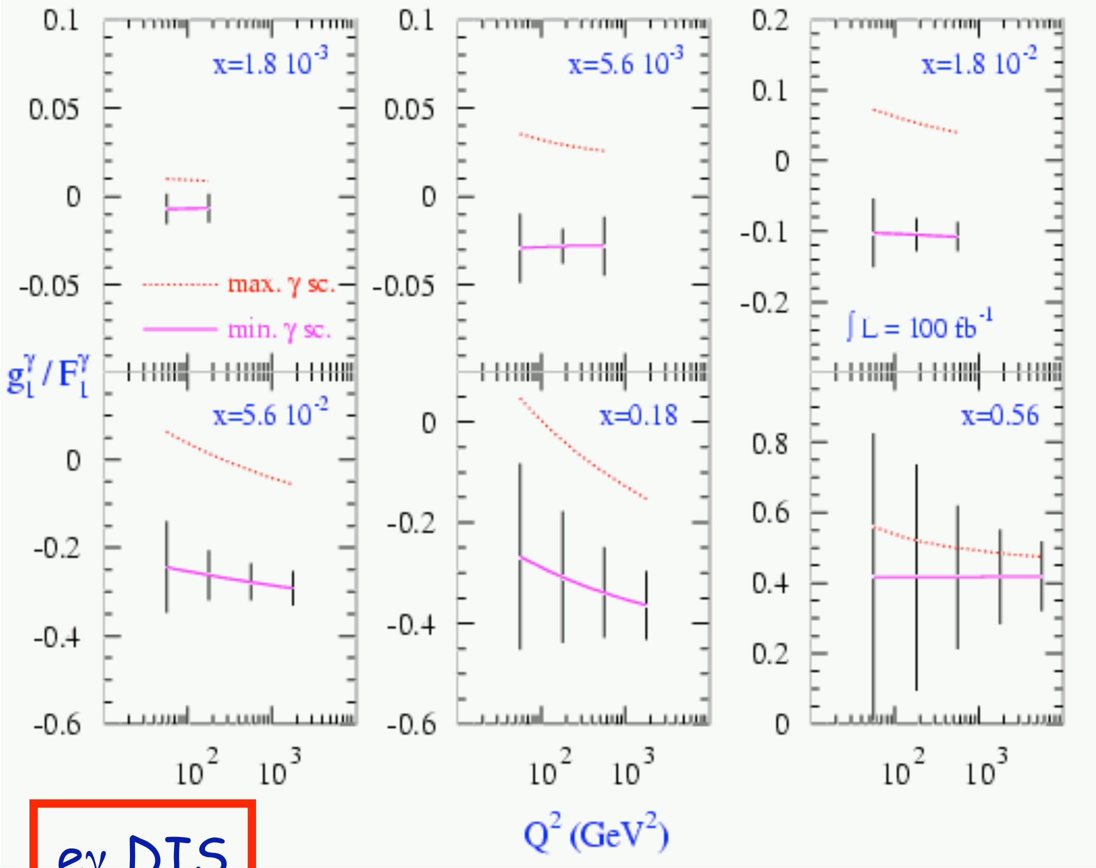
QCD

Unique: the polarised structure of the photon
Use of polarised beams in e+e- or γγ/eγ

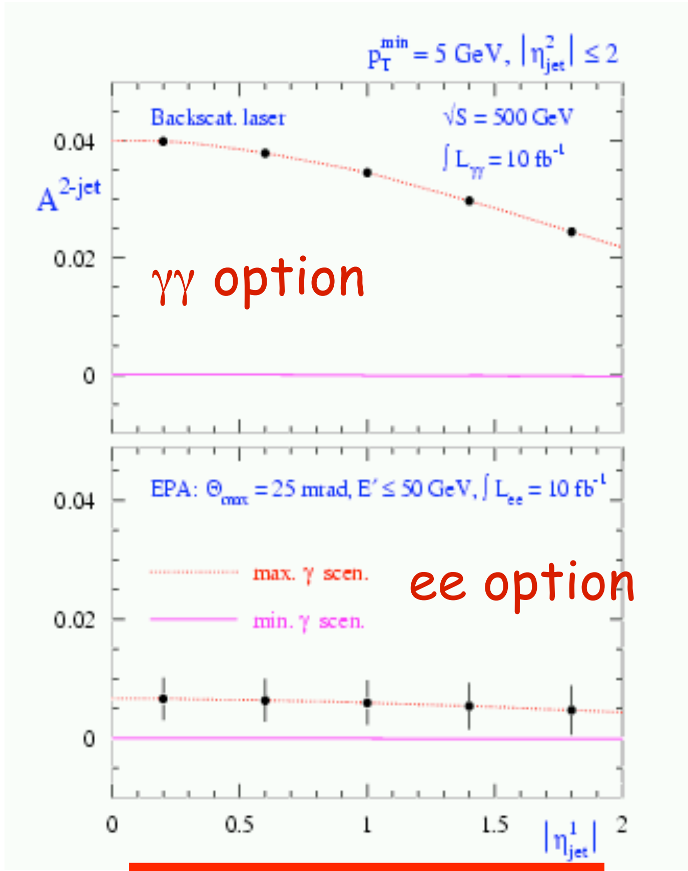
Stratmann and Vogelsang

eγ option

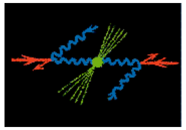
$$g_1^\gamma(x,Q^2) = \frac{1}{2}\Sigma_i e_i^2 \Delta q_i$$



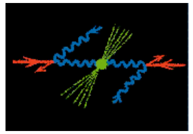
eγ DIS



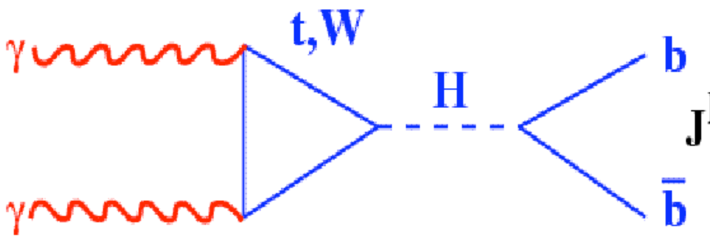
Jet asymmetries



Higgs



Production Mechanism for Neutral Higgs Bosons



Landau-Yang

$J^{PC}=0^{-+}, 0^{++}, 2^{++}$

Heralded as THE key measurement for the gamma-gamma option

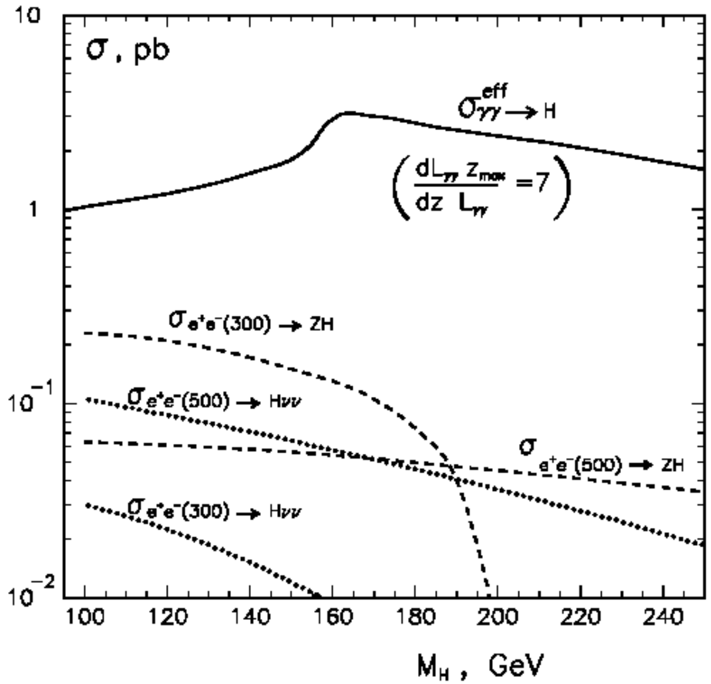
Higgs produced in the s-channel

Enters only at the loop level

Mainly sensitive to tH and WH couplings

All charged particles (also new, unseen ones) contribute! These will affect the partial width $\Gamma(\gamma\gamma)$

Cross section larger than in e+e-



LEP/Tevatron data: SM Higgs M_H > 114 GeV and M_H< ~200 GeV (95 %CL)

Higgs

Suppose Higgs found a the LHC: what would you like to know

- Mass
- Spin & parity
- CP properties/Violation?
- How does it decay
  - Confirm Yukawa-like pattern (allow for up/down differences)
  - Can observe rare decays? ($H \to \gamma\gamma, \gamma Z, \mu\mu$)?
  - Confirm relations between fermion couplings and gauge couplings
  - Unexpected decay modes? Signs/confirmation of new physics?
  - What is the total width?
  - Are there new production modes ($\gamma\gamma \to \gamma h$ or Zh)?
  - Higgs self coupling… etc,..

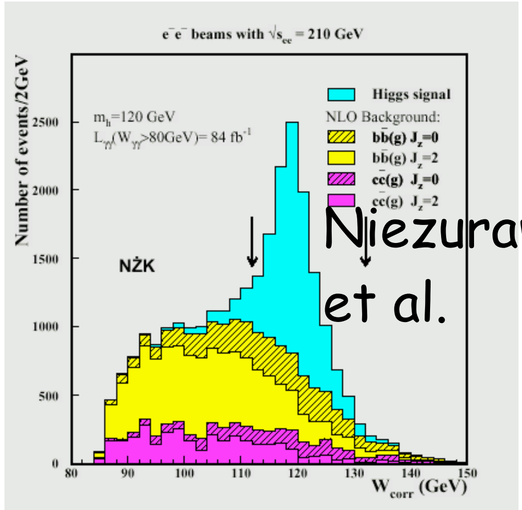
The discovery of an unexpected CP nature of the H would be very exciting

H→bb study

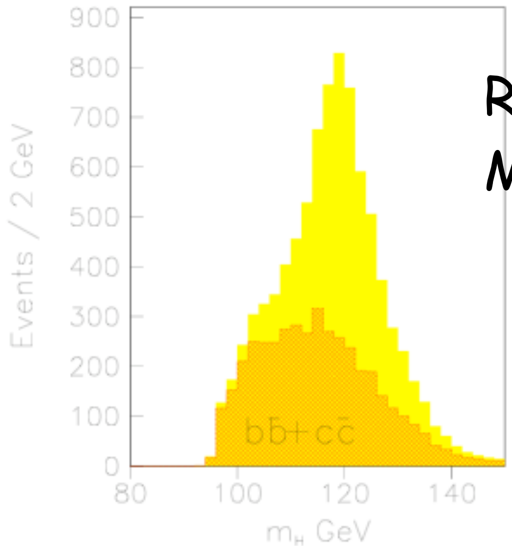
- Detailed analyses for Light SM Higgs
  - Realistic photon spectra: Tune collider energy such that maximum of the peak is at the Higgs mass
  - NLO QCD backgrounds (Jikia)
  - B-tagging via a neural network
  - Mass corrected for neutrinos
  - Add overlap QCD events (~1 per B.C.)
- Typical Cuts:
  - Durham jet algo. (y_{cut} = 0.02); θ_{min} = 450 mrad
  - |Pz|/Evis <0.15

$$\frac{\Delta\sigma(\gamma\gamma \to h \to b\bar{b})}{\sigma(\gamma\gamma \to h \to b\bar{b})} = \frac{\Delta\left[\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})\right]}{\left[\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})\right]} = \frac{\sqrt{N_{obs}}}{N_{obs} - N_{bkgd}}.$$

Several analyses



Niezurawski et al.

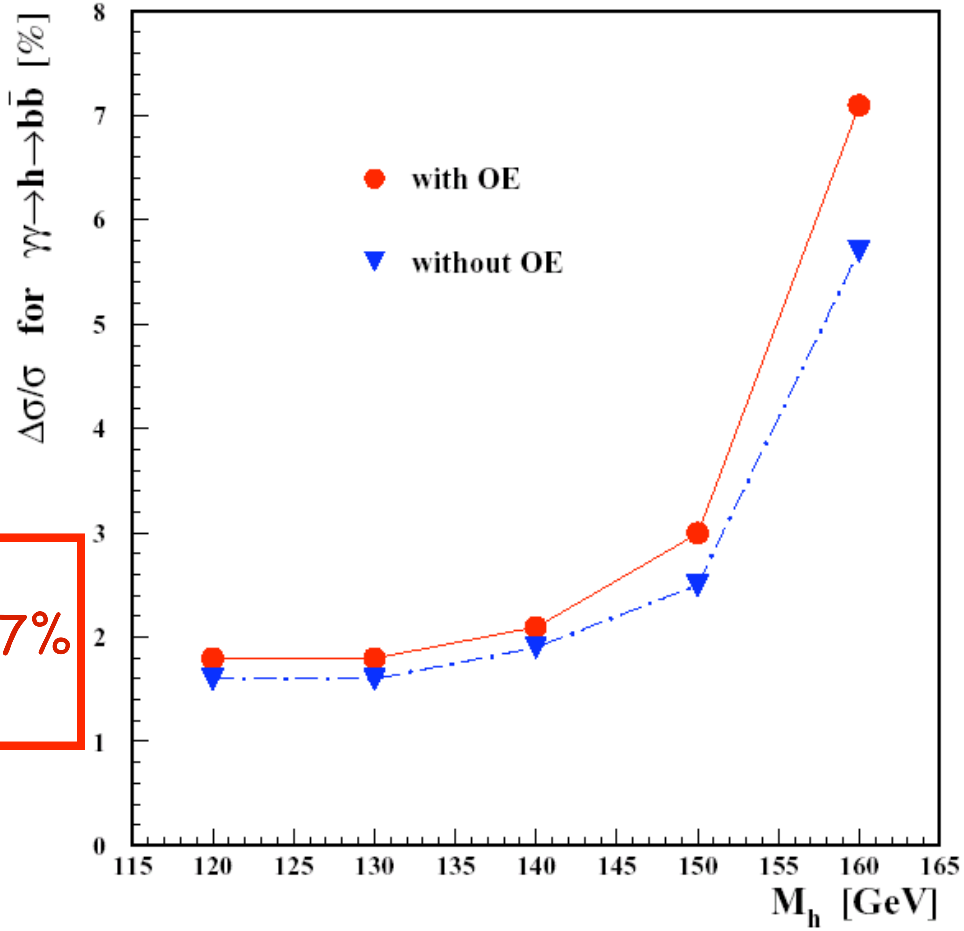


Rosca Moenig

H→bb study

Measurement of Δσ/σ

$$\frac{\Delta[\Gamma(h\to\gamma\gamma)\mathrm{BR}(h\to b\bar{b})]}{[\Gamma(h\to\gamma\gamma)\mathrm{BR}(h\to b\bar{b})]} \approx 1.8\%\text{-}7\%$$



Br(H→bb) in e+e- known to better than 2%

arXiv:0705.1259 ⇒ 2-3%

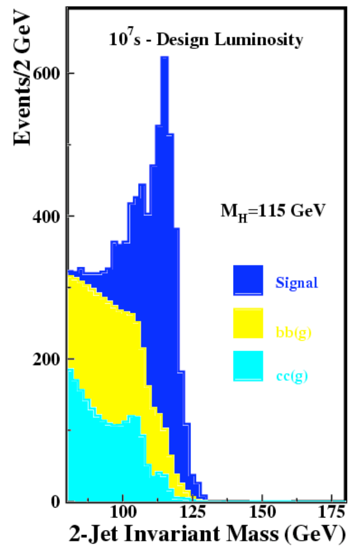
OE: overlap events
Low energy ~ 1 extra events
High energy ~ 2 extra events

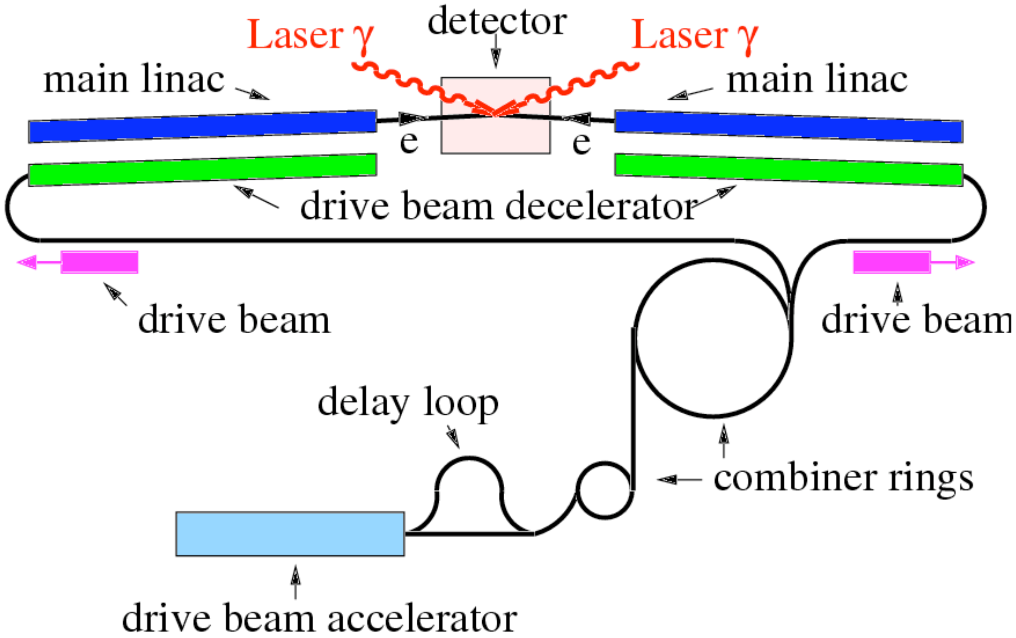
CLICHE

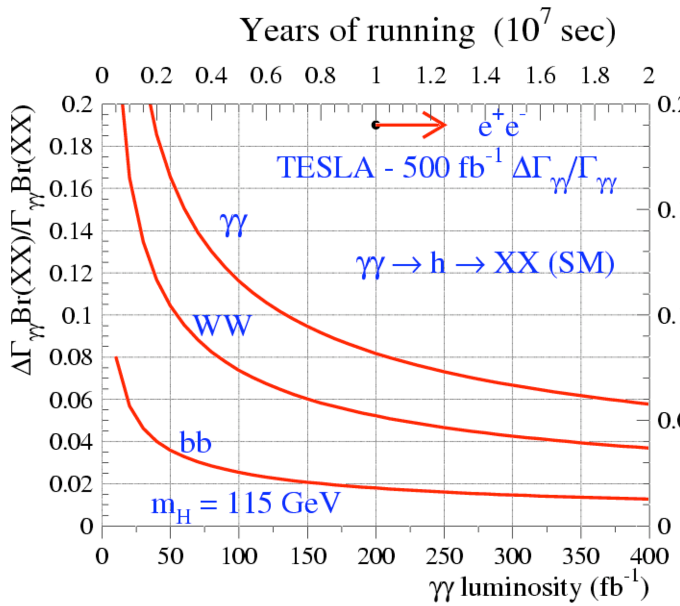
D. Asner, ADR, et al., hep-ex/0111056

CLICHÉ: CLIC Higgs Experiment

- Possible demonstration project for CLIC after CTF3 (ends 2009-2010)
- Uses only 2 CLIC modules (5%)
- Measure Higgs & more

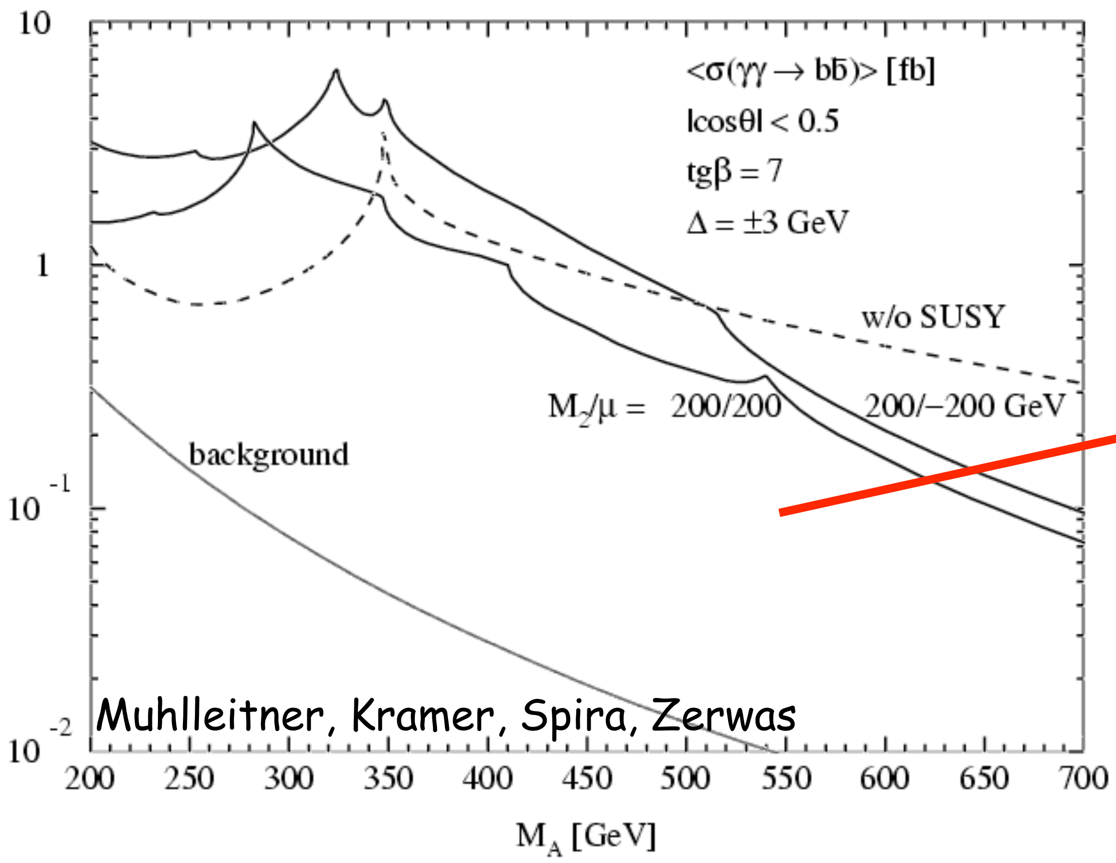


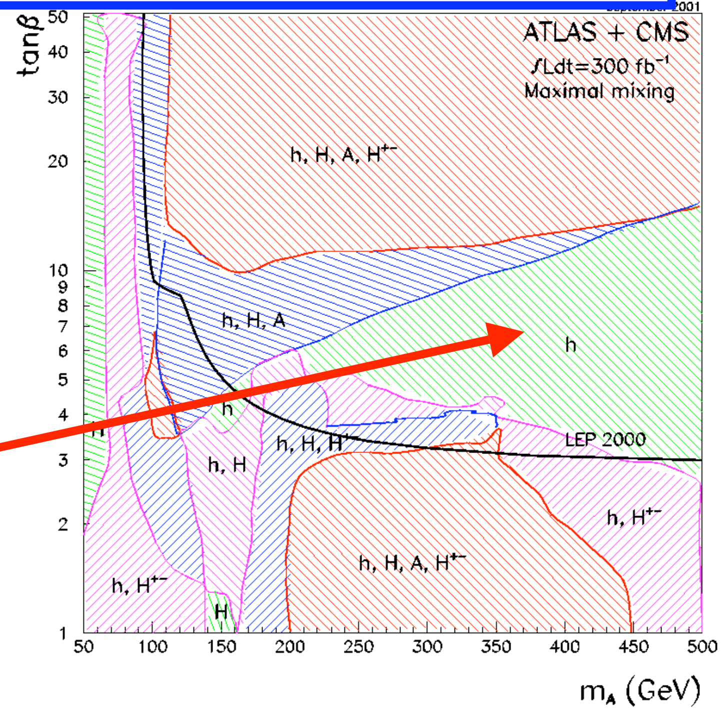




MSSM Higgs: H,A

Minimal Supersymmetric SM: 5 Higgses: h,H (CP even), A (CP odd) and $H^{\pm}$





Can a photon collider close the LHC wedge?

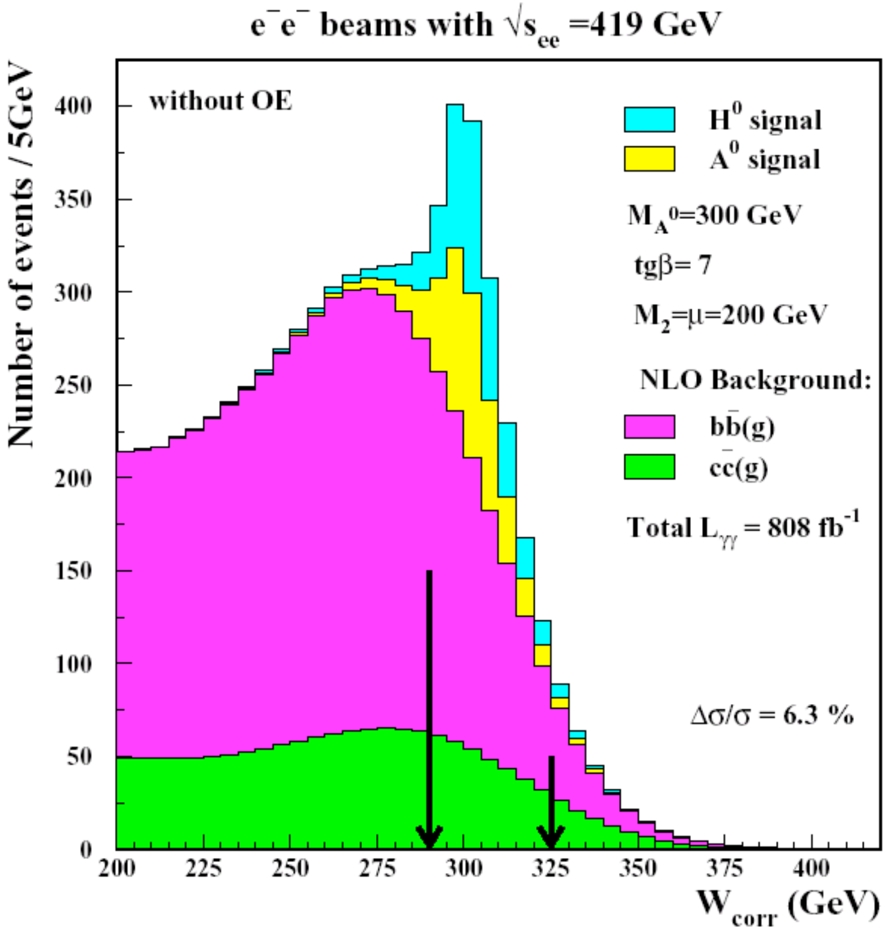
e+e- collider: H,A produced in pairs, hence M_A reach is $\sqrt{s_{ee}}/2$

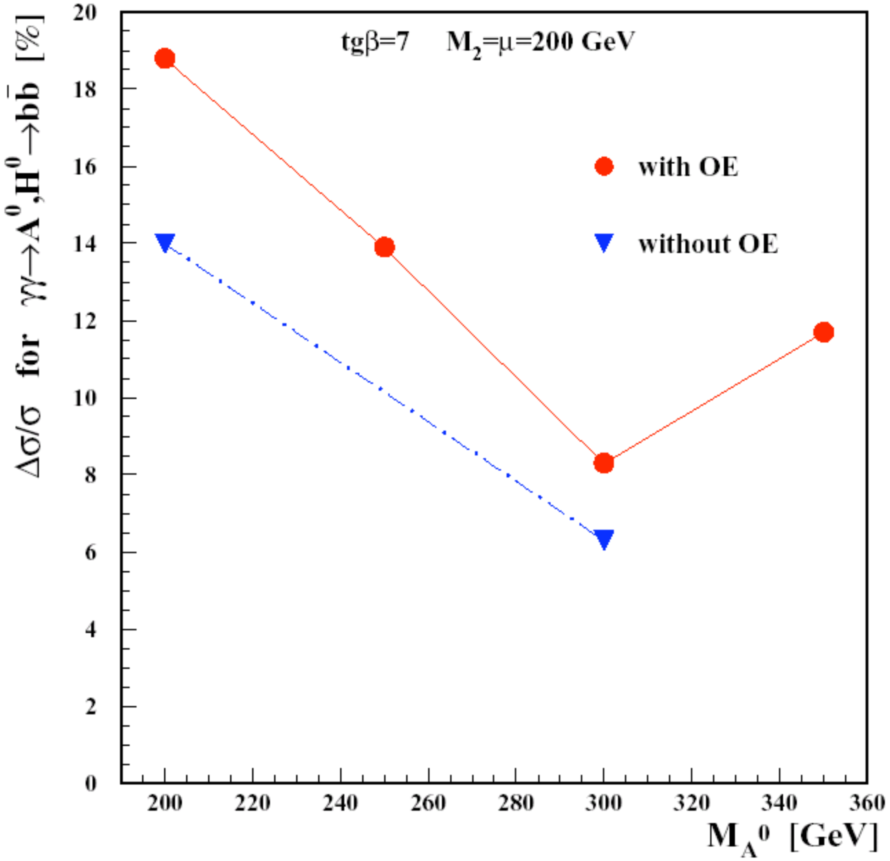
$\gamma\gamma$ collider: s-channel production, hence M_A reach is $0.8\cdot\sqrt{s_{ee}}$

H,A→bb Study

M_A = 200,250,300,350 tanβ =7

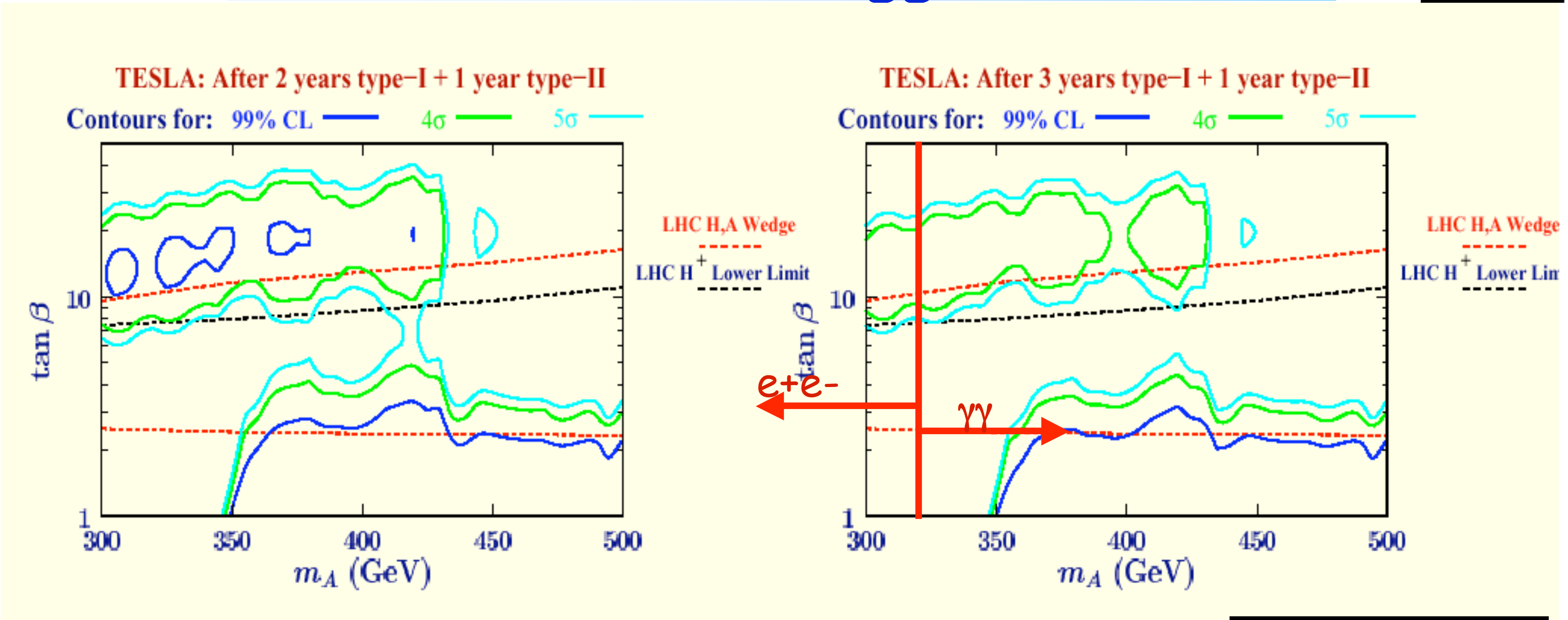
H,A degenerate





Measurement of Δσ/σ to 10-20% (1 year running)

MSSM H/A Higgs Reach



Study for
a e+e- collider
at 630 GeV

US study D.Asner/J.Gunion (LCWS02)

- Extends e+e- reach
- Need few years to close the LHC wedge

Linear polarized beams

If $\vec{\epsilon}_1$ and $\vec{\epsilon}_2$ are the photon polarization vectors (which are perpendicular to the beam), then

$\vec{\epsilon}_i$ are parallel $\longrightarrow$ produce CP-even only → H

$\vec{\epsilon}_i$ are perpendicular $\longrightarrow$ produce CP-odd only → A

Define an asymmetry

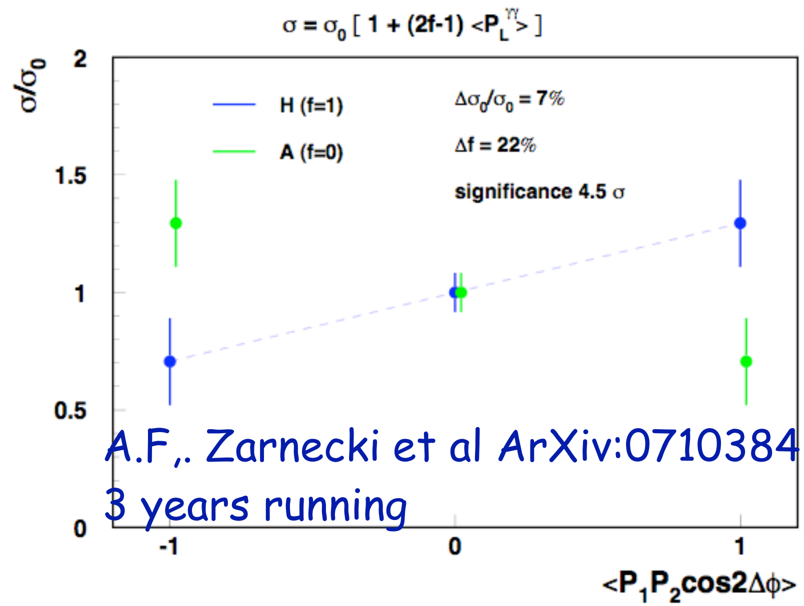
$$A \equiv \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$

After taking backgrounds and realistic polarizat

$$\frac{\delta CP}{CP} = \frac{\delta A}{A} = 0.11$$

after one year.

The CP-even nature of the Higgs boson could b level.



A.F,. Zarnecki et al ArXiv:0710384
3 years running

Linear polarization to produced either H or A (or mixture)

Next-to-MSSM Study

Going beyond the simplest model e.g. NMSSM:

⇒7 Higgs particles: 3 CP even (h1,h2,h3), 2CP odd (a1,a2) and 2 charged

Point Number	1	2	3	4	5	6
Bare Parameters						
λ	0.2872	0.2124	0.3373	0.3340	0.4744	0.5212
κ	0.5332	0.5647	0.5204	0.0574	0.0844	0.0010
$\tan\beta$	2.5	3.5	5.5	2.5	2.5	2.5
$\mu_{\rm eff}$ (GeV)	200	200	200	200	200	200
A_λ (GeV)	100	0	50	500	500	500
A_κ (GeV)	0	0	0	0	0	0
CP-even Higgs Boson Masses and Couplings						
m_{h_1} (GeV)	115	119	123	76	85	51
Relative gg Production Rate	0.97	0.99	0.99	0.00	0.01	0.08
$BR(h_1 \to b\bar{b})$	0.02	0.01	0.01	0.91	0.91	0.00
$BR(h_1 \to \tau^+\tau^-)$	0.00	0.00	0.00	0.08	0.08	0.00
$BR(h_1 \to a_1 a_1)$	0.98	0.99	0.98	0.00	0.00	1.00
m_{h_2} (GeV)	516	626	594	118	124	130
Relative gg Production Rate	0.18	0.09	0.01	0.98	0.99	0.90
$BR(h_2 \to b\bar{b})$	0.01	0.04	0.04	0.02	0.01	0.00
$BR(h_2 \to \tau^+\tau^-)$	0.00	0.01	0.00	0.00	0.00	0.00
$BR(h_2 \to a_1 a_1)$	0.04	0.02	0.83	0.97	0.98	0.96
m_{h_3} (GeV)	745	1064	653	553	554	535
CP-odd Higgs Boson Masses and Couplings						
m_{a_1} (GeV)	56	7	35	41	59	7
Relative gg Production Rate	0.01	0.03	0.05	0.01	0.01	0.05
$BR(a_1 \to b\bar{b})$	0.92	0.00	0.93	0.92	0.92	0.00
$BR(a_1 \to \tau^+\tau^-)$	0.08	0.94	0.07	0.07	0.08	0.90
m_{a_2} (GeV)	528	639	643	560	563	547
Charged Higgs Mass (GeV)	528	640	643	561	559	539
Most Visible Process No.	2 (h_1)	2 (h_1)	8 (h_1)	2 (h_2)	8 (h_2)	8 (h_2)
Significance at 300 fb^{-1}	0.48	0.26	0.55	0.62	0.53	0.16

1) $gg \to h/a \to \gamma\gamma$;
2) associated Wh/a or $t\bar{t}h/a$ production with $\gamma\gamma\ell^\pm$ in the final state;
3) associated $t\bar{t}h/a$ production with $h/a \to b\bar{b}$;
4) associated $b\bar{b}h/a$ production with $h/a \to \tau^+\tau^-$;
5) $gg \to h \to ZZ^{(*)} \to 4$ leptons;
6) $gg \to h \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$;
7) $WW \to h \to \tau^+\tau^-$;
8) $WW \to h \to WW^{(*)}$.

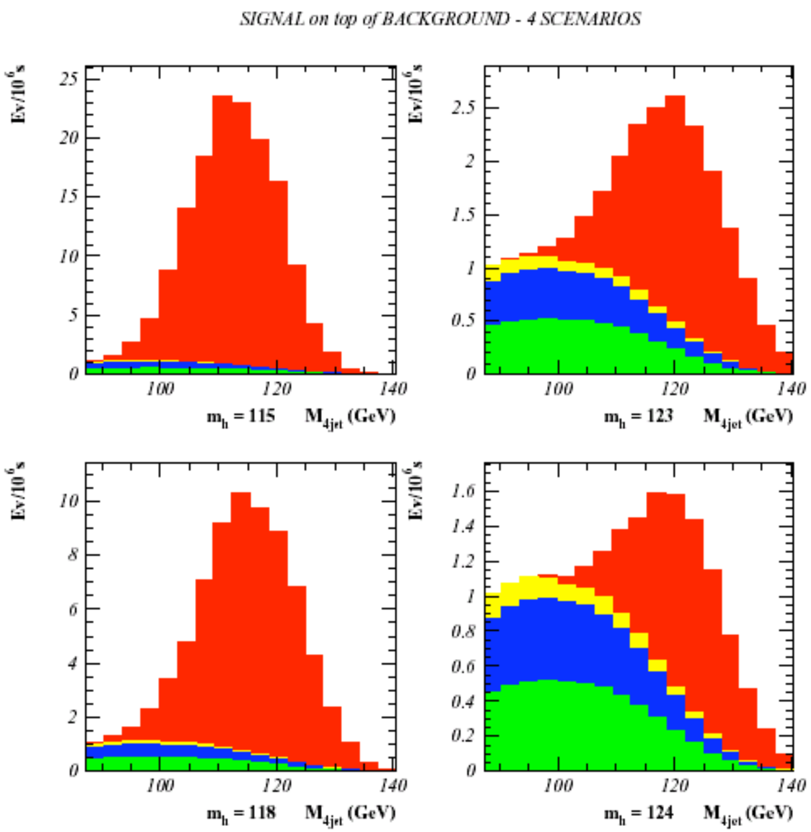
Some of these Higgses cannot be seen at the LHC, if decay $h \to a_1 a_1 \to bbbb$ large

Low significance at the highest lumi

NMSSM at a PC

Scenario	m_h (GeV)	m_a (GeV)	$\sigma(\gamma\gamma \to h)$ (fb)	Acceptance	No. events / $10^6 s$
(1)	115	56	112	0.26	139
(3)	123	35	9.1	0.33	14.7
(4)	118	41	46	0.28	63
(5)	124	59	6.0	0.24	7.1

Asner et al.

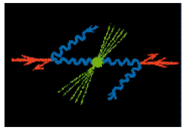


Signals and background for
Four of the difficult LHC scenarios

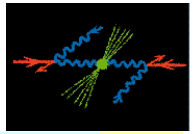
Study $h \to a_1 a_1 \to bbbb$

Clear signals confirming/discovering
these low mass Higgses

Note e+e- $\to$Zh should see these
without problems



Higgs Wrap-up

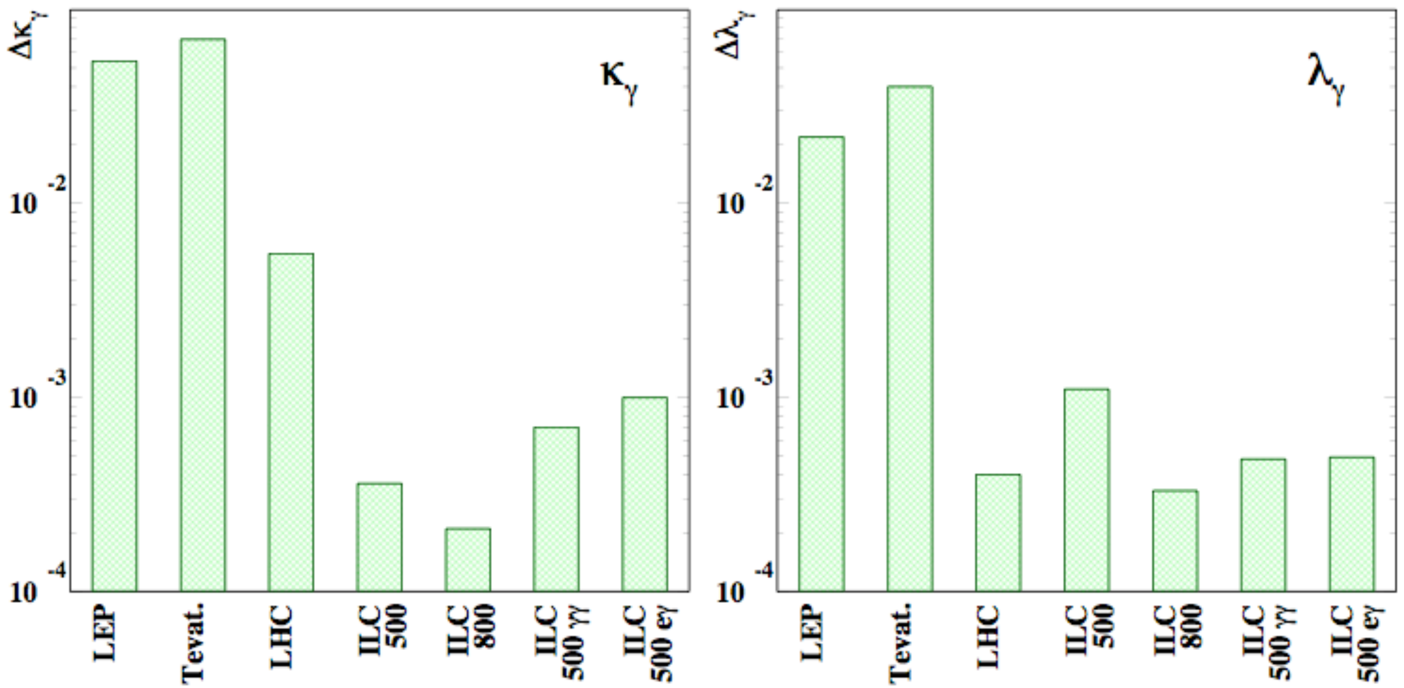


See M. Krawczyk talk

- Mass
  - ~ 100 MeV/ 1 year running — $\sim e^+e^-$
- Partial width $\Gamma(\gamma\gamma)$
  - 2-7% in bb channel (needs H→ bb from e+e-) — 15% in e+e-
  - 3-10% in WW,ZZ channel (needs BR from e+e-) — ~e+e-
- Determination of the phase of the $\gamma\gamma \rightarrow$ Higgs amplitude — Unique?
  - 3-10% in WW,ZZ channel
- CP analysis: many posibilities — More handles than in e+e-
  - h→ZZ,WW angular analysis
  - h →tt interference with QED background, lepton charge asymmetries — Clean tests!
  - Linear polarization
- Rare decay modes
  - $H\rightarrow\gamma\gamma$!, $H\rightarrow\gamma Z$? — Difficult in e+e-
- Discovery reach for H,A
  - Up to 0.8 $\sqrt{s_{ee}}$ for $\sqrt{s_{ee}} \sim 800$ GeV — e+e-:$\sqrt{s}/2$- 50 GeV

Anomalous $WW\gamma$ couplings

K. Moenig et al. arXiv:physics/0601204



Sensitivity to anomalous $WW\gamma$ for different machines

Anomalous couplings

A. Manteuffel

Anomalous Couplings in $\gamma\gamma \to WW$

Gauge and gauge-Higgs anomalous couplings

$$\mathscr{L}_2 = \frac{1}{v^2}\Big(h_W O_W + h_{\tilde{W}} O_{\tilde{W}} + h_{\varphi W} O_{\varphi W} + h_{\varphi \tilde{W}} O_{\varphi \tilde{W}} + h_{\varphi B} O_{\varphi B} + h_{\varphi \tilde{B}} O_{\varphi \tilde{B}} + h_{WB} O_{WB} + h_{\tilde{W}B} O_{\tilde{W}B} + h_\varphi^{(1)} O_\varphi^{(1)} + h_\varphi^{(3)} O_\varphi^{(3)}\Big),$$

$$O_W = \epsilon_{ijk}\, W_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu}, \qquad O_{\tilde{W}} = \epsilon_{ijk}\, \tilde{W}_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu},$$

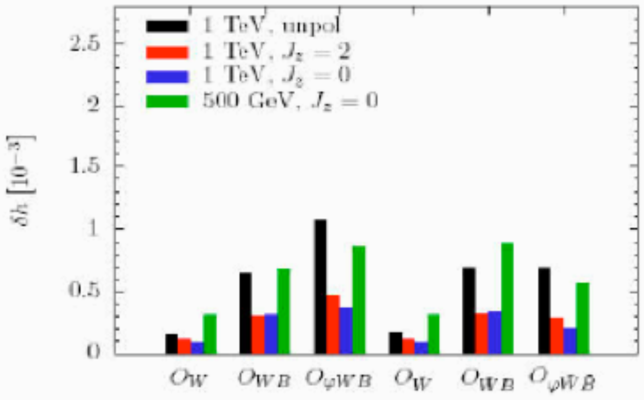
$$O_{\varphi W} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) W_{\mu\nu}^i W^{i\,\mu\nu}, \qquad O_{\varphi \tilde{W}} = \left(\varphi^\dagger \varphi\right) \tilde{W}_{\mu\nu}^i W^{i\,\mu\nu},$$

$$O_{\varphi B} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) B_{\mu\nu} B^{\mu\nu}, \qquad O_{\varphi \tilde{B}} = \left(\varphi^\dagger \varphi\right) \tilde{B}_{\mu\nu} B^{\mu\nu},$$

$$O_{WB} = \left(\varphi^\dagger \tau^i \varphi\right) W_{\mu\nu}^i B^{\mu\nu}, \qquad O_{\tilde{W}B} = \left(\varphi^\dagger \tau^i \varphi\right) \tilde{W}_{\mu\nu}^i B^{\mu\nu},$$

$$O_\varphi^{(1)} = \left(\varphi^\dagger \varphi\right) (\mathcal{D}_\mu \varphi)^\dagger (\mathcal{D}^\mu \varphi), \qquad O_\varphi^{(3)} = \left(\varphi^\dagger \mathcal{D}_\mu \varphi\right)^\dagger \left(\varphi^\dagger \mathcal{D}^\mu \varphi\right)$$

Sensitivity with polarized beams



Comparison of Sensitivities

	LEP & SLD (*) $h_i\ [10^{-3}]$	$ee \to WW$ (*) $\delta h_i\ [10^{-3}]$	$\gamma\gamma \to WW$ unpolarised $\delta h_i\ [10^{-3}]$	$\gamma\gamma \to WW$ $J_z = 0$ $\delta h_i\ [10^{-3}]$
h_W	-69 ± 39	0.3	0.6	0.3
h_{WB}	-0.06 ± 0.79	0.3	1.6	0.7
$h_{\varphi WB}$	×	×	2.2	0.9
$h_\varphi^{(3)}$	-1.15 ± 2.39	36.4	×	×
$h_{\tilde{W}}$	68 ± 81	0.3	0.7	0.3
$h_{\tilde{W}B}$	33 ± 84	2.2	2.0	0.9
$h_{\varphi \tilde{W}B}$	×	×	2.0	0.6

Anomalous Top Couplings

Search for deviations in the top couplings

eγ gives good Sensitivity (1 year running)
Boos et al.

	f_2^L	f_2^R
Tevatron ($\Delta_{\text{sys.}} \sim 10\%$)	$-0.18 \div +0.55$	$-0.24 \div +0.25$
LHC ($\Delta_{\text{sys.}} \sim 5\%$)	$-0.052 \div +0.097$	$-0.12 \div +0.13$
e^+e^- ($\sqrt{s_{ee}} = 0.5$ TeV)	$-0.025 \div +0.025$	$-0.2 \div +0.2$
γe ($\sqrt{s_{ee}} = 0.5$ TeV)	$-0.045 \div +0.045$	$-0.045 \div +0.045$
γe ($\sqrt{s_{ee}} = 2$ TeV)	$-0.008 \div +0.008$	$-0.016 \div +0.016$

The γe collider is more than competitive!

f_2^L & f_2^R anomalous terms in the eff. Langrangian, $\propto 1/\Lambda$ (new physics scale)

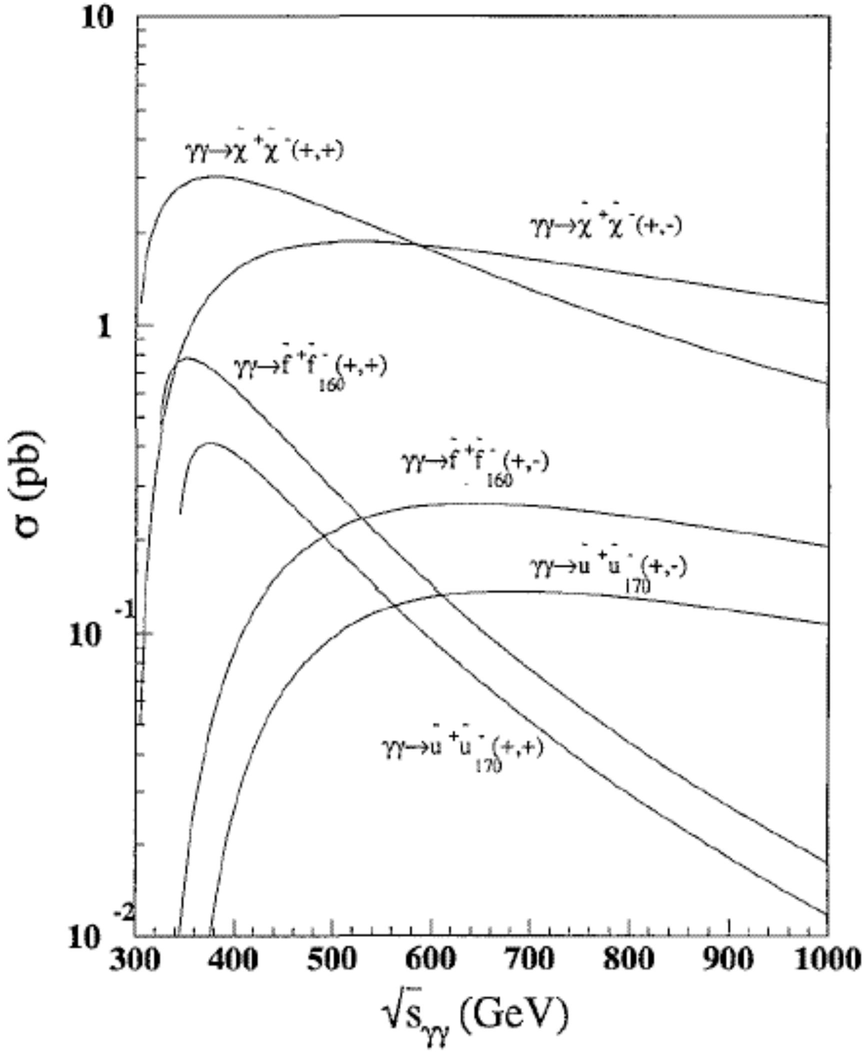
$\gamma\gamma \to tt$
Electric dipole moment
Godbole et al.

Beam energy: 250 GeV. L=20 fb^{-1}. Cut-off angle 30 deg.

No. of events	Charge asymmetry	Limit on dipole Moment
Ideal: 533	-0.031	6.5 X 10^{-17} ecm
Zarnecki: 238	-0.023	1.3 X 10^{-16} ecm

Limits will better by factor 5 for 500 fb^{-1}.

Supersymmetry



Cross sections for SUSY particles at a LC

Note: couplings only to photon

E.g. charginos at 150 GeV

	$\int \mathcal{L}_{th}$ (fb^{-1}/10^7 s)	σ (fb)	Event yield
Spin-0	30	3000	90,000
Spin-2	5	1000	5,000
e^+e^-	160	300	48,000

Two times as many events in $\gamma\gamma$!

Extend reach for sleptons

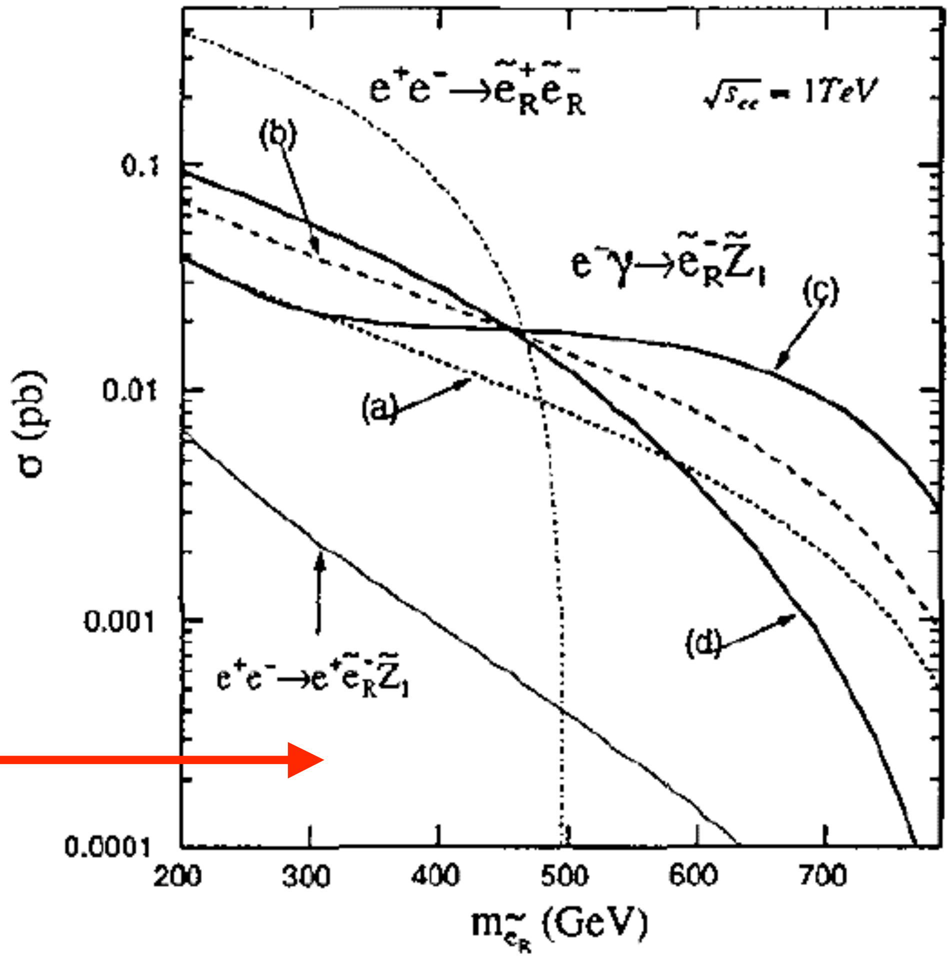
e+e-: reach is √s/2

eγ: reach is 0.8√s-M(LSP)

Can extend the mass range by 100-200 GeV if LSP is light

$$e^-\gamma \to \tilde{e}_{L,R}\chi_1^{(0)} \to e^-\chi^{(0)}\chi^{(0)}$$

M(LSP) = 100 GeV →

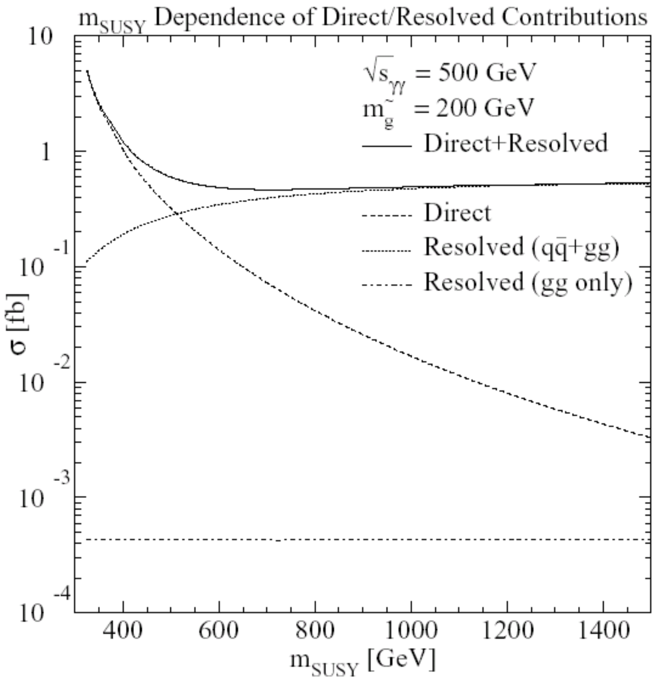


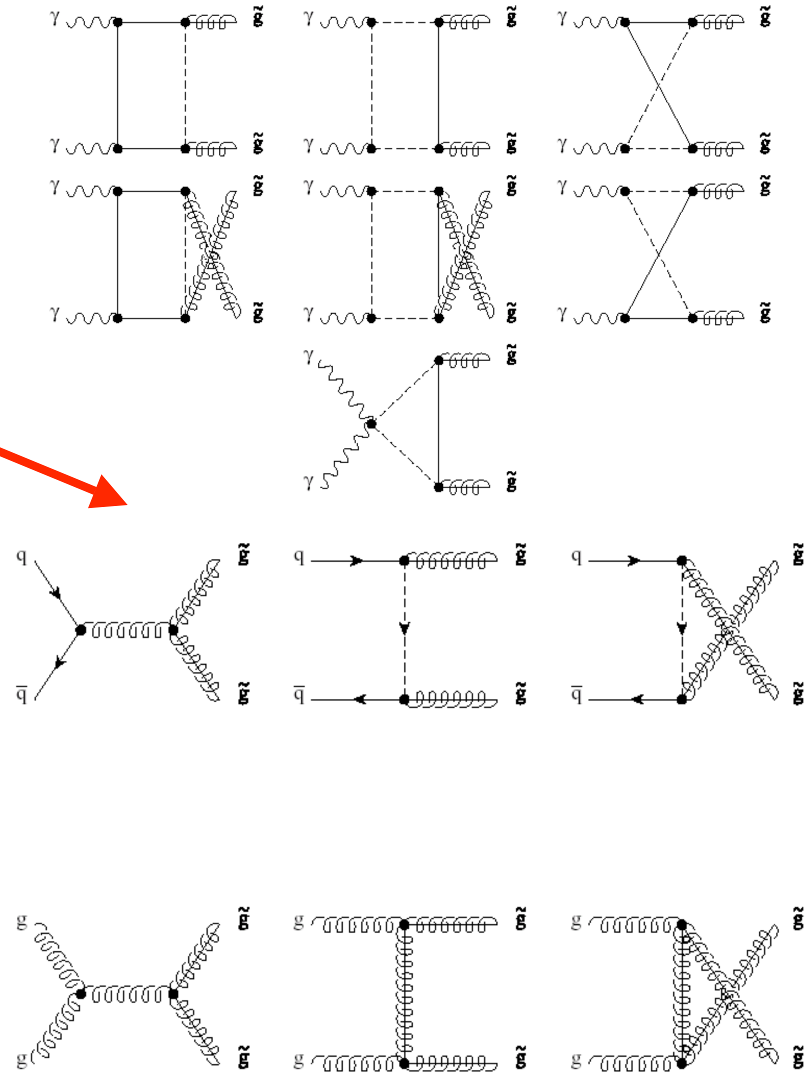
Klasen, Berge

Gluino Production

Berge, Klasen

Gluinos couple only strongly!
Suppressed in e+e- and cannot be measured
Can be produced at
- the loop level in direct $\gamma\gamma$ collisions
- the tree level in resolved $\gamma\gamma$ collisions

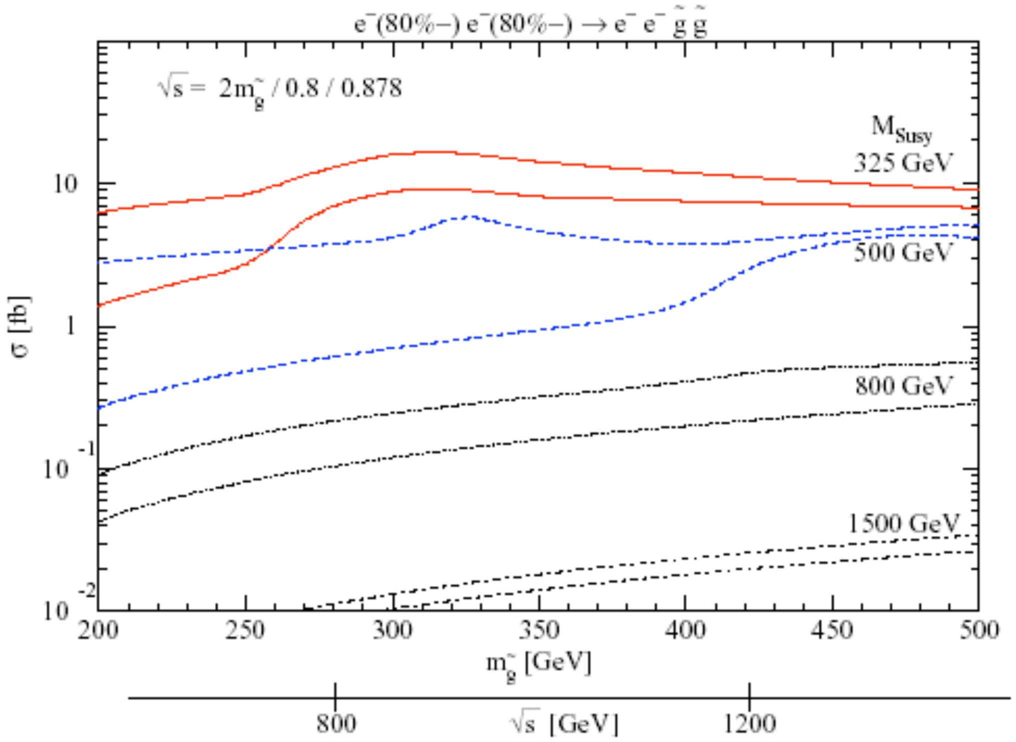




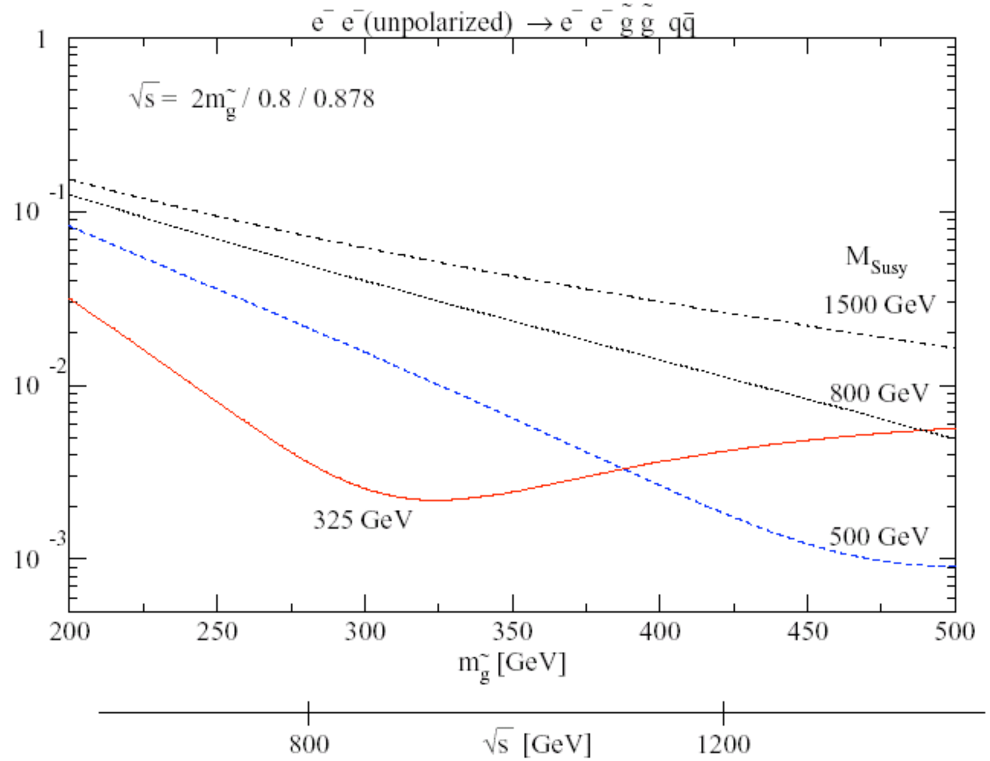
m_{SUSY} = squark mass

Gluino Production

γγ→ Gluinos (Direct)



γγ→ Gluinos (Resolved)



- between 20 events for squarks of 800 GeV and 2000 events per year for light squarks of 325 GeV
- about 20 events per year for heavy squarks (1500 GeV) by resolved contribution

Can PLC add to LHC?

Determination of Tanβ

Methods to determine $\tan\beta$ for large values beyond $\tan\beta = 10$

(a) charginos / neutralinos	$\Rightarrow$	$\cos 2\beta$ slope $\sim 1/\tan^3\beta$ insensitive	Choi et al
(b) τ polarization etc	$\Rightarrow$	$\sim 10\%$	Boos et al
(c) bbH/A, H/A widths etc	$\Rightarrow$	LHC/$300 fb^{-1}$: 12 to 4%	Gunion et al
	$\Rightarrow$	LC/$2,000 fb^{-1}$: 5 to 3% at $M_A = 200$GeV	
(d) LHC sim $H/A \to \tau\tau$	$\Rightarrow$	$30 fb^{-1}$ $\sim 20\%$	Kinnunen et al
(e) $\gamma\gamma \to H/A \to b\bar{b}$	$\Rightarrow$	~ 4 to 10% [estimate]	see: Niezurawski et al and Velasco et al

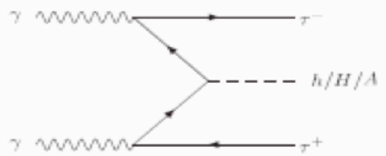
Additional methods strongly required for precision analysis of $\tan\beta$ 2

S.Y.Choi,J.Kalinowski,J.S.Lee, M.M. Muhlleitner, M.Spira,P.M.Zerwas hep-ph/0404119

Tau fusion -> tan beta

New method: Tauon fusion of Higgs $h/H/A/$ at $\gamma\gamma$ collider:

$$\gamma\gamma \to (\tau^+\tau^-)(\tau^+\tau^-) \to \tau^+\tau^- + h/H/A$$



couplings: for large $\tan\beta$

$A\tau\tau = \tan\beta$, $H\tau\tau \simeq \tan\beta$ for A, H heavy

$h\tau\tau \simeq \tan\beta$ A light

Higgs decays: $h/H/A \to bb$ at 90% level $\Rightarrow$ SPS1b

In analysis tan beta 10-50 and mass 100 -500 GeV

Δ $\tan\beta \sim 0.9$-1.3

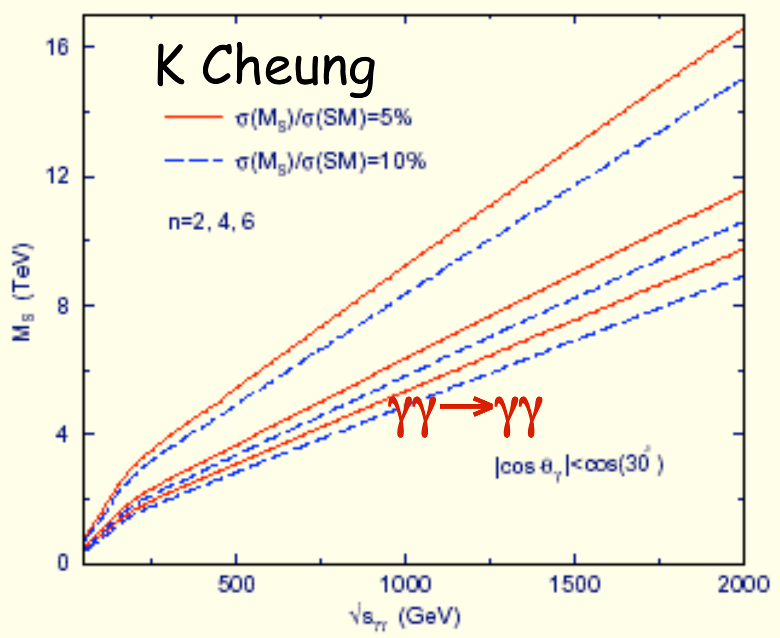
lum 100 (200) fb^{-1} for energy 500 (1000) GeV (background included)

Extra Dimensions

Why is gravity weak?
Has more than 4 dimensions to spread out
Extra dimensions small, μm to TeV^{-1} scale

$\Rightarrow$ Deviations in SM cross sections

ADD: Planck scale in TeV range
Photon collider has a large sensitivity



Reaction	M_S Reach (TeV units) for $L = 100\text{fb}^{-1}$
$e^+e^- \to f\bar{f}$	$6.5\sqrt{s}$
$e^+e^- \to e^+e^-$	$6.2\sqrt{s}$
$e^-e^- \to e^-e^-$	$6.0\sqrt{s}$
$pp \to \ell^+\ell^-$ (LHC)	5.3
$pp \to jj$ (LHC)	9.0
$pp \to \gamma\gamma$ (LHC)	5.4
$\gamma\gamma \to \ell^+\ell^-/t\bar{t}/jj$	$4\sqrt{s}$
$\gamma\gamma \to \gamma\gamma/ZZ$	$4-5\sqrt{s}$
$\gamma\gamma \to W^+W^-$	$11\sqrt{s}$

T.Rizzo

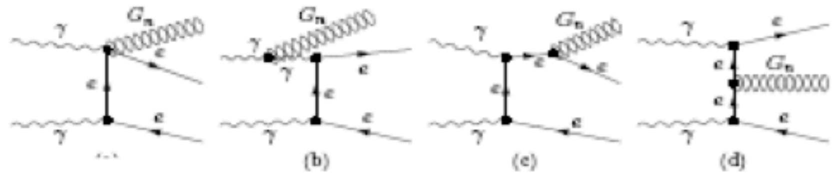
WW production:
-Large statistics
-Many observables

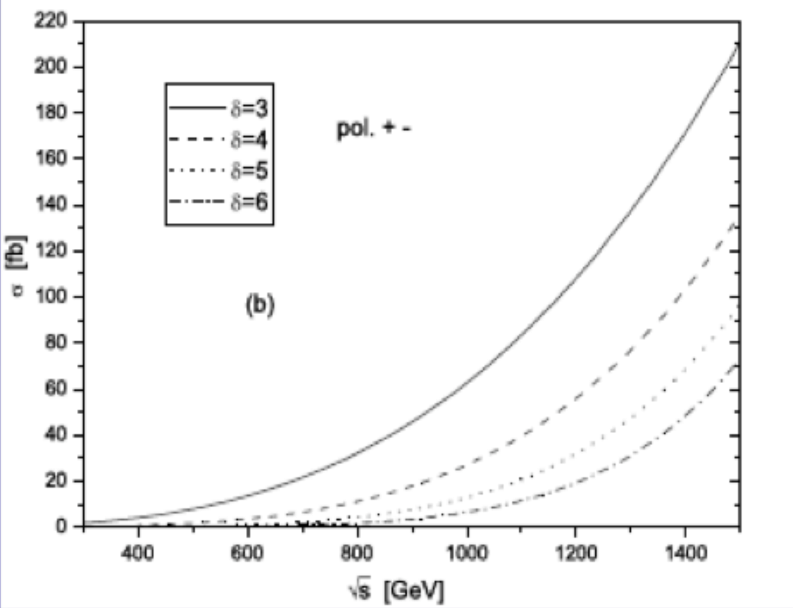
Also studies on Radions in RS-models

Extra Dimensions

Using luminosity measurements process to detect KK graviton in ADD at PLC ; Zhou,Ma,Han,Zhang hep-ph/07081195

- $\gamma\gamma \rightarrow e^+e^-G_n$





For J=2 large cross section

Polarization efficiency

$P_\gamma=(N_+-N_-)/(.+.)$

Fund. scale M_s=1.5 TeV

Extra Dimensions

Signal and background

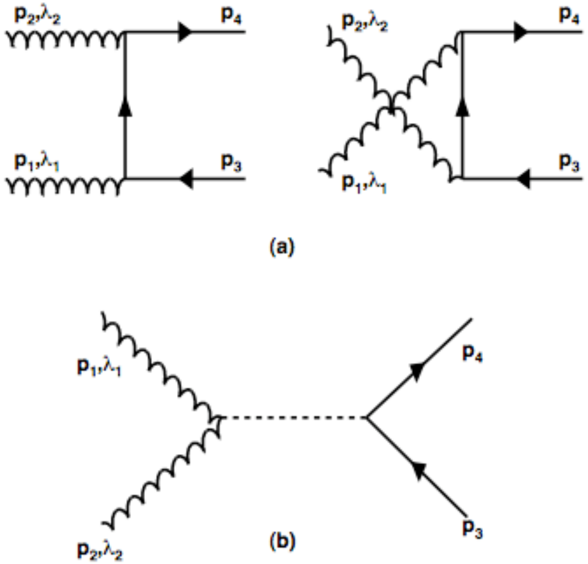
Table 1: Total cross sections for the process $\gamma\gamma \to e^+e^-G_n$, with and without photon polarization. M_S is set to be 1 TeV, the polarization efficiency $P_\gamma = 0.9$, and the cross sections are in fb.

$\sqrt{s}$ [GeV]		$\delta = 3$	$\delta = 4$	$\delta = 5$	$\delta = 6$
500	unpol.	46.46	13.92	4.692	1.700
	$+-$	60.01	19.35	6.853	2.576
	$++$	32.91	8.493	2.532	0.821
1000	unpol.	371.7	222.7	150.1	108.8
	$+-$	480.8	309.6	219.3	164.9
	$++$	262.6	135.8	80.93	52.75

Full bakground simulation

We conclude that by adopting an unpolarized $\gamma\gamma$ collision machine with $\sqrt{s} = 1$ TeV in the case of $\delta = 3$ and $\mathcal{L} = 100 fb^{-1}$, the graviton signal can be detected when $M_S \leq 2.67$ TeV, while in the case of $\sqrt{s} = 500$ GeV, the graviton signal can be detected only when $M_S \leq 1.40$ TeV. If we adopt a $\gamma\gamma$ collider machine in $+-$ polarized photon collision mode, the detecting upper limits on the fundamental scale can be improved up to 2.79 TeV when $\sqrt{s} = 1$ TeV, and 1.44 TeV when $\sqrt{s} = 0.5$ TeV.

Unparticles



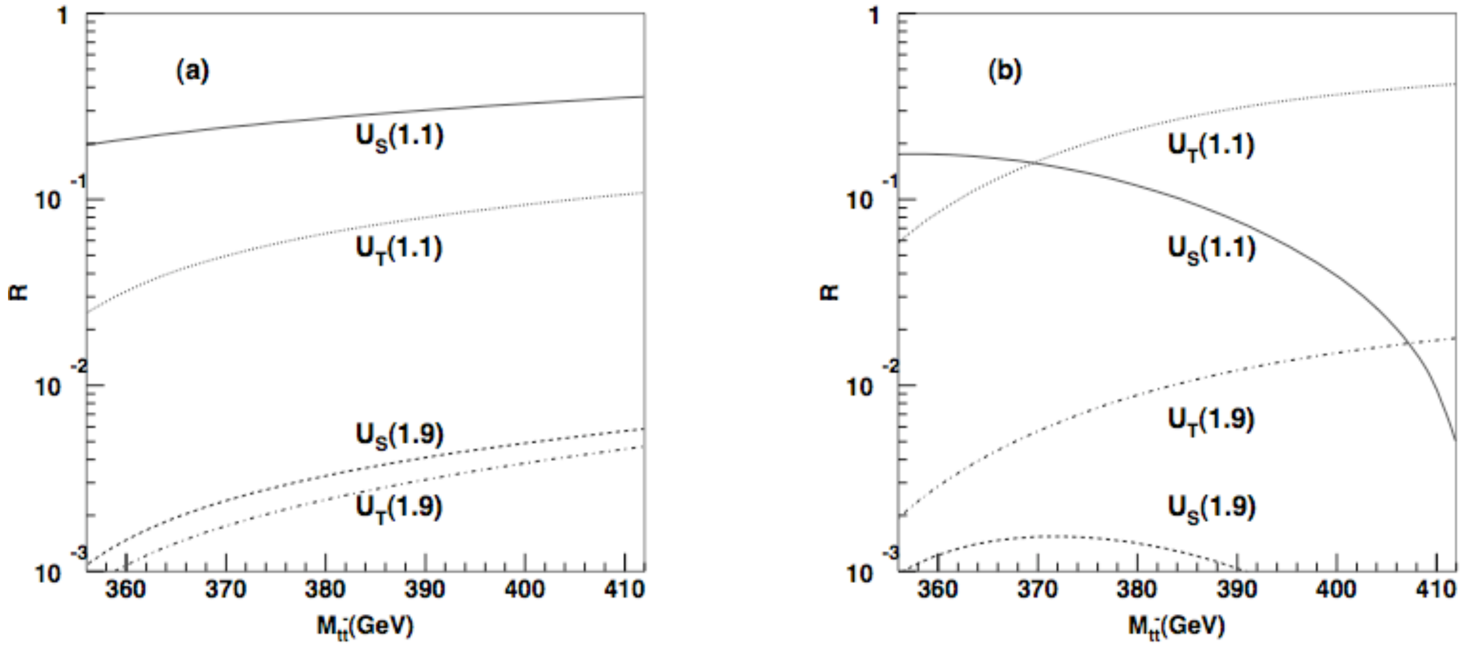
$$R_{\mathcal{U}}^{S(T)} = \frac{\sigma_{SM+\mathcal{U}}^{S(T)} - \sigma_{SM}}{\sigma_{SM}},$$

arXiv:0802.0236

Effect of virtual unparticle contribution to the $\gamma\gamma \rightarrow tt$ cross section

Measurable effects

Also $\gamma\gamma \rightarrow \gamma\gamma$
See arXiv:0801.0018



Timeline for ILC options?

Year:	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29

EDR | Site | Construction | e+e- physics | options

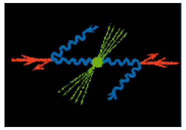
Concrete starts to be poured
Decision are made that we will have to live wit

First Physics from LHC
Our view of what needs to be done will be refined, perhaps changed

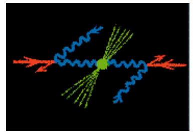
Photon collider?
Is the community in place?

We need to be ready to make decisions for the baseline machine to maximize it's physics potential for the long term.

J. Gronberg LCWS07



Conclusions



Many detailed studies on the physics case for the photon collider

- R&D for a photon collider & detectors ongoing
  - Have to keep up support for these activities (LC & photon workshops!)
- Detail results on physics
  - QCD studies on the structure of the photon and $\sigma(\gamma\gamma)_{tot}$
  - The light Higgs results confirmed and extended → $\Delta\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma}$ ~ 2%
  - H/A study confirms reach for high masses, beyond e+e-
  - Detailed study of the TGCs → λ measurement competitive with e+e-
  - Excellent sensitivity to SUSY and Extra Dimensions/alternative theories

✣ A photon collider is an excellent machine for physics
✣ It is strongly coupled to the faith of ILC/CLIC and hence >2020
✣ Some of its program can be probably be initiated at the LHC with two-photon physics studies…

Backup