

High Energy Physics at a Photon Collider

Stan Brodsky
SLAC

Electron-Electron Interactions
at TeV Energies

UCSC, Dec. 12-14-2003

5th Int. Unlslap

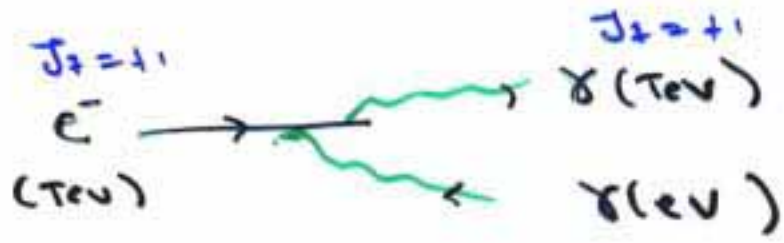
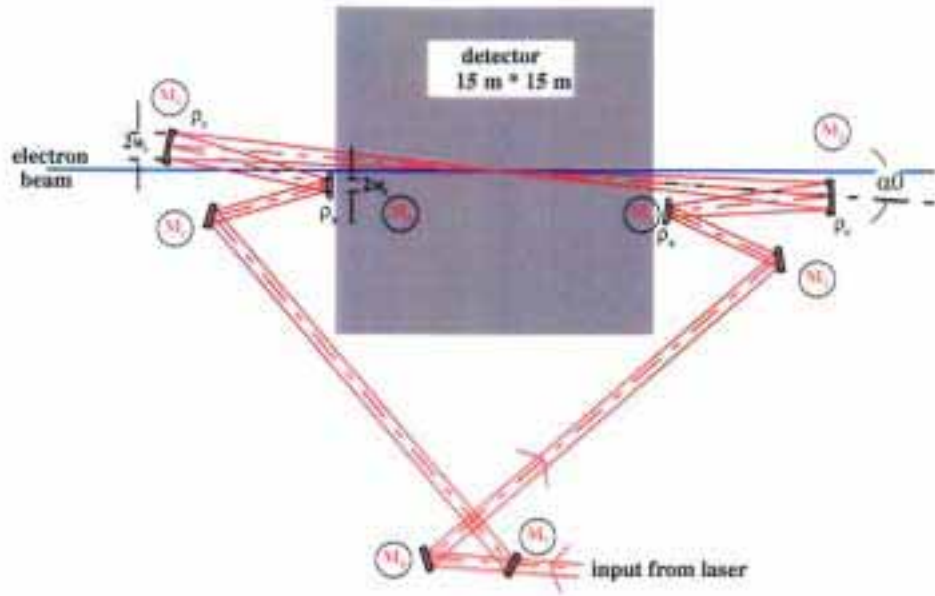
Refs:

A. de Roeck hep-ph/0311138

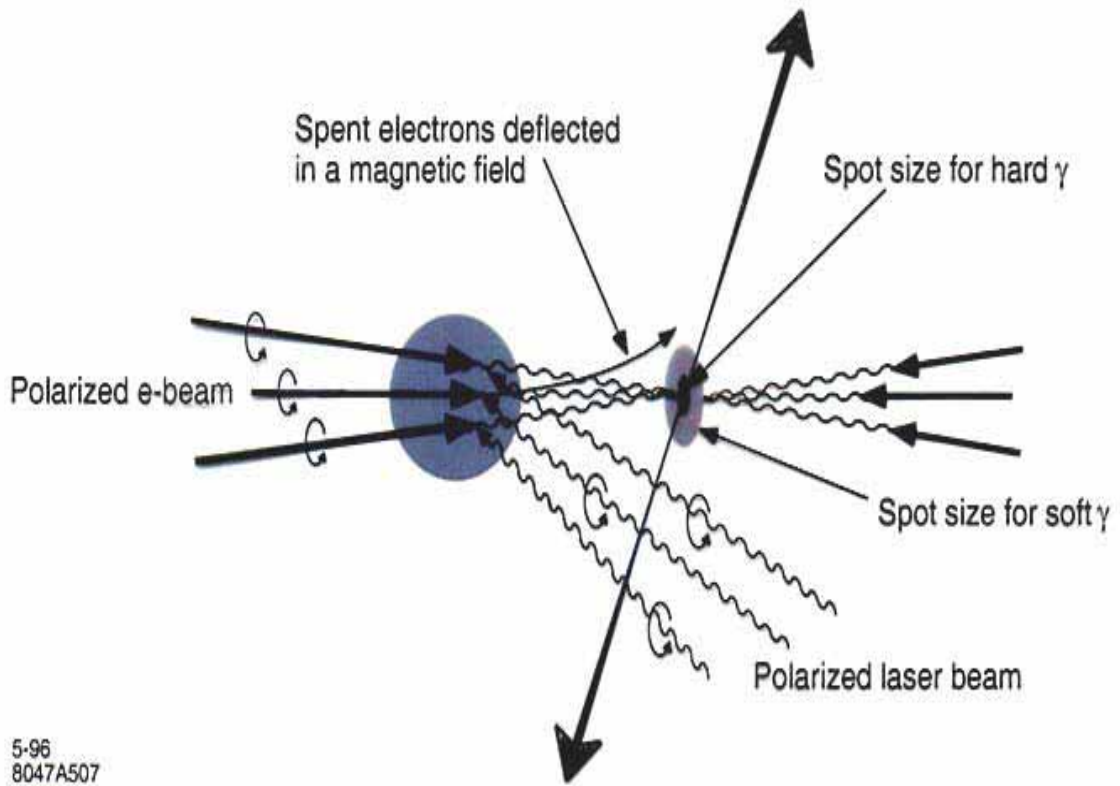
Physics of a $\gamma\gamma$, $e\gamma$, e^+e^- Option for LC

S.J.D. Int Journ. of Mod. Phys. A.

Proc. of 4th Int Unlslap.



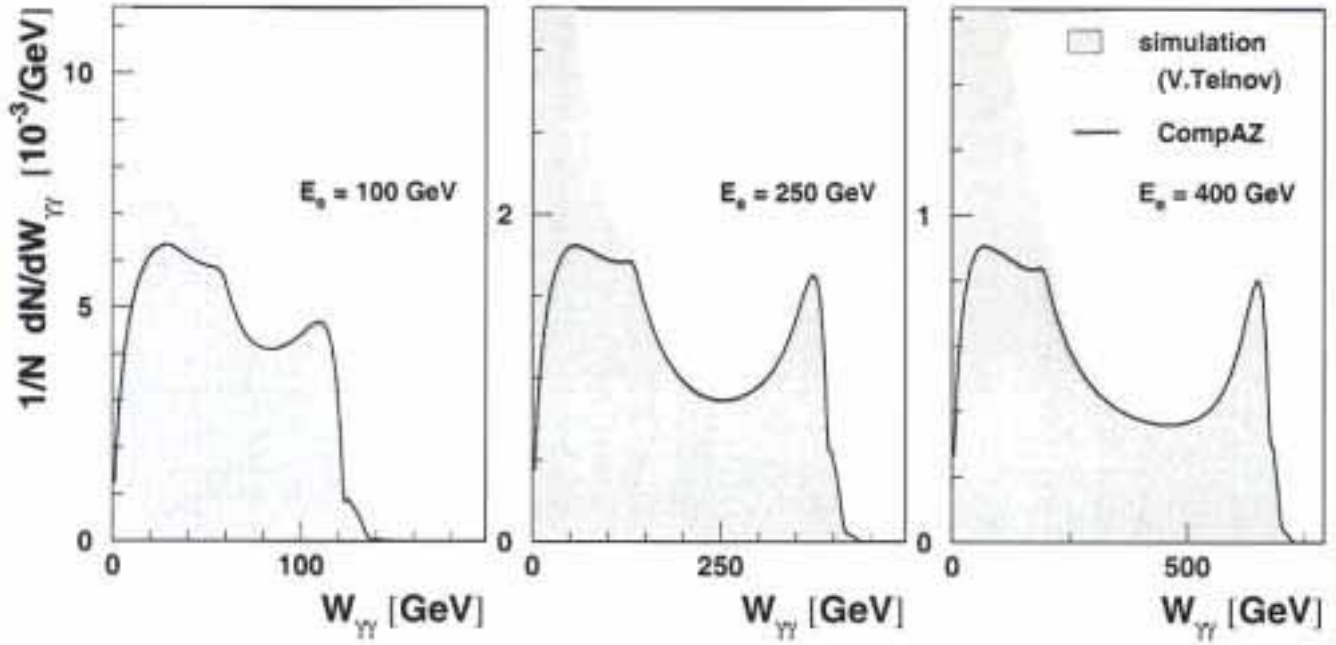
Mixing of Back-scattering



5-96
8047A507

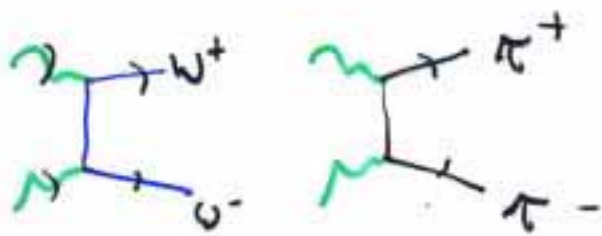
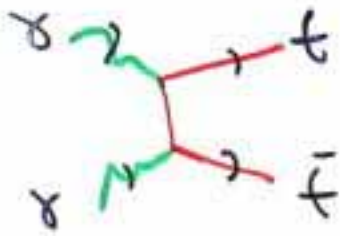
Simulations $\gamma\gamma$ Luminosity

$$\frac{dN}{d\sqrt{s_{\gamma\gamma}}}$$

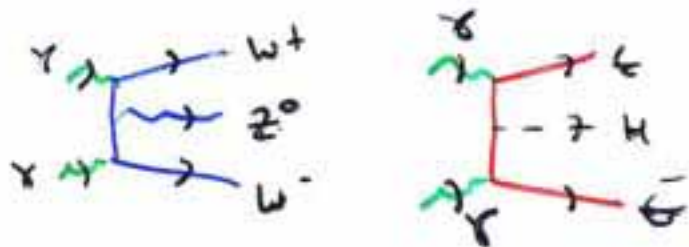
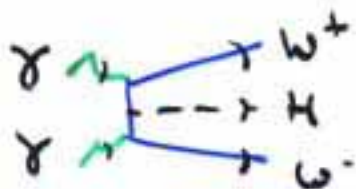
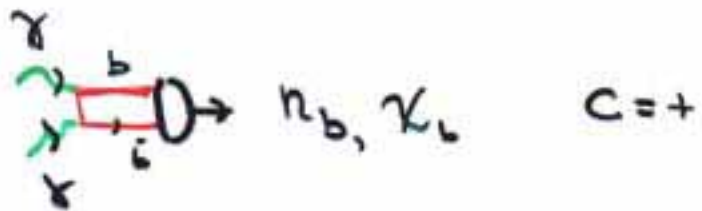
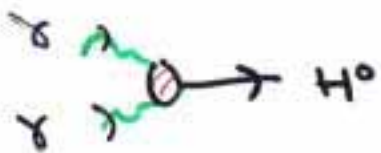
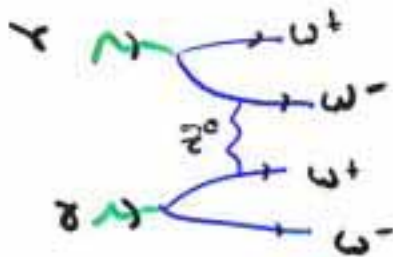
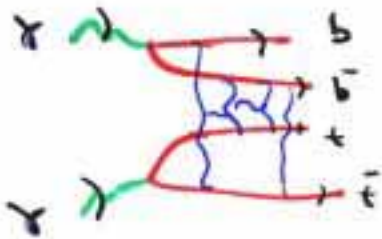
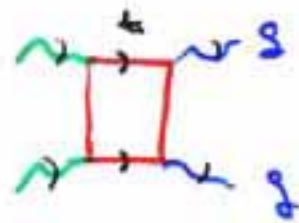
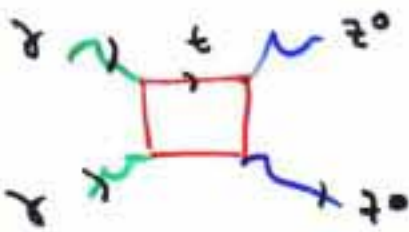


Some examples:

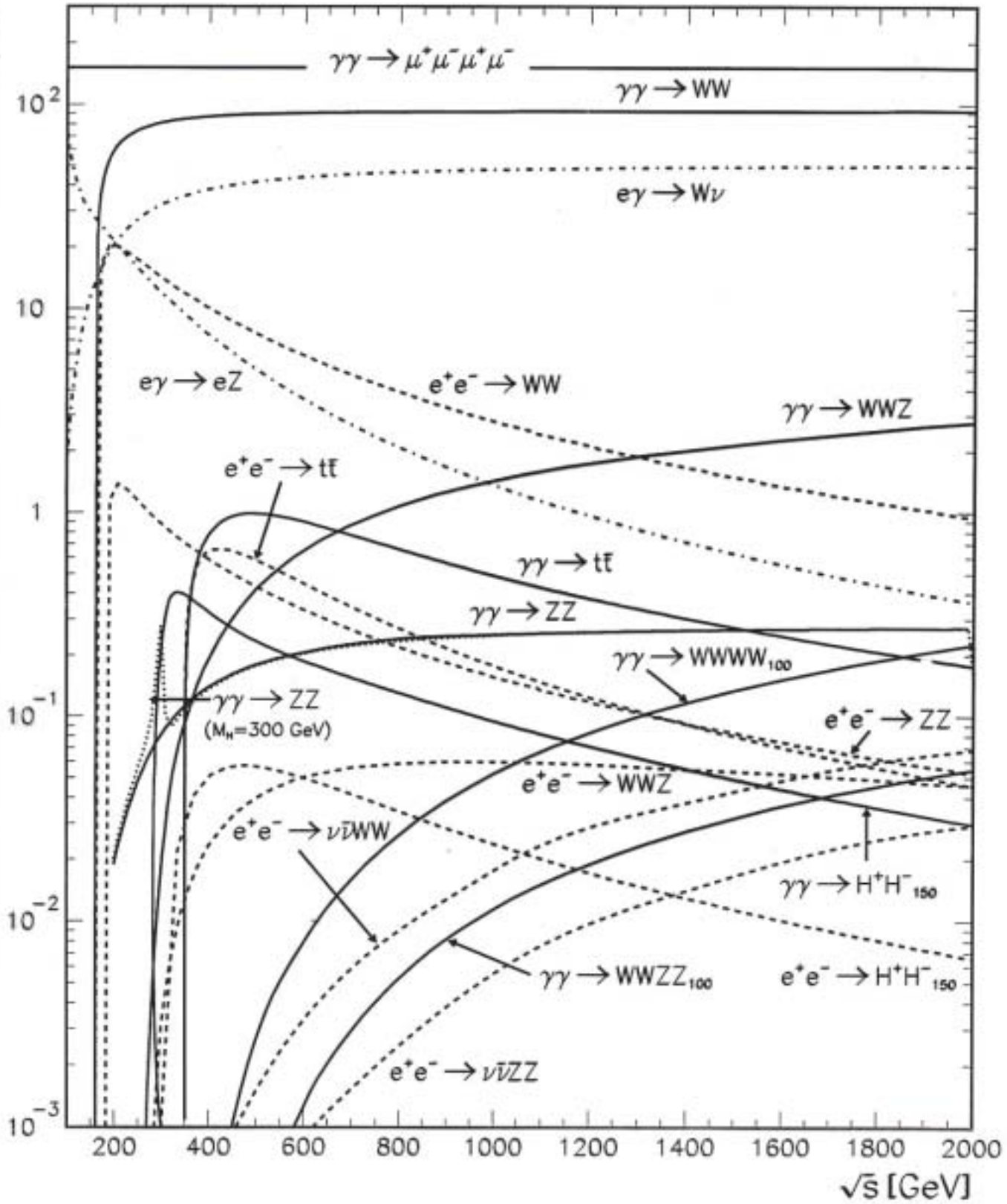
$\gamma\gamma$ collisions



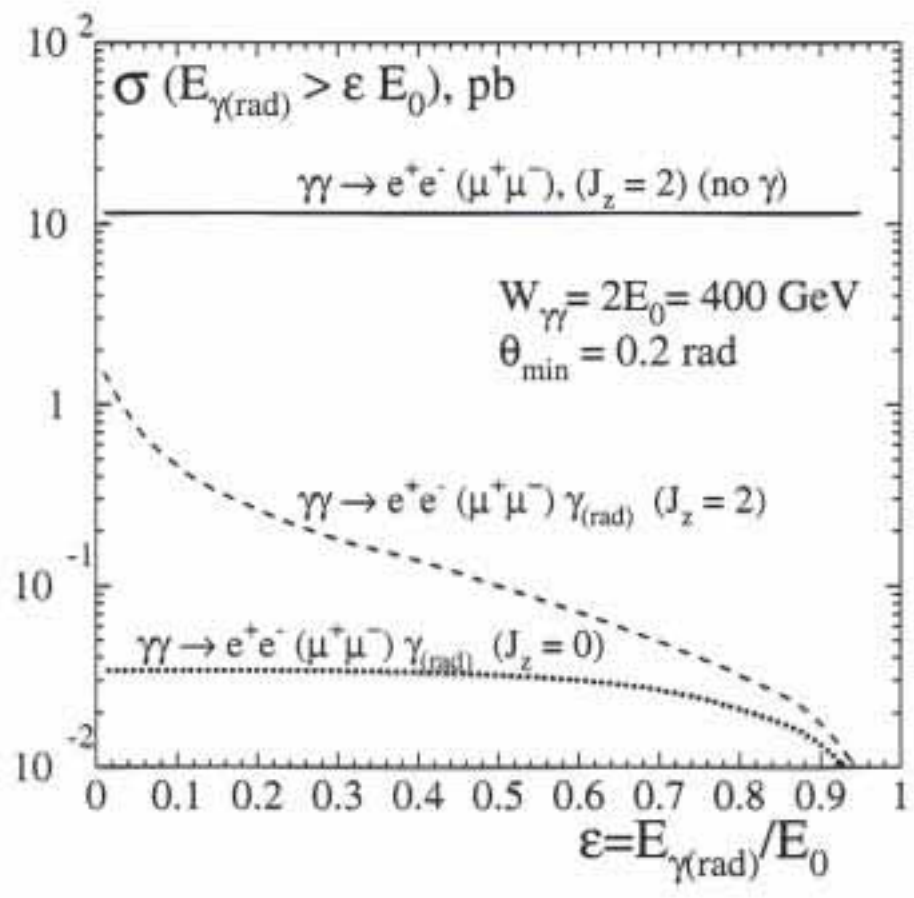
+ SUSY, + charged Higgs



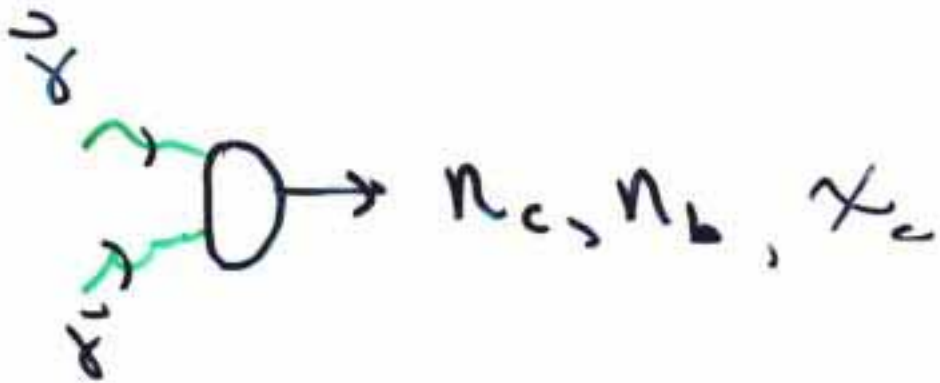
+ SUSY, charged Higgs
pseudoscalar A



QED
calibration



Test study for QCD

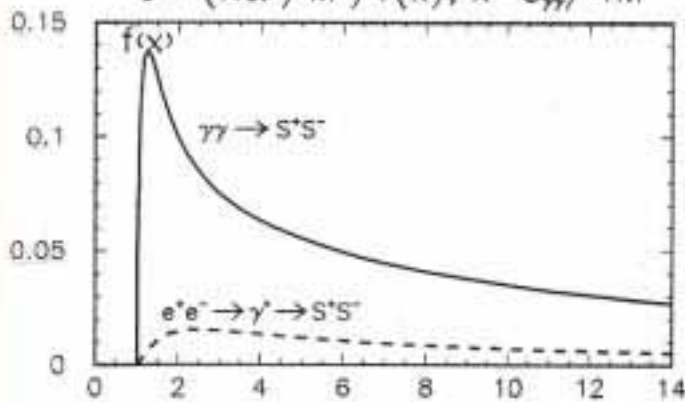


Produce all $e = +$ neutral state

Parity $\hat{E} \cdot \hat{E}$ vs $\hat{E} \times \hat{E}'$

Pair Production

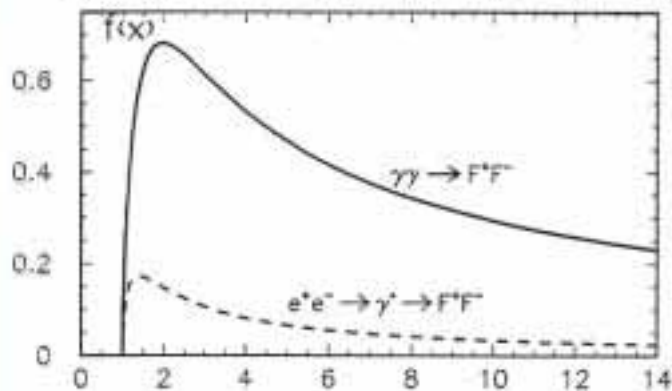
$$\sigma = (\pi\alpha^2/M^2) f(x), \quad x = s_{\gamma\gamma}/4M^2$$



* Large $\gamma\gamma$ cross sections

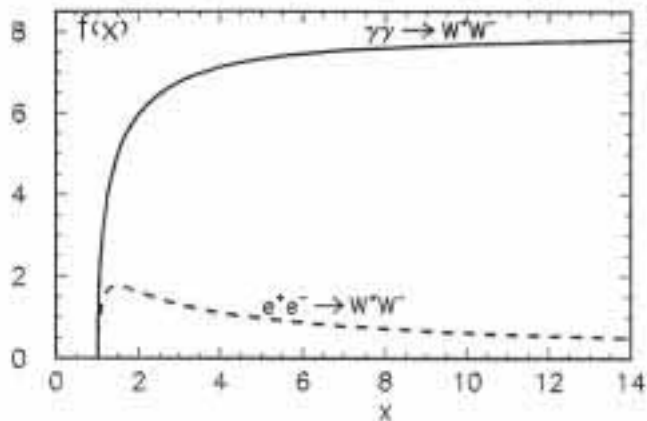
$$\gamma\gamma \rightarrow S^+S^- \quad \text{scalars}$$

$$\sigma \sim \frac{1}{s^2}$$



$$\gamma\gamma \rightarrow F^+F^- \quad \text{spin-1/2 fermions}$$

$$\sigma \sim \frac{1}{s}$$



$$\gamma\gamma \rightarrow W^+W^-$$

spin-1 in t-channel

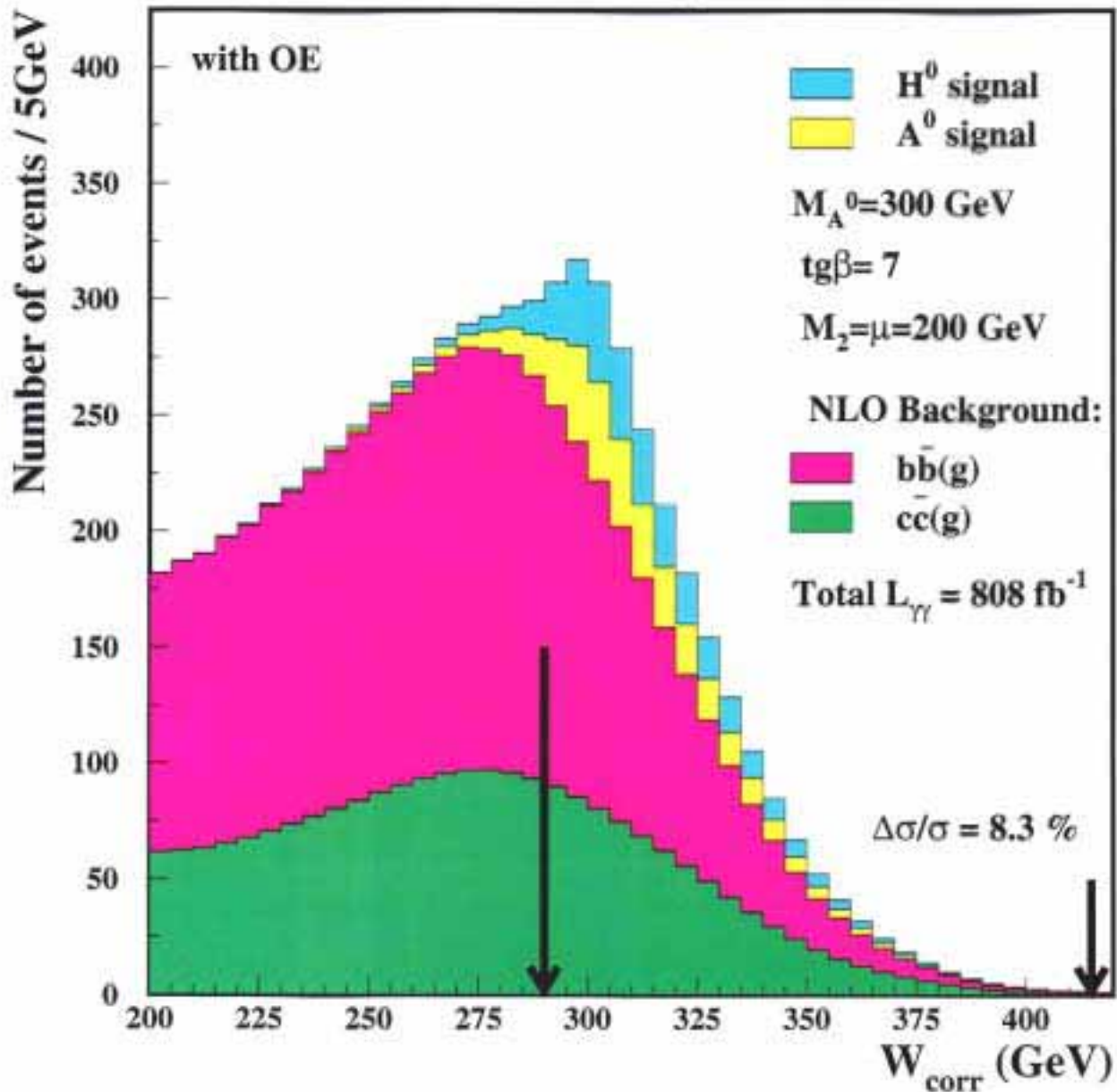
$$\Rightarrow \sigma \sim s^0 \ln s$$

* any decay \neq its couplings

$$\gamma\gamma \rightarrow H, A \rightarrow b\bar{b}$$

$$W_{\text{rec}} = \text{reconstructed invariant mass } \downarrow b\bar{b}$$

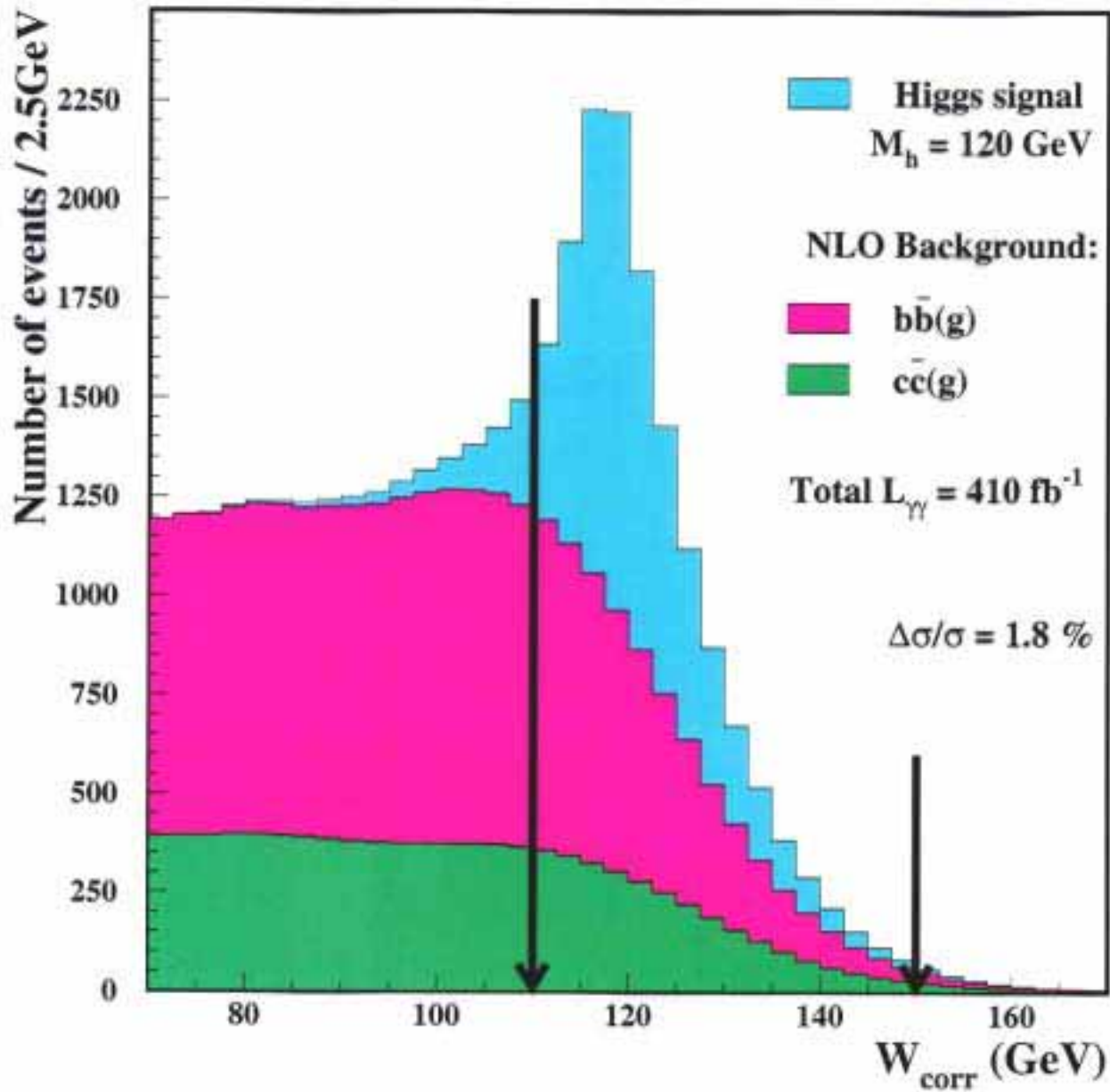
e^-e^- beams with $\sqrt{s_{ee}} = 419$ GeV

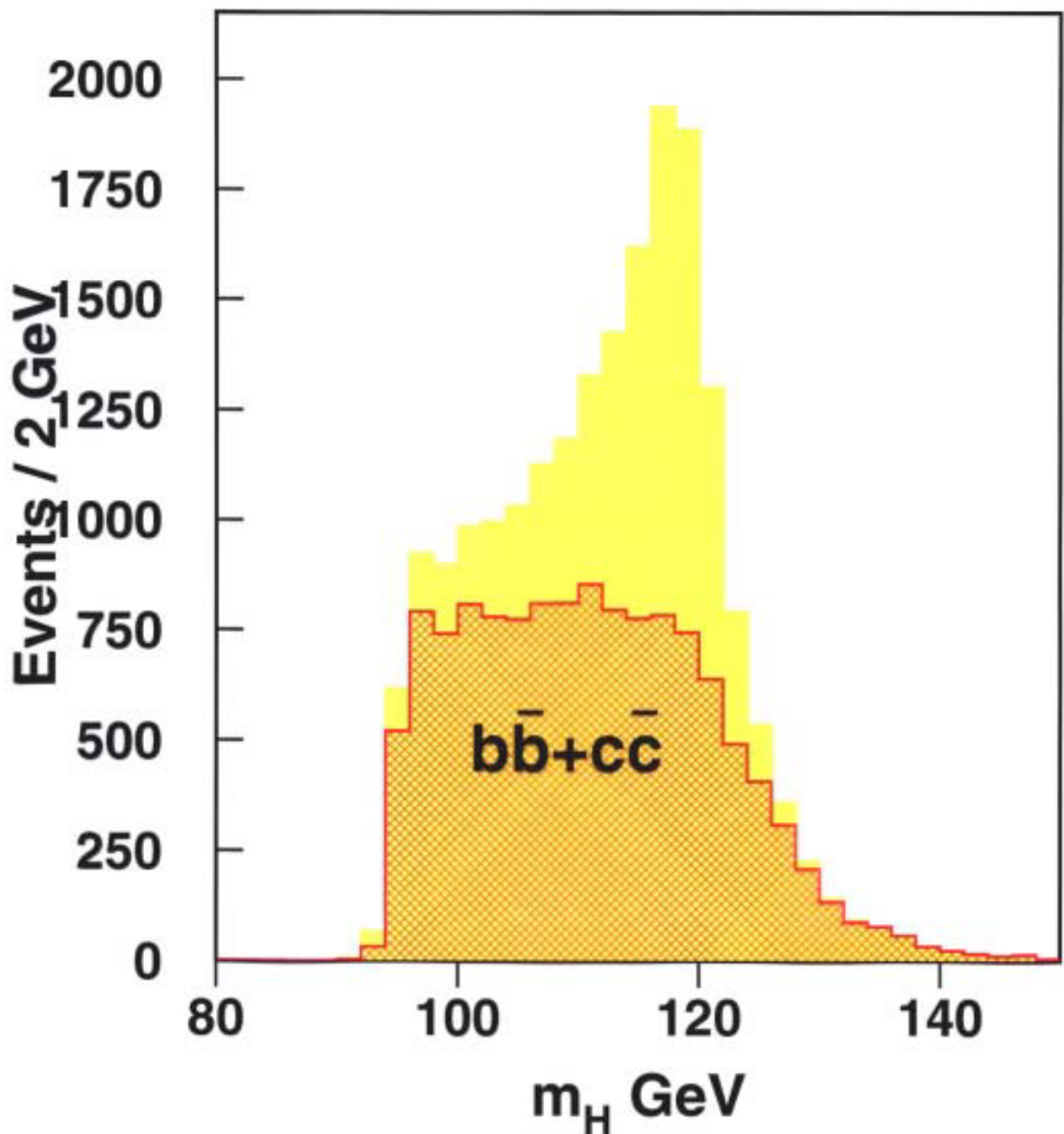


$$\gamma\gamma \rightarrow H^0 \rightarrow b\bar{b}$$

$$W_{\text{rec}} = \text{reconstructed } \gamma\gamma \text{ mass}$$

e^-e^- beams with $\sqrt{s_{ee}} = 210.5 \text{ GeV}$

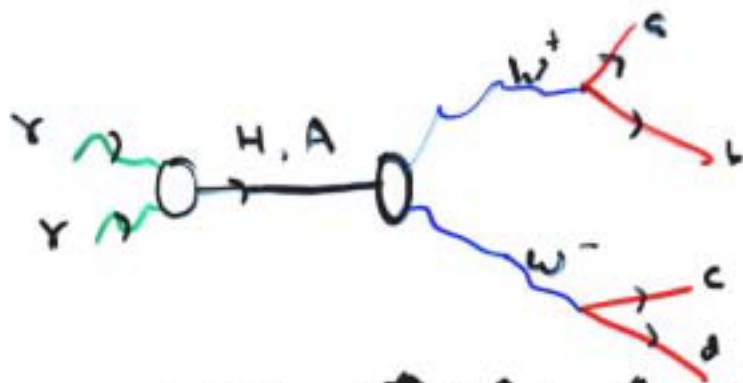
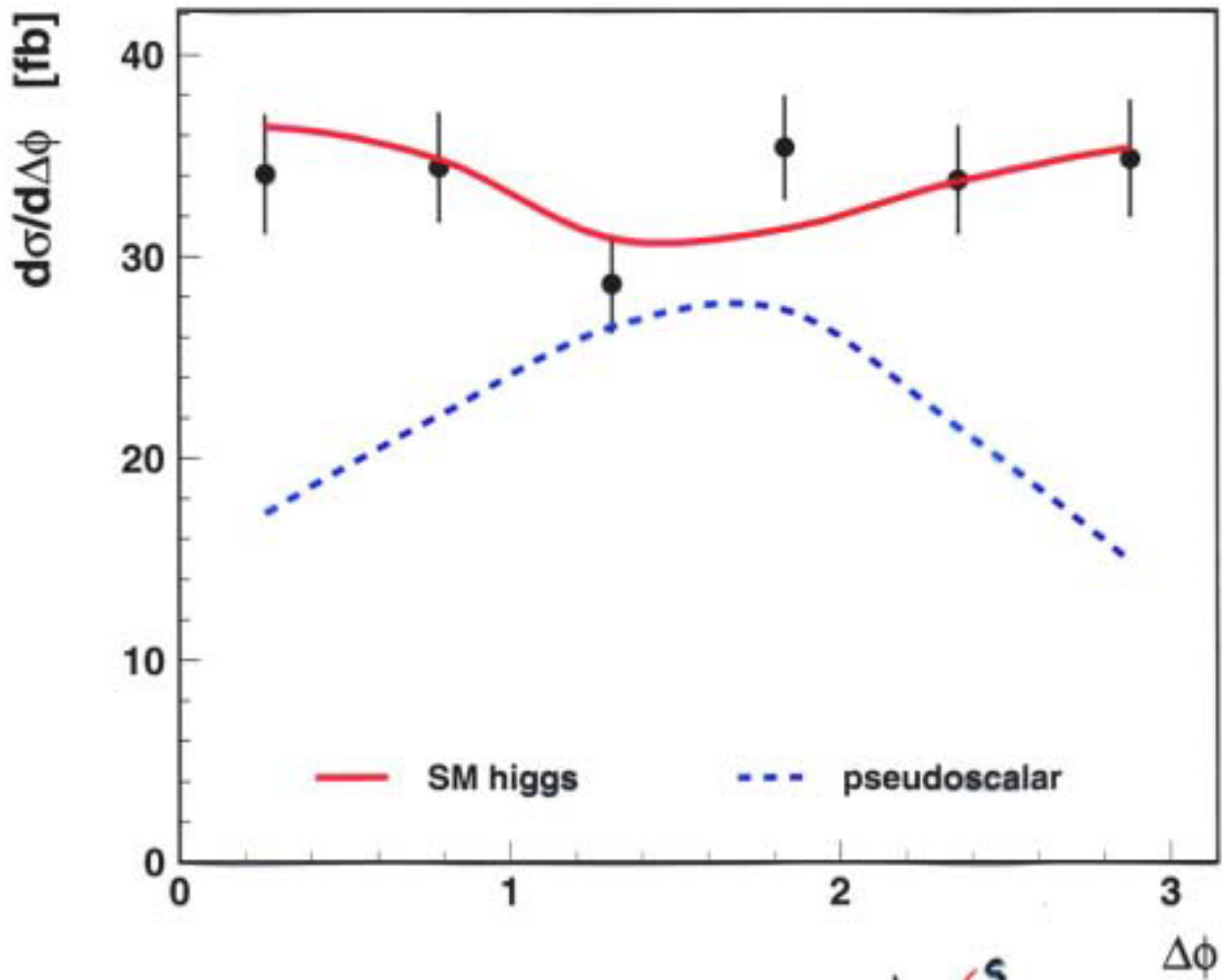




determine $\Gamma(H \rightarrow \gamma\gamma) \mathcal{B}(H \rightarrow b\bar{b})$ to $\sim 20\%$

$\gamma\gamma \rightarrow H \rightarrow b\bar{b}, c\bar{c}$
 $\tilde{\gamma}_\pm = 0$

Signal
 $b\bar{b} \neq$



also 27

$$\cos\phi = (\hat{p}_a \times \hat{p}_b) \cdot (\hat{p}_c \times \hat{p}_d)$$

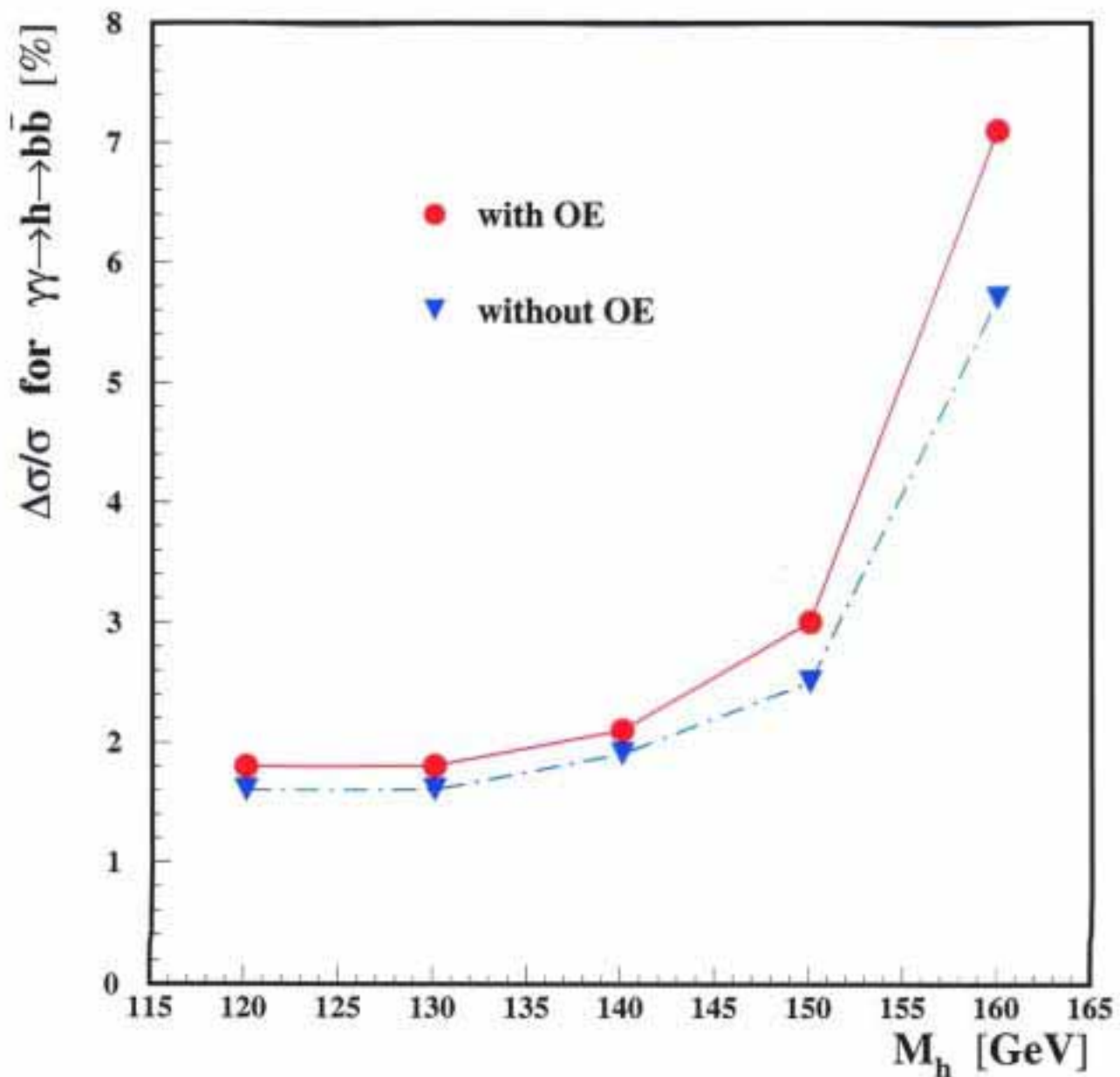
Statistical precision

$$\Gamma(H \rightarrow \gamma\gamma) \text{ BR}(H \rightarrow b\bar{b})$$

← det from etc

OE: Overlapping Events

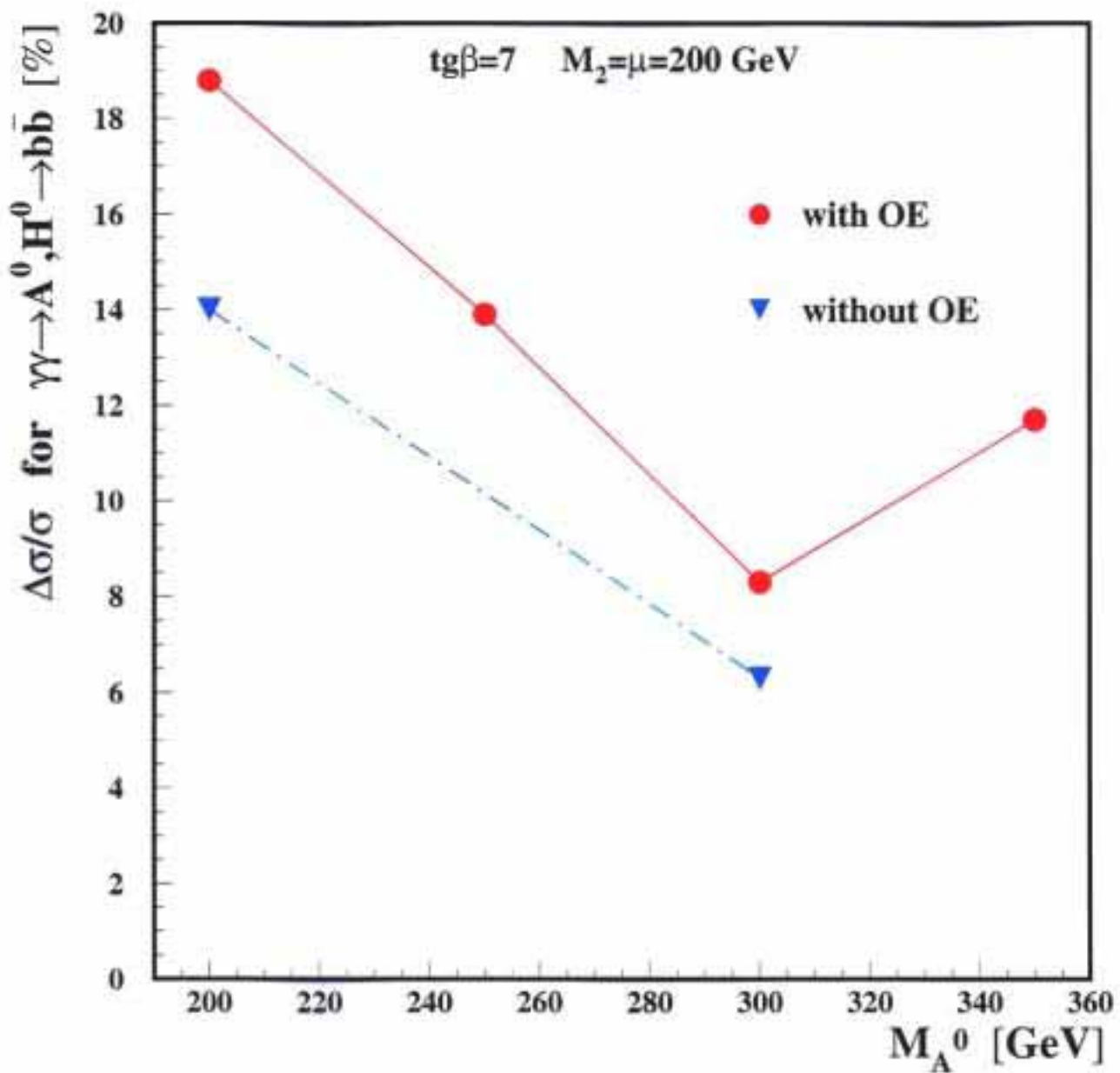
$$\frac{\Delta\sigma}{\sigma} (\gamma\gamma \rightarrow H^0 \rightarrow b\bar{b})$$



Statistical error

$$\sigma(\gamma\gamma \rightarrow A, H \rightarrow b\bar{b})$$

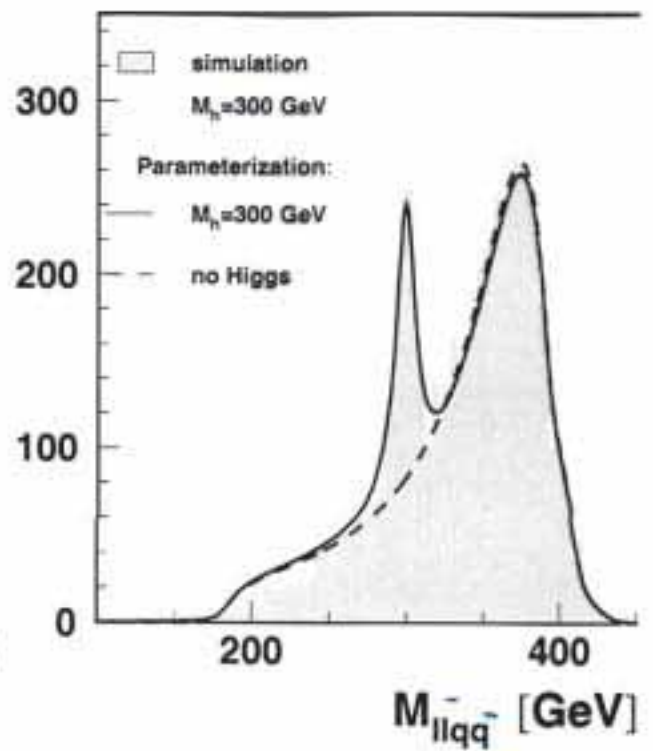
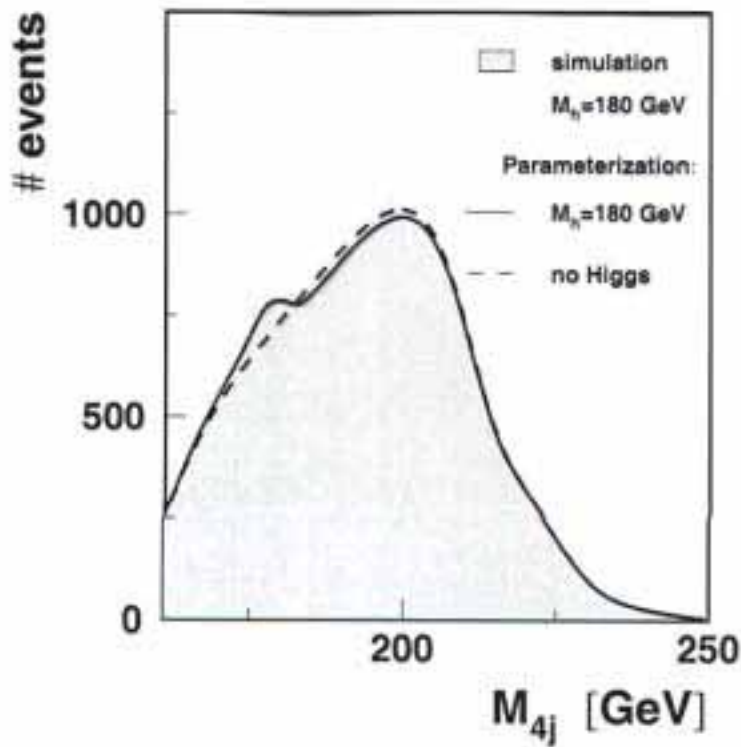
kruczyk
Niezurawski, Fornalicki,
hep-th/0207175
0207292



$\gamma\gamma \rightarrow WW, ZZ$
 $\rightarrow 4 \text{ jets}, \ell\bar{\ell} \tau\bar{\tau}$

$E_e = 152.5 \text{ GeV}$

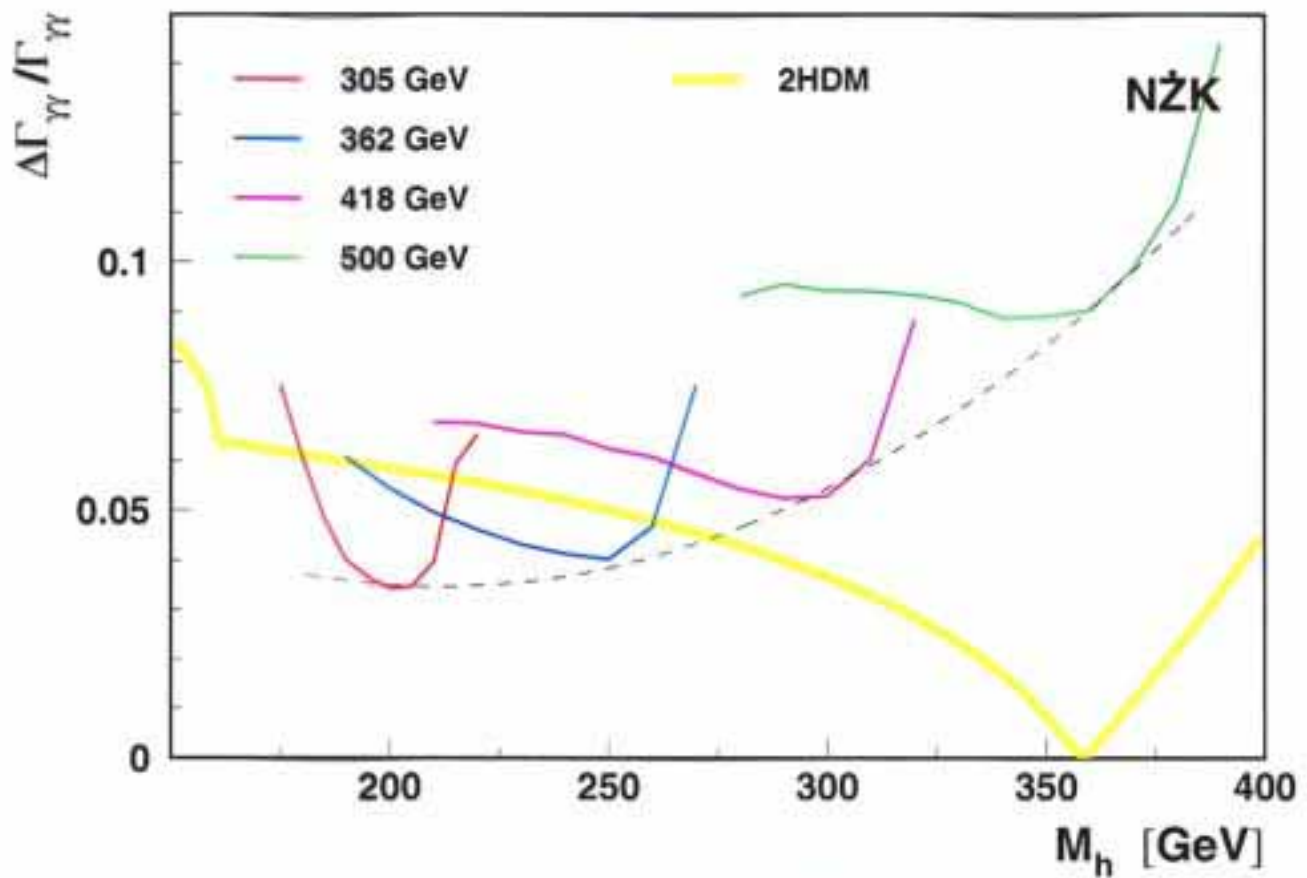
$E_e = 250 \text{ GeV}$



$\gamma\gamma \rightarrow H \rightarrow W^+W^-, 2020$

Statistical determination

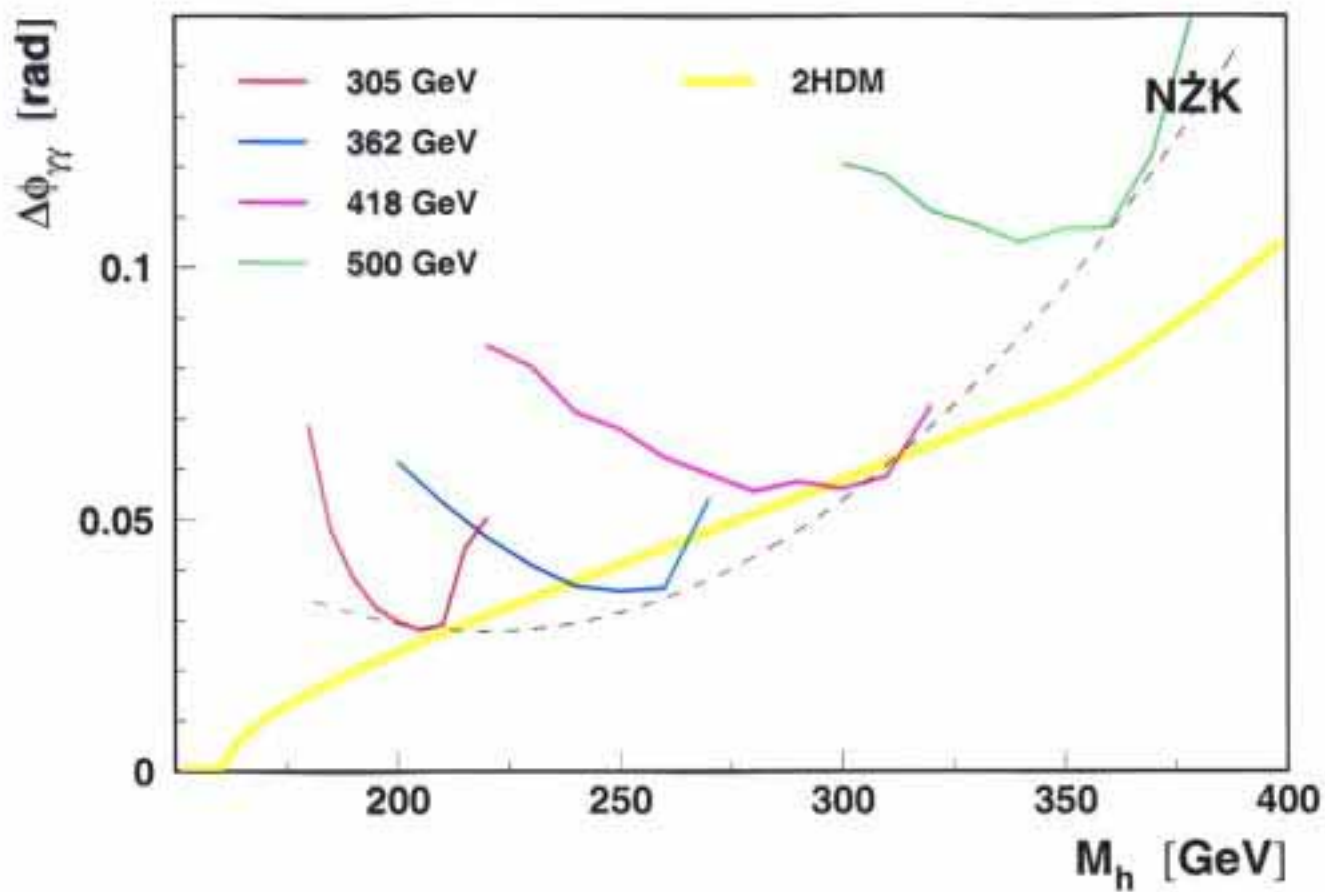
$\uparrow \Gamma_{H \rightarrow \gamma\gamma}$



\times 2HDM (From extra H 800 GeV)

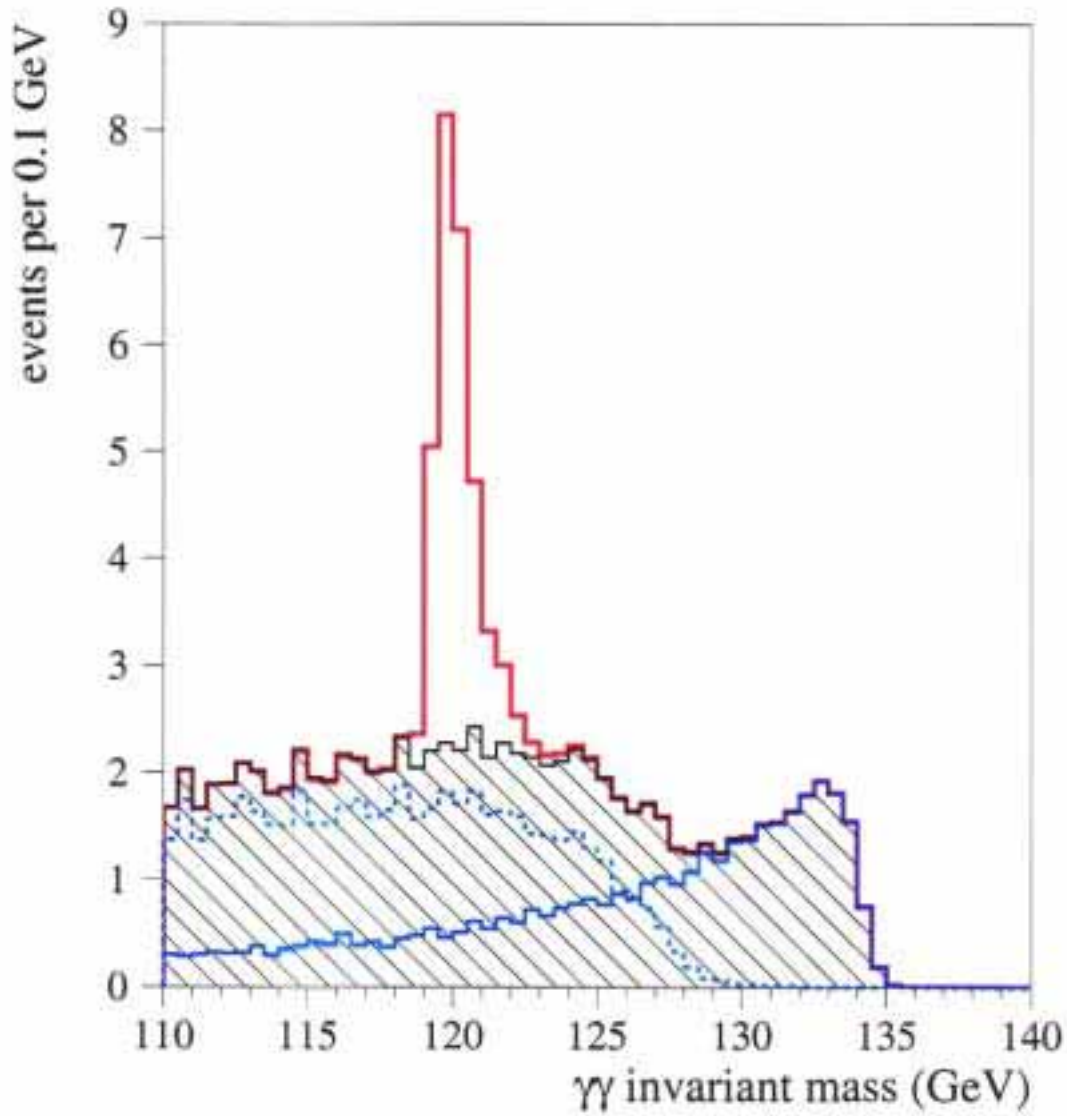
Determine phase

η $H \rightarrow \gamma\gamma$ coupling



$$\gamma\gamma \rightarrow H \rightarrow \gamma\gamma$$

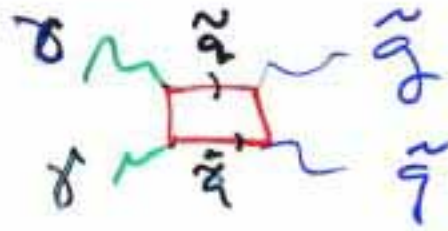
D. Asner et al.
hep-ph/0208219



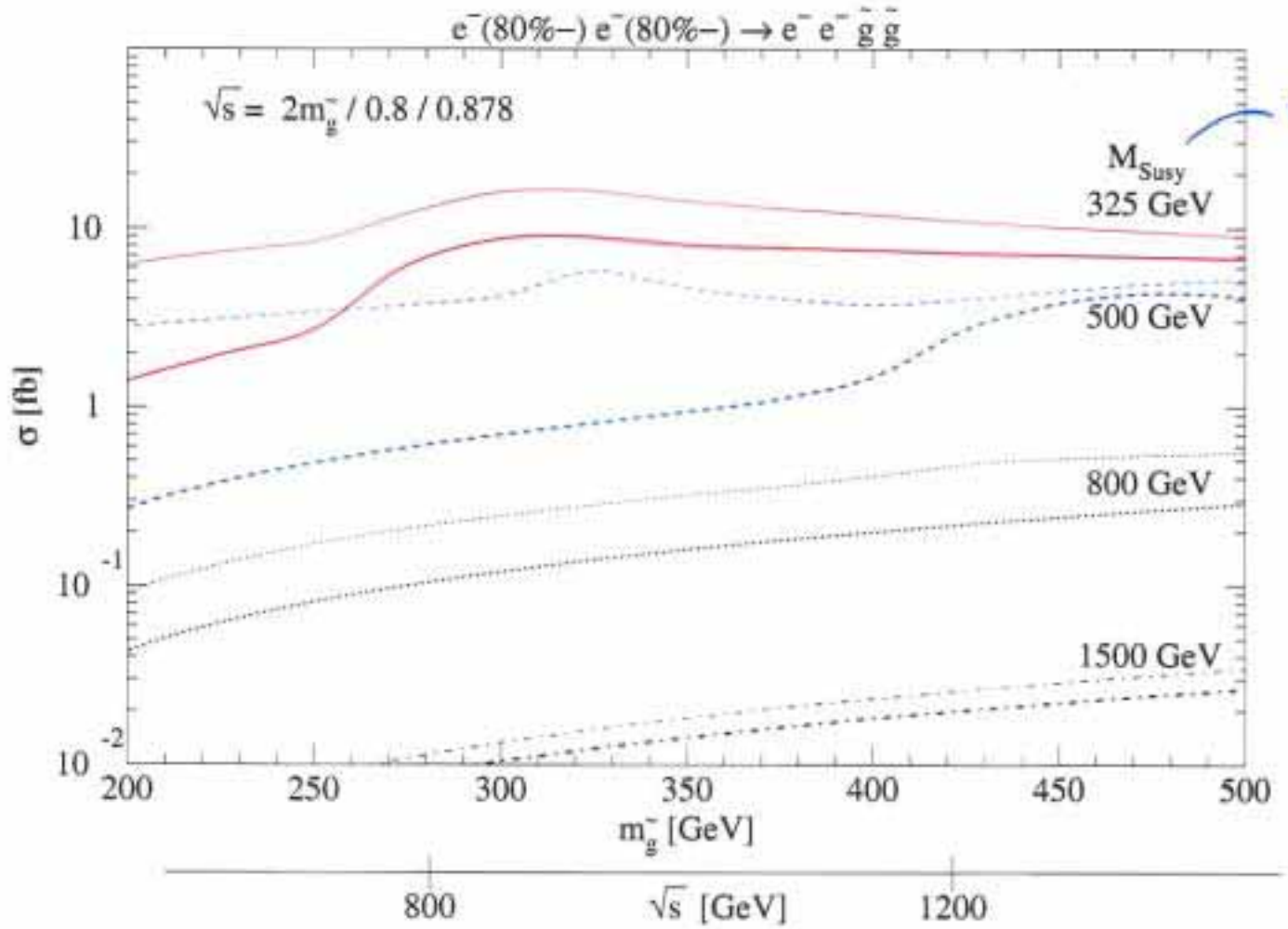
needs
superb
calorimeter
energy resolution

--- $\gamma\gamma \rightarrow \gamma\gamma$ bkgnd
— $e\gamma \rightarrow e\gamma$

gluino pair prod.



Berge, kloster
hr/pt/030303z



Gold - Plated Events at Photon colliders

$$\gamma\gamma \rightarrow H, h \rightarrow b\bar{b}$$

SM/ASSM Higgs

$$\rightarrow H \rightarrow W^+W^-$$

SM Higgs

$$\rightarrow H \rightarrow \tau\tau$$

$$\rightarrow H \rightarrow \gamma\gamma$$

$$\rightarrow H \rightarrow t\bar{t}$$

$$\gamma\gamma \rightarrow H, A \rightarrow b\bar{b}$$

ASSM

$$\gamma\gamma \rightarrow \tilde{F}\tilde{F}^*, \tilde{\chi}^+ \tilde{\chi}^-$$

Sleptons, staus,

gluinos

gluinos

$$\tilde{g}\tilde{g}$$

$$H^+H^-$$

$$(\tilde{F}\tilde{F}^*)$$

Stoponium

$$e\gamma \rightarrow \tilde{e} \tilde{\chi}_0^*$$

Sleptons, gluinos

$$\gamma\gamma \rightarrow \gamma\gamma$$

non-connecting

$$e\gamma \rightarrow eG$$

extra dimensions

$$\gamma\gamma \rightarrow \phi$$

Radions

$$e\gamma \rightarrow \tilde{e}\tilde{\chi}_0^*$$

gravitons

Goldstone Events (cont.)

$\gamma\gamma \rightarrow t\bar{t}$ anomalous top interactions.

$e\gamma \rightarrow t\bar{t}\nu_e$ anomalous W coupl.

$\gamma\gamma \rightarrow W^+W^-$ anomalous W interactions
extra dimensions

$e\gamma \rightarrow W^-\nu_e$ anomalous W couplings

$\gamma\gamma \rightarrow W^+W^-W^+W^-$ WW scattering
 W^+W^-Z anomalous quark
interactions
 WWZ anomalous cubic

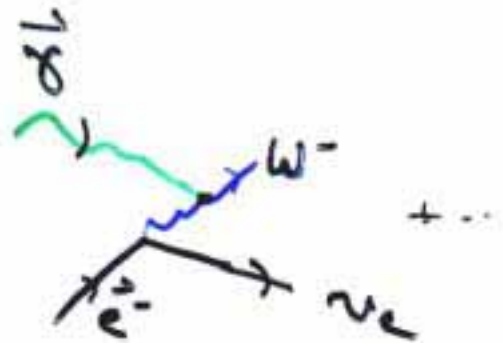
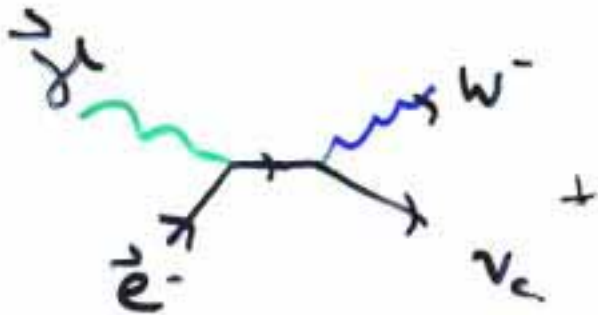
$\gamma\gamma \rightarrow$ hadrons total $\gamma\gamma$

$e\gamma \rightarrow e^-X, \nu_e X$ NC + CC SFs

$\gamma g \rightarrow \tau\bar{\tau}$ gluons $\equiv \gamma$

$\gamma\gamma \rightarrow \gamma\gamma\gamma$ QED Photon

Anomalous W couplings



Measure ALL

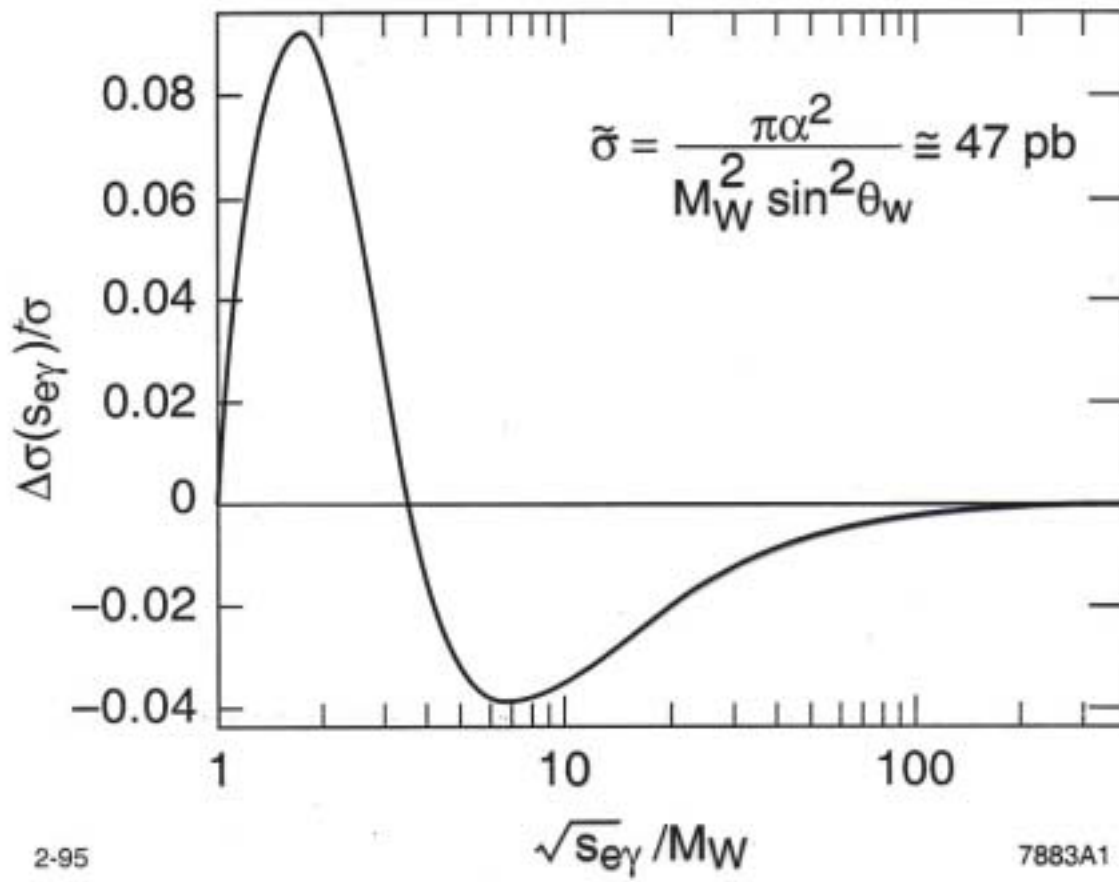
$$\frac{d\sigma}{d\Omega} (\sqrt{s_{\text{ex}}})$$

strong sensitivity

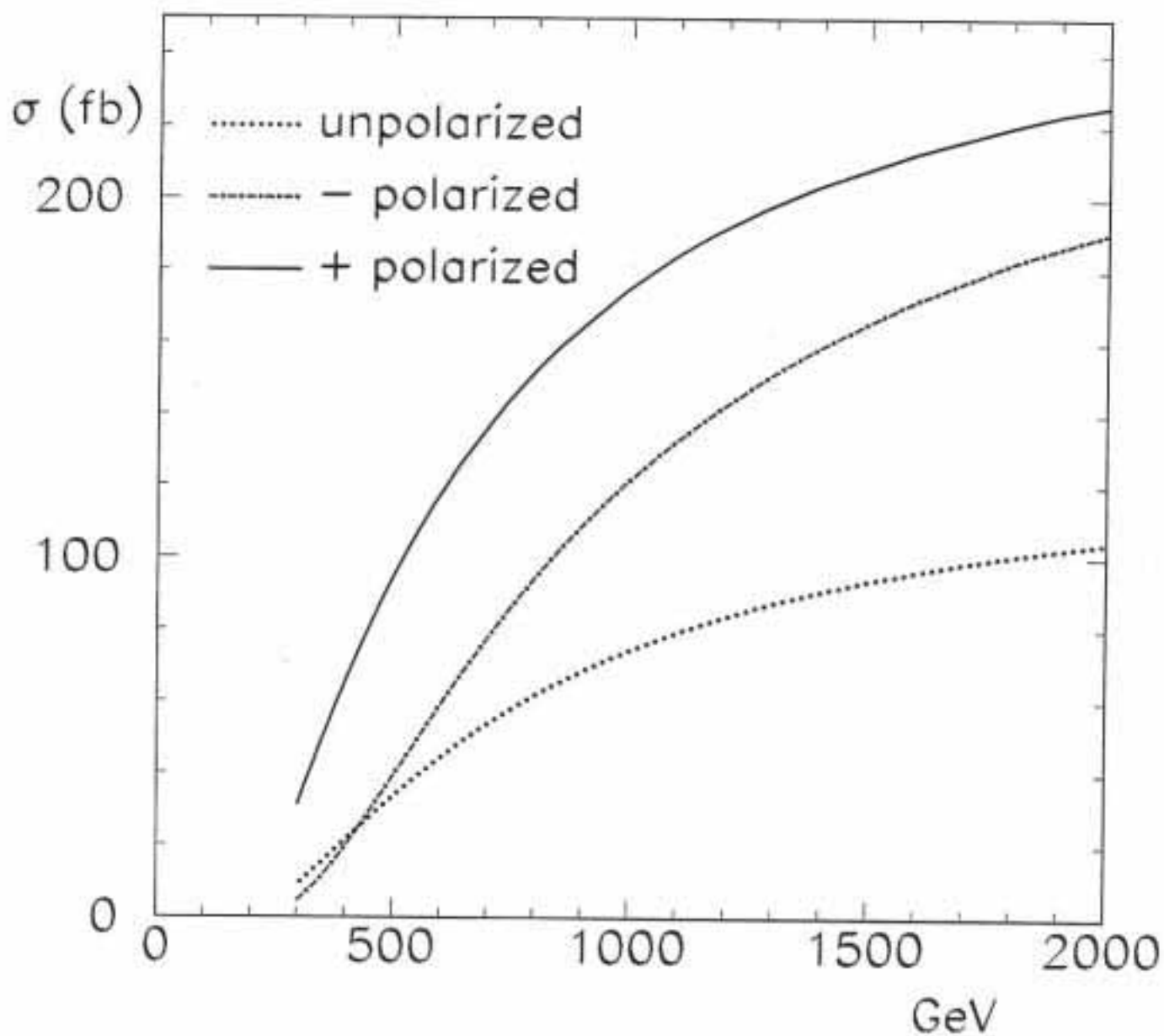
to anom W couplings

zero crossing
(prediction
amplitude zero)

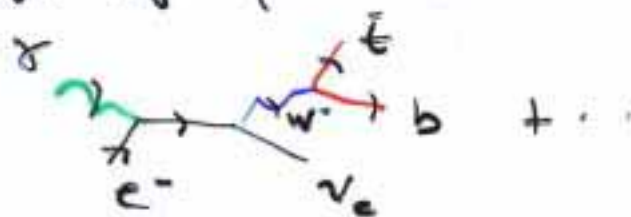
Rizzo
Schwartz
FUB



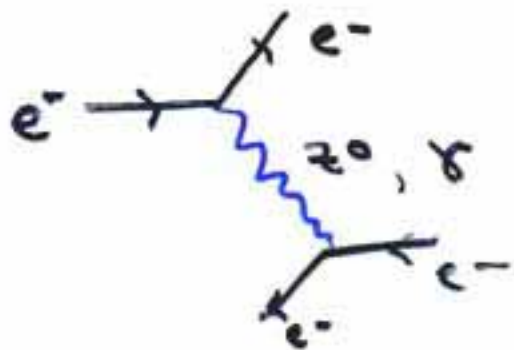
$$\gamma e_L \rightarrow \nu \bar{t} b$$



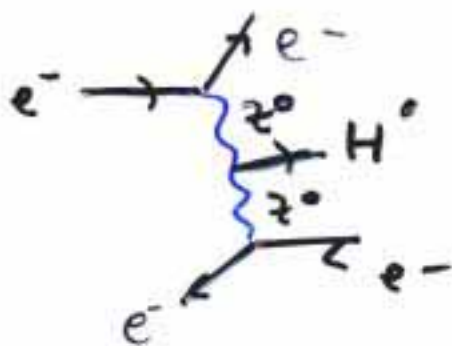
Single top production



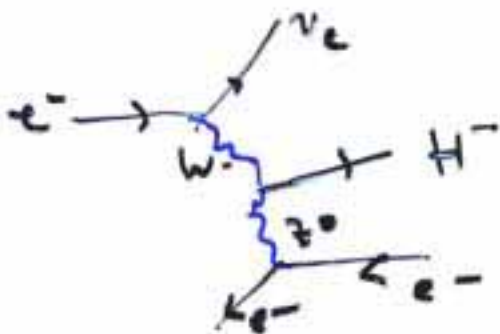
e⁻ e⁻ collisions



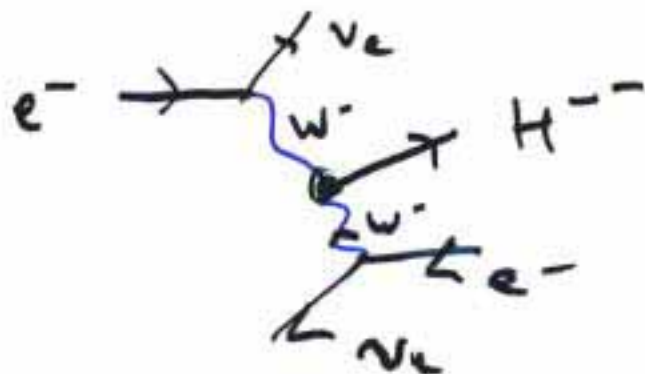
$$\frac{d\sigma}{dt} \sim \frac{4\pi\alpha_e^2}{(t - M_\gamma^2)^2}$$



Higgs production
e⁻ e⁻ → H⁰ e⁻ e⁻



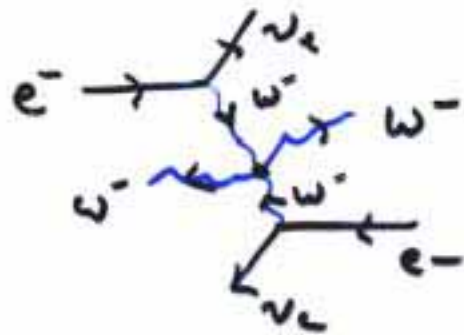
e⁻ e⁻ → H⁻ ν_e e⁻
charged Higgs



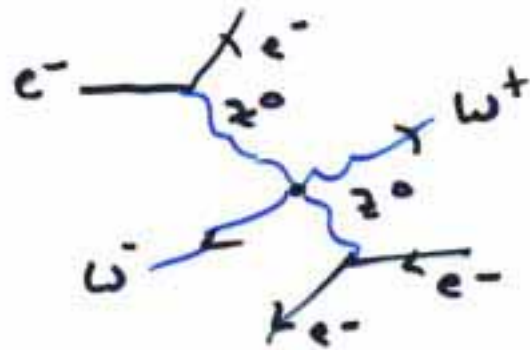
e⁻ e⁻ → H⁻ ν_e ν_e
double
charged
Higgs !

$e^- e^-$ collision

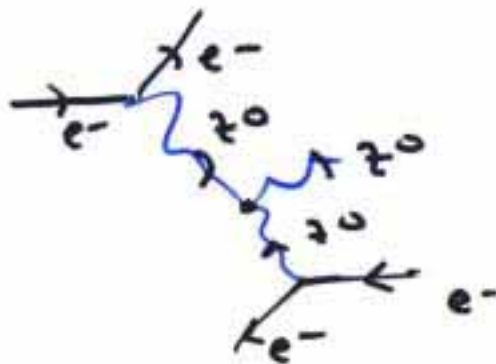
Test 4-point Interactions



$$e^- e^- \rightarrow \nu_e \nu_e W^- W^-$$



$$e^- e^- \rightarrow e^- e^- W^+ W^-$$

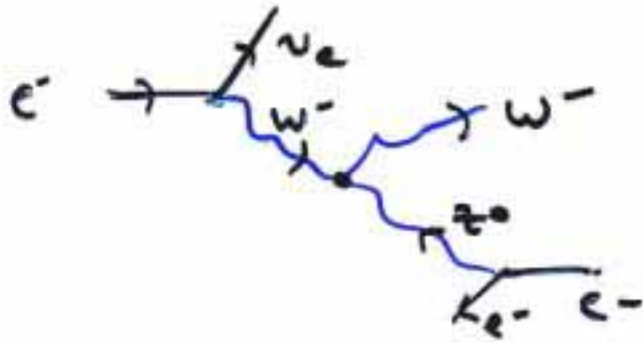


$$e^- e^- \rightarrow e^- e^- Z^0$$

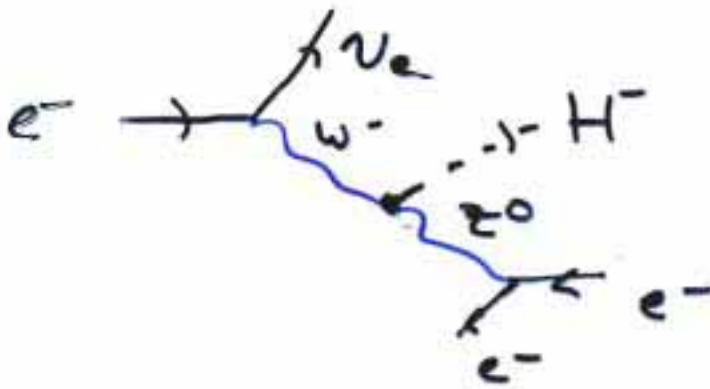
Test
3-pt
interaction

$e^- e^-$ collisions

(also in e^+e^-)

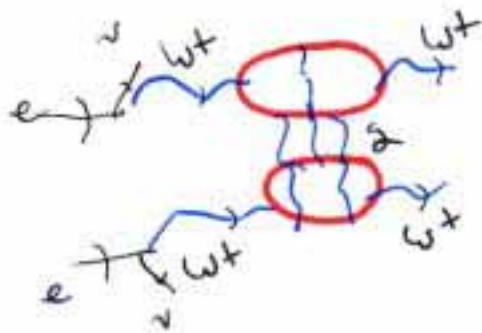


$e^- e^- \rightarrow \nu_e e^- U^-$
test 7-qt int

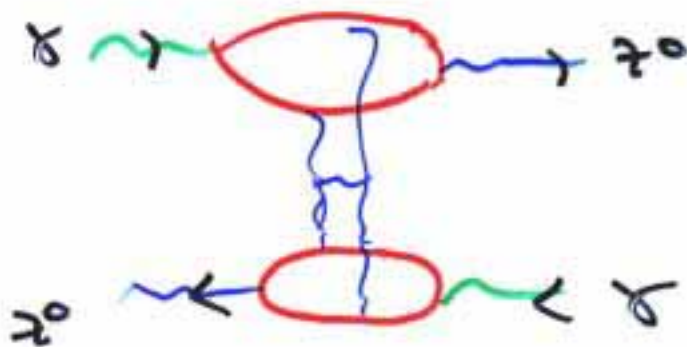
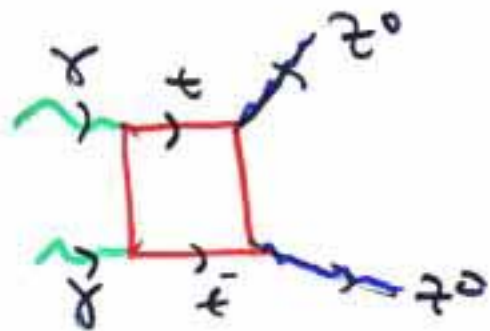
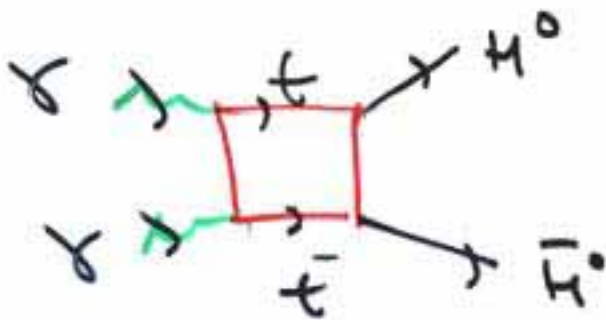


$e^- e^- \rightarrow \nu_e e^- H^-$
charged Higgs prod.

$W W \rightarrow W W$

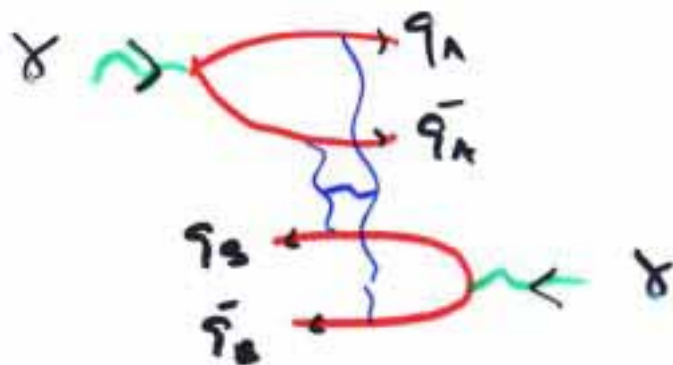
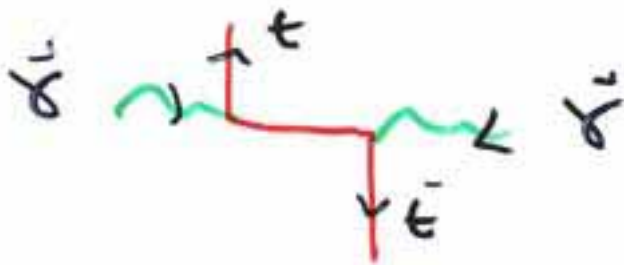


Exclusion EW $\gamma\gamma$ Processes



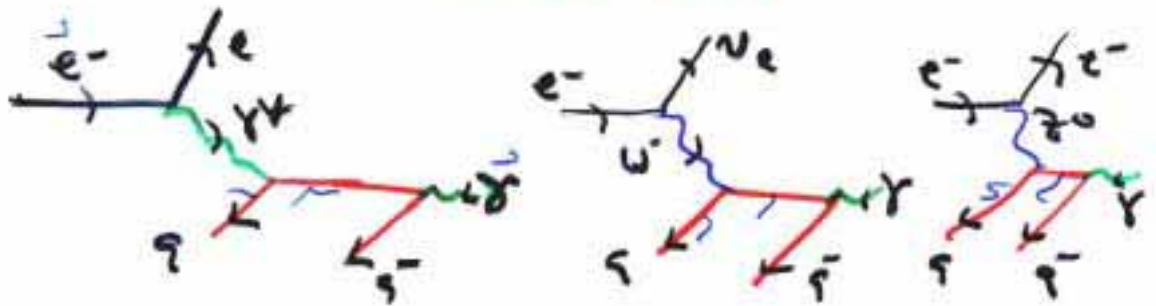
BFL
How QCD
Power

Primary QCD Tests



total $\gamma\gamma \rightarrow h h m m$
 DFLL
 $\sigma \sim s^{d_p-1}$

Photon Structure Functions



with $\log Q^2$

$F_1(x, Q^2), F_2(x, Q^2), F_3(x, Q^2)$

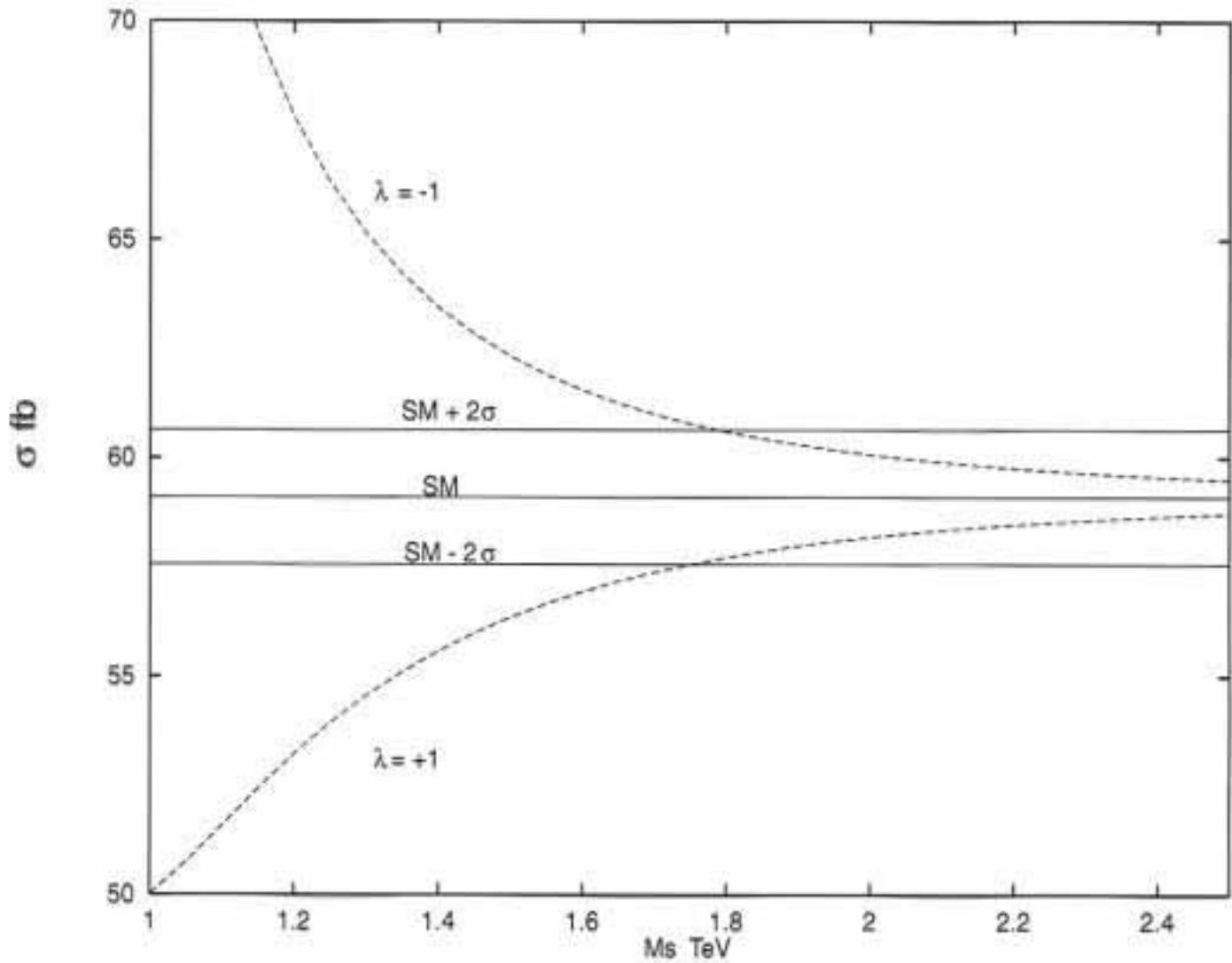
$\tilde{g}_1(x, Q^2) \dots$

charged, neutral current

$q, \bar{q} \ll \gamma$; low x : $\frac{1}{x^2}$

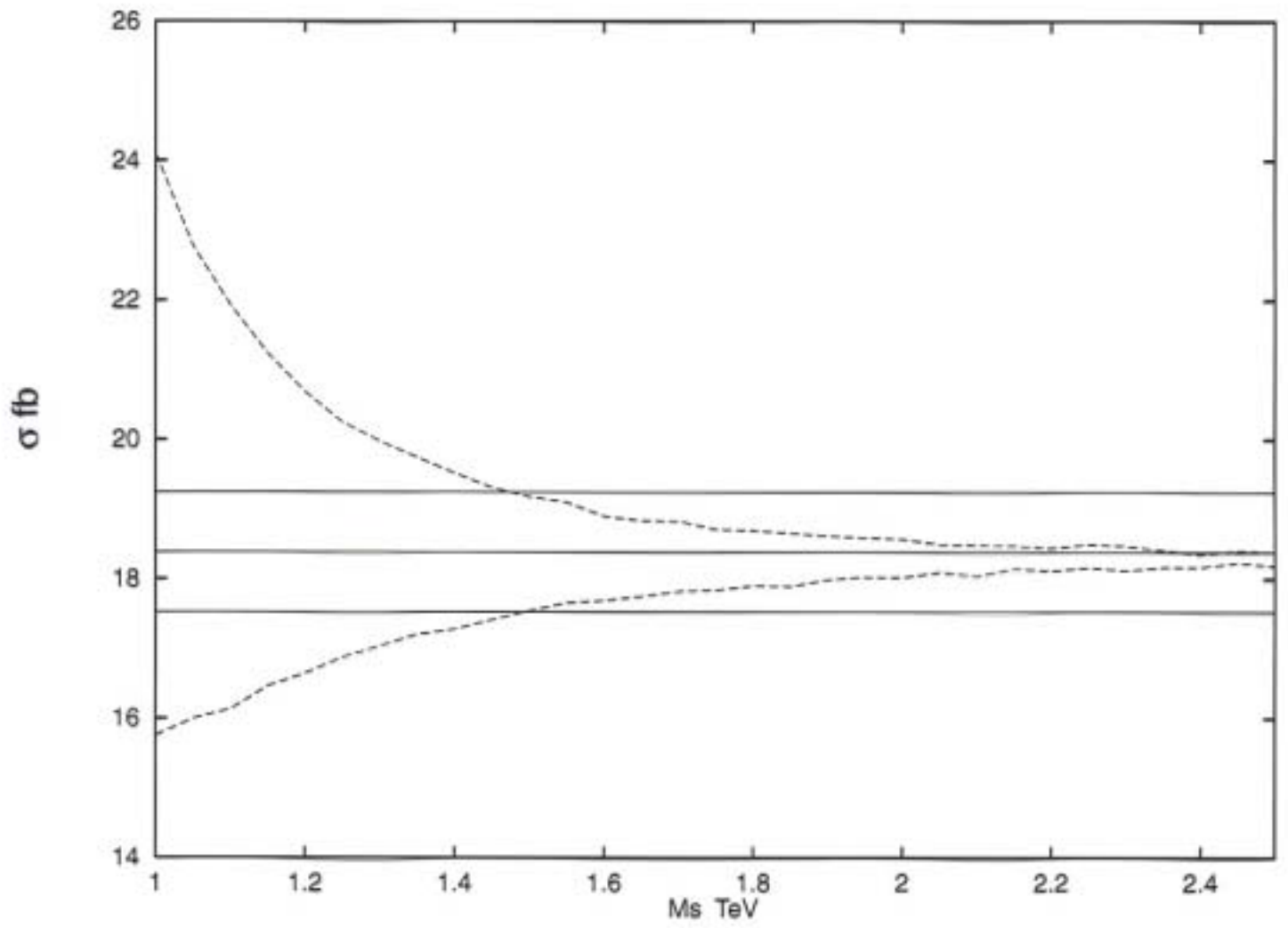
$$\vec{\gamma}\vec{\gamma} \rightarrow t\bar{t}$$

ADD
extra dimensions

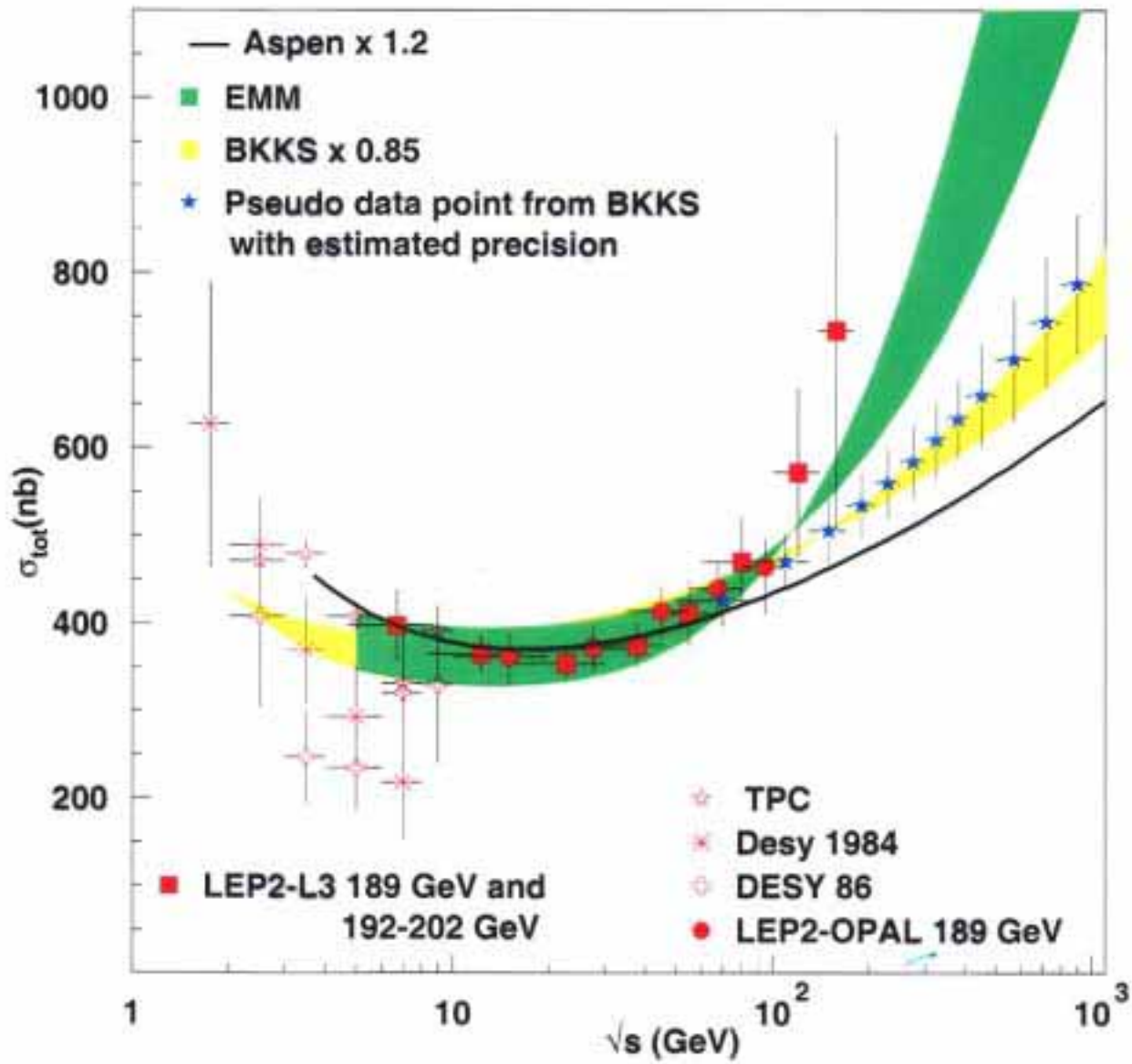


$\gamma\gamma \rightarrow t\bar{t}$
Godwin, et al

$\gamma\gamma \rightarrow W^+W^-$
Pizzo
hep-ph/0008037

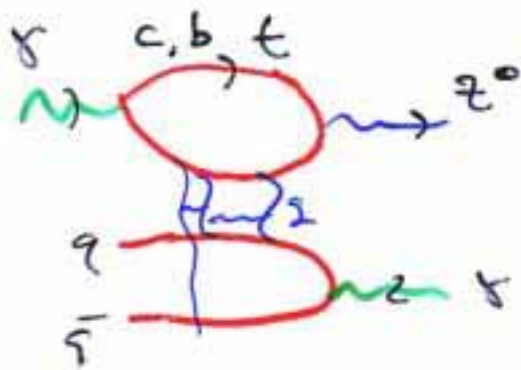


E. laud Ami-dab

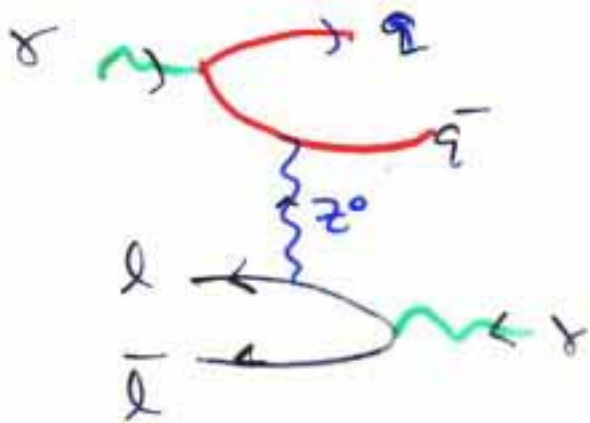


$\sigma(\gamma\gamma \rightarrow X)$

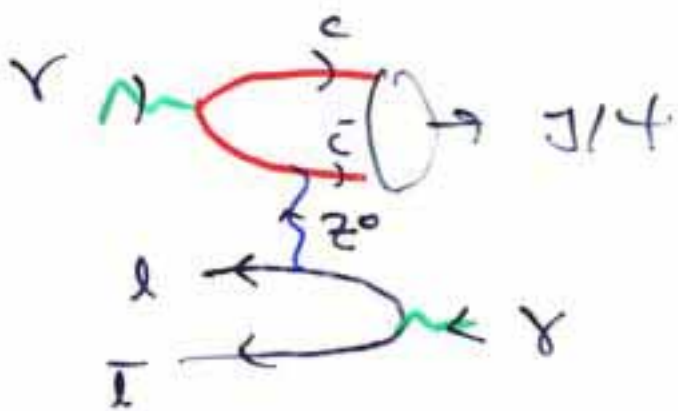
hep/ph/0705071
Gudgate
De Boer
Crew
Pacheco



test of RFL
 QCD Param
 of $(\alpha_s \sim 0.12)$

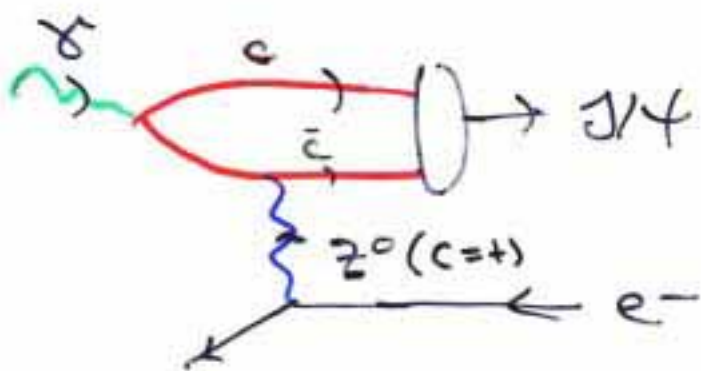


$$\sigma \sim S^0 \ln^2 S$$



Semi-exclusive

$$\sigma \sim S^1 \ln^2 S$$



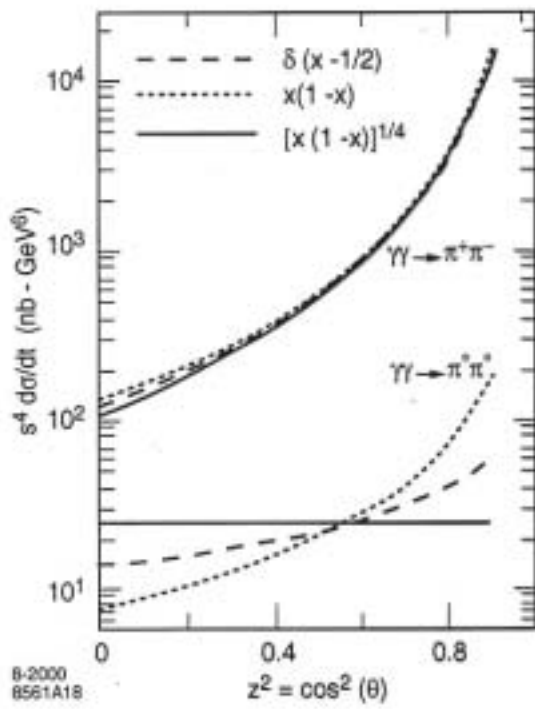
$$-t = 0^2$$

probe $Z^0 \gamma \rightarrow J/\psi, \nu$

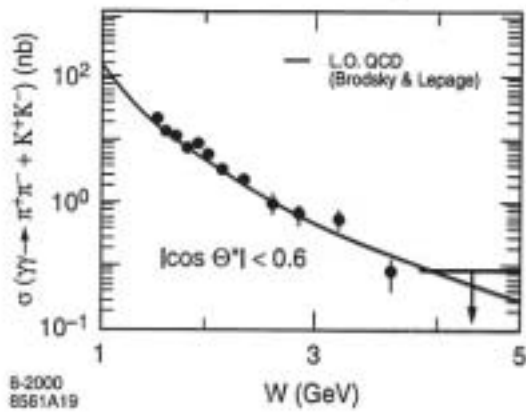
energy $\gamma \gamma \rightarrow \pi^0$

$$\sigma \sim \frac{A_{J/\psi}^2}{|t|} \sigma_{\pi^0}$$

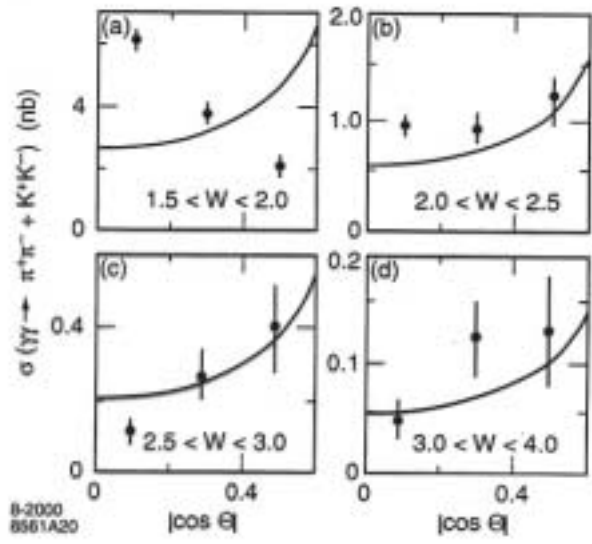
Produces J/ψ at high p_T



Generative to
 heavy meson production
 $\gamma\gamma \rightarrow \bar{B}_c B_c$



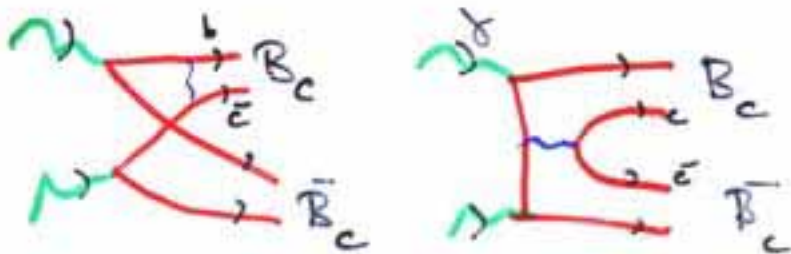
B-2000
 8561A19



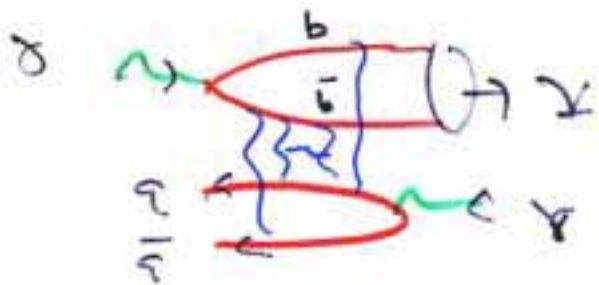
B-2000
 8561A20

QCD Tests at $\gamma\gamma$, γe colliders

Exclusive Meson - Pair Production



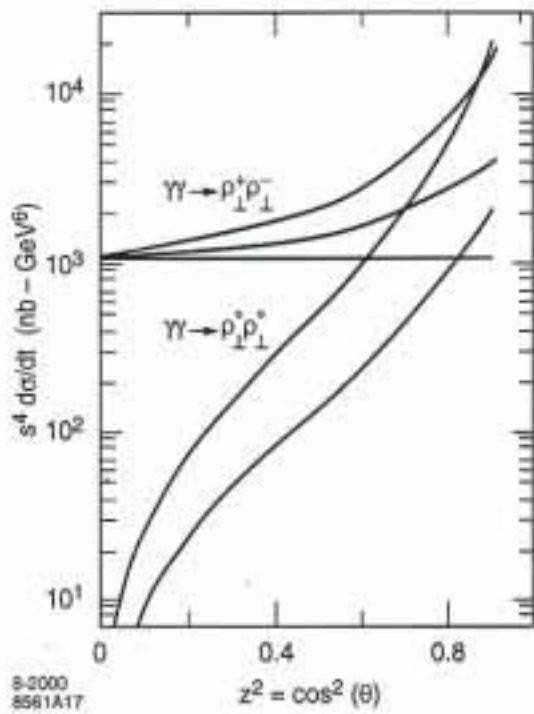
$\gamma\gamma \rightarrow B\bar{B}, B^+\bar{B}^-, B^+\bar{B}^+, B^-\bar{B}^-$, γX
↑
semi-exclusive



semi-exclusive

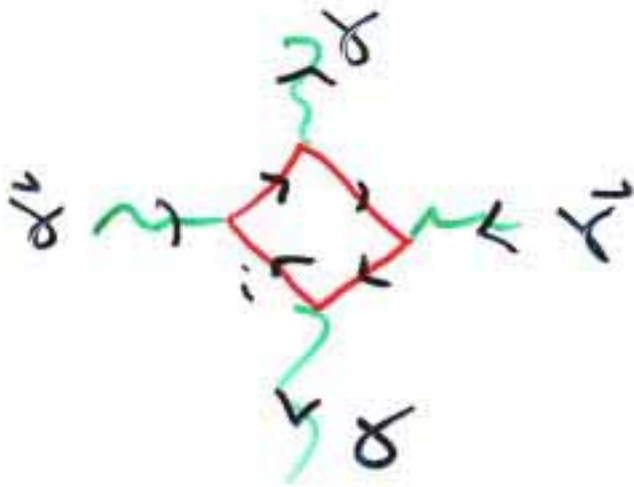
$$M \sim S^{\alpha(t)}$$

BFKL pom.



Extd +
 $\gamma\gamma \rightarrow B_c^+ B_c^-$

Light-by-Light Scattering



<015177107

$$M \sim \sum_i e_i^4 F_i(s, t)$$

at small t : $M \sim \frac{t^2}{M_i^4}$

at large t : sensitive to high mass
 $M_i^2 \sim |t|$

Input to $(S^{-2})_m$

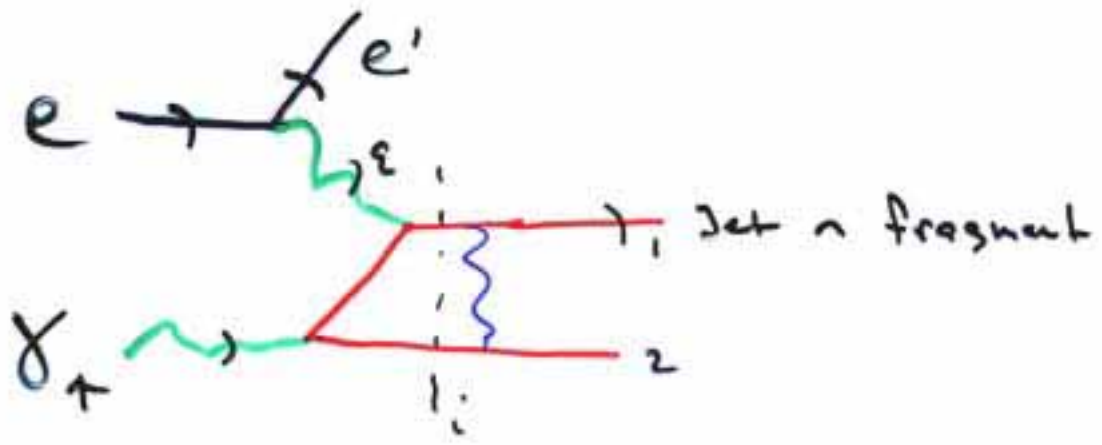
$$\gamma\gamma \rightarrow \gamma\gamma$$

Gaussian
 ch-d

Single Spin Asymmetric

$$\rightarrow i \vec{S}_y \cdot \vec{P}_i \times \vec{P}_f$$

$$i \epsilon_{\mu\nu\rho\sigma} S_y^\mu k_1^\nu k_2^\rho k_3^\sigma$$



SSA: Measure orb. ang. non. in plane LFWF

"Sivers Effect"

See at HERMES JLab

$$i \vec{S}_y \cdot \vec{q} \times \vec{P}_i$$

leading twist!

Heavy
Schw
S13

Also ep SSA

These require γ tag "jet et

A-A collisions:

Fraction of $\sqrt{s_{NN}}$ converted to high density
 q, \bar{q} medium

materialize as hadrons $\sim 10^4$

hot, dense hadronic system

$\frac{dN}{dy}$ uniform: is limited by energy avail.



more hadrons produced
transverse to
principal axis

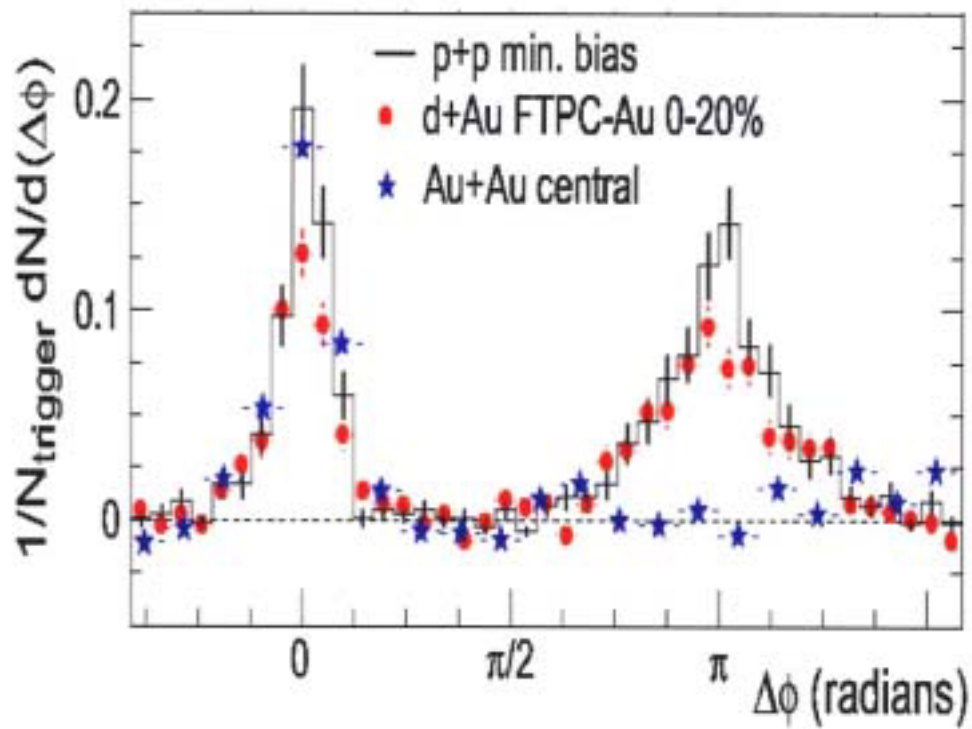
\Rightarrow production axis

Correlation
between
event and production axes

$$V_2(p_T) = \langle \cos(\phi_{p_T} - \phi_0) \rangle$$

High p_T particles aligned with event axis!

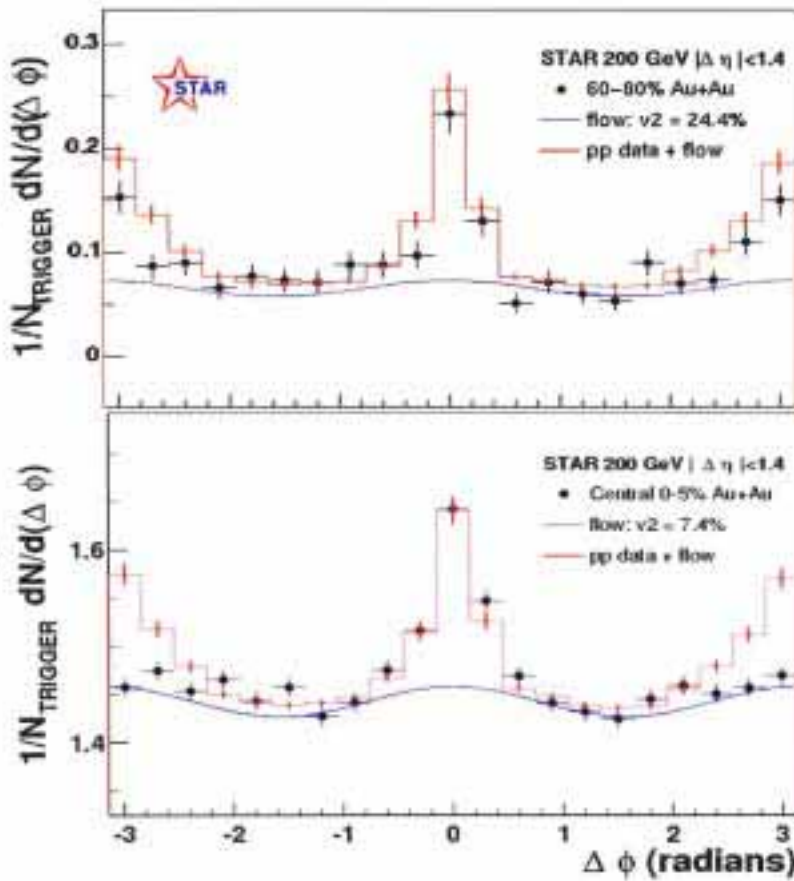
away side jet strongly suppressed



Removable
 suppression
 of away side
 particles

STAR Collab.
 PRL91, 072304 (2003)

Periph.:



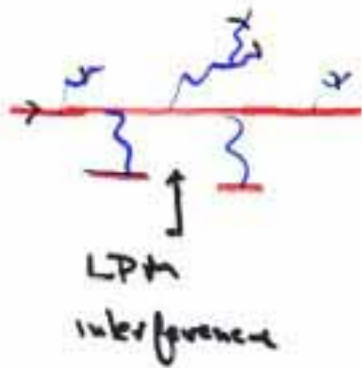
Trigger particle aligns with event plane

Red histogram: p+p (+flow)
Black points: Au+Au
Blue curve: flow contribution

Central:

P. Jacobs, J. Klay
(STAR Collab.)
nucl-ex/0308023

Energy Loss of Quarks



$$\frac{dE}{dx} \sim 0.5 \frac{\text{GeV}}{\text{fm}} \quad \text{in cold matter}$$

(including elastic collisions)

Away side suppression in $A_1 A_2$ central collisions

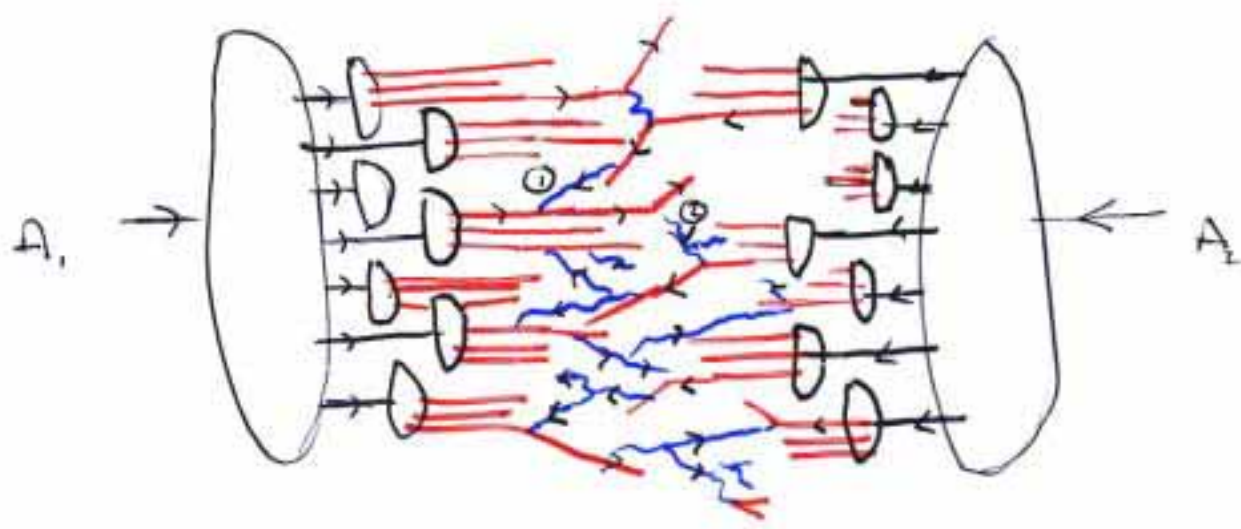
$$\frac{dE}{dx} \sim 15 \frac{\text{GeV}}{\text{fm}}$$

Increase by factor of ~ 30 !

X.N. Wang
M. Gyulassy

Strong evidence for $q-g$ plasma

Model for formation of QCD plasma



Analogy of back-scattered Qeber!



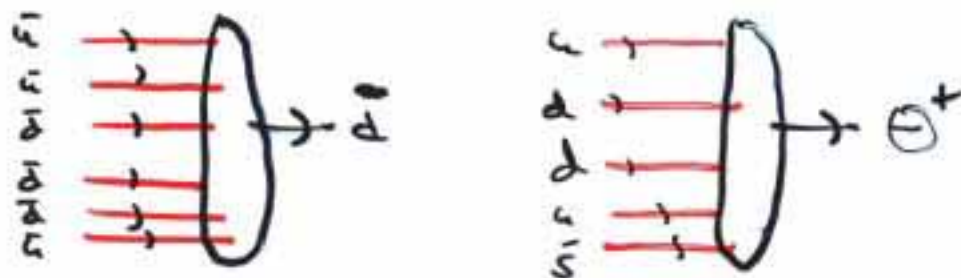
* Compton produce high energy polarized photon beam.

* In heavy ions : converts quark energy to gluon energy Gluon Avalanche!

* "Colliding nuclei": Cascading gluons
 { converts heavy ion energy to high density gluons, qq

q, \bar{q} plasma

multiquark condensation



look for exotic hadrons, glueballs

cascading flows \Rightarrow multiquark systems

What are critical parameters?

$$A_1, A_2$$
$$\sqrt{\delta A_1, A_2}$$