Physics at a Linear Collider

— Basic Knowledge and Techniques

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ILC Workshop/Summer School,
TsingHua University, Beijing, China
(July 15 – 20, 2005)

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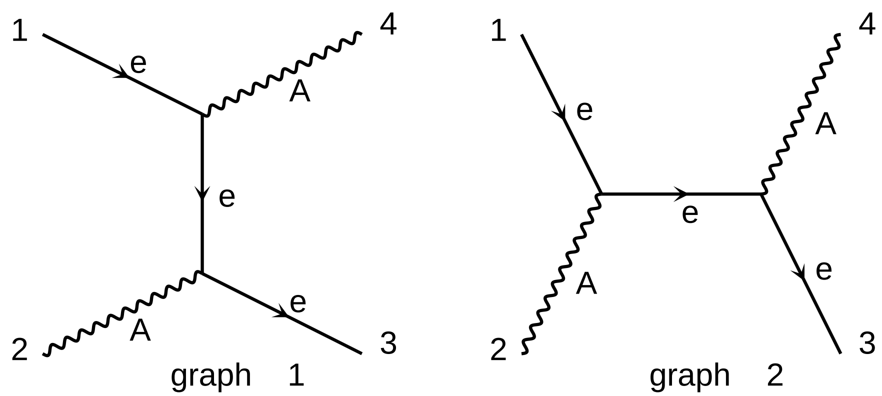
I. Basics for e^+e^- Physics: SM expectations
II. Beyond the SM: SUSY and CP Violation
III. Other Operational Modes of a Linear Collider
IV. Techniques and Tools
V. High Energy Physics: Where We Are

III. Other Operational Modes of an e^+e^- Collider

$e^-\gamma$ and $\gamma\gamma$ Options:

Let us first consider $e^-\gamma$ Collisions

Diagrams by MadGraph



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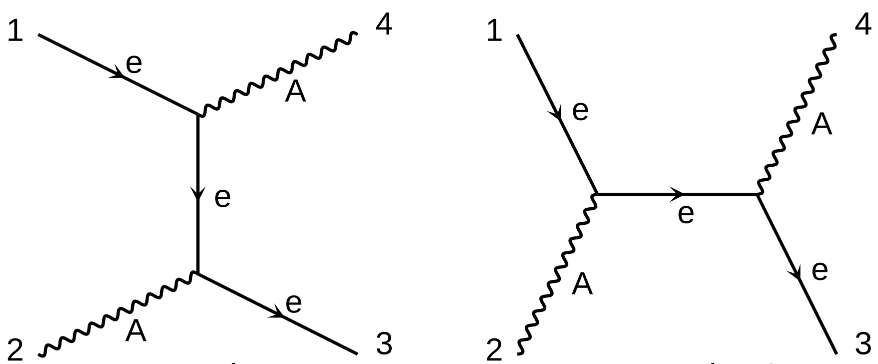
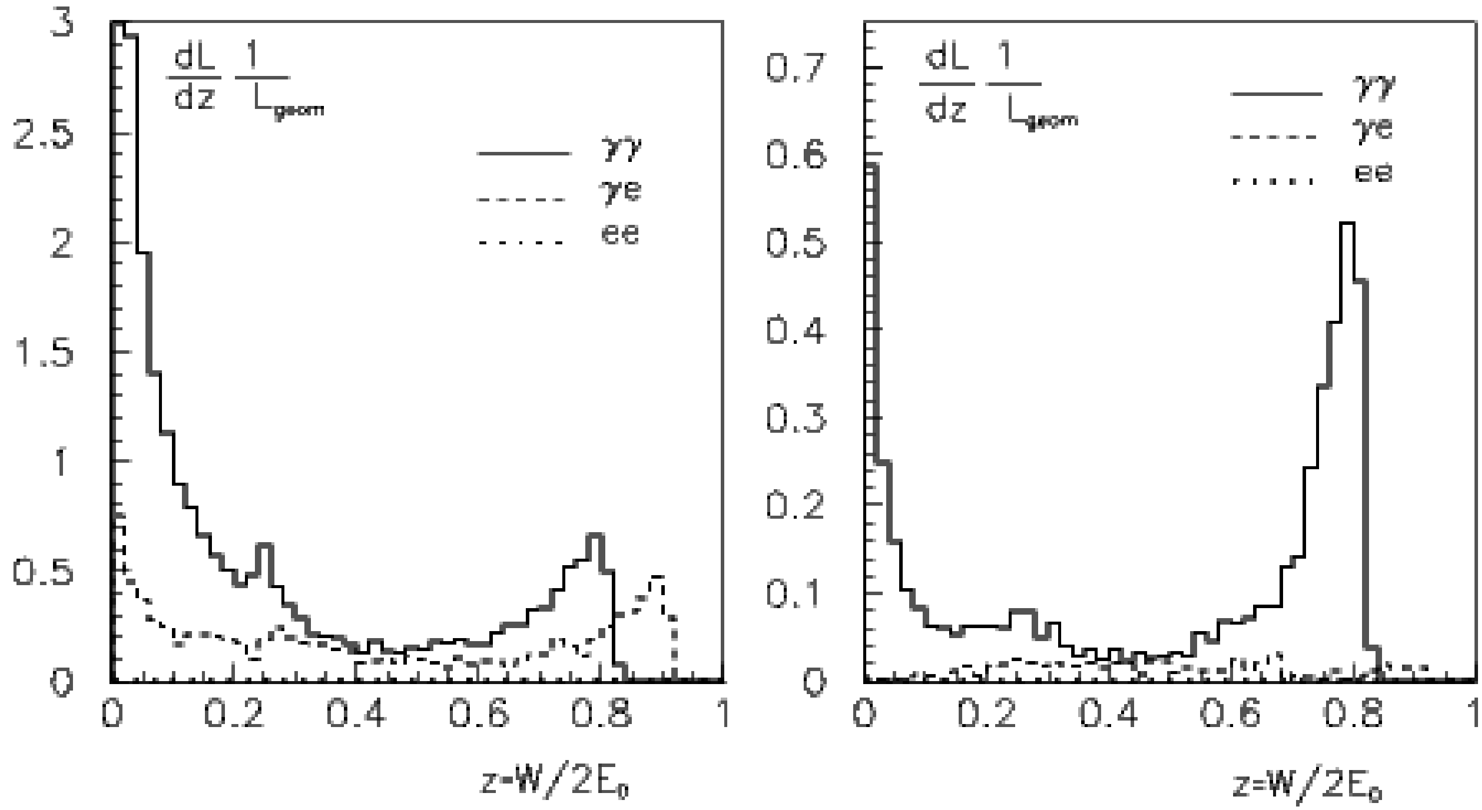


graph 1 graph 2

Homework III-1: Which diagram is singular and what would be the physical implication?

Realistic luminosity spectra:



Formally,

$$P_{\gamma/e} \propto 1 - x + \frac{1}{1-x} - \frac{4x}{\eta(1-x)} + \frac{4x^2}{\eta^2(1-x)^2}$$
$$- 2\lambda_e p_c\left(\frac{x}{1-x} - \frac{2x^2}{(1-x)^2\eta}\right)(2-x).$$

when $2\lambda_e p_c = -1$, it peeks at 90% for $e\gamma$ and 80% for $\gamma\gamma$.

Major advantages for an $e\gamma$ Collider:

- Single fermion production and lower new physics threshold,
- Sensitive to electron flavor oscillation.

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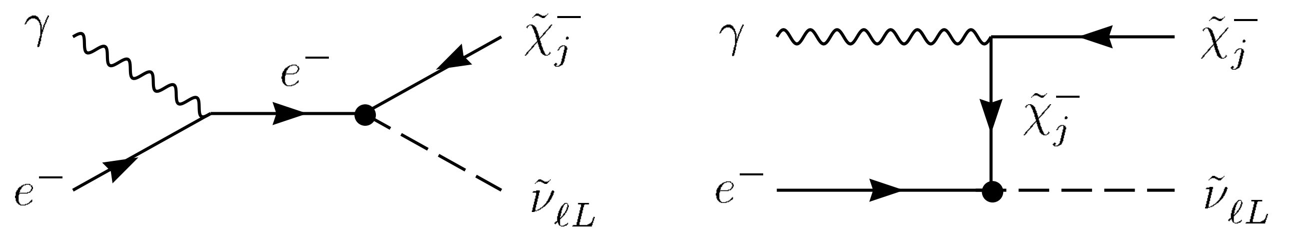
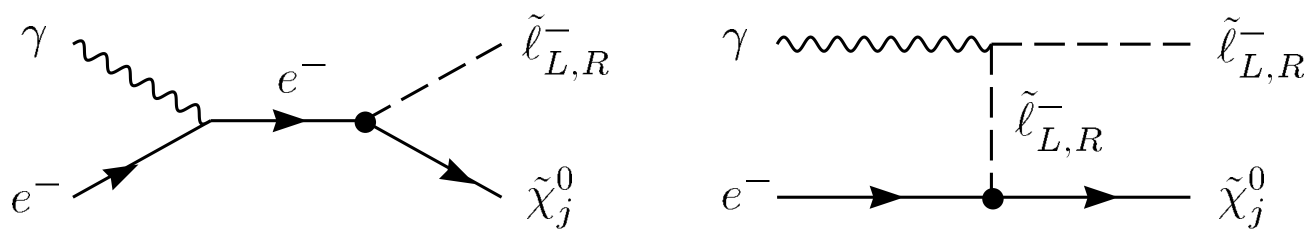
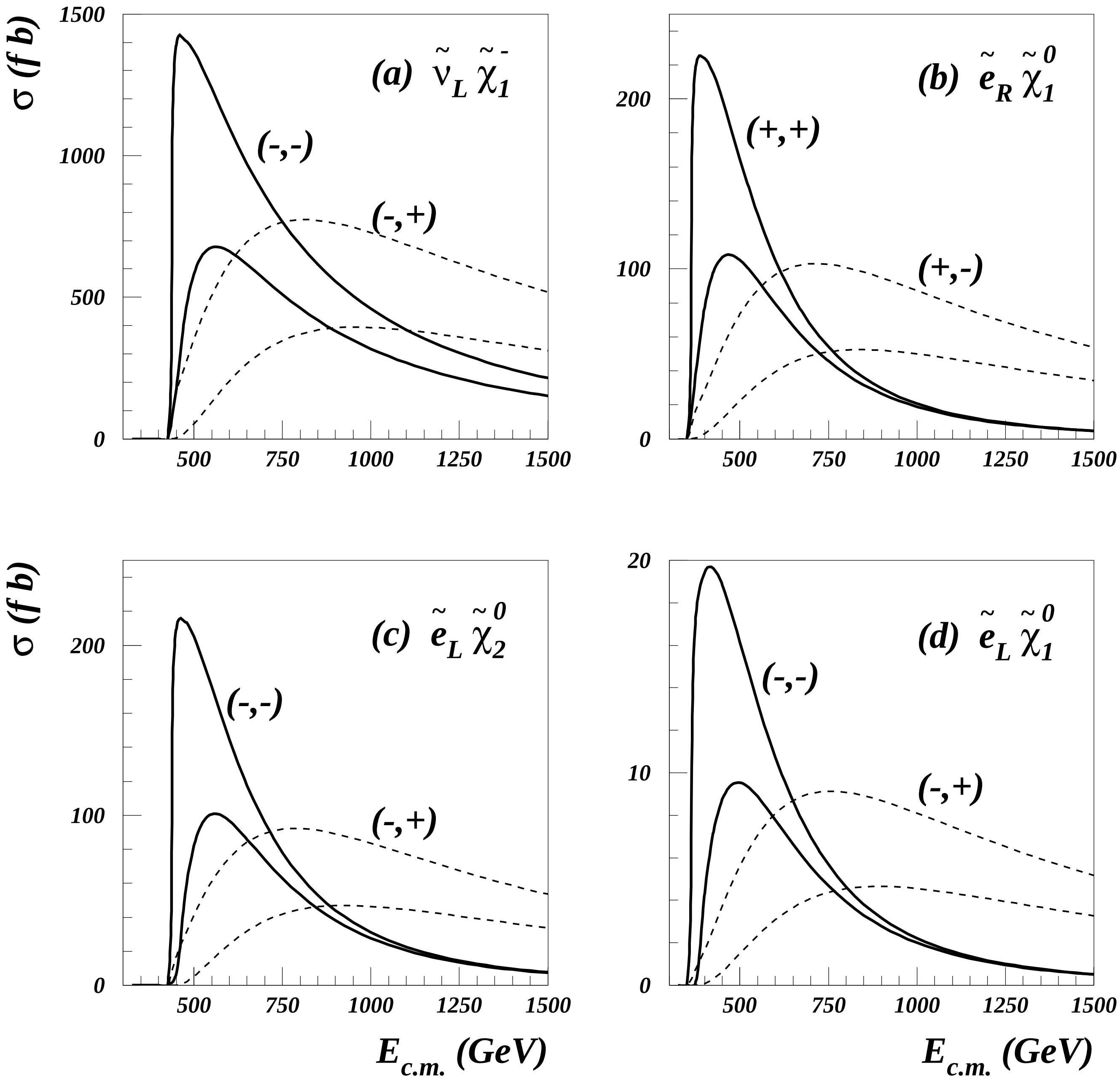
SUSY Example: Gaugino production



(a)



(b)



σ (f b)
(a) $\tilde{\nu}_L \tilde{\chi}_1^-$
(-,-)
(-,+)
(b) $\tilde{e}_R \tilde{\chi}_1^0$
(+,+)
(+,-)
(c) $\tilde{e}_L \tilde{\chi}_2^0$
(-,-)
(-,+)
(d) $\tilde{e}_L \tilde{\chi}_1^0$
(-,-)
(-,+)
$E_{c.m.}$ (GeV)

$\gamma\gamma$ Collisions

Important features for a $\gamma\gamma$ Collider:

- Allow high energy and high luminosity

  $E_{\gamma\gamma} \sim 0.8\ E_{e^+e^-},\ L_{\gamma\gamma} \sim (0.1 - 0.3)\ L_{e^+e^-}.$
- Angular momentum states:

  For circular polarizations: $J_Z = 0,\ 2\ \Rightarrow$ Higgs or gravitons!

  e.g. $\gamma\gamma \to X \to W^+W^-,\ t\bar{t},\ ,,,$

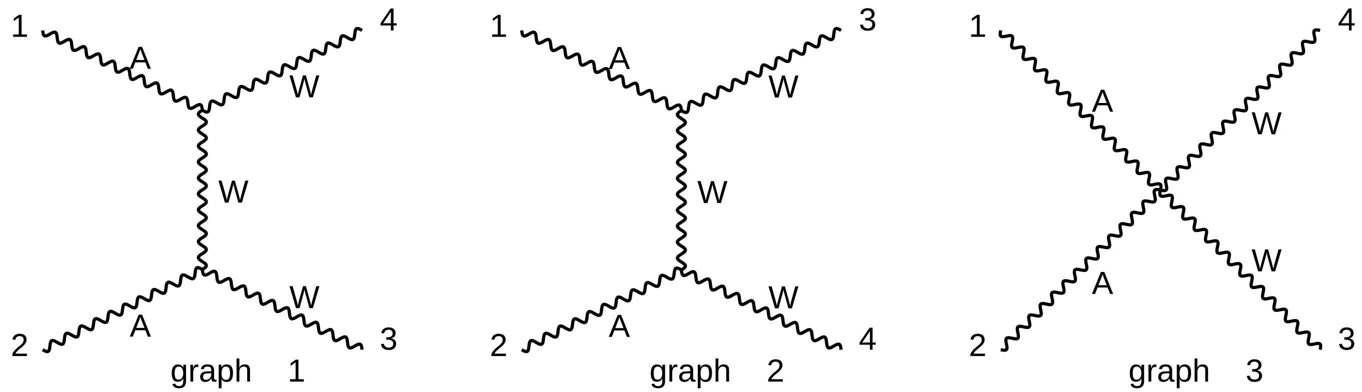
  complementary to $e^+e^-\ J_Z = 1.$

  For linear polarizations: CP properties with respect to

  the polarization direction scalar versus pseudo scalar: H, A.

  e.g. $\gamma\gamma \to H,\ A,\ QED \to W^+W^-,\ t\bar{t},\ ,,,$

Diagrams by MadGraph



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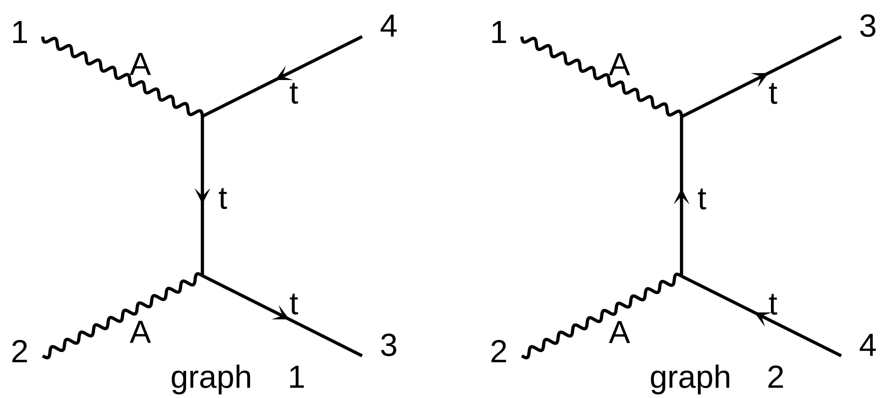
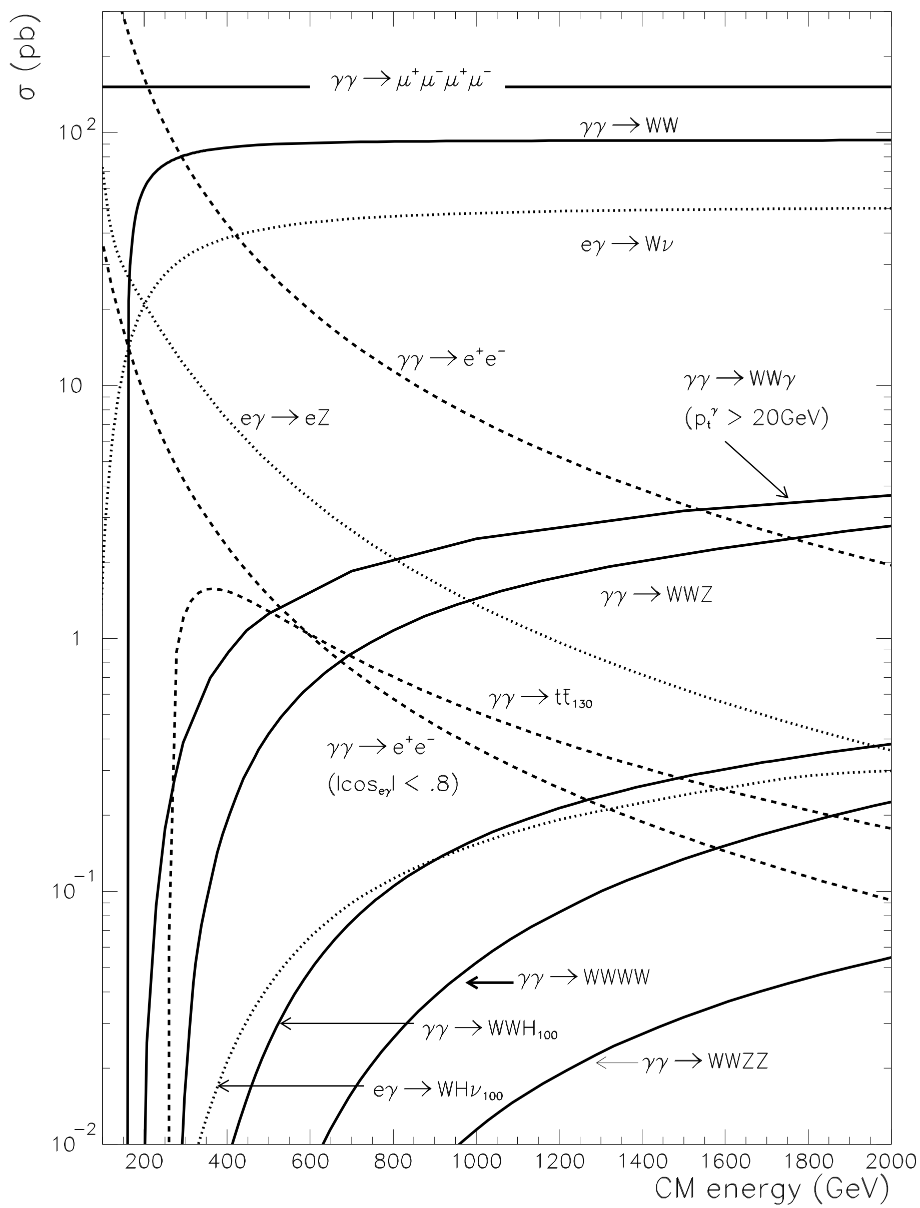
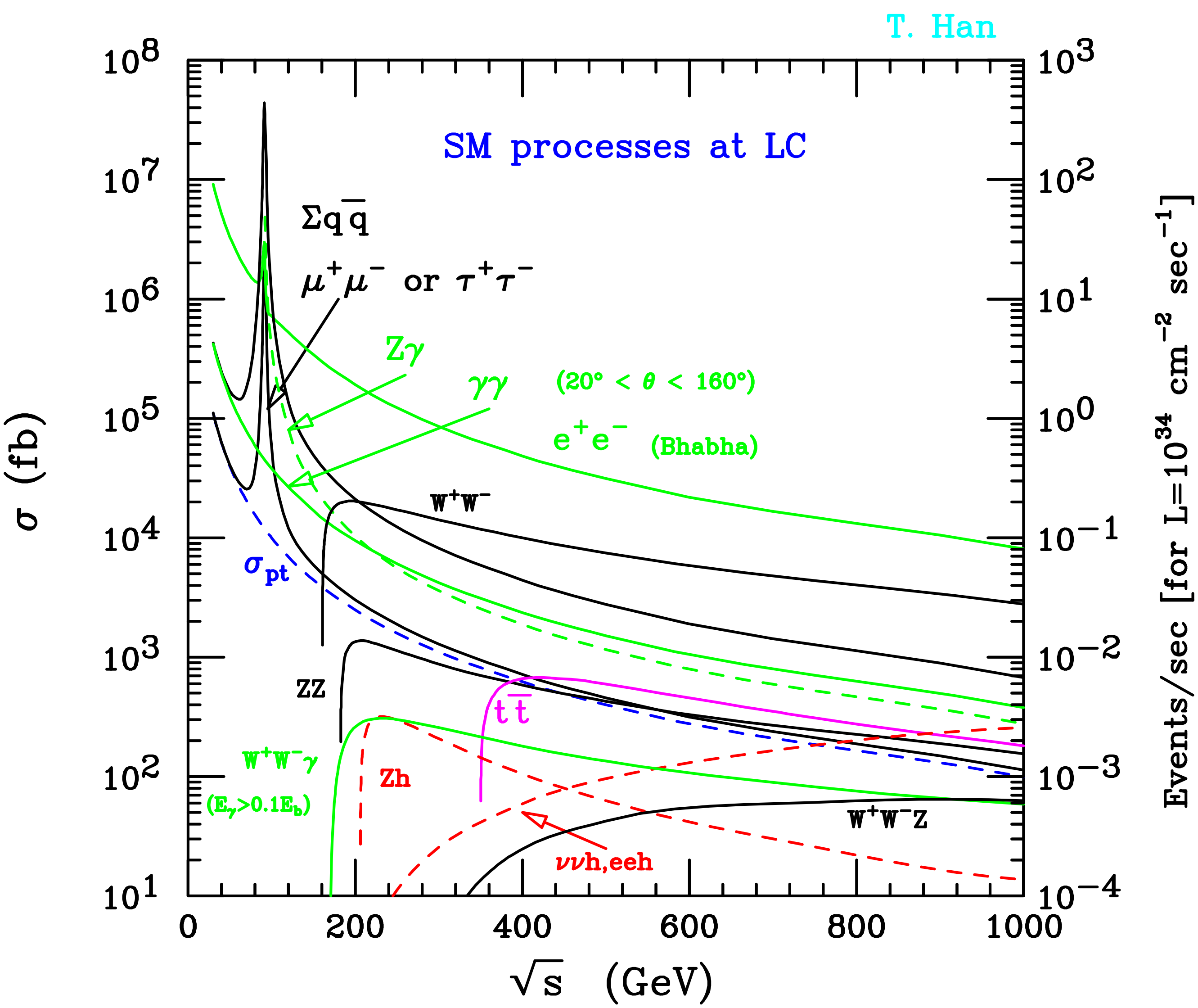


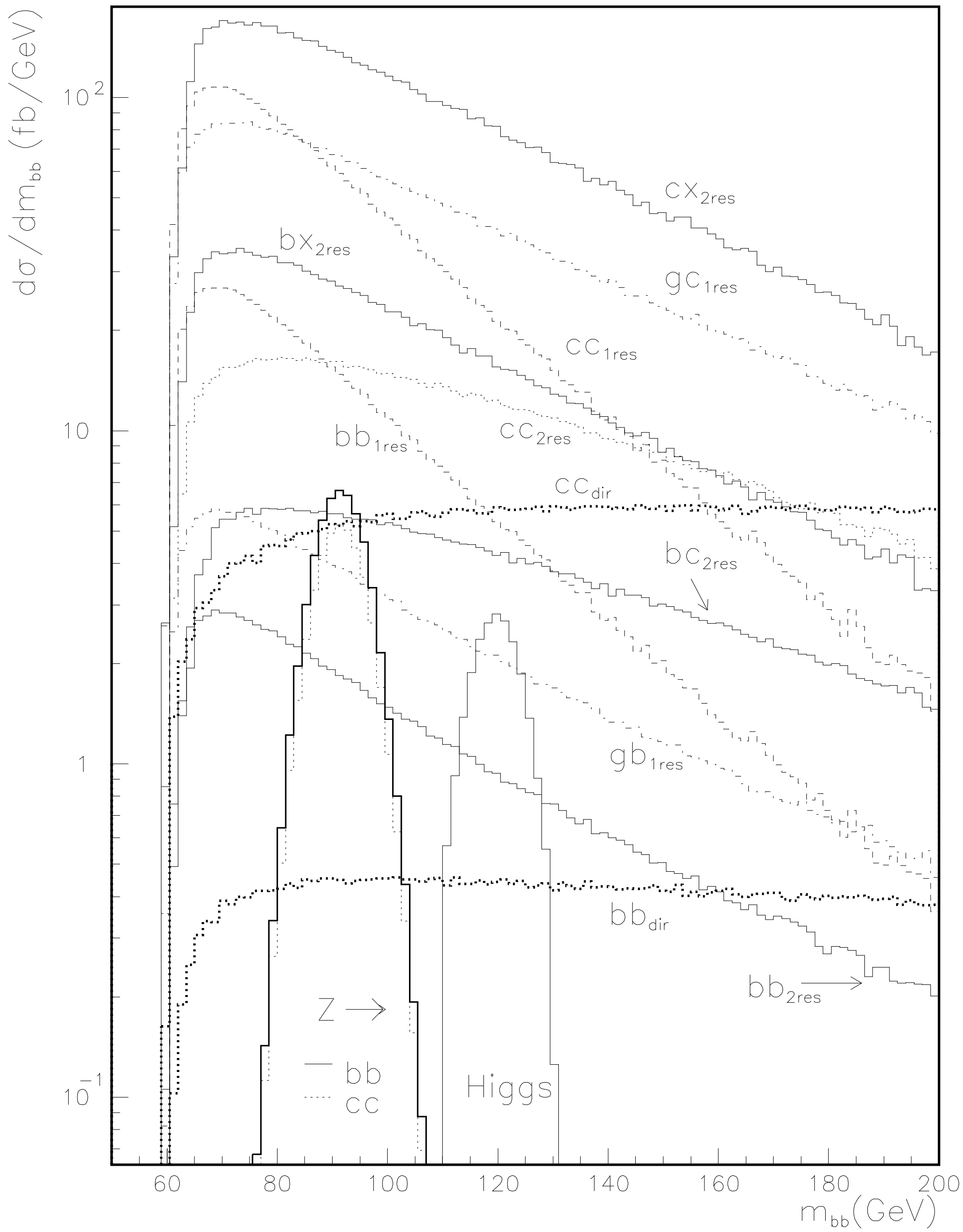
Total cross sections for $e\gamma$, $\gamma\gamma$ Collisions:



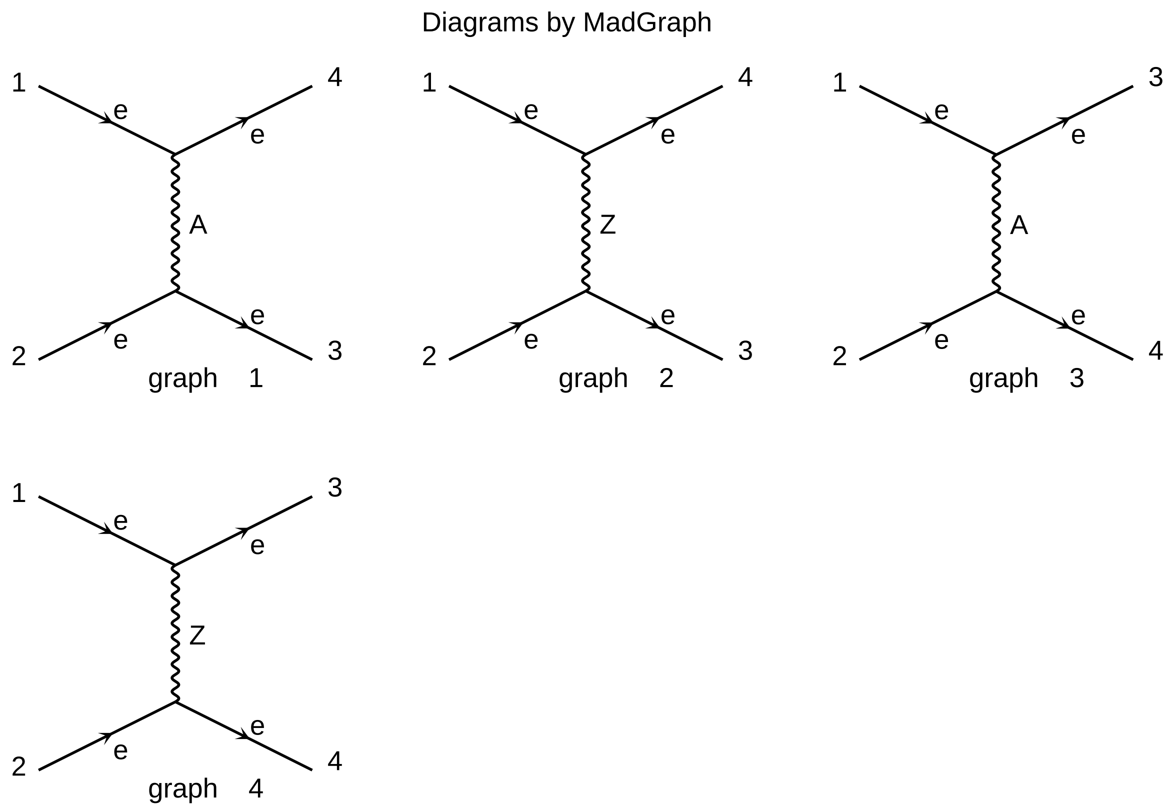
For comparison, recall that:



Example: $\gamma\gamma \to H$: Resonance signal



e^-e^- Collisions



Unique Features:

- Easy to impliment for e^-e^- collisions;
  luminosity a little lower: $L_{e^-e^-} \sim (0.1 - 0.3)\ L_{e^+e^-}$. Think: why?
- Disadvantage: $L = 2$, so that it's all Möller scattering (almost).

- Advantage: $L = 2$, sensitive to new physics:

$$
\begin{aligned}
e^-_L e^-_L &\to W^- W^- \quad \text{via Majorana } \nu' s, \\
&\to \nu\nu W^- W^- \quad I = 2\ WW \text{ strong scattering}, \\
&\to \nu\nu H^{--} \quad \text{extended Higgs sector}, \\
&\to \tilde{e}_L \tilde{e}_L; \quad \text{neutralino exchange, s} - \text{wave near threshold},
\end{aligned}
$$

$$
\begin{aligned}
e^-_L e^-_R &\to \tilde{e}_L \tilde{e}_R; \\
e^-_R e^-_R &\to \tilde{e}_R \tilde{e}_R.
\end{aligned}
$$

In contrast, $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ all via P-wave. `Think: sure you know why.`

Although $e^-e^- \to W^-W^-$ via Majorana ν's extremely interesting, the bound from neutrinoless double-β decay $(0\nu2\beta)$ is too severe.

`Homework III-2: Draw a Feynman diagram for` $0\nu2\beta$ `via a Majorana neutrino.`

The only Higgs signal from ZZ fusion:

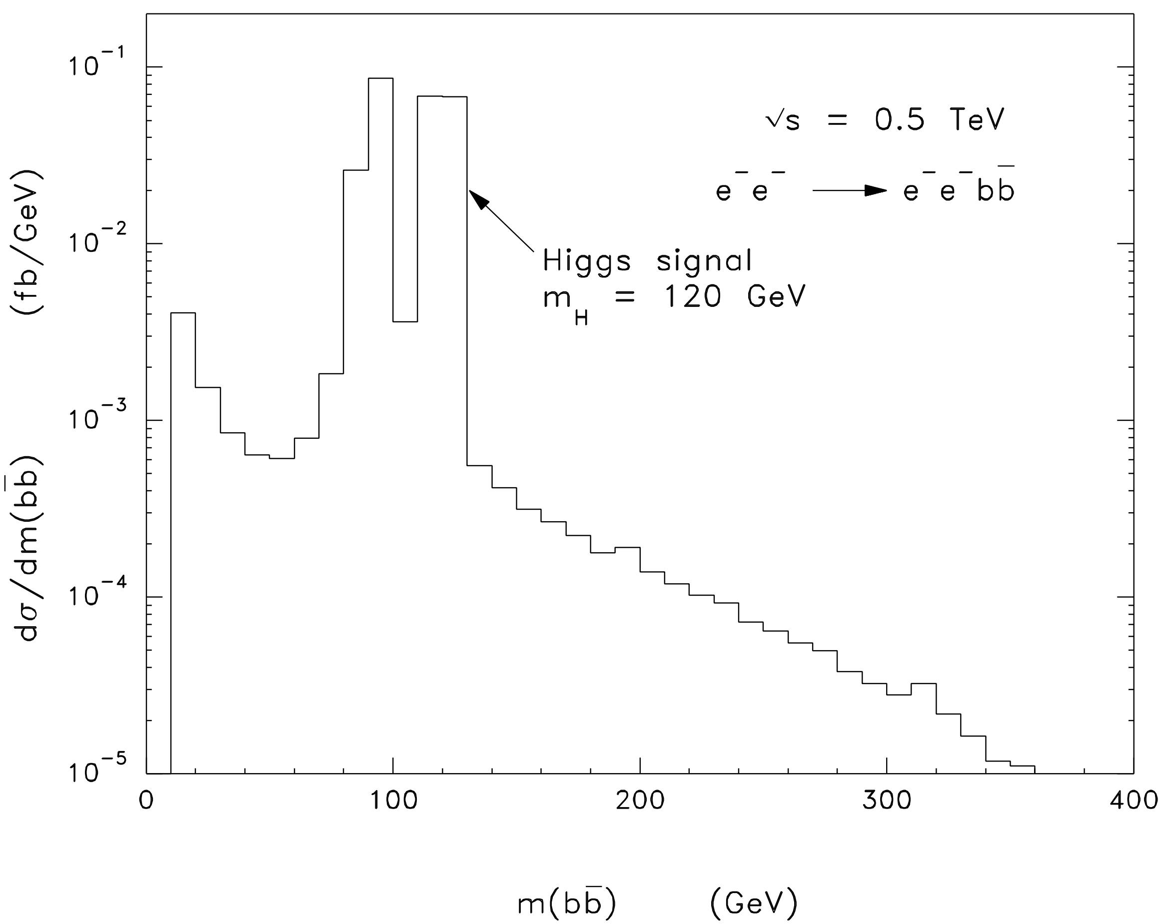


Fig. 7

The doubly charged Higgs signal:

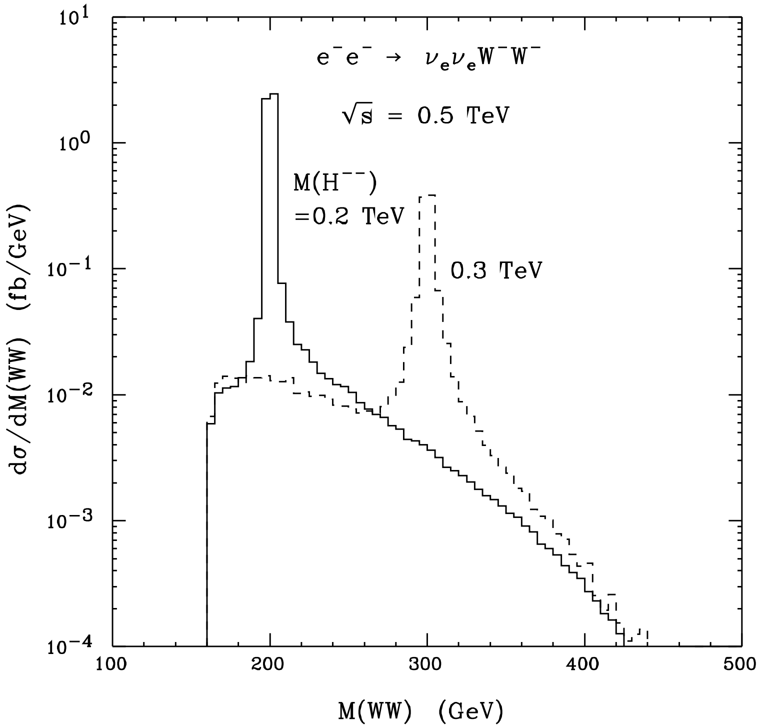


Fig. 11

Giga Z Options

Setting $\sqrt{s} = M_Z$, creating 10^9 Z's .

Thus, with e^+ polarization as well,

$$\frac{\delta\delta M_Z}{M_Z} \sim 2 \times 10^{-8}, \quad \frac{\delta\alpha_{em}(M_Z^2)}{\alpha_{em}(M_Z^2)} \sim 2.5 \times 10^{-4},$$
$$\frac{\delta A_{LR}}{A_{LR}} \sim 4 \times 10^{-5}, \quad \delta \sin^2\theta_W \sim 10^{-5}.$$

$\Rightarrow$ very powerful EW constraints.

IV. Techniques and Tools

Basic Techniques

- Traditional "Trace" Techniques:
  - * You should be good at this — QFT course!

  With algebraic symbolic manipulations:
  - * REDUCE
  - * FORM
  - * MATHEMATICA, MAPLE ...

- Helicity Techniques: More suitable for direct numerical evaluations.
  - * Hagiwara-Zeppenfeld: best for massless particles... (NPB)
  - * CalCul Method (by T.T. Wu et al., Parke-Mangano: Phys. Report);

  `Homework III-3: Work out the helicity amplitude for` $e^+e^- \to ZZ$.

- Phase space treatment:

$$dPS_n = \Pi_i^n \frac{1}{(2\pi)^3} \frac{d^3\vec{p}_i}{2E_i} (2\pi)^4 \, \delta(P - \sum_i^n p_i)$$

Must know (well)

* Two-body kinematics
* Three-body kinematics
* Reduction formula, e.g.:

$$dPS_3 = dPS_2(i) \frac{dm_{prop}^2}{2\pi} dPS_2(f).$$

Calculational Tools

- Monte Carlo packages for phase space integration:

(1) VEGAS by P. LePage: adaptive important-sampling MC
http://en.wikipedia.org/wiki/Monte-Carlo_integration

(2) SAMPLE, RAINBOW, MISER ...

- Automated software for matrix elements:

(1) REDUCE — an interactive program designed for general algebraic computations, including to evaluate Dirac algebra, an old-time program,
http://www.uni-koeln.de/REDUCE;
http://reduce-algebra.com.

(2) FORM by Jos Vermaseren: A program for large scale symbolic manipulation, evaluate fermion traces automatically,
and perform loop calculations,s commercially available at
http://www.nikhef.nl/ form

(3) FeynCalc and FeynArts: Mathematica packages for algebraic calculations in elementary particle physics.
http://www.feyncalc.org;
http://www.feynarts.de

(4) MadGraph: Helicity amplitude method for tree-level matrix elements available upon request or
http://madgraph.hep.uiuc.edu

Example:
Standard Model particles include:
Quarks: d u s c b t d u s c b t
Leptons: e- mu- ta- e+ mu+ ta+ ve vm vt ve vm vt
Bosons: g a z w+ w- h

Enter process you would like calculated in the form e+ e- $\to$ a.
(return to exit MadGraph.)

a a $\to$ w+ w-

Generating diagrams for 4 external legs
There are 3 graphs.
Writing Feynman graphs in file aa_wpwm.ps
Writing function AA_WPWM in file aa_wpwm.f.

- Automated evaluation of cross sections:

(1)MadGraph/MadEvent and MadSUSY:
Generate Fortran codes on-line!
http://madgraph.hep.uiuc.edu

(2) CompHEP: computer program for calculation of elementary particle processes in Standard Model and beyond. CompHEP has a built-in numeric interpreter. So this version permits to make numeric calculation without additional Fortran/C compiler. It is convenient for more or less simple calculations.

— It allows your own construction of a Lagrangian model!

http://theory.npi.msu.su/k̃ryukov

(3) GRACE and GRACE SUSY:
http://minami-home.kek.jp

(4) Pandora by M. Peskin:
C++ based package for e^+e^-, including beam effects.

http://www-sldnt.slac.stanford.edu/nld/new/Docs/Generators/PANDORA.htm

The program pandora is a general-purpose parton-level event generator which includes beamstrahlung, initial state radiation, and full treatment of polarization effects. (An interface to PYTHIA that produces fully hadronized events is possible.)

This version includes the SM physics processes:

$$
\begin{aligned}
e^+e^- &\to \ell^+\ell^-,\ q\bar{q},\ \gamma\gamma,\ t\bar{t},\ Z\gamma,\ ZZ,\ W^+W^- \\
&\to Zh,\ \nu\bar{\nu}h,\ e^+e^-h,\ \nu\bar{\nu}\gamma \\
\gamma\gamma &\to \ell^+\ell^-,\ q\bar{q},\ t\bar{t},\ e^+e^-,\ W^+W^-,\ h \\
e\gamma &\to e\gamma,\ eZ,\ \nu W \\
e^-e^- &\to e^-e^-.
\end{aligned}
$$

and some illustrative Beyond the SM processes:

$$
\begin{aligned}
e^+e^- &\to Z' \to \ell^+\ell^-,\ q\bar{q} \\
&\to KK - gravitons \to \ell^+\ell^-,\ q\bar{q},\ \gamma\gamma,\ ZZ,\ W^+W^- \\
&\to \gamma\ graviton \\
&\to \rho_{TC}W^+W^-.
\end{aligned}
$$

- Numerical simulation packages:

(1) PYTHIA:

PYTHIA and JETSET are programs for the generation of high-energy physics events, i.e. for the description of collisions at high energies between elementary particles such as e+, e-, p and pbar in various combinations. Together they contain theory and models for a number of physics aspects, including hard and soft interactions, parton distributions, initial and final state parton showers, multiple interactions, fragmentation and decay.
http://www.thep.lu.se/ torbjorn/Pythia.html

(2) ISAJET
ISAJET is a Monte Carlo program which simulates p-p, pbar-p, and e-e interactions at high energies. It is based on perturbative QCD plus phenomenological models for parton and beam jet fragmentation.
http://www.phy.bnl.gov/ isajet