Extra Dimensions At DELPHI & LEP
An Overview.

- DELPHI $\rightarrow$ Detector at LEP $\mathrm{e^+e^-}$ collider.
- DELPHI $\rightarrow$ Collaboration of ~550 physicists, 56 institutes, 22 countries.
- LEPII C.O.M energies 1996-2001 :

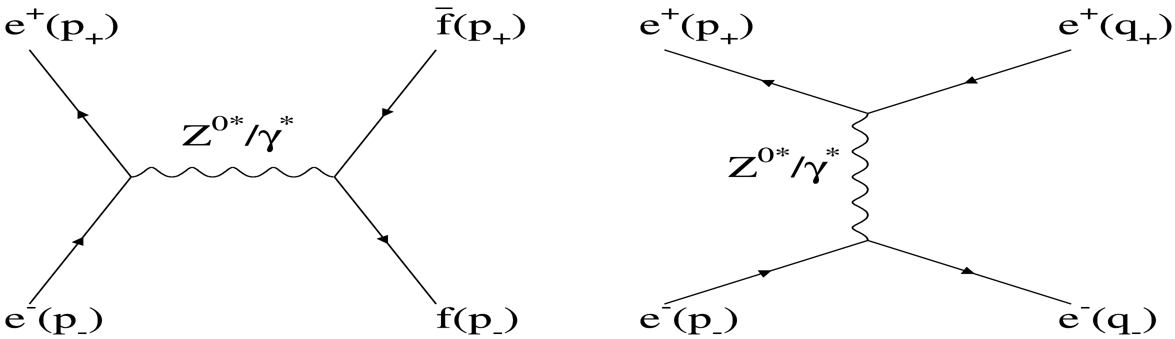
$$161\ \mathrm{GeV} \rightarrow 210\ \mathrm{GeV}$$
$$(\mathrm{W^+W^-} \rightarrow \mathrm{ZH^0}) \quad .$$

- 1996-2001 DELPHI collects ~ 1,000,000 hard scattering events.
- Biggest & most energetic lepton collider ~20 MW (local power station) in synchrotron.
- Lepton collider $\Rightarrow$ clean environment.
- Highly sophisticated detectors & data analyses

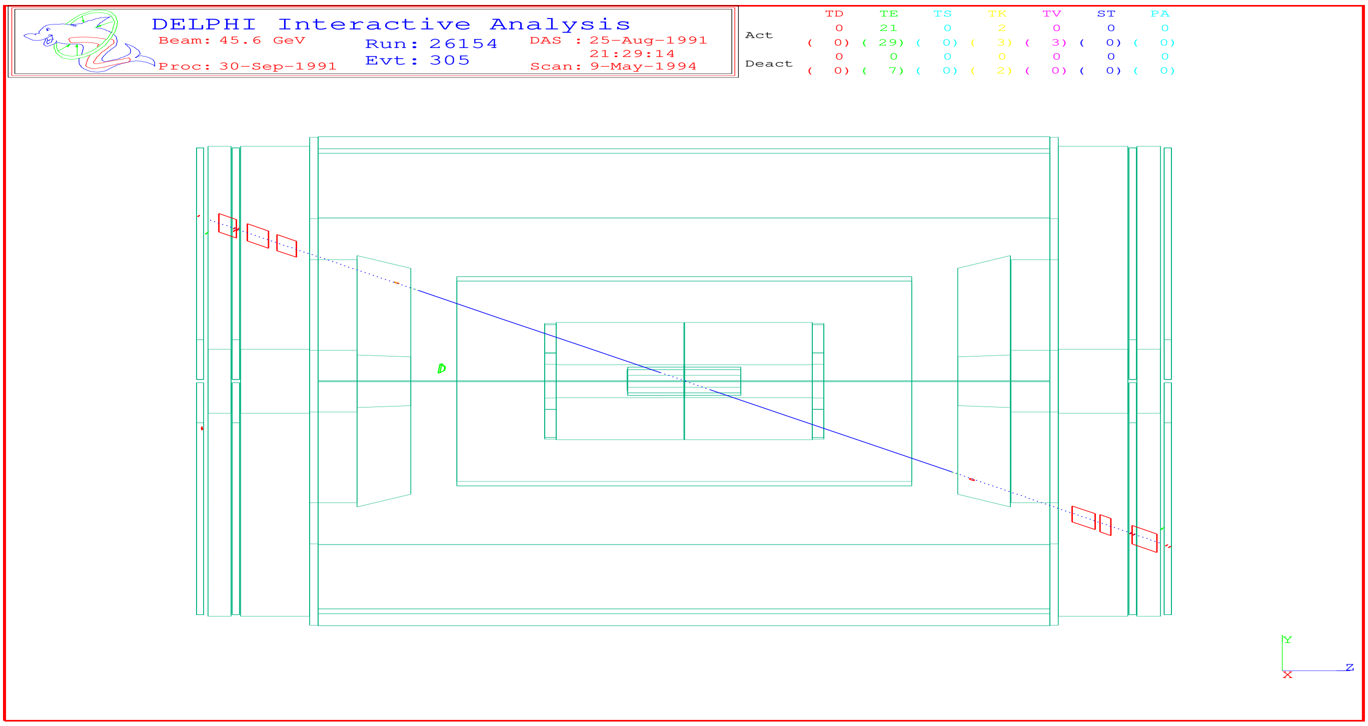
  $\Rightarrow$ Small systematic errors "LEP PRECISION DATA".

Difermions 1/7: Tree Level.

▹ Two tree graphs:



▹ A Dimuon event:



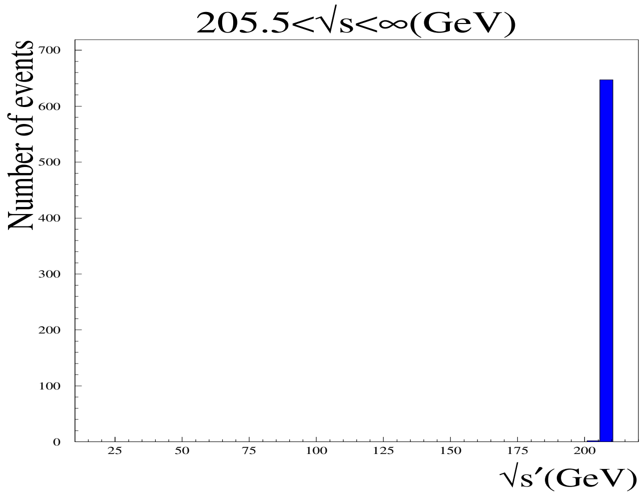
▹ We measured: σ, A_{FB}, $\frac{d\sigma}{d\Omega}$.

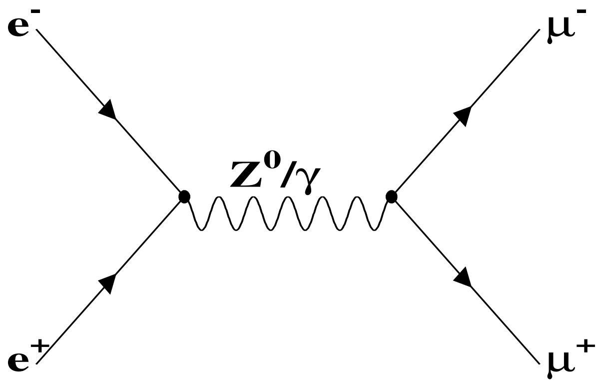
▹ Clean environment, clean signals, low multiplicities, perturbative Standard Model physics.

▹ Expect high signal:background & high level of data Monte Carlo agreement.

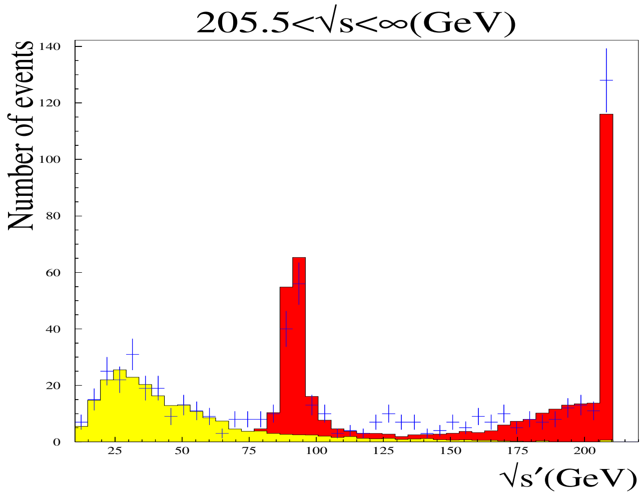
Difermions 2/7: ISR and s'.

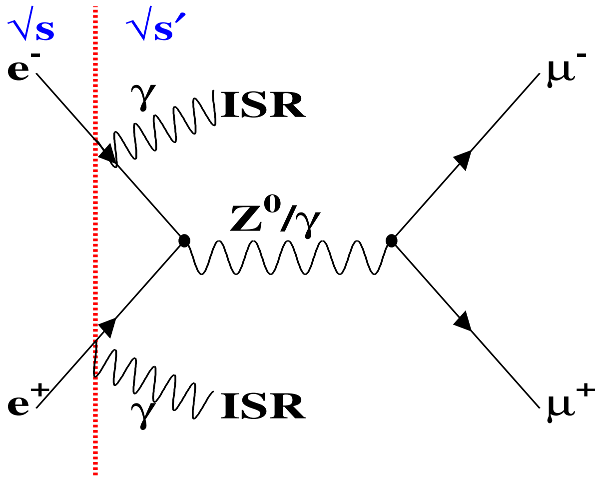
- ▷ Naively:





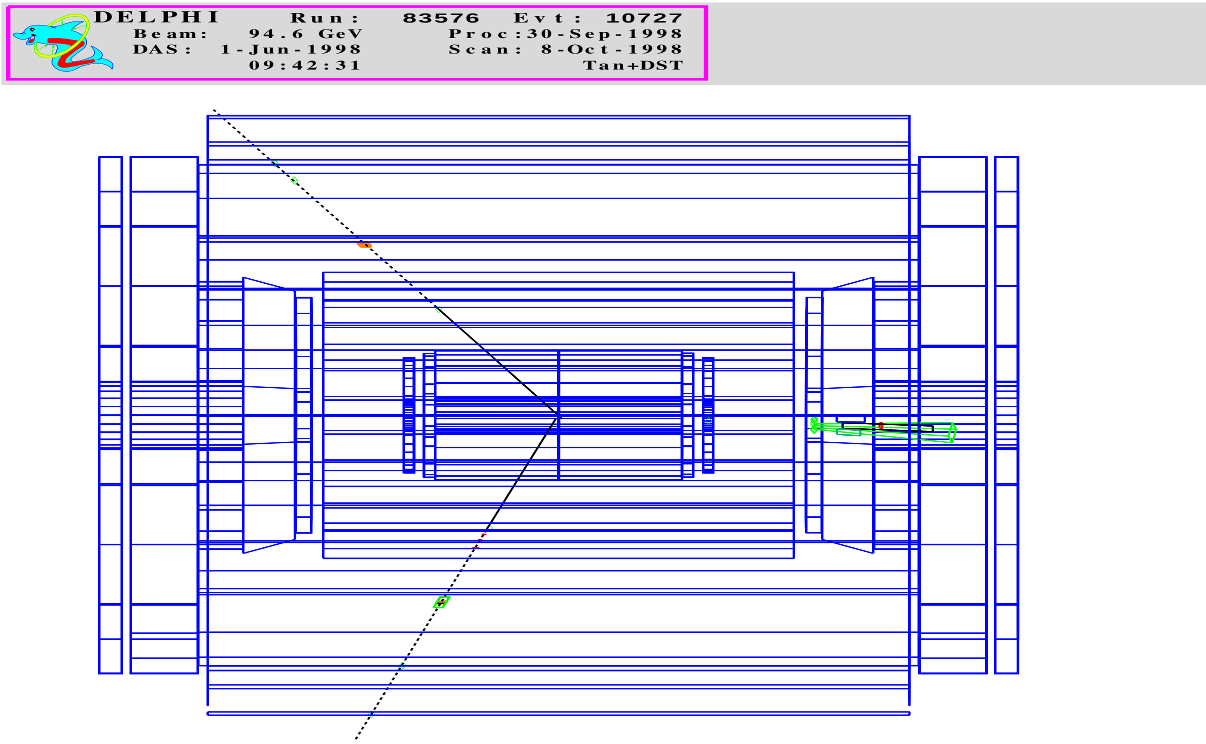
- ▷ Actually:



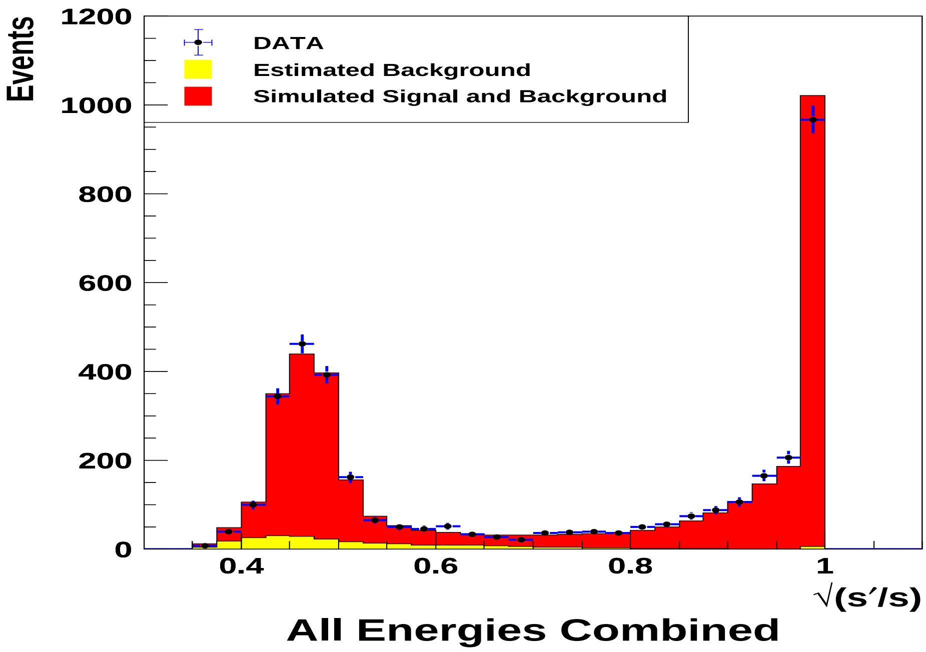


Difermions 3/7: ISR and s'.

▹ A Dimuon event with ISR:

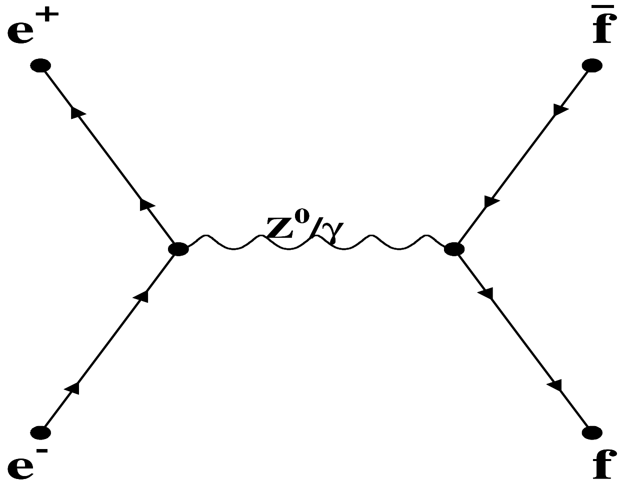


▹ $\sqrt{s'/s}$ distribution for *all* LEP2 Dimuons:



Difermions 4/7: Radiative Corrections.

▹ *LEP physics is the physics of radiative corrections:*



▹ The Radiator Function:

$$\sigma\,(S)_{MEASURED} = \int \mathrm{d}S'\ F\,(S, S', cos\theta) \times \sigma\,(S')_{BORN}$$

⊗ $f\bar{f}$ energy $\neq 2 \times E_{BEAM}$.

⊗ Final state fermions are acolinear.

⊗ Photons in difermion events.

▹ Must understand radiative corrections to make believable theory predictions to check with experiment - TREE LEVEL NOT GOOD ENOUGH.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/Paper 332 - Draft 1.

13 September 2003

Measurement and Interpretation of Fermion-Pair Production at LEP energies above the Z Resonance

DELPHI Collaboration

Abstract

This paper presents measurements and interpretations of cross-sections, forward-backward asymmetries, and angular distributions, $\mathrm{d}\sigma/\mathrm{d}\cos\theta$, for the $\mathrm{e^+e^-} \to \mathrm{f\bar{f}}$ process for centre-of-mass energies above the Z resonance, from $\sqrt{s} \sim 130 - 207$ GeV, as measured in the DELPHI experiment at LEP, CERN. The measurements are consistent with the predictions of the Standard Model, and are used to study a variety of models including the S-Matrix ansatz for $\mathrm{e^+e^-} \to \mathrm{f\bar{f}}$ scattering and several models which include physics beyond the Standard Model: the exchange of $\mathrm{Z'}$ bosons, contact interactions between fermions and the exchange of gravitons in large extra dimensions.

(To be submitted to Euro. Phys. J. C.)

Send comments up to 01/10/2003 to

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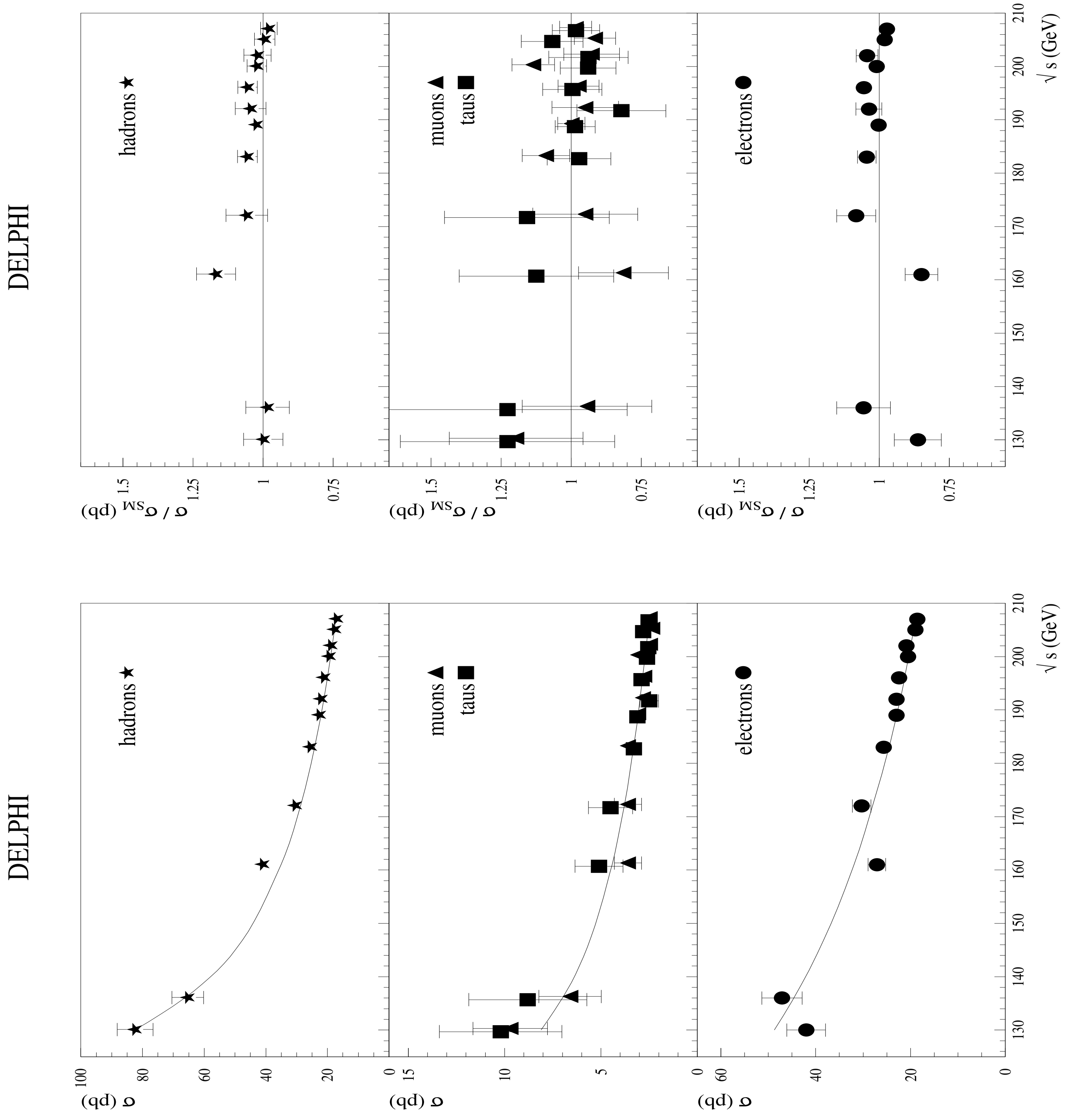
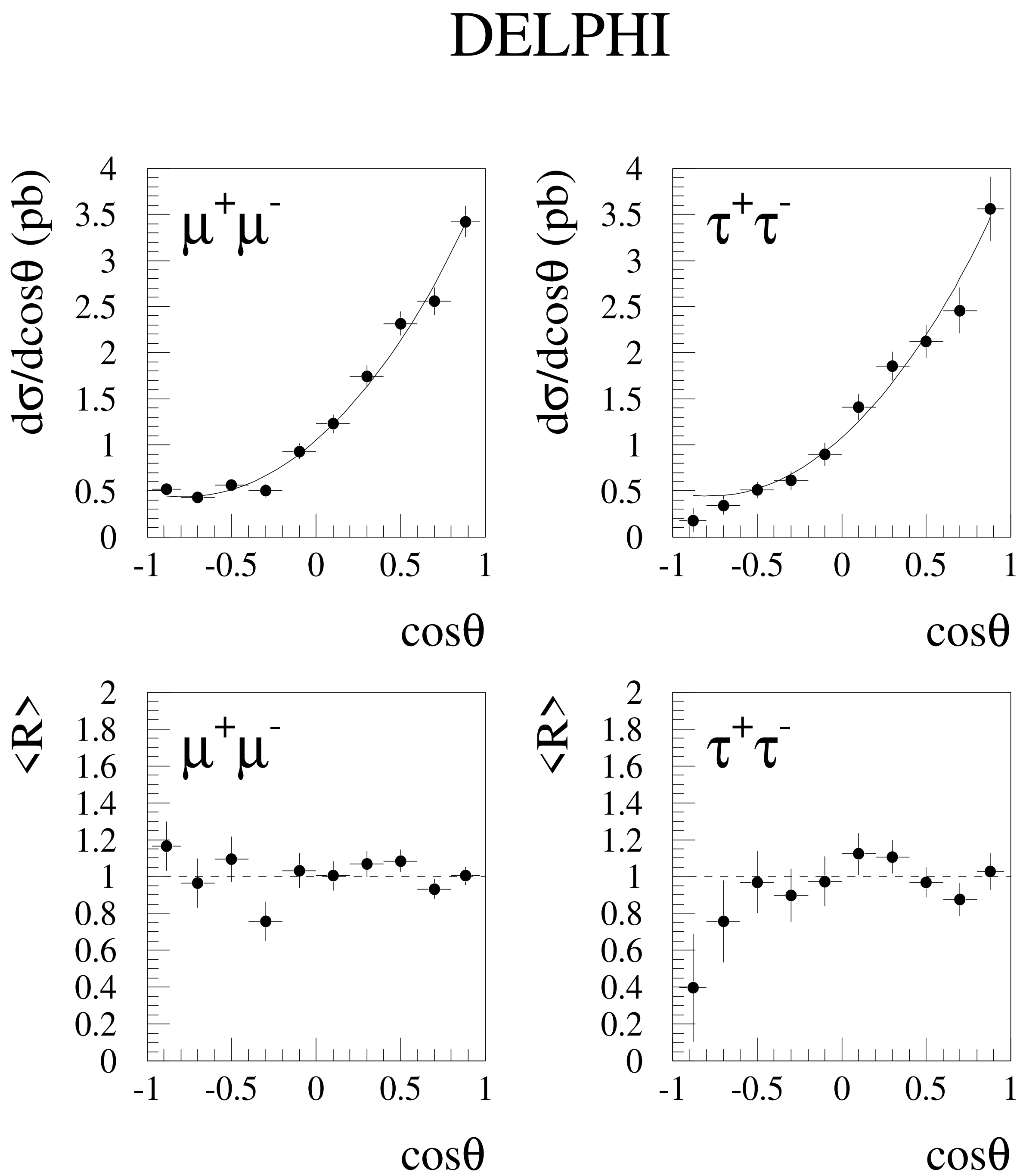
Difermions 6/7: DELPHI Cross Sections (Preliminary).

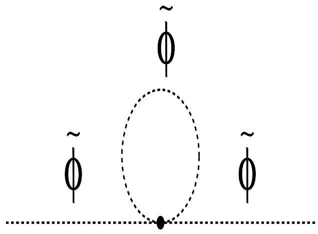


Difermions 7/7: DELPHI Differential Cross Sections (Preliminary).



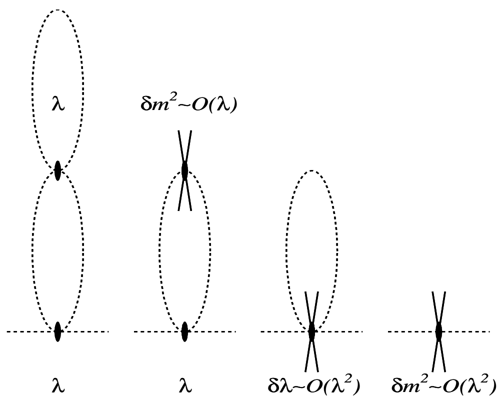
...also $e^+e^- \to e^+e^-$.

Extra Dimensions 1/9: Getting Motivated.



$$-\frac{i\lambda}{32\pi^2}\left(\Lambda^2 - m_{\tilde{\phi}}^2 \ln\left(\frac{\Lambda^2}{m_{\tilde{\phi}}^2}\right)\right)$$

▹ Fundamental scalars have quadratically divergent self energies.



$$\sim \lambda^2 \Lambda^2 \ln \frac{\Lambda^2}{m_{\tilde{\phi}}^2}$$

▹ Fundamental scalars have quadratically divergent self energies at every order in perturbation theory.

▹ $m_{\tilde{\phi},phys}^2 = m_{\tilde{\phi}}^2 + \Sigma_i c_i \alpha_i \int_0^{\Lambda^2} \mathrm{d}k^2 + \mathcal{O}\left(\alpha_i^2\right)$

▹ $\sum_i c_i \alpha_i \int_0^{\Lambda^2} \mathrm{d}k^2 \not\sim \Lambda^2$ requires a symmetry not a miracle.

Extra Dimensions 2/9: Getting Motivated (ctd).

- No such symmetry in SU$(3)\otimes$SU$(2)\otimes$U(1): $m_H^2\tilde{\phi}^2$ is trivially gauge invariant.

- 'tHooft's naturalness: δm_e correction vanishes appropriately in chiral $m_e \to 0$ limit $\Rightarrow \delta m_e \propto m_e \ln \frac{\Lambda^2}{m_e^2}$ log divergent on dimensional grounds.

- No more symmetry in $m_H \to 0$ limit *i.e.* no analogy to chiral limit (conformal is broken anomalously).

- Reject physical significance of Λ^2 (dimensional regularization) GHP persists if have indirect couplings to heavy particles *e.g.* $\lambda\tilde{\phi}\tilde{\phi}SS$ trivially gives $\mathcal{O}\left(m_S^2 \ln\left(\frac{\Lambda^2}{m_s^2}\right)\right)$ *quadratic* correction after throwing away Λ^2.

- Barring new symmetries the Higgs looks quadratically sensitive to new heavy particles

Extra Dimensions 3/9: Lowering $\mathrm{M_S}$.

- Witten - Nucl. Phys. B **475** (1996) -

$$\mathrm{M_S} \approx \mathrm{M_{Pl}} \sqrt{\frac{\alpha_{GUT}}{2}}$$

  Ginsparg tree level relation no good - $E_8 \times E_8$ heterotic string on Calabi-Yau manifold receives large corrections in strong coupling string limit:

  M_S can be brought down to M_{GUT}!

- J.Lykken in "Weak Scale Superstrings" - Phys. Rev. **D54** (1996) - pushes it to the limit: $\mathrm{M_S} \sim \mathrm{M_W}$?

- Arkani-Hamed, Dimopoulos, Dvali - Phys. Rev. **D59** (1999) - $\mathrm{M_S}$ could be ~1 TeV if extra dimensions are large -

  Planck mass in bulk reduced,

  hierarchy problem is solved

  (hierarchy thrown away).

- Lots of arguments & problems - many foreseen and noted in Lykken's work.

- Importantly "The hierarchy problem becomes isomorphic to the problem of the largeness of the extra dimensions." March-Russell *et al.* Phys. Rev. **D63** (2001).

Extra Dimensions 4/9: Compact Dimensions.

- Extra dimensions are *compact and flat*. For heuristic purposes imagine extra dimensions are a δ dimensional box of side L *i.e.* volume $V_\delta = L^\delta$.

$$
\begin{aligned}
x_M &= (x_0,\ x_1,\ x_2,\ x_3,\ y_1,\ \dots\ , y_\delta) \\
g_{MN} &= \begin{pmatrix}
g_{00} & g_{01} & g_{02} & g_{03} & 0 & . & 0 \\
g_{10} & g_{11} & g_{12} & g_{13} & 0 & . & 0 \\
g_{20} & g_{21} & g_{22} & g_{23} & 0 & . & 0 \\
g_{30} & g_{31} & g_{32} & g_{33} & 0 & . & 0 \\
0 & 0 & 0 & 0 & 1 & . & 0 \\
. & . & . & . & . & . & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}.
\end{aligned}
$$

- $g_{\mu\nu}$ components are independent of the y_i coordinates.

Extra Dimensions 5/9: The Volume Factor.

▹ Not hard to show for such a metric

$$\sqrt{-\mathrm{Det}\left(g_{MN}\right)} \;=\; \sqrt{-\mathrm{Det}\left(g_{\mu\nu}\right)}$$

$$g^{MN}R_{MN} \;=\; g^{\mu\nu}R_{\mu\nu}$$

▹ So integrand of S_{EH} independent of extra dimensions

$$\begin{aligned} S_{EH} \;&=\; \tfrac{1}{16\pi\tilde{G}_N}\int \mathrm{d}^D x\ \sqrt{-\mathrm{Det}\left(g_{MN}\right)}g^{MN}R_{MN} \\ &=\; \tfrac{1}{16\pi\tilde{G}_N}\int \mathrm{d}^D x\ \sqrt{-\mathrm{Det}\left(g_{\mu\nu}\right)}g^{\mu\nu}R_{\mu\nu} \end{aligned}\;.$$

▹ Integrating out extra dimensions $\left(\int \mathrm{d}y = L\right)$ gives volume factor

$$S_{EH} = L^\delta \times \frac{1}{16\pi\tilde{G}_N}\int \mathrm{d}^4 x\ \sqrt{-\mathrm{Det}\left(g_{\mu\nu}\right)}g^{\mu\nu}R_{\mu\nu}$$

$$\Rightarrow G_N = \frac{1}{V_\delta}\tilde{G}_N.$$

▹ A little dimensional analysis shows

$$\Rightarrow M_{Pl}^2 = V_\delta M_D^{2+\delta}.$$

Extra Dimensions 6/9: A Model And Its Ansatz.

- The GRW model: Giudice Rattazzi and Wells (hep-ph/**9811291**).
- GRW start from the most natural place

$$\mathcal{G}_{AB} \equiv \mathcal{R}_{AB} - \frac{1}{2} g_{AB} \mathcal{R} = -\frac{T_{AB}}{\bar{M}_D^{\delta+2}}$$

- $\bar{M}_D$ is the *reduced Planck mass* $M_D = (2\pi)^{\delta/(\delta+2)} \bar{M}_D$.
- SM confined to a 3-brane, the δ extra dimensions are circles of radius R.
- **Ansatz:** GRW appeal to infra-red limit, long wavelength gravitons; loosely speaking a factorization from the (unknown) UV physics *i.e.* model independence.
- The gravitons are too long wavelength to probe small scale distortions, $q_T \ll M_D$, the metric looks flat.

Extra Dimensions 7/9: A Model And Its Ansatz.

▹ Expand about flat background as: $g_{AB} = \eta_{AB} + 2\bar{M}_D^{-1-\delta/2} h_{AB}$.

▹ Substitute into $4+\delta$ dimensional Einstein equation and linearize:

$$\begin{aligned} \bar{M}_D^{1+\delta/2}\mathcal{G}_{AB} &= \Box h_{AB} - \partial_A\partial^C h_{CB} - \partial_B\partial^C h_{CA} + \partial_A\partial_B h^C_C \\ &- \eta_{AB}\Box h^C_C + \eta_{AB}\partial^C\partial^D h_{CD} = -\bar{M}_D^{-1-\delta/2} T_{AB} \end{aligned}.$$

▹ Extra dimensions are periodic $R\theta_i = R\theta_i + 2\pi R$

$$\Rightarrow h_{AB}\left(x, R\theta_i\right) = \sum_{n_1=-\infty}^{\infty} \ldots \sum_{n_\delta=-\infty}^{\infty} h_{AB}^{(n_1,\ldots,n_\delta)}\left(x\right) \prod_{i=1}^{\delta} \left(\frac{1}{\sqrt{2\pi R}} e^{i n_i \theta^i}\right).$$

▹ Kaluza-Klein (KK) states: $h_{AB}^{(n_1,\ldots,n_\delta)}$

▹ $T_{AB}\left(x, R\theta_i\right) = \eta^\mu_A \eta^\nu_B T_{\mu\nu}\left(x\right)\delta\left(y\right)$.

▹ GRW write down minimum Lagrangian consistent with E.O.M

$$\mathcal{L} = -\frac{1}{2}h^{AB}\Box h_{AB} + \frac{1}{2}h^A_A\Box h^B_B - h^{AB}\partial_A\partial_B h^C_C + h^{AB}\partial_A\partial_C h^C_B - \frac{1}{\bar{M}_D^{1+\delta/2}} h^{AB}T_{AB}.$$

▹ Integrate out extra dimensions to get 4D action, quantized momenta transverse to the brane appear as particle masses, heuristically

$$\begin{aligned} &\int \mathrm{d}^\delta\theta_i \; \phi\left(x, R\theta_i\right)\partial_A\partial^A\phi\left(x, R\theta_i\right) \\ = \; &\textstyle\sum_{n'_1=-\infty}^{+\infty} \cdots \sum_{n'_\delta=-\infty}^{\infty} \phi^{\left(n'_1,\ldots,n'_\delta\right)}\left(x\right)\left(\partial_\mu\partial^\mu + n'^2\right)\phi^{\left(n'_1,\ldots,n'_\delta\right)}\left(x\right) \end{aligned}.$$

▹ A graviton in the $4+\delta$ dimensions $\sim$ an infinity ("*tower*") of graviton fields in 4D each of different mass.

Extra Dimensions 8/9: $\mathrm{e^+e^-} \rightarrow$ Graviton $\rightarrow \mathrm{f\bar{f}}$.

- Feynman rules easily obtained from 4D theory (in principle).
- Easy to write down the amplitude for *a single graviton Kaluza-Klein mode* to be exchanged in $\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}$.
- Really an infinity of such gravitons

$$\mathcal{A} = \frac{\mathcal{T}}{M_D^{\delta+2}} \sum_n \frac{1}{s - m_n^2}$$

where $\mathcal{T} = T_{\mu\nu}T^{\mu\nu} - \frac{1}{\delta+2} T^{\mu}_{\mu} T^{\nu}_{\nu}$.

- Graviton mass may be rewritten as q_T^2 and the sum is rewritten as an integral over q_T:

$$\sum_n \frac{1}{s - m_n^2} \rightarrow \int \mathrm{d}^\delta q_T \; \frac{1}{s - q_T^2}.$$

- Momentum cut-off produces GRW result valid "for phenomenological purposes"

$$\begin{aligned} \int^\Lambda \mathrm{d}^\delta q_T \; \tfrac{1}{s-q_T^2} &= -\tfrac{S_{\delta-1}}{2} \int_0^{\Lambda^2} \mathrm{d}x \; \tfrac{x^{\delta/2-1}}{x-s} \\ &= -\tfrac{S_{\delta-1}}{2} c_1 \Lambda^{\delta-2} + \mathcal{O}\left(\Lambda^n\right) + \mathcal{O}\left(\Lambda^{n-1}\right) + \\ & \quad \ldots \;\; (n < \delta - 2; \;\; \delta > 2) \end{aligned}$$

$S_{\delta-1}$ from the angular integration of δ dimensional sphere and c_1 is an unknown coefficient[1].

---

[1] Using the momentum (q_T) cut-off prescription described above the coefficient appears to be $\left(\frac{\delta}{2} - 1\right)^{-1}$, though we shall restrict ourselves to the discussion in [?] which argues that such coefficients are not rigorously calculable without a better knowledge of the underlying theory.

Extra Dimensions 9/9: $\mathrm{e^+e^-} \rightarrow$ Graviton $\rightarrow \mathrm{f\bar{f}}$.

▷

$$\mathcal{A} = -\frac{1}{2} S_{\delta-1} c_1 \frac{\Lambda^{\delta-2}}{M_D^{\delta+2}} \mathcal{T} \ \ (\delta > 2)$$

▷ Coefficient of $\mathcal{T}$ reparametrized as

$$\mathcal{A} = \frac{4\pi}{\Lambda_T^4} \mathcal{T} \ \ (\delta > 2)$$

where $\Lambda_T \sim M_D$.

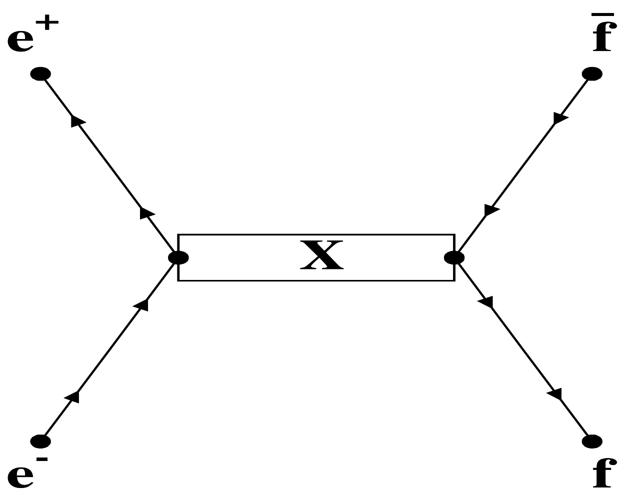
▷ $\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = A\left(\cos\theta\right) + \frac{\lambda}{\Lambda_T^4} B\left(\cos\theta\right) + \frac{\lambda^2}{\Lambda_T^8} C\left(\cos\theta\right) \ (\lambda = \pm 1)$.

▷ For historical reasons adopt parametrization:

$$\frac{1}{\mathrm{M_S^4}} = \frac{\pi}{2} \frac{1}{\Lambda_T^4}.$$

Radiative Corrections 1/8: Making Predictions.

- Get new physics prediction for observable.
- Vary new physics parameters to generate likelihood curve: $\mathrm{P} \propto \exp -\frac{1}{2}\chi^2$.
- Integrate likelihood curve to get limit.
- New physics is searched for in non-radiative events $\sqrt{s'} \geq 90\%\sqrt{S}$.
- New physics prediction *needs* radiative corrections.
- Find a universal procedure to "fix on" radiative corrections.



- Previously 10 "correction factors".

Radiative Corrections, New Physics Fits and $e^+e^- \to ? \to f\bar{f}$.

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November 2003

Abstract

This document reviews the general approach to correcting the process $e^+e^- \to X^0 \to f\bar{f}$ for radiative effects, where X^0 represents an exchanged boson arising from some new physics. The validity of current methods is discussed in the context of the differential cross section. To this end the universality of the dominant QED radiative corrections to such processes is discussed and an attempt is made to quantify it. The paper aims to justify, as much as possible, the general approach taken by e^+e^- collider experiments to the issue of how to treat the dominant radiative corrections in fitting models of new physics using inclusive and exclusive cross section measurements. We conclude that in all but the most pathological of new physics models the dominant radiative corrections (QED) to the tree level processes of the Standard Model can be expected to hold well for new physics. This argument follows from the fact that the phase space of indirect new physics searches is generally restrictive (high $\sqrt{s'}$ events) in such a way that the factorization of radiative corrections is expected to hold well and generally universal infrared corrections should be prevalent.

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Radiative Corrections 3/8: Explorations in ZFITTER.

- ZFITTER: precision $\mathcal{SM}$ physics predictions of $\mathrm{e}^+\mathrm{e}^- \to \mathrm{f}\bar{\mathrm{f}}$ observables.
- ZFITTER has the radiator function for the $\mathcal{SM}$.
- Does the radiator function work for non-$\mathcal{SM}$ physics?
- Can we get it anyway?
- Deconvolve it.

Radiative Corrections 4/8: Getting a radiator function.

$$\sigma_{ISR}\left(\sqrt{s}\right) = \int_{\sqrt{s_0}}^{\sqrt{s}} \mathrm{d}s' \; R\left(s, s'\right) \sigma_{BORN}\left(\sqrt{s'}\right)$$

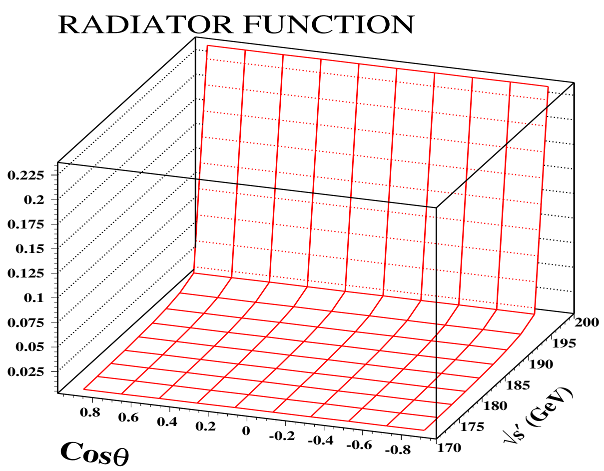
▷ Integral → rectangle as $\Delta\sqrt{s} = \sqrt{s_{i+1}} - \sqrt{s_i} \to 0$

$$\sigma_{ISR}\left(\sqrt{s}\right) \approx \Sigma_{\sqrt{s_o}}^{\sqrt{s}} R\left(s, \frac{\sqrt{s_i}+\sqrt{s_{i+1}}}{2}\right) \sigma_{BORN}\left(\frac{\sqrt{s_i}+\sqrt{s_{i+1}}}{2}\right) \Delta\sqrt{s}$$

▷ All rectangles come from ZFITTER!

▷ Now have numerical radiator function to correct new physics with

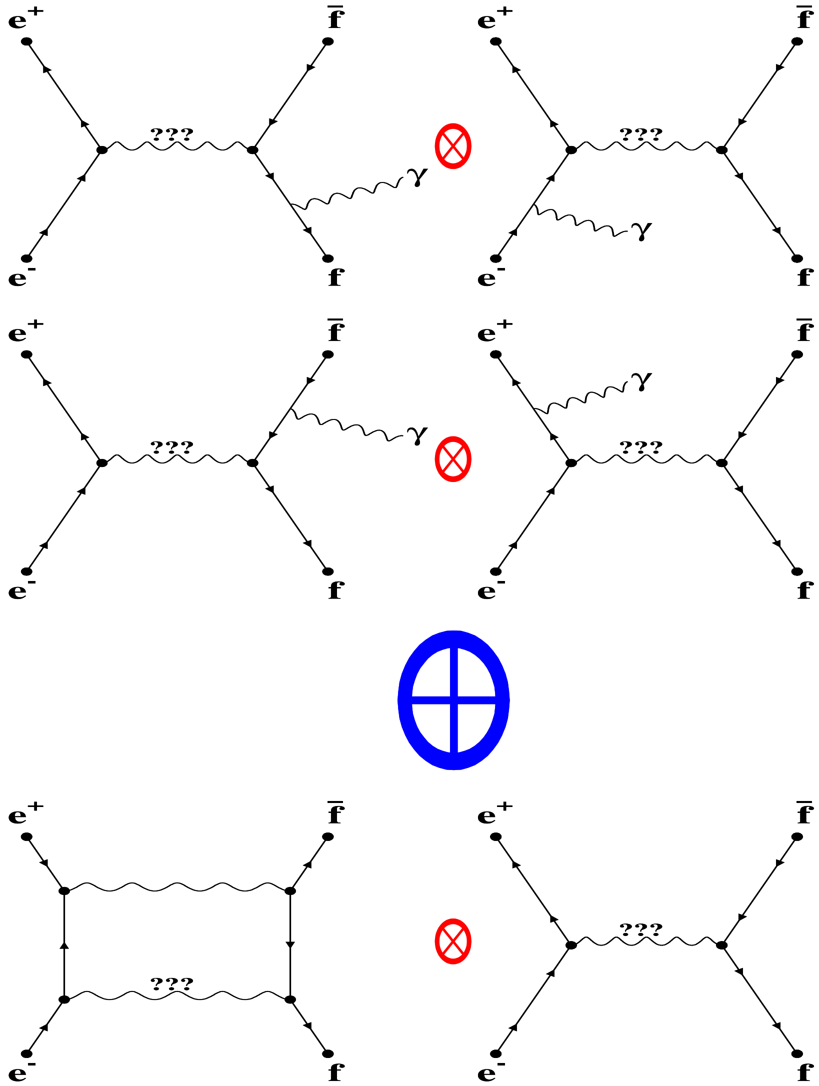
$$\begin{aligned}&\sigma_{ISR(NP)}\left(\sqrt{s}\right)\\ \approx\;& \Sigma_{\sqrt{s_o}}^{\sqrt{s}} R\left(s, \tfrac{\sqrt{s_i}+\sqrt{s_{i+1}}}{2}\right) \sigma_{BORN(NP)}\left(\tfrac{\sqrt{s_i}+\sqrt{s_{i+1}}}{2}\right) \Delta\sqrt{s}\end{aligned}$$

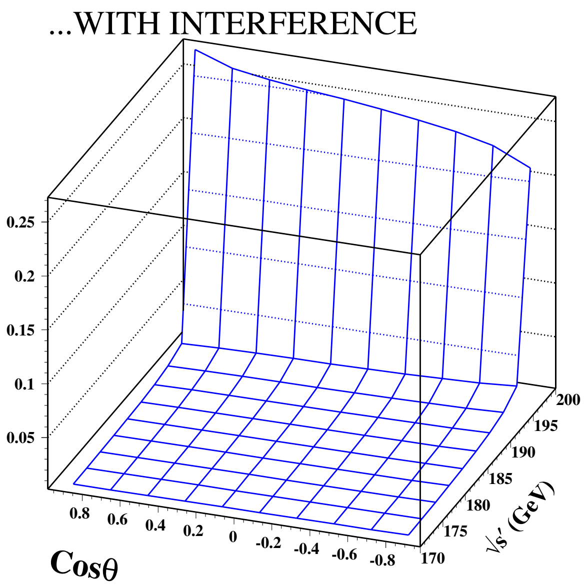


▷ Can derive entirely by solving Gribov Lipatov.

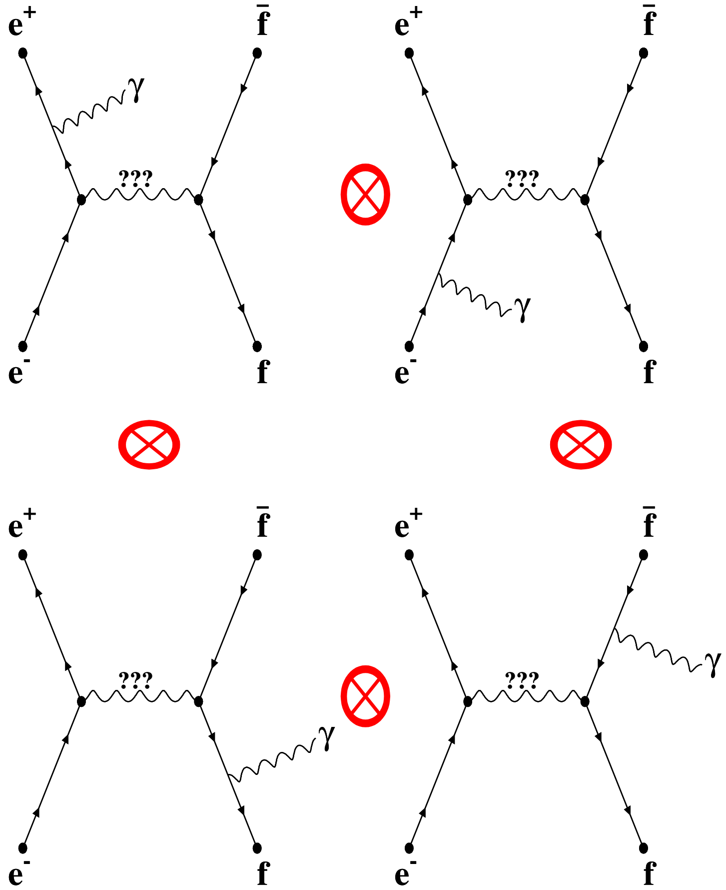
▷ Jadach & Skrzypek non-singlet structure function produces σ to ~0.5%.

Radiative Corrections 5/8: IFI (Interference).





Radiative Corrections 6/8: Soft Bremsstrahlung.



$$\mathcal{M} = \epsilon^{\mu} \bar{\nu}\left(p_{+}\right) \left\{ \gamma^{\mu} \frac{(- \not{p}_{+} + \not{k}) + m}{\left(p_{+} - k\right)^{2} - m^{2}} \right\} ...HARD... \nu\left(q_{+}\right)$$

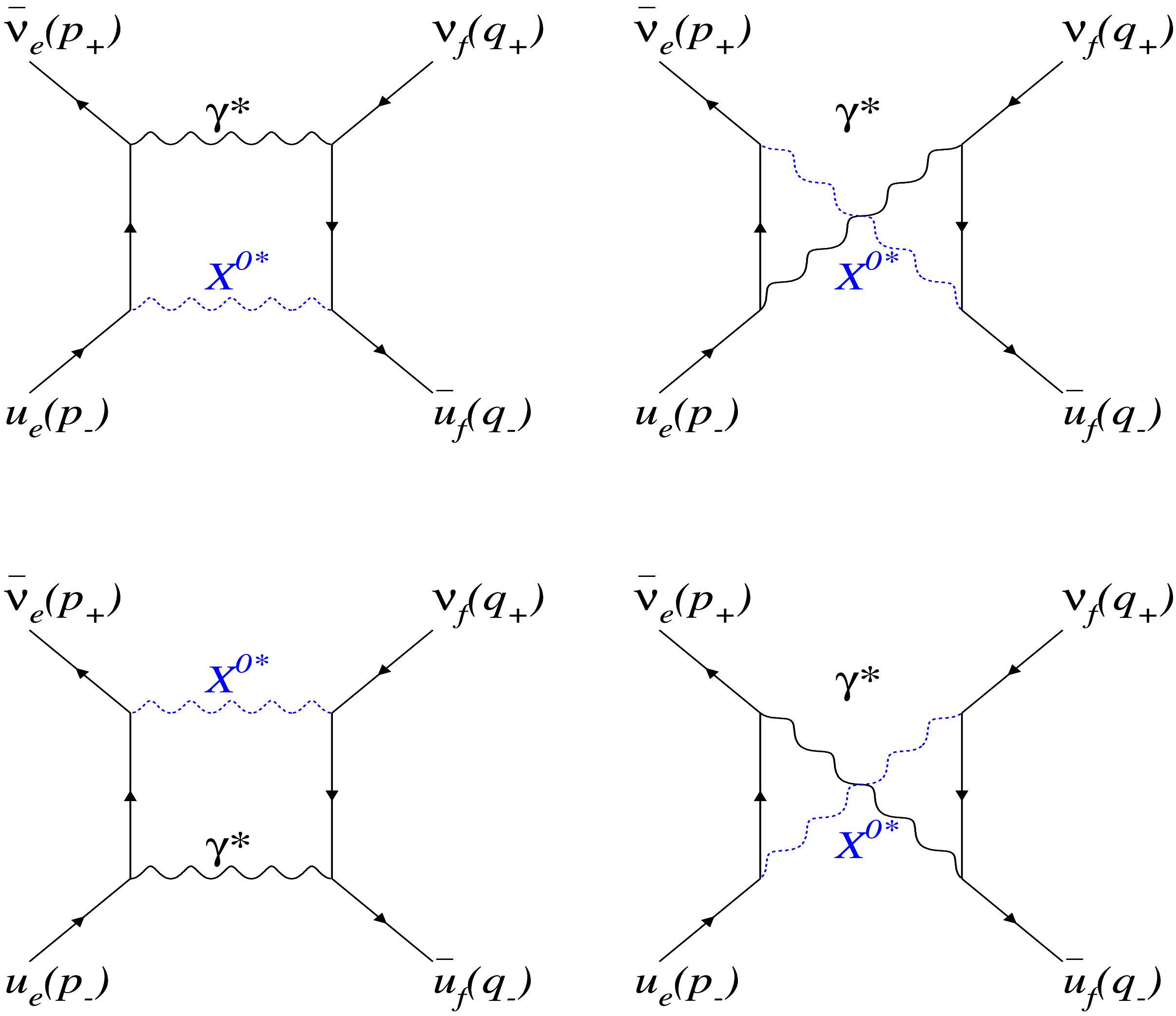
▷ Soft photon approximation ($k \approx 0$).

▷ Dirac equation: $\bar{\nu}(p_{+})\gamma^{\mu}\left(- \not{p}_{+} + m\right) = \bar{\nu}\left(p_{+}\right)\left(-2p_{+}^{\mu}\right)$:

$$\mathrm{d}\sigma_{SOFT} = \left[\frac{\alpha}{4\pi^{2}} \int_{|k|<\omega} \frac{\mathrm{d}^{3}k}{k_{0}} \Sigma_{i,j} \left(\frac{p_{i}.p_{j}}{\left(p_{i}.k\right)\left(p_{j}.k\right)} \right) \right] \times \mathrm{d}\sigma_{BORN}$$

▷ Soft bremsstrahlung: universal and IR divergent.

Radiative Corrections 7/8: Virtual IFI - Boxes.



- ▷ At NLO only 1 loop contributions come from interference with Born graph.
- ▷ The boxes have universal bits too - easy to show (play same games as before with Dirac eqn).
- ▷ The universal bit involves an IR divergent scalar integral

$$\int \frac{\mathrm{d}^4 k}{(2\pi)^4} \frac{1}{k^2 \left((k+p_+)^2 - m_e^2\right) \left((k+q_+)^2 - m_f^2\right) \left((k+p_+ + p_-)^2 - m_X^2\right)}.$$

Radiative Corrections 8/8: Virtual IFI - Boxes.

▷ This integral is split in two: a universal bit independent of m_X (IR divergent) and a non-universal *non-divergent* bit depending on m_X.

▷ We find

$$\begin{aligned} \mathrm{d}\sigma_{Box}|_{Universal} &= \frac{2\alpha}{\pi}\Big[\Big(-\frac{1}{\hat{\epsilon}} + \log\Big(\frac{\mu^2}{s}\Big)\Big)\log\Big(\frac{t}{u}\Big) \\ &\quad +\frac{1}{2}\log^2\Big(\frac{-u}{s}\Big) - \frac{1}{2}\log^2\Big(\frac{-t}{s}\Big)\Big]\,\mathrm{d}\sigma_{Born}. \end{aligned}$$

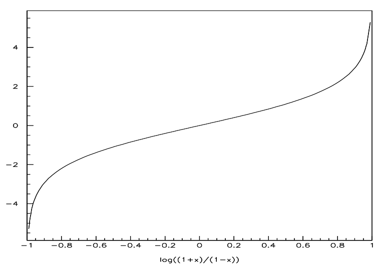
▷ Also we find

$$\begin{aligned} \mathrm{d}\sigma_{Soft,Int} &= \frac{2\alpha}{\pi}\Big[\Big(\frac{1}{\hat{\epsilon}} + \log\Big(\frac{4\omega^2}{\mu^2}\Big)\Big)\log\Big(\frac{t}{u}\Big) \\ &\quad -\mathrm{Li}_2\Big(1+\frac{s}{t}\Big) + \mathrm{Li}_2\Big(1+\frac{s}{u}\Big)\Big]\,\mathrm{d}\sigma_{Born}. \end{aligned}$$

▷ These combine to cancel $\hat{\epsilon}^{-1}$'s and give a big log

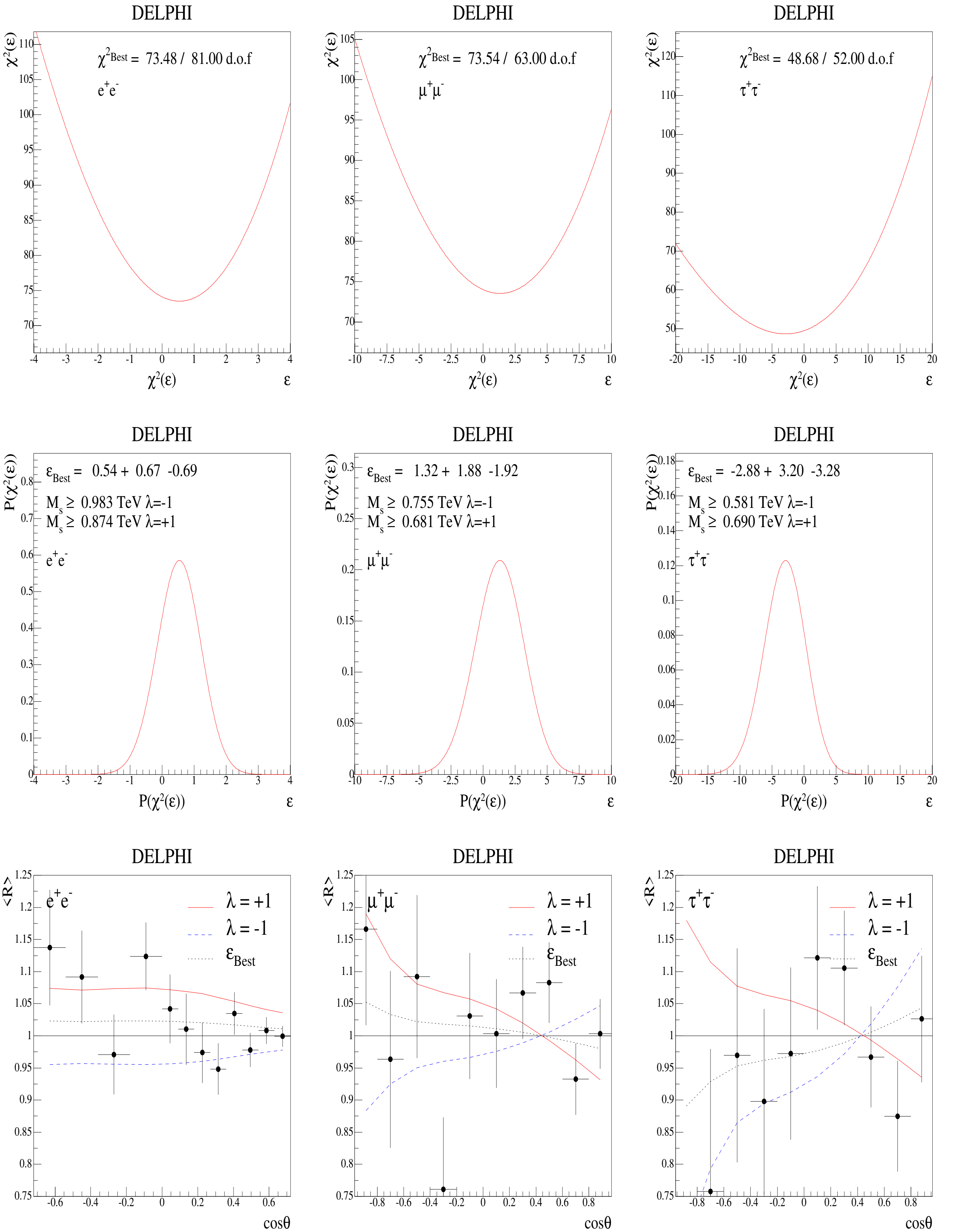
$$\begin{aligned} \mathrm{d}\sigma_{Universal} &= \mathrm{d}\sigma_{Soft,Int} + \mathrm{d}\sigma_{Box}|_{Universal} \\ &= \frac{2\alpha}{\pi}\Big(\log\Big(\frac{s}{4\omega^2}\Big)\log\Big(\frac{u}{t}\Big) - \mathrm{Li}_2\Big(1+\frac{s}{t}\Big) + \mathrm{Li}_2\Big(1+\frac{s}{u}\Big)\ \cdot \\ &\quad +\frac{1}{2}\log^2\Big(\frac{-u}{s}\Big) - \frac{1}{2}\log^2\Big(\frac{-t}{s}\Big)\Big)\,\mathrm{d}\sigma_{Born} \end{aligned}$$

▷ $\log\left(\frac{u}{t}\right)$:



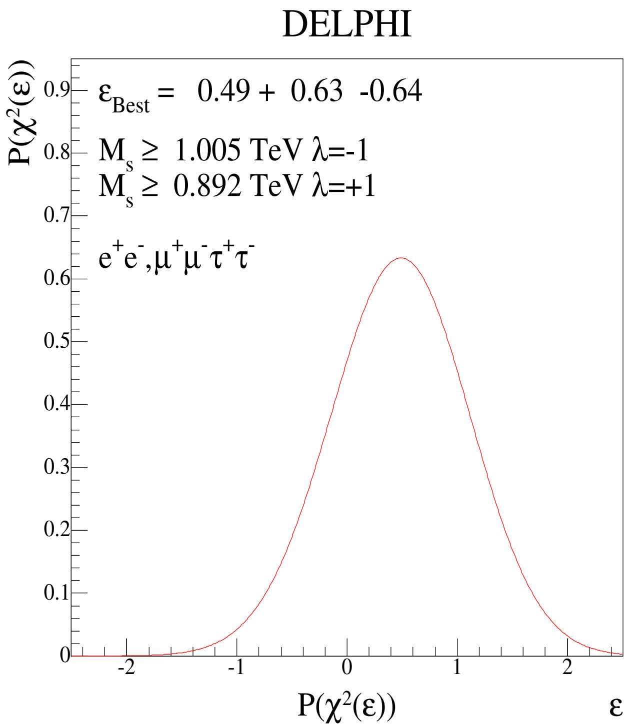
▷ Verified for QED using FeynCalc for Passarino-Veltman's.

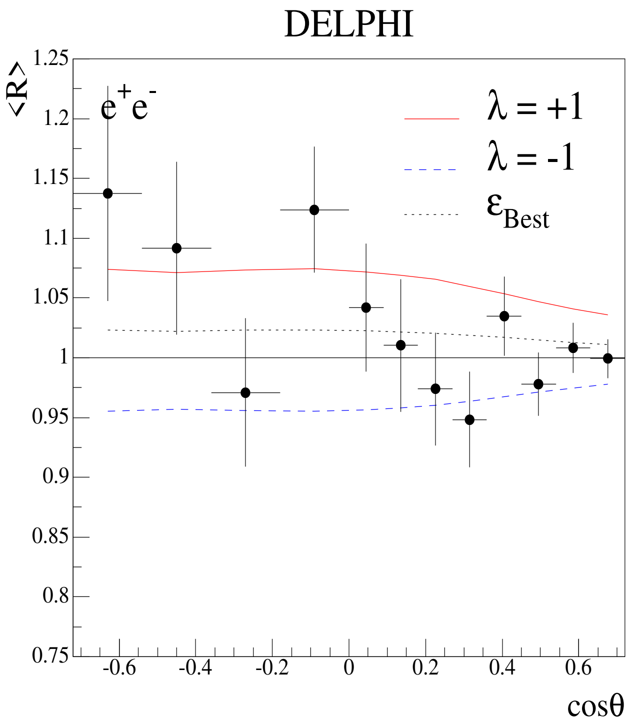
Limits 1/2: DELPHI Limits.



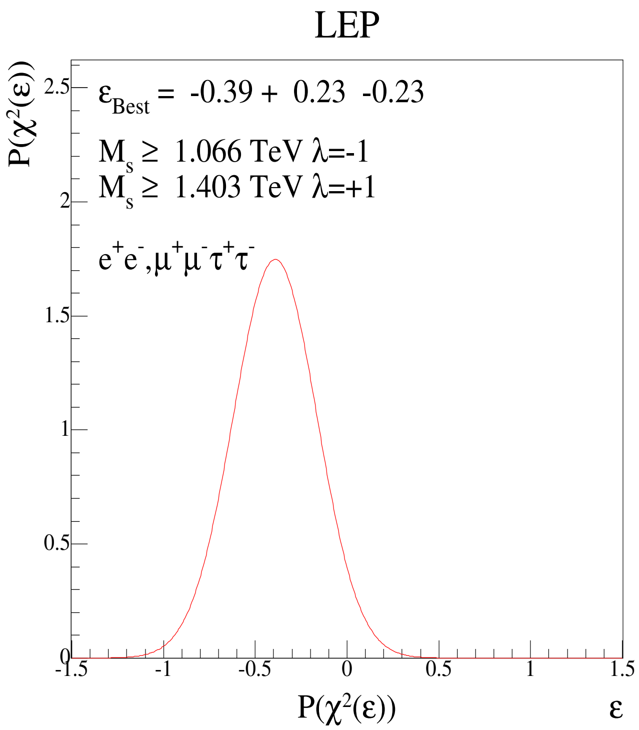
Limits 2/2: DELPHI and LEP Limits.

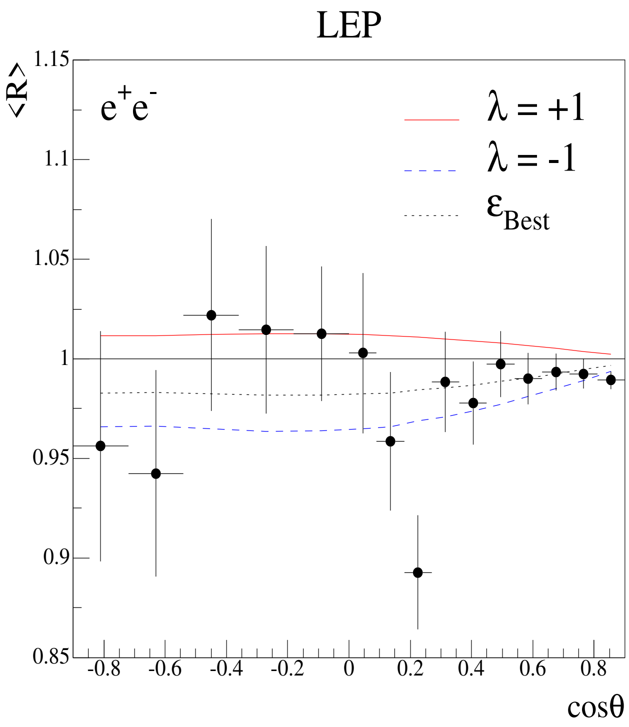
▷ DELPHI limits using all difermion channels

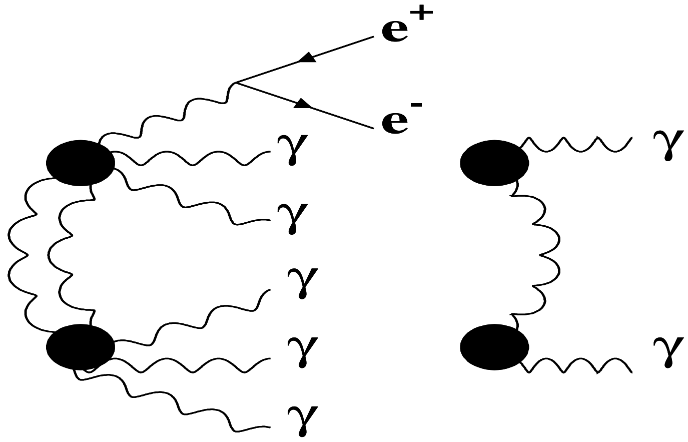


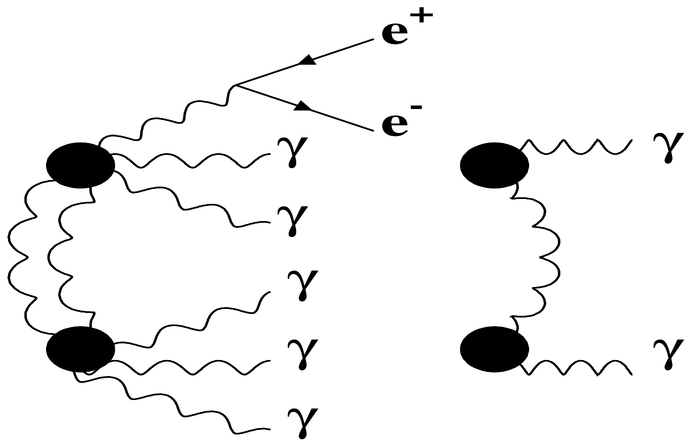


▷ LEP limits using all difermion channels (preliminary)






e^+
e^-
γ
γ
γ
γ
γ
γ
γ


e^+
e^-
γ
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