Standard Model Measurements

- Fermion pair production cross-sections and asymmetries
- Gauge boson pair production cross-sections
- Running of $\alpha_{\text{em}}$
- QCD and running of $\alpha_s$
- W mass
- LEP combined electroweak results

Searches for Physics Beyond the Standard Model

- Indirect Searches via precision Standard Model measurements
- Direct searches for new particles
  - Supersymmetry (gravity-mediated, gauge mediated), excited fermions, contact interactions, large compact extra dimensions, leptoquarks, additional gauge bosons, anomalous gauge boson couplings
Two phase experimental program:

1989-1995 \( E_{CM} \sim M_Z \)

1996-2000 \( E_{CM} > 2M_W \)

Highest energy running in 2000 achieved \( E_{CM} \sim 209 \text{ GeV} \)
The OPAL Data Sample

OPAL Online Data-Taking Statistics

Integrated Luminosity pb⁻¹ vs Week number

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
Fermion Pair Production Cross-sections

OPAL 206 GeV preliminary

$\sqrt{s'} \equiv$ Effective centre-of-mass energy in initial state (after ISR)

- $s' > 0.01$
- $s' > 0.7225$

non-radiative sample

Peter Krieger, Carleton University
WRNPPC, Lake Louise, February 2001
Fermion Pair Production Cross-sections

e^+e^- → hadrons at 208 GeV

OPAL preliminary

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
Fermion Pair Production Cross-sections

Bhabha event at 209 GeV!

Cross-section / pb

OPAL preliminary $e^+e^- \rightarrow e^+e^-$

$\sqrt{s}$/GeV vs. Cross-section / pb

| cos$\theta$|<0.96; $\theta_{acol}$<10$^\circ$
| cos$\theta$|<0.9; $\theta_{acol}$<170$^\circ$
| cos$\theta$|<0.7; $\theta_{acol}$<10$^\circ$

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
Fermion Pair Production Cross-sections

- $e^+e^- \rightarrow \mu^+\mu^-$  
- $e^+e^- \rightarrow \tau^+\tau^-$

Small excess at highest energies $\sim 2.5\sigma$

Peter Krieger, Carleton University  
WRNPPC, Lake Louise, February 2001
Fermion Pair Production: Neutrinos!

Invisible final states can be investigated via ISR (neutrino counting at LEP1)

Agreement with SM good for energies up to 189 GeV

And no evidence for anything new in the 2000 data

**OPAL**

\[ e^+ e^- \rightarrow \gamma(\gamma) + \text{invisible particles} \]

2000 data: \( \sqrt{s} = 200 - 209 \text{ GeV} \)

\[ \int \mathcal{L} dt = 166.3 \text{ pb}^{-1} \]

- \( N_{\text{obs}} = 526 \)
- \( N_{\text{exp}} = 530 \pm 26 \)

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
Lepton Pair $A_{FB}$ and differential cross-sections

OPAL preliminary

(a) $e^+e^- |\cos\theta_e|<0.7; \theta_{acol}<10^\circ$

(b) $\mu^+\mu^-$

- $s/s > 0.01$
- $s/s > 0.7225$

(c) $\tau^+\tau^-$

- $s/s > 0.01$
- $s/s > 0.7225$

OPAL 207 GeV preliminary

(a) $e^+e^-$

(b) $\mu^+\mu^-$

(c) $\tau^+\tau^-$

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Running of Electromagnetic Coupling Constant

\[ \alpha^{-1}(Q) \]

Fits to leptonic data from:

\[ \star \text{DORIS}, \oplus \text{PEP}, \square \text{PETRA}, \triangle \text{TRISTAN} \]

Charged lepton total non-radiative cross-sections and forward backwards asymmetries at each energy used for fit to \( \alpha_{\text{em}} \)

OPAL 2-fermion fits:

average: •

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
QCD Analyses

Select non-radiative $e^+e^- \rightarrow q\bar{q}$ events

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>OPAL (preliminary)</th>
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<tr>
<td></td>
<td>204.9</td>
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<td>206.6</td>
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</table>

| $\int L$ (pb$^{-1}$) | 82.3 | 137.3 |

| Selected          | 1183 | 1802 |
| Expected          | 1175 | 1919 |

OPAL measurements of $\alpha_s(Q)$

- OPAL (preliminary)

$\alpha_s(M_Z) = 0.1184 \pm 0.0031$

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
\( e^+ e^- \rightarrow \gamma \gamma (\gamma) \) has negligible electroweak contributions at LEP2 energies

Differential cross-section extremely well predicted by SM
$W^\pm$ Boson Pair Production Cross-section

Cross-section measurement uses reconstruction in all final states

Assuming SM branching fractions for the W decays

$\sigma(161 \text{ GeV})$ sensitive to $M_W$

$M_W = 80.40 \pm 0.46_{0.43} \text{ GeV}$

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
W± Boson Mass Measurement

OPAL 183-209 GeV \[\int L \, dt = 677 \, \text{pb}^{-1}\]

\begin{align*}
\text{Events} & \quad 0 & 50 & 100 & 150 & 200 & 250 & 300 \\
\text{m/GeV} & \quad 60 & 65 & 70 & 75 & 80 & 85 & 90 & 95 & 100 & 105 \\
\text{Signal} & \quad \text{Yellow} & \text{Combinatorial b/g} & \text{Green} & \text{Other b/g} & \text{Magenta} \\
\end{align*}

\[M_W \text{ from 480 pb}^{-1} 172-202 \text{ GeV}\]

\begin{align*}
M_W &= 80.510 \pm 0.067 \pm 0.031 \text{ GeV (qqll)} \\
M_W &= 80.408 \pm 0.066 \pm 0.100 \text{ GeV (qqqq)} \\
M_W &= 80.486 \pm 0.053 \pm 0.039 \text{ GeV (combined direct)} \\
\end{align*}

LEP combined (direct +threshold)

\[M_W = 80.427 \pm 0.046 \text{ GeV}\]

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
ZZ Production Cross-section

Reconstruct decay channels:
qqqq, qqll, qqvv, llvv, llll

Cross-sections assume SM Z decays fractions

At $\sqrt{s} = 205$ GeV select 77 events
expected SM bkgd = 37 events

At $\sqrt{s} = 207$ GeV select 85 events
expected SM bkgd = 45 events

OPAL preliminary

$\sigma(\mu^+\mu^- \rightarrow ZZ)$

★ 2000 data

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
LEP Electroweak Combined Results

W-Boson Mass [GeV]

- pp-colliders
- LEP2
- Average
- NuTeV/CCFR
- LEP1/SLD

\[ m_W \approx 80.452 \pm 0.062 \] for pp-colliders

\[ m_W \approx 80.427 \pm 0.046 \] for LEP2

\[ m_W \approx 80.436 \pm 0.037 \] (with \( \chi^2/\text{DoF}: 0.1/1 \)) for the average

\[ m_W \approx 80.25 \pm 0.11 \] for NuTeV/CCFR

\[ m_W \approx 80.374 \pm 0.034 \] for LEP1/SLD

\[ m_W \approx 80.436 \pm 0.037 \] (with \( \chi^2/\text{DoF}: 0.1/1 \)) for the average

\[ m_W \approx 80.25 \pm 0.11 \] for NuTeV/CCFR

\[ m_W \approx 80.374 \pm 0.034 \] for LEP1/SLD

Preliminary

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
$m_t = 174.3 \pm 5.1$ GeV (Tevatron)

$e^+ e^- \rightarrow \bar{t}c, \bar{t} \rightarrow bW^*$

Kinematically accessible at LEP2 energies: proceeds via loop diagram

$\sigma(\text{SM}) \sim 10^{-9}$ pb

Some SM extensions can enhance this production cross-section

30 events selected
29.4 events expected from SM

Signal distributions for $\sigma = 3$ pb
Four Fermion Contact Interactions

from fermion pair-production differential cross-sections measurements

$$L_{\text{contact}} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{i,j=L,R} \eta_{ij} [\bar{c}_i \gamma^\mu c_i][\bar{f}_j \gamma^\mu f_j]$$
**Limits on Additional Neutral Gauge Bosons**

$Z'$ predicted in various extensions to the Standard Model

Limits depend on mass of additional state and mixing with $Z^0$

Possible $Z'$ exchange in fermion pair production modifies observed cross-sections and asymmetries
Searches for Anomalous Triple Gauge Couplings

Charged current TGCs (from W- pair and single-W production)

Limits also on:

QGC’s WWγγ, ZZγγ (ννγγ, qqγγ)

Neutral Current TGCs (ννγ, qqγ)

All results consistent with Standard Model expectations

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
Limits on Deviations from QED from Photonic Final States

1740 event selected
1776 events expected from SM

Fit for deviations from QED

$$\left( \frac{d\sigma}{d\Omega} \right)_{\Lambda_{\pm}} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Born}} \pm \frac{s^2}{2\Lambda_{\pm}^4} (1 + \cos^2 \theta)$$

Most current limits (2000 data)
\[ \Lambda_+ > 344 \text{ GeV} \]
\[ \Lambda_- > 325 \text{ GeV} \]

Limit on mass of excited electron (contributes via t-channel exchange)

\[ M_{e^*} > 354 \text{ GeV} \]
Indirect Searches for Large Compact Extra Dimensions

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{LSG}} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{SM}} \pm A(\cos \theta) \frac{|\lambda|}{M_S^4} + B(\cos \theta) \left[ \frac{|\lambda|}{M_S^4} \right]^2
\]

Limits set on \( M_S(\lambda = \pm 1) \) (different signs of interference)

Peter Krieger, Carleton University

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Indirect Searches for Large Compact Extra Dimensions

**OPAL preliminary**

Data, Background, ZZ signal

LSG fit with 95% CL boundaries

**OPAL preliminary**

<table>
<thead>
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<tbody>
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<tr>
<td>150</td>
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<tr>
<td>175</td>
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<tr>
<td>200</td>
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</table>

**OPAL preliminary**

$|\cos\theta_Z|$ vs. number of events

**OPAL preliminary**

$\sigma(e^+e^- \rightarrow ZZ)$ (pb)

$\Delta(-\log L)$

$\lambda/M_S^4 = -0.1^{+0.9}_{-0.8}$ TeV$^{-4}$

$M_s > 0.90/0.83$ TeV @ 95% CL for $\lambda = +/-1$

Peter Krieger, Carleton University

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Direct Searches for Large Compact Extra Dimensions

\[ e^+ e^- \rightarrow G_{KK} \gamma \rightarrow \gamma + E_T \] final state

from Mirabelli, Perelstein, Peskin

For graviton search
\[ E_\gamma < 34 \text{GeV} \]

SM
\( v \nu \gamma(\gamma) \)

\begin{align*}
n=6 & \quad M_D=520 \text{ GeV} \\
n=2 & \quad M_D=1200 \text{ GeV} \\
\end{align*}

\[
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
n & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
\sigma^{95} (\text{fb}) & 309 & 298 & 290 & 283 & 276 & 271 \\
M_{\nu}^{95} (\text{GeV}) & 1086 & 862 & 710 & 605 & 528 & 470 \\
\hline
\end{array}
\]

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Supersymmetric Particle Searches

R-parity conservation: SUSY particles must be produced in pairs
There must be some lightest SUSY particle (LSP)
→ missing energy signature

MSSM: 105 free parameters in addition to those of the SM

CMSSM (mSUGRA)
- gravity-mediated SUSY breaking
- LSP (usually) the lightest neutralino
- 5 parameter model: $m_o$, $m_{1/2}$, tan$\beta$, $\mu$, $A$
- phenomenology dictated by identity of LSP

Gauge-mediated SUSY
- SUSY breaking mediated by SM gauge interactions
- LSP is a very light gravitino
- 6 parameter version
- phenomenology dictated by identity of NLSP
- NLSP either the lightest neutralino or the lightest slepton
- NLSP lifetime is arbitrary – can be long lived

Peter Krieger, Carleton University
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95% CL upper limits are on $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-) \times BR^2(\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0W^*)$ for each mass pairing in the plane.
CMSSM: Neutralino Production Limits

OPAL Preliminary

\[ \sqrt{s} = 208 \text{ GeV} \]

- For each mass pairing in the plane

\[ \sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0) \times \text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0Z^{(*)}) \]

95% CL upper limits are on

\[ e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0Z^{(*)} \]

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CMSSM: Mass Limits for Chargino/Neutralinos

OPAL Preliminary

(a) $\tan \beta = 1.5$

(b) $\tan \beta = 45$

(c) $\tan \beta = 1.5$

(d) $\tan \beta = 45$

Absolute lower limit on the mass of the lightest neutralino (WIMP candidate for Cold Dark Matter)

Peter Krieger, Carleton University

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CMSSM: Slepton Searches

Peter Krieger, Carleton University

WRNPPC, Lake Louise, February 2001
CMSSM: Squark Searches

$e^+ e^- \rightarrow \tilde{t}_1 \tilde{t}_1$
$\tilde{c} \tilde{\chi}_1^0$
$c \tilde{\chi}_1^0$

$\tilde{t} \rightarrow c \tilde{\chi}_1^0$
$\theta_{\tilde{t}} = 0.0 \sim \theta_{\tilde{t}} = 0.98$

$\tilde{b} \rightarrow b \tilde{\chi}_1^0$
$\theta_{\tilde{b}} = 0.0 \sim \theta_{\tilde{b}} = 1.17$

Limits depend on squark mixing angles

Same topology can be used for sbottom search

OPAL Preliminary
$\tilde{t} \rightarrow c \tilde{\chi}_1^0$
$\theta_{\tilde{t}} = 0.0$

OPAL Preliminary
$\tilde{b} \rightarrow b \tilde{\chi}_1^0$
$\theta_{\tilde{b}} = 0.0$

Excluded by CDF

Limits depend on squark mixing angles

OPAL Preliminary
$\tilde{t} \rightarrow c \tilde{\chi}_1^0$
$\theta_{\tilde{t}} = 0.0$

OPAL Preliminary
$\tilde{b} \rightarrow b \tilde{\chi}_1^0$
$\theta_{\tilde{b}} = 0.0$

Excluded by CDF

Limits depend on squark mixing angles

Same topology can be used for sbottom search

Limits depend on squark mixing angles

Same topology can be used for sbottom search

Peter Krieger, Carleton University
WRNPPC, Lake Louise, February 2001
SUSY with a Light Gravitino: Neutralino NLSP Search

Variety of final states (similar to CMSSM signatures but with additional energetic photons from $\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$ decays at end of decay chain)

Some unusual signatures: $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (\tilde{G} \gamma)(\tilde{G} \gamma) \rightarrow \gamma \gamma + E_T$  
final state no longer invisible

SM background from  $e^+e^- \rightarrow \nu \overline{\nu} \gamma\gamma$

Gravitino LSP scenario occurs in various SUSY models (GMSB, no-scale supergravity)

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Is this supersymmetry?

Event: 2 $e + 2 \gamma + E_T$

Can be interpreted as selectron pair production in light gravitino scenario

$\tilde{e}\tilde{e} \rightarrow ee\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma\gamma$

Peter Krieger, Carleton University

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SUSY with a Light Gravitino: Slepton NLSP Searches

Signature as before in CMSSM with gravitinos instead of neutralinos i.e. $\tilde{\tau} \rightarrow \tilde{\chi} \tilde{l}$ instead of $\tilde{\tau} \rightarrow \tilde{\chi}_1 \tilde{l}$

$\sqrt{s} = 189$ GeV

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<tr>
<th>Right handed stau mass (GeV)</th>
<th>Right handed smuon mass (GeV)</th>
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<td>90</td>
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</table>

$\text{BR}^2 = 0.35$ for $\text{BR} = 1.0$

Expected limit for $\text{BR}^2 = 1.0$

$\text{BR}^2 = 0.5$

Limits for $M_{LSP} = 0$ axis and $\text{BR}=1.0$ apply

Peter Krieger, Carleton University

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Slepton NLSP with long lifetime ➫ heavy “stable” charged particles (decays far outside the detector)

Get mass limits near the kinematic limit for $\tau > 1\mu s$

Limits as well for (“heavy stable”) $|Q/e| = 2/3$ spin-1/2 particles $|Q/e| = 1$ spin-1 particles

Cross-section predictions shown for model with GMSB

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Search for Excited Leptons with Photonic Decays

\[ e^+ e^- \rightarrow \ell^* \ell^*, \ell\ell^* \] 

Mass reach best in single-production

\[ \sqrt{s} = 189 - 209 \text{ GeV} \]

\[ \sqrt{s} = 207 \text{ GeV} \]

Signal distributions for \( f/\Lambda = 0.5 \)

Peter Krieger, Carleton University

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Search for Excited Leptons

\[ \sqrt{s} = 189 - 209 \text{ GeV} \]

\[ \sqrt{s} = 207 \text{ GeV} \]

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Leptoquark Pair Production

Leptoquark X

$e^+ e^- \rightarrow XX \rightarrow \ell q \ell' q'$

Assume coupling to a single generation

$eeqq$ $e\nuqq$

$\mu\muqq$ $\mu\nuqq$

$\tau\tauqq$ $\tau\nuqq$

$\nu\nuqq$

Signal distributions for 99 GeV leptoquark

Peter Krieger, Carleton University

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The decommisioning of LEP represents the end of an era

Both the LEP1 and LEP2 experimental programs have yielded valuable precision measurements of the SM as well as varied searches for whatever physics lies (just?) beyond it.

Electroweak combinations are already advanced

Searches combinations are in progress, but no real hints of anything new

The LHC is a hadron machine so a “discovery machine”

LEP’s real legacy is represented by the SM measurements at $\sqrt{s} \approx 90 - 209 \text{ GeV}$