OPAL physics results

Pamela Ferrari

CERN

on behalf of the OPAL Collaboration

- W and Z bosons
- 2-fermion pair-production
- Z peak data analyses
- QCD
- Searches
- Higgs

LEP Jamboree 15 July 2003

Z and W bosons

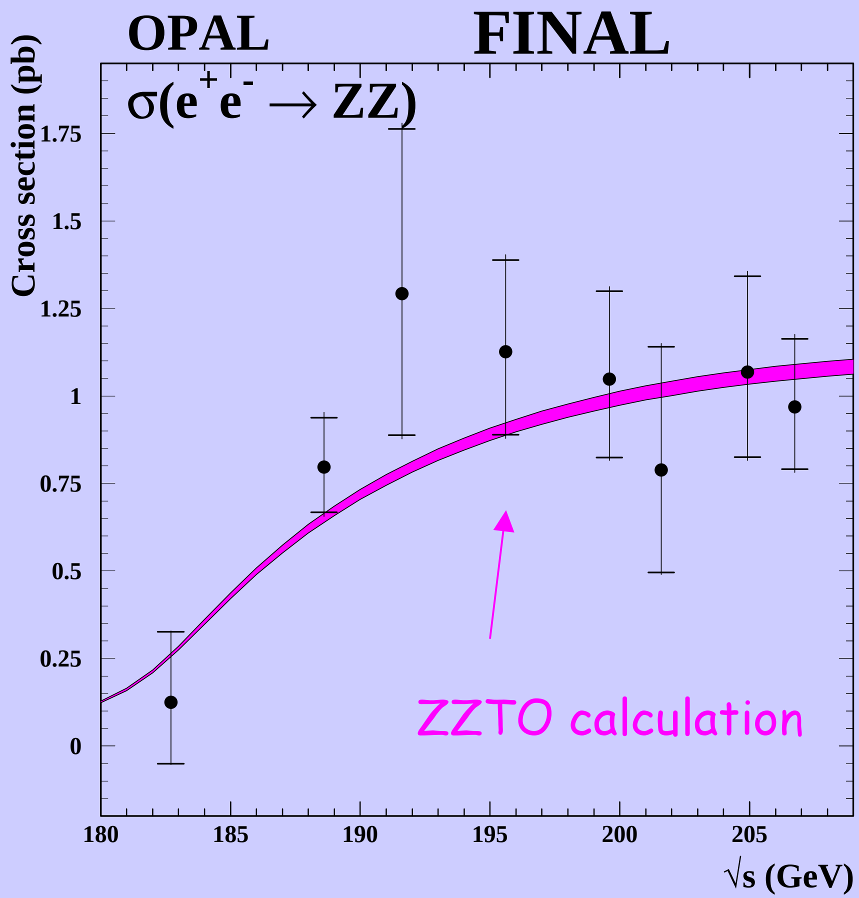
- -Z pair production *PR384*
- -TGC with WW pairs *PR387*
- -Study of $W^+W^-\gamma$ *PR381*
- -Inter WW Bose Einstein Correlations *PN523*
- -W polarisation *PN522*
- -LEP E_b measurement *PN520*

Study of Z pair production

- **Final states analysed:**

  @183<E_{CM}<209 GeV

  - $l^+l^-l^+l^-$
  - $l^+l^-\nu\nu$ (except $\tau^+\tau^-\nu\nu$)
  - qql^+l^-
  - $qq\nu\nu$
  - $qqqq$



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Limits on neutral TGC from ZZ analysis

Obtained by using

1) the cross-section info

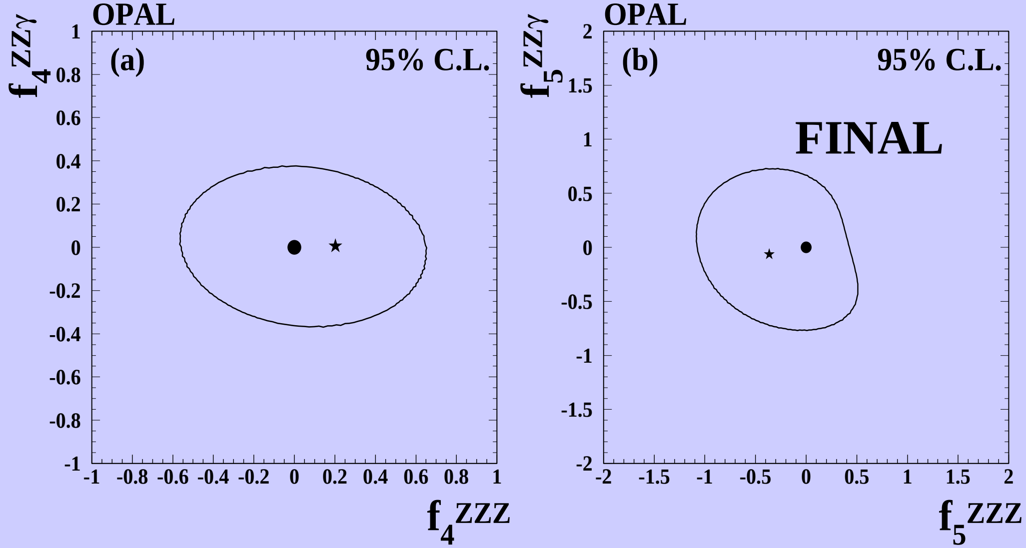
2) kinematic info from an optimal observable (OO) method for qqll and qqqq,qqbb selections.

95% CL limits on anomalous TGC are obtained by combining the likelihood associated with the χ^2 fit from the OO analysis with x-section fit.

1D

Coupling	95% CL lower limit	95%CL upper limit
f_4^{ZZZ}	-0.46	0.58
f_5^{ZZZ}	-0.95	0.25
$f_4^{ZZ\gamma}$	-0.31	0.33
$f_5^{ZZ\gamma}$	-0.72	0.60

2D



Low scale gravity Extra Dimensions

- Gravity is allowed to propagate in D=4+n dimensions, while other particles are confined to four dimensional space.
  (N.Arkani-Hamed et al. phys.lett. B429 (1998) 263)
- Newtonian gravity in 3D holds if:

$$M^2_{Planck} \propto R^n M_D^{(n+2)}$$

M/M_D= Planck scale in 4D/D dimensional space, R=compactification radius of n extra dimensions (n=1 excluded by cosmological observations)

# of ED	95%CL on Ms
n=2	0.92 TeV
n=3	0.82 TeV
n=4	0.73 TeV
n=5	0.67 TeV
n=6	0.62 TeV
n=7	0.59 TeV

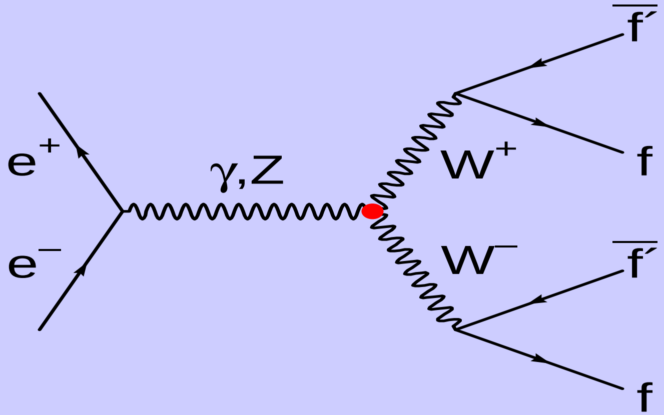
Gravity propagates in ED ⇨ LO contributions from s-channel exchange KK graviton states to Z-pair production amplitude

$\sigma=\sigma_{SM}+\varepsilon\sigma_{interference}+\varepsilon^2\sigma_{gravity}$

Limits are given on M_s= ultraviolet divergencies cutoff, by fitting cross –section with ε as free parameter (where $\varepsilon \div 1/M_S^4$ in most of the cases)

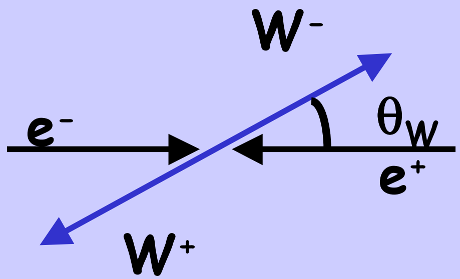
TGC measurement using W-pairs (I)

WW production:
TGC vertex s-channel
most constraining

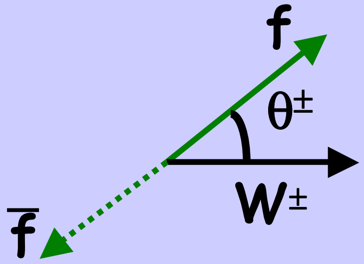


sensitive observables

W^+W^- production angle $\cos\theta_W$



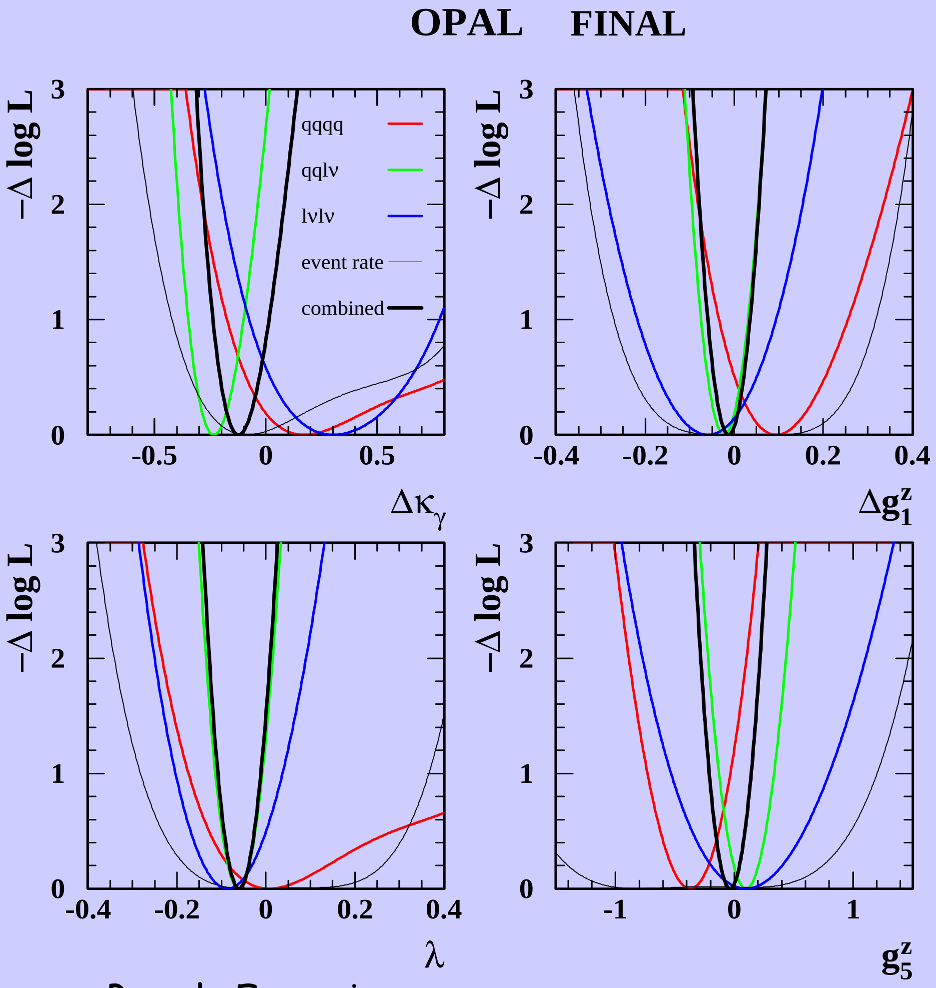
$W^\pm$ decay angles (helicity)



$W^\pm$ rest frame
θ and ϕ of W
decay products

TGC measurement using W-pairs (II)

- 4 independent couplings: $k_\gamma, g^z_1, \lambda_\gamma, g^z_5$
- final states: $l\nu_l l' \nu_{l'}, qql\nu_l, qqqq$



measurement of SM TGC:

Optimal Observable
+Event Rate

$k_\gamma = 0.88^{+0.09}_{-0.08}$

$g^z_1 = 0.987^{+0.034}_{-0.033}$

$\lambda = -0.060^{+0.034}_{-0.033}$

$g^z_5 = -0.04^{+0.13}_{-0.12}$

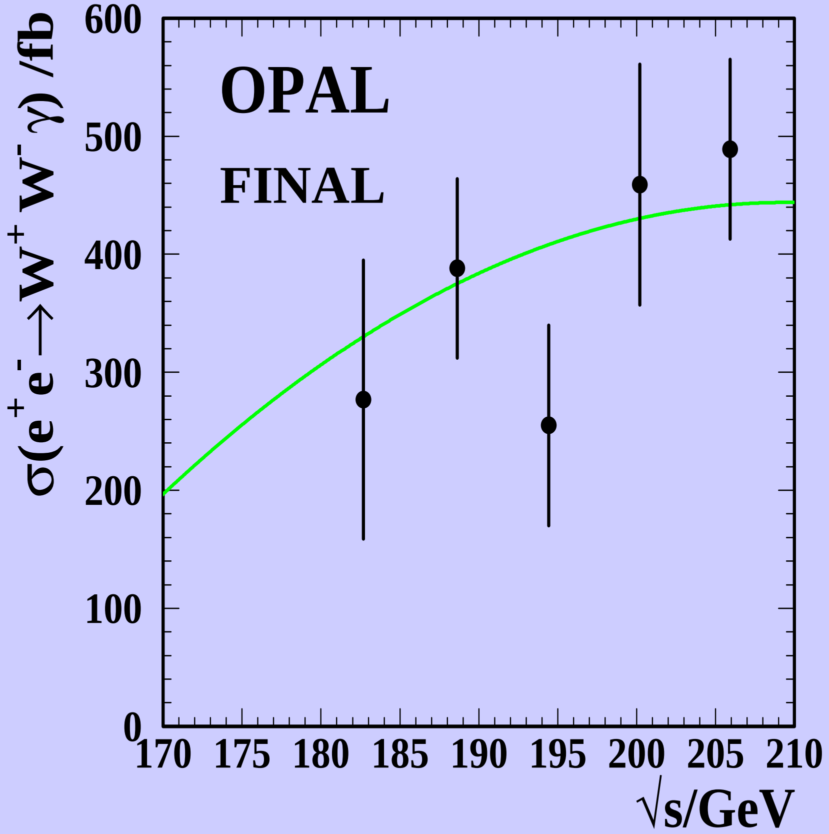
A study of $W^+W^-\gamma$ events @LEP2

Selection of WW events with non collinear hard γ ($E\gamma$>2.5 GeV),

Aim: measurement of effects of O(a) radiative corrections

- Cross section results vs $\sqrt{s}$
  - Calculate ratio of data/MC combine all Energy point and compare MC's
  - Models with $O(\alpha)$ radiation * give better x-sec description (main effect ISR and WSR interference)

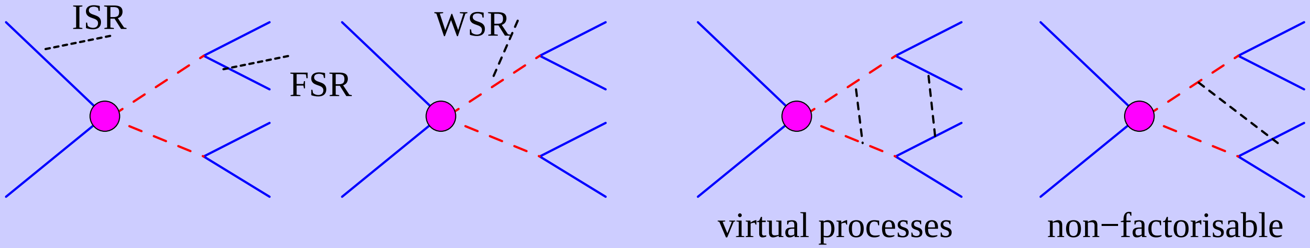
Monte Carlo	Data/MC
KandY *	0.99 ±0.09 ± 0.04
Racoon*	0.98 ±0.09 ± 0.06
EEWG	0.91 ±0.09 ± 0.04
KoralW	0.84 ±0.08 ± 0.04



γ from the final state quark or from associated parton shower, both considered as bkg since they are experimentally indistinguishable

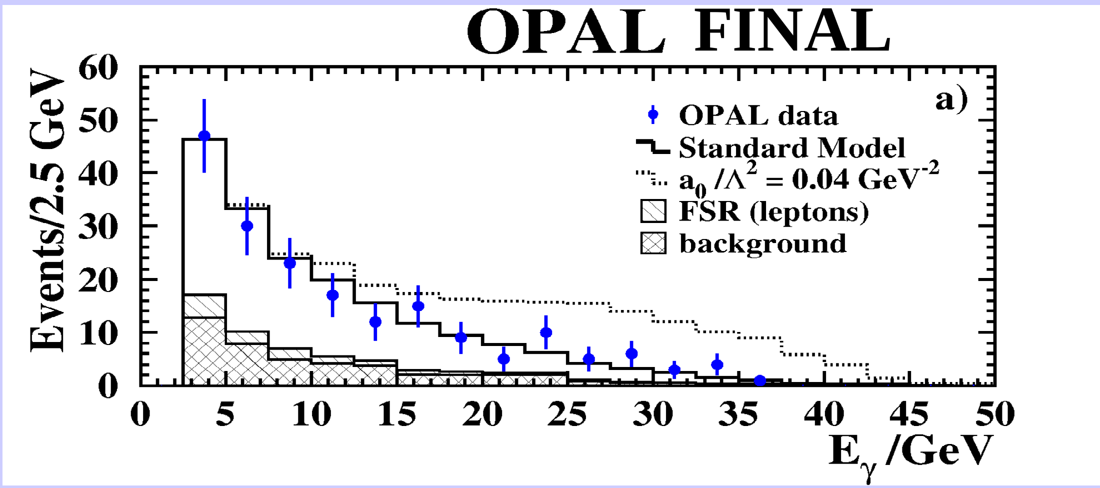
m_W O(α) systematics

m_W calibrated on Monte Carlo with O(α) photon radiation but not all diagrams are completely included:

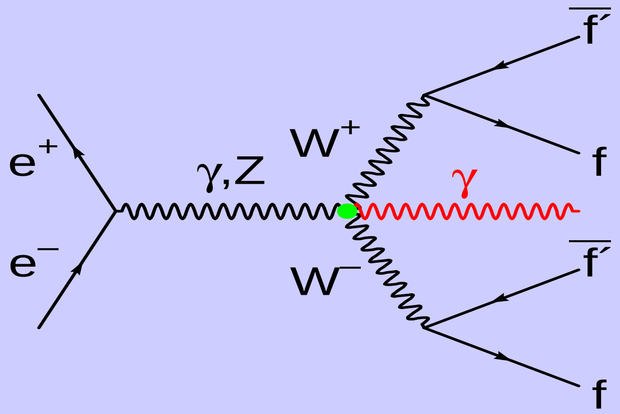


Aim: estimate on data the contribution of real γ production using WWγ events by fitting $|\cos\theta_\gamma|$ distribution
(the weight of O(α) correction in KANDY is used as free parameter)

Estimated mass shift due to real photon production from data corresponds to a maximum correction of ~ 6 MeV



Quartic Gauge Coupling from $W^+W^-\gamma$



in SM these couplings exist but too small to be seen at LEP

look for anomalous contributions parameterised by additional terms in the Lagrangian

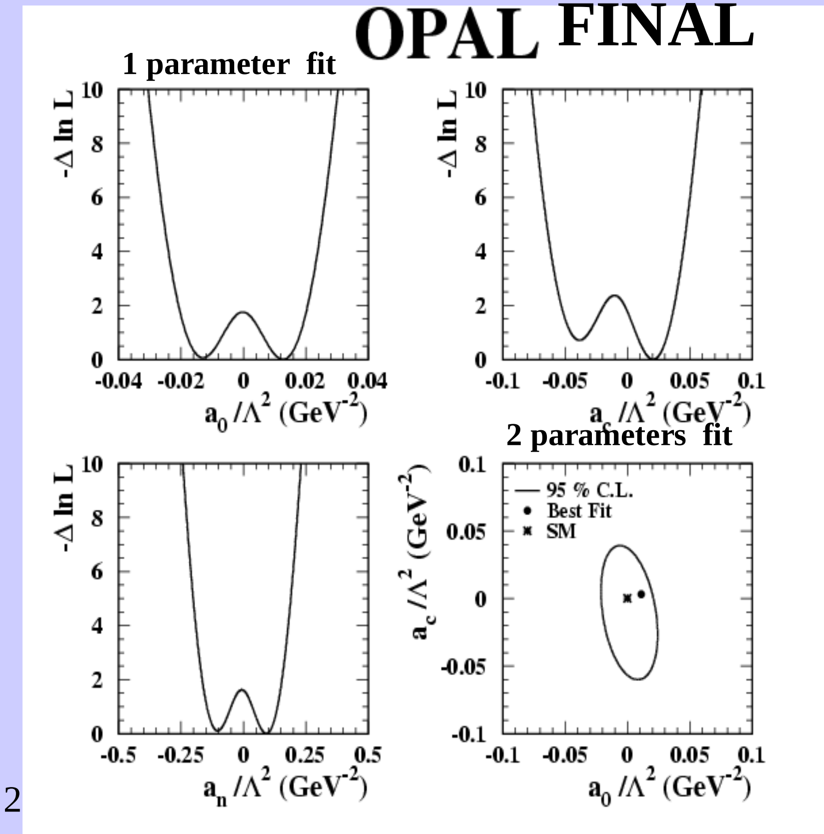
couplings a_0, a_c, a_n;
New physics scale Λ

95% CL on anomalous contributions on $W^+W^-\gamma\,\gamma$, $W^+W^-Z^0\gamma$ vertices by binned max likelihood fit to observed $E\gamma$, $|\cos\theta_\gamma|$ distributions

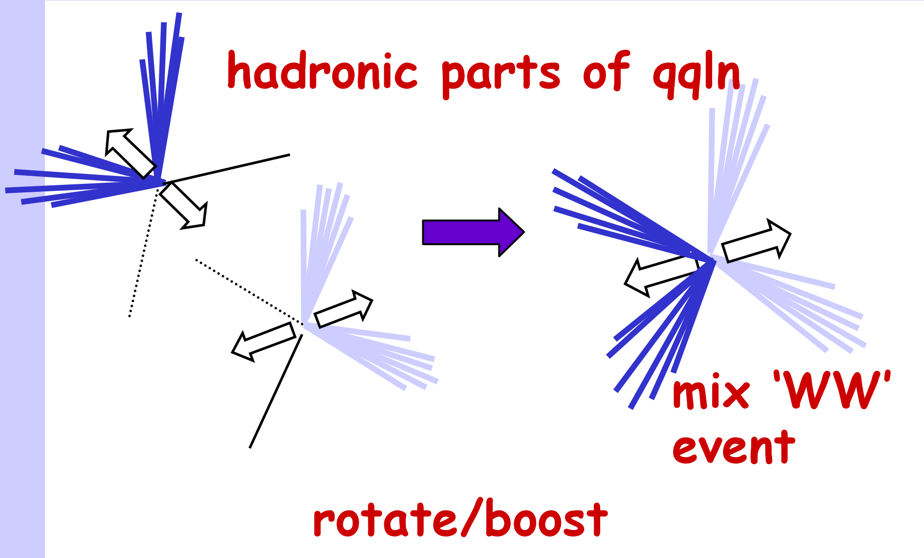
$-0.020 < a_0/\Lambda^2 < 0.020\ \mathrm{GeV}^{-2}$

$-0.053 < a_c/\Lambda^2 < 0.037\ \mathrm{GeV}^{-2}$

$-0.16 < a_n/\Lambda^2 < 0.15\ \mathrm{GeV}^{-2}$



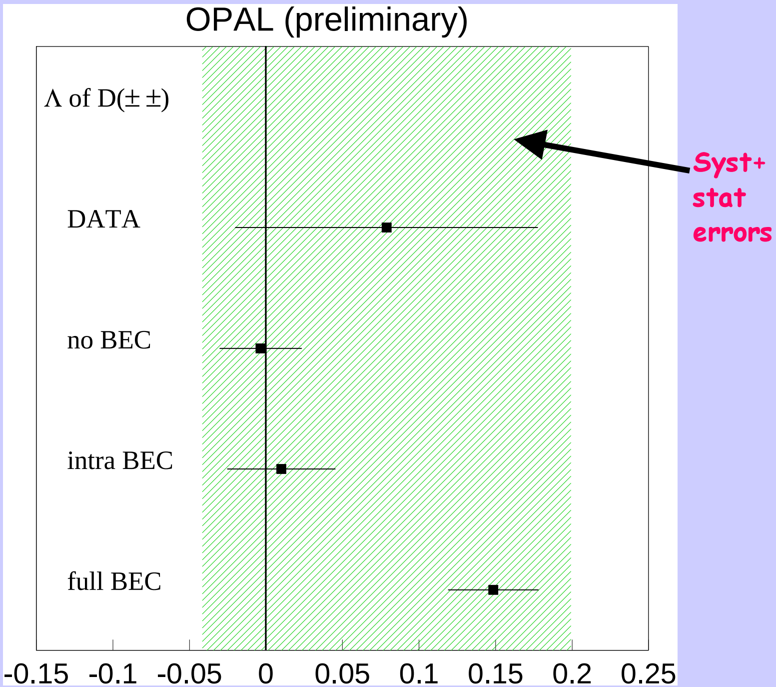
Bose Einstein correlations in WW events



BEC in WW pair hadronic decays affect the production of identical hadrons from different W's

comparing $\rho_2(Q)$, 2 ptc densities in 4q and 'mixed' WW events:

$$D(Q) = \rho_2^{WW}(Q)/[2\rho_2^{W}(Q) + 2\rho_{mix}^{WW}(Q)]$$



Fitting with empirical parametrisation

$$D(Q) = N(1 + \delta \cdot Q)(1 + \Lambda \cdot \exp(-Q/R))$$

N=norm, δ difference due long range interactions,
Λ= strength of BEC, R width of enhancement due to inter-WW BEC

NO significant effects observed. Limited by statistics, LEP combination is needed

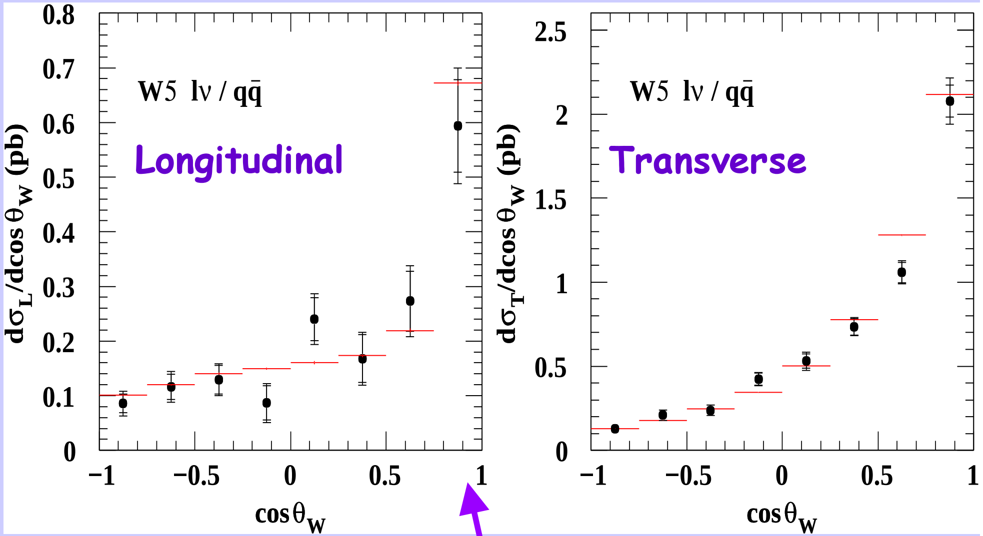
W boson polarisation at LEP2

The spin of W bosons in $WW \to q\bar{q}' l\bar{\nu}_l$ $l=e,\mu,\tau$ events are obtained by angular analysis of W decay products $183 < \sqrt{s} < 209$ GeV

1. Get Spin density matrix elements from angular distributions of decay products $\rho_{\tau\tau}^{W-}$, where τ =W helicity (-1,0,1)

2. Obtaining:
   $d\sigma_L/d\cos\theta_W = \rho_{00} d\sigma/d\cos\theta_W$
   $d\sigma_T/d\cos\theta_W = (\rho_{++} + \rho_{--})\, d\sigma/d\cos\theta_W$

3. Luminosity weighted averages compared with SM expectations (KANDY MC)



Hadronic and leptonic decays

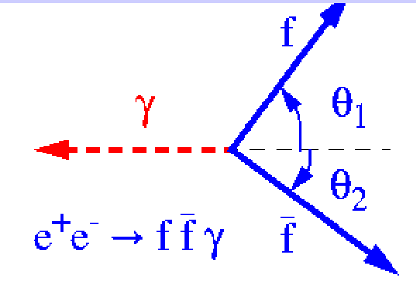
average longitudinal polarisation:

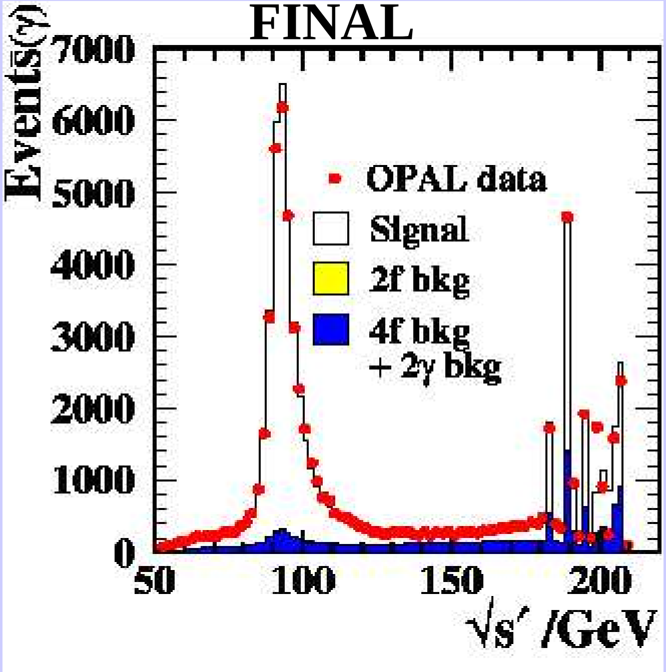
23.8 ±2.1 ±1.4%	23.9 ±0.1%
measured	expected

Determination of LEP E_b with radiative ff events

Overall E scale checked by using
e^+e^- -> Zγ, Z->ff events (f=q,e,μ,

modelling of variations of LEP
energies assumed to be correct





Fits comparing data and MC:

Fit analytic function to the √s' distribution of leptonic and hadronic events around the Z mass peak.
The Eb shift is estimated by the position of the fitted Z mass peak

less than 0.1 σ from LEP measurement when including 20 MeV syst error

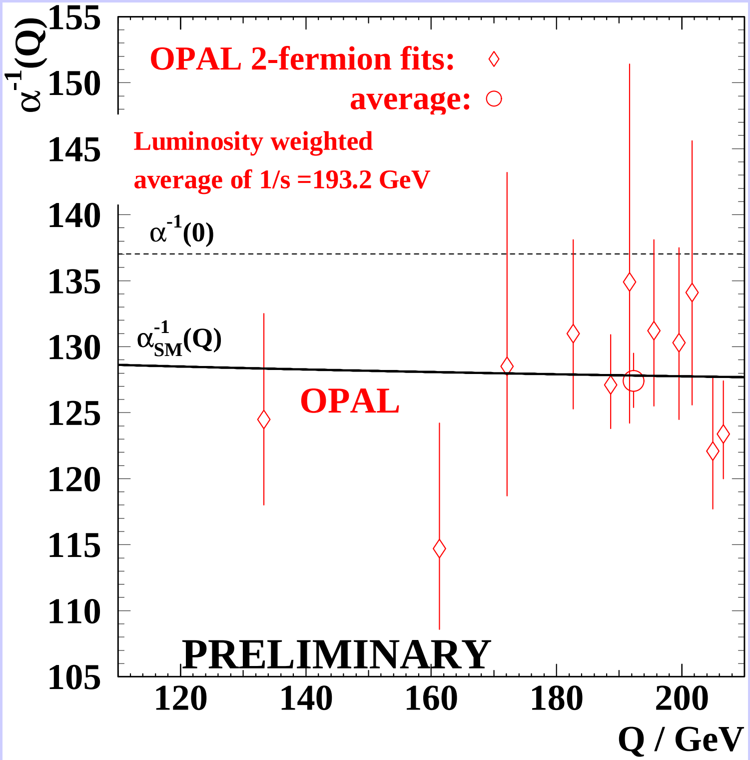
2-fermion pair production

- Tests of the Standard Model and Constraints on New Physics from Fermion-Pair Production *PN521*

Fermion pair-production

Measurements of x-sections and asymmetries for hadronic and lepton-pair production $189<\sqrt{s}<209$ GeV

(inclusive s'/s >0.01, non-radiative s'/s >0.7225)



agreement with SM:

(ZFITTER,BHWIDE for e)

~1% for hadrons

~3% for leptons

from non-radiative sample :

$1/\alpha_{em}(193.2\ \text{GeV})=127.4^{+2.1}_{-2.0}$

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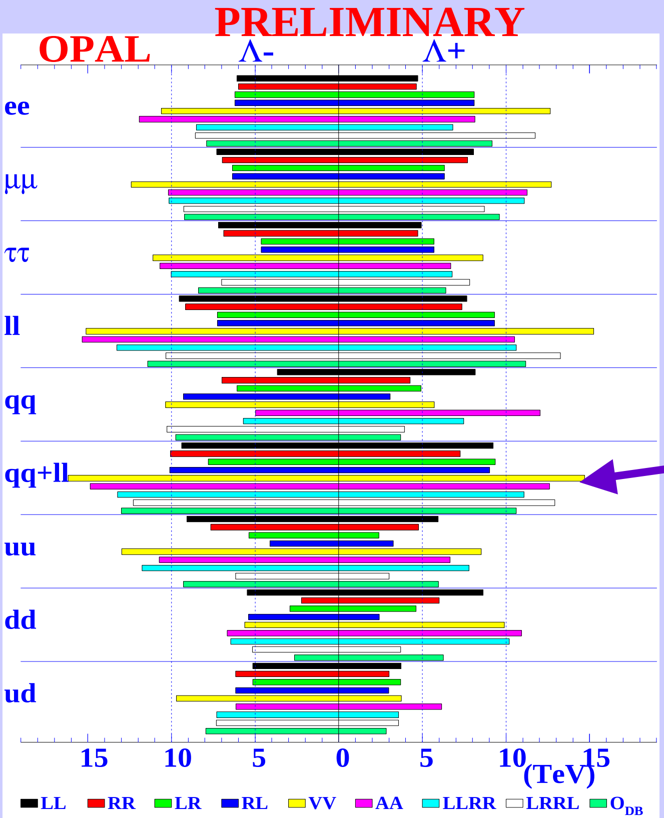
Limits on new physics

Contact interactions would modify x-section and angular distributions.



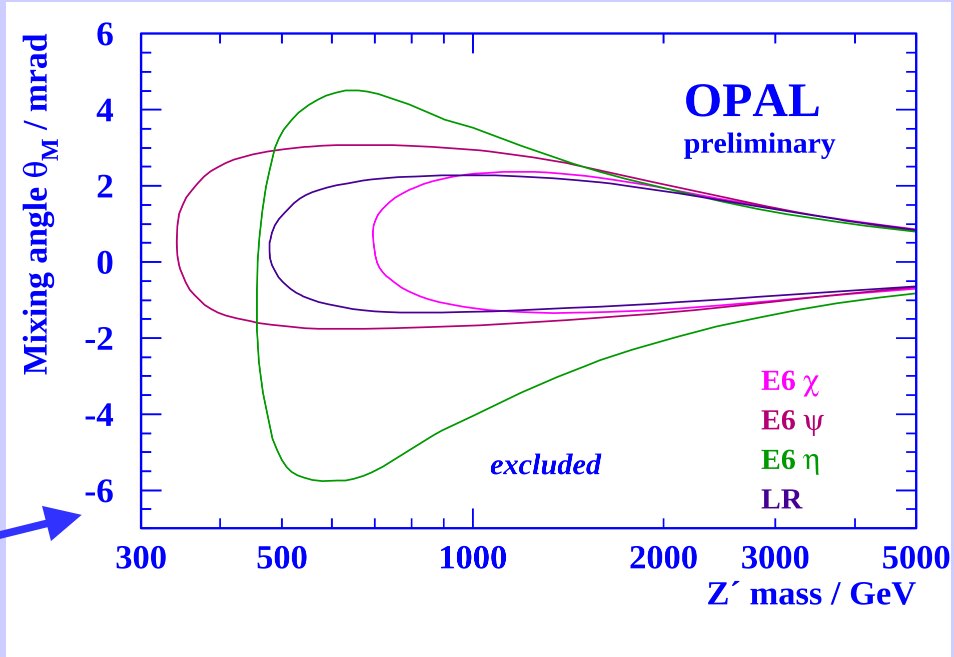
Limits on 4-fermion contact interactions:

$|\Lambda|<$3-13 /5-16 TeV(scale of new physics Assuming $g^2/4\pi=1$)

$Z^{0\prime}$ would mix with Z^0 interactions

θ_M mixing angle, free parameter

Limits on Z' mass and θ_M



E6 GUT & Left-Right (LR) symmetric models

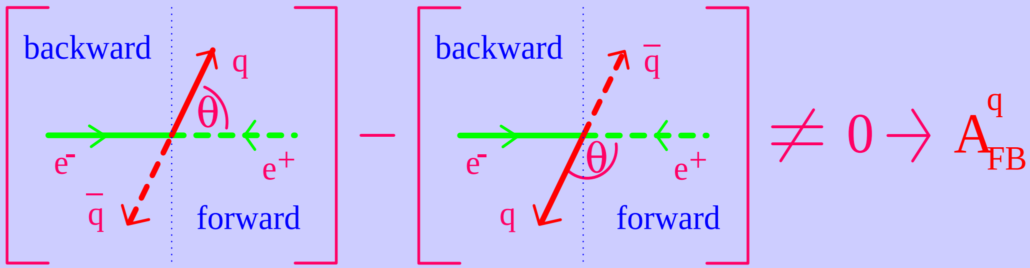
Z-peak analyses

- -Heavy quark A_{FB} *PR383*
- -Charm quark production in b decays *PR382*

Heavy quark A_{FB} (I)

SM A_{FB} arises from $\cos\theta$ term in :

$$d\sigma/d\cos\theta_{\ qq} \propto 1 + \cos^2\theta + (8/3)\, A^b_{FB} \cos\theta$$



Measurement of A_{FB} provides precise value of $\sin\theta^l_{eff}$

Measure A_{FB} of ee→bb/cc using e/μ produced in semileptonic decays: Neural Networks are used to identify b→l and c→l in a maximum likelihood fit of events containing 1 or 2 leptons

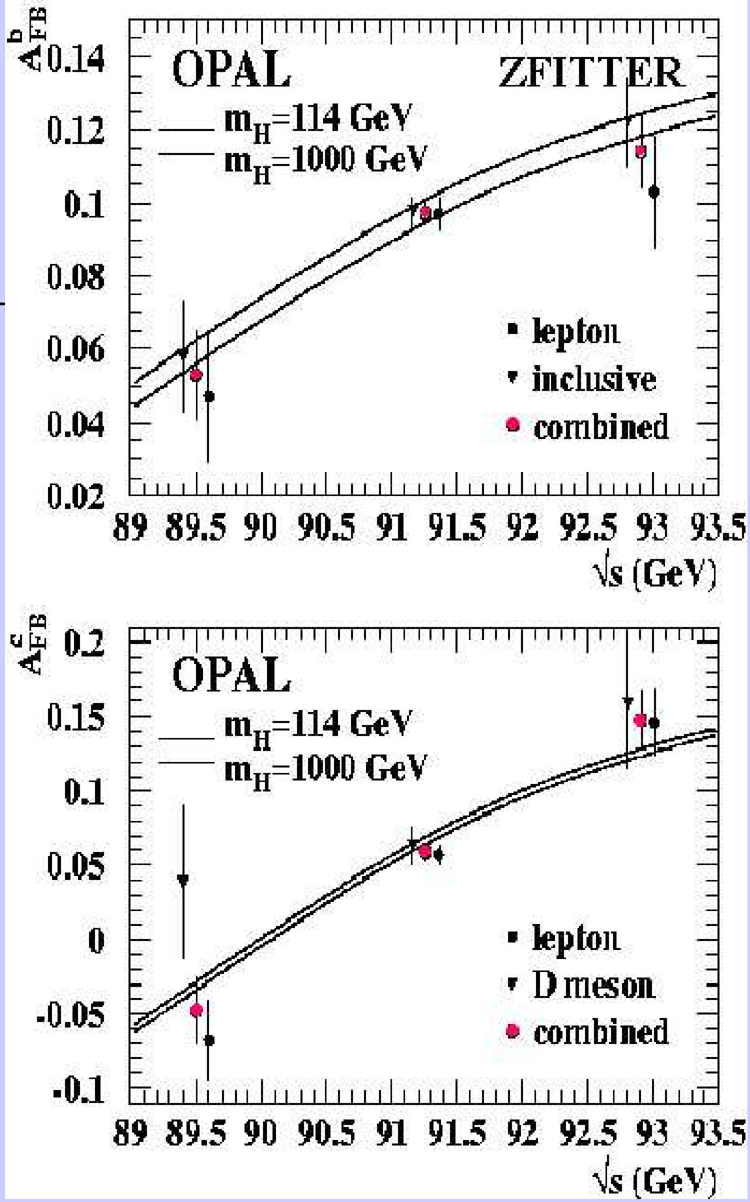
Asymmetries are fitted simultaneously with $A_{FB}{}^b$, $A_{FB}{}^c$ and the average B mixing parameter (reducing $A_{FB}{}^b$) as fitting parameters

Heavy quark A_{FB} (II)

FINAL

Using all OPAL data near the Z mass:

$\sqrt{s}$ GeV	A_{FB}^{bb}	A_{FB}^{cc}
89.51	4.7 ±1.8 ±0.1	4.7 ±1.8 ±0.1
91.25	9.72 ±0.42 ±0.15	5.68 ±0.54 ±0.39
92.95	10.3 ±1.5 ±0.2	14.6 ±2.0 ±0.8



Average B mixing parameter:

χ=(13.12 ±0.49 ±0.42)%

Results favour large values for m_H

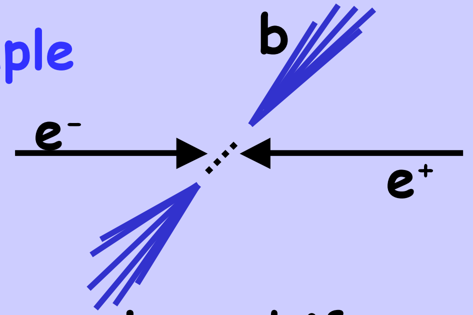
As other heavy flavour asymmetries

$\sin^2 \theta^l_{eff}$=0.23238 ± 0.00052

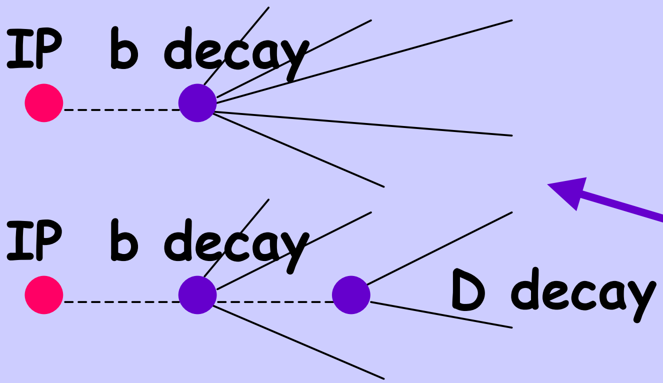
Charm quark production in b decays

Br($b \to D\bar{D}X$) measured with inclusive method in hadronic Z^0 decays

Unbiased sample of b-jets



Jet selected if opposite is tagged as b



To identify tracks from D we use signed r-ϕ impact parameter significance S, S of tracks is used to calculate joint probability Pj for each jet

Br($b \to D\bar{D}X$) is measured by fitting ln(Pj) distributions for data with MC

$$Br(b \to D\bar{D}X) = (10.0 \pm 3.2(stat)^{+2.4}_{-2.9}\,(det)\,^{+10.4}_{-9.0} \pm (phys))\%$$

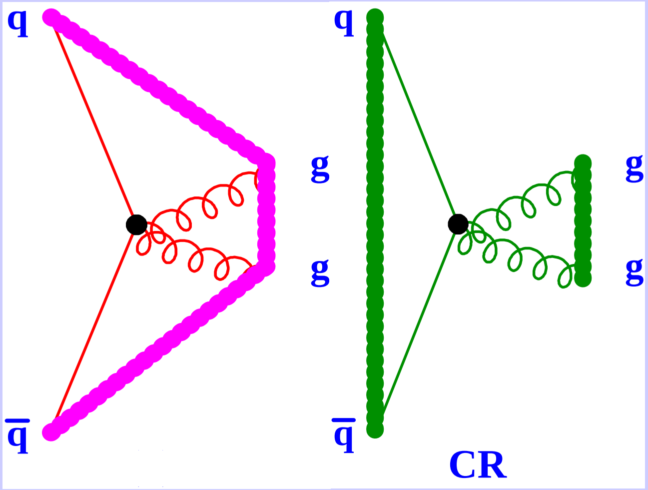
FINAL

QCD studies

-Color reconnection in g-jets *CERN-EP-2003-031*

-Measurement of α_s in qqγ events *PN519*

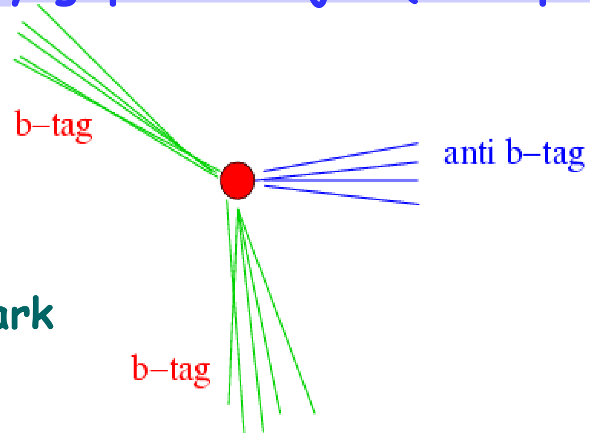
-Measurement of Isolated prompt photon production in photon-photon collisions *CERN-EP-2003-023*

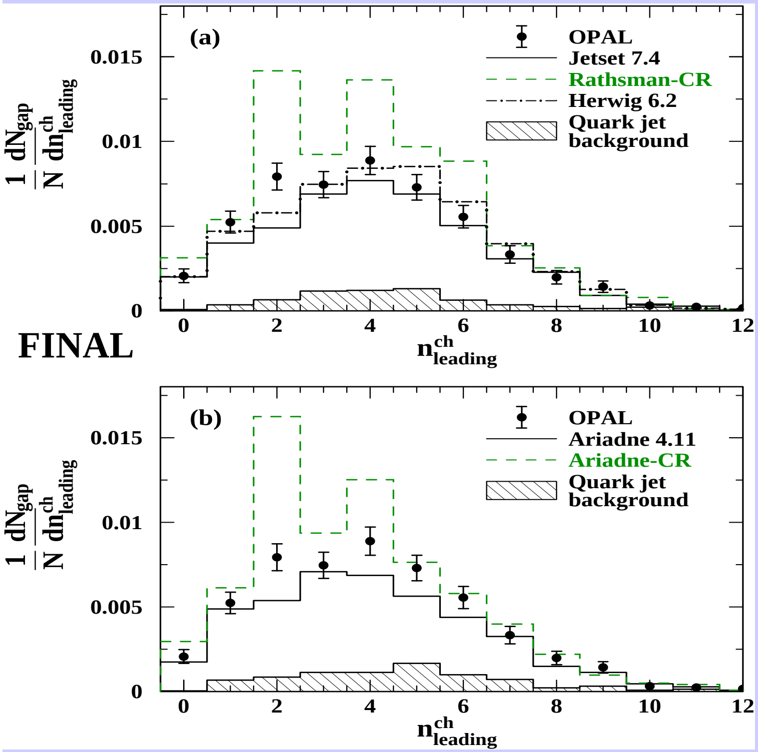


Color Reconnection in gluon jets

- Gluon jets are selected from hadronic Z^0 decays at $\sqrt{s} \sim m_Z$
- rapidity gaps could arise from CR: selection requires a large rapidity gap in the jet (86% purity)

g-jet identified by antitagging: b-tagging of quark jets





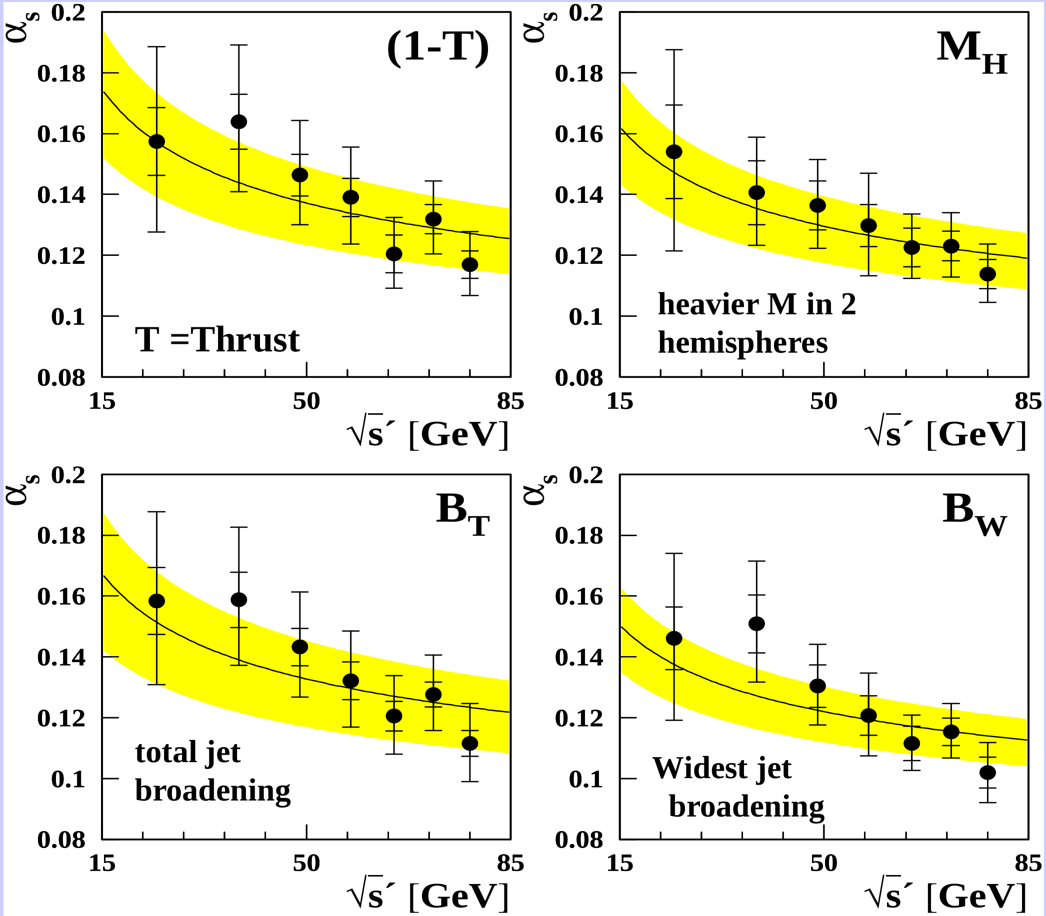
- MC with CR do not describe the g-jet data. If MC's are retuned to reproduce the data they do not reproduce anymore some global properties of Z hadronic events: sphericity, aplanarity
- The models with CR are excluded

Measurement of α_s in $qq\gamma$ events (I)

Hadronic final states with hard isolated photons at $\sqrt{s} \approx M_Z$,

Assuming γ are emitted before (ISR) or just after Z^0 production measure of α_s at different $20 < \sqrt{s'} < 80$ GeV

PRELIMINARY



Fits of $O(\alpha_s^2)$ and NLLA QCD predictions of 4 event shape variables of hadronic system boosted into centre-of-mass frame, with α_s as free parameter.

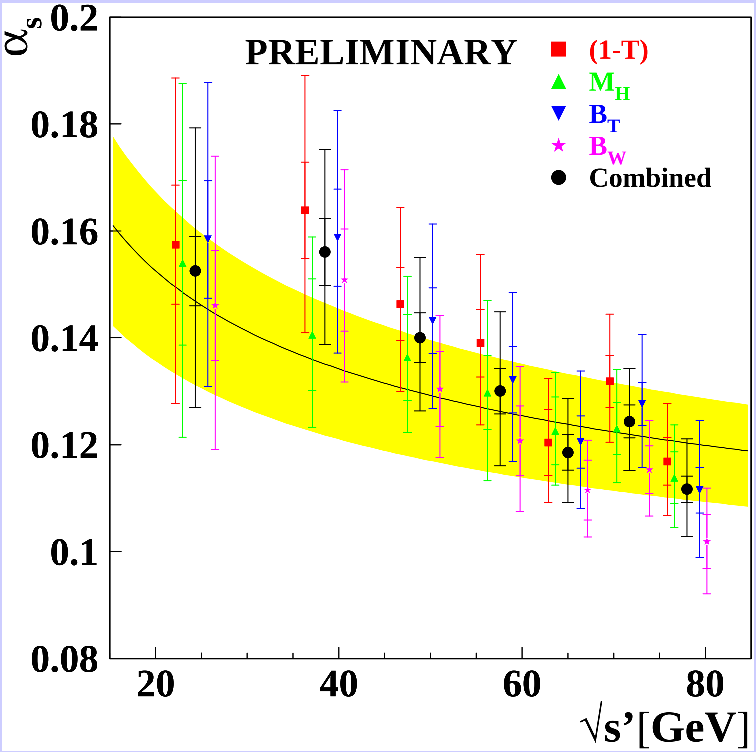
Hadronization with:
JETSET, HERWIG, ARIADNE

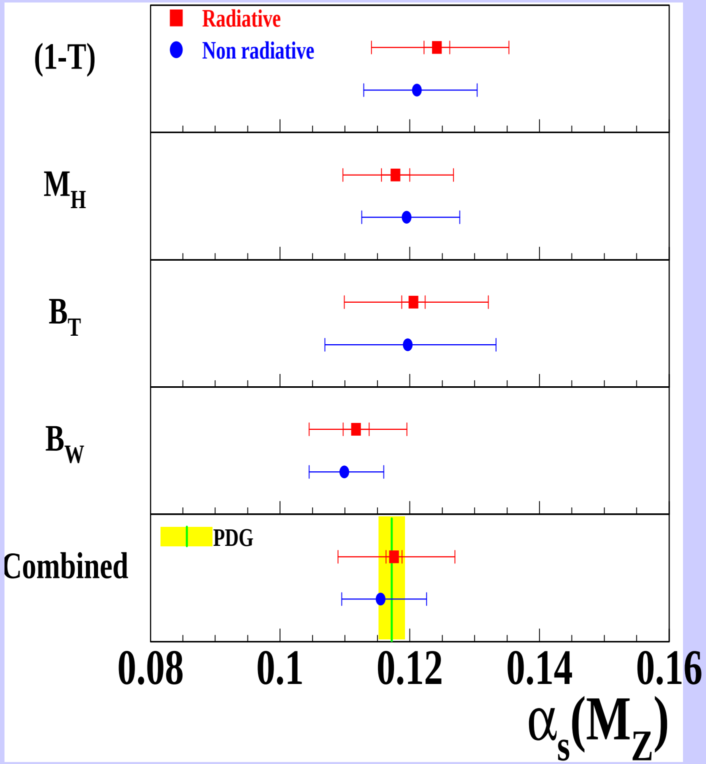
Measurement of α_s in qqγ events (II)

- α_s is extrapolated to M_Z using the renormalisation group equation at NNLO:

$$\alpha_s(M_Z)=0.1176 \pm 0.0012(stat)^{+0.0093}_{-0.0085}(syst)$$

agreement with non-radiative LEP1 data and world average PDG



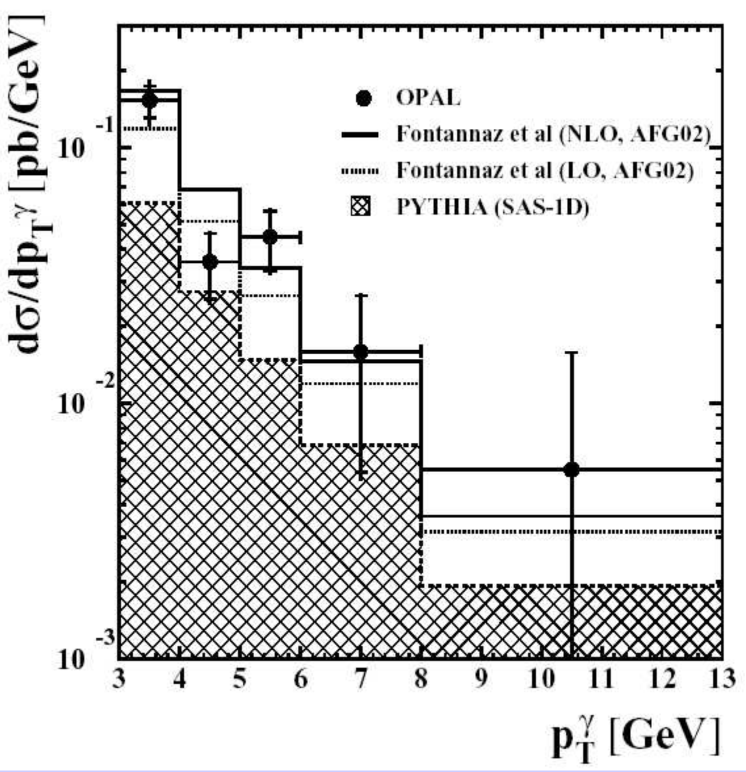


Measurements of isolated prompt photon production in photon-photon collisions

Measurement of inclusive x-section for the production of isolated prompt photons in anti-tagged $\gamma\gamma$ collisions.

- prompt photons are selected by an isolation criterion
- $p_\gamma^T > 3$ GeV, $|\eta^\gamma| < 1$

$\sigma_{TOT} = 0.32 \pm 0.04(stat) \pm 0.04(syst)$



Differential x-sec are calculated
$d\sigma/dp^T$, $d\sigma/d\eta^\gamma$, $d\sigma/dx^T$

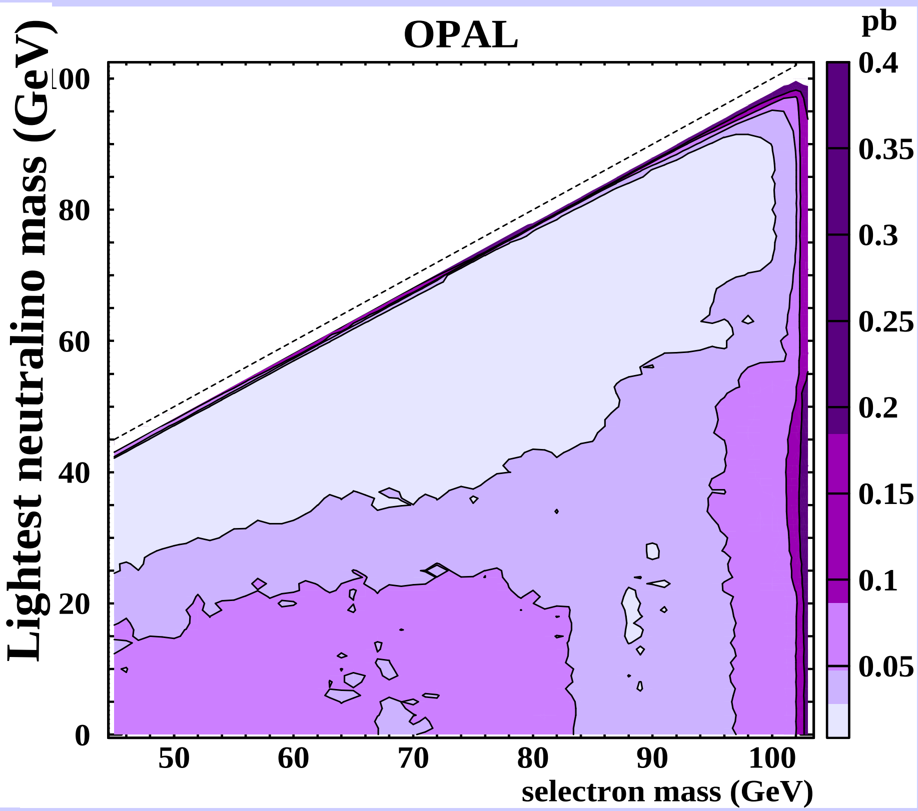
PYTHIA underestimates the x-sec
NLO calculation describes well shape and normalization

New particles and Higgs searches

-Acoplanar di-lepton pairs *PR385*
-Searches for R-parity Violation *PR380*
-Pair produced lepto-quarks *CERN-EP-2003-021*
-MSSM CP violating and conserving *PN524*
-Doubly charged Higgs *PN524*

Search for anomalous production of di-lepton pairs

- Search for acoplanar di-lepton events with significant E_{tmiss}
  $l=e,\mu,\tau$ $183<\sqrt{s}<209$ GeV $\mathcal{L}=$ 680 pb^{-1}
- possible signature of new particles that decay in a charged lepton + one or more invisible particles



95% CL limits on x-sec*BR²

s-leptons Limit on x-section*BR²
μ=-100 GeV $\tan\beta$=1.5
MSSM mass limit on
- $\tilde{e}_R$ with $m_{\tilde{e}-} - m_{\tilde{\chi}^0_1}$>11 GeV
- $\tilde{\mu}_R$ with $m_{\tilde{\mu}-} - m_{\tilde{\chi}^0_1}$>4 GeV
- $\tilde{\tau}_R$ with $m_{\tilde{\tau}-} - m_{\tilde{\chi}^0_1}$> 8 GeV

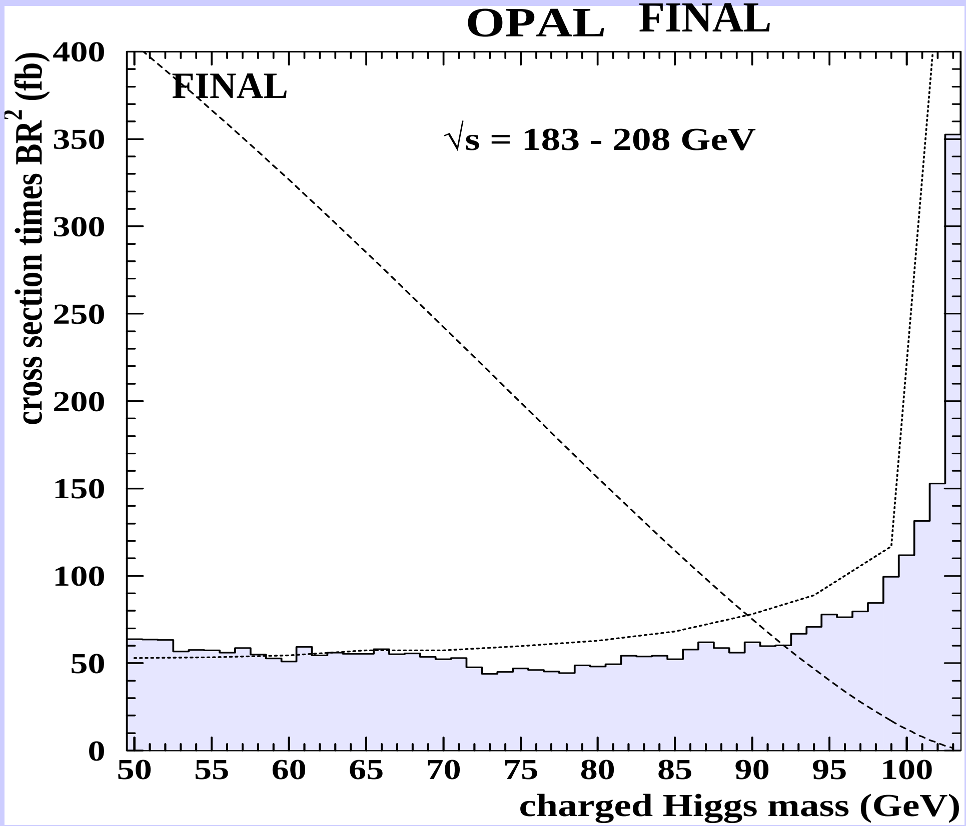
$m_{\tilde{e}_R}$ > 97.5 GeV

$m_{\tilde{\mu}_R}$ > 94.0 GeV

$m_{\tilde{\tau}_R}$ > 89.8 GeV

Search for anomalous production of di-lepton pairs

- Search for acoplanar di-lepton events with significant E_{tmiss}
  $l=e,\mu,\tau$ 183<$\sqrt{s}$<209 GeV $\mathcal{L}$ = 680 pb^{-1}
- possible signature of new particles that decay in a charged lepton + one or more invisible particles



95% CL limits on x-sec*BR^2

Charged Higgs Limit on x-section
$H^{\pm} \to \tau^{\pm} \nu_{\tau}$

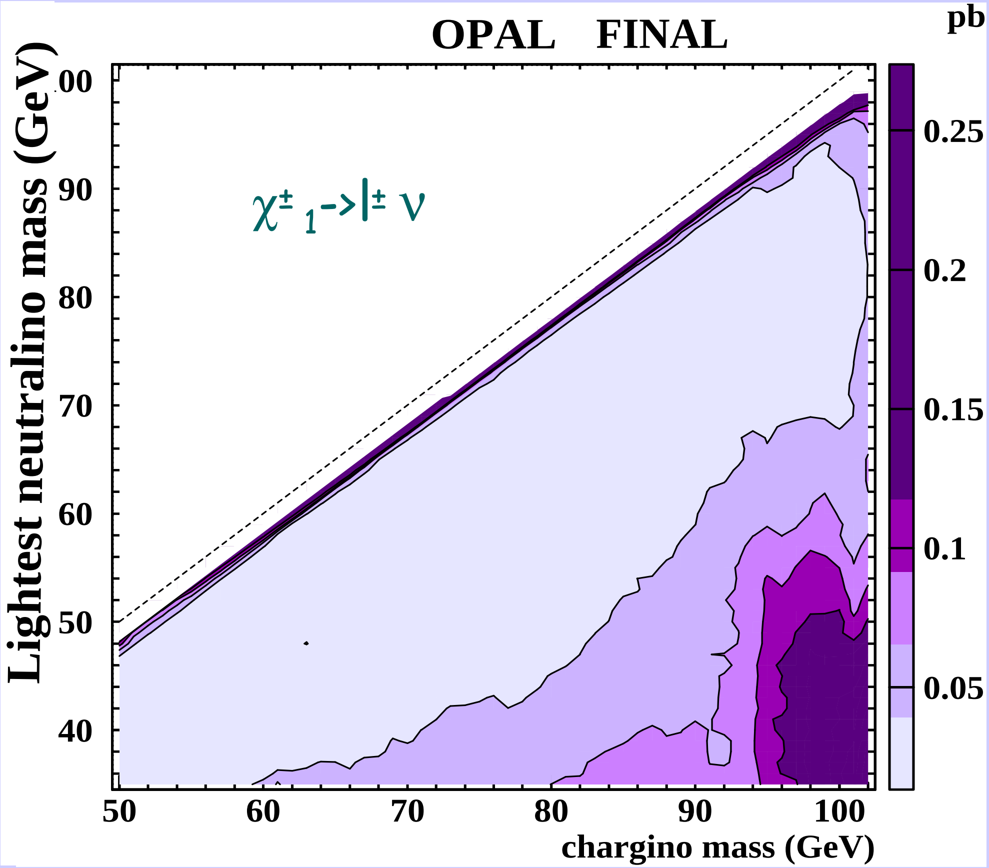
mass limit
assuming 100% BR $H^{\pm} \to \tau^{\pm} \nu_{\tau}$

$m_{H\pm}$ > 92.0 GeV

Search for anomalous production of di-lepton pairs

- Search for acoplanar di-lepton events with significant E_{tmiss}
  $l=e,\mu,\tau$ $183<\sqrt{s}<209$ GeV $\mathcal{L}$ = 680 pb^{-1}

- possible signature of new particles that decay in a charged lepton + one or more invisible particles



- 2-body decay
  $\tilde{\chi}^{\pm}_1 \to l^{\pm} \tilde{\nu}$

- 3-body decay
  $\tilde{\chi}^{\pm}_1 \to l^{\pm} \nu \tilde{\chi}^0_1$

Search for RPV decays of Scalar fermions

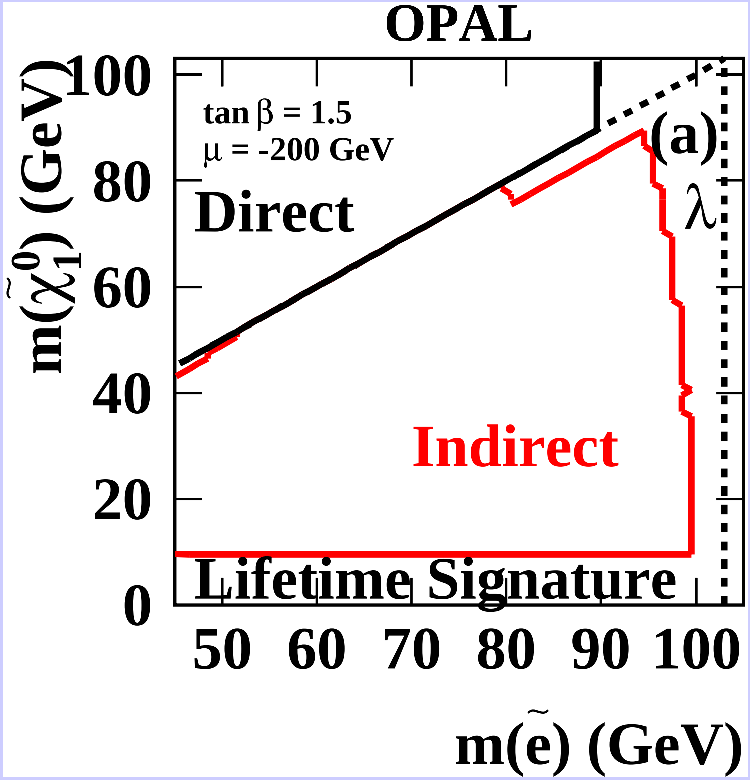
$R_P=(-1)^{2S+3B+L}$ S= spin B,L baryon and lepton numbers $189 \le \sqrt{s} \le 209$ GeV

R_P =+1 for SM ptc R_P =-1 for supersymmetric-ptc

R_P Violation: LSP decays to SM particles

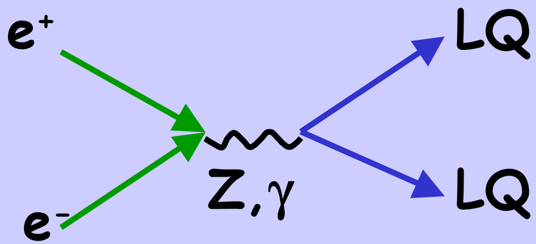
Topologies: $2\ell + E_{miss}$, 4ℓ ($+ E_{miss}$)
6l + E_{miss}, 2jets +2 ℓ
4jets +2ℓ, 4 jets ($+ E_{miss}$)

Indirect decays: decays of s-fermions
via LSP ($\tilde{\chi}^0_1$)
Direct decays: decays of s-particles
to SM particles



-limits on production x-section of s-fermions
-Mass limits in CMSS with tanβ=1.5 μ=-200

Search for pair-produced leptoquarks



all 3 generations of LQ produced
Lagrangian satisfies:
-$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
-baryon and lepton numbers

9 scalar (S) and 9 vector (V) leptoquarks

Topologies studied

- for a given search channel only decays into one lepton generation are considered
- coupling to fermions $10^{-6} < \lambda < 10^{-2}$
- channels $\nu_l \nu_l qq$, $qql^{\pm}\nu_l$, $qql^+ l^-$ with $l = e, \mu, \tau$
- topology: isolated lepton+ hadronic jet or large E_{miss}+jet

95% CL limits on LQ masses

FINAL

Scalars			generations			Vectors			generations		
LQ	Q_{em}	β	1	2	3	LQ	Q_{em}	β	1	2	3
S_0	-1/3	[0.5,1]	69	79	45	V_0	-2/3	[0.5,1]	99	99	97
S_0	-4/3	1	99	100	98	V_0	-5/3	1	102	102	101
S_1	-4/3 -1/3 -4/3	0 0.5 1	97 69 100	97 79 101	97 45(*) 99	V_1	1/3 -2/3 -5/3	0 0.5 1	101 99 102	101 99 102	101 97 101
$S_{1/2}$	-2/3 -5/3	[0,1] 1	94 100	94 100	93 98	$V_{1/2}$	-1/3 -4/3	[0,1] 1	99 102	99 102	97 101
$S_{1/2}$	1/3 -2/3	0 1	89 97	89 99	89 96	$V_{1/2}$	2/3 -1/3	0 1	99 101	99 101	99 99

Limits expressed in GeV

MSSM CP conserving scenarios

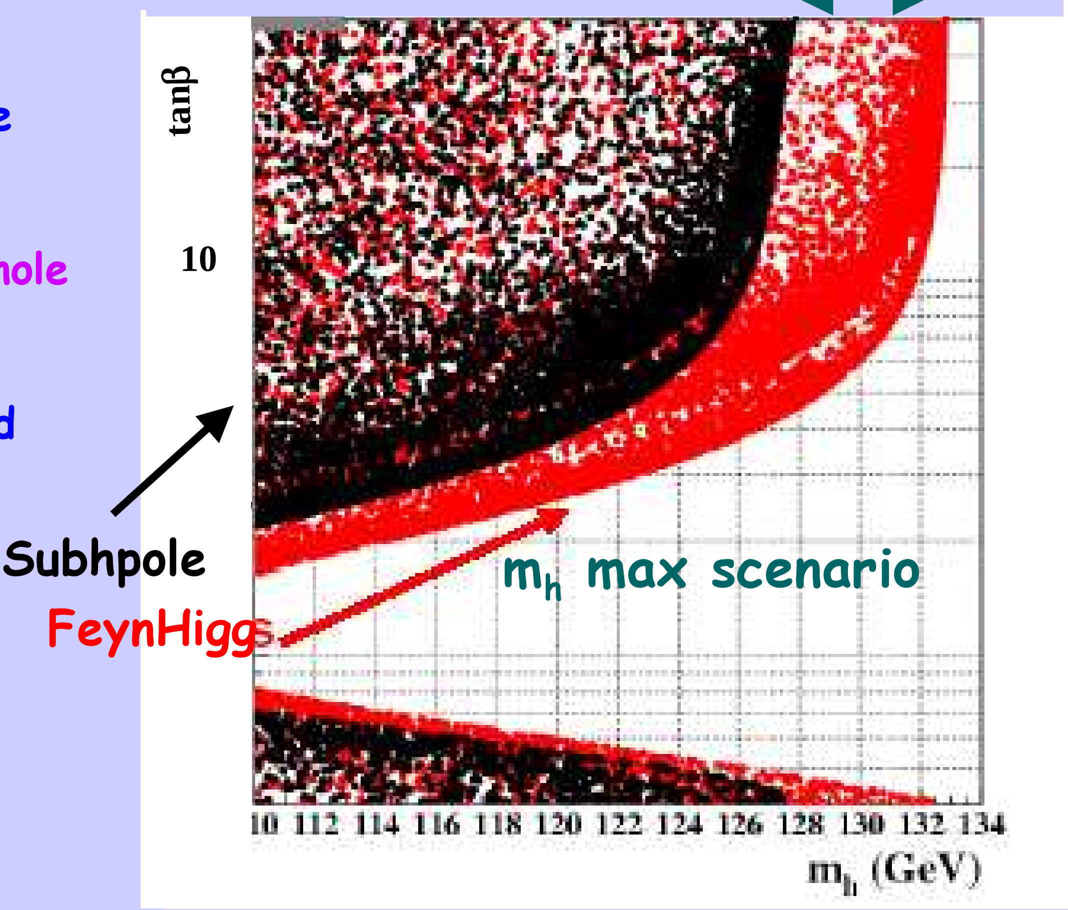
•New version of FeynHiggs2.0 (Frank et al.):

-MS-bar renormalisation scheme used(hep-ph/0202166)

-O($alpha^2_t$) corrections (A. Brignole et al hep-ph/0112177)

-Delta(m_b) corrections calculated

Δm_h~ 5 GeV



MSSM scans

- **Traditional benchmarks:**
  - No mixing in stop sector
  - m_h max: designed to yield maximal value of the m_H
  - Large μ: has suppressed H-> bb

7 parameters:
(Carena et al. hep-ph/9912223)
Mtop=174.3 GeV top mass
M_{SUSY} sfermion mass at EW scale
μ Higgs mixing parameter
M_2 gaugino mass at EW scale
M_g gluino mass
Xt= Stop mixing parameter
$A_b=A_t$ = Xt $+\mu\cot\beta$ = trilinear Higgs-stop coupling

- **New benchmarks:**
  - m_h-max with reversed μ sign
  - constrained m_h-max reversed sign for A_t and X_t

  } Favoured by $(g-2)_\mu$ and Br(b->sγ)

  - gluophobic gg->h suppressed
  - small α_{eff} h->bb,$\tau\tau$ suppressed

  } Regions of the parameter space where Hadron colliders might have problems in detecting the Higgs

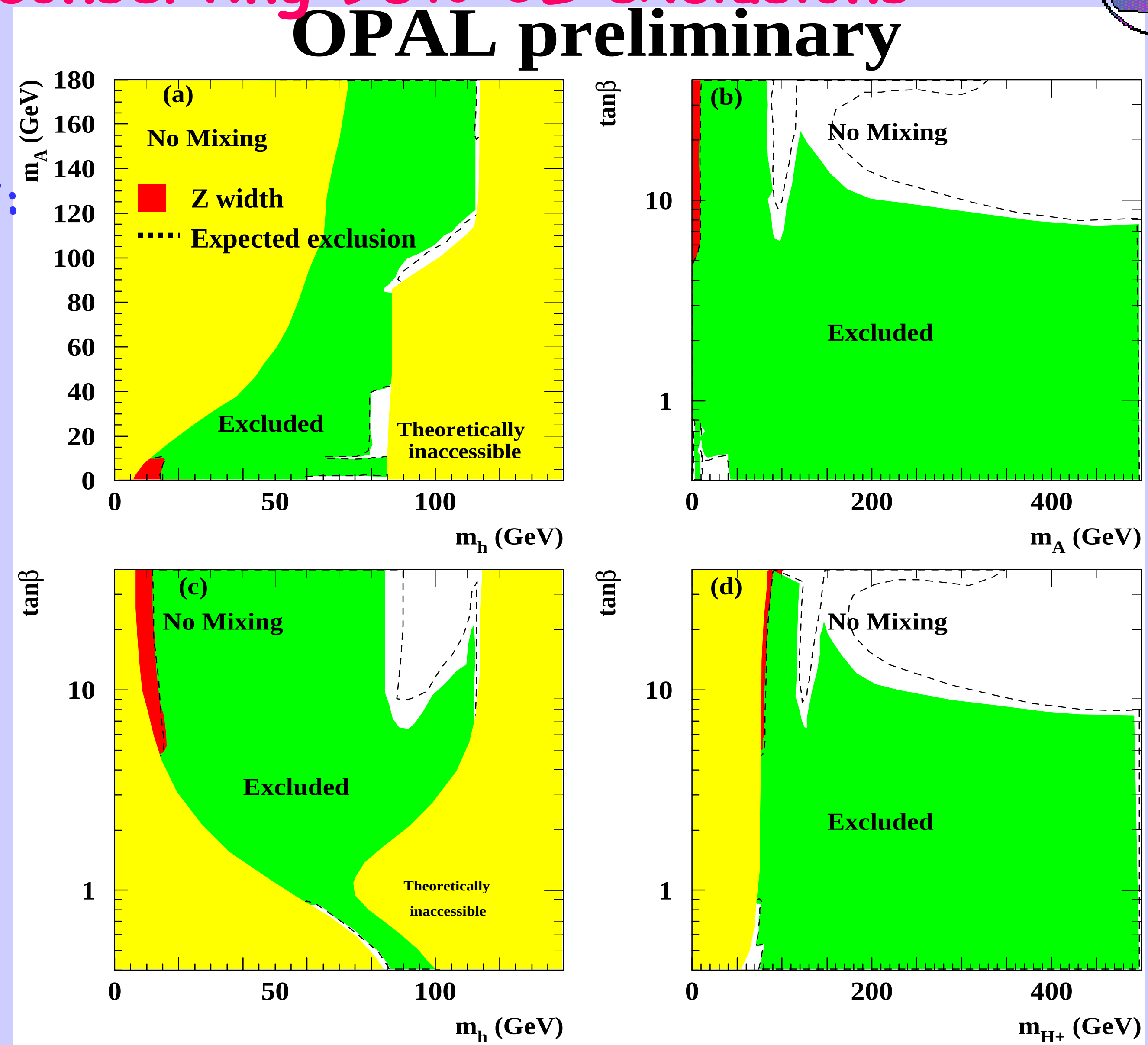
CP conserving 95% CL exclusions

Search channels used $\sqrt{s} \leq 209$ GeV:

SM Searches:
hZ->bbqq, bb l^+l,
$\tau^+\tau^-$bb, bb$\nu\nu$

Flav-independent:
hZ->qqqq, qq l^+l^-,
qq $\tau^+\tau^-$, qq$\nu\nu$

Pair-production:
hA->bbbb, $\tau^+\tau^-$bb



CP conserving 95% CL exclusions

Search channels used $\sqrt{s} \leq 209$ GeV:

SM Searches:

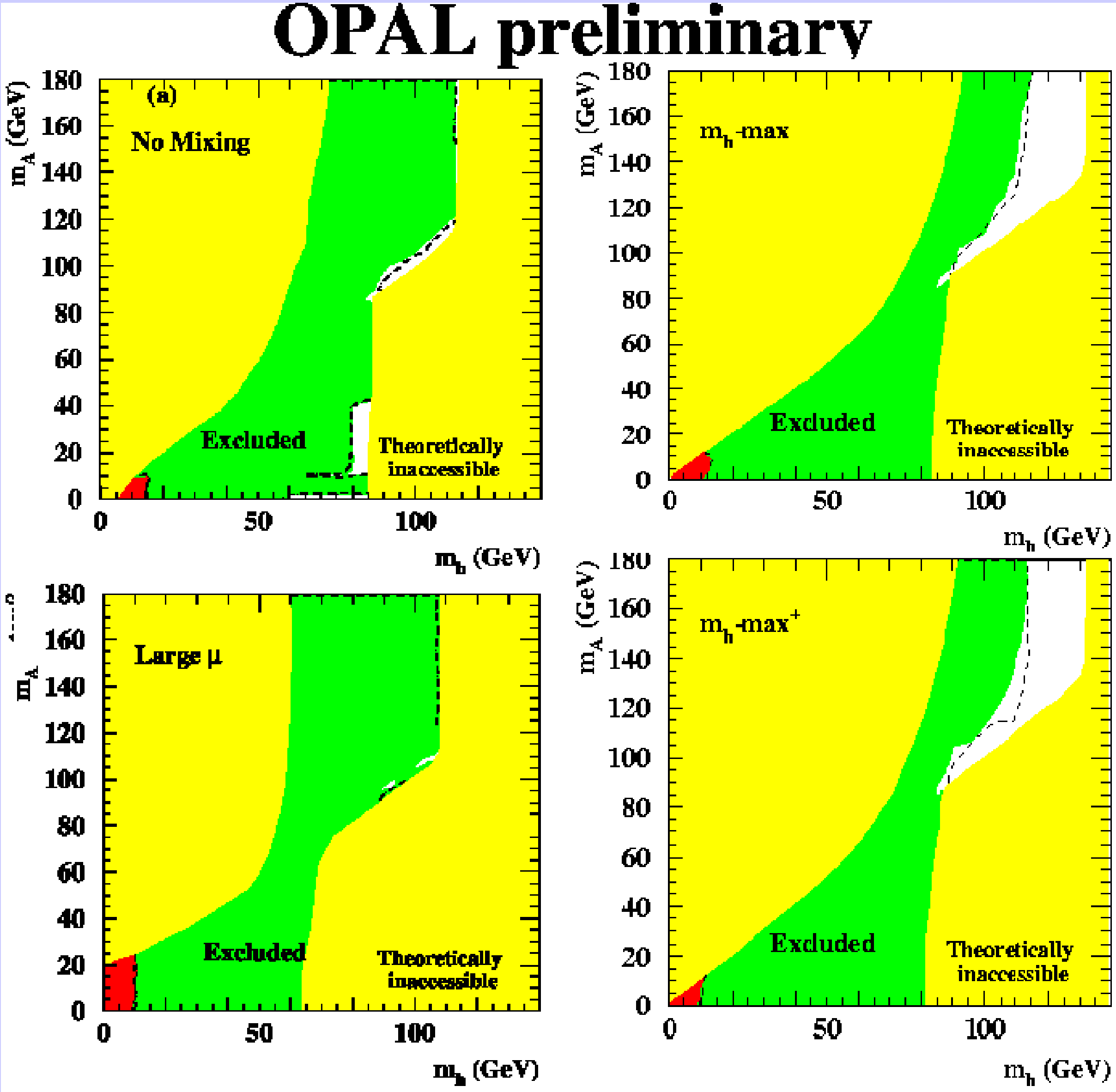
hZ->bbqq,bb l^+l,
$\tau^+\tau^-$bb, bb$\nu\nu$

Flav-independent:

hZ->qqqq,qq l^+l^-,
qq $\tau^+\tau^-$,qq$\nu\nu$

Pair-production:

hA->bbbb, $\tau^+\tau^-$bb



CP conserving 95% CL exclusions

Search channels used $\sqrt{s} \leq 209$ GeV:

SM Searches:

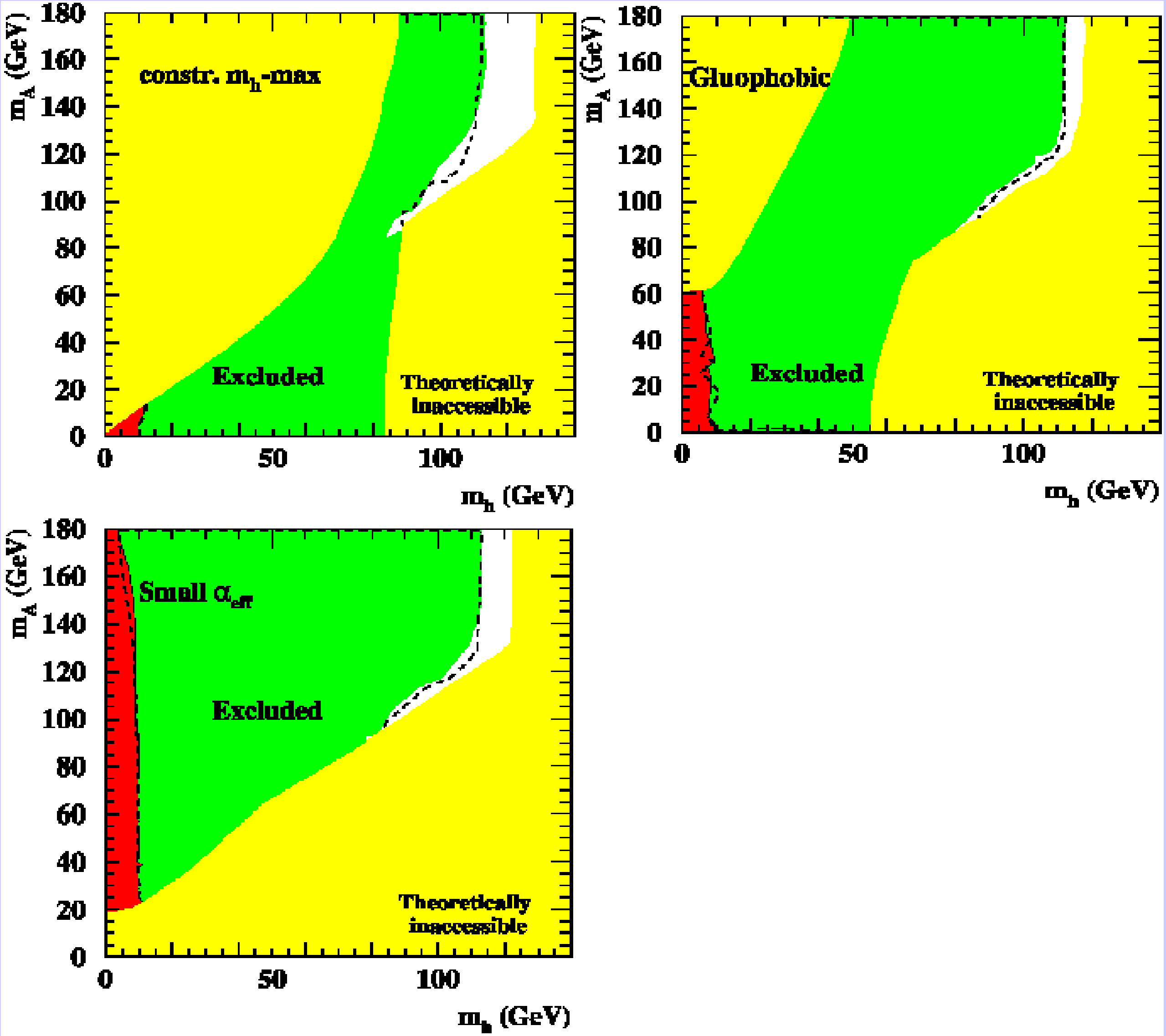
$hZ \to bbqq, bb\, l^+l, \tau^+\tau^- bb, bb\nu\nu$

Flav-independent:

$hZ \to qqqq, qq\, l^+l^-, qq\, \tau^+\tau^-, qq\nu\nu$

Pair-production:

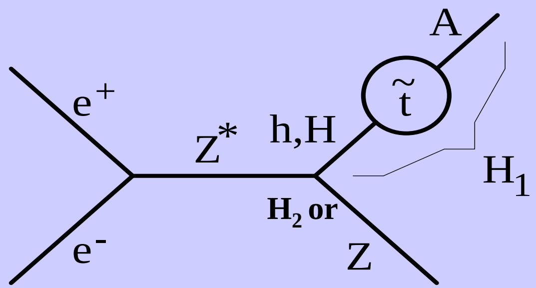
$hA \to bbbb, \tau^+\tau^- bb$



CP violating MSSM

- Spontaneous symmetry breaking of CP via radiative corrections:
- The phases of A_x (SUSY breaking trilinear coupling) and $M_{\tilde{g}}$ introduce CP violation into the Higgs potential via loop effects
- CP violating effect scales as:

$$\mathcal{M}^2_{SPij} \propto M^4_{top}\, \mathcal{Im}(\mu A_t)/v^2\, m^2_{SUSY}$$



Benchmark has been designed fulfilling EDM constaints:

$\tan\beta$	m_{H+}	μ	M_{SUSY}	M_2	$\lvert A_q \rvert$	$\arg(A_q)$	$\lvert M_g \rvert$	$\arg(M_g)$
0.4 -40	0- 1TeV	2 TeV	500 GeV	200 GeV	1 TeV	90°	1 TeV	90°

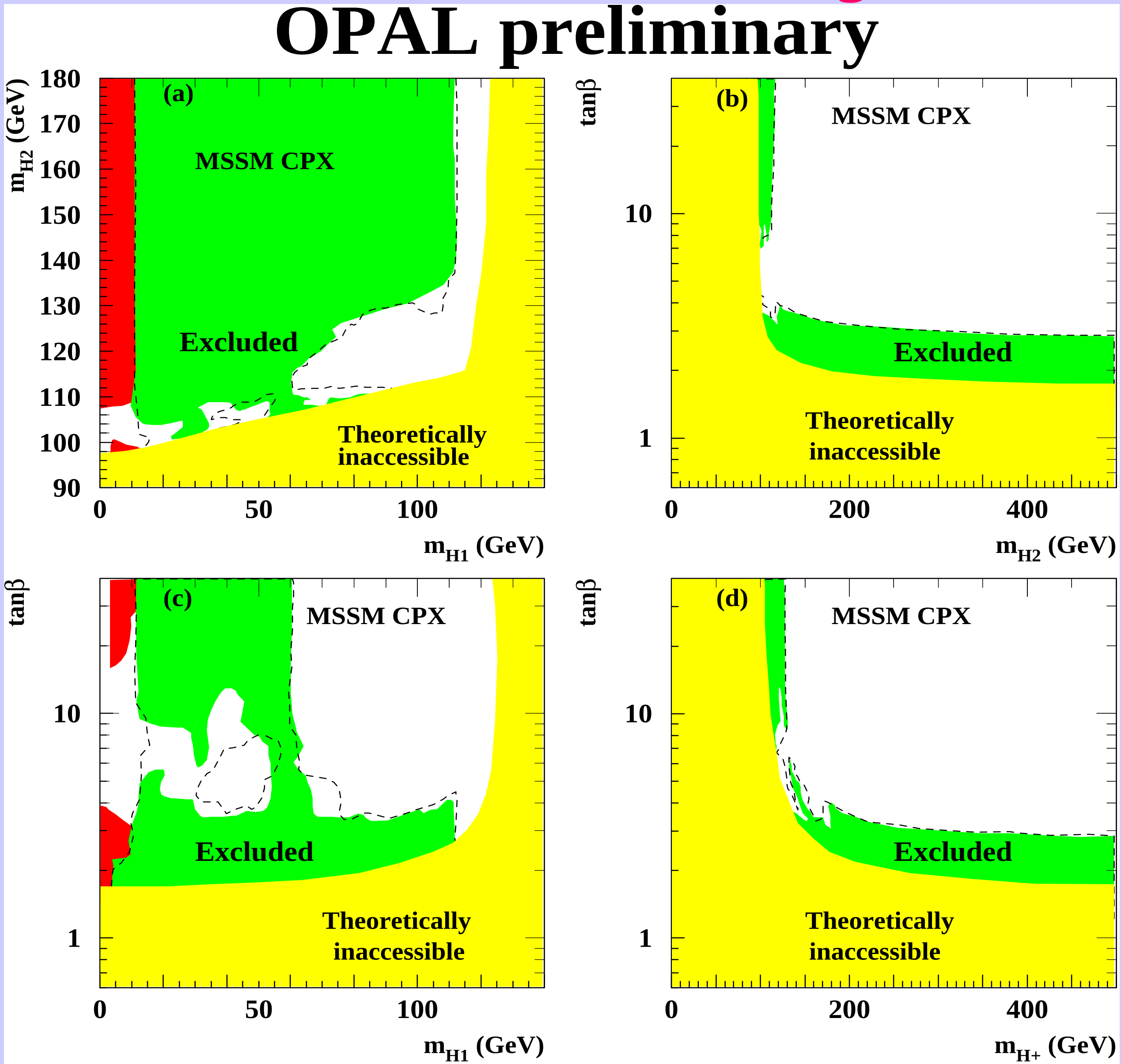
Scan parameters

-2 Higgsstrahlung processes present: chose H_1Z^0, H_1H_2 or H_2Z^0, H_1H_2 depending on which has the best expected CL.

-H_2-> H_1H_1 dominant if kinematically allowed

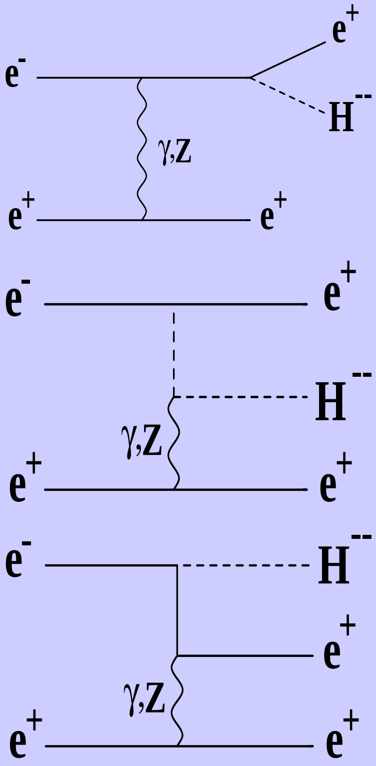
-Z^o width constraint used

95%CL limits on CP violating MSSM



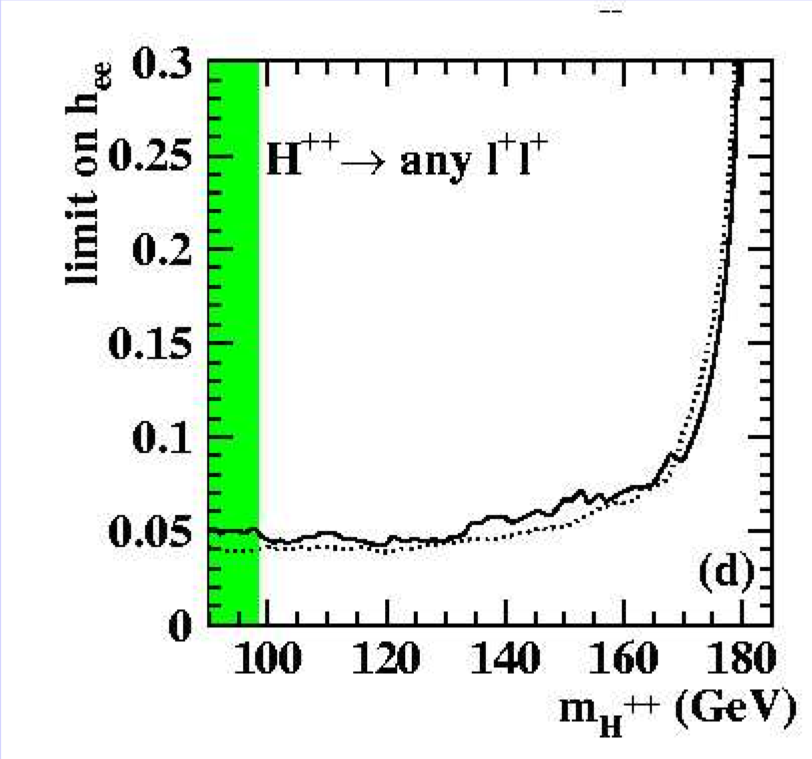
Single production of doubly charged Higgs

Direct constraints on h_{ee}



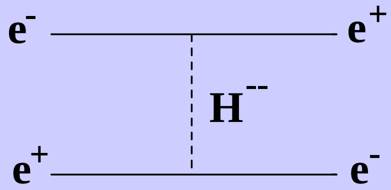
- Decay modes into all lepton flavour combinations: ee, μμ, ττ, eμ, eτ, μτ.
- Topology: 2/3 lepton final state
- Production x-section depends only on Yukawa coupling h_{ee}
- $189 < E_{CM} < 209$ GeV

FINAL

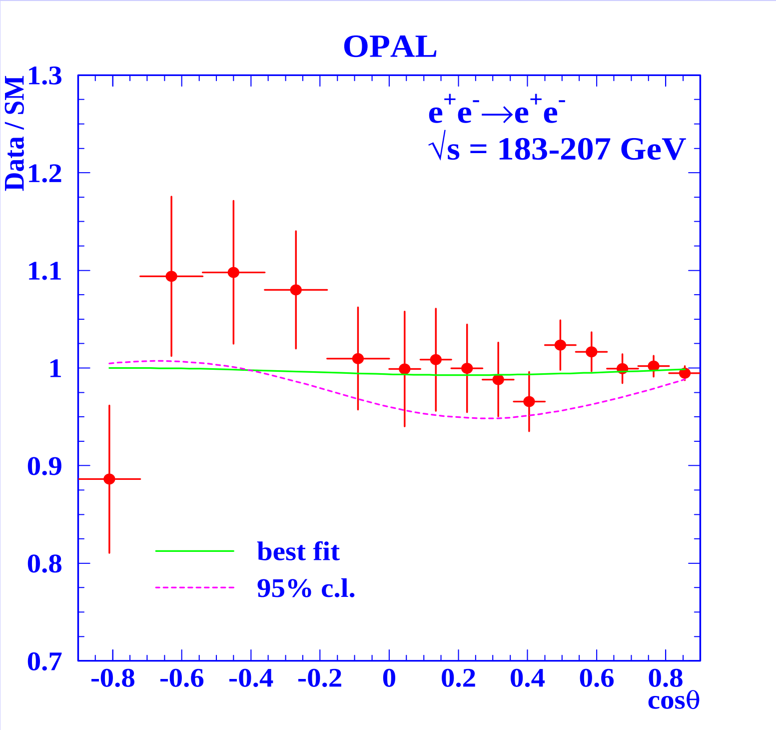


$h_{ee} < 0.071$ for $m_{H^{++}} < 160$ GeV at 95% CL mainly determined by ττ (assuming 100% BR(H++) to leptons

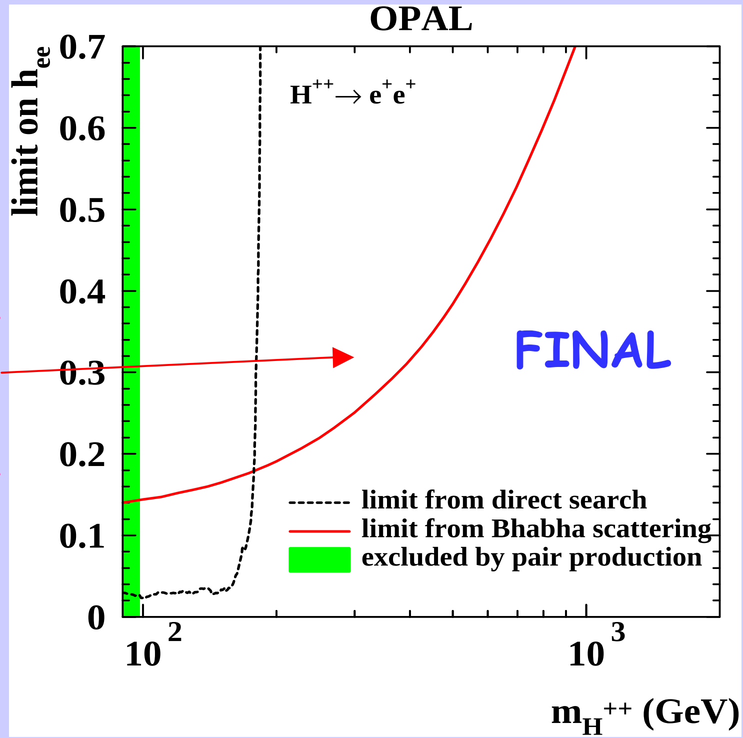
Indirect constraints on h_{ee}



- doubly charged Higgs bosons would affect Bhabha x-sec ⇨ change in the observed angular distribution of outgoing e
- χ^2 fit of measured differential σ_{Bhabha} $(183 < E_{CM} < 209$ GeV) with theoretical prediction



Less restrictive than direct search but extend to much higher masses



Conclusions

- Many new results have been produced for the summer conferences by OPAL
- 37 PHD students

since the beginning of the year:

14 new papers

9 new notes

The Activity will continue during 2004

A lot of interesting results still to come:

Searches/ Higgs: finalisation of several results

W mass

QCD and two photon physics

LEP COMBINATIONS