OPAL Physics Highlights

at $\sqrt{s} = 183$ GeV

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All Results are PRELIMINARY

- Analysis of the 1997 high energy data
- $57\,\mathrm{pb}^{-1}$ data at $\sqrt{s} = 183\,\mathrm{GeV}$

Topics covered:

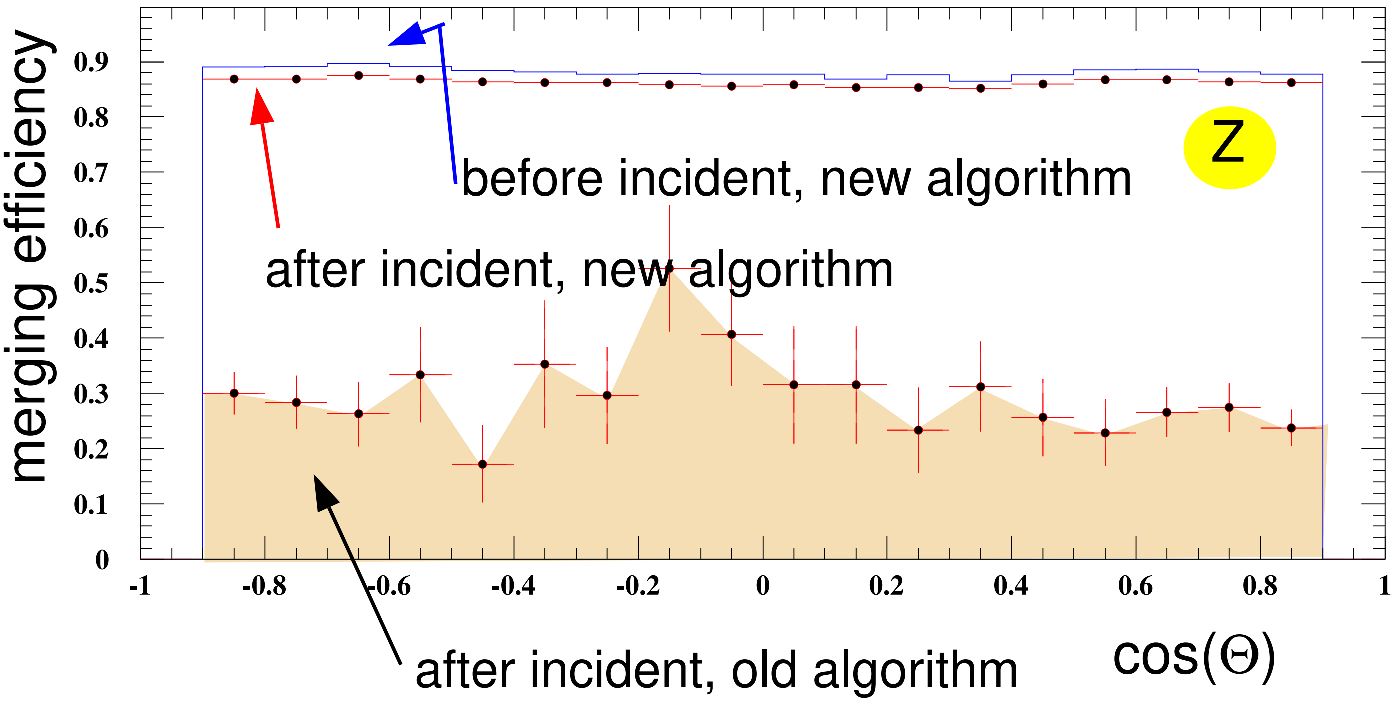
- Detector News
- 2-fermion production
- 4-fermion production (mainly WW)
- SM Higgs search
- Beyond the SM : SUSY searches

Detector : Vertex Chamber Incident

- After 130 GeV run : 2 wires broke in the stereo part of the VERTEX WIRE chamber.
- Main use : matching tracks in the large JET chamber to Silicon z hits.
- 1/3 of stereo part of chamber OFF
- Hardware intervention not foreseen

- Software fix :

NEW track-Si(z) merging algorithm



- Final effect of physics : minor

- b-tagging essentially unaffected !

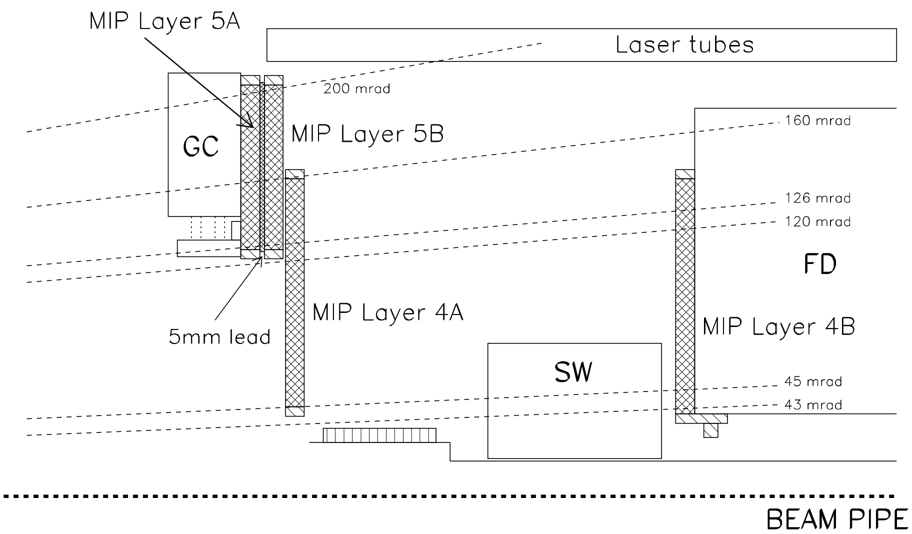
Detector : MIP Plug

OPAL (1996)

- ECAL coverage down to 25 mrad
- No efficient coverage for minimum ionizing particles (MIPs) beyond 160 mrad

OPAL (1997)

- Installed scintillator tiles (MIP-plugs)
- Coverage for MIPs between 45-200 mrad



First physics application

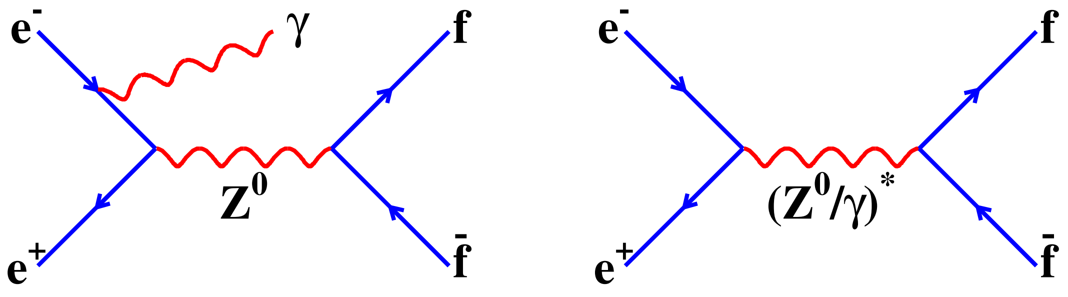
- Scalar lepton search:

  two-photon background rejection

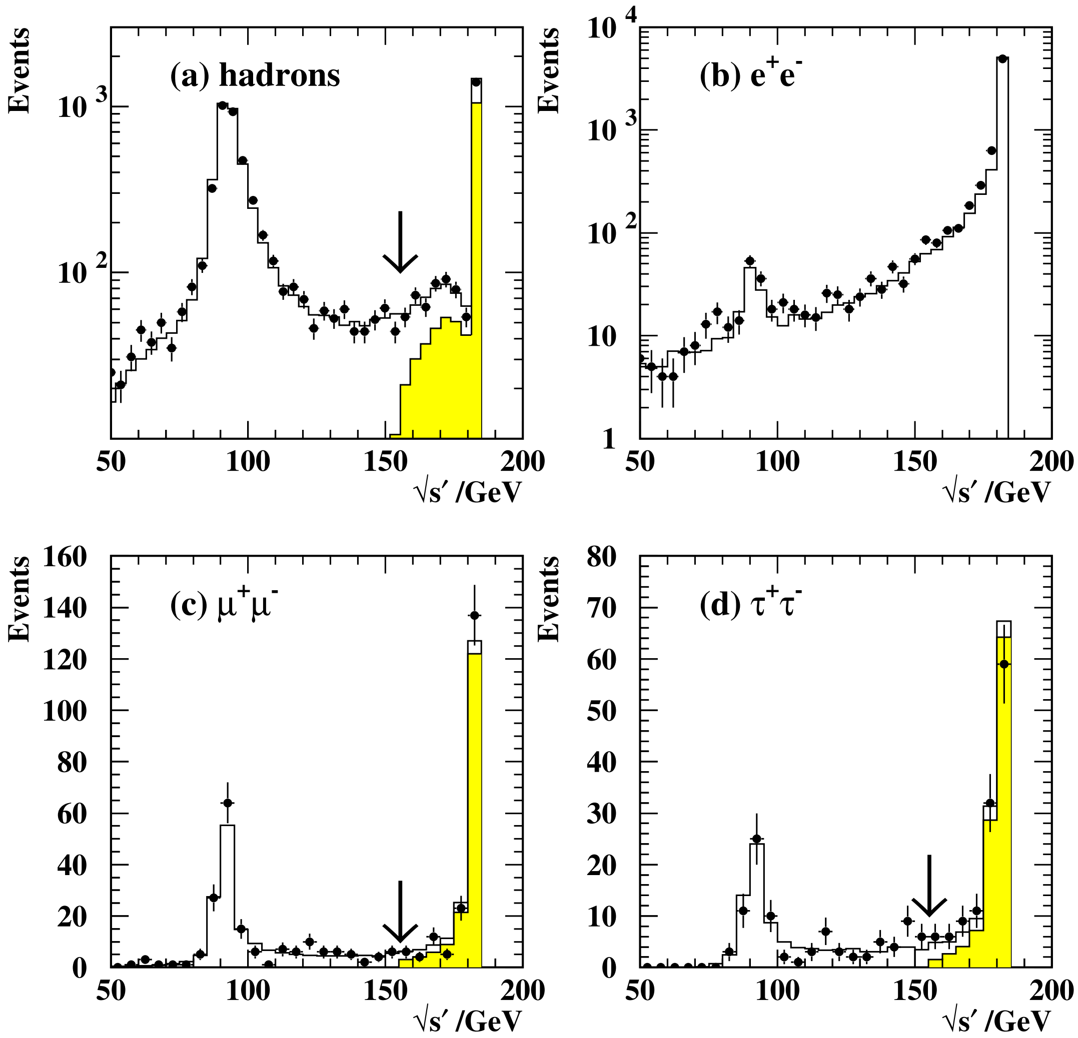
  i.e. $e^+e^- \to e^+e^-\mu^+\mu^-$ with a forward μ

2 Fermion Production

- Measure inclusive and non-radiative cross sections
- Non-radiative: $\sqrt{s'}/\sqrt{s} > 0.85$

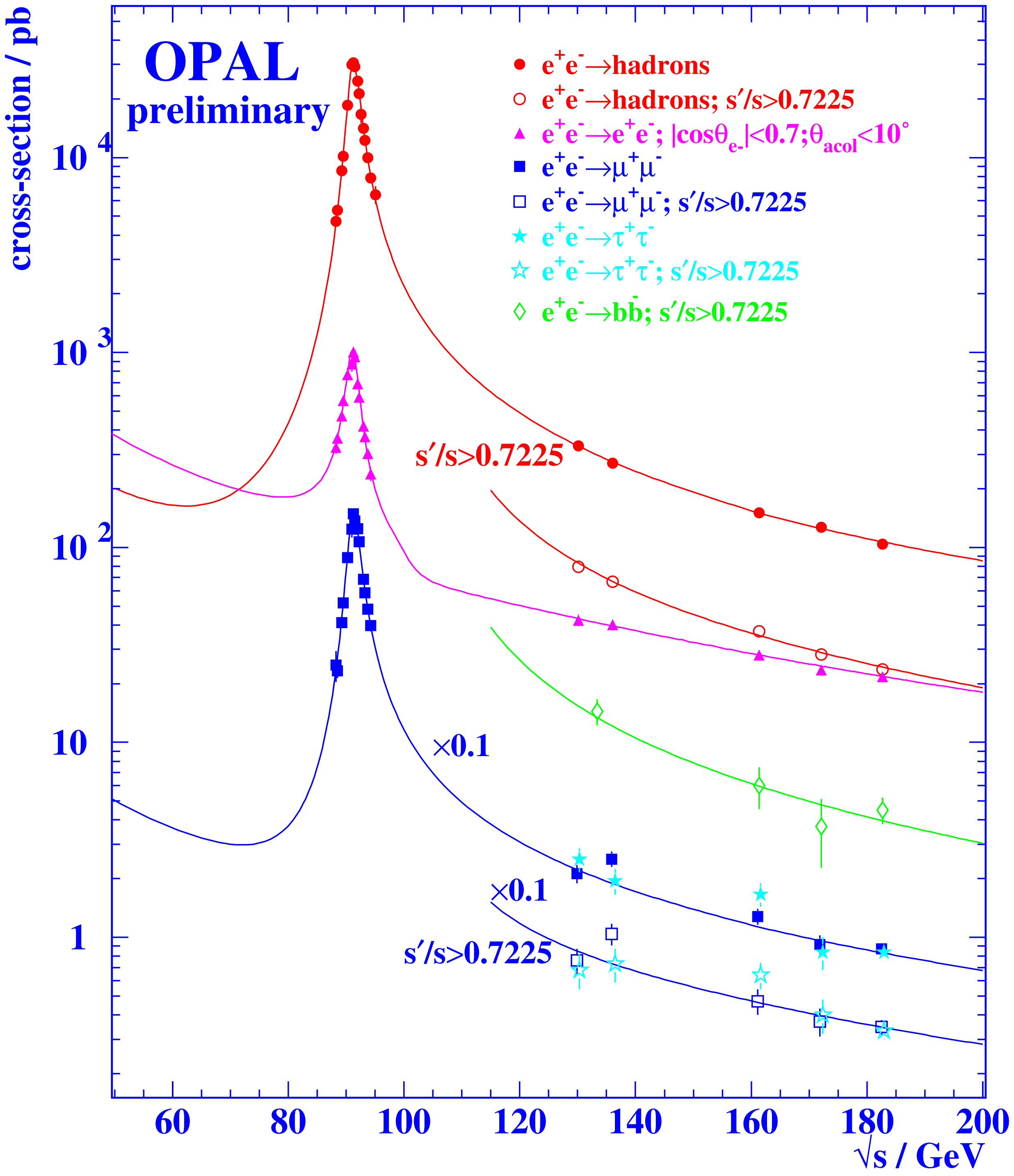


OPAL 183 GeV preliminary



YELLOW $=$ MC component with true $\sqrt{s'}/\sqrt{s} > 0.85$

2 Fermion Cross Sections



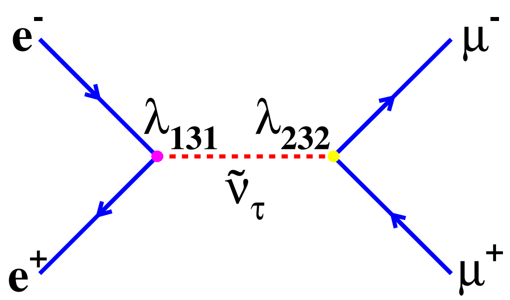
- Good agreement with ZFITTER prediction for all $\sqrt{s}$
- Also measured asymmetries and R_b at $\sqrt{s} = 183\ \mathrm{GeV}$

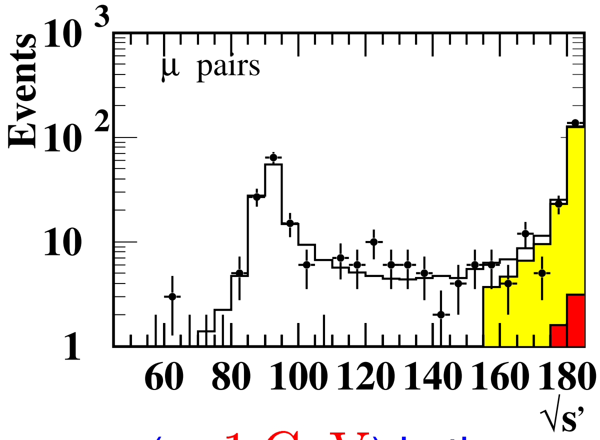
2 Fermion : limits on new physics

Cross sections and asymmetries $\longrightarrow$ limits on new physics, *e.g.*

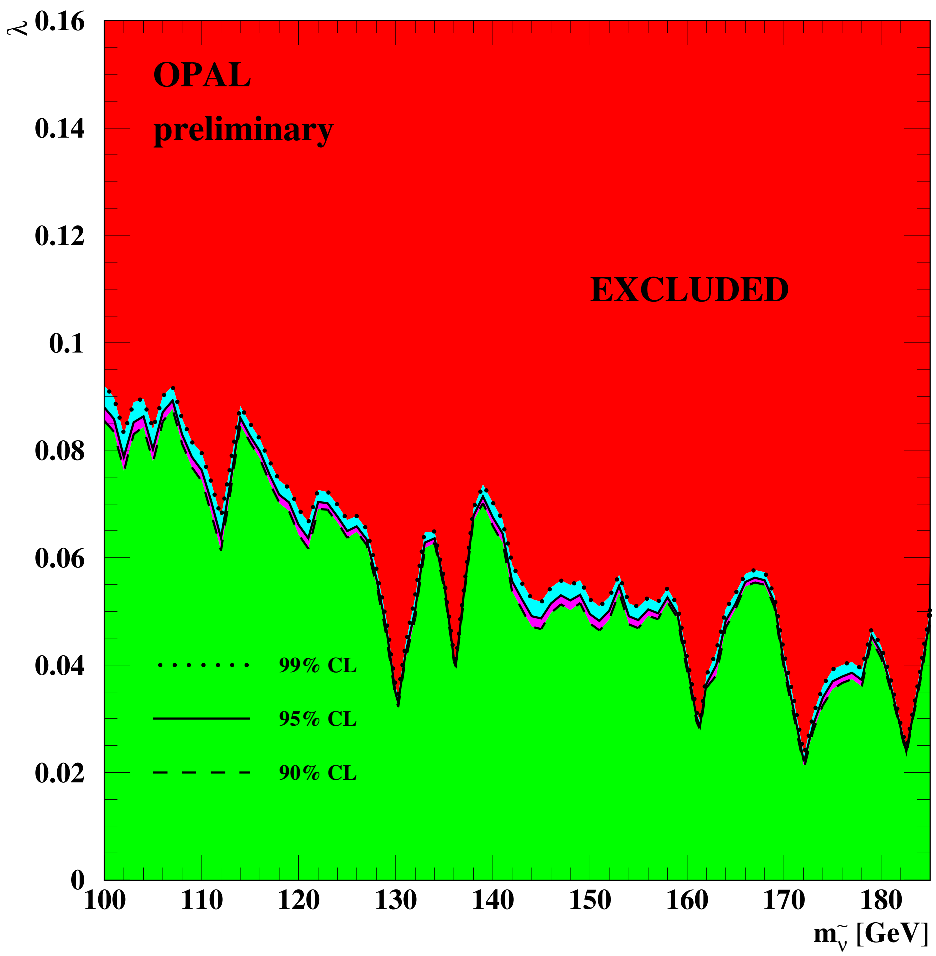
Four-fermion contact interactions, Lepto-Quarks, etc.

One example: resonant (RPV SUSY) $\tilde{\nu_\tau}$ production



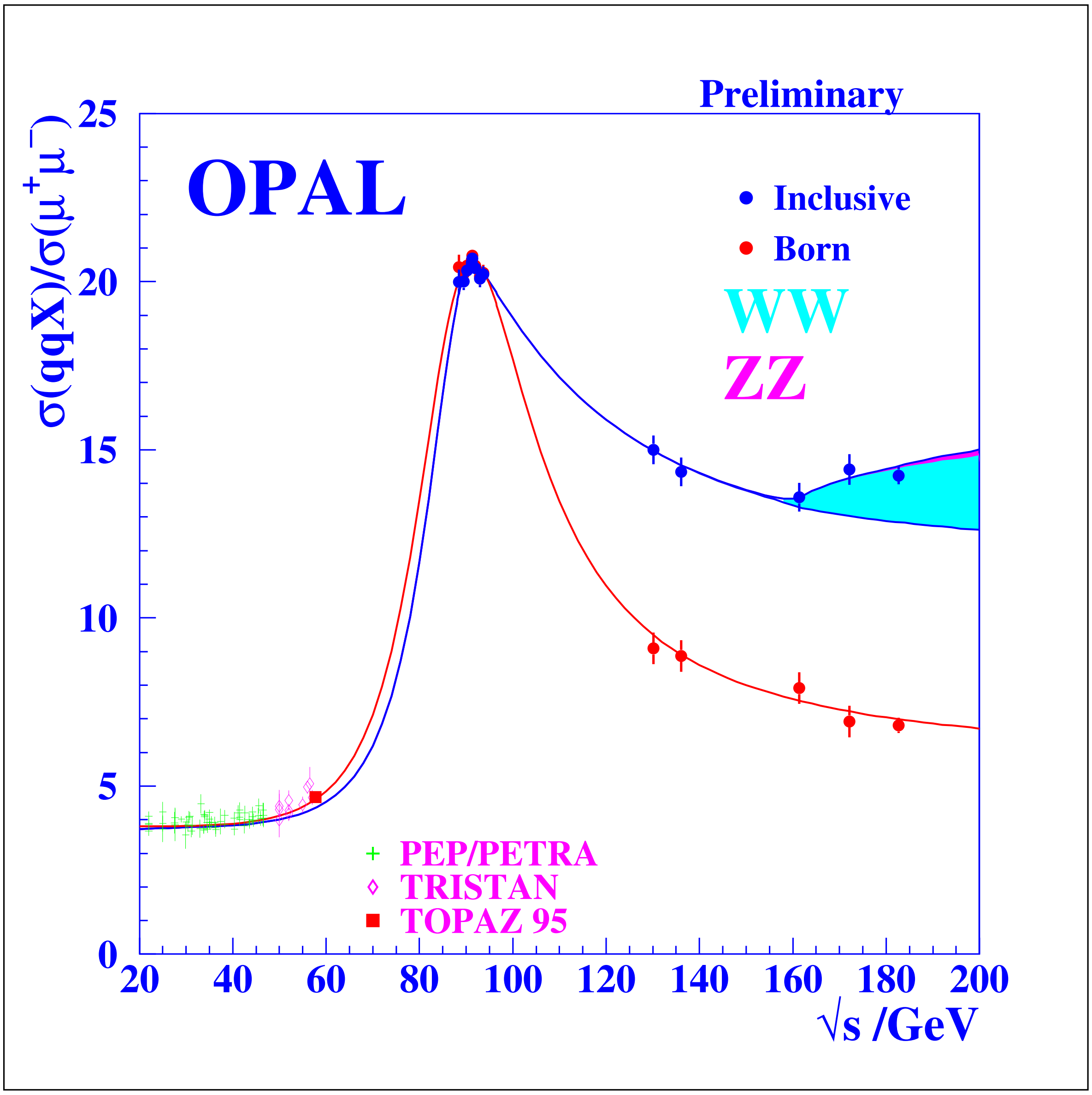


- Would result in a narrow resonance ($\sim 1\ \mathrm{GeV}$) in the $\mu^-\mu^+$ $\sqrt{s'}$ distribution.



R_{had}

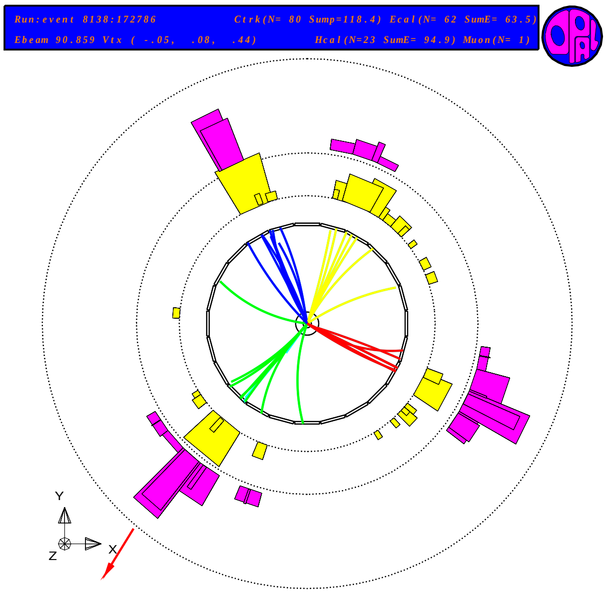
- Compare inclusive $e^+e^- \to q\overline{q}X$ cross section with theoretical $e^+e^- \to \mu^+\mu^-$ cross section.
- Also shown is the comparison for the non-radiative $e^+e^- \to q\overline{q}X$ cross section corrected to Born level.

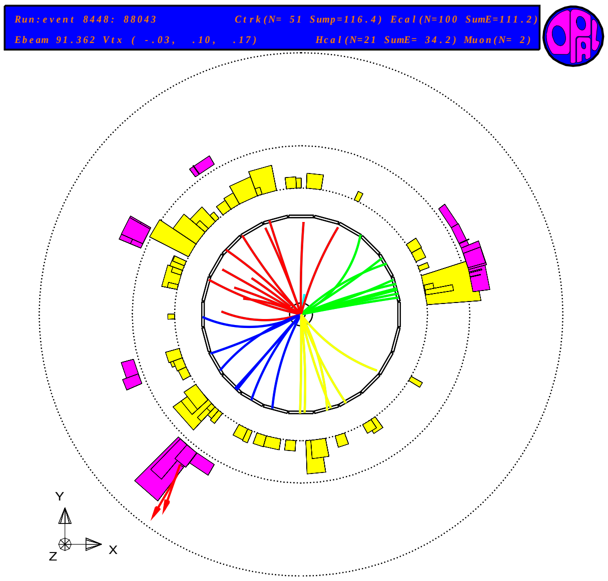


- W^+W^- production clearly visible.
- Z^0Z^0 production not yet important.

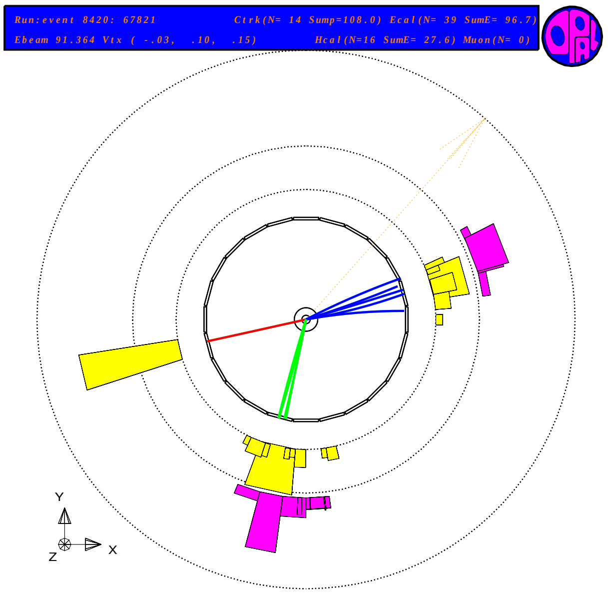
W Physics - Event Selections

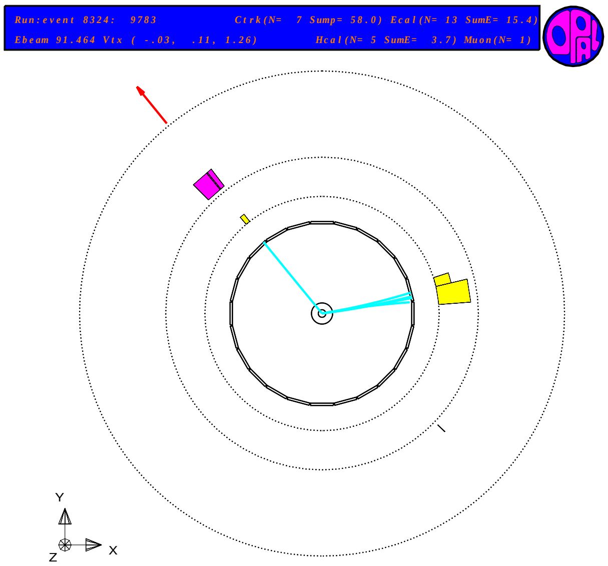
- Efficient Selections for all WW final states:





$$W^+W^- \to q\overline{q}q\overline{q}$$



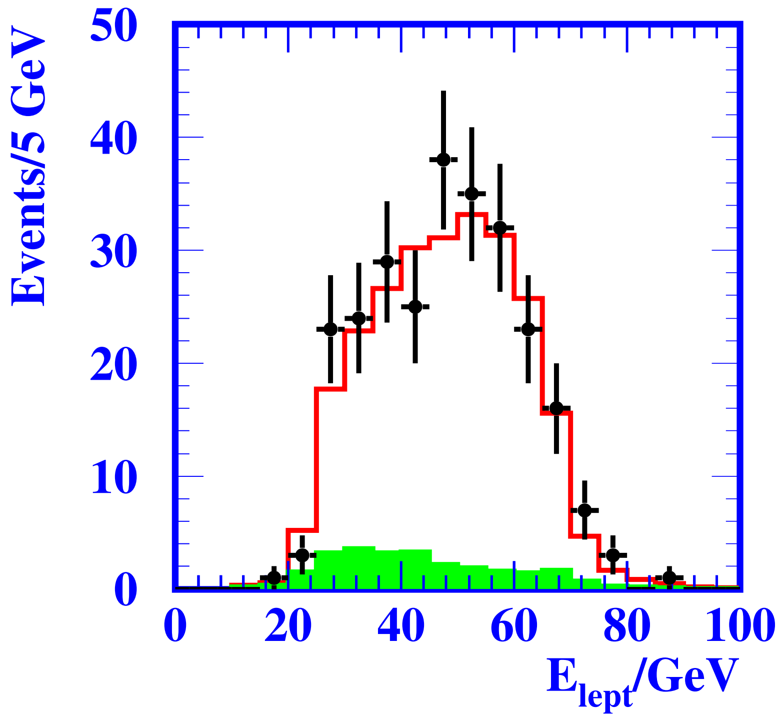


$$W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell \qquad W^+W^- \to \ell^+\nu_\ell\ell'^-\overline{\nu}_{\ell'}$$

W Decay Branching Fractions

Selection	Effic.	Purity	Expect	Observe
$\mathrm{W^+W^-} \to \mathrm{q\overline{q}q\overline{q}}$	85%	79%	434	433
$\mathrm{W^+W^-} \to \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$	86%	90%	374	362
$\mathrm{W^+W^-} \to \ell^+\nu_\ell\ell'^-\overline{\nu}_{\ell'}$	77%	95%	77	78
Combined	85%	85%	885	873

- Good agreement between data and MC, e.g. lepton energy in $\mathrm{W^+W^-} \to \mathrm{q\overline{q}e}\overline{\nu}_\mathrm{e}$ and $\mathrm{W^+W^-} \to \mathrm{q\overline{q}}\mu\overline{\nu}_\mu$ events

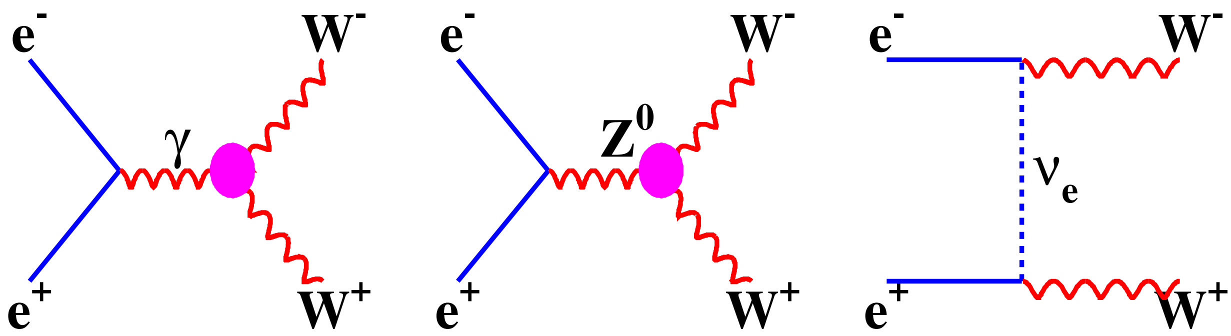


Assuming W decays only to SM fermions:

$$\mathrm{BR(W \to q\overline{q}) = 0.679 \pm 0.012 \pm 0.006}$$

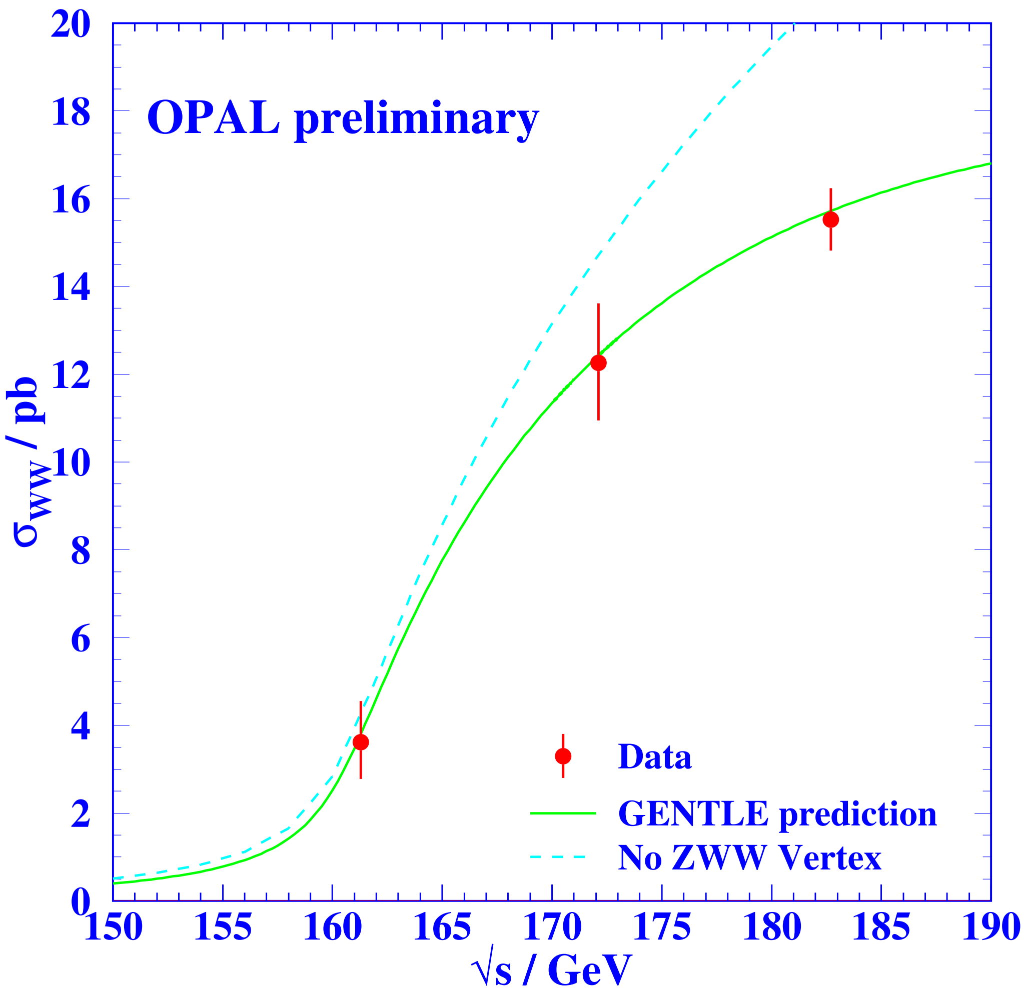
BR(W$\to$ $\mathrm{q\overline{q}}$) = 0.675 (Standard Model)

WW Production Cross section



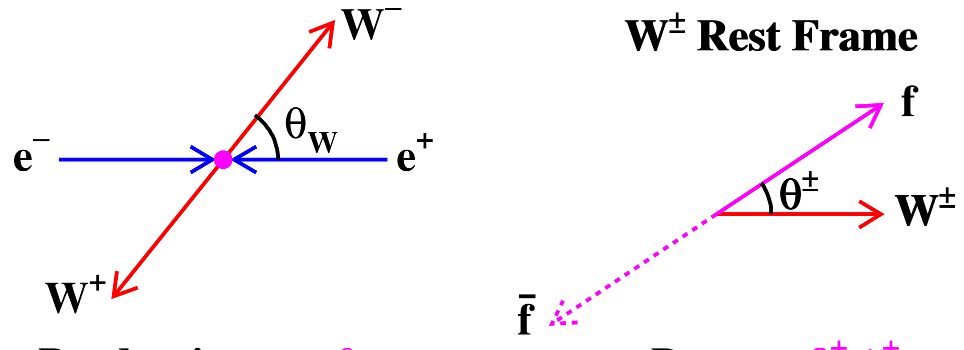
- Measure CC03 WW production cross section
- Sensitive to Triple Gauge Couplings (TGCs)

$$\sigma_{WW}(183\ \mathrm{GeV}) = 15.52 \pm 0.62 \pm 0.35\ \mathrm{pb}$$



TGC from $q\bar{q}\ell\bar{\nu}_\ell$ and $q\bar{q}q\bar{q}$

- Use kinematic fit ⇒ W production and decay angles.

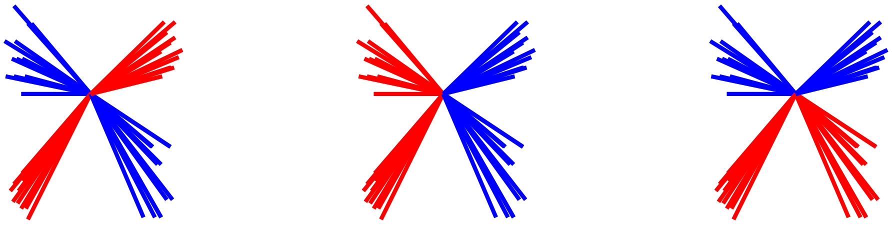


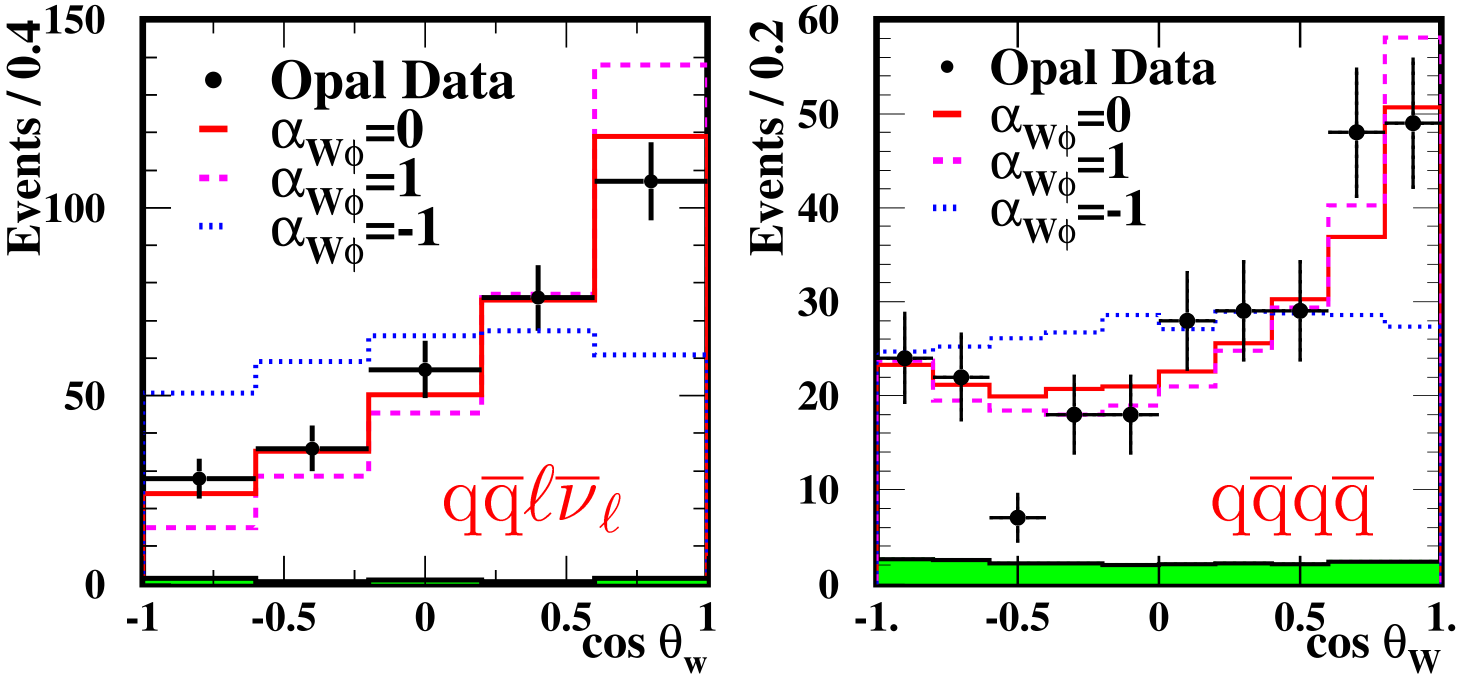
Production: $\cos\theta_W$ **Decay:** $\theta^\pm$ $\phi^\pm$

- $q\bar{q}q\bar{q}$ channel more difficult than $q\bar{q}\ell\bar{\nu}_\ell$

  Use jet charge to get sign of $\cos\theta_W$

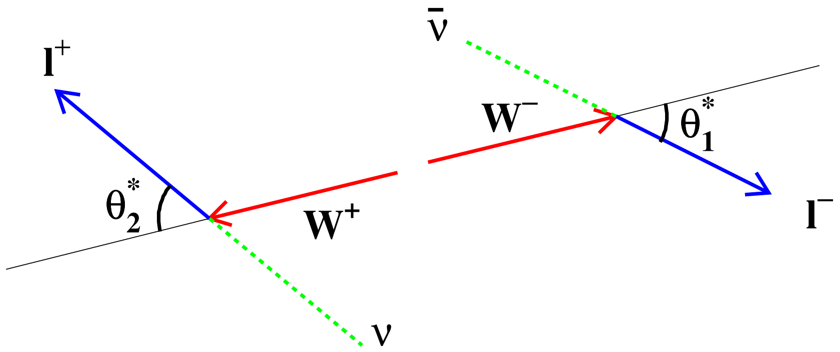
  Jet Pairing combinatoric background

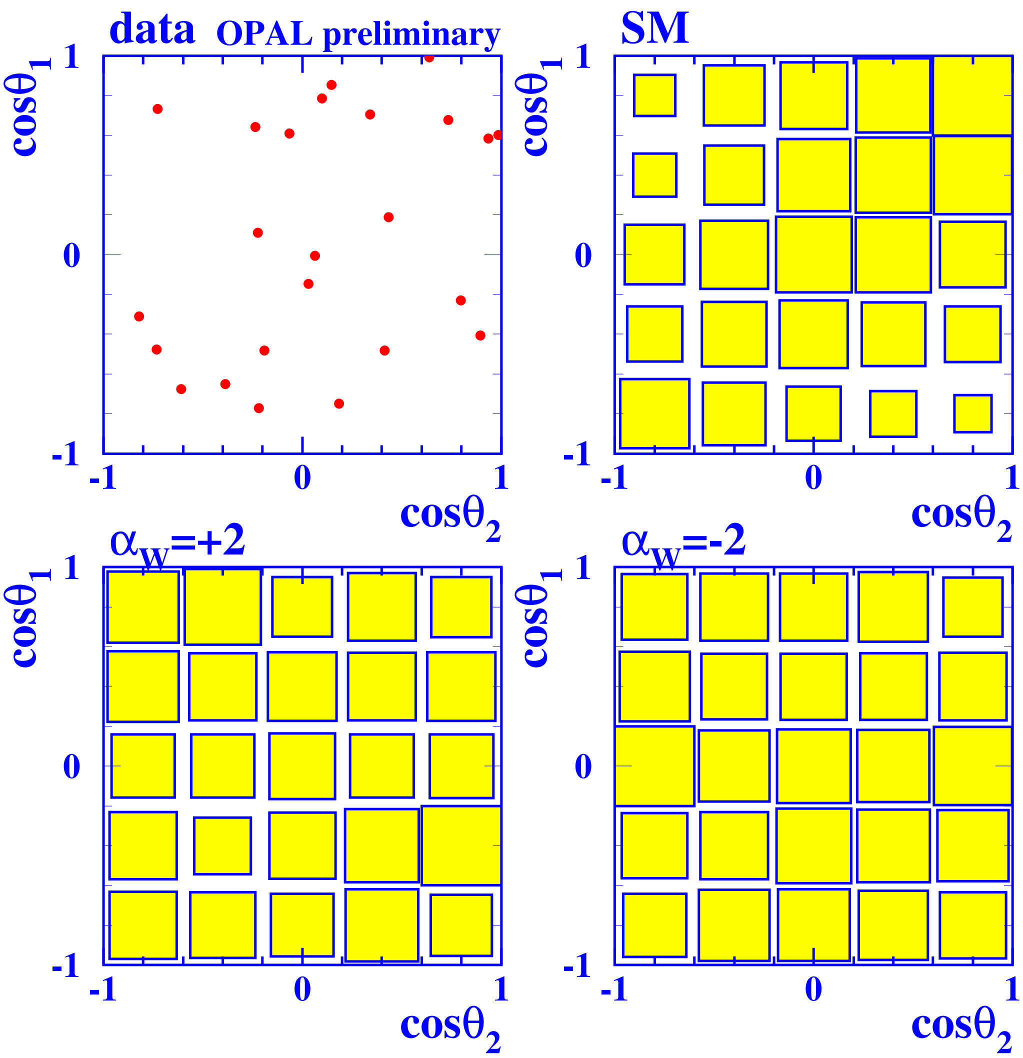




TGCs from $W^+W^- \to \ell^+\nu_\ell \ell'^- \overline{\nu}_{\ell'}$

- BR($W^+W^- \to \ell^+\nu_\ell \ell'^- \overline{\nu}_{\ell'}$) $\sim 11\%$
- Final states with τs not useful
- Useful BR $\sim 5\%$ BUT sensitive to different angles.
- Both W-decay polar angles be determined.





Combined TGC Results

Previously used

- Event count from all channels
- Angular distributions from $\mathrm{W}^+\mathrm{W}^- \rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$

Now use

- Event count and angular distributions from all channels

$$\mathrm{W}^+\mathrm{W}^- \rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$$

$$\mathrm{W}^+\mathrm{W}^- \rightarrow \ell^+\nu_\ell\ell'^-\overline{\nu}_{\ell'}$$

$$\mathrm{W}^+\mathrm{W}^- \rightarrow \mathrm{q\overline{q}q\overline{q}}$$

$$\alpha_{W\phi} = +0.25^{+0.61}_{-0.51}$$

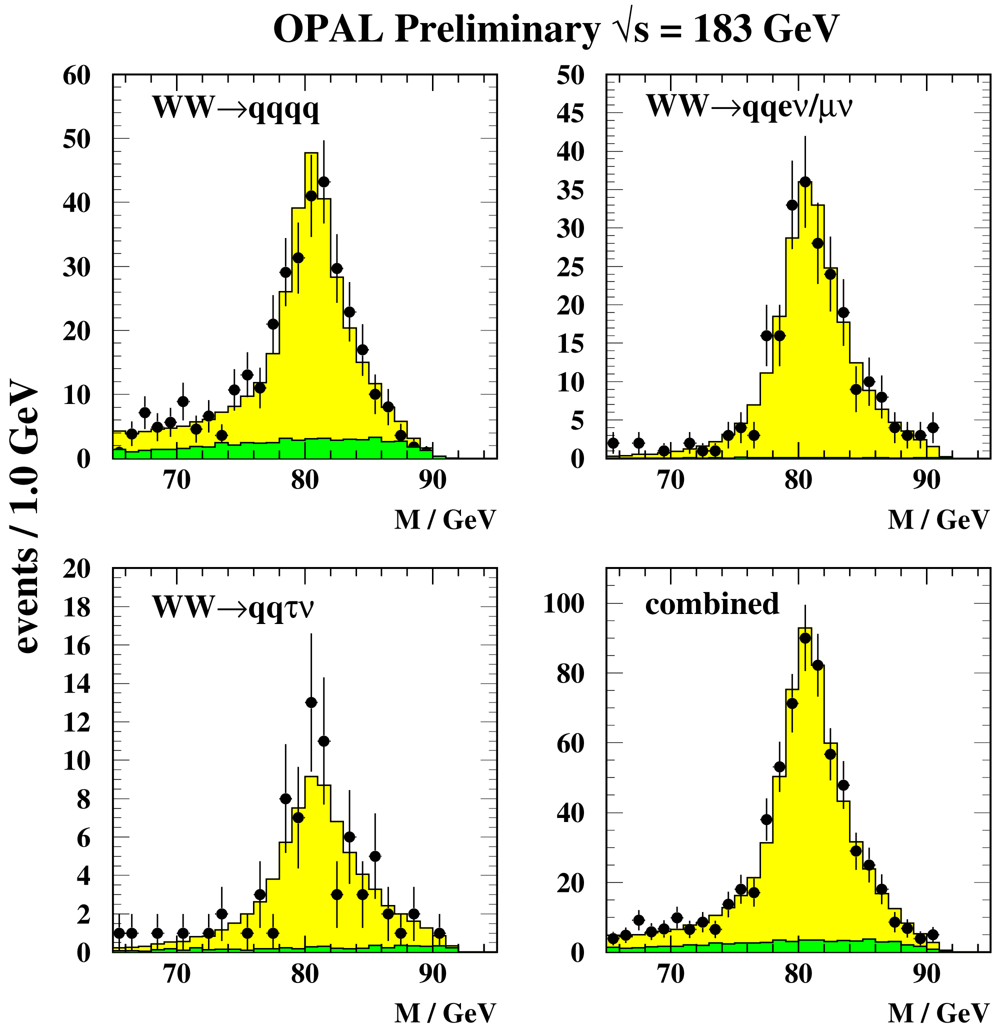
$$\alpha_{B\phi} = -0.03 \pm 0.13$$

$$\alpha_{W} = +0.05^{+0.23}_{-0.21}$$

(All 0 in SM)

M_{W} Results

- Use MC reweighting technique to fit mass distribution.



- 183 GeV results :

$$M_{\mathrm{W}} = 80.34 \pm 0.14 \pm 0.08\,\mathrm{GeV}$$

$$\Gamma_{\mathrm{W}} = 2.25 \pm 0.37 \pm 0.17\,\mathrm{GeV}$$

Combining with results from 161 GeV and 172 GeV gives:

$$\boxed{M_{\mathrm{W}} = 80.35 \pm 0.12 \pm 0.07\ \mathrm{GeV}}$$

Final State Hadronic Interactions

- Standard Monte Carlos assume independent fragmentation for the two W bosons in $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}q\overline{q}}$ events
- If not independent $\Rightarrow$ mass shifts can occur
- Currently assign $100\ \mathrm{MeV}$ uncertainty on the mass from $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}q\overline{q}}$ events for Bose-Einstein Correlations and 'colour reconnection' effects
- The real size of these effects could be larger :

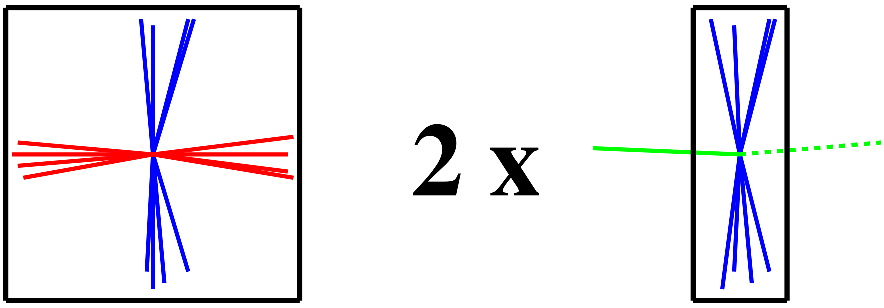
  Ellis-Geiger ~ 400 MeV

- Compare mass from $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{q\overline{q}q\overline{q}}$:

$$M_{\mathrm{W}}^{\mathrm{q\overline{q}q\overline{q}}} = 80.48 \pm 0.23\ \mathrm{GeV}$$
$$M_{\mathrm{W}}^{\mathrm{q\overline{q}}\ell\overline{\nu}_\ell} = 80.25 \pm 0.18\ \mathrm{GeV}\ \ (\mathrm{stat.only})$$

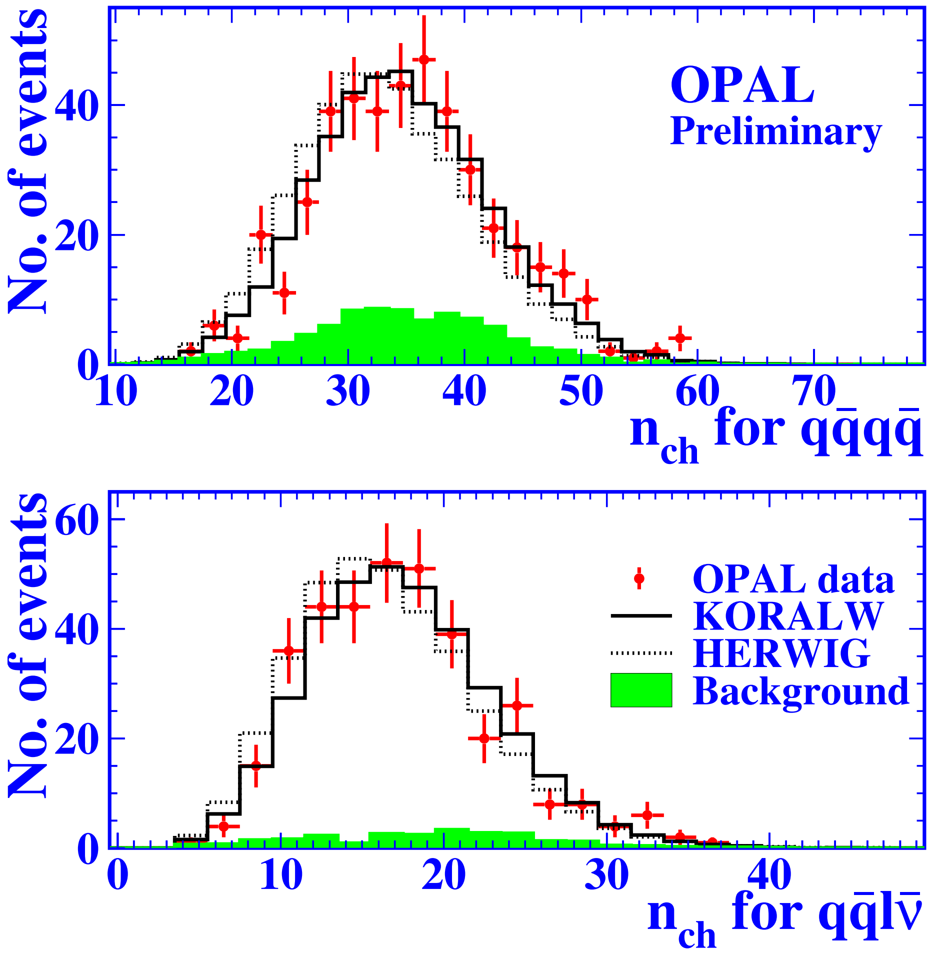
WW Charged Particle Multiplicities

- Compare $\Delta\langle n_{\mathrm{ch}}\rangle$= $\langle n_{\mathrm{ch}}^{4\mathrm{q}}\rangle$- 2$\langle n_{\mathrm{ch}}^{\mathrm{qq}\ell\nu}\rangle$



qqqq 2 x qqlν

- Ellis-Geiger predict $\Delta\langle n_{\mathrm{ch}}\rangle \sim -3$ units.

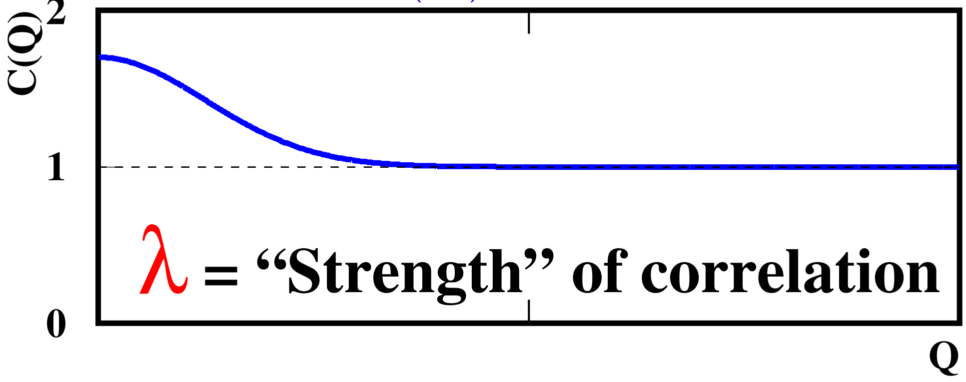


$$\Delta\langle n_{\mathrm{ch}}\rangle = +0.7 \pm 0.8 \pm 0.4$$

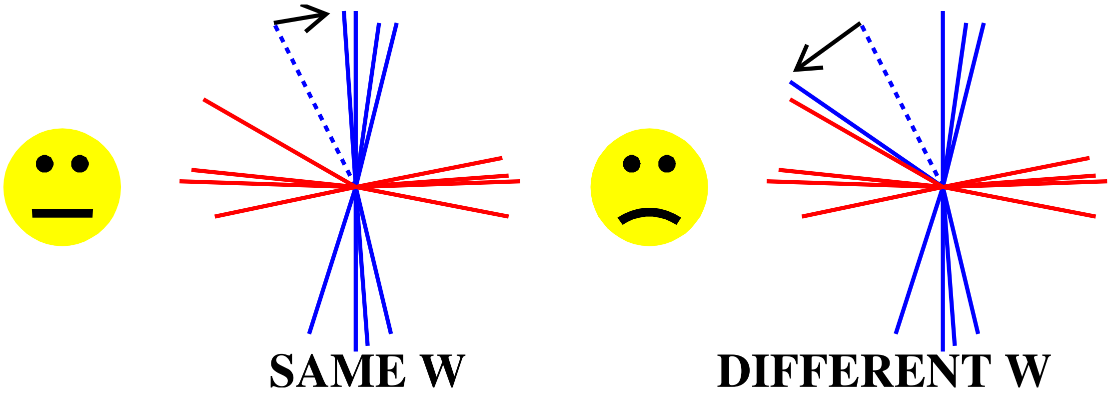
Bose-Einstein Correlations in WW ?

- BEC - Quantum mechanical effect
- Like bosons tend to be produced close in phase space (Q^2)
- Parameterized by correlation function $C(Q)$:

$$C(Q) \quad = \quad \frac{N^{\pm\pm}(Q)}{N^{+-}(Q)}; \quad Q^2 = M^2(\pi\pi) - 4m_\pi^2$$



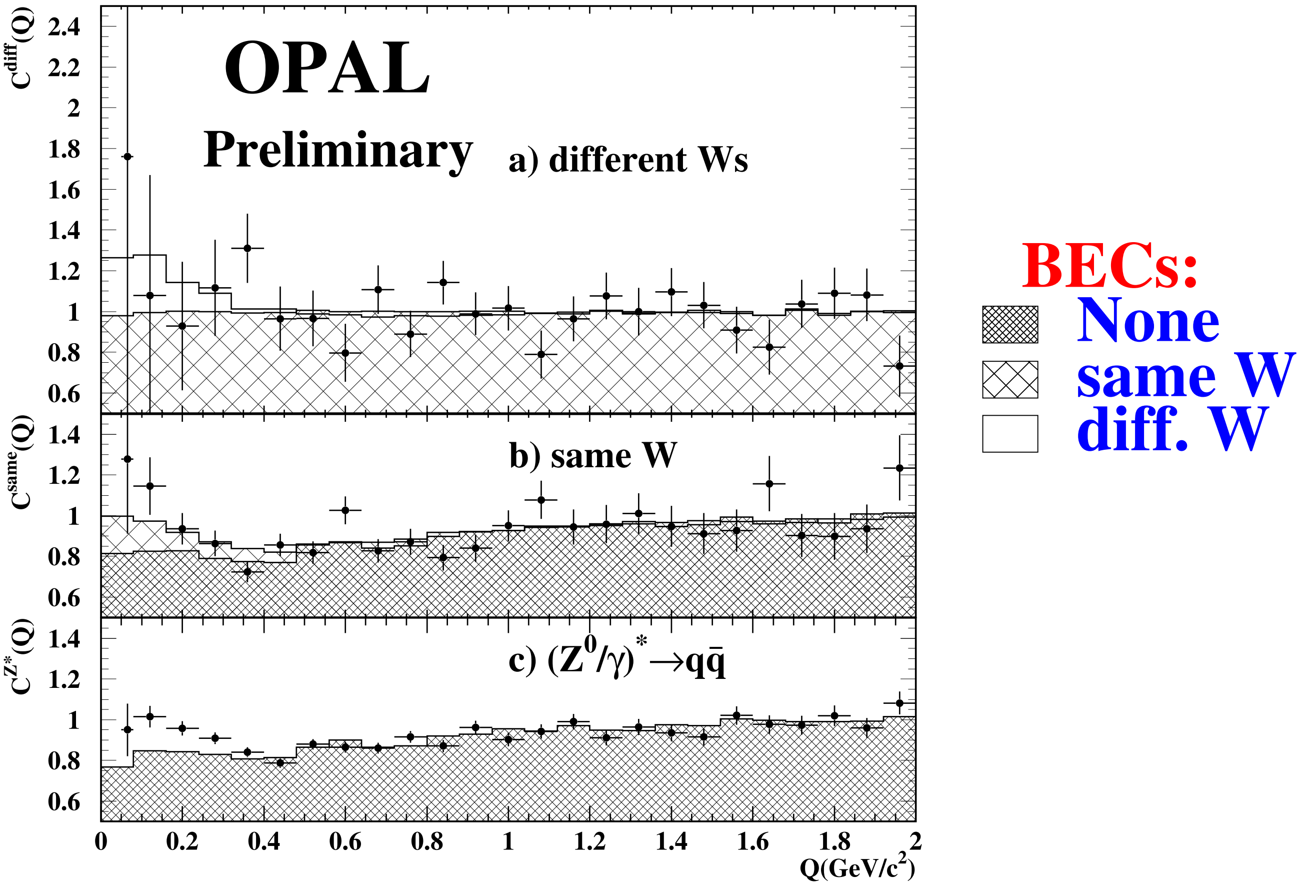
- BEC between pions from different Ws ?



- Simultaneous fit to correlation distributions for $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}q\overline{q}}$, $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{Z^0}/\gamma \rightarrow \mathrm{q\overline{q}}$.
- Extract λ^{same}, $\lambda^{\mathrm{different}}$ and $\lambda^{(\mathrm{Z^0}/\gamma)^*}$
- Fit takes account of Cross-contamination

Bose-Einstein Results

- "Unfolded" distributions



- Fit results:

$$\lambda^{\text{same}} = 0.72 \pm 0.25 \pm 0.25$$

$$\lambda^{\text{diff}} = 0.40 \pm 0.50 \pm 0.39$$

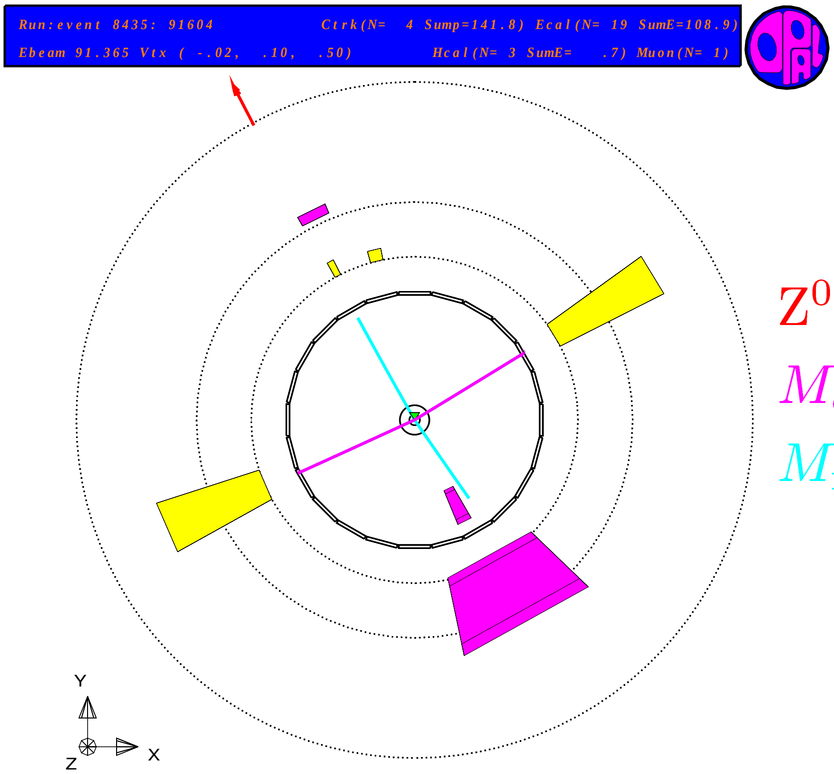
- Compare:

No BEC correlations $\Rightarrow \lambda = 0$

Z^0 data : $\lambda \sim 0.9$

ZZ Production

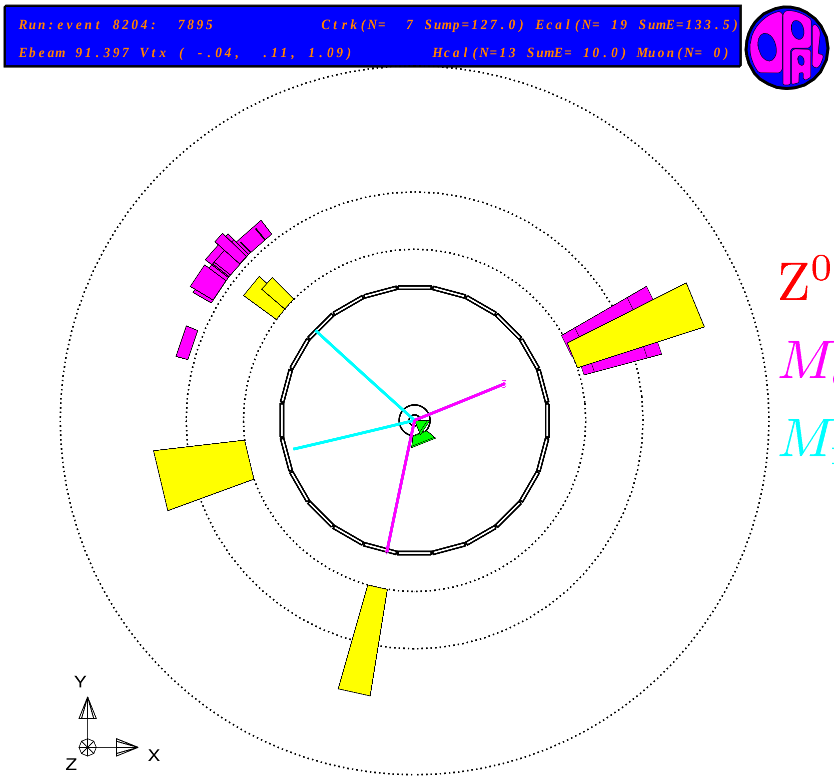
- Analysis underway. Some nice events, e.g.



$Z^0 Z^0 \to e^+ e^- \tau^+ \tau^-$

$M_{ee} \sim 90$ GeV

$M_{\mathrm{recoil}} \sim 91$ GeV



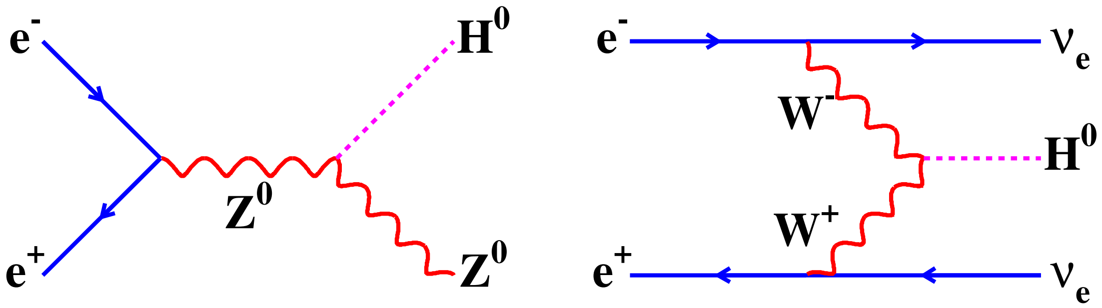
$Z^0 (Z^0/\gamma)^* \to e^+ e^- \tau^+ \tau^-$

$M_{ee} \sim 91$ GeV

$M_{\mathrm{recoil}} \sim 54$ GeV

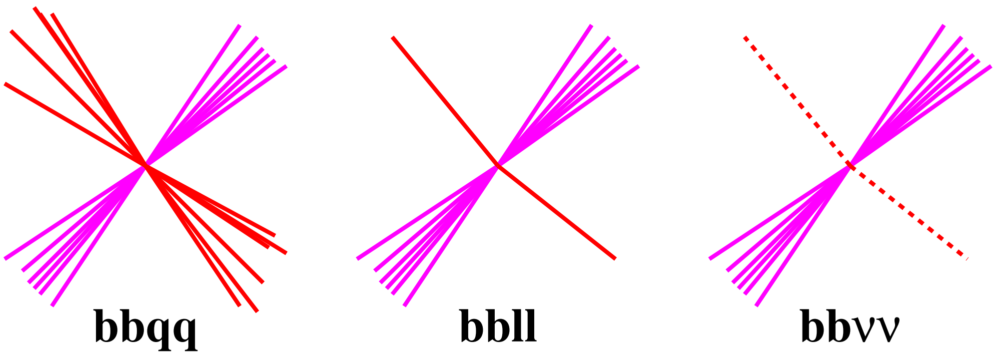
SM Higgs

- Higgs Production : Dominated by $e^+e^- \to Z^0H^0$



- Higgs Decay : $86\%\ H^0 \to b\overline{b}$ $(m_{H^0} < 2M_W)$

- Search Topologies:



- Backgrounds : Z^0Z^0, W^+W^-

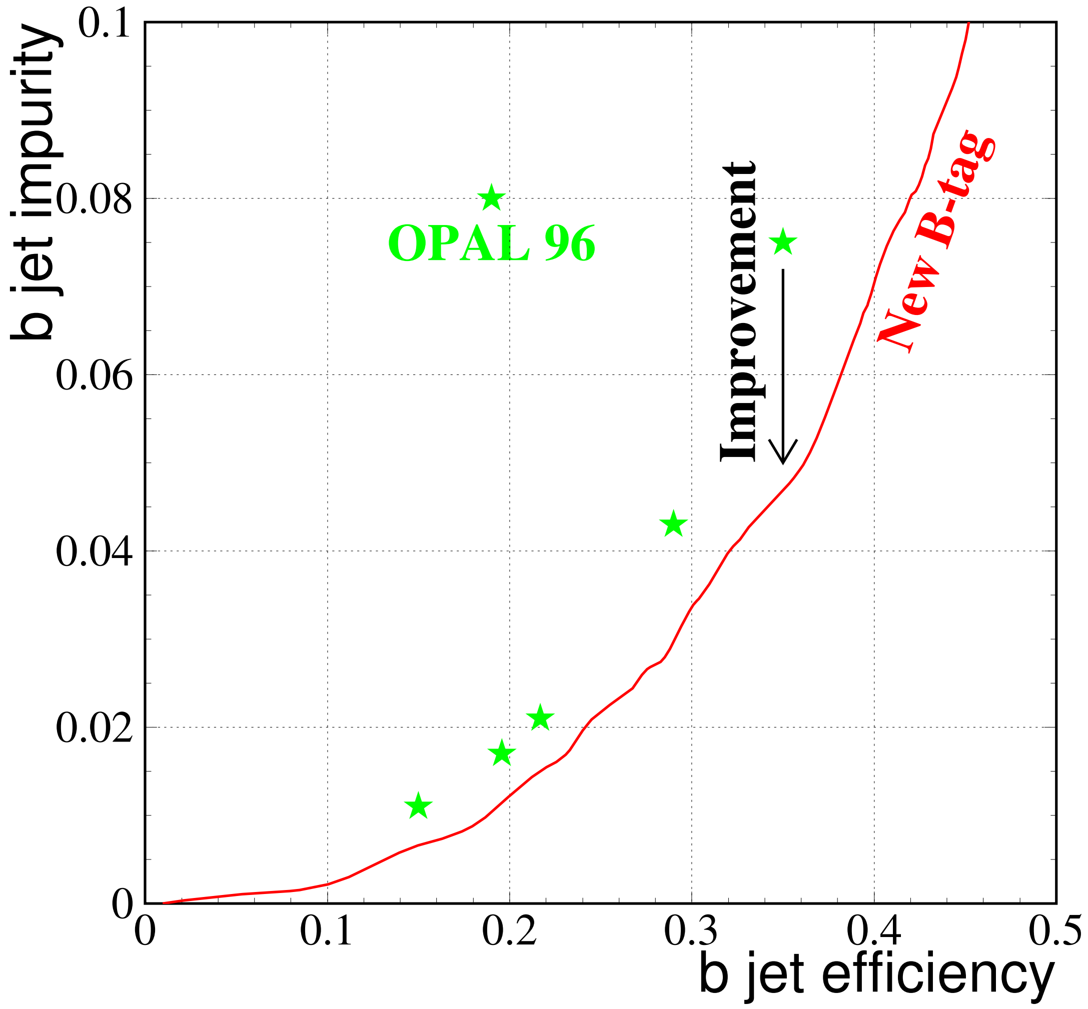
- b-tagging very important

SM Higgs : b-Tagging

- Developed Improved 'Searches' b-tag
- Multivariate Analysis (ANN + ANN + .. $\Rightarrow$ Likelihood)
- using: vertex information, leptons and event shapes

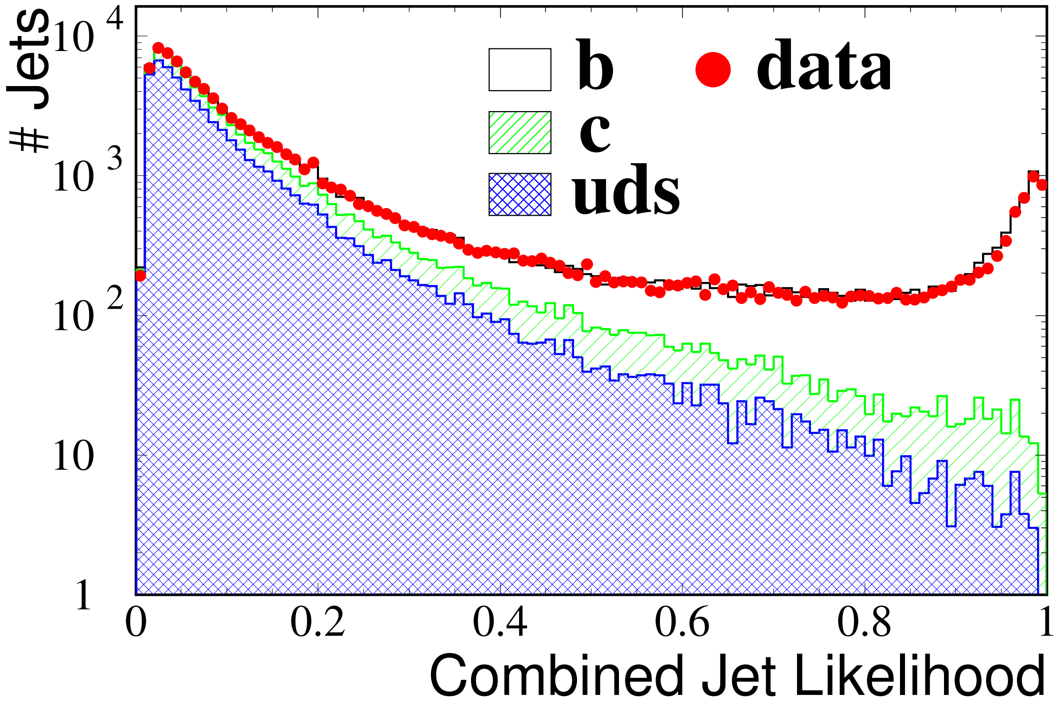
This is not an '$\mathrm{R_b}$' tag !

- Emphasis on optimizing efficiency
- Less concerned about correlations, etc.



SM Higgs : b-tag performance

- Check performance using 1997 Z^0 Calibration data.



- Tag used in the selections :

  qqqq (Likelihood Selection)

  qq$\nu\nu$ (Likelihood Selection)

  qqee and qq$\mu\mu$

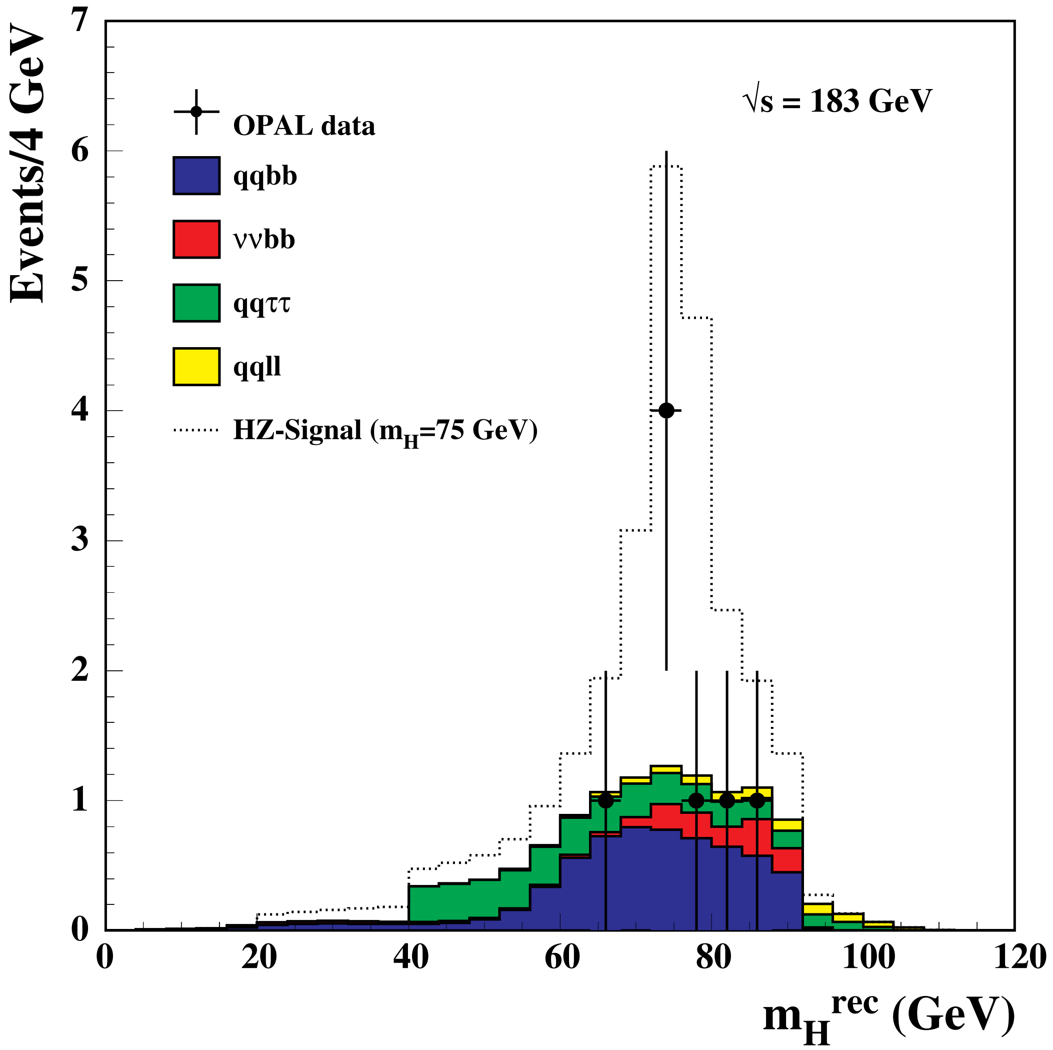
- Tag not used in the qq$\tau\tau$ selection

SM Higgs : Results

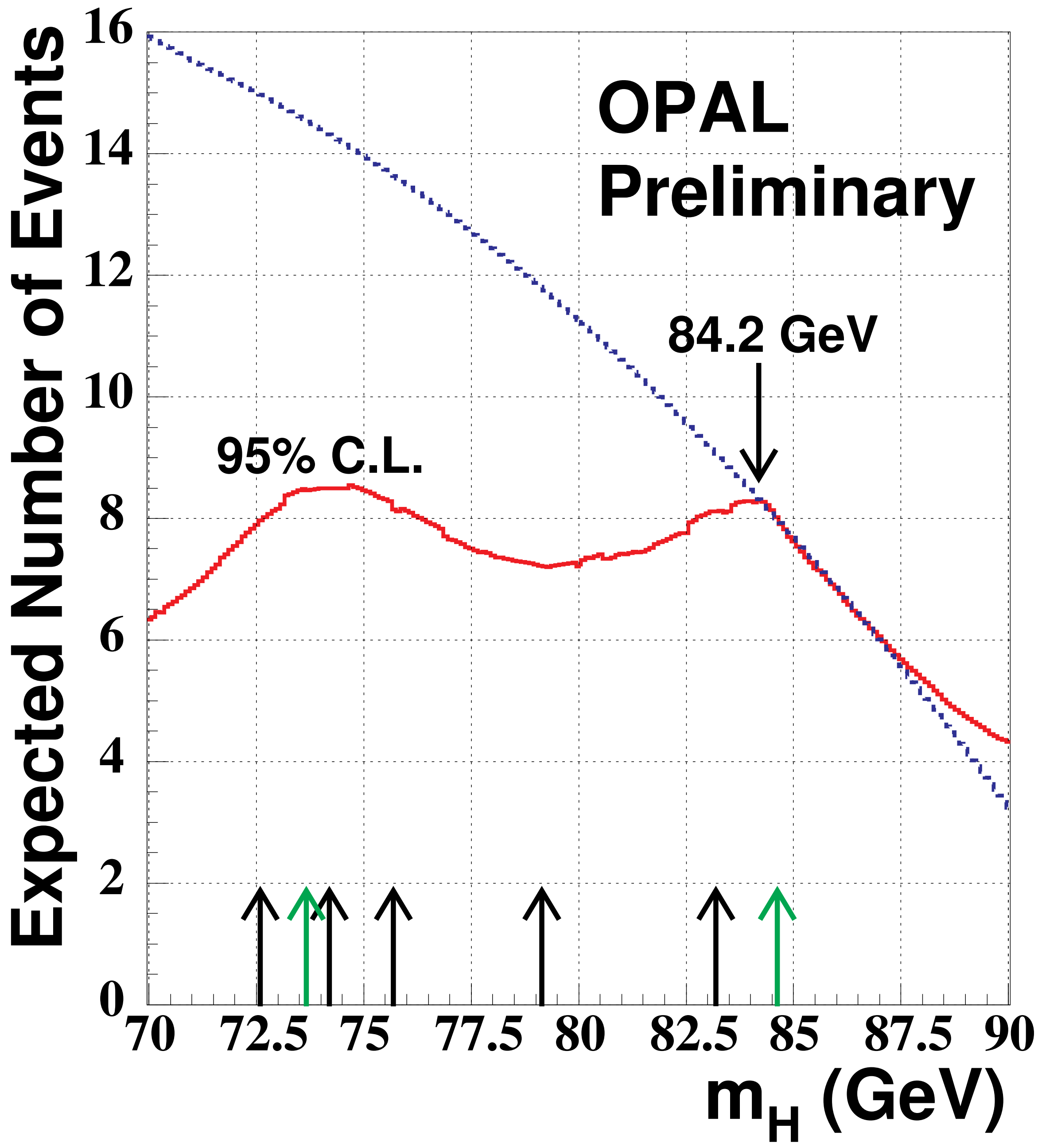
- Observed and expected numbers of events.
- Efficiency and expected excess for $m_{\mathrm{H}^0} = 80$ GeV

Channel	Total Bkd.	Observed	Effic.	Nsig
$\mathrm{b\bar{b}q\bar{q}}$	6.1 ± 1.1	6	37%	6.5
$\mathrm{b\bar{b}l\bar{l}}$	4.0 ± 0.8	2	40%	1.9
$\mathrm{b\bar{b}}\nu\bar{\nu}$	1.4 ± 0.3	0	41%	2.6
Combined	11.4 ± 1.4	8	38%	11.0

OPAL PRELIMINARY



SM Higgs : Mass Limit



$$m_{H^0} > 84.2\,\text{GeV} \quad (95\%\text{C.L.})$$

- Expected limit 86.5 GeV

Searching for SUSY

“Classical” SUGRA inspired SUSY:

- Neutralino, $\tilde{\chi}^0_1$, is Lightest SUSY Particle (LSP)

  $\Rightarrow$ MISSING ENERGY

Gauge Mediated SUSY breaking (GMSB):

- Gravitino is LSP
- $\tilde{\chi}^0_1 \to \tilde{G}\gamma$

  $\Rightarrow$ PHOTONS + MISSING ENERGY

- Slepton can be NLSP, $\tilde{\ell}^{\pm} \to \tilde{G}\ell^{\pm}$

R-Parity Violating (RPV) SUSY:

- Sparticles decay to particles

  $\Rightarrow$ signals with/without MISSING ENERGY

SUSY searches necessarily cover many topologies

- Sensitive to other new physics !

SUSY : MSSM Higgs Analysis

- MSSM : 2 Higgs doublets $\Rightarrow$ 5 Higgs bosons

  $h^0\ A^0\ H^0\ H^+\ H^-$

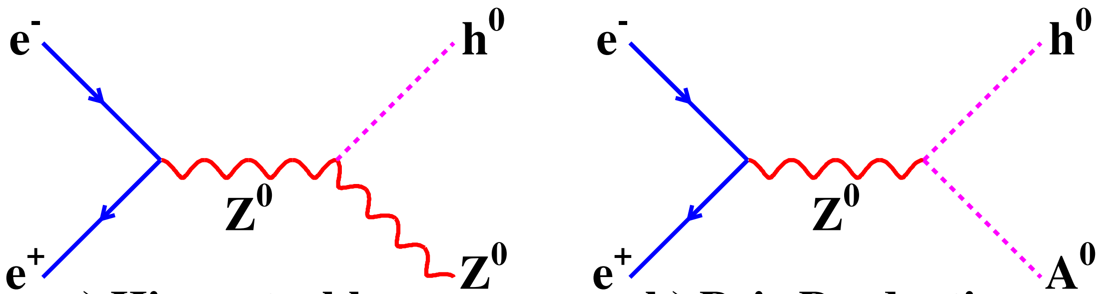
- MSSM : low mass for lightest Higgs

$$m_{h^0}^2 \leq m_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \ln \frac{M_{\tilde{t}}^2}{m_t^2} + \ldots$$

- Strongest experimentally testable prediction of MSSM :

  $m_{h^0} \leq 135\ \mathrm{GeV}$

- MSSM Higgs production



a) Higgs-strahlung
b) Pair Production

Search Topologies:

a) Recycle SM Higgs Search $(\mathrm{h^0 Z^0})$

b) Dedicated $\mathrm{h^0 A^0} \rightarrow \mathrm{b\bar{b}b\bar{b}}$ search

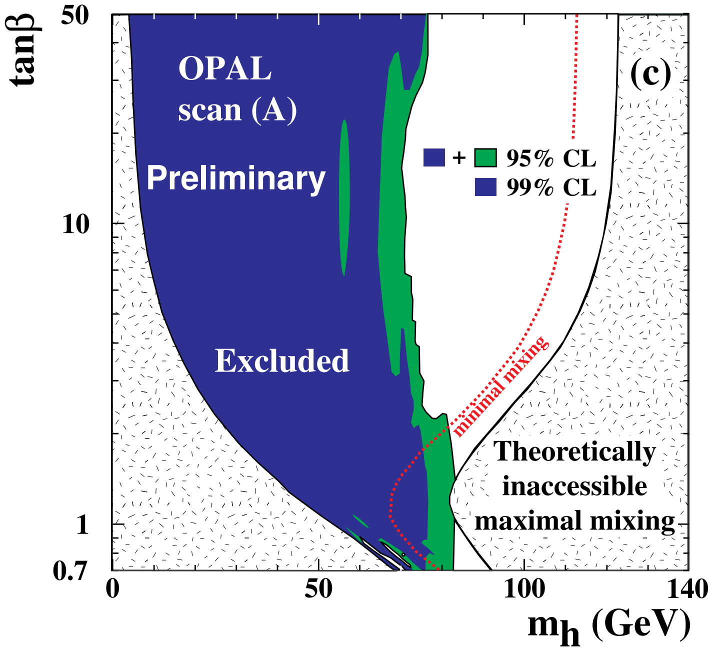
- $\mathrm{h^0 A^0} \rightarrow \mathrm{b\bar{b}b\bar{b}}$ search : similar to SM Higgs search but more emphasis on b-tagging.

MSSM Higgs : Exclusion Limits

Channel	Background	Observe
$b\bar{b}b\bar{b}$	6.3 ± 1.3	7

Limits vs. MSSM parameter scans assuming:

- $A = 0$ or $A = \sqrt{6}m_0$ (minimal/maximal stop mixing)
- Regions incompatible with other OPAL searches discarded



SCAN A

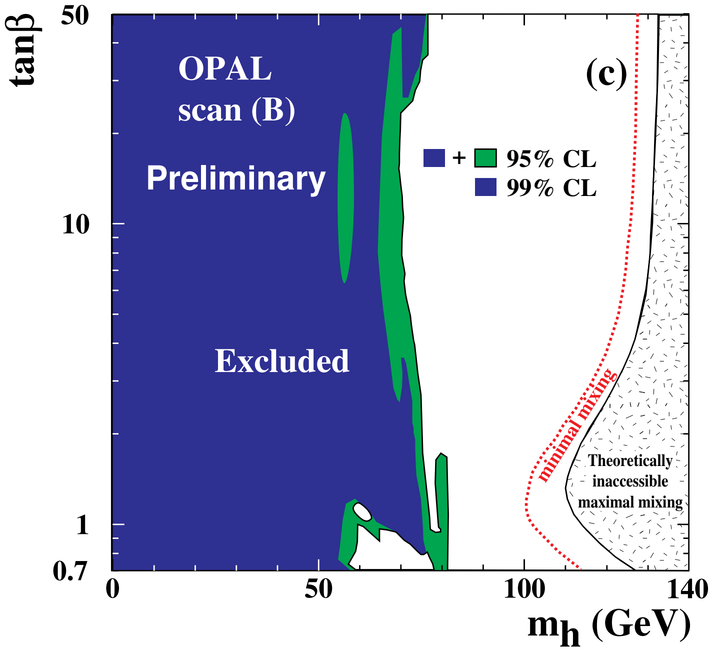
m_0 = 1 TeV

M_2 = 1 TeV

m_{top} = 175 GeV

$5 < m_{A^0} < 160$ GeV

$\mu = -0.1 m_0$



SCAN B

$0 < m_0 < 1$ TeV

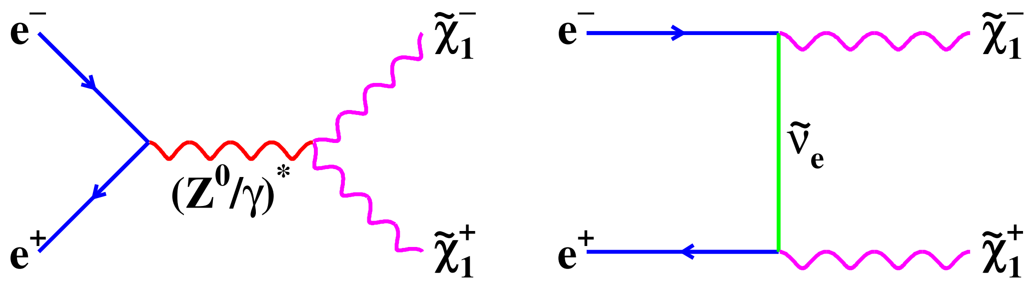
$0 < M_2 < 1$ TeV

m_{top} = 165,175,185 GeV

5 GeV$< m_{A^0} < 1$ TeV

$\mu = -0.1 m_0$

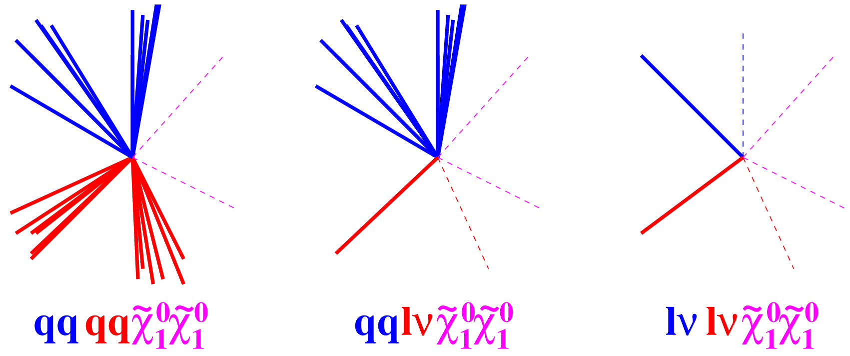
Ssearches : Charginos



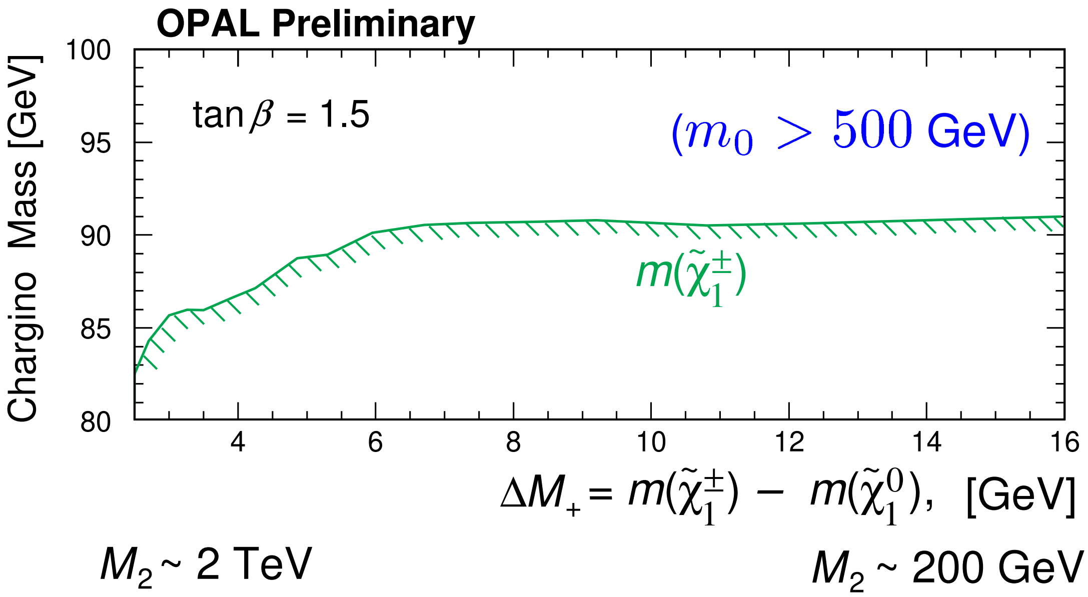
- Large cross section $\sim 4\,\mathrm{pb}$ unless $\tilde{\nu_e}$ is light.
- Chargino decay via W (in a large fraction of MSSM space)

$$\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow (\mathrm{W}^+\tilde{\chi}_1^0)(\mathrm{W}^-\tilde{\chi}_1^0)$$

- Signature : $\mathrm{W}^+\mathrm{W}^-$ plus missing energy

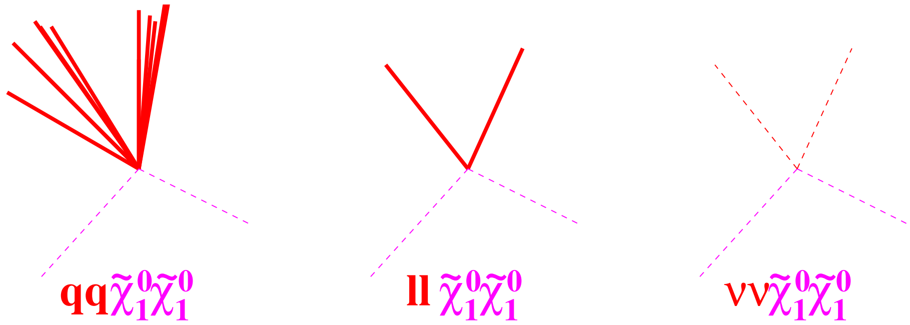


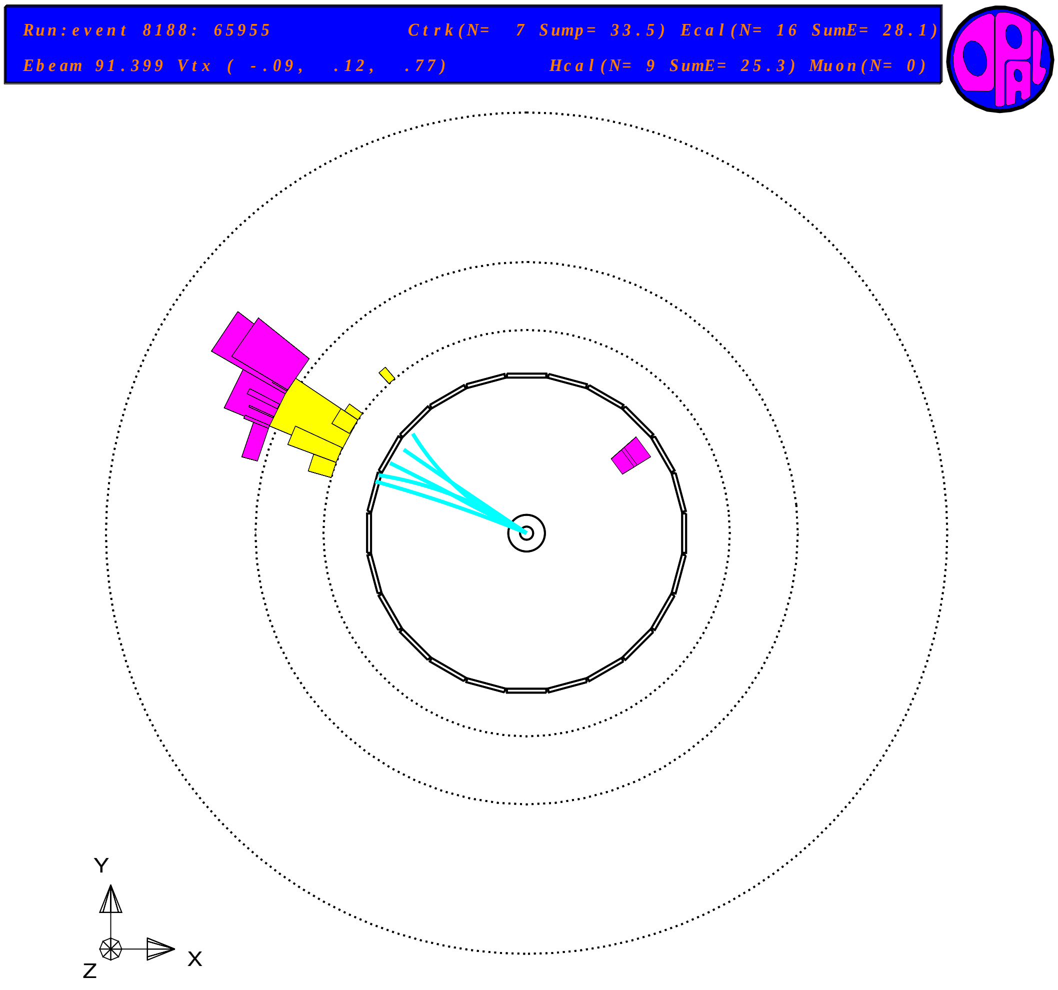
- Data consistent with SM expectation



SUSY : Neutralino Production

- Enough luminosity to search for neutralino production
- Observed as : $\tilde{\chi}^0_2\tilde{\chi}^0_1 \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1 Z^* \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1 f\bar{f}$



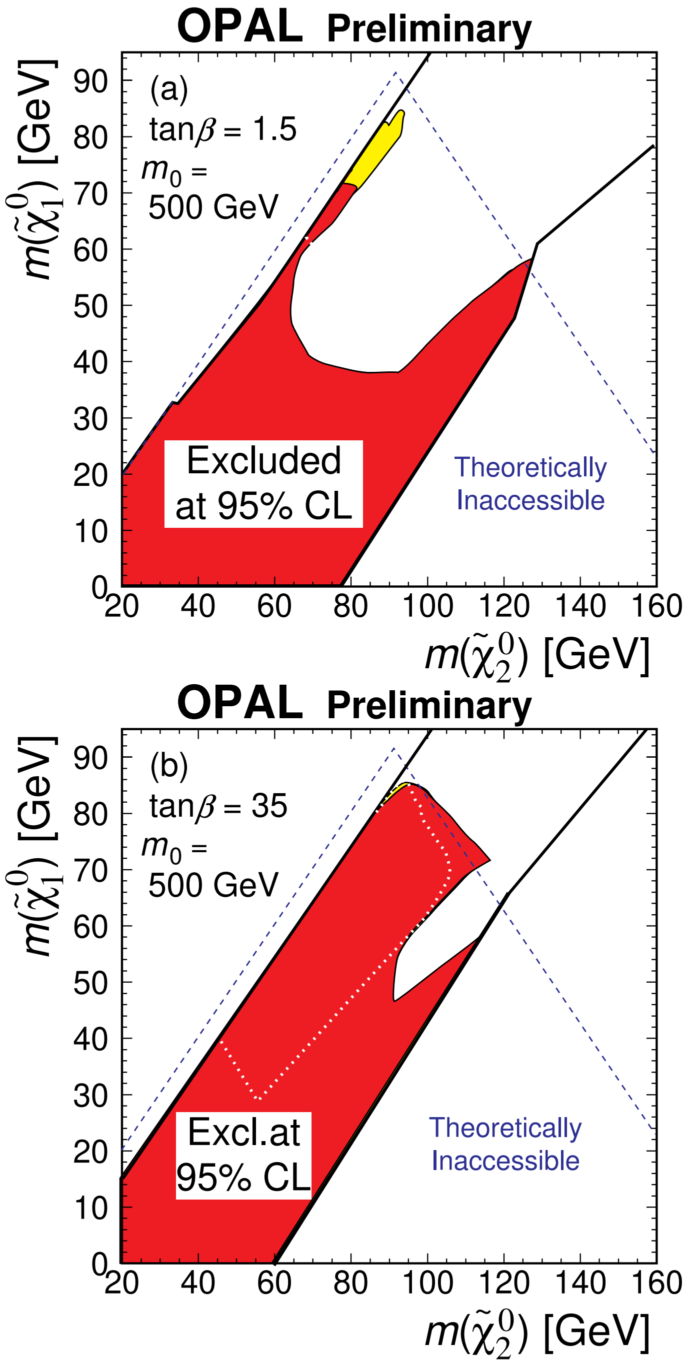


Consistent with :

- Signal : $\tilde{\chi}^0_2\tilde{\chi}^0_1 \rightarrow q\bar{q}\tilde{\chi}^0_1\tilde{\chi}^0_1$
- SM Background : four fermion $q\bar{q}\nu\bar{\nu}$

MSSM : Neutralino Limit

- Chargino and Neutralino Searches can be interpreted as limits in the $\tilde{\chi}^0_1, \tilde{\chi}^0_2$ plane.



- For heavy sfermions, $m_0 > 500\,\mathrm{GeV}$:

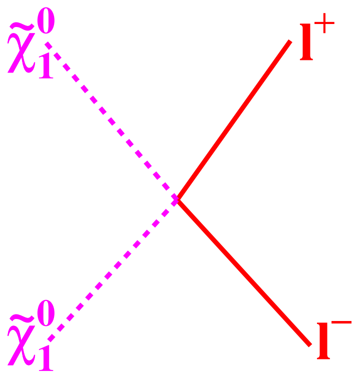
$$m(\tilde{\chi}^0_1) > 30.1\,\mathrm{GeV}\ \textbf{(all}\ \tan\beta\textbf{)}$$

Scalar Lepton Searches

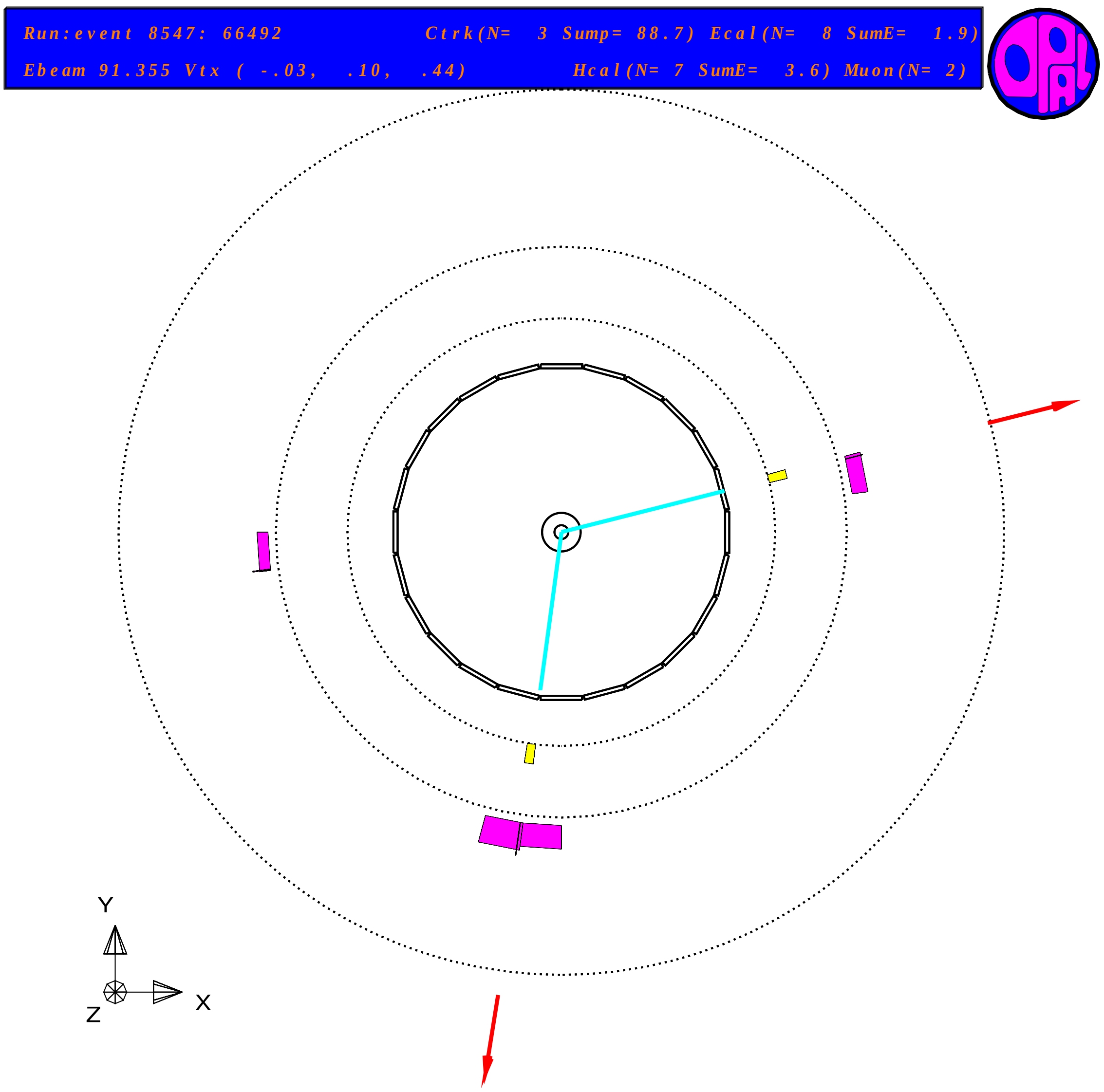
$e^+e^- \to \tilde{l}^+\tilde{l}^-$

$\tilde{l}^- \to l^-\tilde{\chi}^0_1$

$\tilde{l}^+ \to l^+\tilde{\chi}^0_1$



- Acoplanar leptons
- Missing E_T



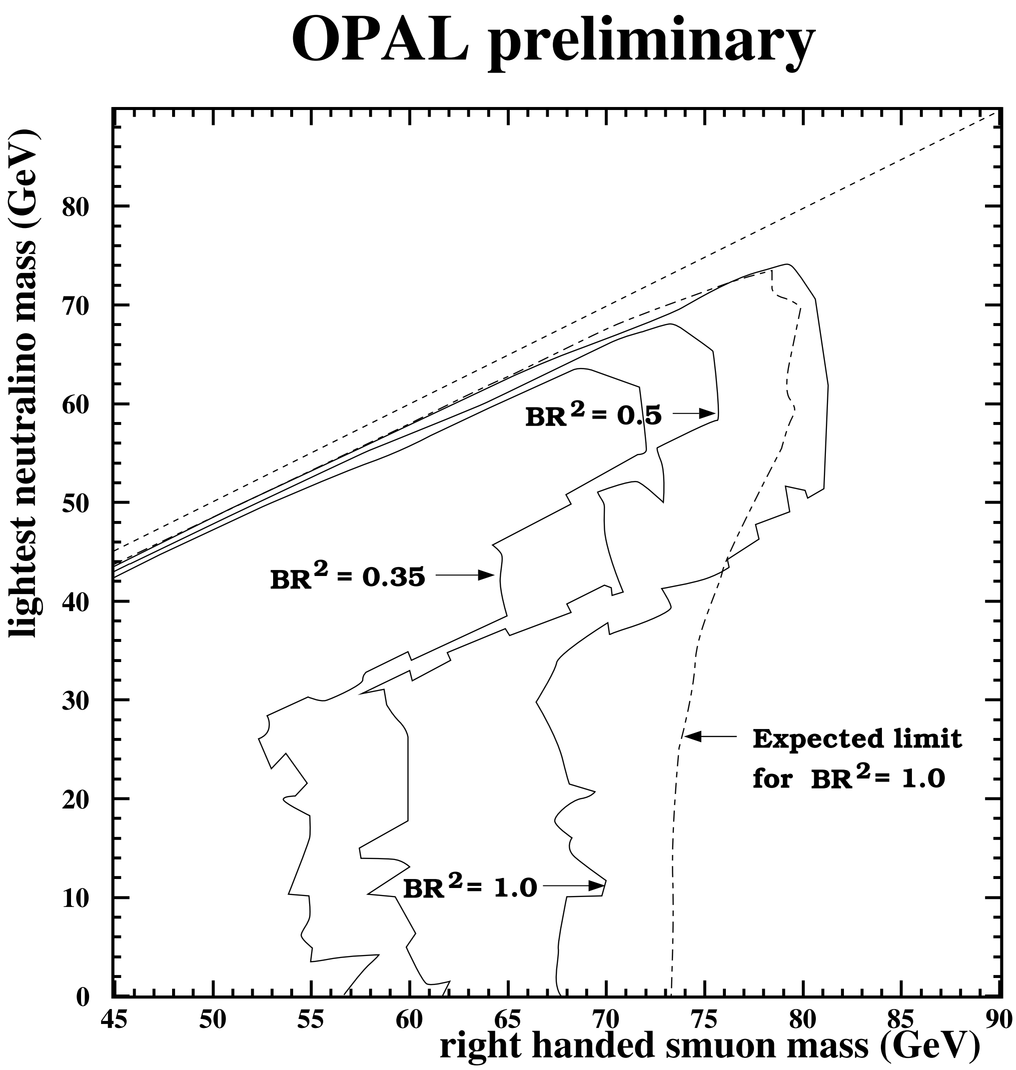
Candidate for : $\tilde{\mu}^+\tilde{\mu}^- \to \mu^+\tilde{\chi}^0_1\mu^-\tilde{\chi}^0_1$

Background : $\mathrm{W}^+\mathrm{W}^- \to \mu^+\nu_\mu\mu^-\overline{\nu}_\mu$

Search for Scalar Leptons

Channel	Background	Observe
$\tilde{e}^+\tilde{e}^-$	13.5	16
$\tilde{\mu}^+\tilde{\mu}^-$	10.5	12
$\tilde{\tau}^+\tilde{\tau}^-$	10.2	9

- Limits vs. $\mathrm{BR}(\tilde{\ell}^\pm \to \ell^\pm \tilde{\chi}_1^0)$



Squarks

- Loop corrections to $m_{\tilde{t}}$

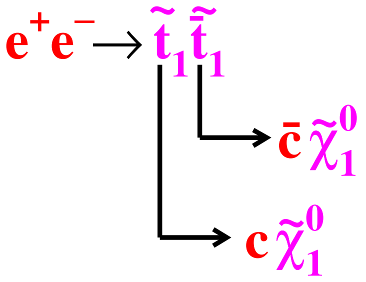
  $\Rightarrow \tilde{t}_R, \tilde{t}_L$ expected to be lightest of the squarks

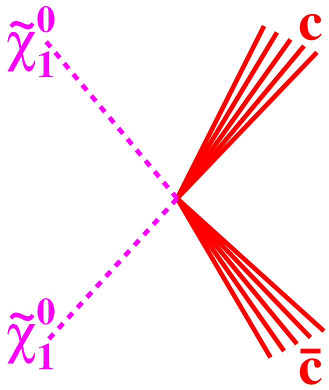
- Mix to form the physical mass eigenstates, $\tilde{t}_1, \tilde{t}_2$

$$\tilde{t}_1 = \cos\theta_{\tilde{t}}\tilde{t}_L + \sin\theta_{\tilde{t}}\tilde{t}_R$$

- For large m_{top} : $\tilde{t}_1$ can be light.

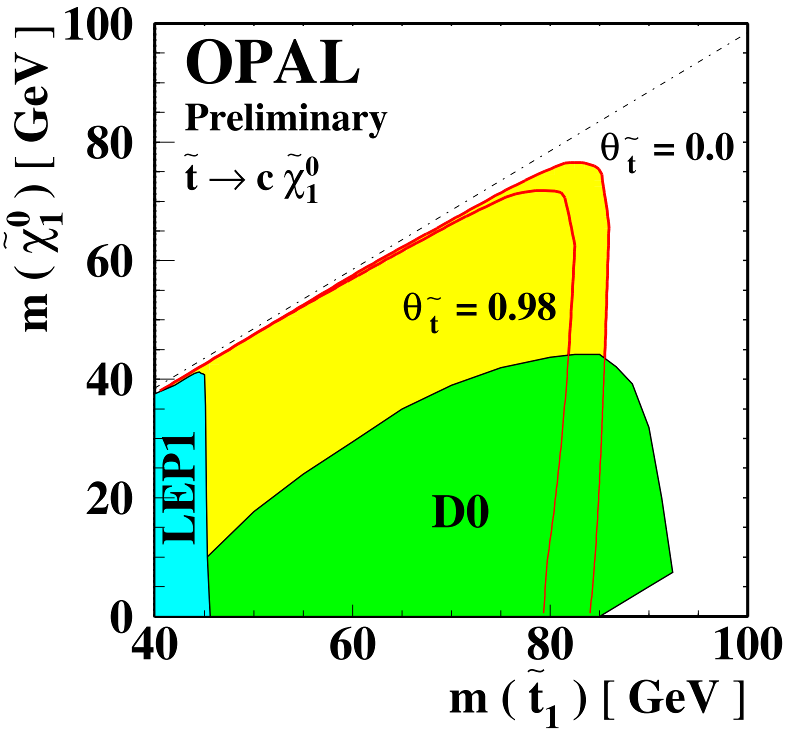
Search for





- **Acoplanar Jets**
- **Missing E_T**

- No candidates $\Rightarrow$



Also Searched for:

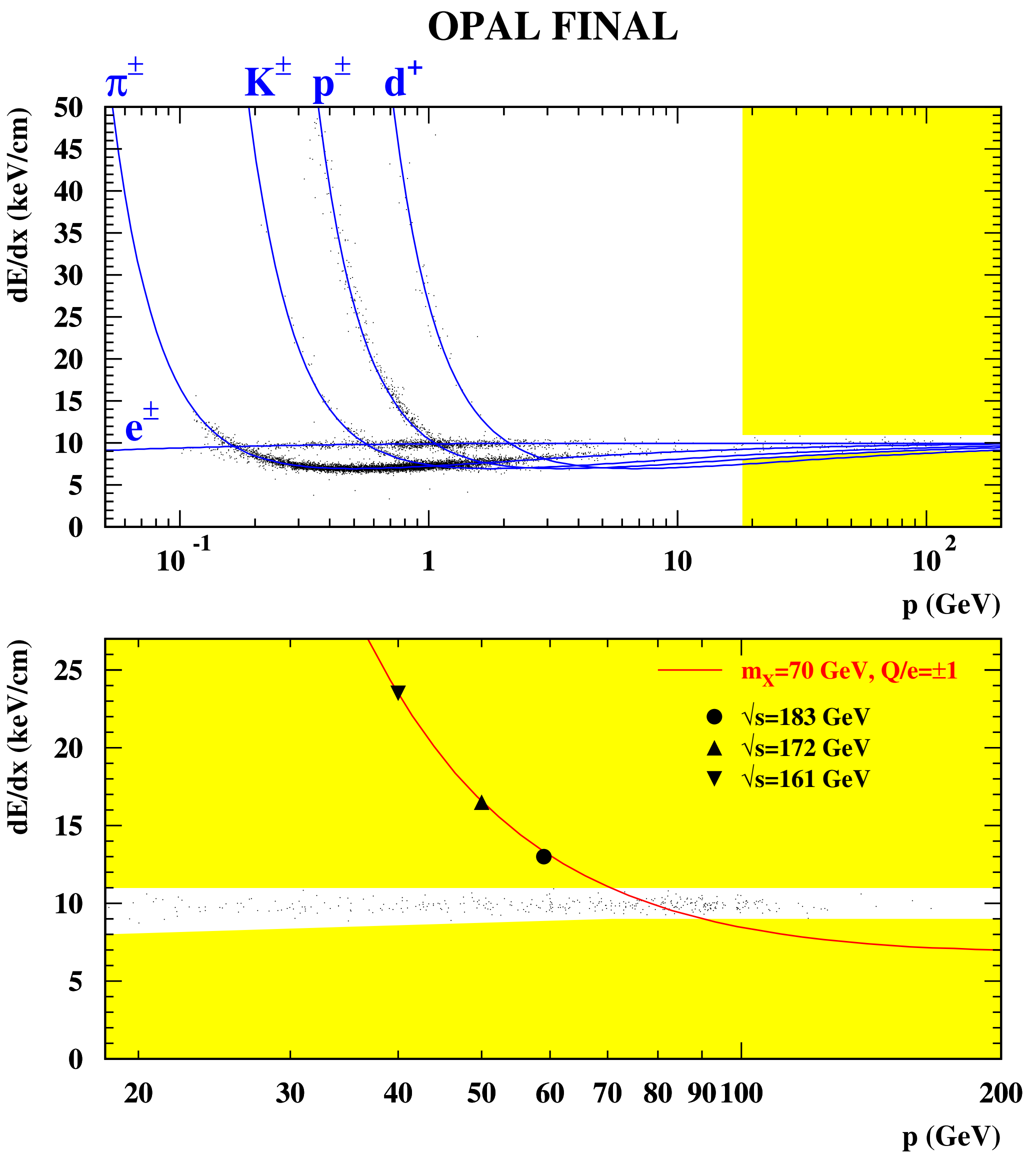
$\tilde{t}_1 \rightarrow b\ell^+\tilde{\nu}$

$\tilde{b}_1 \rightarrow b\tilde{\chi}^0_1$

large $\tan\beta$

Stable Charged Particle Search

- Search for Pair-produced massive long-lived/stable charged particles, e.g. Stable sleptons, stable charginos...
- Use the OPAL jet chamber's excellent dE/dx resolution.
- Search Topology : two back-to-back tracks.



- No candidates: $\sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{X}^+\mathrm{X}^-) < 0.2\,\mathrm{pb}$

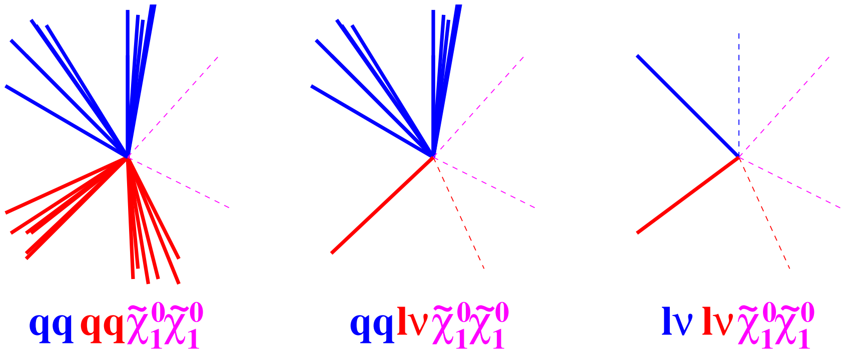
$\Rightarrow$ long-lived charginos excluded for $m(\tilde{\chi}^\pm_1) < 89\,\mathrm{GeV}$

Charginos : GMSB Search

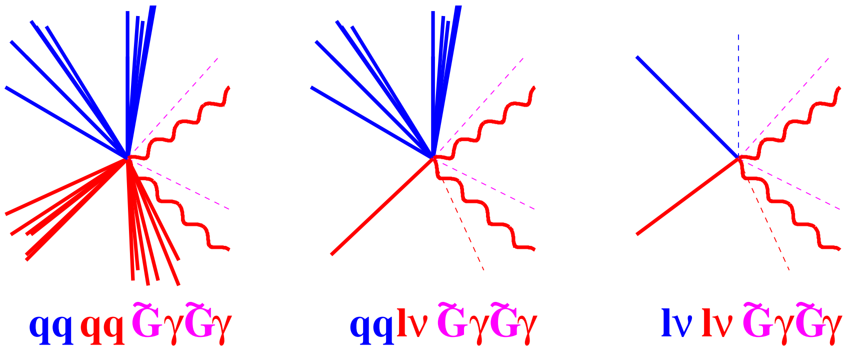
- In Gauge Mediated SUSY Breaking (GMSB) models the Gravitino is the LSP.
- NLSP can be $\tilde{\chi}^0_1$ or $\tilde{\ell}^{\pm}$ (this search assumes $\tilde{\chi}^0_1$ is NLSP)
- $\tilde{\chi}^0_1 \rightarrow \tilde{\mathrm{G}}\gamma$
- Typically $\tilde{\mathrm{G}}$ is light $(< 1\ \mathrm{GeV})$

GMSB $\tilde{\chi}^+_1\tilde{\chi}^-_1$ topology depends on the $\tilde{\chi}^0_1$ decay length ($c\tau$)

Long τ :



Short τ :



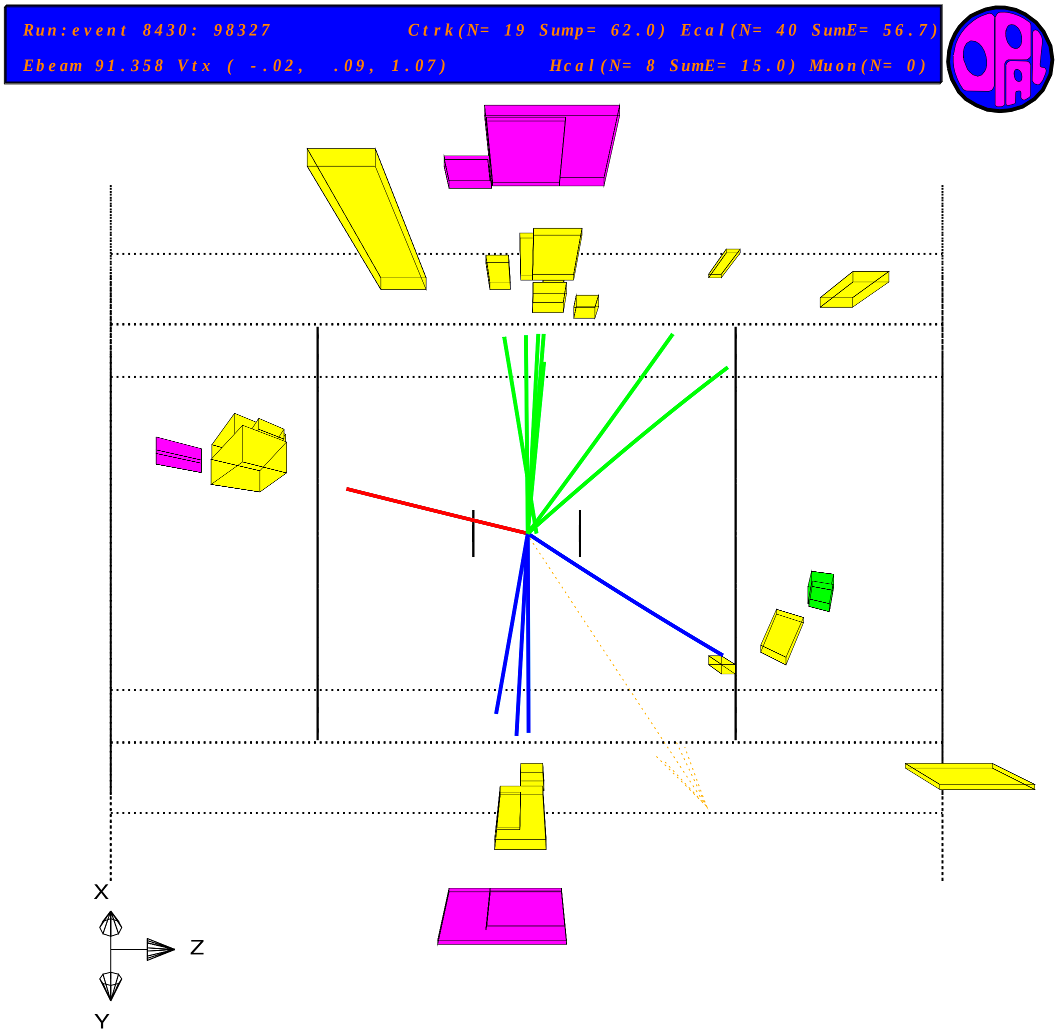
- Search topology: ≥ 1 photon + missing energy

  Separate High and Low multiplicity selections.

GMSB Results

Channel	Background	Observe
Low Multiplicity	4.9 ± 1.3	4
High Multiplicity	2.1 ± 1.3	2

- High Multiplicity Candidate : $E_\gamma = 25\ \mathrm{GeV}$

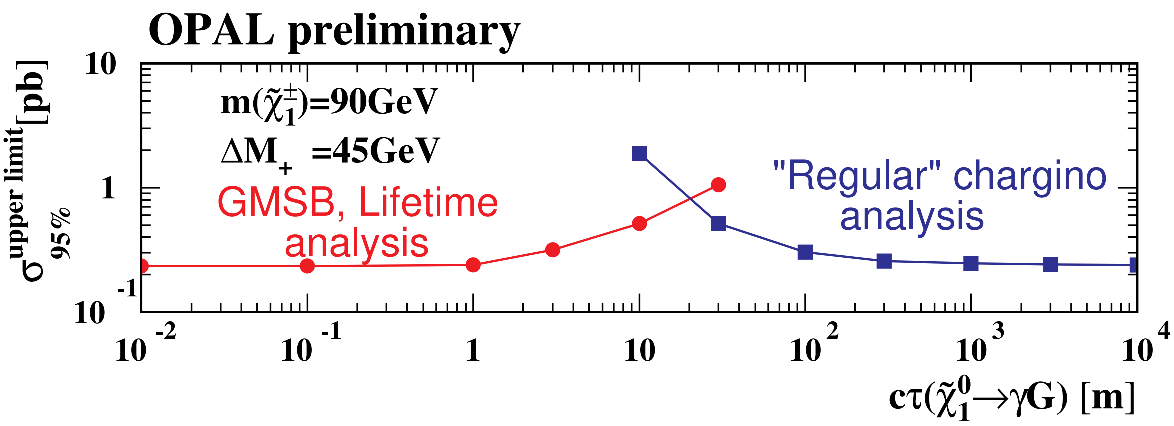


Consistent with :

- Signal : $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow q\overline{q}\tilde{\chi}_1^0 \tau\nu\tilde{\chi}_1^0$

  with 1 $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ in the detector
- SM Background : $W^+W^- \rightarrow q\overline{q}\tau\overline{\nu}_\tau$ isolated (γ/π^0)

GMSB : Chargino Limit

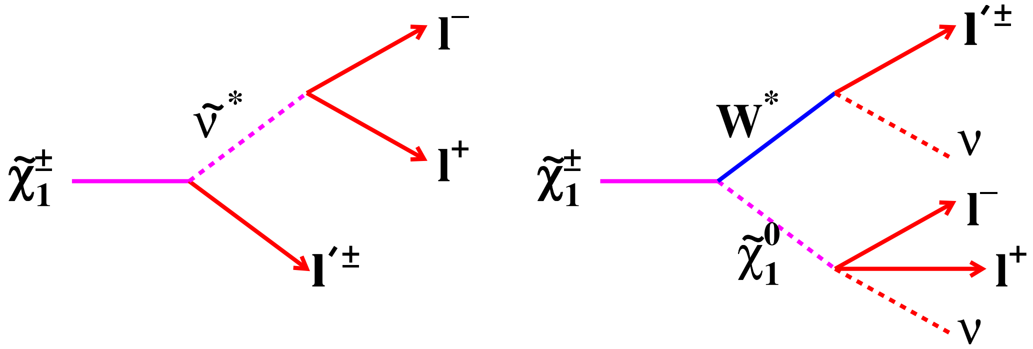


- Complementary to 'Standard' chargino search

RPV SUSY

- LSP no longer stable
- Sparticles decay to particles
- Final states with or without missing energy
- Many channels examined, e.g.

Six charged leptons



- No Signal Observed:
- $\sigma^{RPV}(\tilde{\chi}_1^+\tilde{\chi}_1^-) < 0.2\,\text{pb}$

Conclusions

- SM in excellent shape

  Survived another round of ‘Searching’

  Excellent description of 2/4-fermion production

  The Higgs is still missing

- Look forward to the 189 GeV Run

  Big step in integrated luminosity $\Rightarrow$

  First sign of non-SM physics ?

- LEP 2 physics is fun !