Salvatore Mele

INFN/Napoli CERN/EP

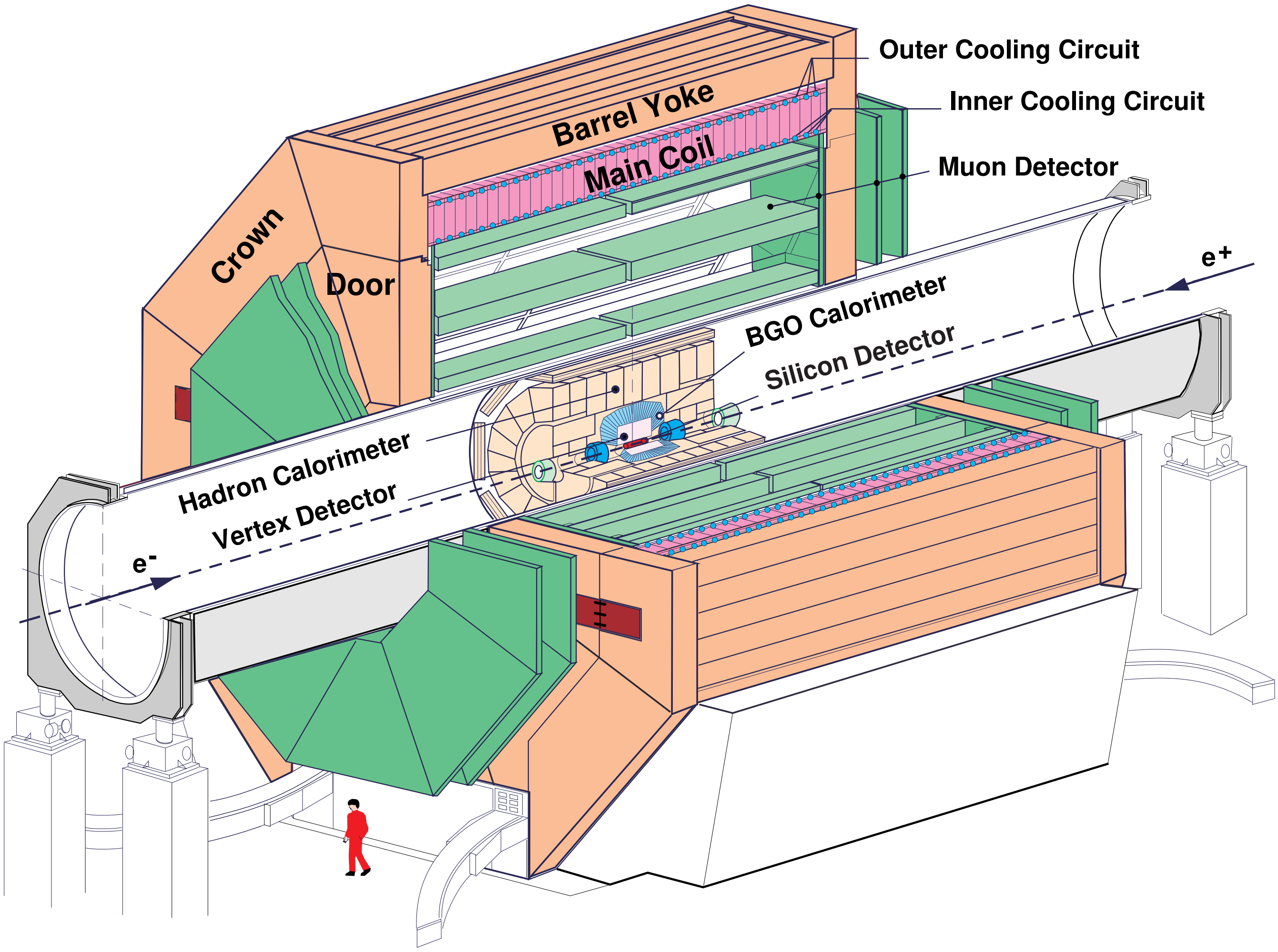
Physics of Neutral Bosons with the L3 Detector at LEP 2

- The Data
- Two Z
- One Photon and One Z
- Two (or more) Photons
- . . . in the Extra Dimensions

CERN EP Seminar
Monday 8^{th} November 1999

The Data

The Data

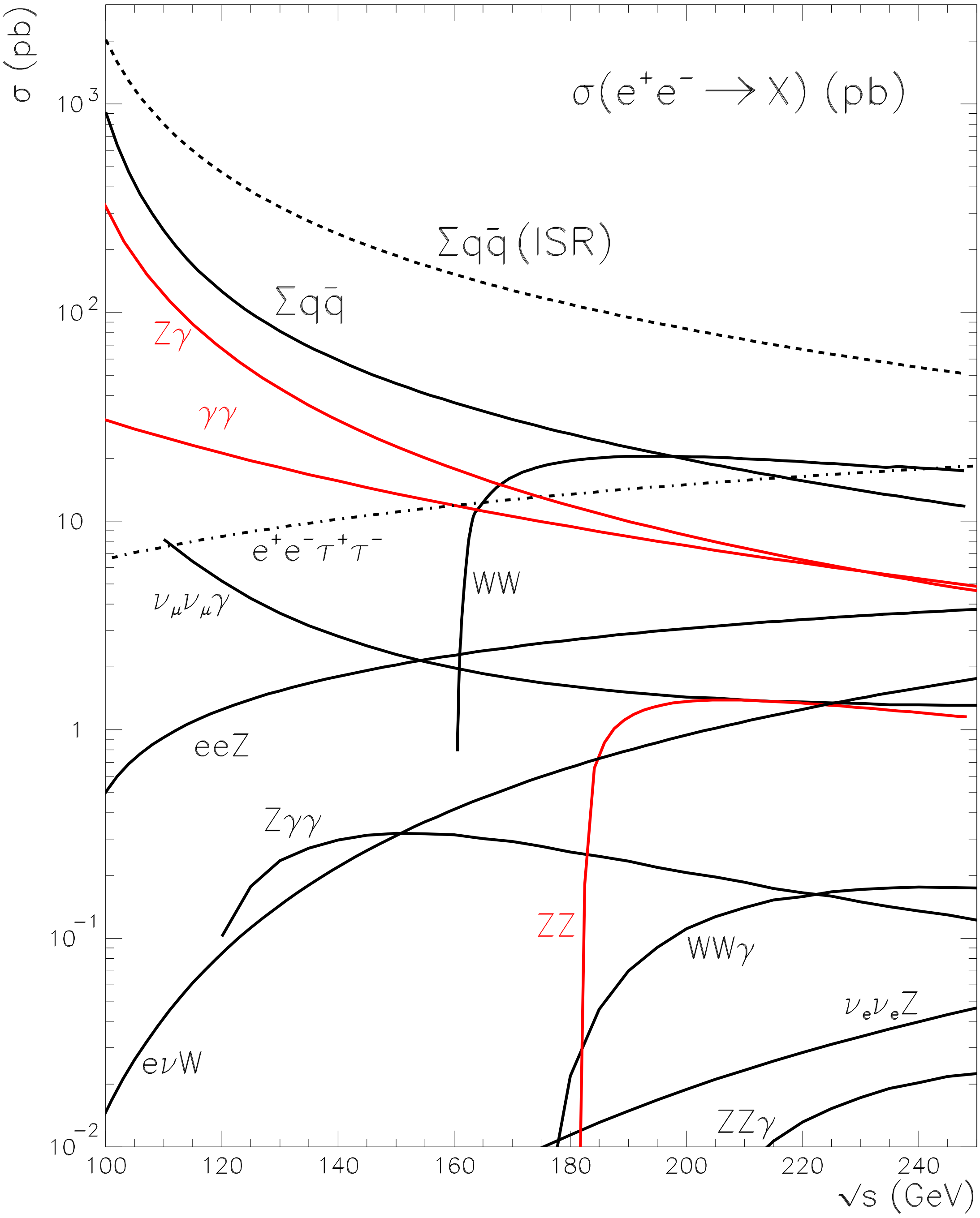


High resolution for Photon, Electron, Muons.
Hermeticity for jet reconstruction.

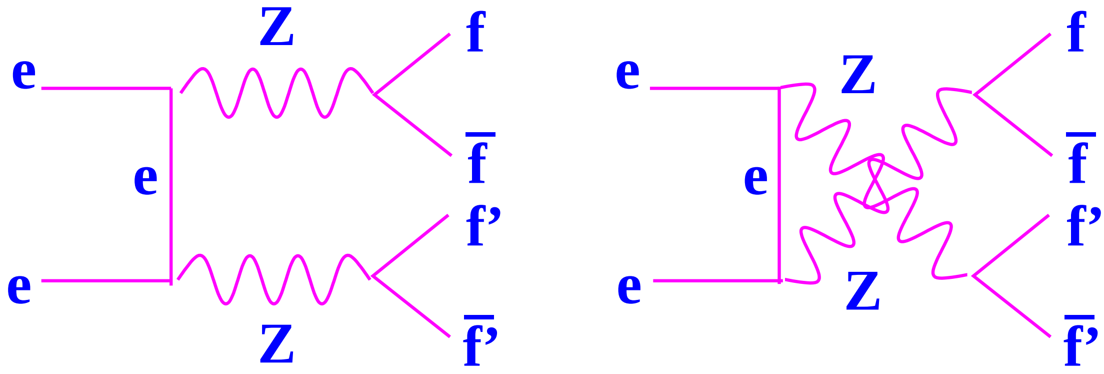
Focus on 183–189 GeV data.

Year	$\sqrt{s}$ (GeV)	$\int \mathcal{L}dt$ (pb^{-1})	
1995	130–140	5+5	The Warm-Up Run
1996	161–172	10+10	W Pairs, W Mass
1997	183	55	Z Pairs
1998	189	175	High statistic measurements
1999	192–202	230	Come and see tomorrow LEPC

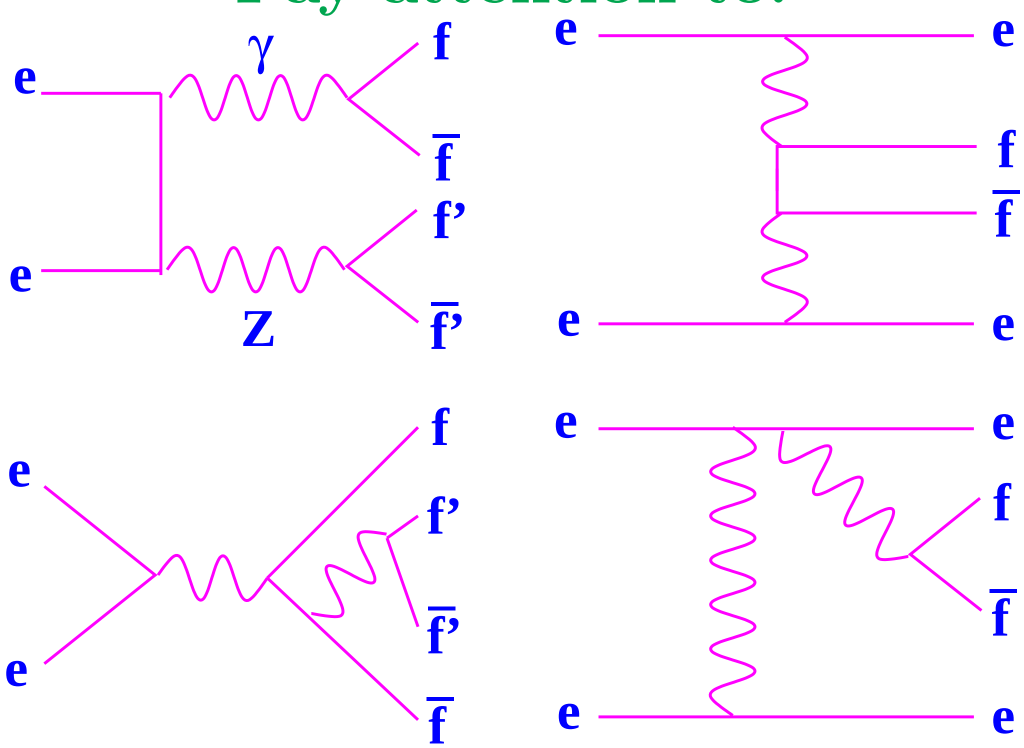
Expected Cross Sections



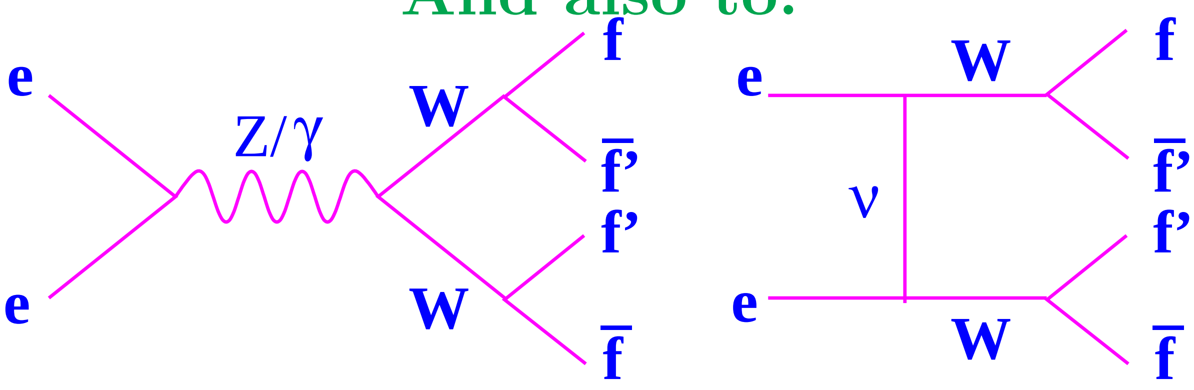
Two Z



Pay attention to:

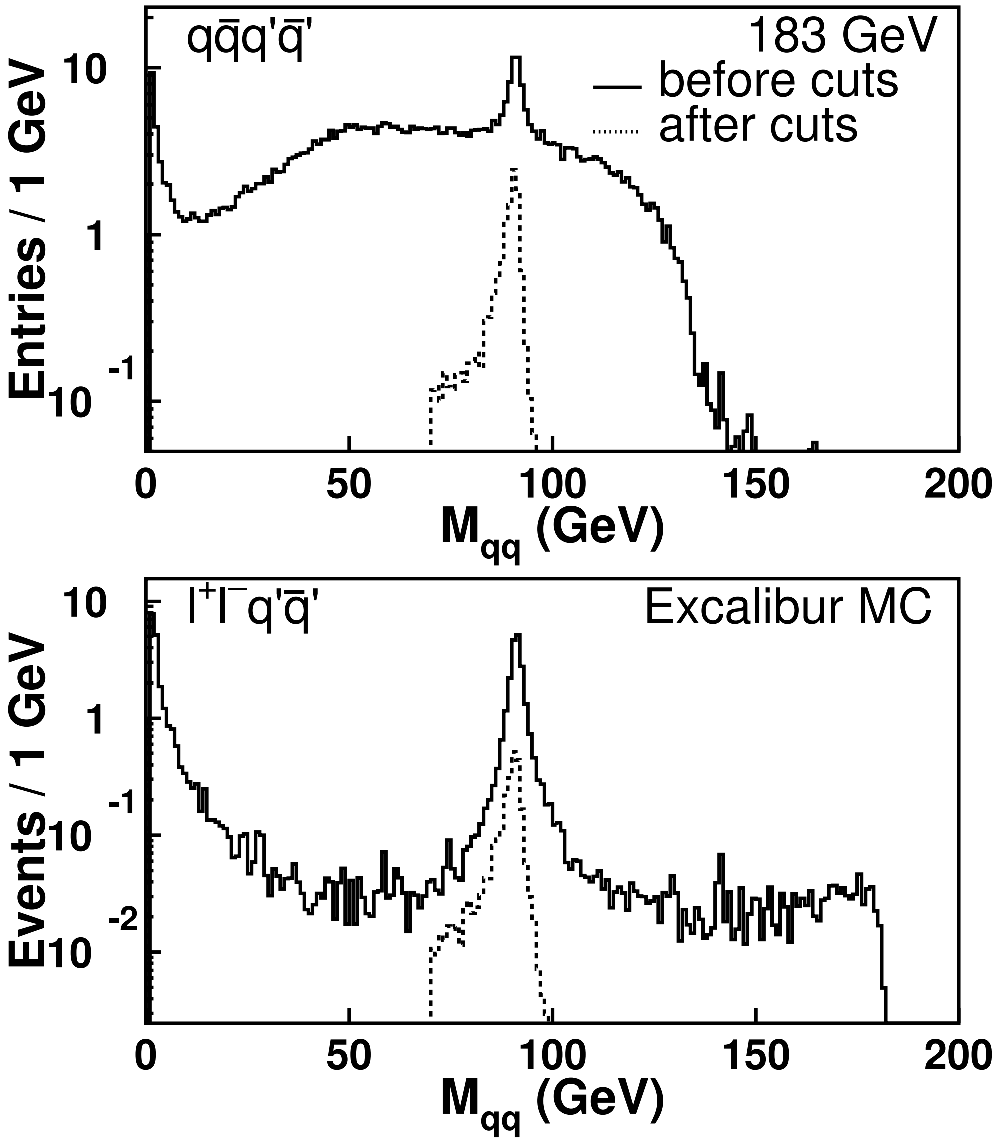


And also to:



Signal Definition

$$
\begin{array}{rll}
\mathbf{M_{f\bar{f},f'\bar{f}'}} \in (\mathbf{70-105})\ \mathbf{GeV} & vs. & \gamma^* \\
|\cos\theta_{\mathrm{e}}| < \mathbf{0.95} & vs. & \text{Multiperipheral Diagrams} \\
\mathbf{M_{f\bar{f}',f'\bar{f}}} \notin (\mathbf{75-85})\ \mathbf{GeV} & vs. & \text{WW}
\end{array}
$$

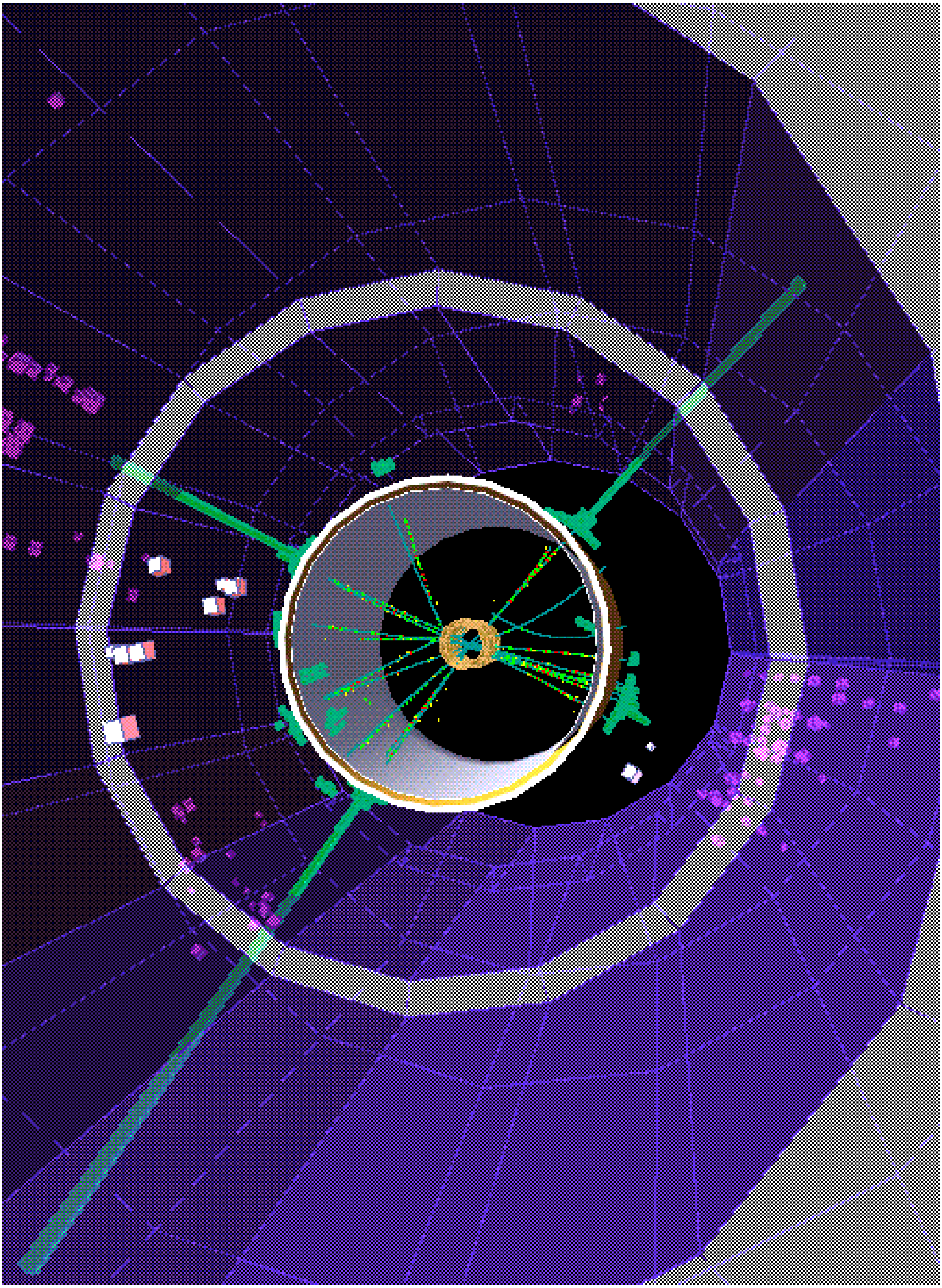


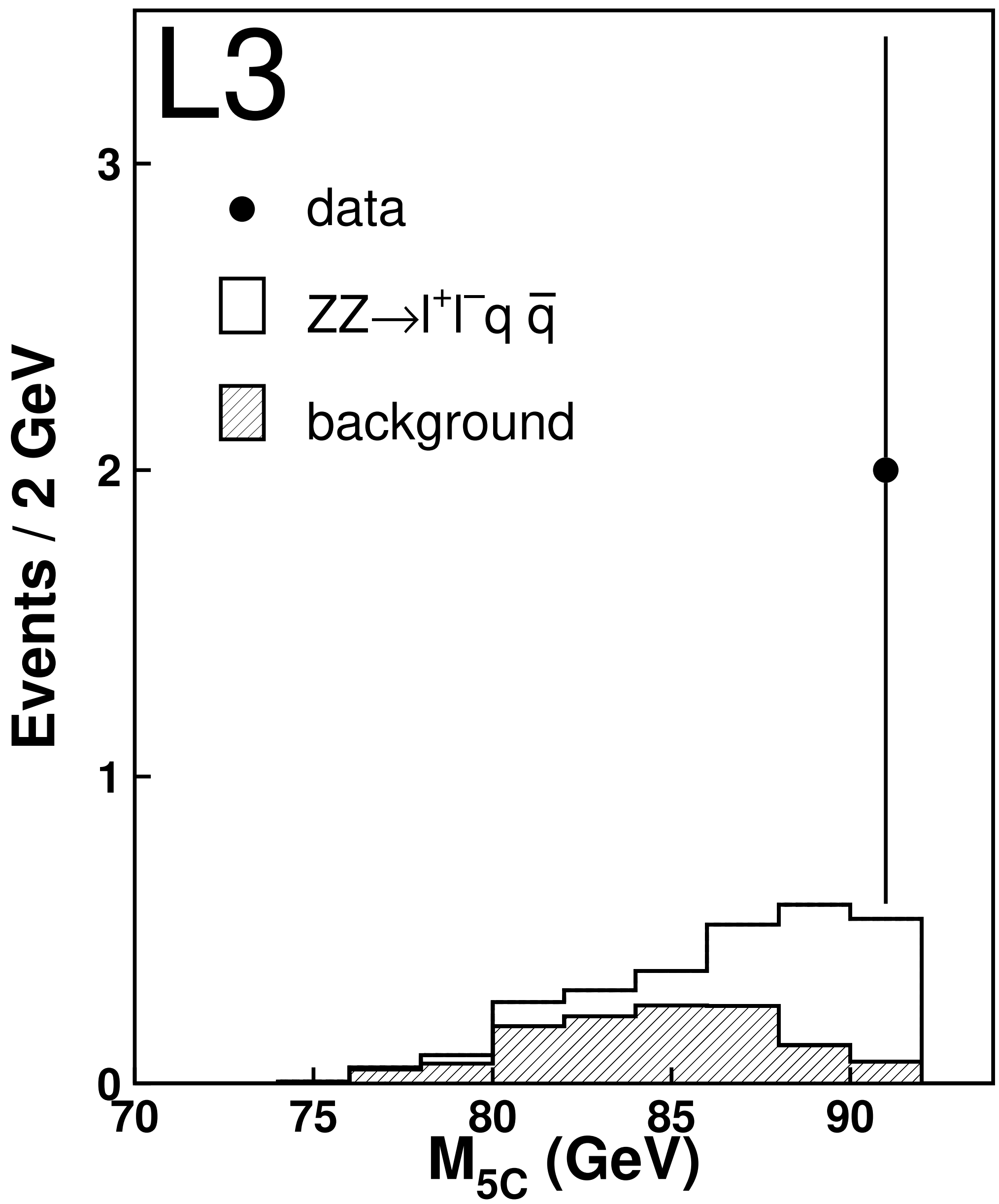
$$\sigma^{\mathrm{SM}}_{\mathrm{e^+e^-\to ZZ}}(\mathbf{183\ GeV}) = \mathbf{0.25\,pb}$$
$$\sigma^{\mathrm{SM}}_{\mathrm{e^+e^-\to ZZ}}(\mathbf{189\ GeV}) = \mathbf{0.66\,pb}$$

Signal Definition

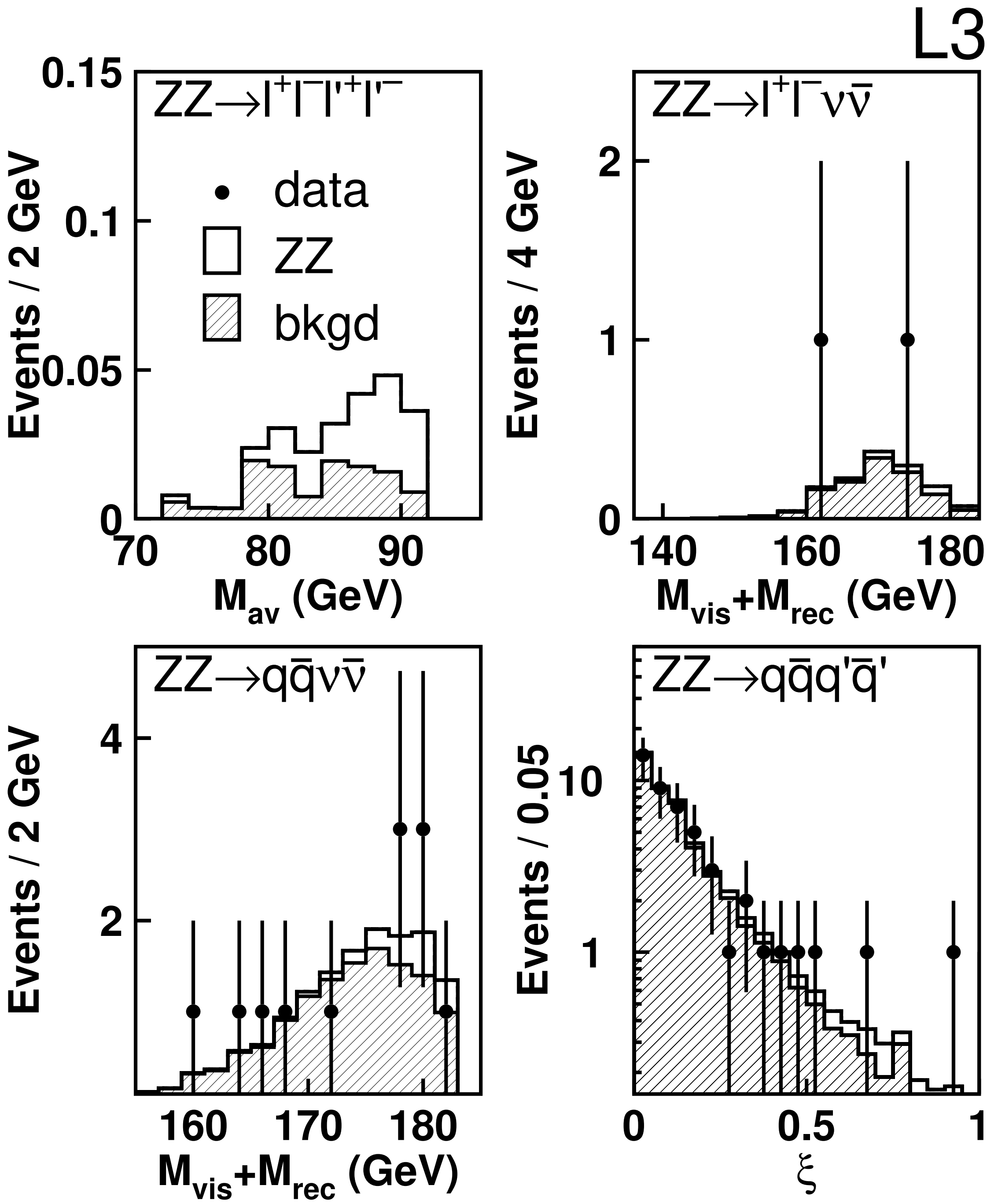
Channel	Statistics	Signature	Background	Contamination
$q\bar{q}q'\bar{q}'$	High	4 jets	QCD $W^+W^- \longrightarrow$ 4 jets	High
$q\bar{q}\nu\bar{\nu}$	High	2 jets + Missing energy	QCD $W^+W^- \longrightarrow q\bar{q}\ell\nu$ $We\nu$	Average
$q\bar{q}\ell^+\ell^-$	Average	2 jets + 2 leptons	W^+W^- 4f not ZZ	Low
$\ell^+\ell^-\nu\bar{\nu}$	Average	2 leptons + Missing energy	4f not ZZ W^+W^- $\ell^+\ell^-$	Average
${\ell_1}^+{\ell_1}^-{\ell_2}^+{\ell_2}^-$	Low	4 leptons	4f not ZZ	Low

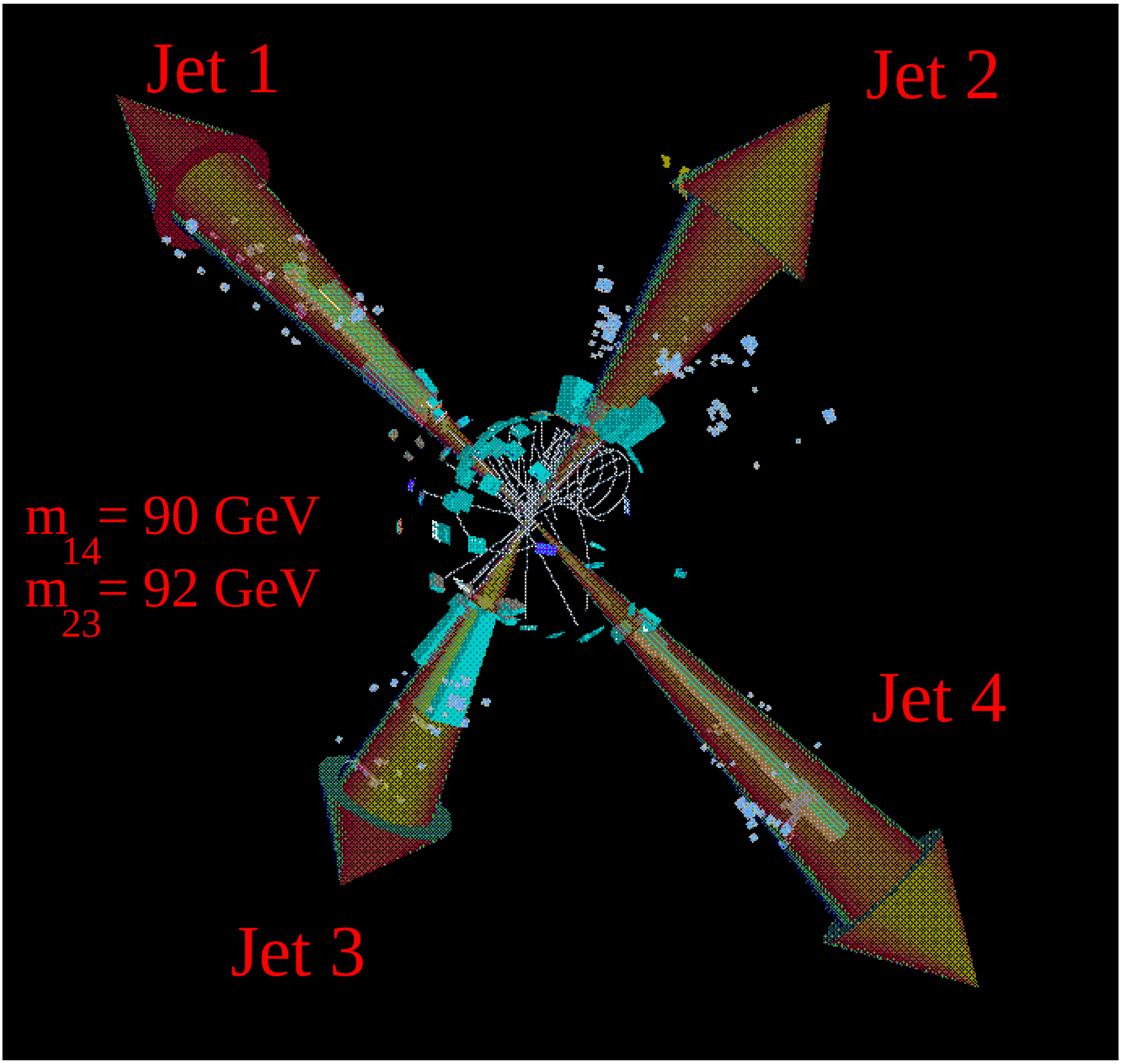
Kinematics at 183 GeV different from 189 GeV one ($m_Z = 91$ GeV) $\Longrightarrow$ design two different analyses.



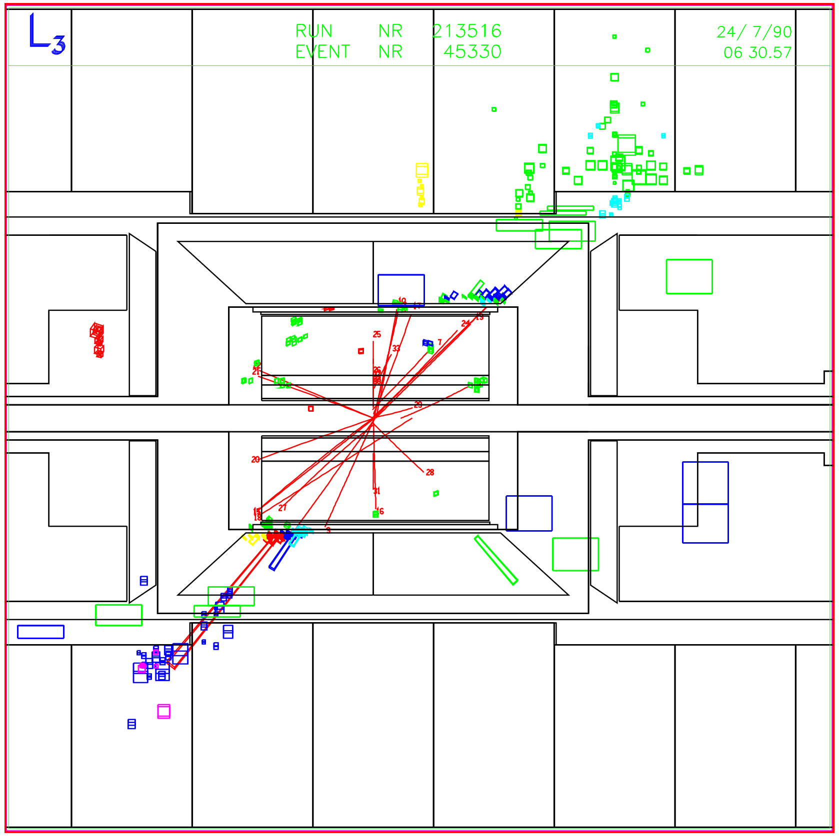

L3
data
ZZ→l⁺l⁻q q̄
background
Events / 2 GeV
M5C (GeV)
0
1
2
3
70
75
80
85
90

$e^+e^- \rightarrow ZZ$ @ 183 GeV



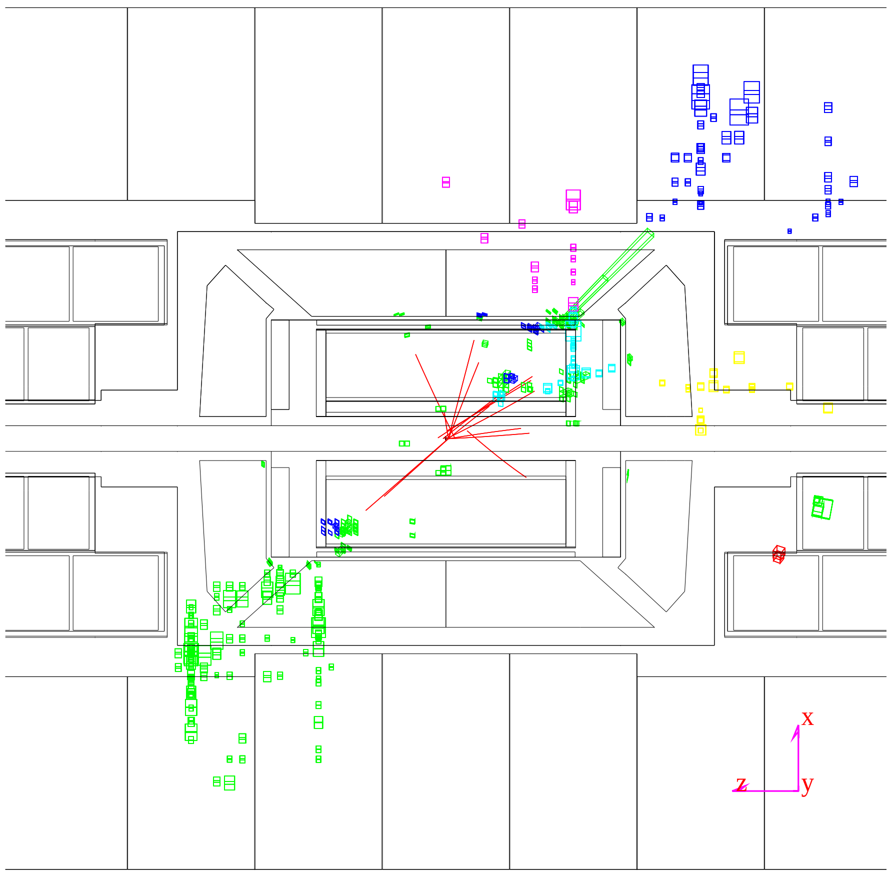

Jet 1
Jet 2
Jet 3
Jet 4
m 14 = 90 GeV
m 23 = 92 GeV

$e^+e^- \rightarrow Z \rightarrow q\bar{q}$ @ 91 GeV

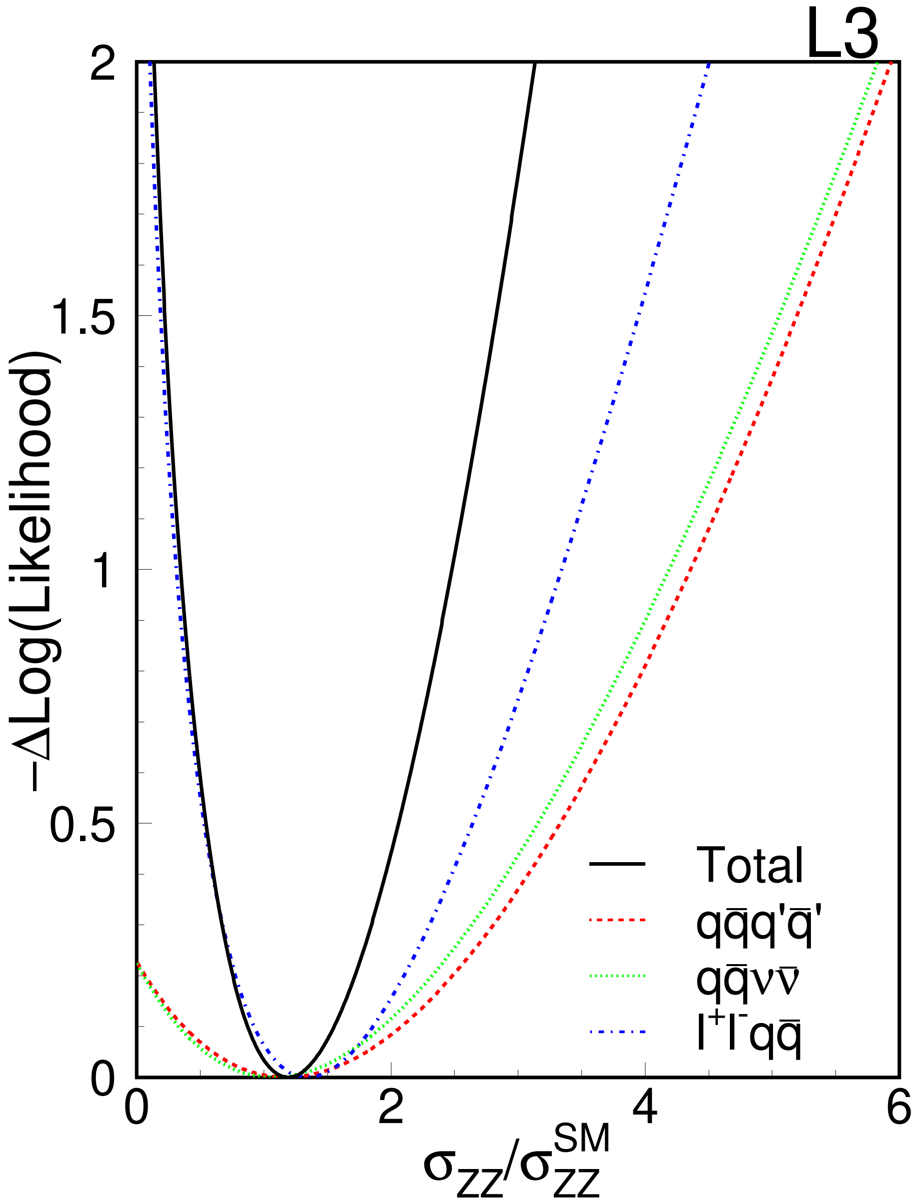


$e^+e^- \rightarrow ZZ \rightarrow q\bar{q}\nu\bar{\nu}$ @ 183 GeV

Run # 671506 Event # 1534 DAQ Time: 03-08-1997 15:18:18



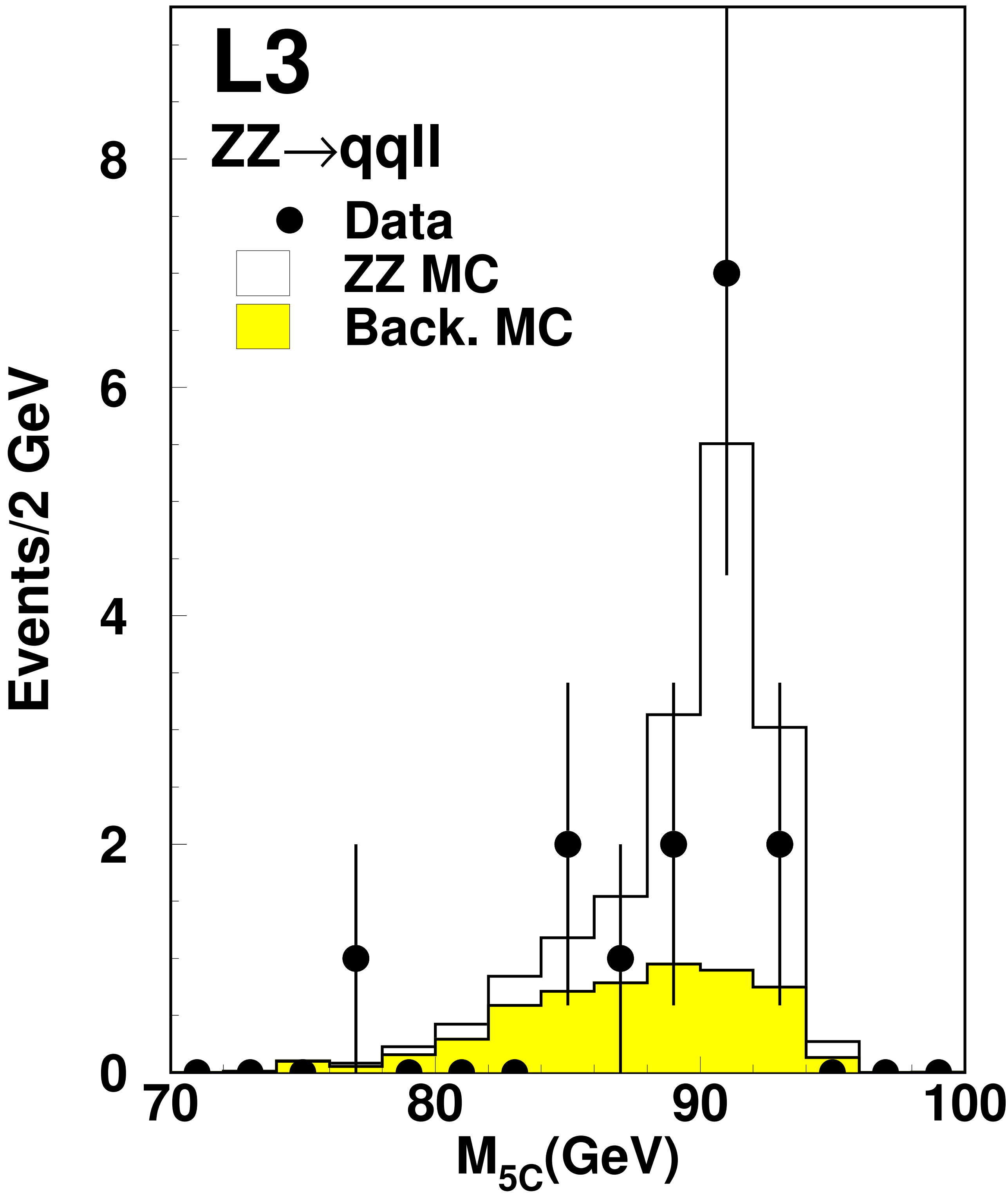
$e^+e^- \rightarrow ZZ \rightarrow q\bar{q}\nu\bar{\nu}$ @ 183 GeV



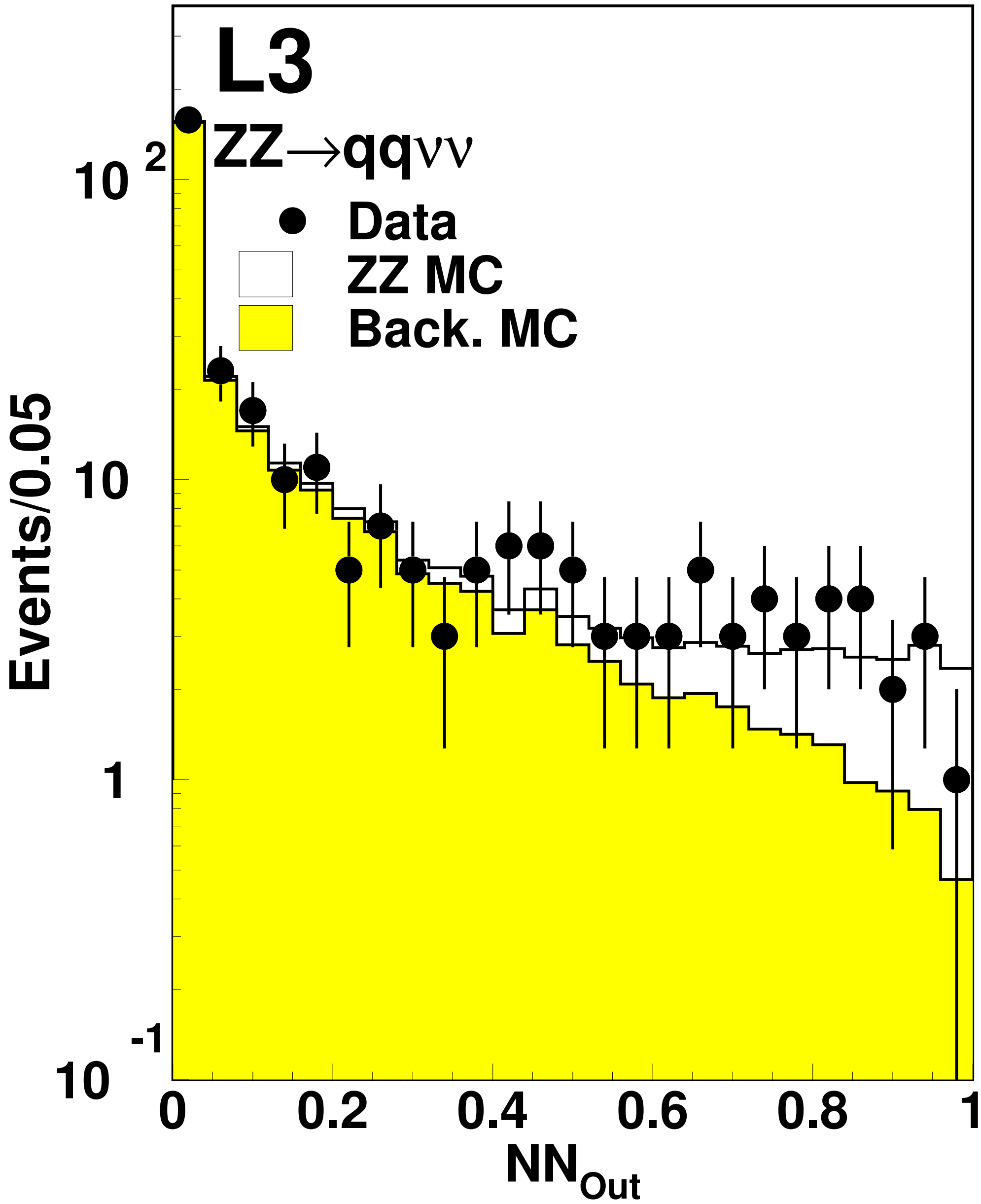
Observation of the ZZ threshold production
L3 Collab. Phys. Lett. B 450 (1999) 281.

$$\sigma_{ZZ}(183\text{ GeV}) = 0.30^{+0.22}_{+0.16}{}^{+0.07}_{+0.03}\,\text{pb}$$

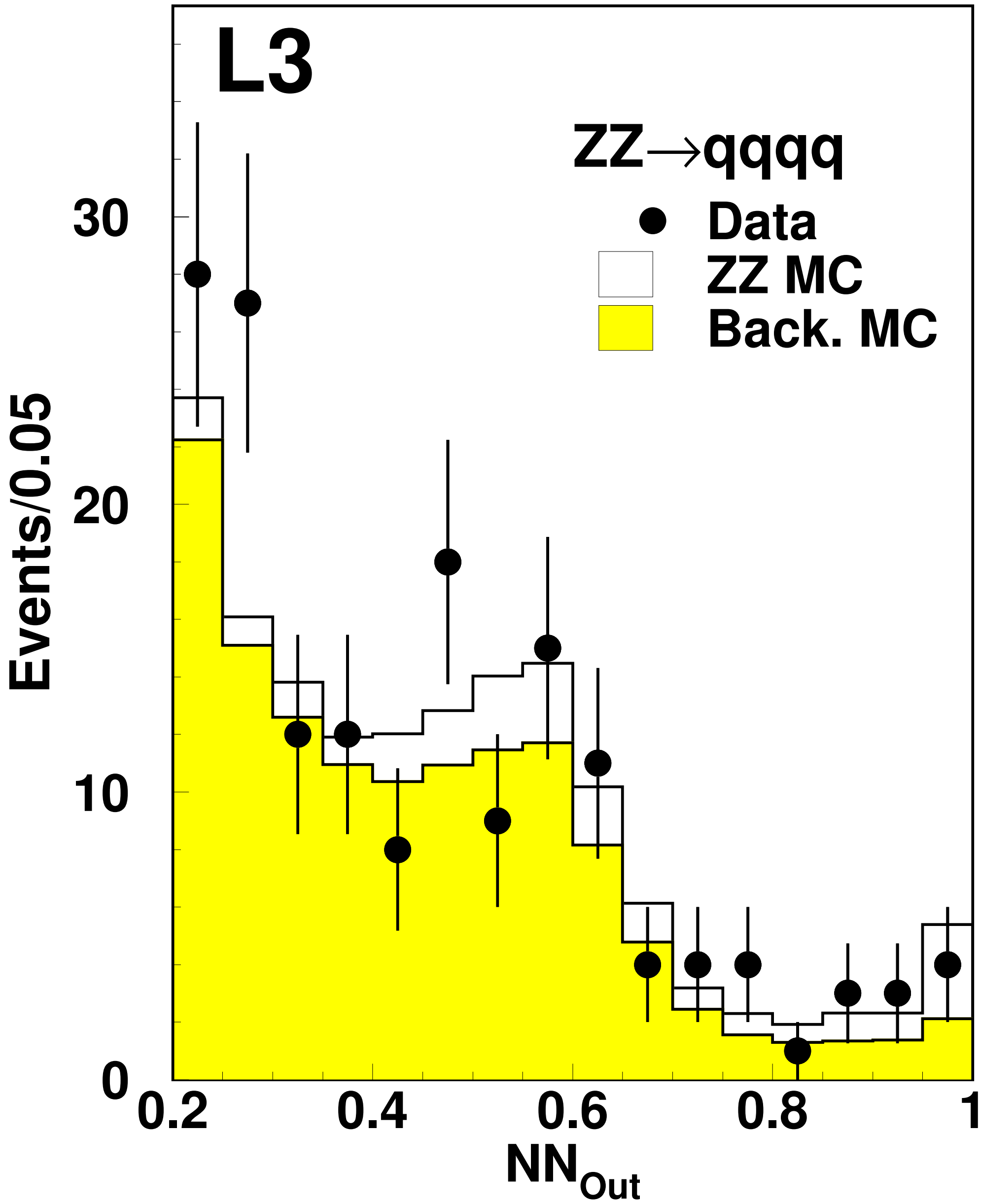
$$\sigma_{ZZ}^{SM}(183\text{ GeV}) = 0.25\,\text{pb}$$



L3
ZZ→qqll
Data
ZZ MC
Back. MC
Events/2 GeV
0
2
4
6
8
70
80
90
100
M5C(GeV)

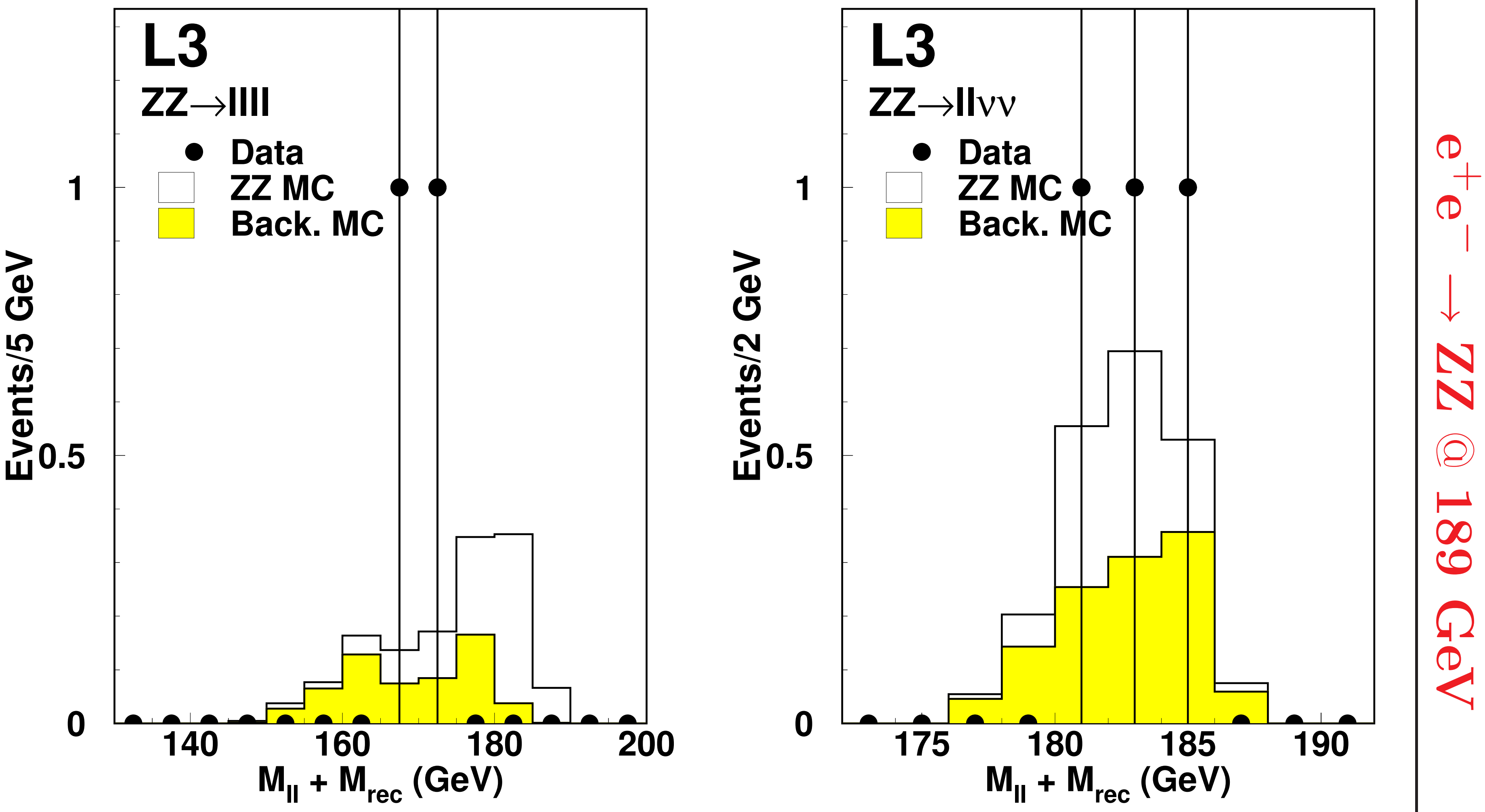


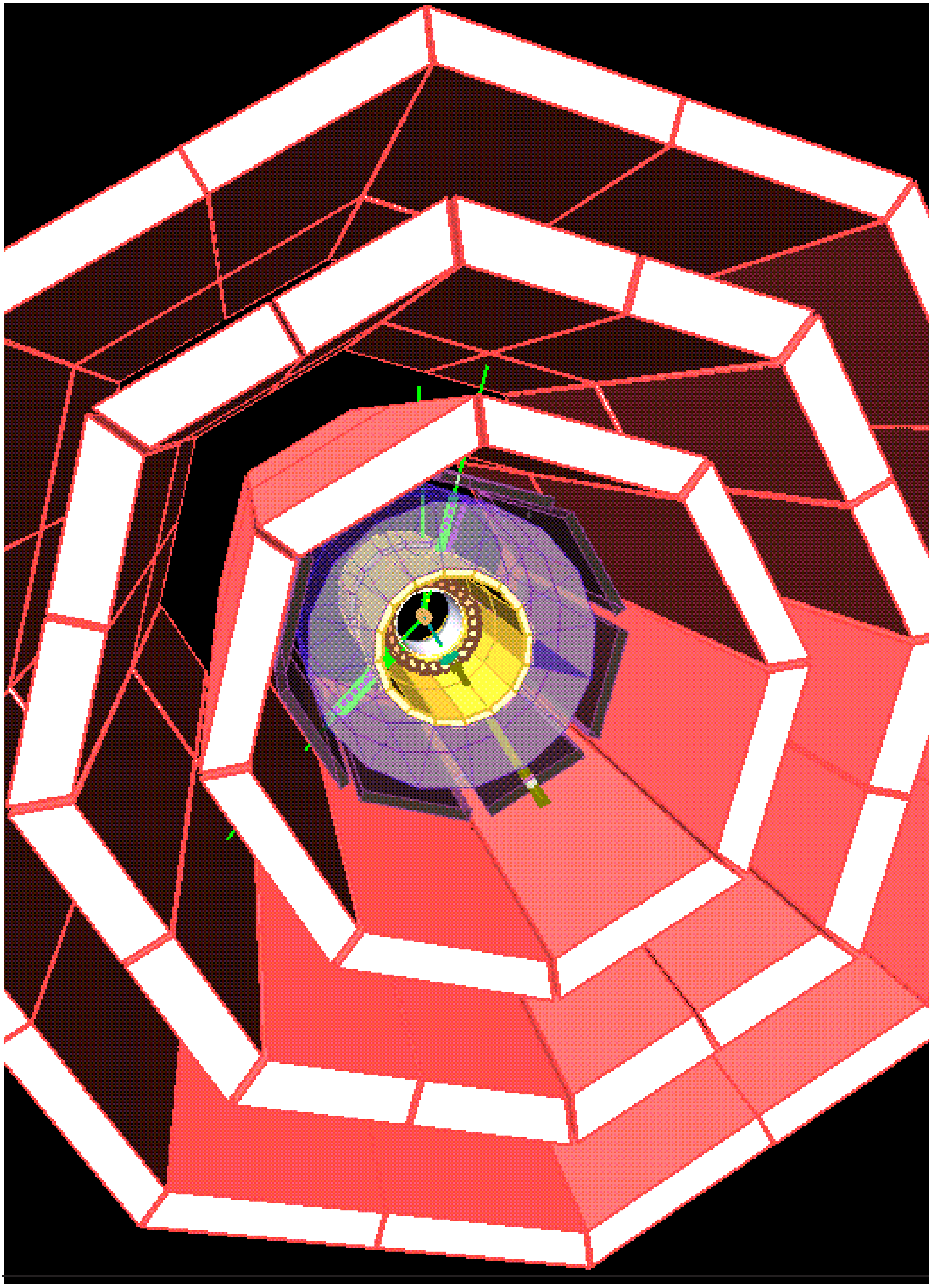
- Event shape variables
- Invariant and missing masses
- Missing momentum

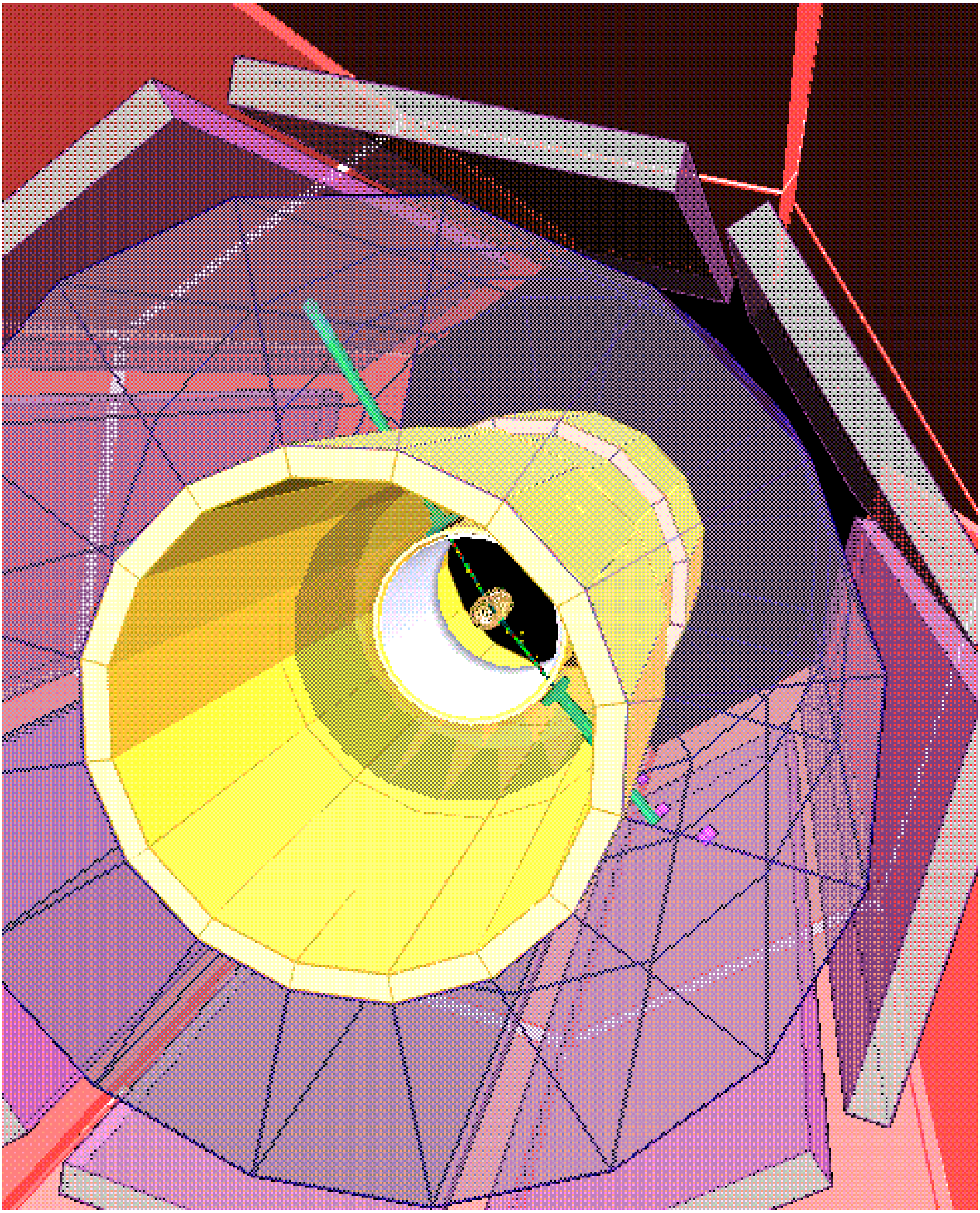


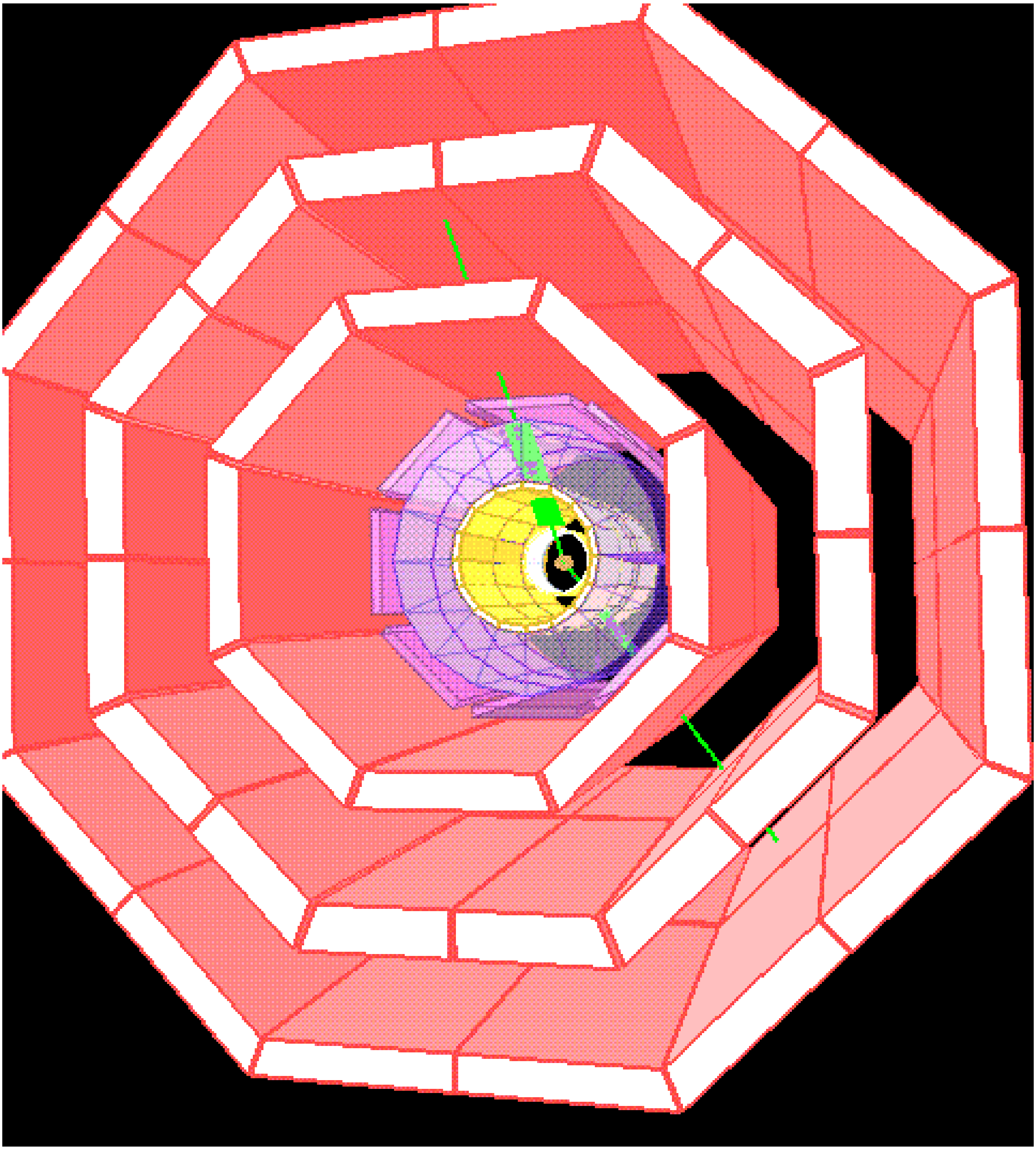
- **First Neural Net for 2–jets *vs.* 4–jets**
- **Dijet masses and mass difference**
- **b–tag**

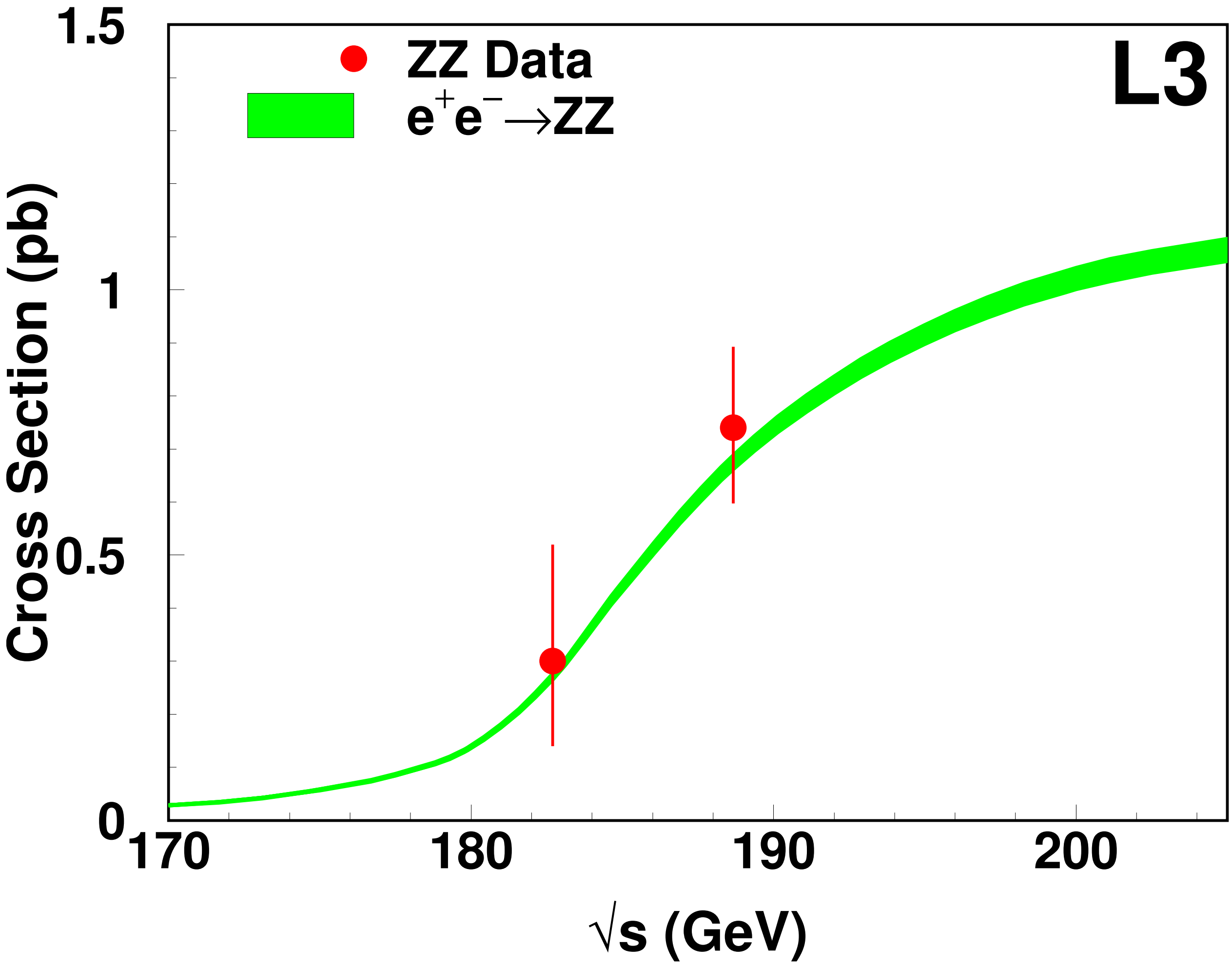
$e^+e^- \to ZZ$ @ 189 GeV







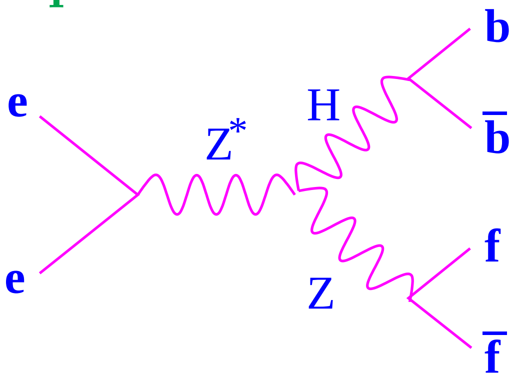




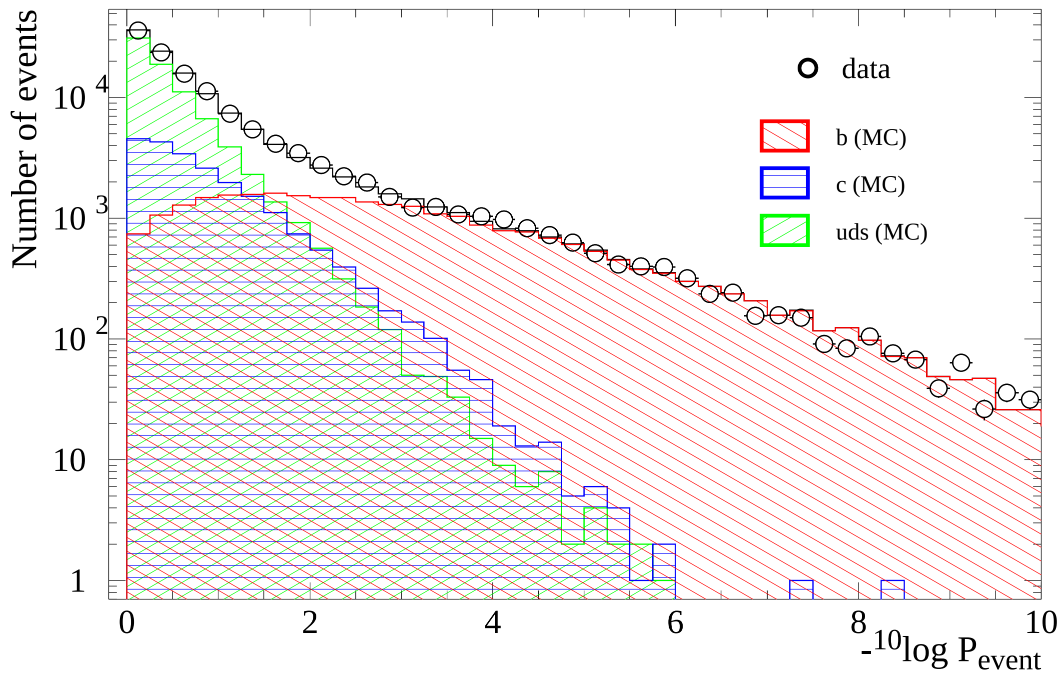
$\sqrt{s}$	$\sigma_{e^+e^-\rightarrow ZZ}$	$\sigma^{SM}_{e^+e^-\rightarrow ZZ}$
183 GeV	$0.30^{+0.22+0.07}_{-0.16-0.03}$ pb	0.25 pb
189 GeV	$0.74^{+0.15}_{-0.14} \pm 0.04$ pb	0.66 pb

L3 Collab. hep-ex/9909043.

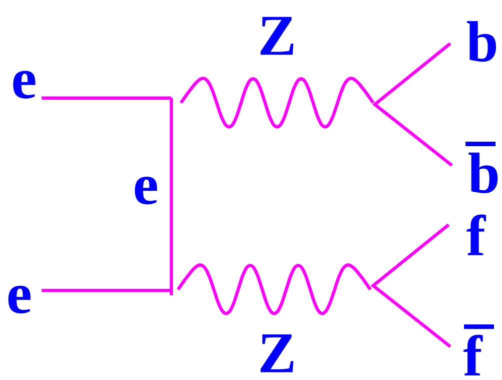
The boson pair production we are dreaming of:

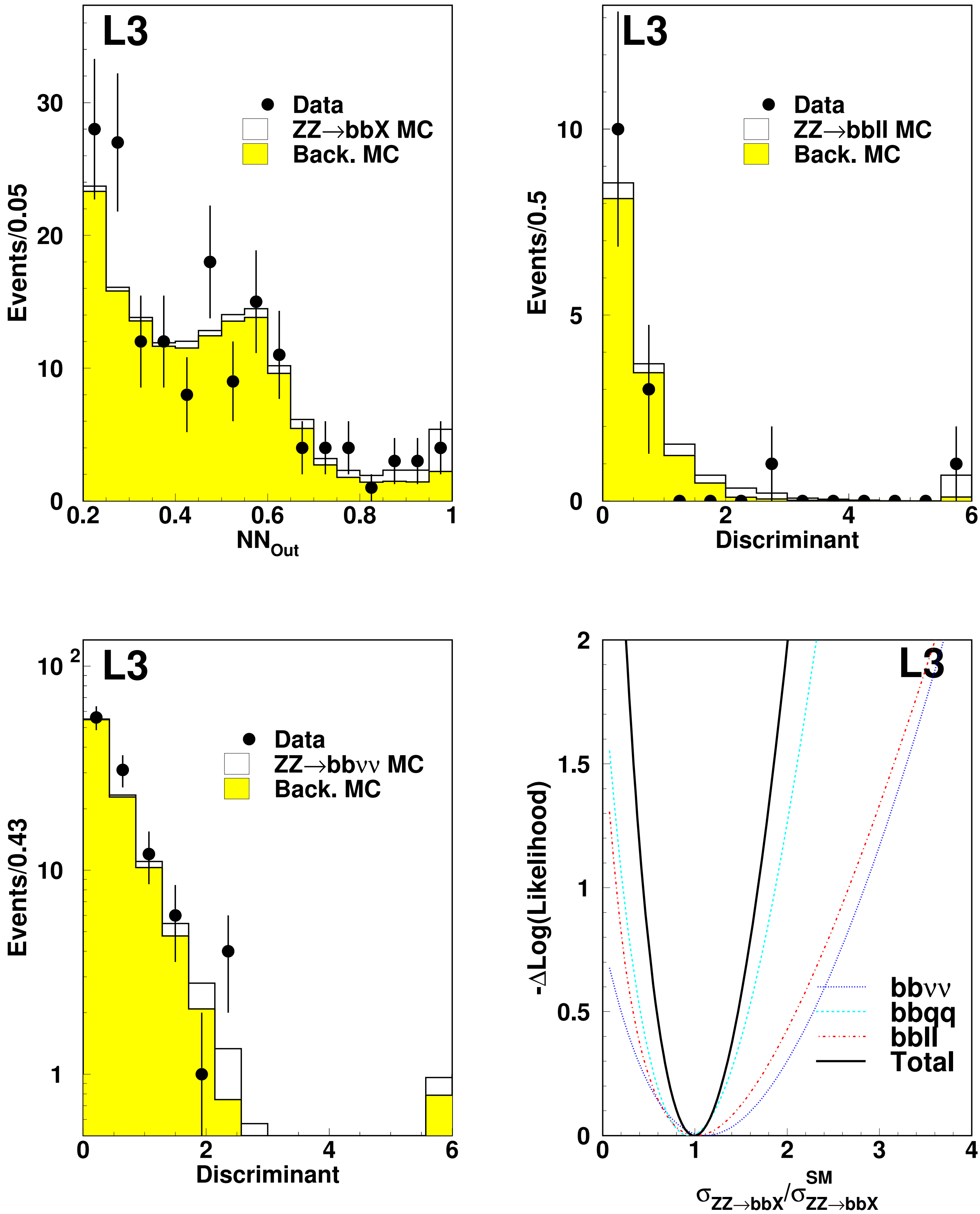


Separate the b quarks with:

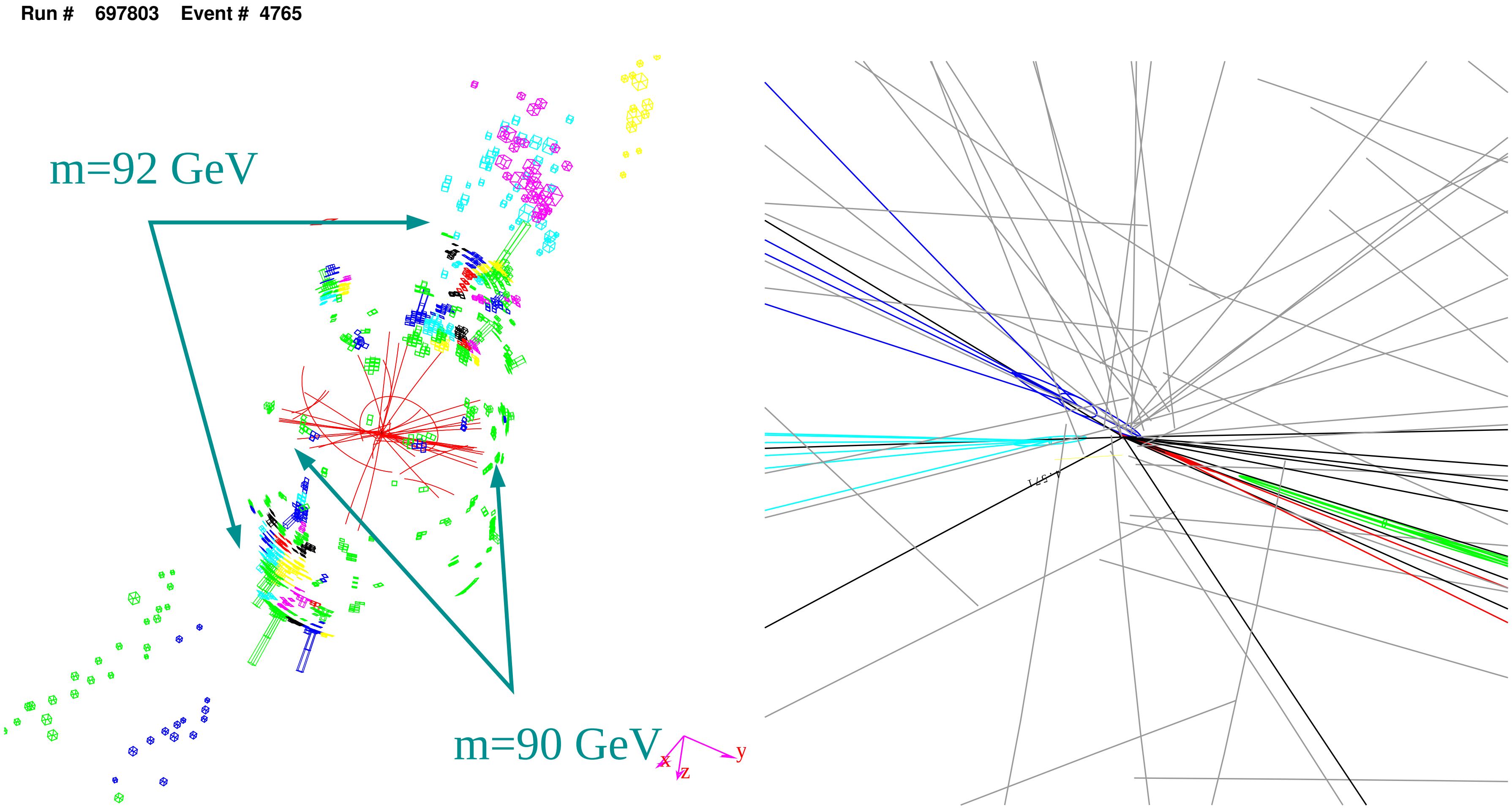


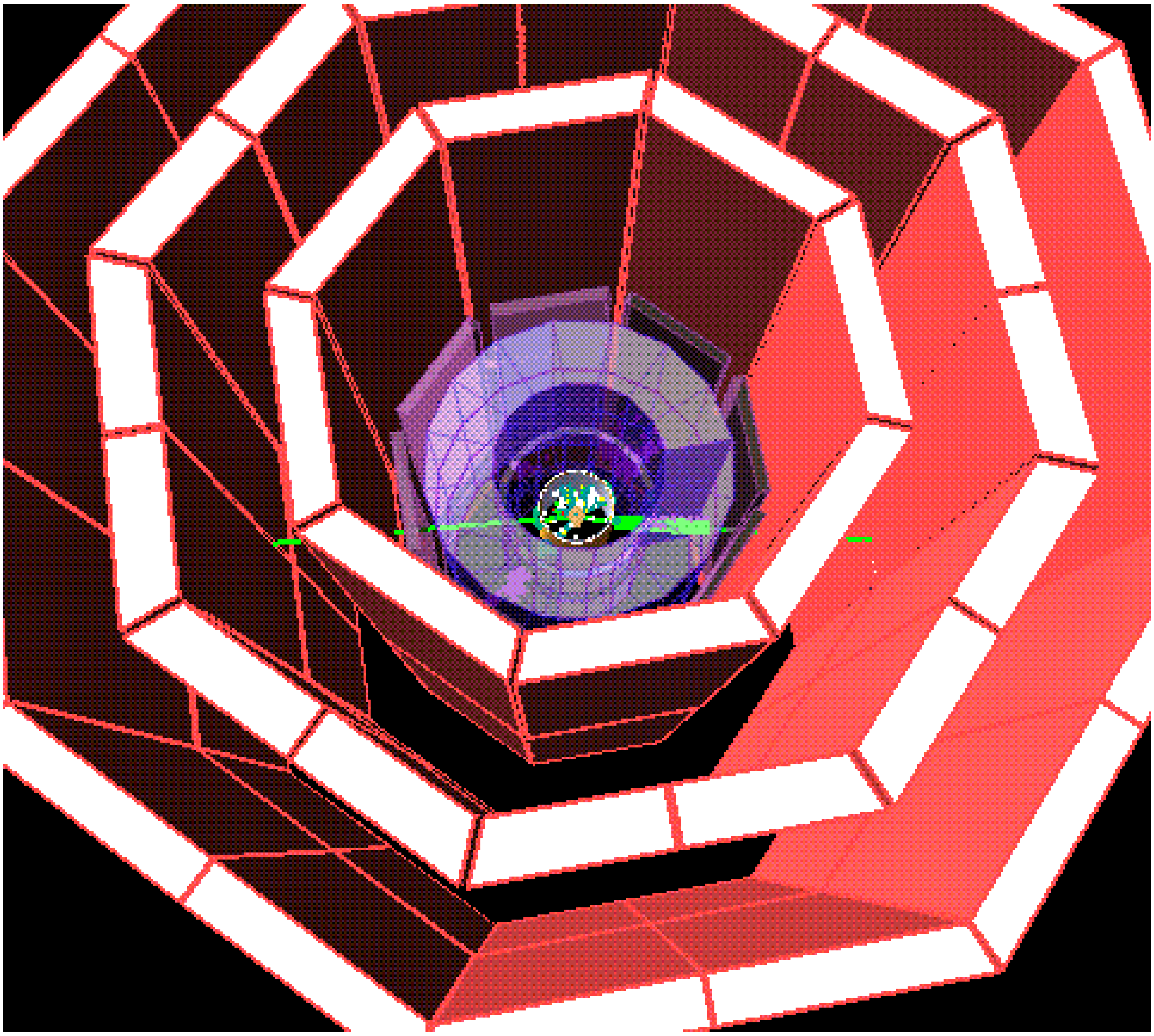
Can we actually see it? Yes if we can see:

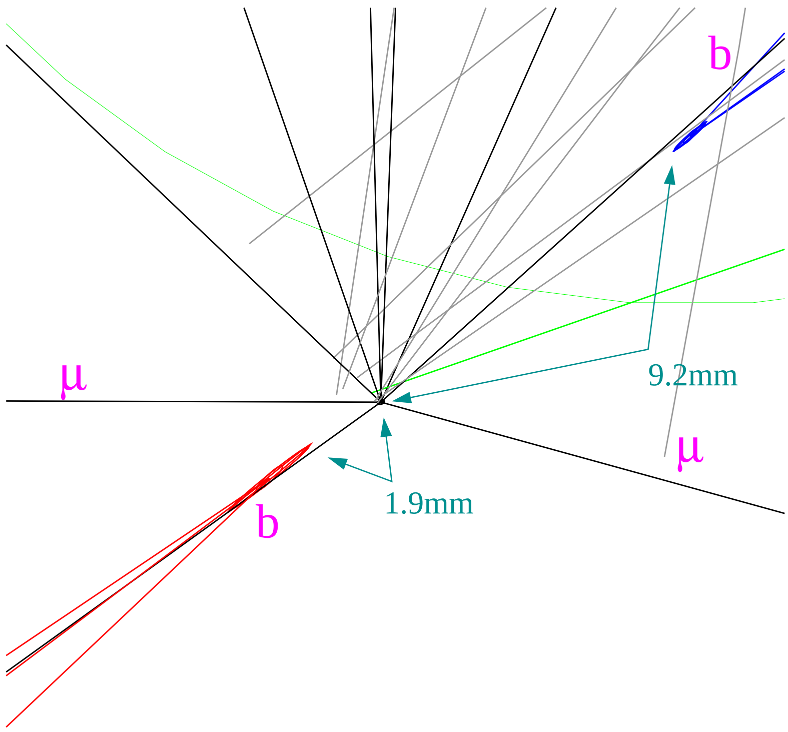



L3
Events/0.05
Data
ZZ→bbX MC
Back. MC
NN$_{Out}$
L3
Events/0.5
Data
ZZ→bbll MC
Back. MC
Discriminant
L3
Events/0.43
Data
ZZ→bbνν MC
Back. MC
Discriminant
L3
-ΔLog(Likelihood)
bbνν
bbqq
bbll
Total
$\sigma_{ZZ\to bbX}/\sigma^{SM}_{ZZ\to bbX}$

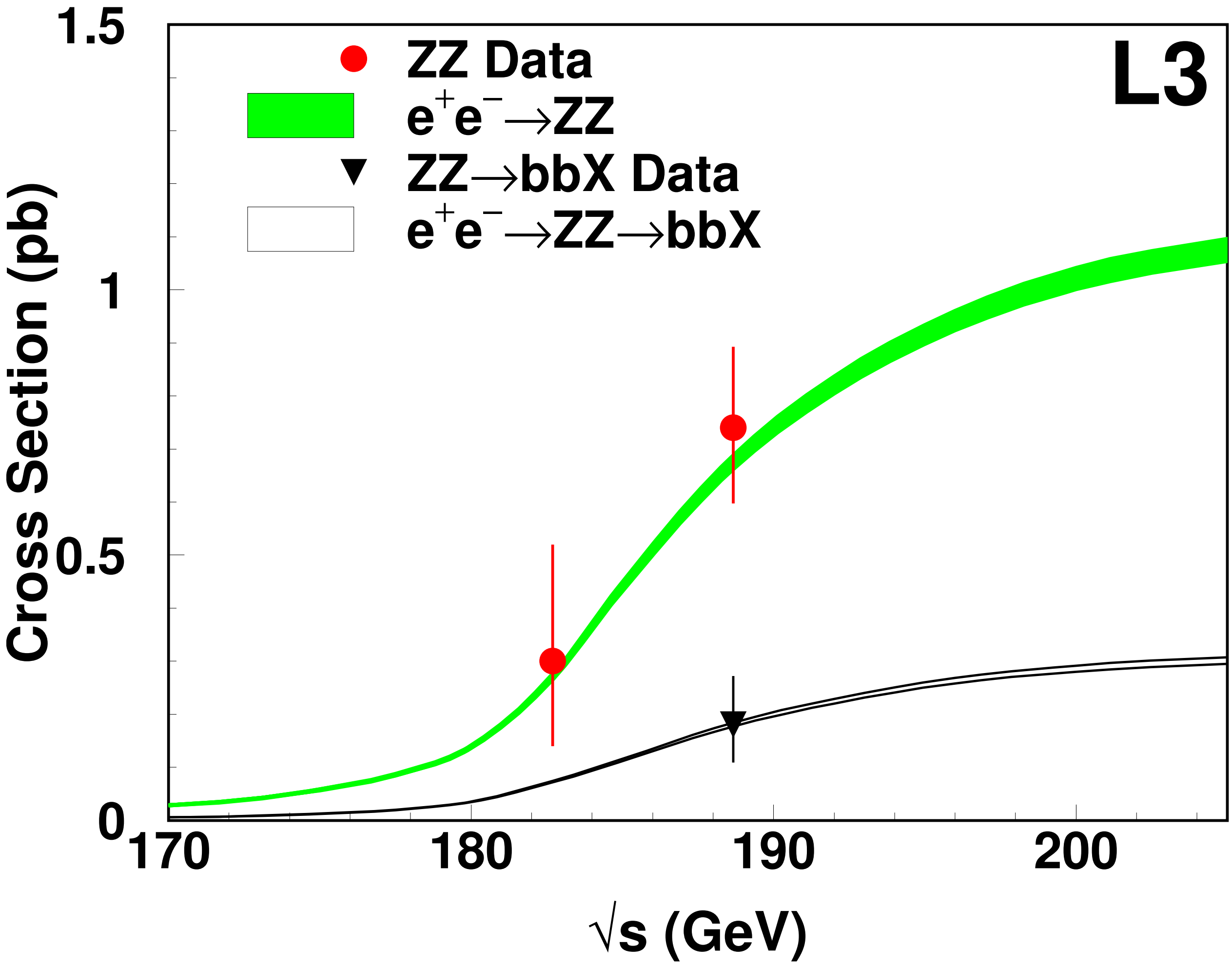
$e^+e^- \rightarrow ZZ \rightarrow q\bar{q}b\bar{b}$ @ 189 GeV






b
μ
9.2mm
μ
1.9mm
b

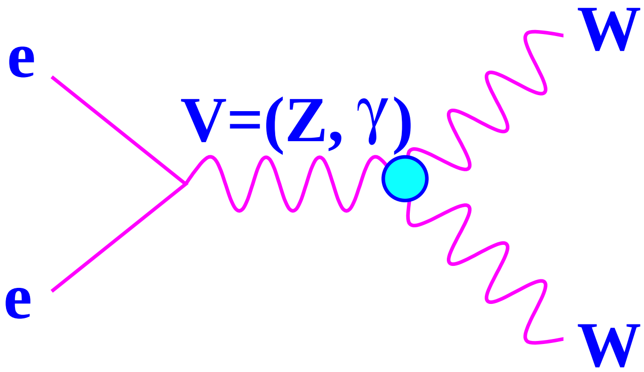
$ZZ \rightarrow b\bar{b}X$ Cross Section



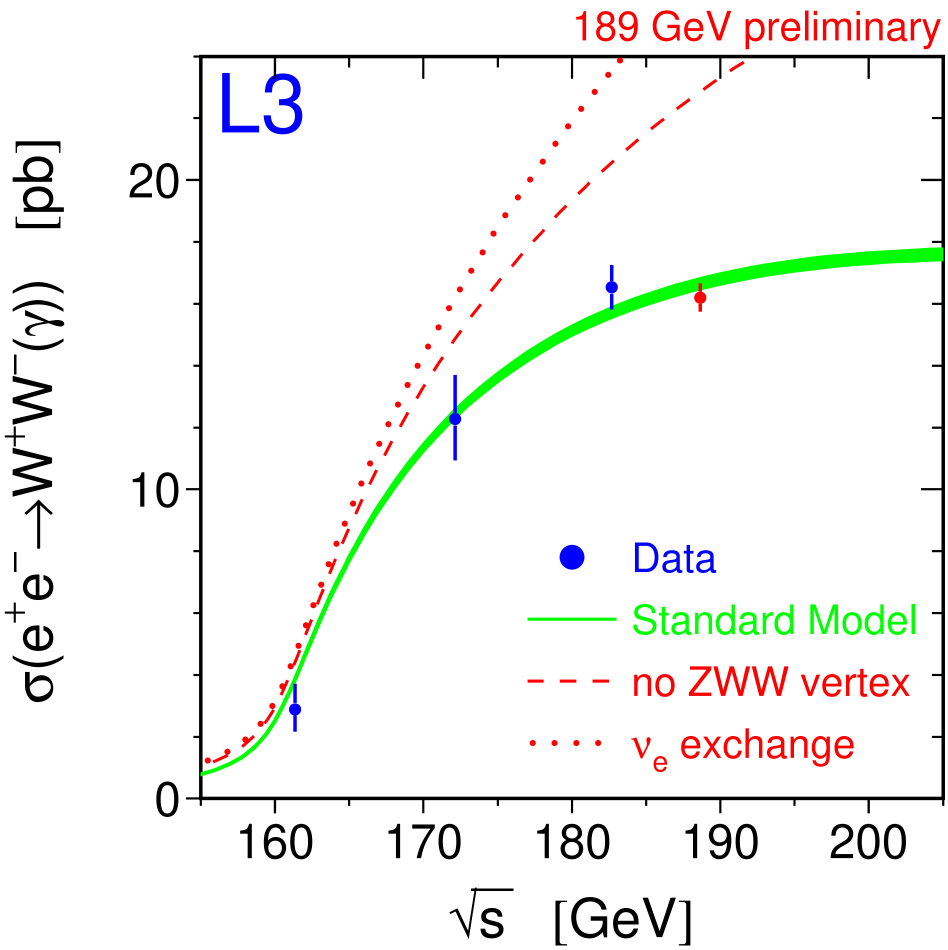
$\sqrt{s}$	$\sigma_{e^+e^- \rightarrow ZZ}$	$\sigma^{SM}_{e^+e^- \rightarrow ZZ}$
183 GeV	$0.30^{+0.22}_{-0.16}{}^{+0.07}_{-0.03}$ pb	0.25 pb
189 GeV	$0.74^{+0.15}_{-0.14} \pm 0.04$ pb	0.66 pb
$\sqrt{s}$	$\sigma_{ZZ \rightarrow b\bar{b}X}$	$\sigma^{SM}_{ZZ \rightarrow b\bar{b}X}$
189 GeV	$0.18^{+0.09}_{-0.07} \pm 0.02$ pb	0.18 pb

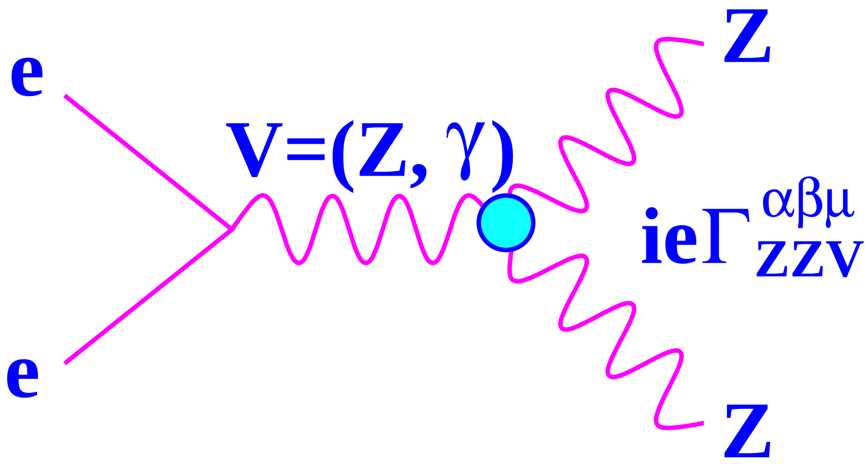
L3 Collab. hep-ex/9909043.

Triple Gauge Boson Vertices



The existence of the triple vertices γWW and ZWW is confirmed: the Standard Model is a non Abelian theory.





$$\Gamma^{\alpha\beta\mu}_{ZZV}(q_1, q_2, P) = \frac{s - m_V^2}{m_Z^2} \times$$

$$[i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho]$$

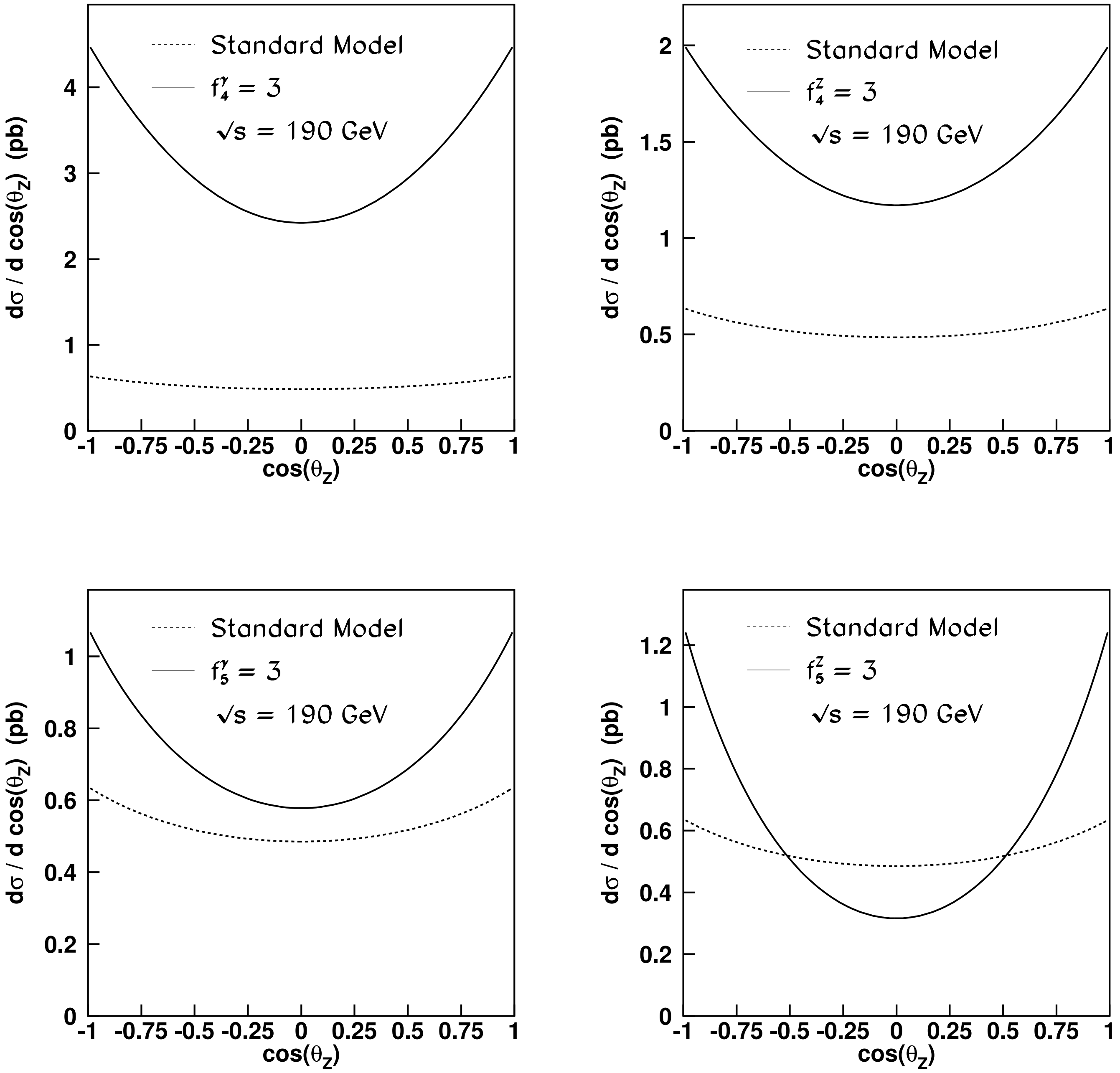
K. Hagiwara *et al.* Nucl. Phys. **B282** (1987) 253
G. Gounaris *et al.* hep-ph/9910395.

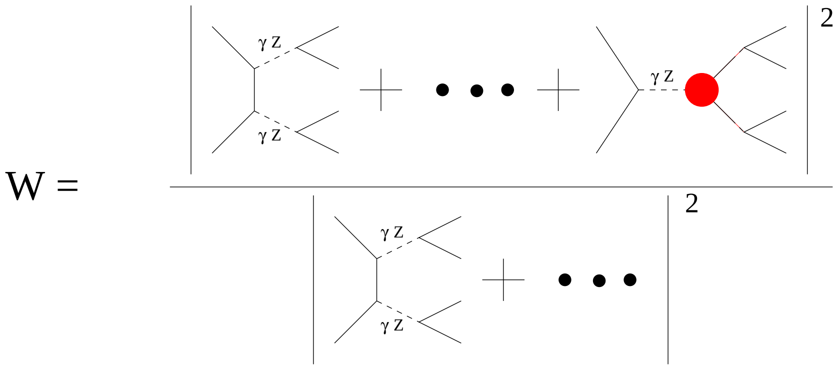
f_4^V violates CP; f_5^V conserves CP

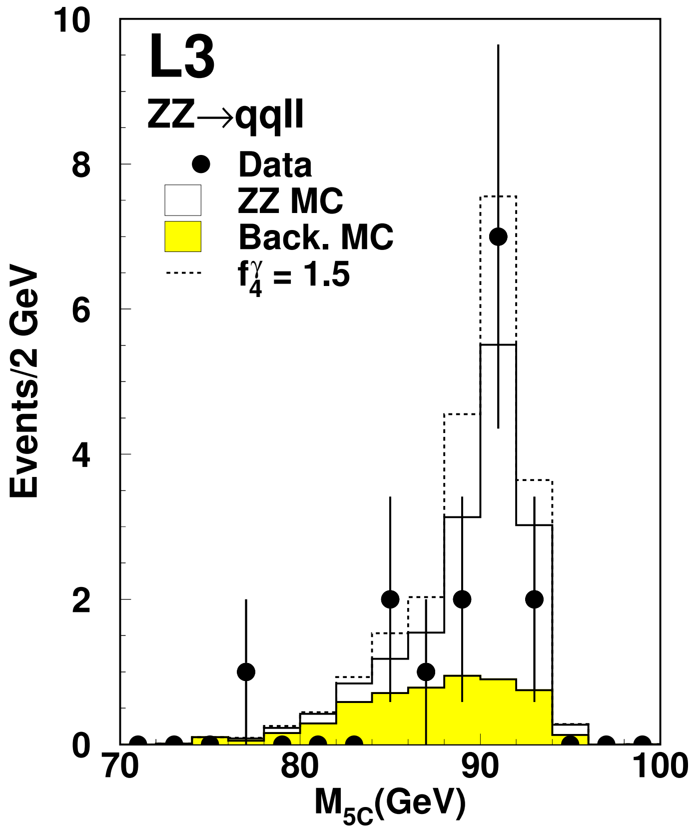
Complex couplings but New Physics will manifest in the real part first: neglect the imaginary one.

Triple Neutral Gauge Boson Vertex?

J. Alcaraz *et al.* hep-ph/9812435.







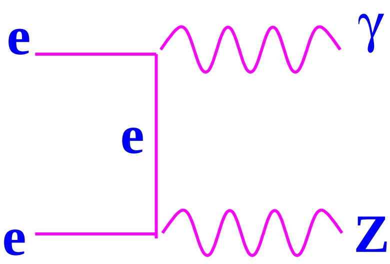
At 95% C.L.:

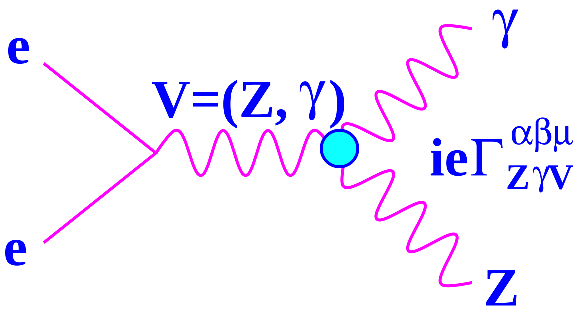
$-1.9 < f_4^Z < 1.9$	$-5.0 < f_5^Z < 4.5$
$-1.1 < f_4^\gamma < 1.2$	$-3.0 < f_5^\gamma < 2.9$

Including 183 GeV data

One Photon and One Z

Neutral Boson Couplings ?





$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1, q_2, P) = i\frac{s - m_V^2}{m_Z^2}\times$$

$$[h_1^V(q_2^\mu g^{\alpha\beta}) - q_2^\alpha g^{\mu\beta} + \frac{h_2^V}{m_Z^2}P^\alpha(P\cdot q_2\, g^{\mu\beta} - q_2^\mu P^\beta)$$

$$+h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}]$$

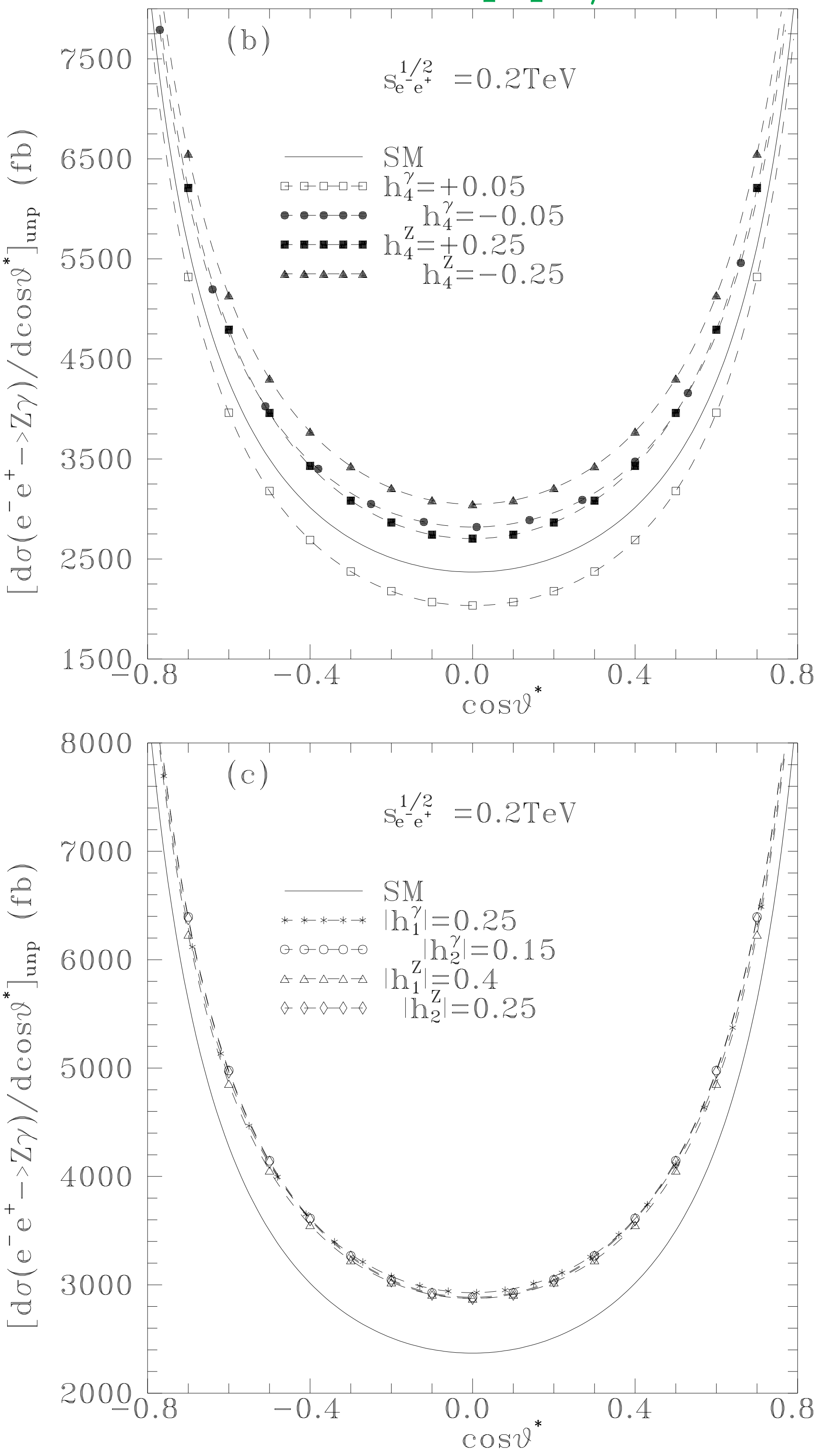
K. Hagiwara *et al.* Nucl. Phys. **B282** (1987) 253
G. Gounaris *et al.* hep-ph/9910395.

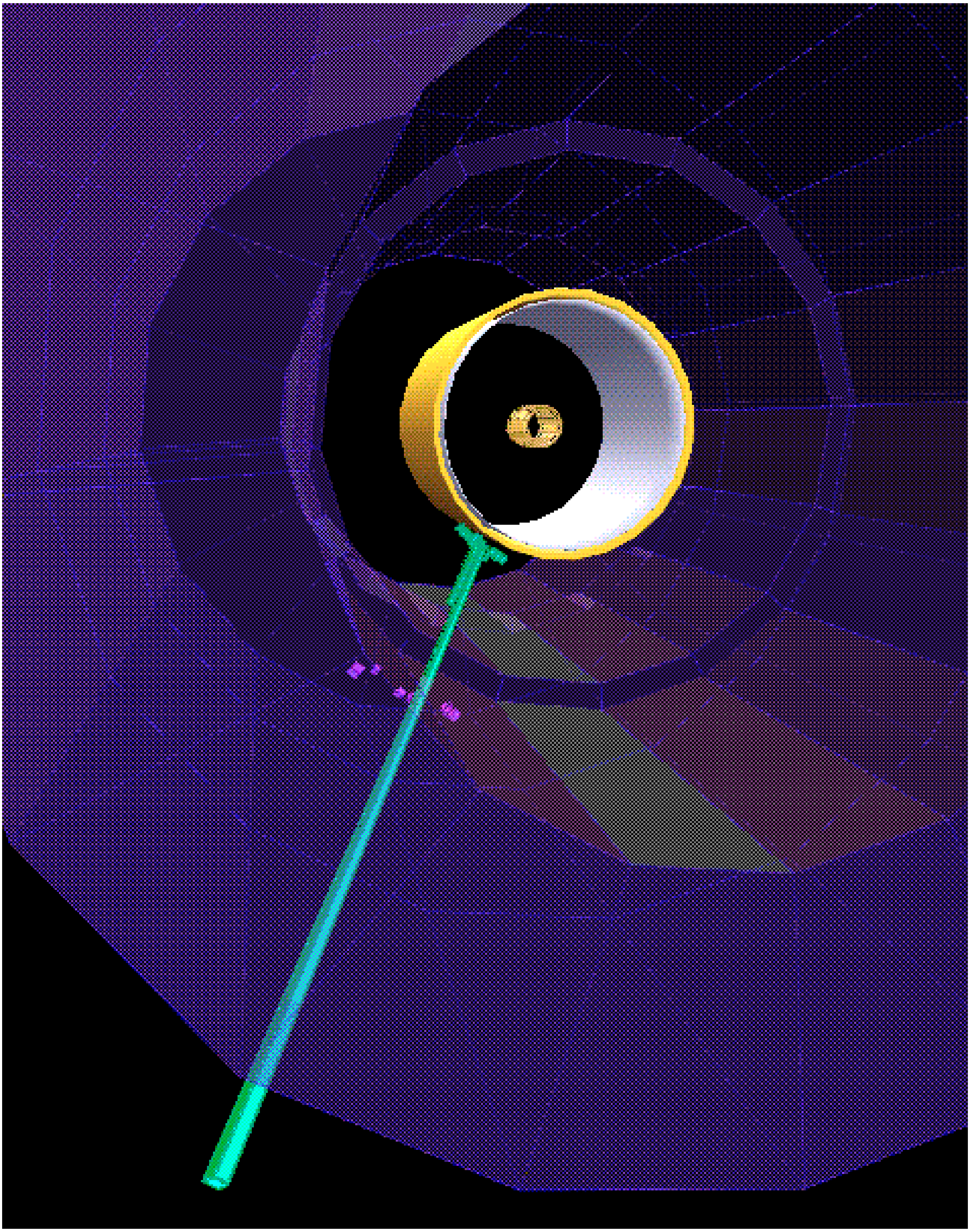
h_1^V, h_2^V Violate CP, 0 in SM
h_3^V, h_4^V Conserve CP, $\sim 10^{-4}$ in SM.

Restrict to the real part: where New Physics will show up first.

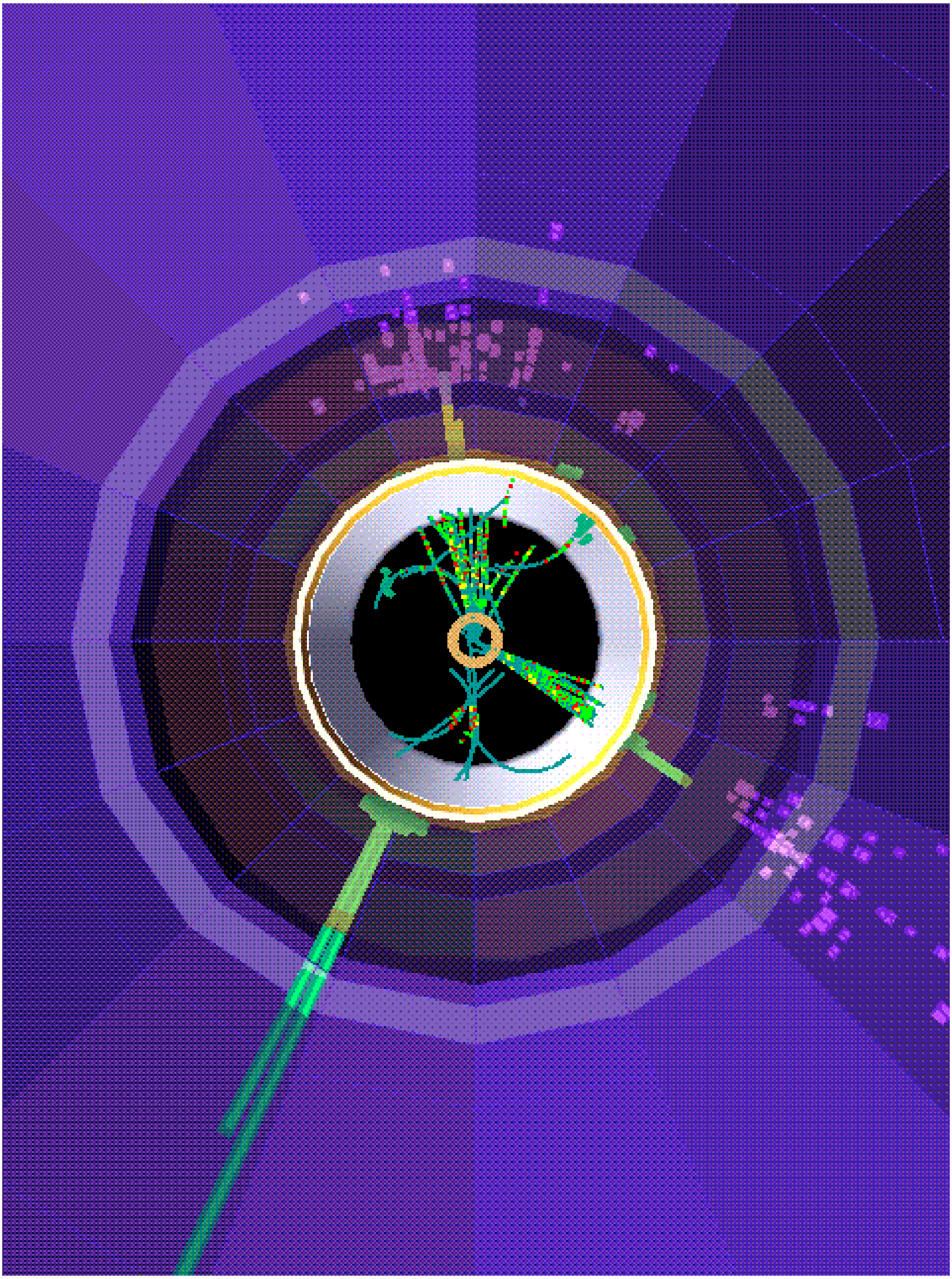
Neutral Boson Couplings ?

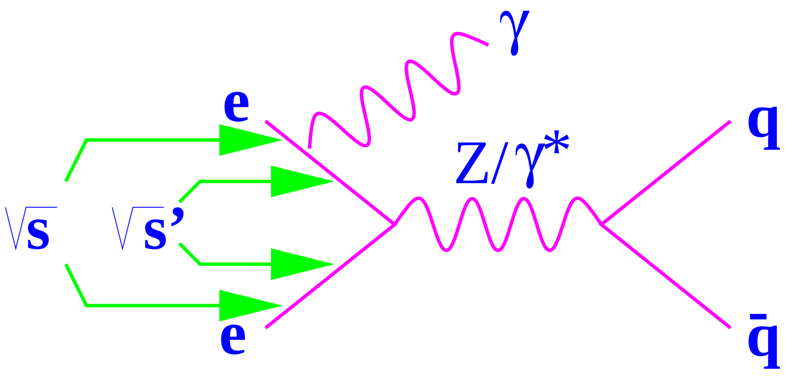
G. Gounaris *et al.* hep-ph/9910395.

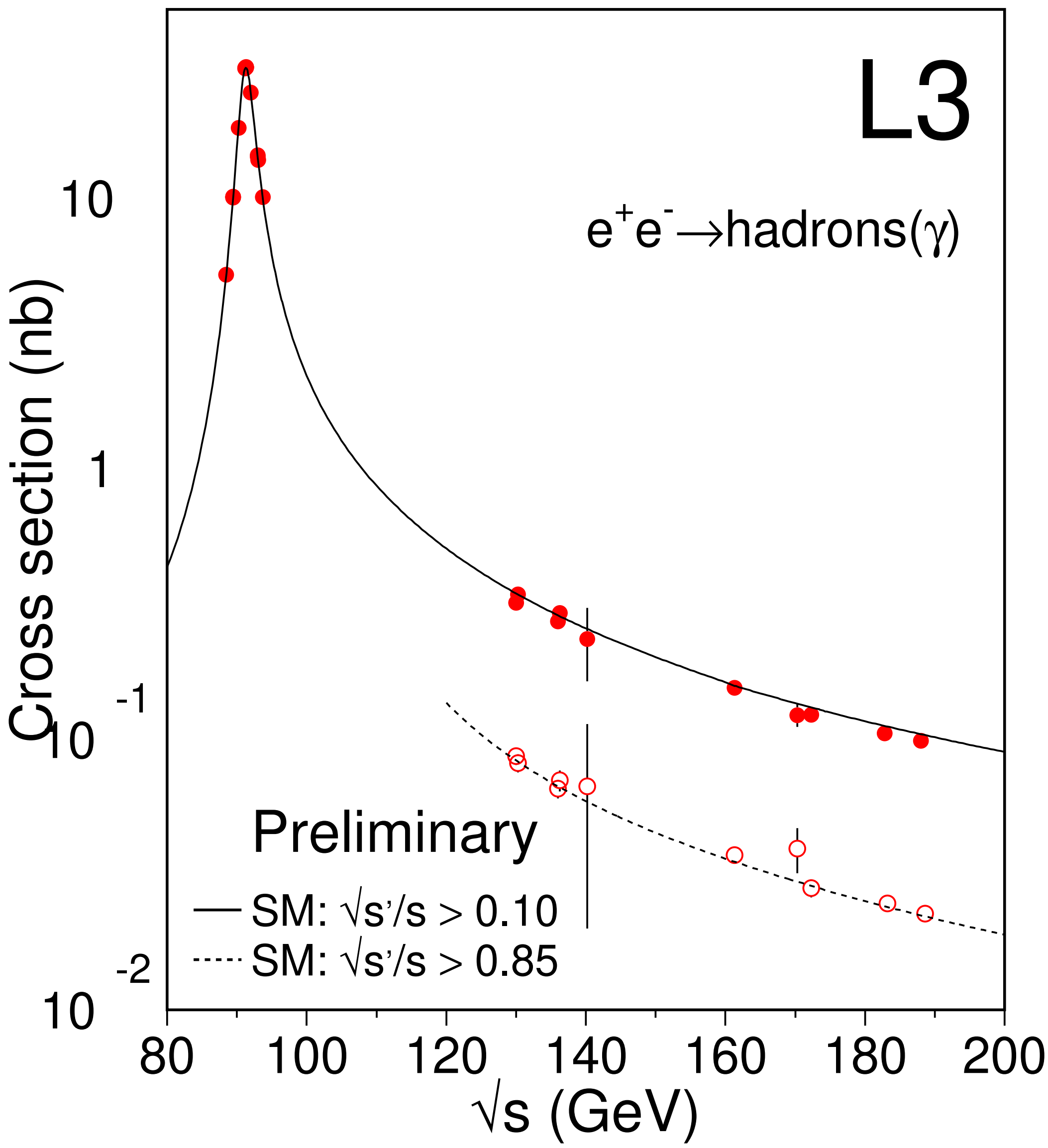




$e^+e^- \rightarrow Z \rightarrow q\bar{q}\gamma$

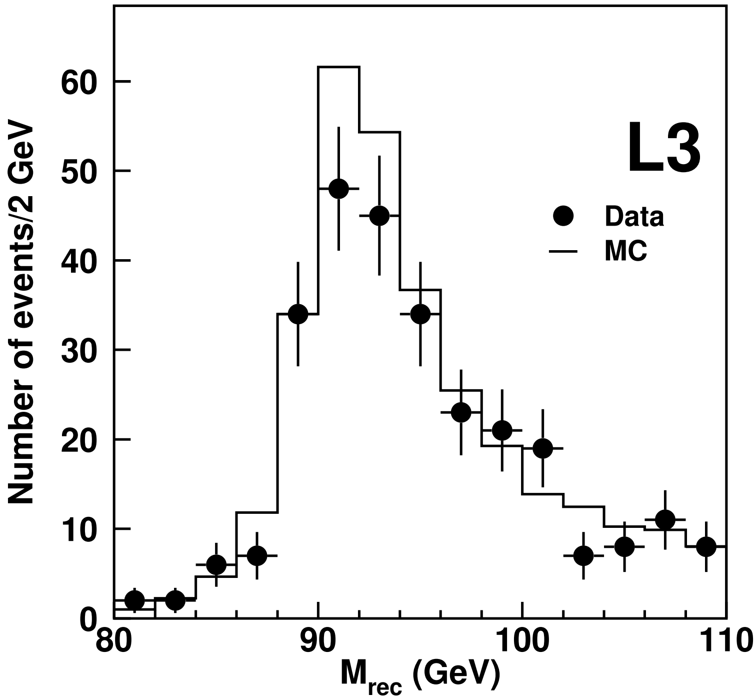



γ
e
q
Z/γ*
√s
√s'
e
q̄

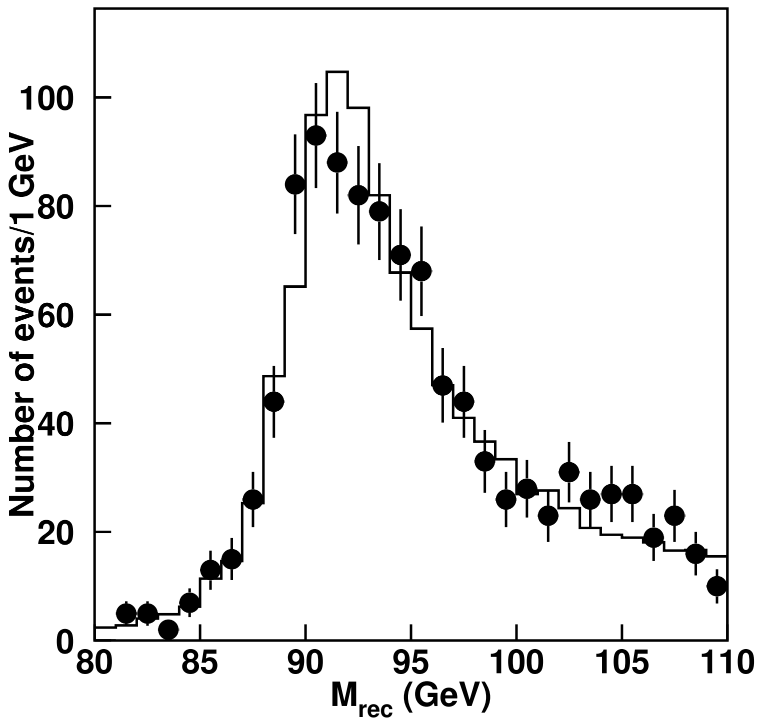

L3
e+e-→hadrons(γ)
Cross section (nb)
10
1
10-1
10-2
Preliminary
SM: √s'/s > 0.10
SM: √s'/s > 0.85
80
100
120
140
160
180
200
√s (GeV)

Photon Recoil Mass @ 189GeV

$$e^+e^- \rightarrow \gamma Z \rightarrow \gamma\nu\bar{\nu}$$



$$e^+e^- \rightarrow \gamma Z \rightarrow \gamma q\bar{q}$$

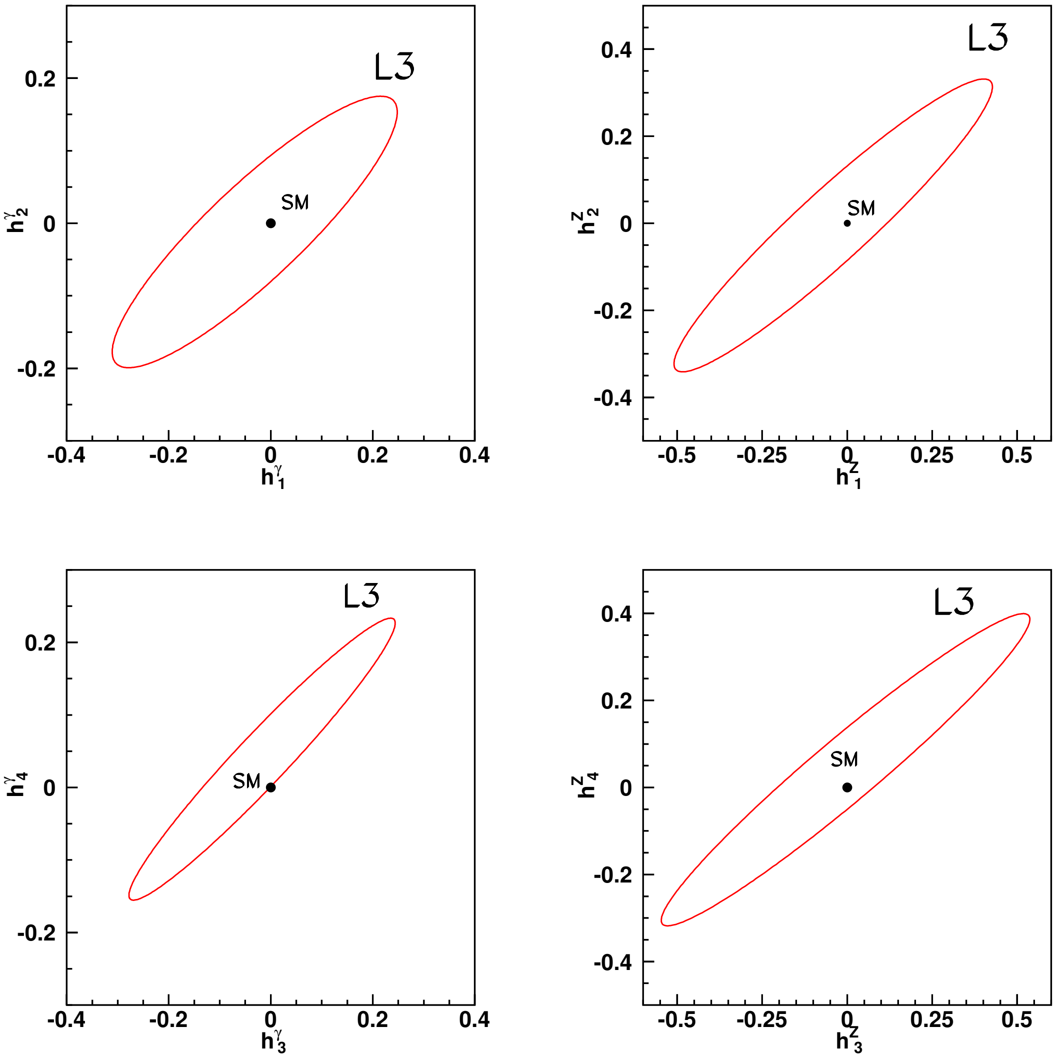


Limits on Anomalous Couplings

At 95% Confidence Level

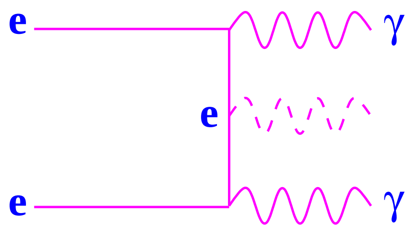
$$-0.16 < h_1^Z < 0.09 \qquad -0.12 < h_1^\gamma < 0.09$$
$$-0.07 < h_2^Z < 0.11 \qquad -0.06 < h_2^\gamma < 0.07$$
$$-0.22 < h_3^Z < 0.10 \qquad -0.12 < h_3^\gamma < 0.01$$
$$-0.06 < h_4^Z < 0.14 \qquad -0.01 < h_4^\gamma < 0.09$$

Two–parameter fits to couplings with the same CP–parity and exchanged boson



Update of:L3 Collab. Phys. Lett. **B 436** (1998) 187.

Two (or more) Photons



Process dominated by QED even at these high energies

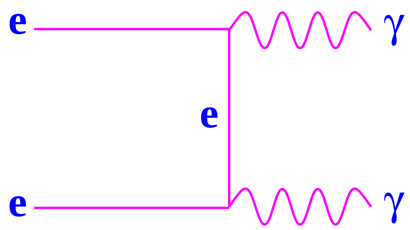
$$\frac{d\sigma(\mathrm{e^+e^-} \to \gamma\gamma)}{\mathrm{d}\cos\theta_\gamma} = \frac{2\alpha^2\pi}{s}\frac{(1+\cos^2\theta_\gamma)}{(1-\cos^2\theta_\gamma)}$$

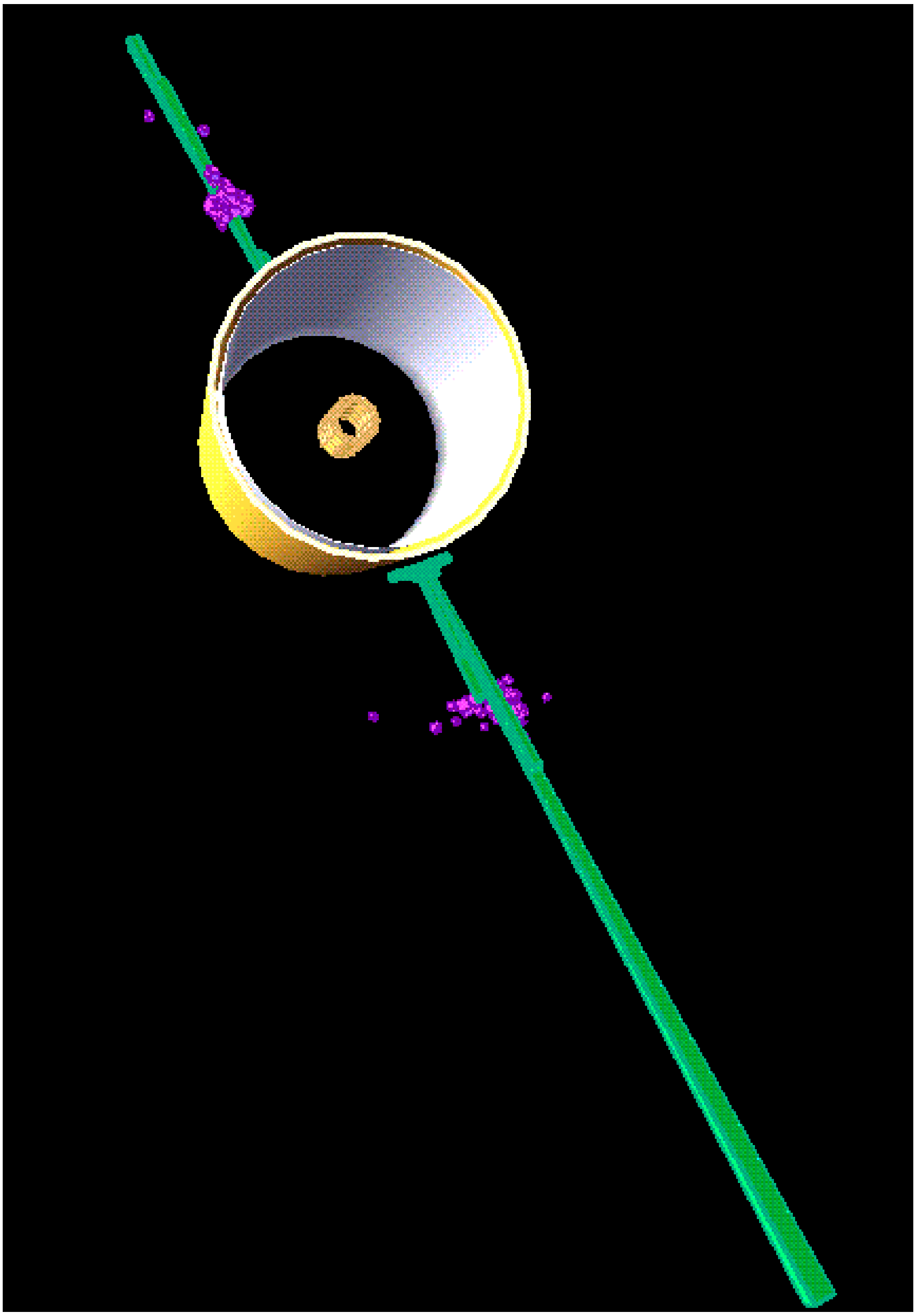
Fiducial volume:

$$14^\circ < \theta_\gamma < 166^\circ \text{ for } E_\gamma > 1\,\mathrm{GeV}$$

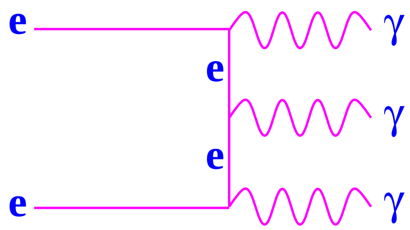
	$\sqrt{s} = 183\,\mathrm{GeV}$		$\sqrt{s} = 189\,\mathrm{GeV}$	
	Observed	Expected	Observed	Expected
$2\,\gamma$	436	453	1302	1345
$3\,\gamma$	23	24	72	69
$4\,\gamma$	1	0	0	0

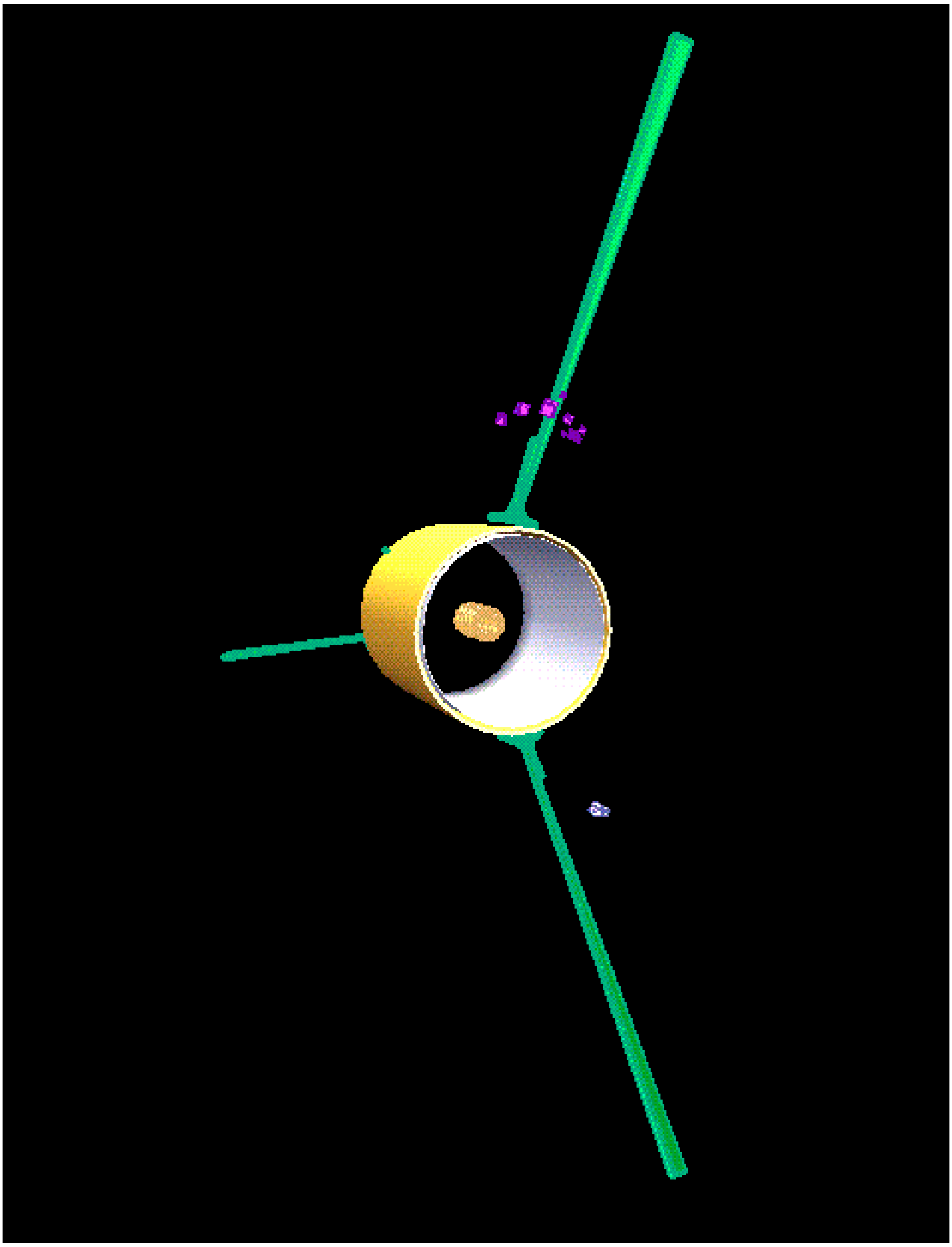
Two Photons

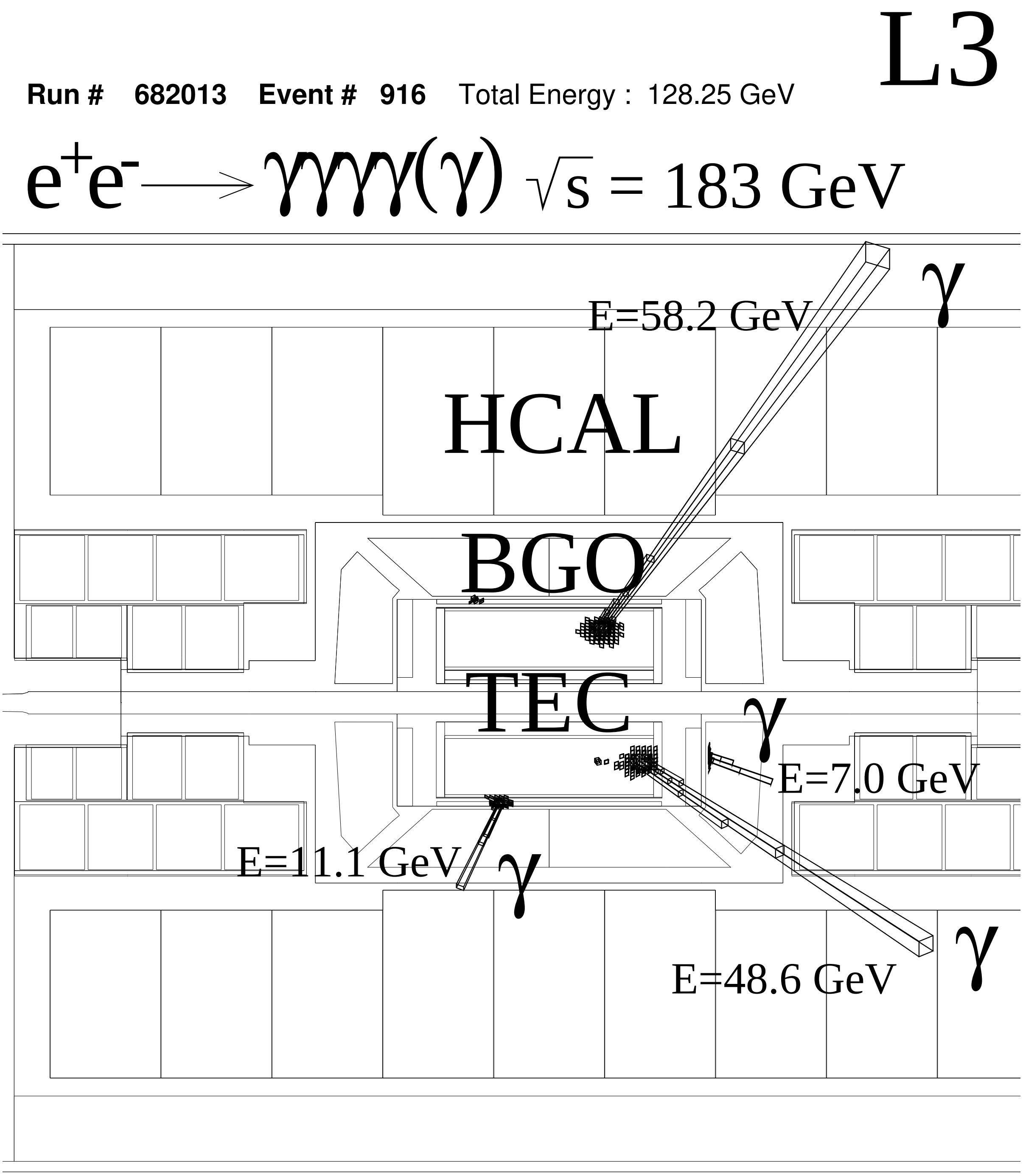




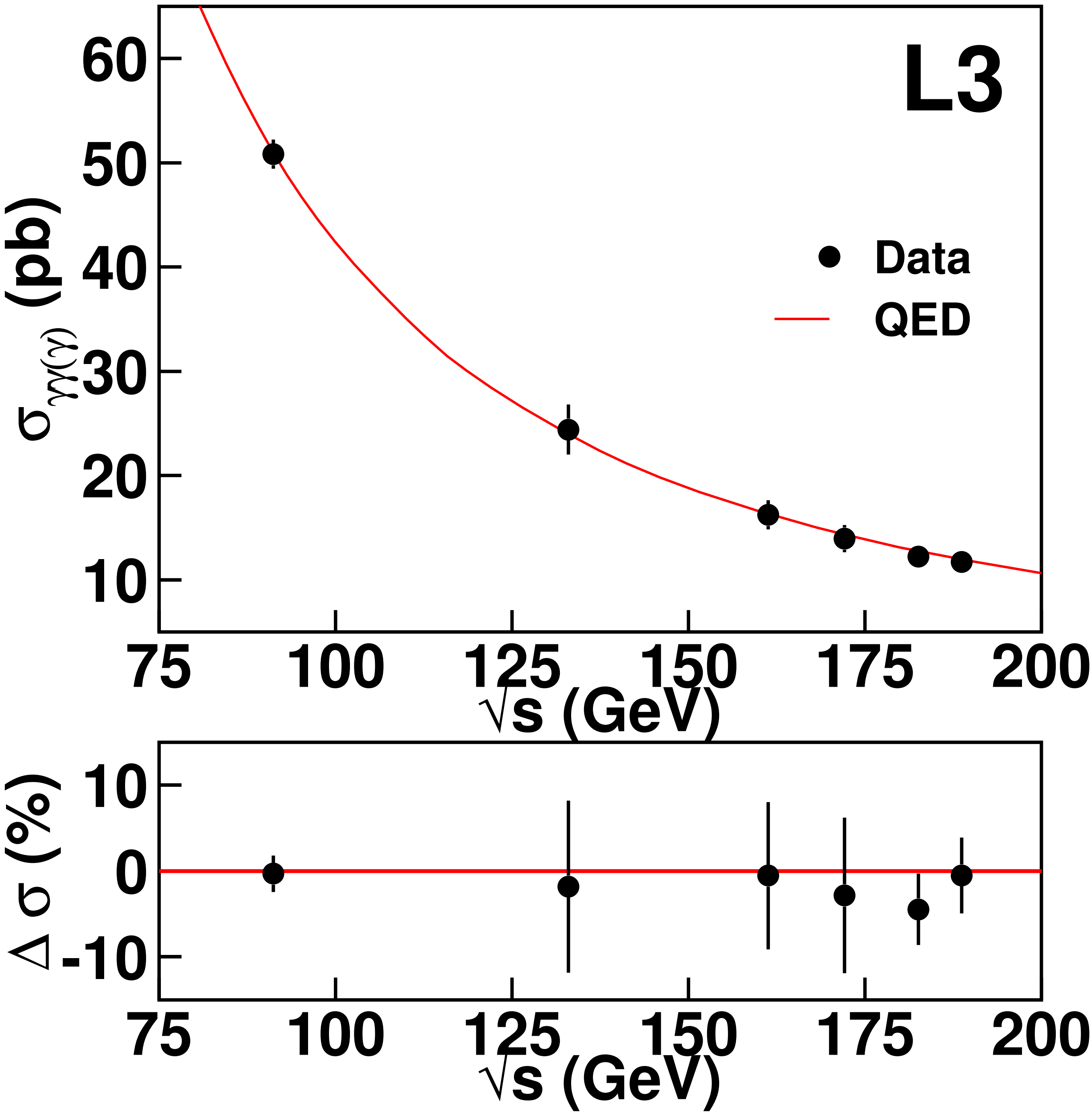
Three Photons







The fifth (sixth) photon escaped down the beam pipe.

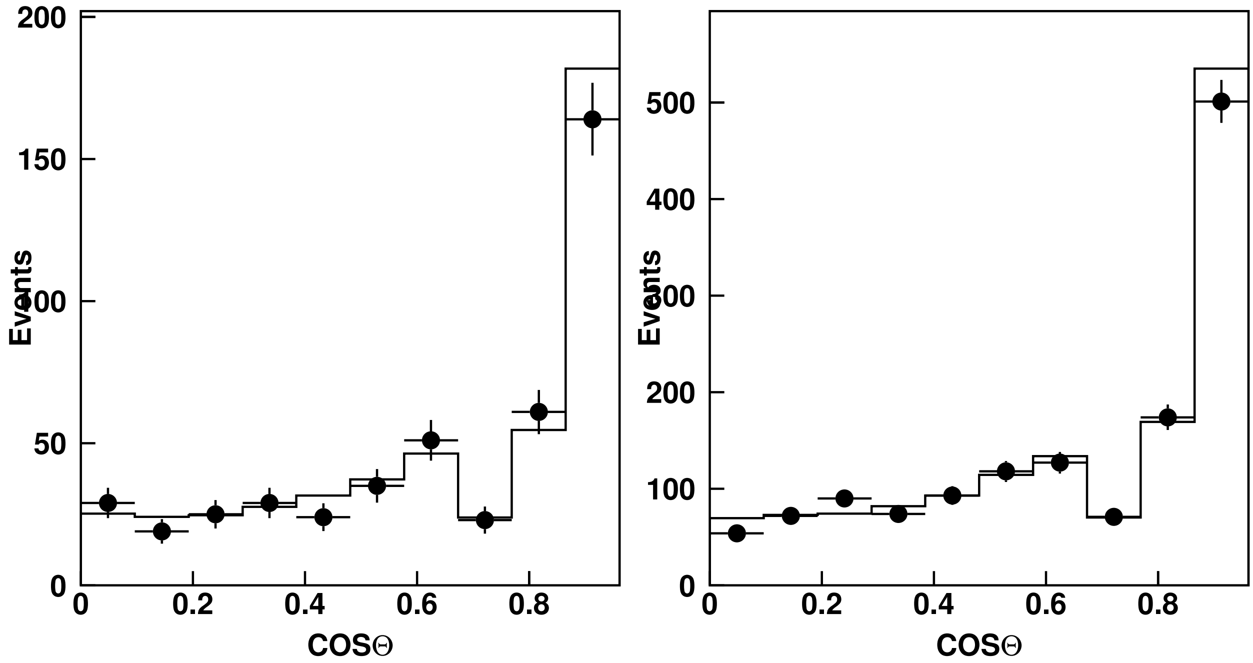

L3
Data
QED
$\sigma_{\gamma\gamma(\gamma)}$ (pb)
60
50
40
30
20
10
75
100
125
150
175
200
$\sqrt{s}$ (GeV)
$\Delta\sigma$ (%)
10
0
-10
75
100
125
150
175
200
$\sqrt{s}$ (GeV)

QED Deviations

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{QED}}{d\Omega}\left(1 + \frac{s^2}{\alpha}\frac{1}{\Lambda^4}(1-\cos^2\theta)\right)$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{QED}}{d\Omega}\left(1 + \frac{s^3}{32\pi\alpha^2}\frac{1}{\Lambda'^6}\frac{1-\cos^2\theta}{1+\cos^2\theta}\right)$$

Cut-offs $\Lambda_\pm = \left(\frac{\alpha}{2}\right)^{\frac{1}{4}} \Lambda$

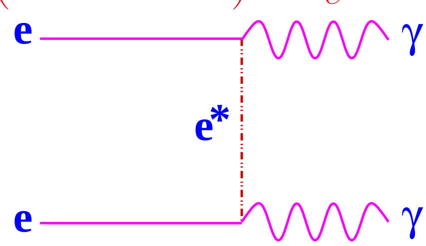


95% C.L. limits on QED deviations, excited electron mass:

$\Lambda > 1304$ GeV $\quad \Lambda_+ > 320$ GeV

$\Lambda_- > 282$ GeV $\quad \Lambda' > 702$ GeV

$m_{e^*} > 323$ GeV (non-chiral) $\quad m_{e^*} > 282$ GeV (chiral)

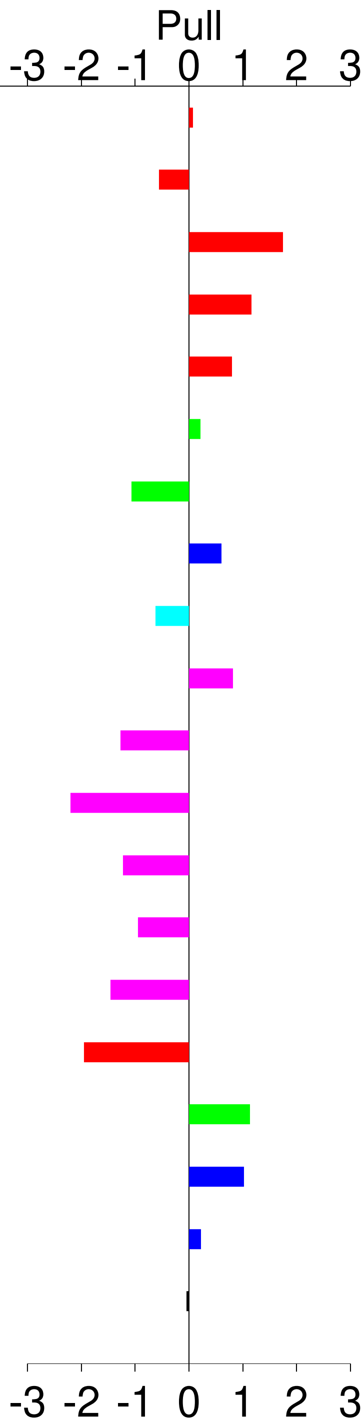


...In the Extra Dimensions

The Standard Model is healthier than ever:

Stanford 1999

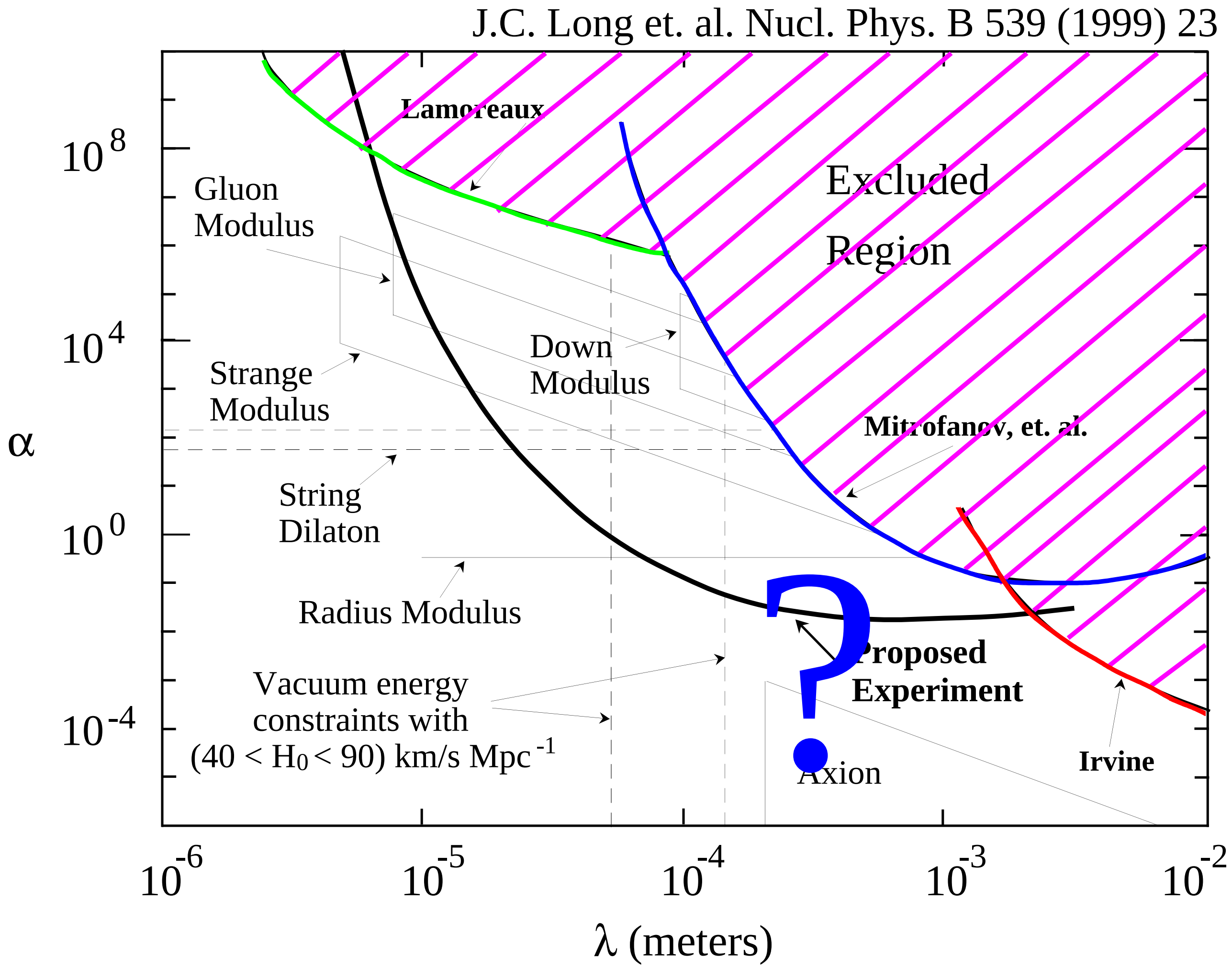
	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.08
Γ_Z [GeV]	2.4944 ± 0.0024	-.56
σ^0_{hadr} [nb]	41.544 ± 0.037	1.75
R_e	20.768 ± 0.024	1.16
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.80
A_e	0.1483 ± 0.0051	.21
A_τ	0.1425 ± 0.0044	-1.07
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.60
m_W [GeV]	80.350 ± 0.056	-.62
R_b	0.21642 ± 0.00073	.81
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0988 ± 0.0020	-2.20
$A^{0,c}_{fb}$	0.0692 ± 0.0037	-1.23
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.46
$\sin^2\theta^{lept}_{eff}$	0.23099 ± 0.00026	-1.95
$\sin^2\theta_W$	0.2255 ± 0.0021	1.13
m_W [GeV]	80.448 ± 0.062	1.02
m_t [GeV]	174.3 ± 5.1	.22
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.05



And it is tested at its characteristic distance

$1/m_{ew}$ (Easy we've built LEP such that $\sqrt{s} \simeq m_{ew}$)

Gravity is far from being tested at $1/M_{Pl} = 10^{-35}$ cm:



$$V(r) = -\int dr_1 \int dr_2 G_N \frac{\rho_1(r_1)\rho_2(r_2)}{r_{12}}(1+\alpha e^{\frac{-r_{12}}{\lambda}})$$

Another Introduction

Three facts:

- $\mathbf{M_{Pl} \sim 10^{19}\ GeV \gg m_{ew} \sim 10^{2}\ GeV}$
- Standard Model tested at $\mathbf{1/m_{ew}}$
- Gravity far from being tested at $\mathbf{1/M_{Pl}}$

Arkani-Hamed et al. Phys. Lett. B 544 (1998) 263

(and $\mathcal{O}(\mathbf{200})$ more papers in 1 year)

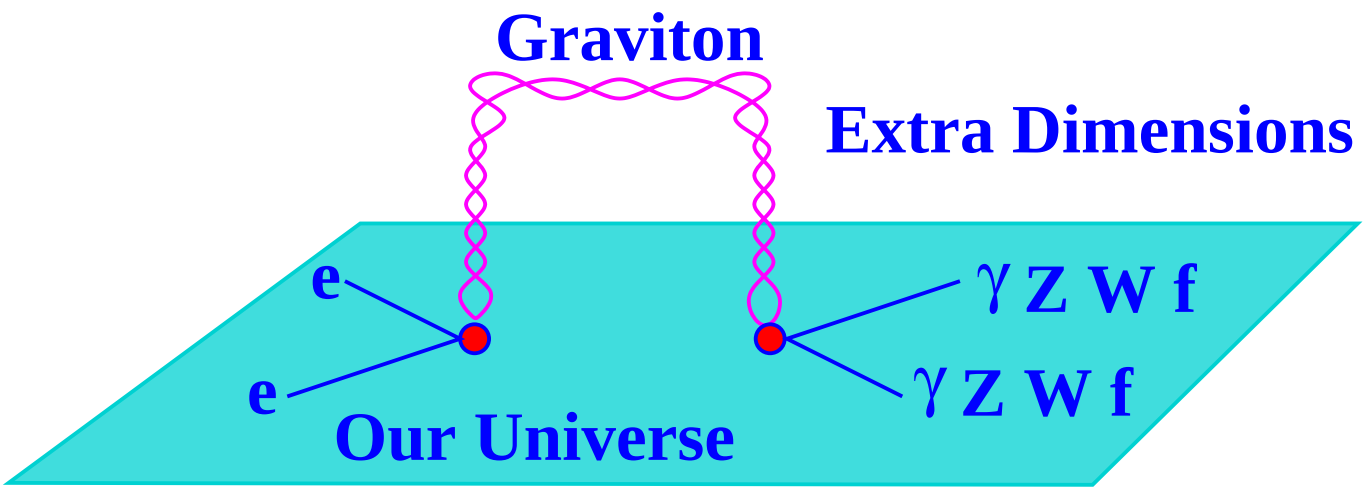
- **The scale of Gravity, $\mathbf{M_S}$, is of order $\mathbf{m_{ew}}$**
- **There are n extra dimensions of size R such that with the Gauss' theorem:**

$$\mathbf{M_{Pl}^2 \sim R^n M_S^{n+2}}$$

$$\mathbf{M_S \sim 1\ TeV \quad n = 1 \quad R \sim Solar\ System}$$
$$\mathbf{M_S \sim 1\ TeV \quad n = 2 \quad R \sim 1mm}$$

Low Scale Gravity

Spin 2 gravitons propagate in these extra dimensions interacting with Standard Model particles in our four ones



$$\frac{d\sigma}{d\Omega}(s,t) = \frac{d\sigma^{SM}}{d\Omega}(s,t) +$$

$$+\frac{\lambda}{M_S{}^4}\alpha_{\text{Interf.}}(s,t) + \frac{\lambda^2}{M_S{}^8}\beta_{\text{Low Scale Gravity}}(s,t)$$

λ depends on the (unknown) full theory, use ±1 for different signs in interference

Two approaches to investigate extra dimensions with photon and Z pairs (and other final states)

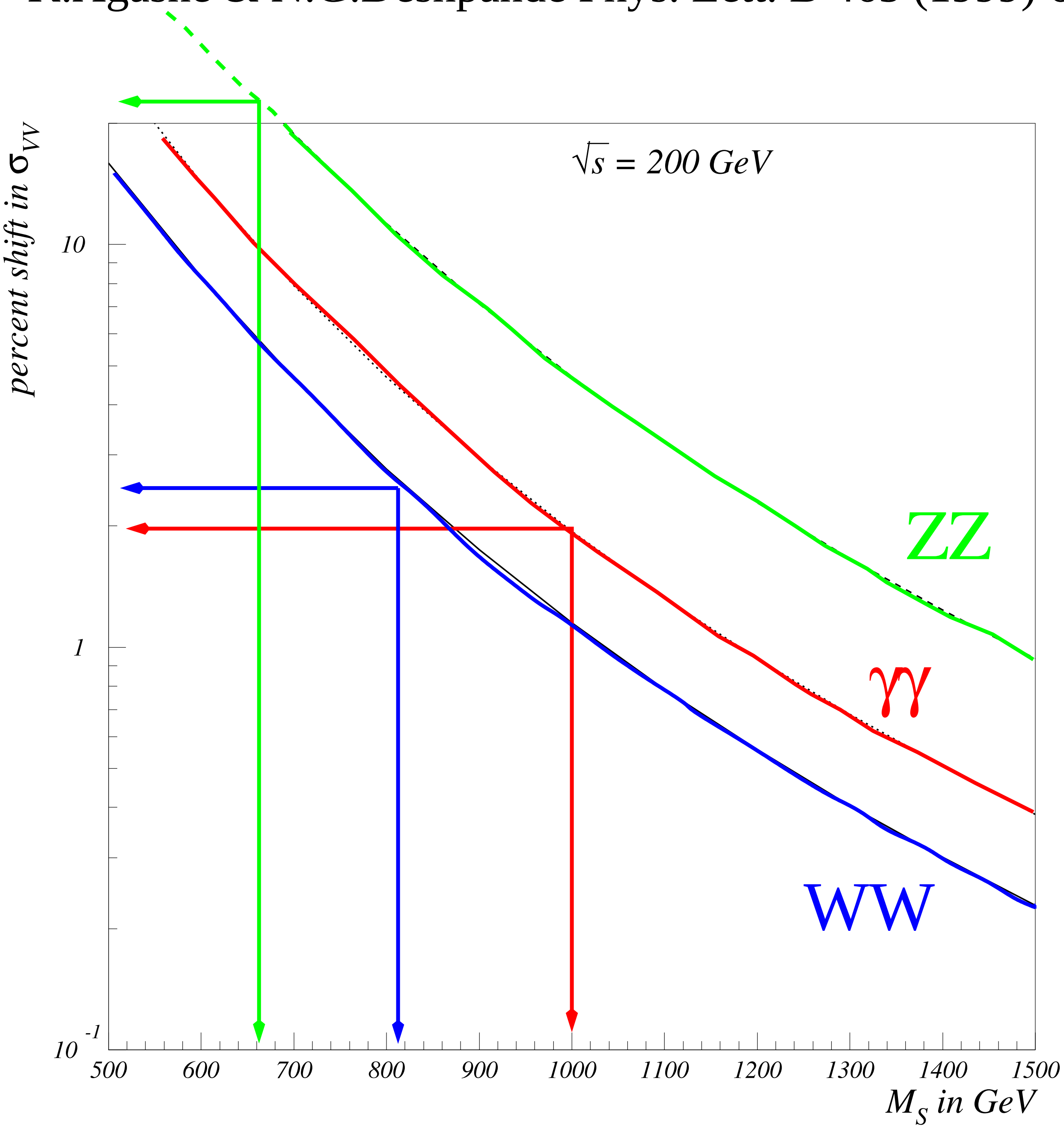
1. **Study the combined LEP ZZ (and WW) cross section and QED limits as a function of $\lambda/\mathrm{M_S^4}$.**

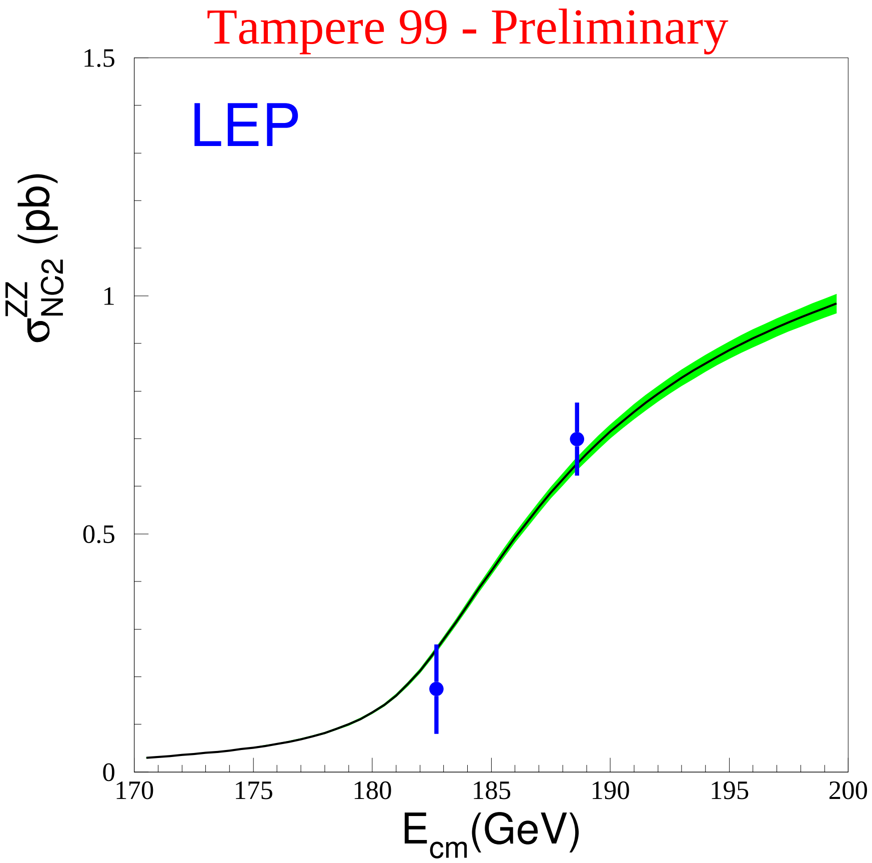
   S. Mele & E. Sanchez, hep-ph/9909294

2. **Investigate experimental distributions for all final states**

   L3 collab., hep-ex/9909019 (183 GeV)
   L3 collab., hep-ex/9910007 (189 GeV)

K.Agashe & N.G.Deshpande Phys. Lett. B 465 (1999) 60



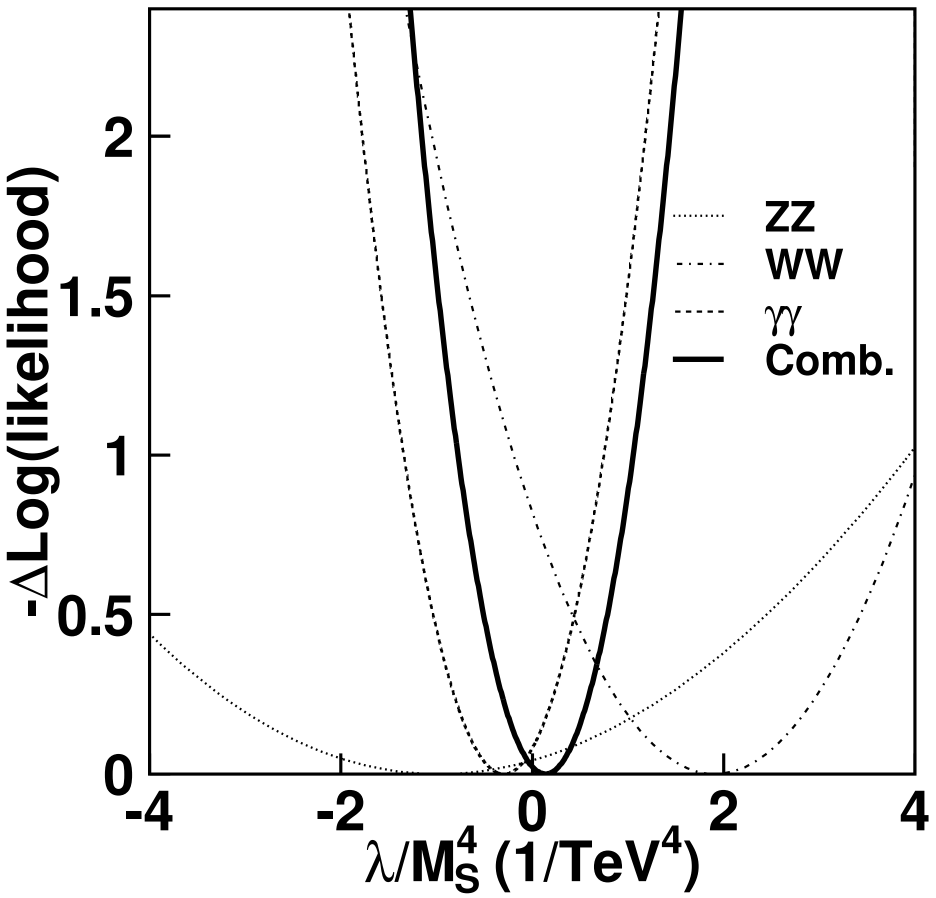


$\sqrt{s}$ (GeV)	σ_{ZZ} (pb)	σ^{SM}_{ZZ} (pb)
183	0.17 ± 0.09	0.26
189	0.70 ± 0.08	0.65

Compare measured cross section with SM + LSG one as a function of λ/M_S^4.

Combine the limits from $e^+e^- \to \gamma\gamma$ on $\Lambda_\pm$ from the LEP experiments and scale them to limits on λ/M_S^4

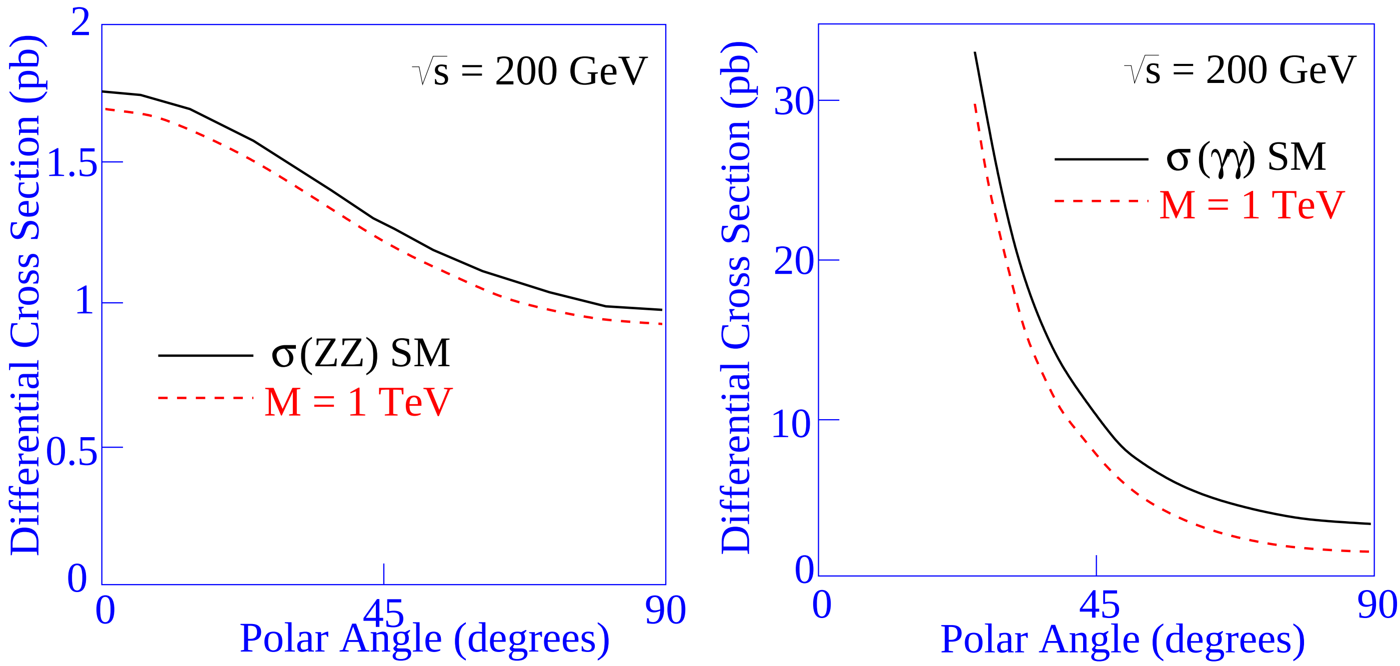
LSG from LEP Results



Process (95% CL)	$\lambda = -1$ M_S (TeV)	$\lambda = +1$ M_S (TeV)
$e^+e^- \to \gamma\gamma$	0.88	0.94
$e^+e^- \to W^+W^-$	0.85	0.68
$e^+e^- \to ZZ$	0.62	0.63
Combined	0.96	0.93

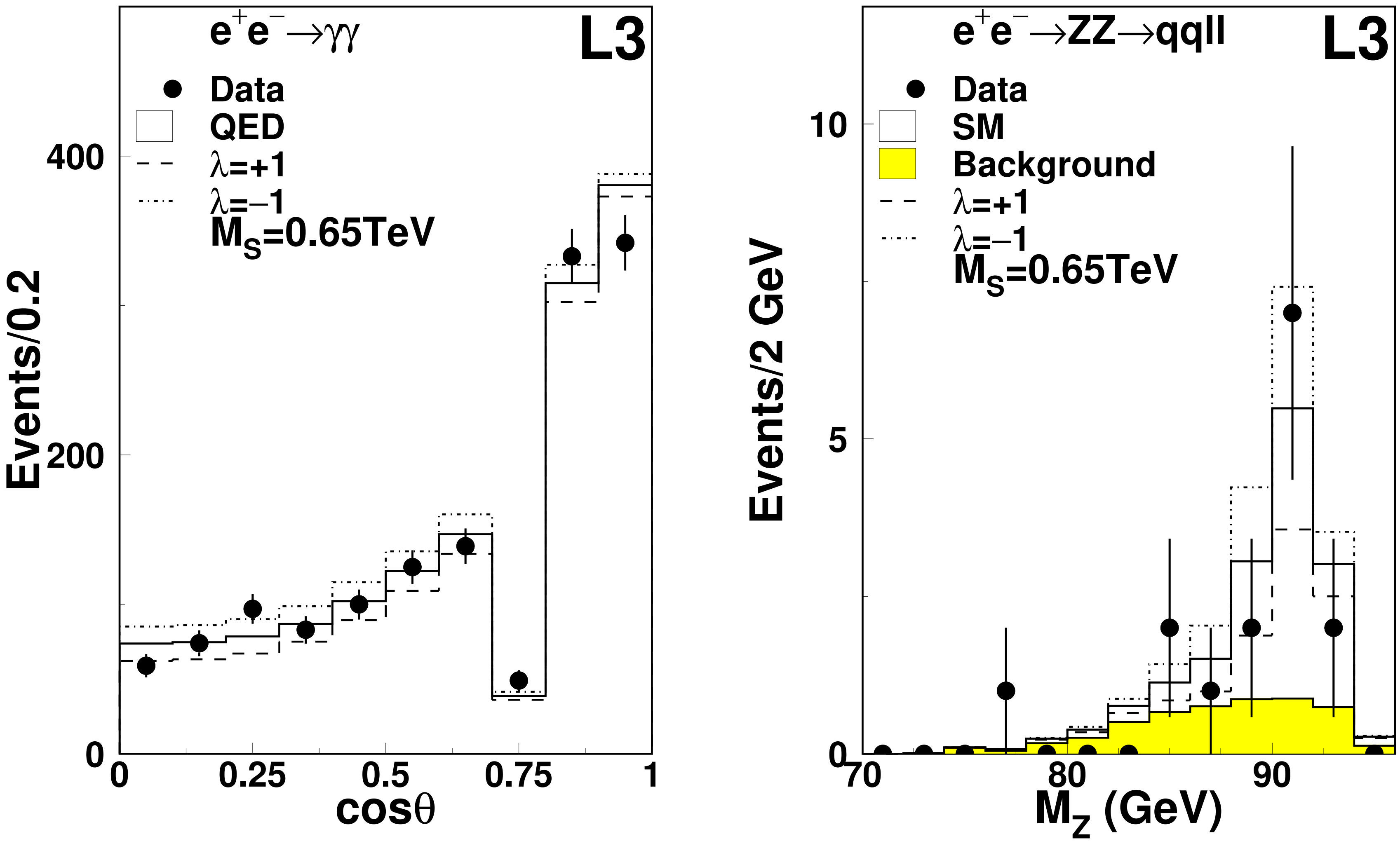
LSG from Experimental Distributions

K. Agashe & N.G. Deshpande Phys. Lett. **B 465** (1999) 69



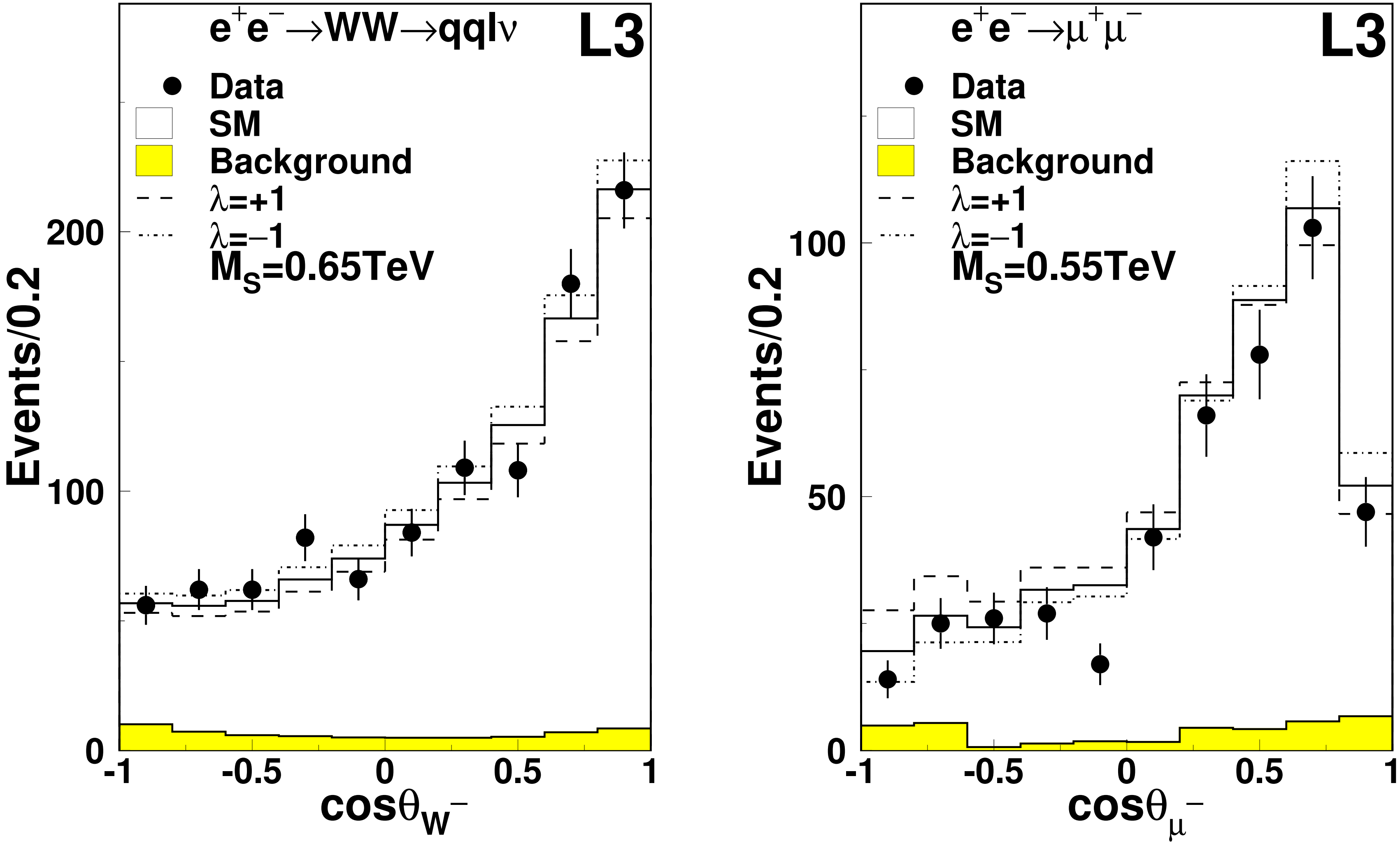
λ/M_S^4 **as a free fit parameter for:**

- **Fit to the ZZ distributions as for ZZ couplings**
- **Fit to angular distribution of** $e^+e^- \to \gamma\gamma$ **as for QED deviations**
- **Fit to** $e^+e^- \to W^+W^-$ **angular distributions as for TGCs (thanks to R. Pittau for the CC03 LSG Excalibur)**
- **Fit to the polar angle distribution for** $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$
- **Fit of the total hadronic cross section and the Bhabha differential cross section**

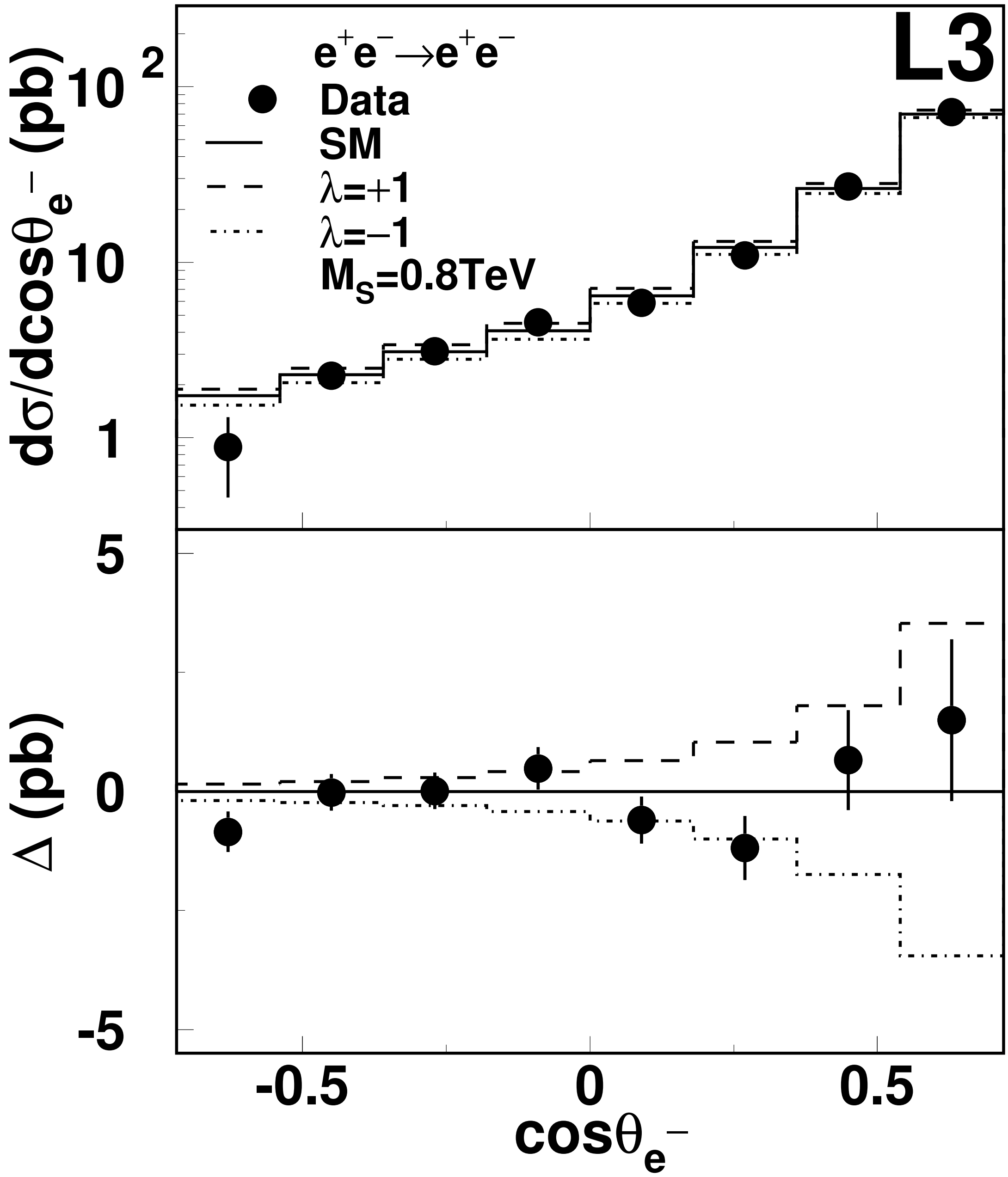


e+e−→γγ
L3
Data
QED
λ=+1
λ=−1
MS=0.65TeV
Events/0.2
400
200
0
0
0.25
0.5
0.75
1
cosθ
e+e−→ZZ→qqll
L3
Data
SM
Background
λ=+1
λ=−1
MS=0.65TeV
Events/2 GeV
10
5
0
70
80
90
MZ (GeV)

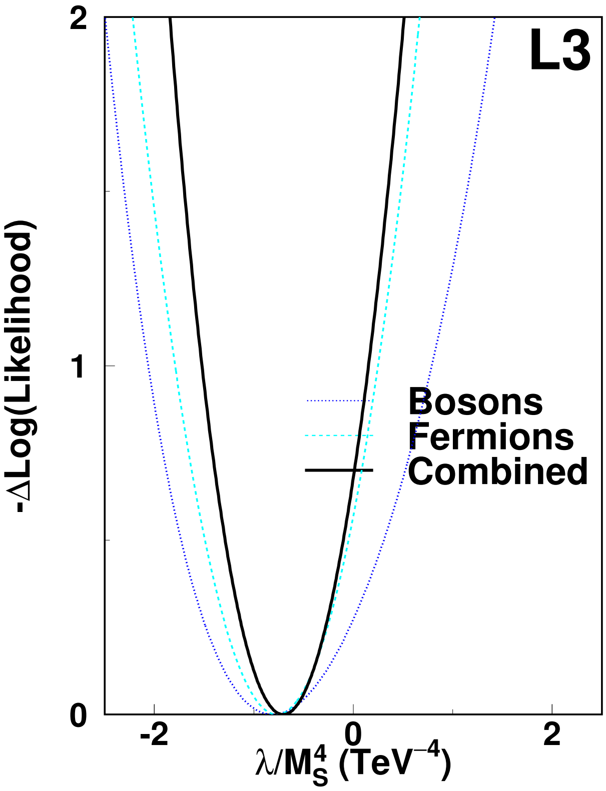
L3 in the Extra Dimensions

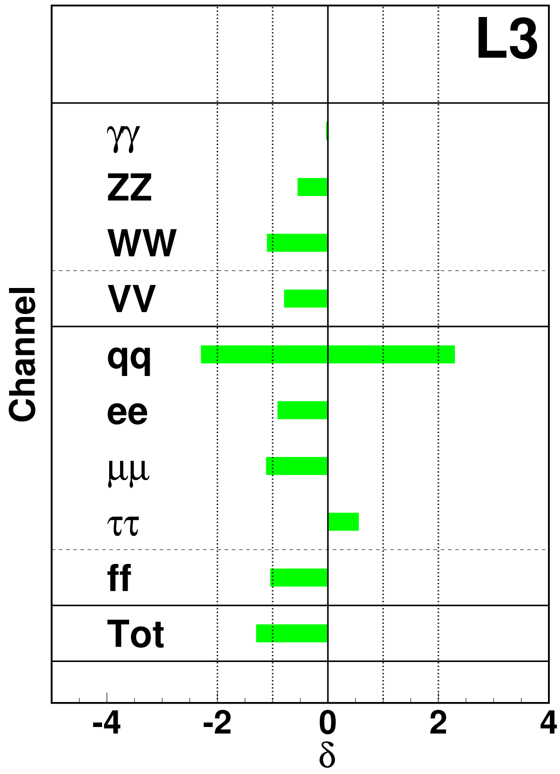


High sensitivity as large interference with SM t−channel



L3 in the Extra Dimensions





Process (Limits at 95% CL)	M_S (TeV) $\lambda = +1$	M_S (TeV) $\lambda = -1$
$e^+e^- \rightarrow \gamma\gamma$	0.79	0.80
$e^+e^- \rightarrow ZZ$	0.77	0.76
$e^+e^- \rightarrow W^+W^-$	0.79	0.68
Bosons Combined	0.89	0.82
$e^+e^- \rightarrow q\bar{q}$	0.49	0.49
$e^+e^- \rightarrow e^+e^-$	0.98	0.84
$e^+e^- \rightarrow \mu^+\mu^-$	0.69	0.56
$e^+e^- \rightarrow \tau^+\tau^-$	0.54	0.58
Fermions Combined	1.00	0.84
Bosons + Fermions	1.07	0.87

Extra Dimensional Conclusion

Excluded size of the Extra Dimensions from L3 Limits (All in meters)

REFERENCE SIZES

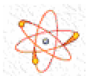
1 light Year ~ 10^{+16}

1 AU = $1.5\times10^{+11}$

Typical cell size ~ 10^{-5}

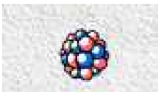
DNA Molecule size ~ 10^{-7}

Typical Molecule size ~ 10^{-8}



Bohr Radius = 0.53×10^{-10}

$\lambda_{COMPTON}$ of the electron = 3.8×10^{-13}



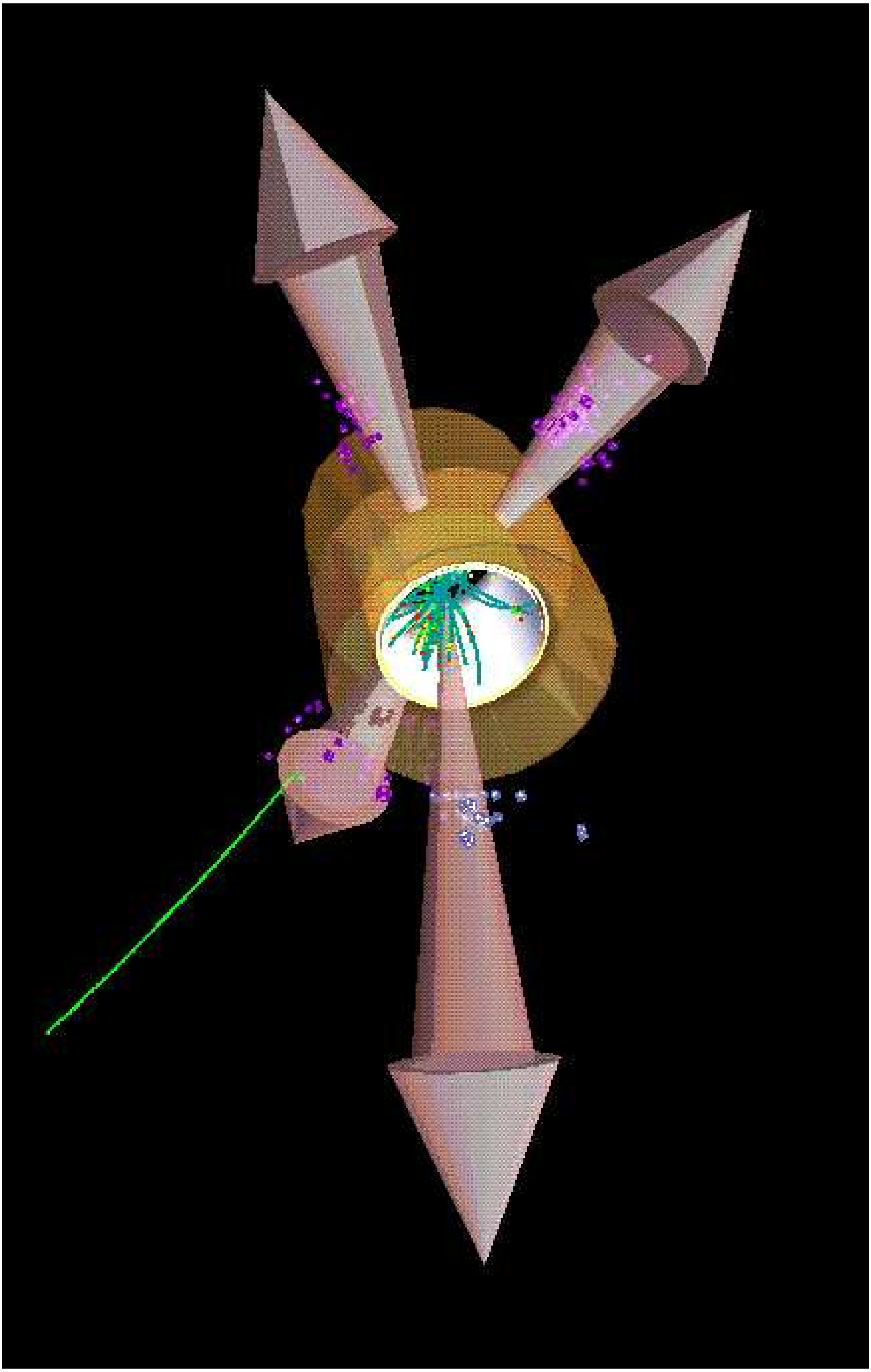
Typical Nucleus Size ~ 10^{-14}

Proton Size ~ 2.8×10^{-15}

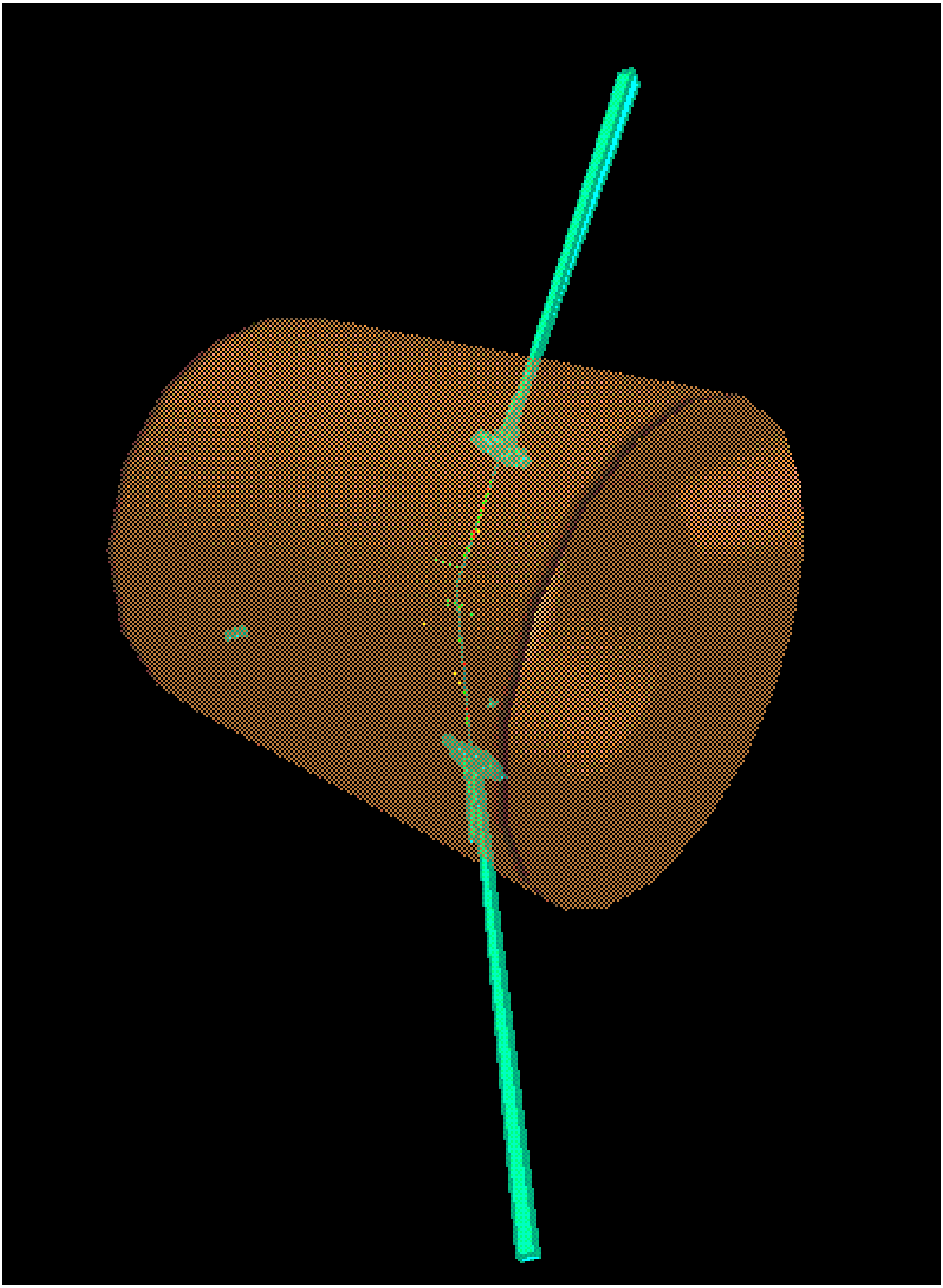
electron or quark size ~ 10^{-18}

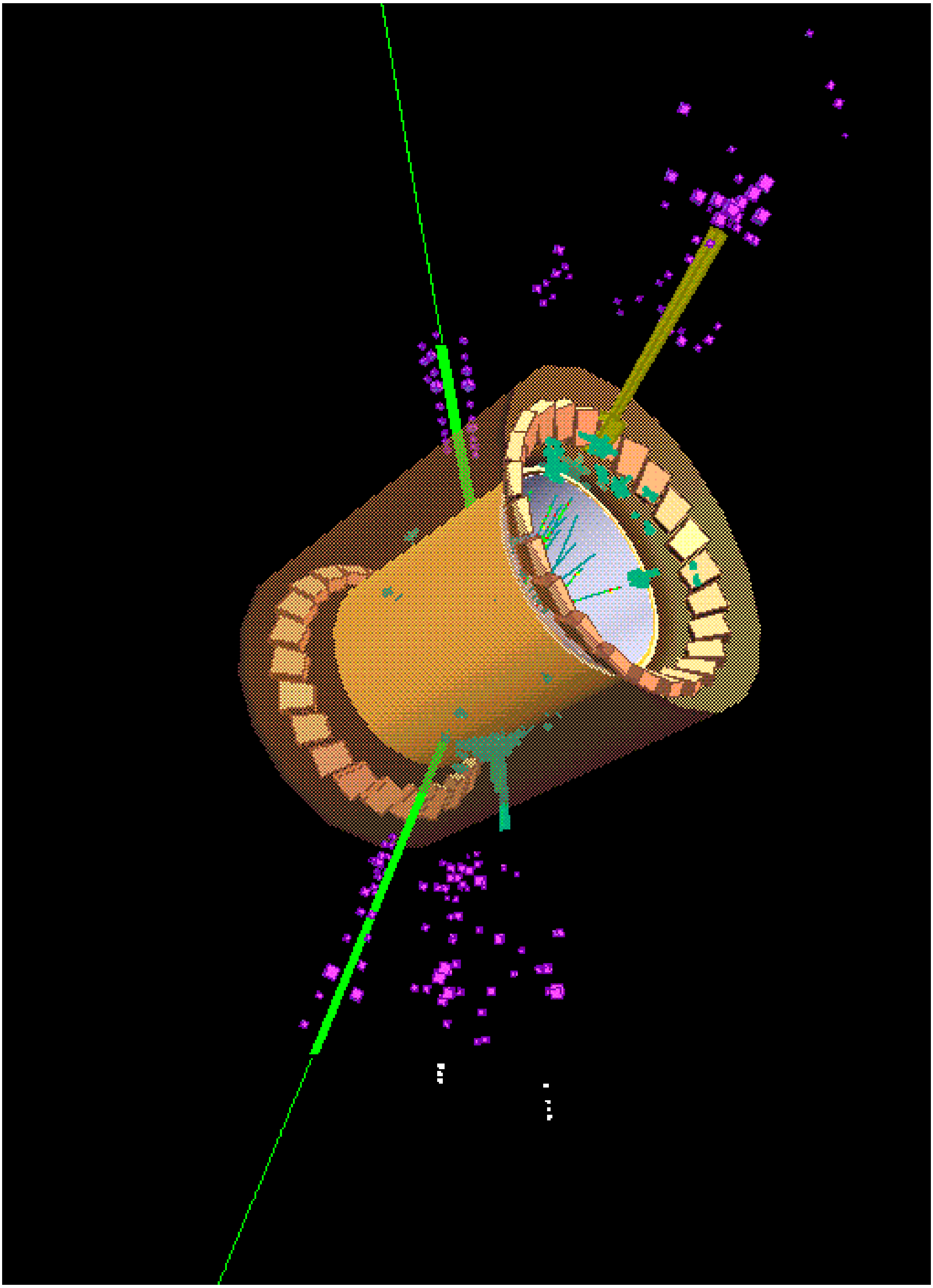
δ	$\lambda=+1$	$\lambda=-1$
1	$2.4 \times 10^{+13}$	$4.5 \times 10^{+13}$
2	2.1×10^{-3}	3.2×10^{-3}
3	9.3×10^{-9}	1.3×10^{-8}
4	1.9×10^{-11}	2.7×10^{-11}
5	4.9×10^{-13}	6.5×10^{-13}
6	4.1×10^{-14}	5.5×10^{-14}
7	7.1×10^{-15}	9.3×10^{-15}

Preview from 192 GeV – 202 GeV

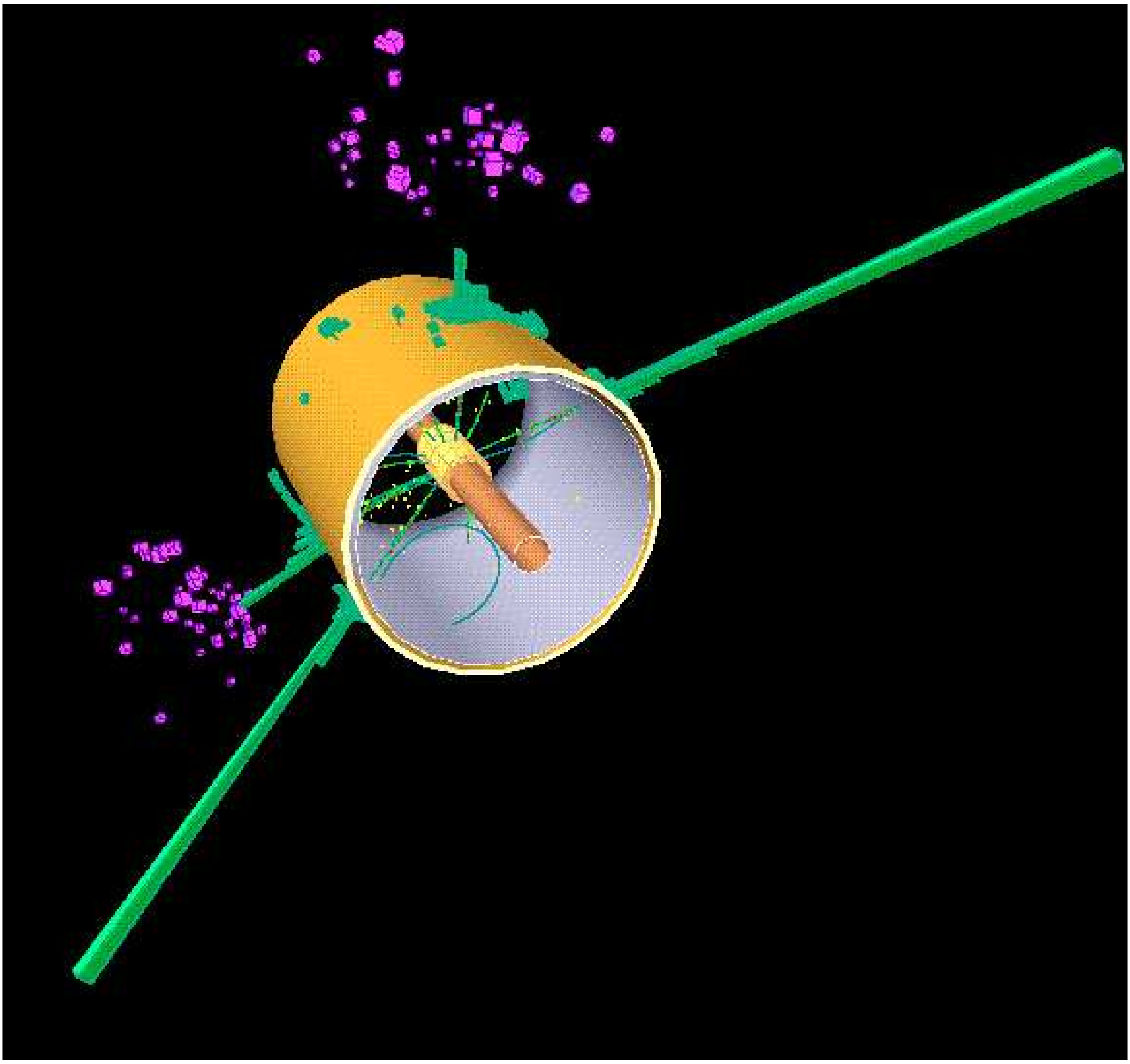


Preview from 192 GeV – 202 GeV

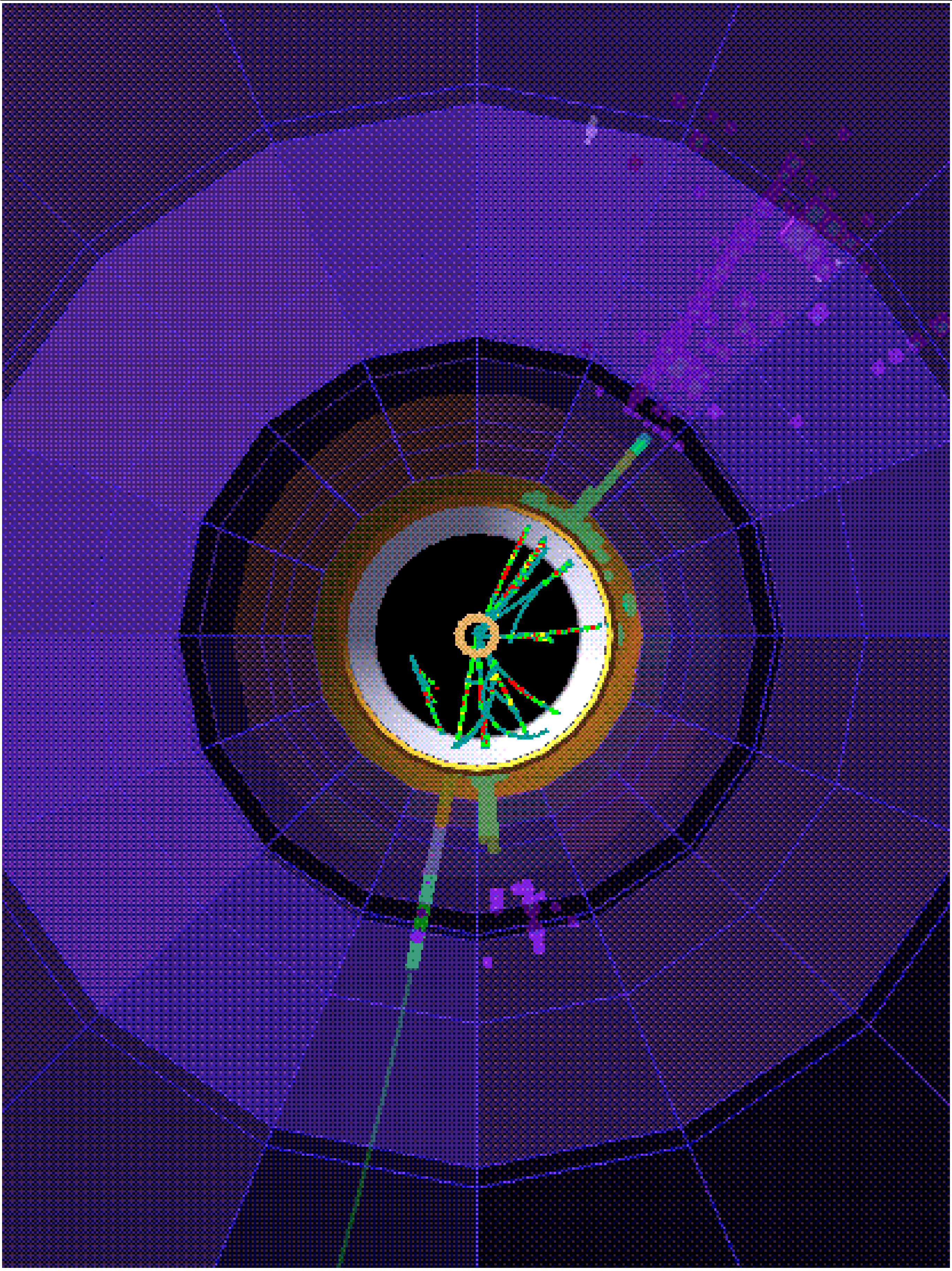




Preview from 192 GeV – 202 GeV



Preview from 192 GeV – 202 GeV



Conclusions

- The Neutral Boson sector of the Standard Model is extensively studied in L3
- No deviation from the expectations are observed in the statistically increasing precision of the measurements
- Eagerly wait for the completion of this year data taking and more energy and luminosity in 2000

Acknowledgements + Happy Ending

I am grateful to my L3 colleagues with whom I am sharing this challenging part of the LEP 2 physics programme and that contributed to these results:

Juan Alcaraz, Tariq Aziz, Angela Bajo, Michela Biglietti, Dimitri Bourilkov, Frederic Brochu, Francesco Conventi, Massimo della Pietra, Miguel Falagan, Marta Felcini, Andre Holzner, Isabel Josa, Andreas Kopp, Andrei Kounine, Jeremiah Mans, Eusebio Sanchez, Chris Tully, Martin Weber.

We all are waiting for the **Happy Ending...**