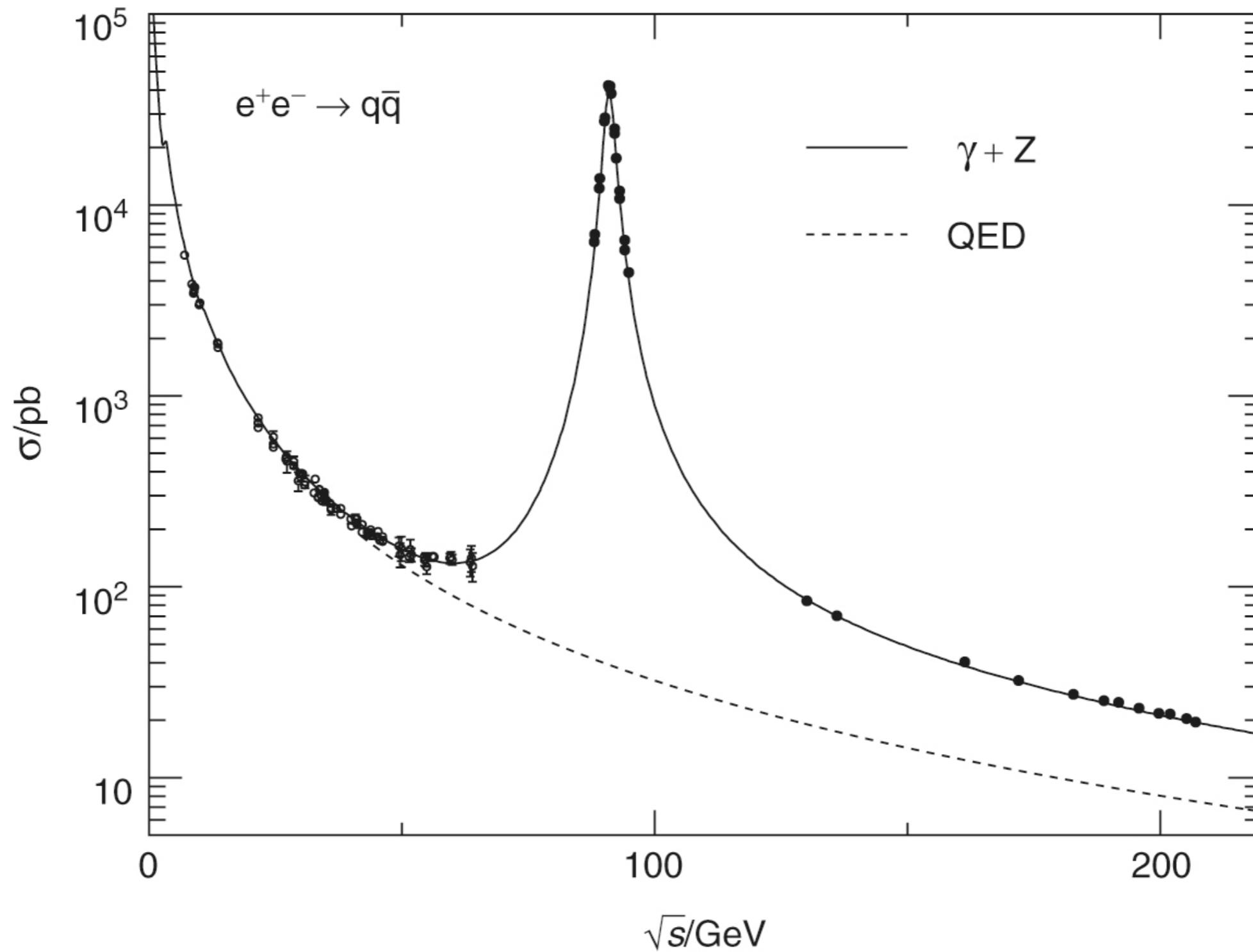


# Electron-positron annihilation

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# Physics of the Z-Boson

Cross Section for  
 $e^+e^- \rightarrow \gamma/Z \rightarrow f\bar{f}$ :

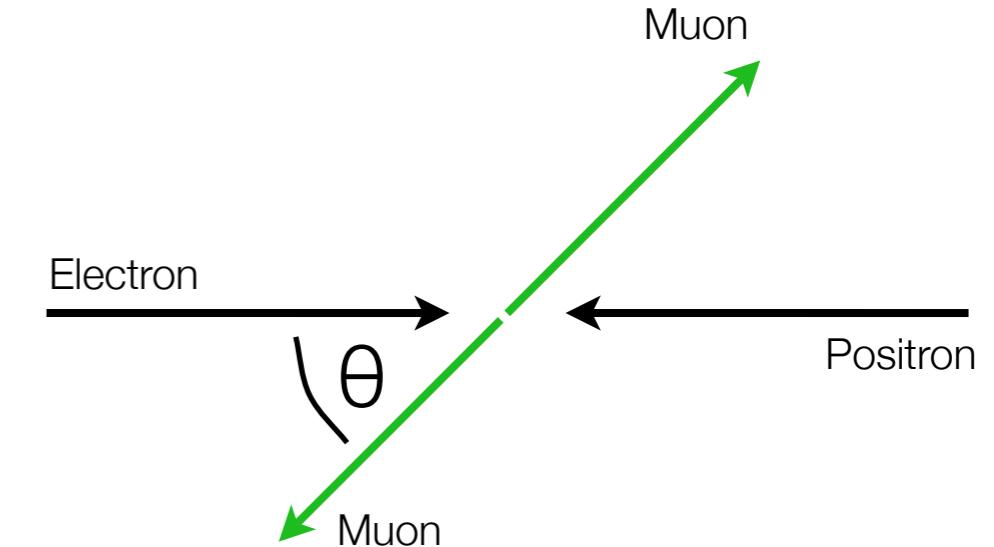
$$|M|^2 = \left| \frac{1}{2}(g_V - g_A \gamma^5)}{\gamma} + \frac{1}{2}(g_V - g_A \gamma^5)}{Z} \right|^2$$

For  $e^+e^- \rightarrow \mu^+\mu^-$ :

$$M_\gamma = -ie^2(\bar{u}_\mu \gamma^\nu v_\mu) \frac{g_{\rho\nu}}{q^2} (\bar{v}_e \gamma^\rho u_e)$$

$$M_Z = -i \frac{g^2}{4 \cos^2 \theta_W} [(\bar{u}_\mu \gamma^\nu (g_V^\mu - g_A^\mu \gamma^5) v_\mu] \underbrace{\frac{g_{\rho\nu} - q_\rho q_\nu / M_Z^2}{(q^2 - M_Z^2) + i M_Z \Gamma_Z}}_{Z \text{ propagator} \\ [\text{with finite width; unitary gauge}]} [(\bar{v}_e \gamma^\nu (g_V^e - g_A^e \gamma^5) u_e)]$$

# Physics of the Z-Boson



Differential cross section  
for  $e^+e^- \rightarrow \mu^+\mu^-$ :

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s} \left\{ Q_\mu^2 (1 + \boxed{\cos^2 \theta}) \right.$$

symmetric  
in  $\cos\theta$ 
asymmetric  
in  $\cos\theta$ 
[ $\gamma$ -exchange]

$$- Q_\mu [2g_V^e g_V^\mu (1 + \cos^2 \theta) + \boxed{4g_A^e g_A^\mu \cos \theta}] \Re\{\chi\}$$

[ $\gamma Z$ -interference]

$$+ ((g_V^e)^2 + (g_A^e)^2) [(g_V^\mu)^2 + (g_A^\mu)^2] (1 + \cos^2 \theta) + \boxed{8g_V^e g_A^e g_V^\mu g_A^\mu \cos \theta} |\chi|^2 \left. \right\}$$

[Z-exchange]

with

$$\chi = \frac{1}{\sin^2 \theta_W \cos^2 \theta_W} \cdot \frac{s}{s - m_Z^2 + i\Gamma_Z m_Z}$$

[Z-propagator]

$$\Gamma_Z = \sum_f \Gamma_f , \quad \Gamma_f = N_c^f \frac{\alpha m_Z}{12 \sin^2 \theta_W \cos^2 \theta_W} \left[ (g_V^f)^2 + (g_A^f)^2 \right]$$

number of  
colors
[partial Z-widths]

# Physics of the Z-Boson

---

Total cross section  
for  $e^+e^- \rightarrow f\bar{f}$ :

$$\sigma_f = \frac{4\pi\alpha^2}{3s} N_c^f \left\{ Q_f^2 - 2Q_f g_V^e g_V^f \Re\{\chi\} + [(g_V^e)^2 + (g_A^e)^2] [(g_V^f)^2 + (g_A^f)^2] |\chi|^2 \right\}$$

/ small @  $\sqrt{s} = m_Z$   
\ vanishes @  $\sqrt{s} = m_Z$

with  $\chi = \frac{1}{\sin^2 \theta_W \cos^2 \theta_W} \cdot \frac{s}{s - m_Z^2 + i\Gamma_Z m_Z}$

Total cross section  
at  $\sqrt{s}=m_Z$ :

$$\sigma_f(\sqrt{s} = m_Z) \approx \frac{12\pi}{m_Z^2} \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2} = \frac{12\pi}{m_Z^2} \cdot \text{BR}(Z \rightarrow e^+e^-) \cdot \text{BR}(Z \rightarrow f\bar{f})$$

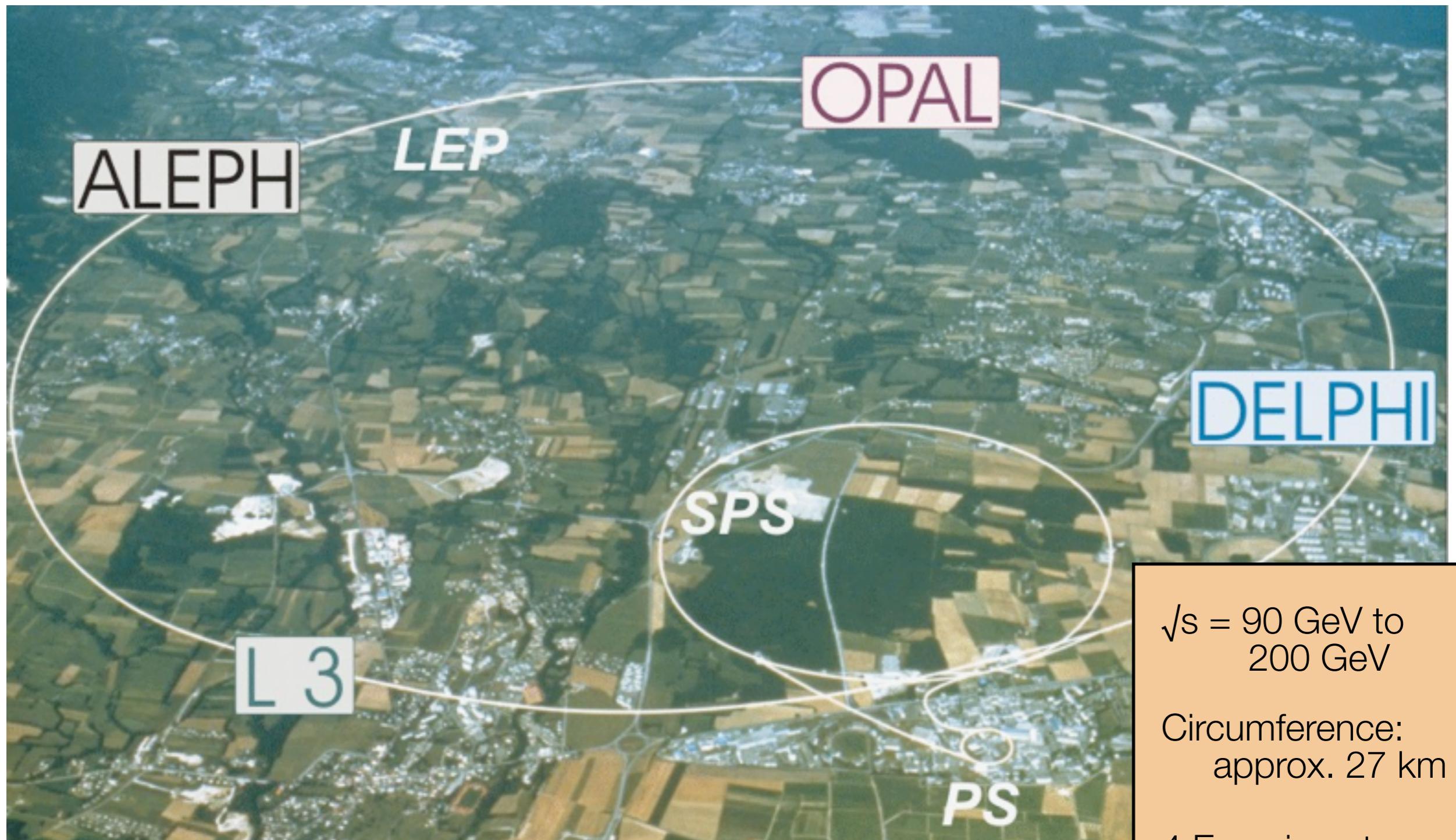
with

$$\Gamma_Z = \sum_f \Gamma_f, \quad \Gamma_f = N_c^f \frac{\alpha m_Z}{12 \sin^2 \theta_W \cos^2 \theta_W} [(g_V^f)^2 + (g_A^f)^2]$$

\ Branching Ratios

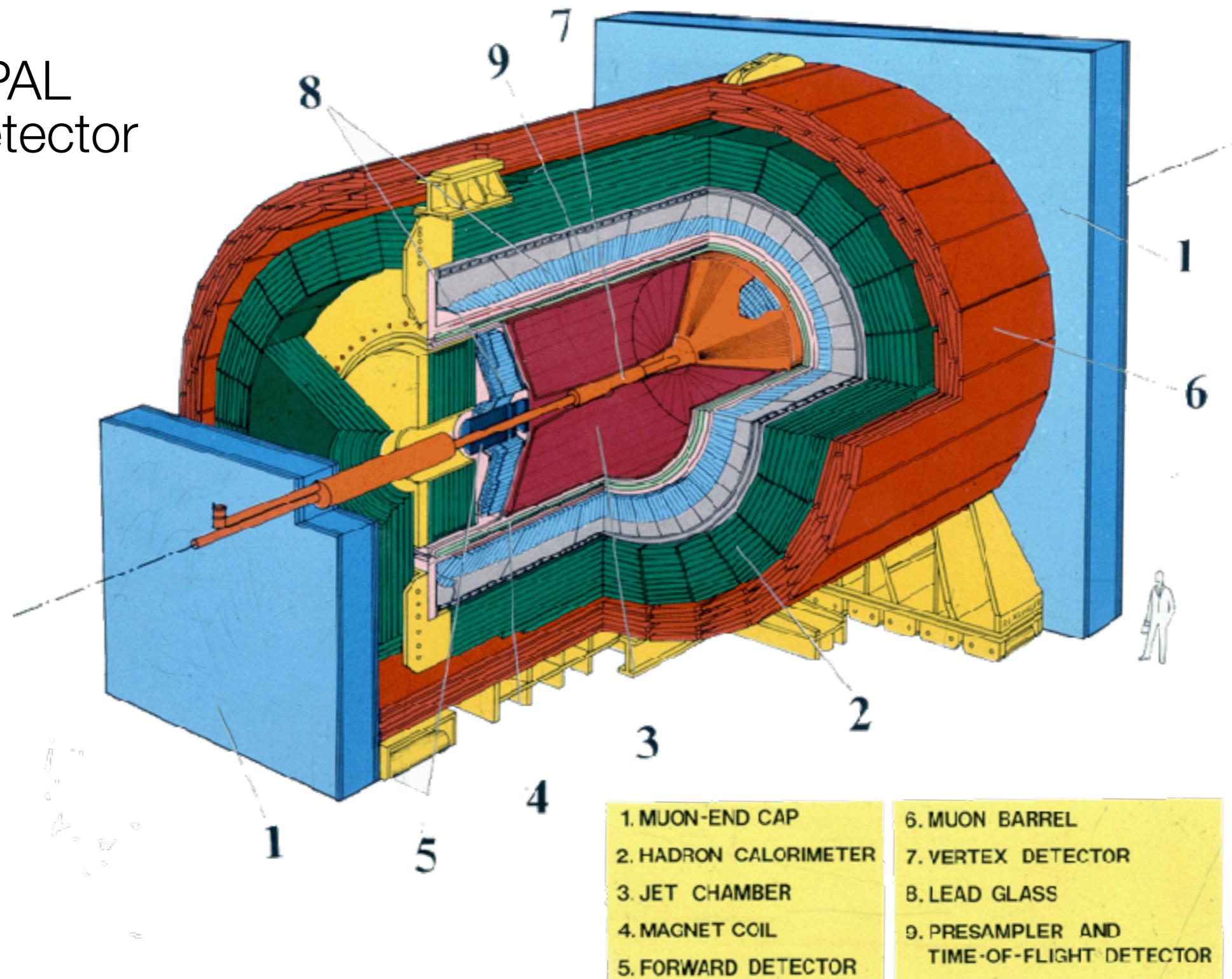
[calculable within SM]

# The LEP Collider



# The LEP Experiments - OPAL

OPAL  
Detector

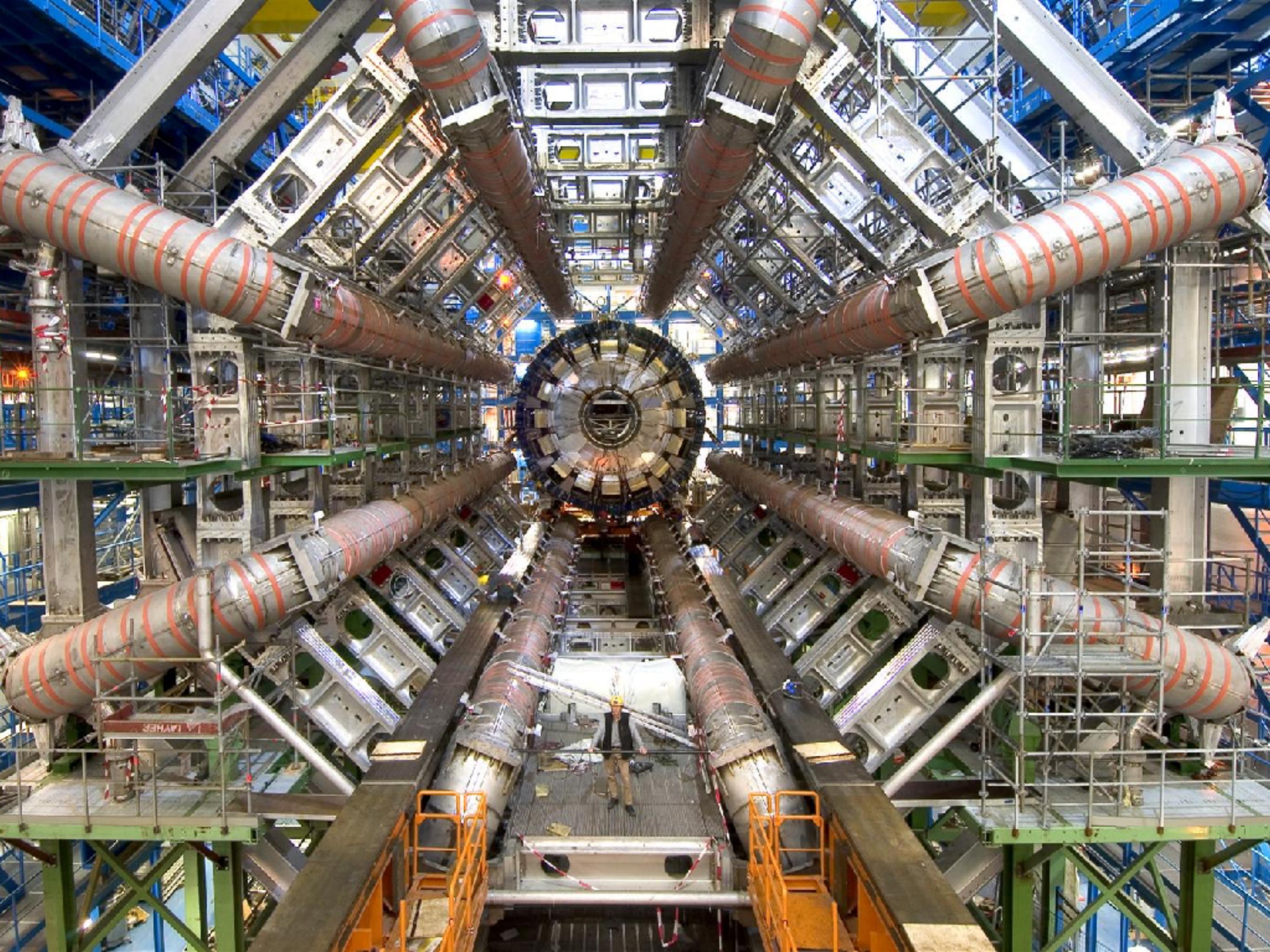


# The LEP Experiments - OPAL

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OPAL Jet Chamber installation







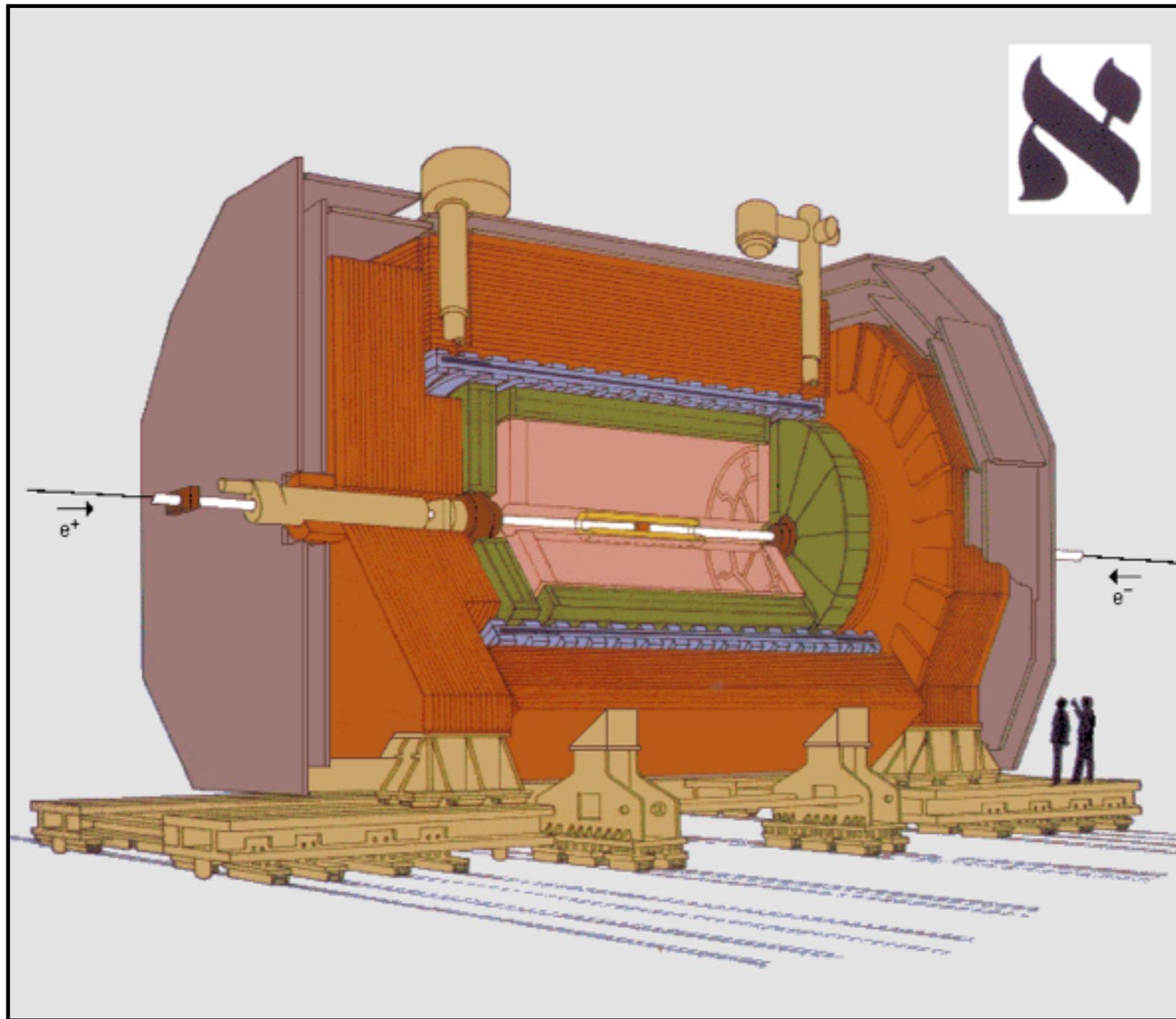
**CONVOI EXCEPTIONNEL**

60 70 80

E 7538 BBY

B 204 BPZ

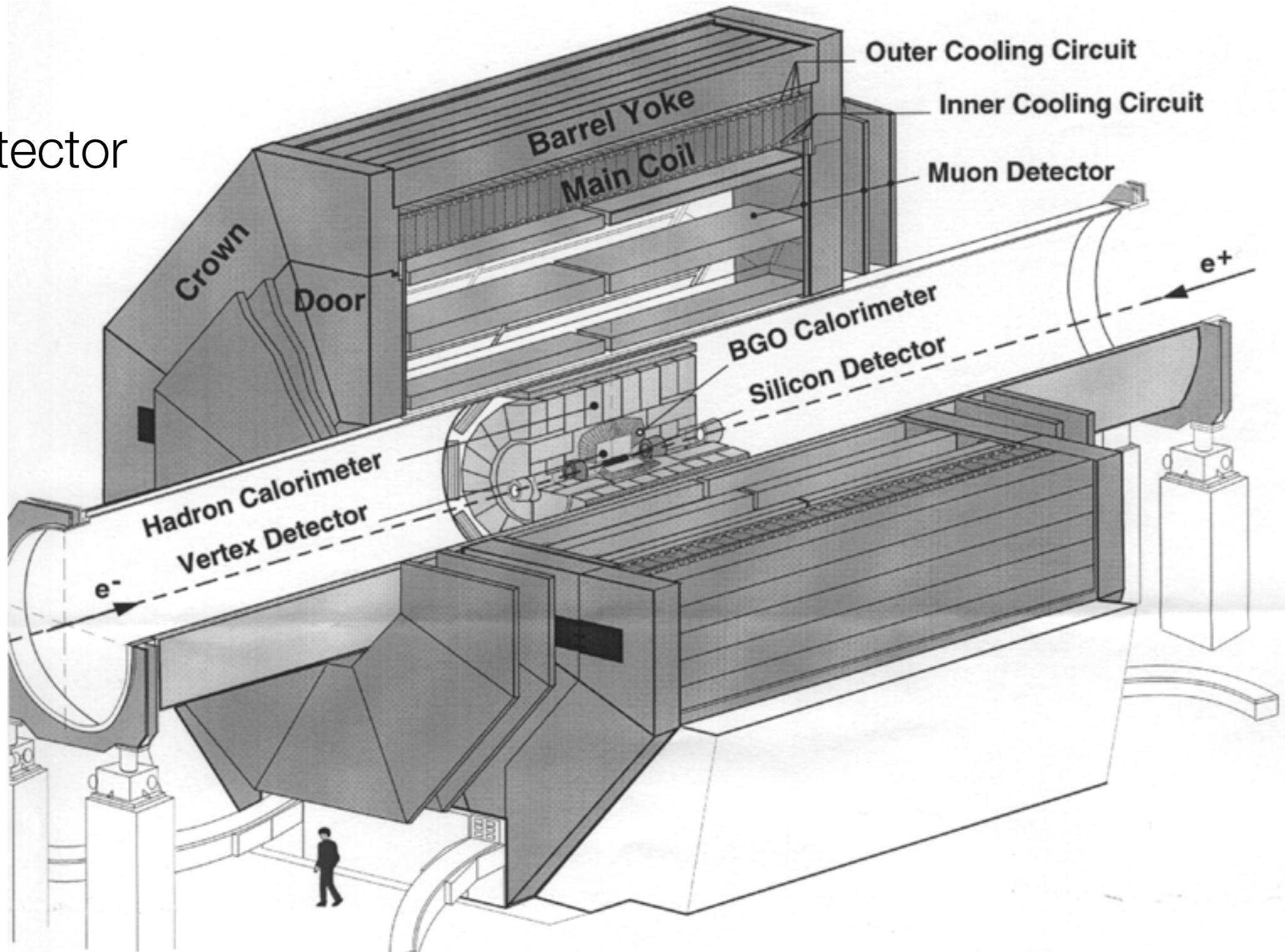
# The LEP Experiments - ALEPH



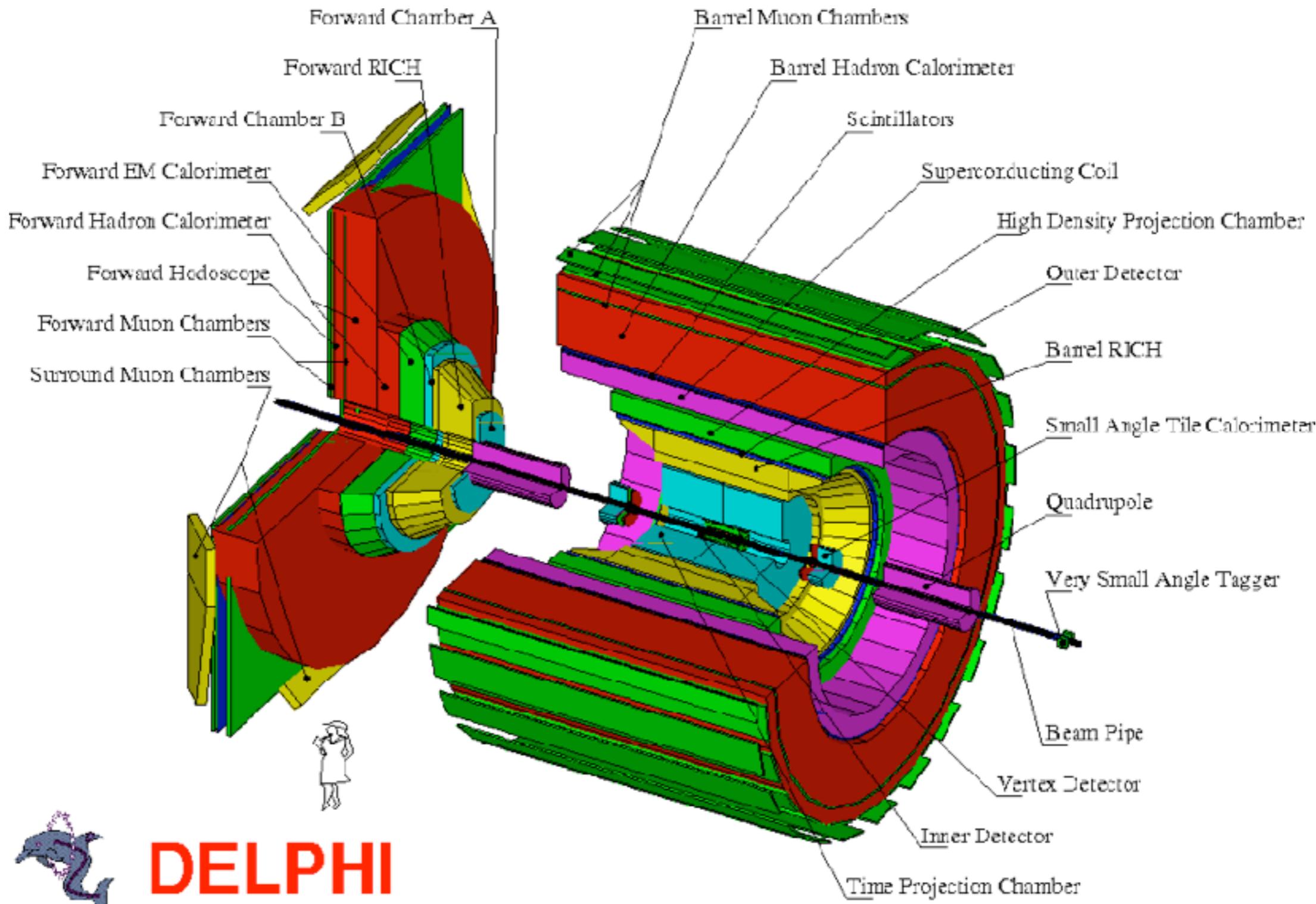
- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

# The LEP Experiments - L3

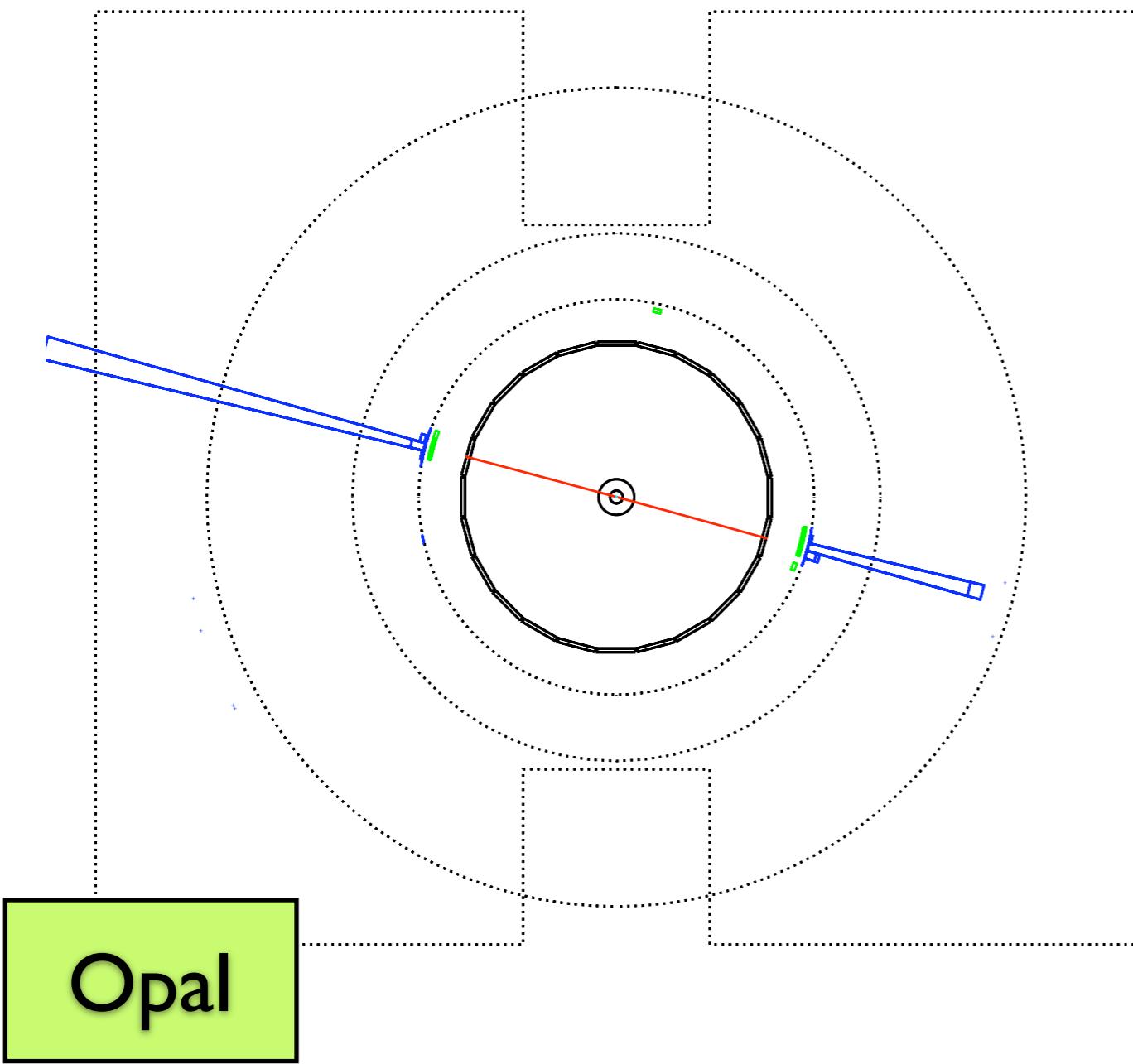
L3  
Detector



# The LEP Experiments - DELPHI

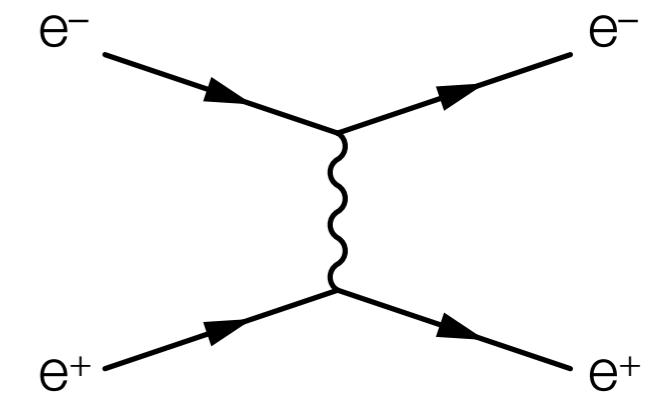
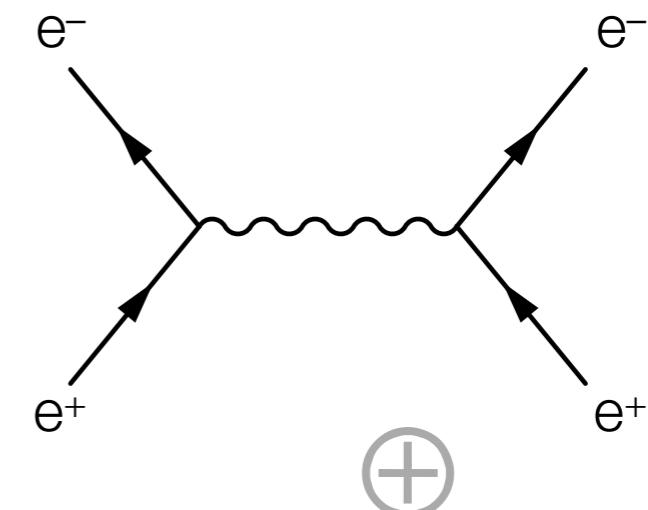


# Experimental Signatures



Signature:

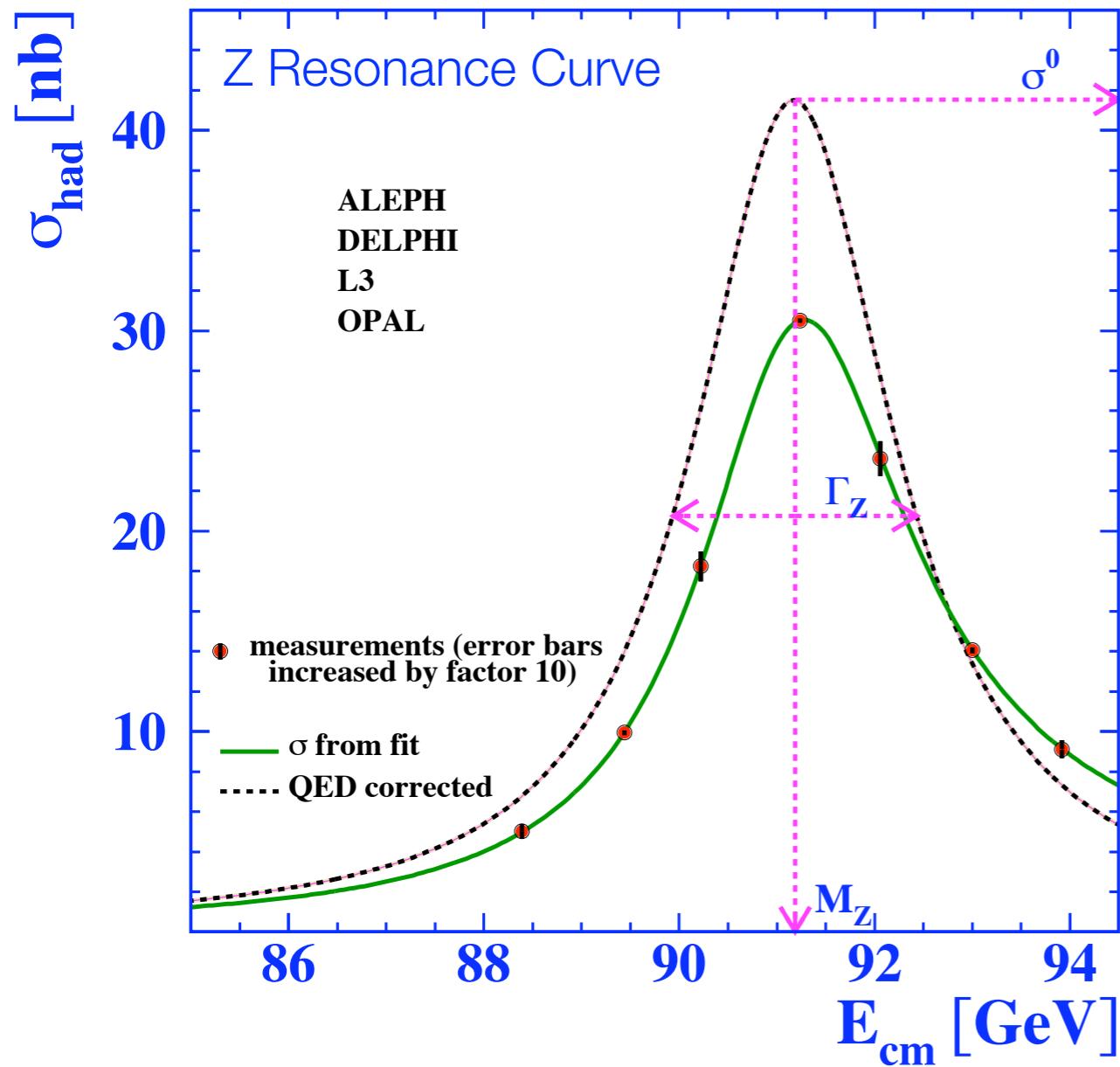
$$e^+ e^- \rightarrow e^+ e^-$$



# Measurement of Z Lineshape

$$\sigma^0(s) \approx 12\pi \frac{\Gamma_e \Gamma_f}{m_Z^2} \cdot \frac{s}{(s - m_Z^2)^2 + \Gamma_Z^2 m_Z^2}$$

Breit  
Wigner

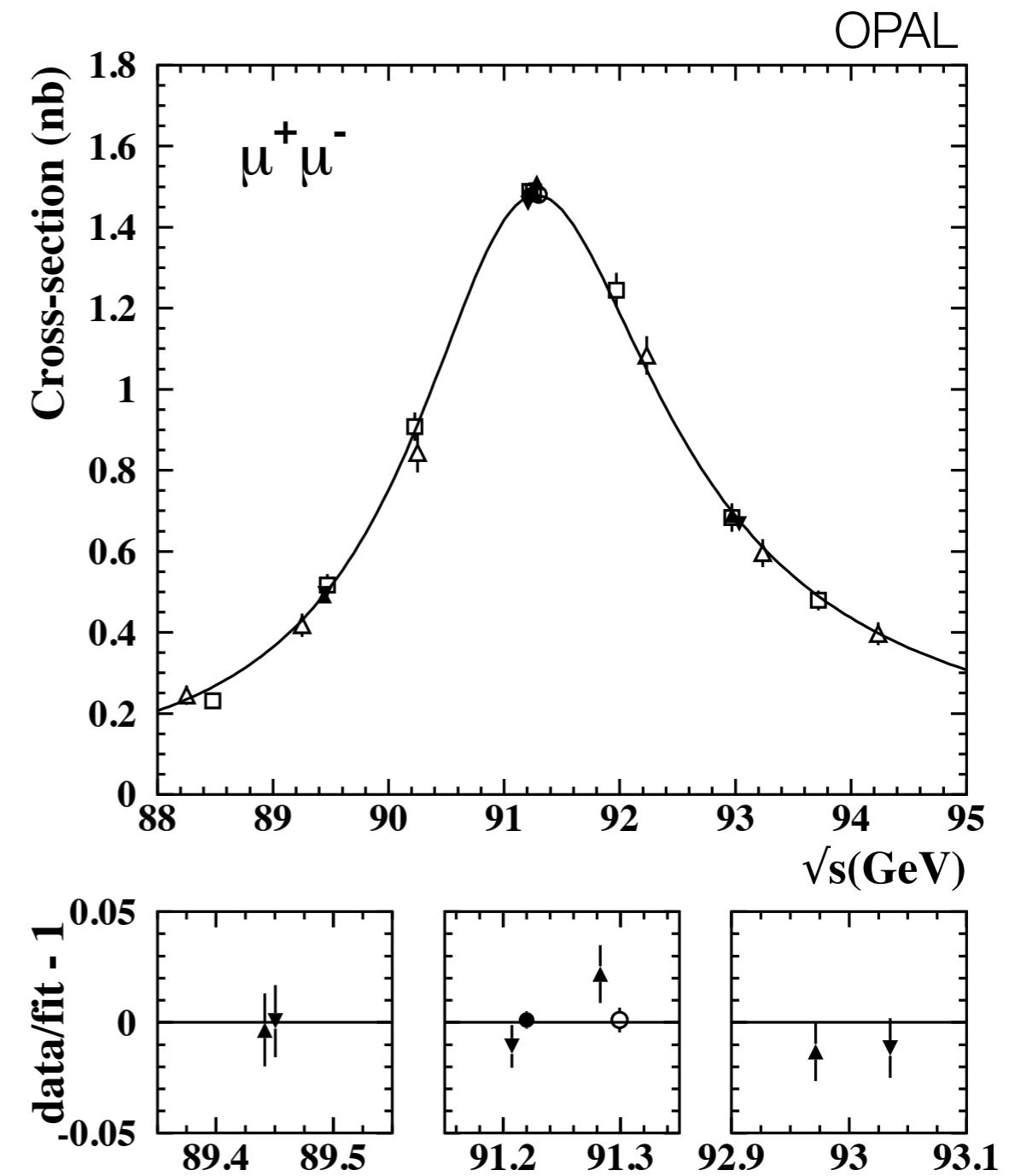
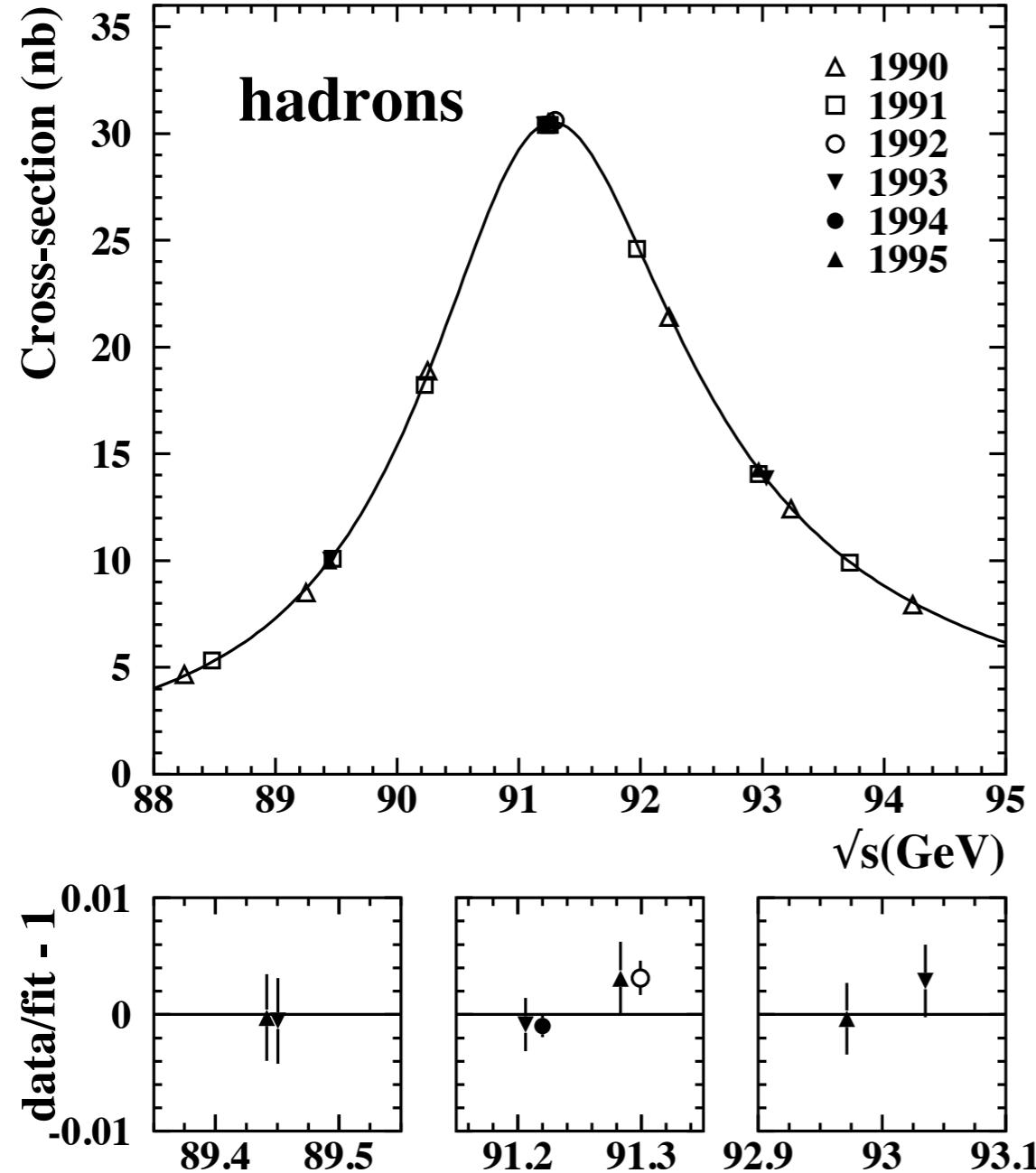


Peak:  $\sigma^0 \approx \frac{12\pi}{m_Z^2} \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2}$

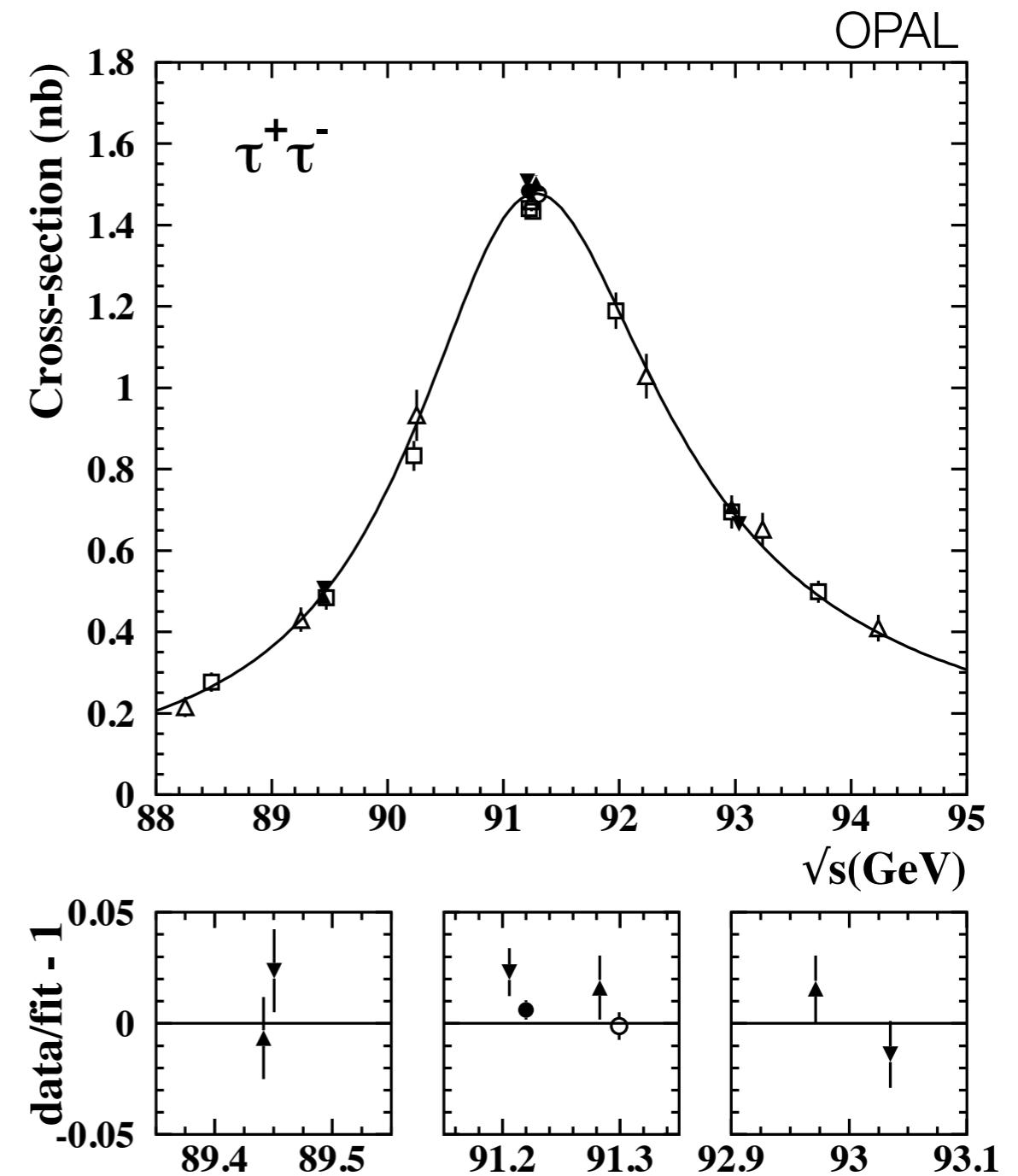
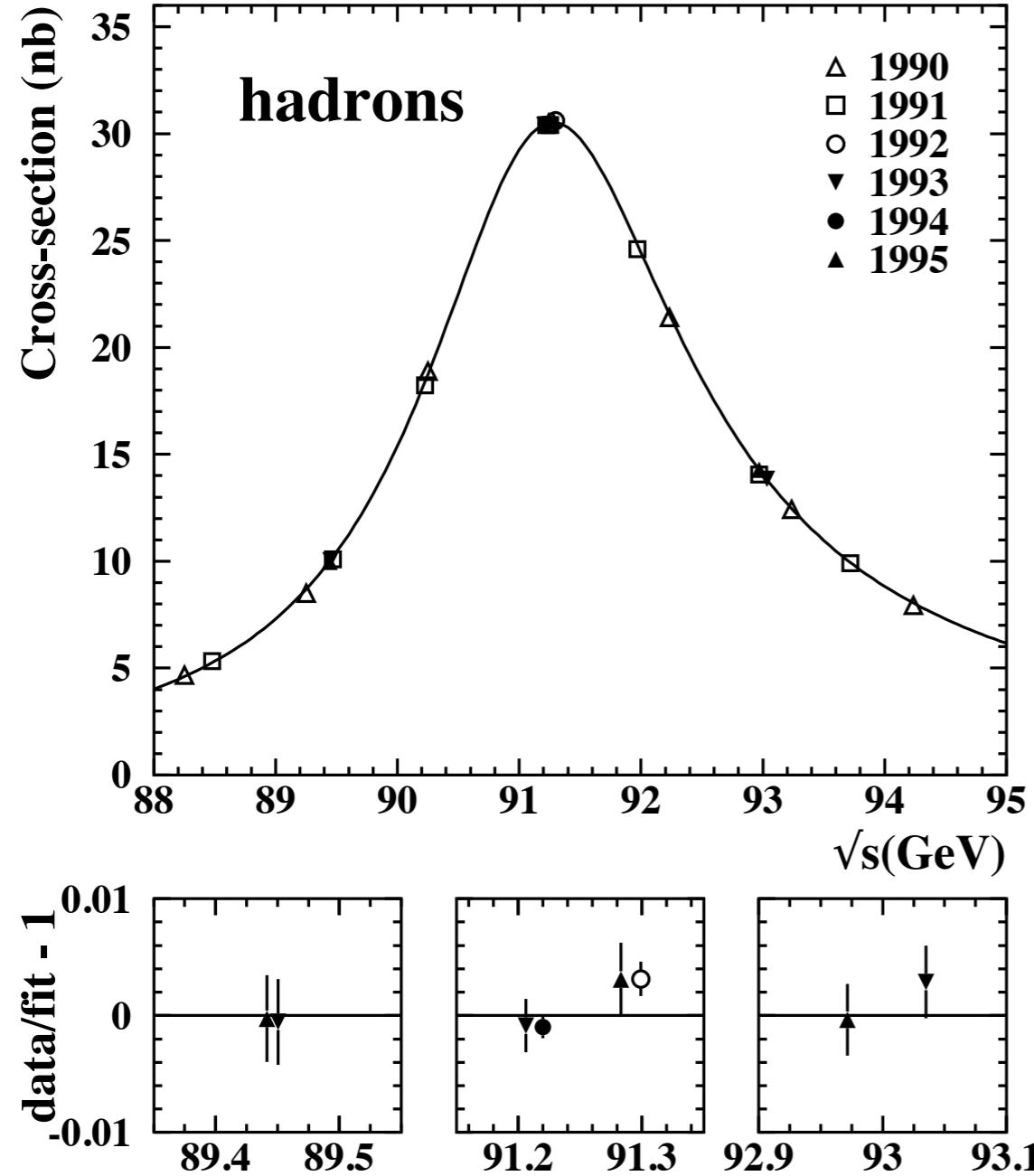
- Resonance position  $\rightarrow m_Z$   
Peak cross section  $\rightarrow \Gamma_e \Gamma_f$   
Resonance width  $\rightarrow \Gamma_Z$

But: must consider QED corrections !  
[especially initial state Bremsstrahlung]

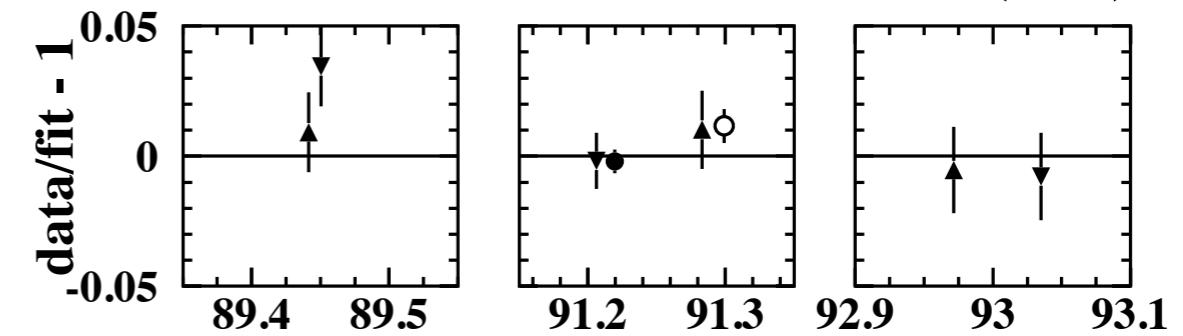
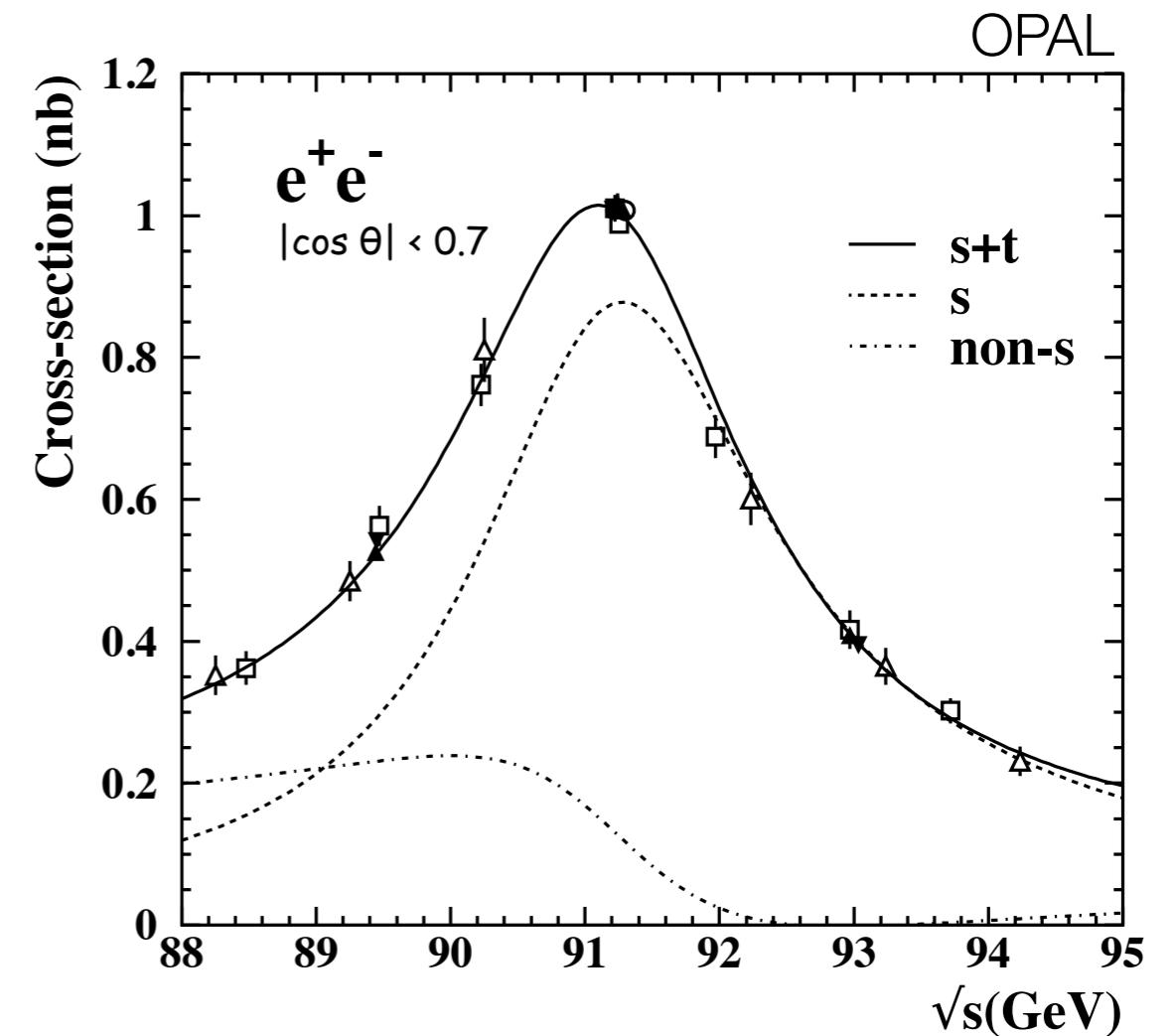
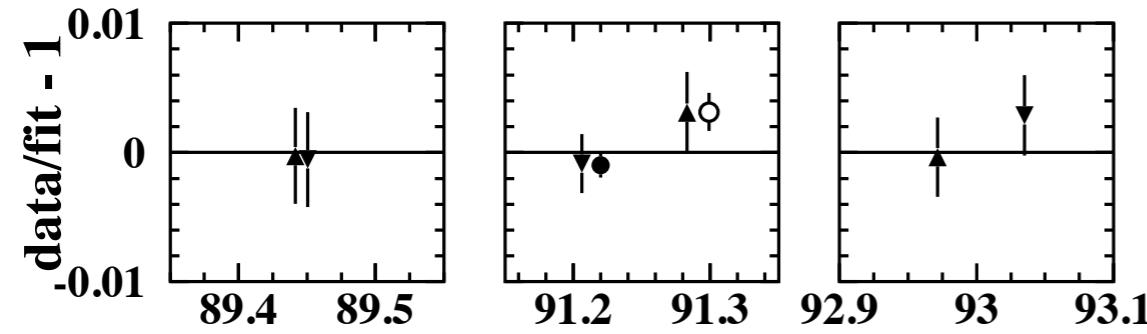
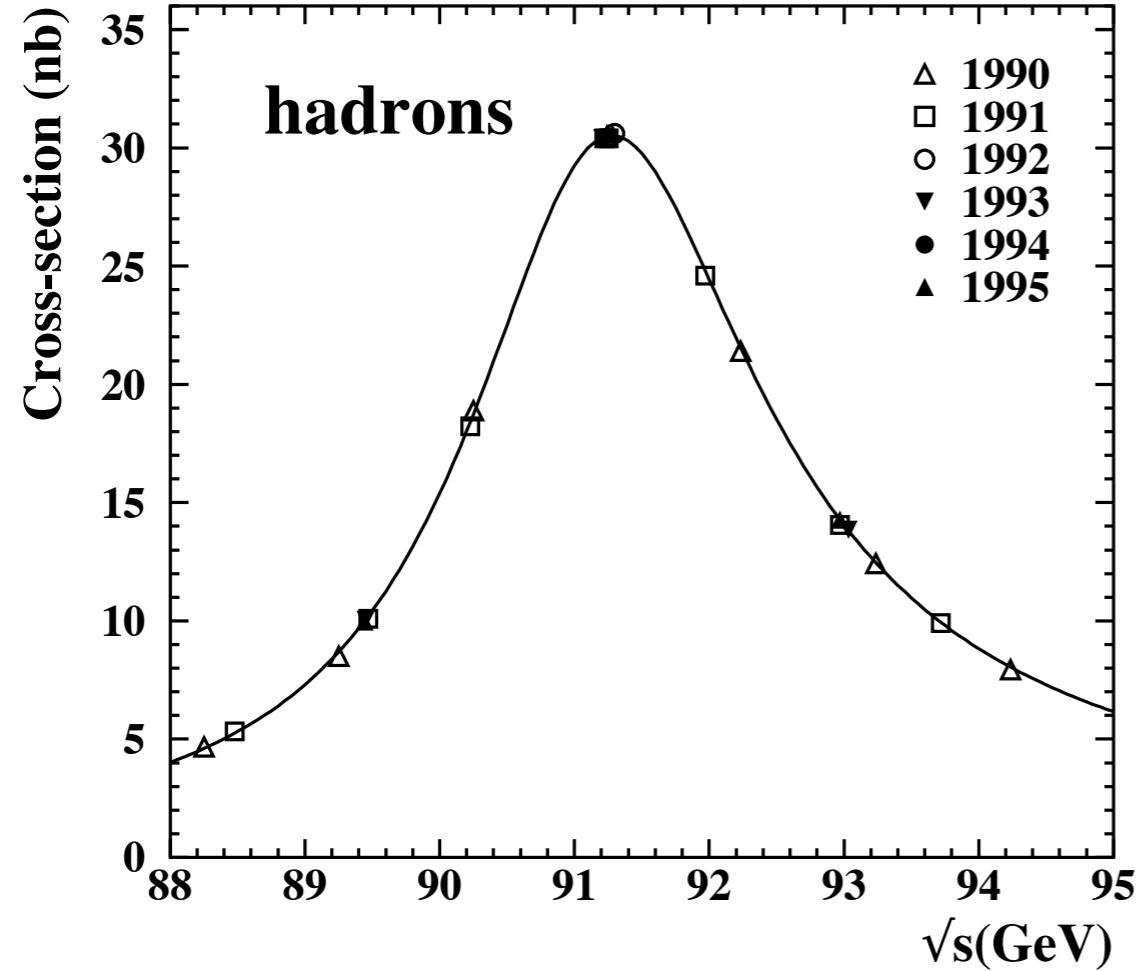
# Measurement of Z Lineshape



# Measurement of Z Lineshape



# Measurement of Z Lineshape



# Measurement of Z Lineshape

$$M_Z = 91.1876 \pm 0.0021 \text{ GeV}$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

$$\Gamma_{\text{had}} = 1.7458 \pm 0.0027 \text{ GeV}$$

$$\Gamma_e = 0.08392 \pm 0.00012 \text{ GeV}$$

$$\Gamma_\mu = 0.08399 \pm 0.00018 \text{ GeV}$$

$$\Gamma_\tau = 0.08408 \pm 0.00022 \text{ GeV}$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

$$\Gamma_{\text{had}} = 1.7444 \pm 0.0022 \text{ GeV}$$

$$\Gamma_e = 0.083985 \pm 0.000086 \text{ GeV}$$

$\pm 23 \text{ ppm}$   
[LEP energy measurement: 19ppm]

$\pm 0.09 \%$

e,μ,τ treated  
independently

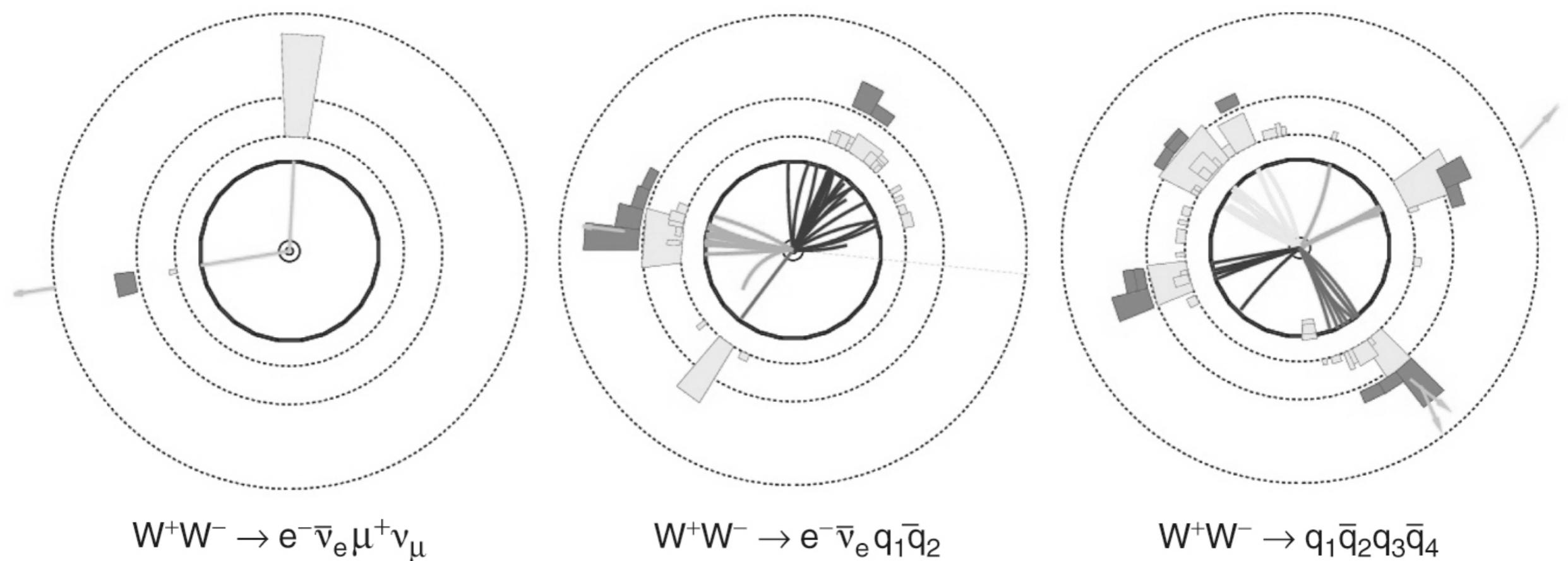


Test of  
lepton universality

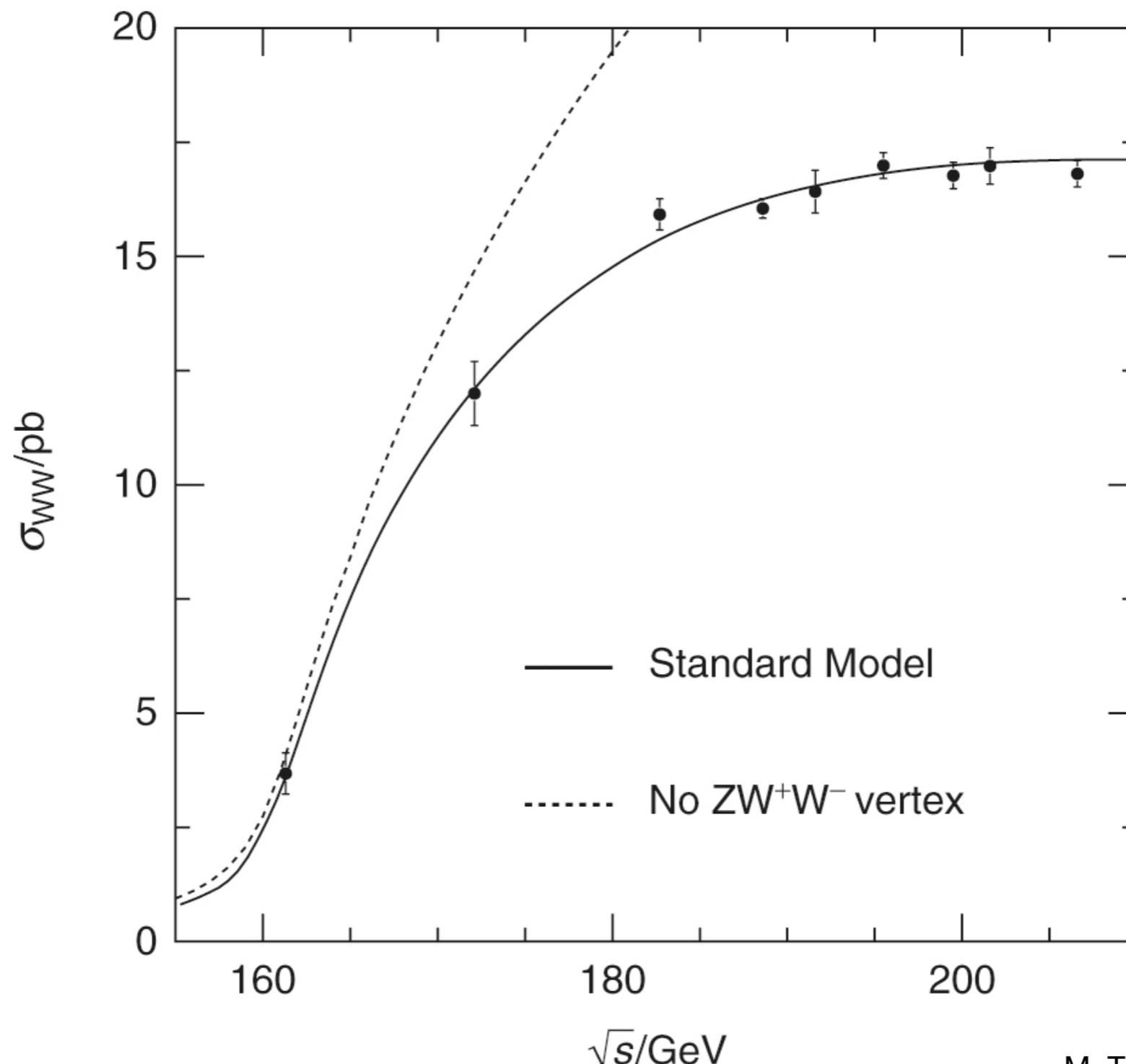


assuming  
lepton universality

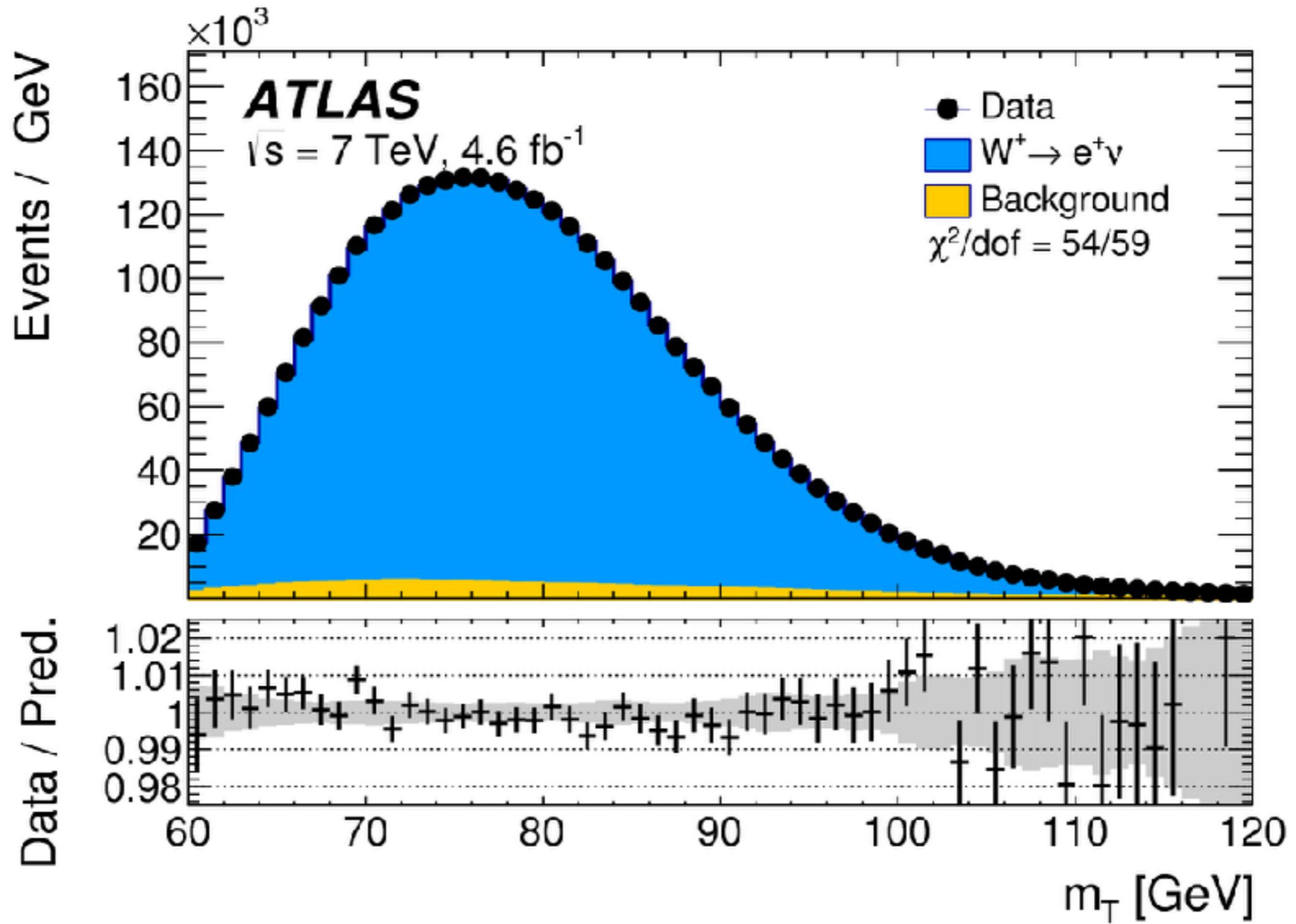
# Event Topologies for W Pair Production



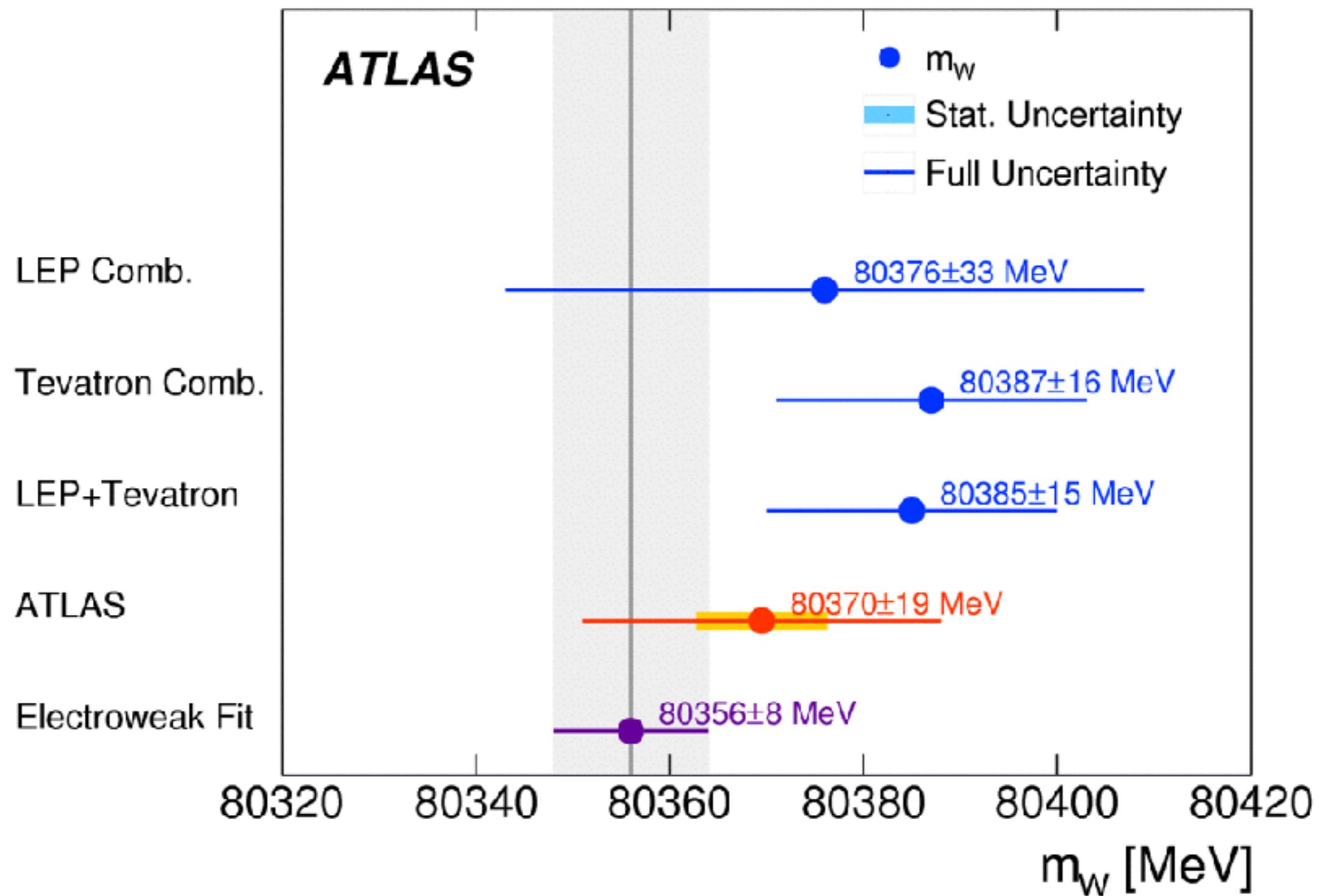
# W Pair Production Cross Section



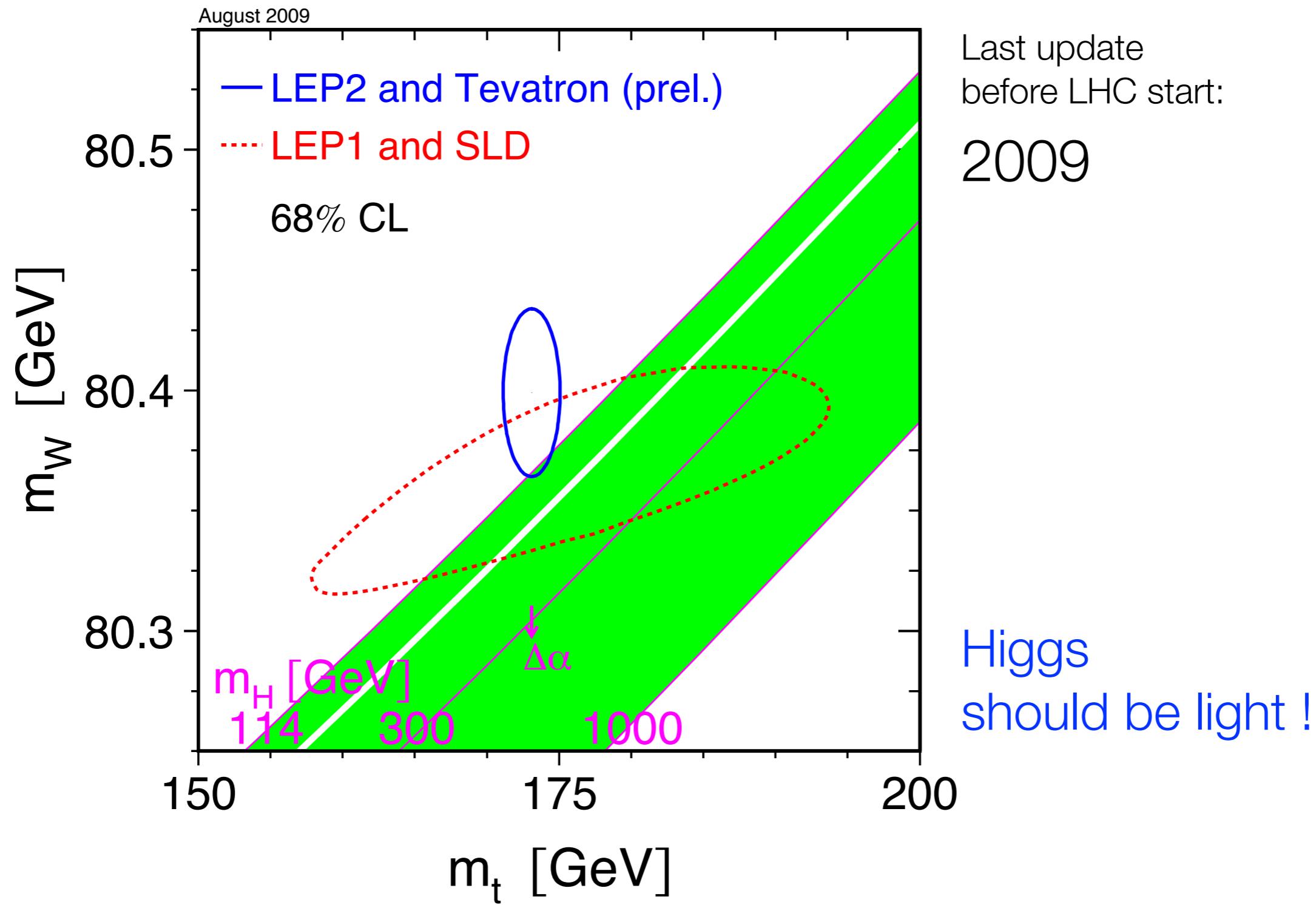
# W mass measurements



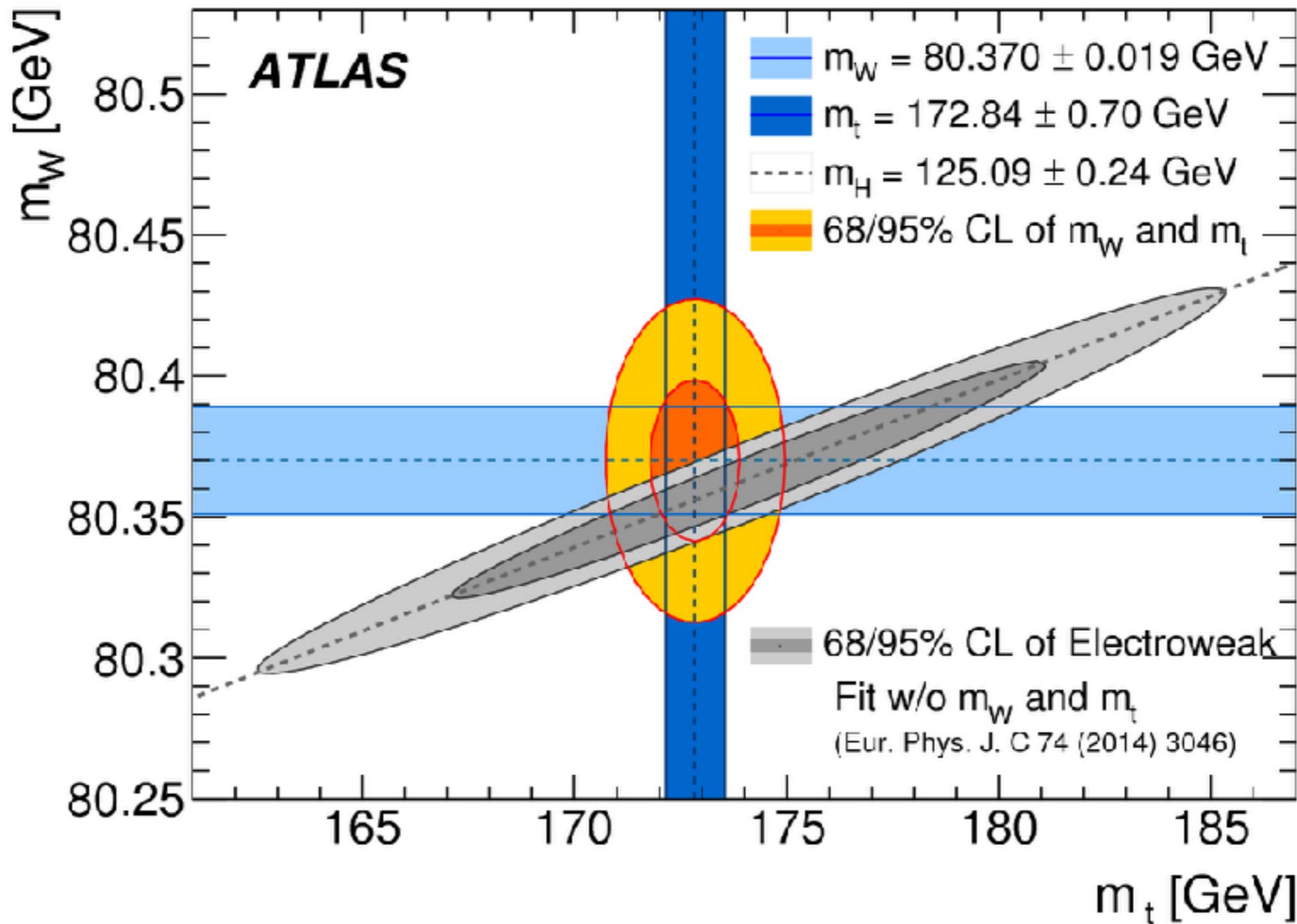
# W Mass



# Constraining the Standard Model

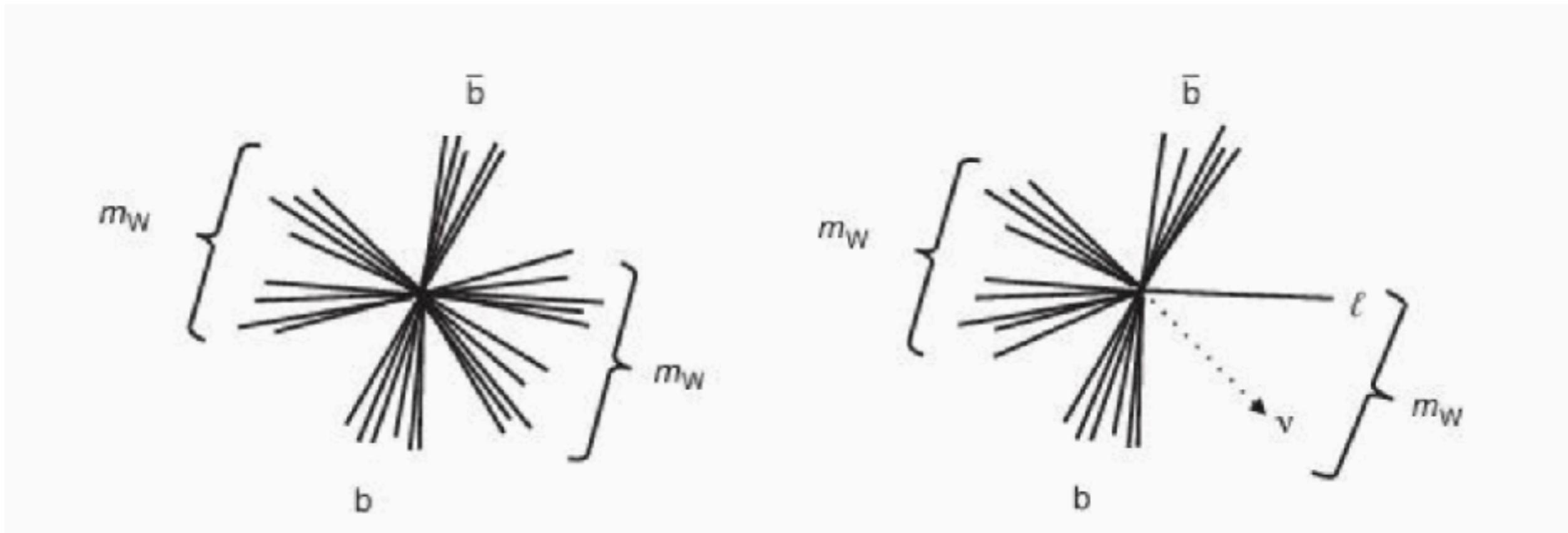


# Current results



# Top decays

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# Top mass

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