Standard Model Physics
Results from LEP2

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on behalf of the LEP collaborations
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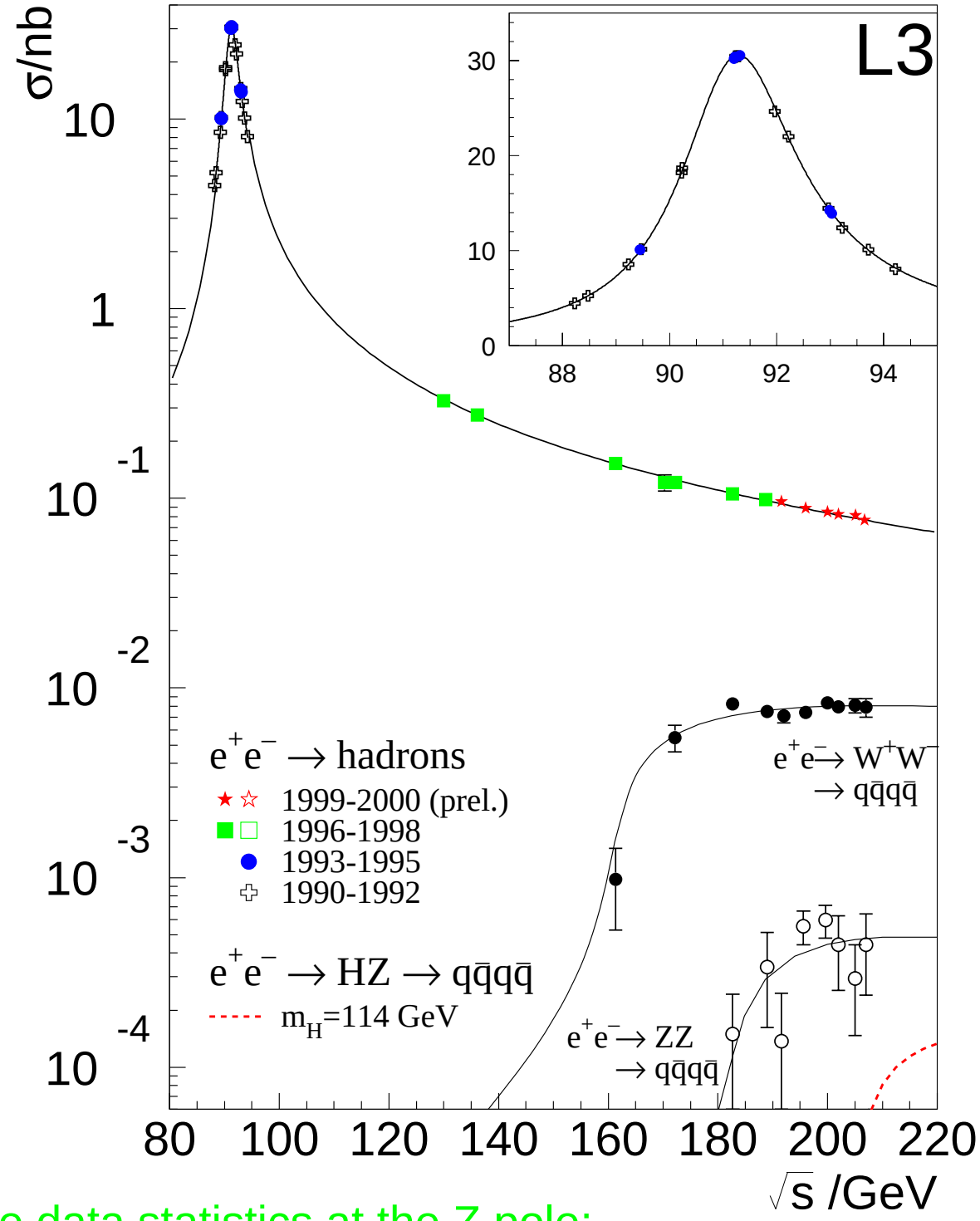
5th International Symposium on Radiative Corrections
Carmel, USA
11.-15. September 2000

- Fermion Pair Production
  - Cross sections and Asymmetries
  - S-matrix
  - Contact interactions
- Boson Cross Sections
  - ZZ Production
  - Single W Production
- W^+W^- Production
  - Cross Section
  - Branching Fractions
- W Mass Measurement
  - Mass extraction
  - Systematic Errors
  - Comparison of Direct and Indirect Results
- Standard Model Fits



- large data statistics at the Z pole:

  15 million hadronic and 2 million leptonic events

- above the Z resonance:

  luminosity 590 – 630 pb^{-1} per experiment

- more than 8000 W-pair events per experiment

See LEP2MC workshop proceedings
hep-ph/0005309, hep-ph/0007180

2-Fermion Processes

- ZFITTER, KKMC
  better than 0.2% precision in σ_{tot} of hadrons, leptons

- KKMC covers LEP, LC, μ-colliders, τ- and b-factories.

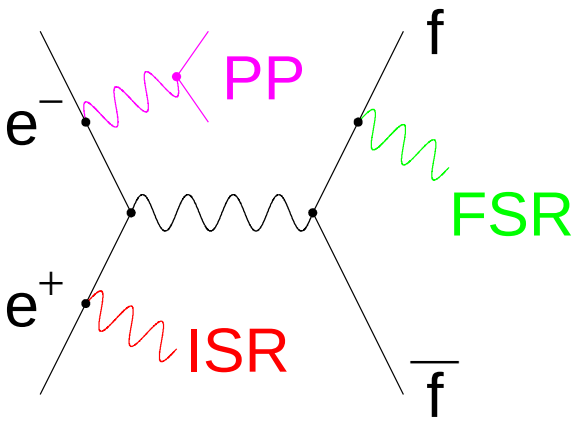
4-Fermion Processes

- RacoonWW, YFSWW3
  $\sigma(\mathrm{W^+W^-})$ to 0.4%. (double-pole approx. above threshold.)
- WPHACT, grc4f, WTO, ...
  $\sigma(We\nu)$ to 4-5%. (fermion loop scheme.)
- YFSZZ, ZZTO
  $\sigma(ZZ)$ to 2%.

$\Downarrow$

Excellent match in precision

Experiment $\Longleftrightarrow$ Theory

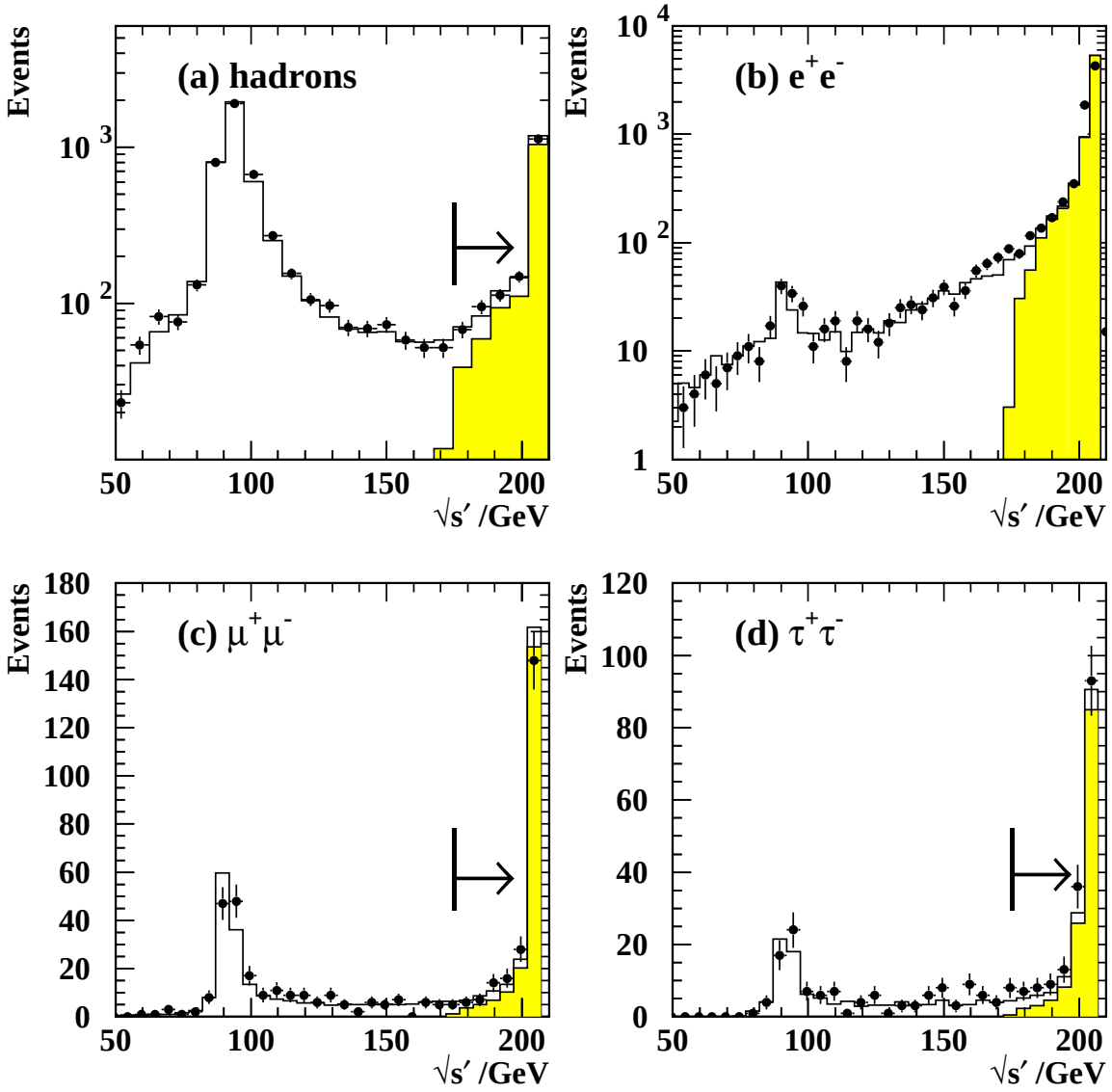


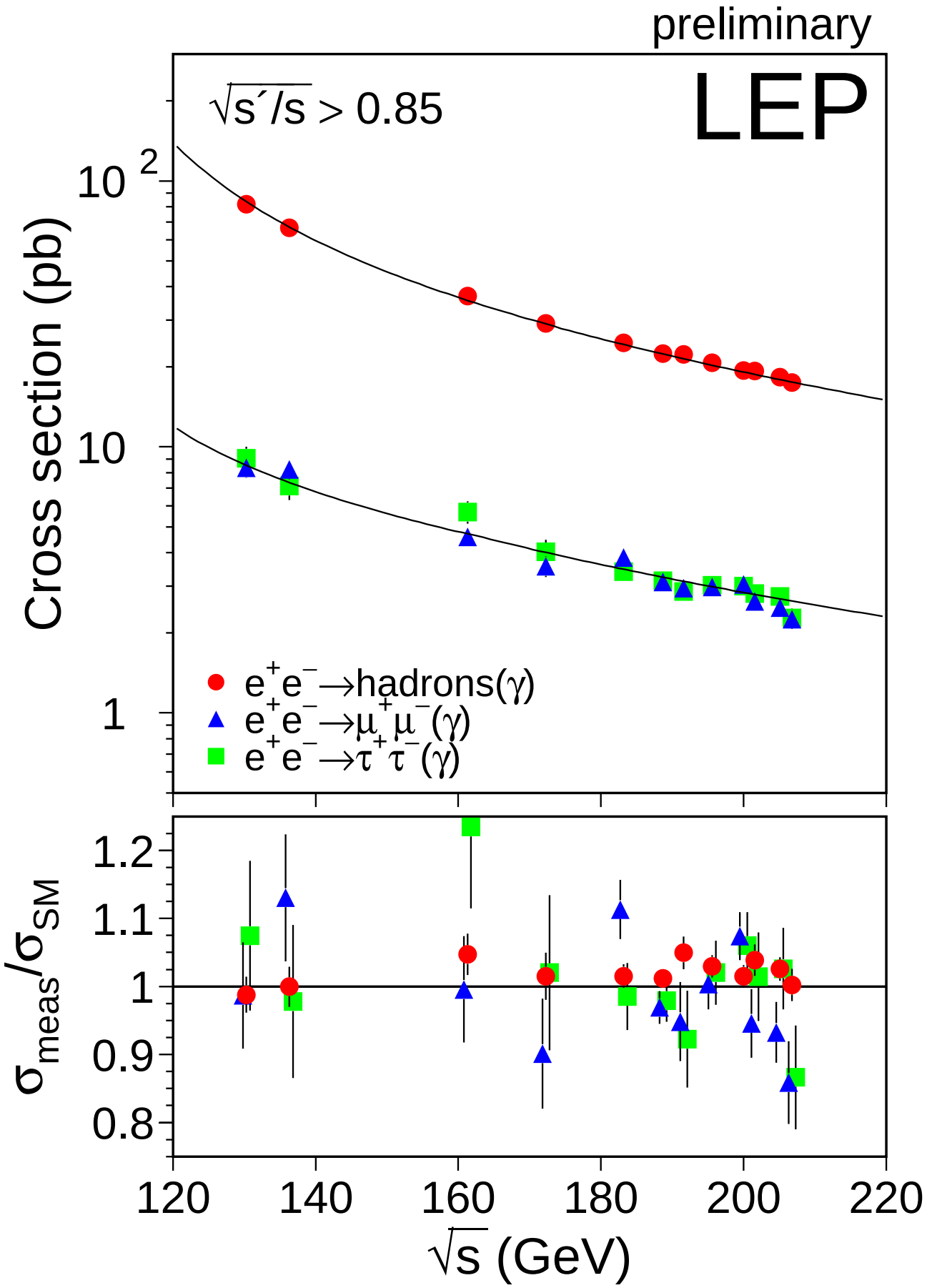
- Initial State Radiation
- Pair Production:
- Final State Radiation

$\sqrt{s'}$:= mass of outgoing lepton pair or γ^*/Z propagator

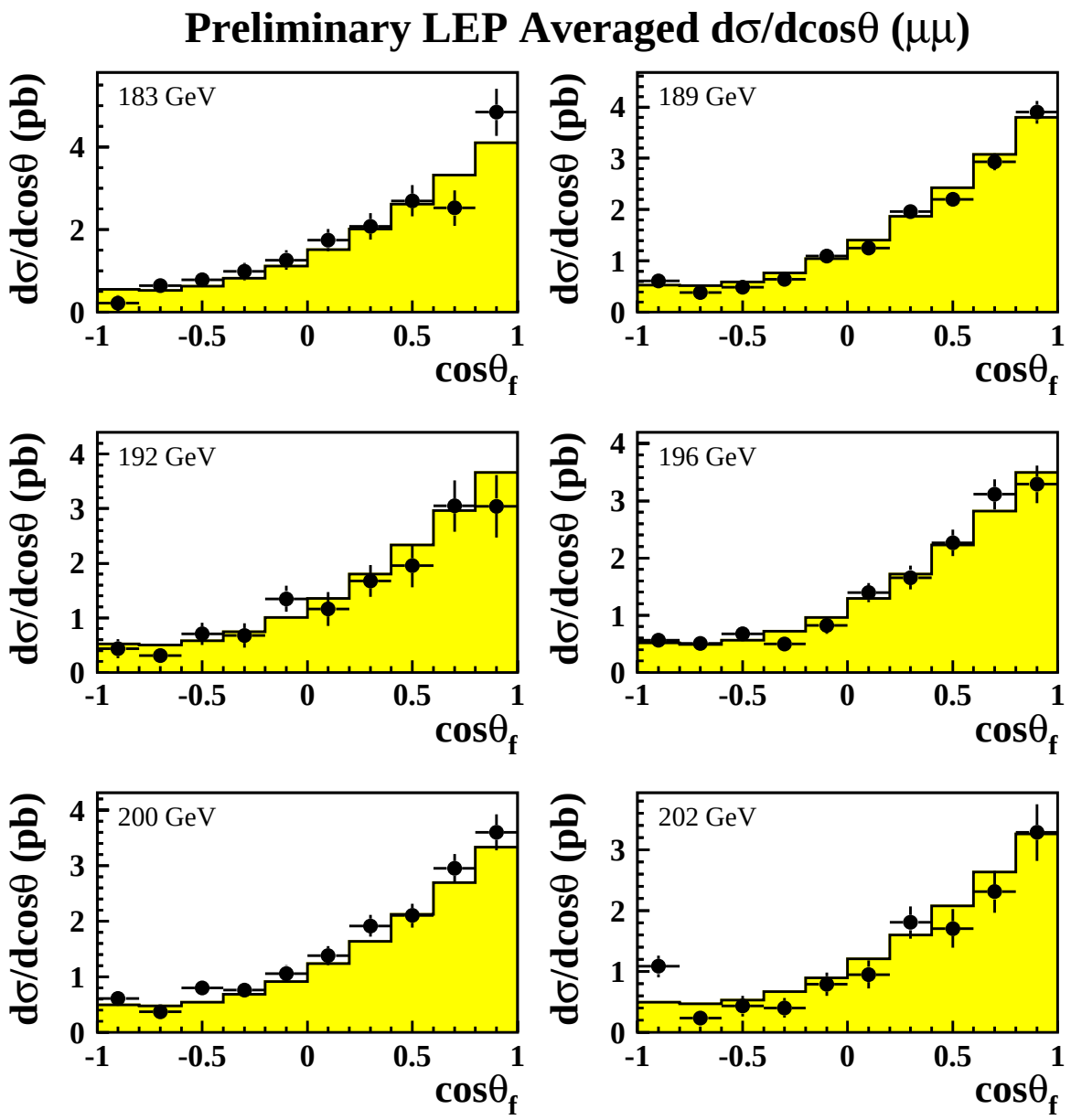
→ high energy events: $\sqrt{s'} > 0.85\sqrt{s}$

OPAL 205.4 GeV preliminary



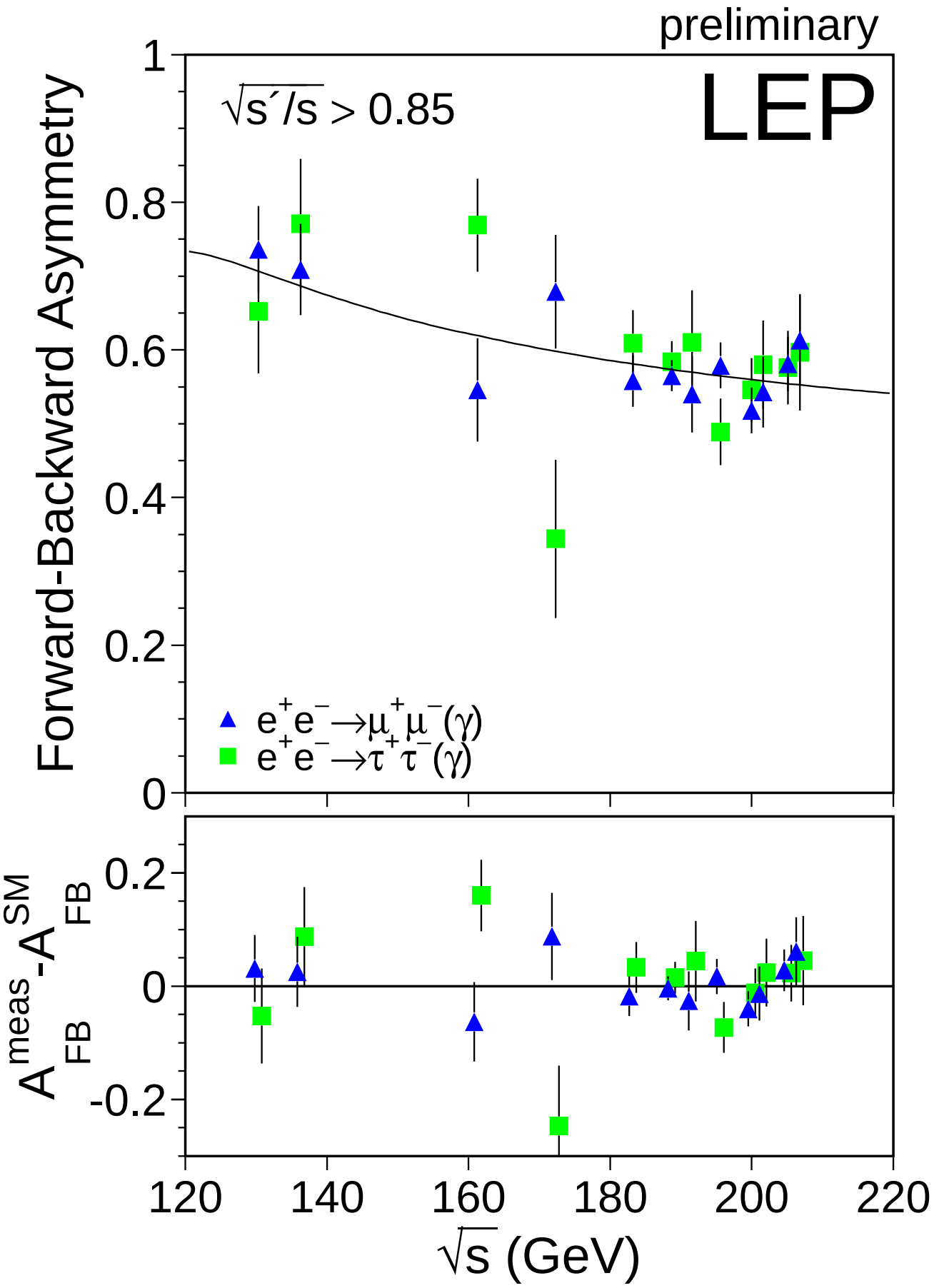

preliminary
LEP
$\sqrt{s'/s} > 0.85$
Cross section (pb)
10^2
10
1
$e^+e^- \to \text{hadrons}(\gamma)$
$e^+e^- \to \mu^+\mu^-(\gamma)$
$e^+e^- \to \tau^+\tau^-(\gamma)$
$\sigma_{meas}/\sigma_{SM}$
1.2
1.1
1
0.9
0.8
120
140
160
180
200
220
$\sqrt{s}$ (GeV)

Differential cross sections for Muon-, Tau-pair production

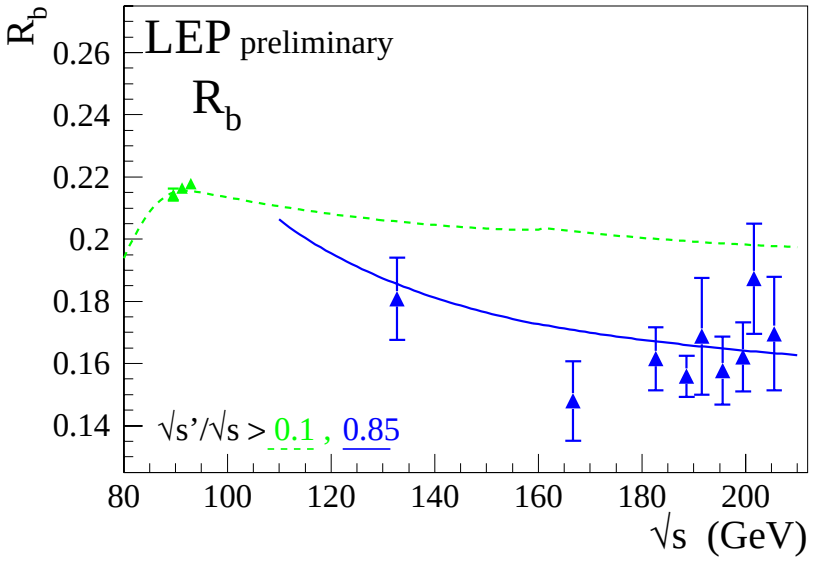


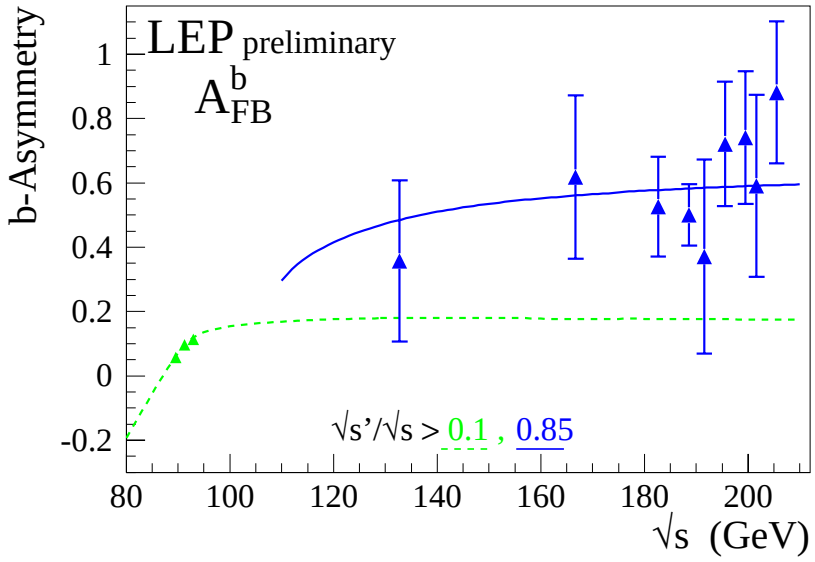
Use for limits on

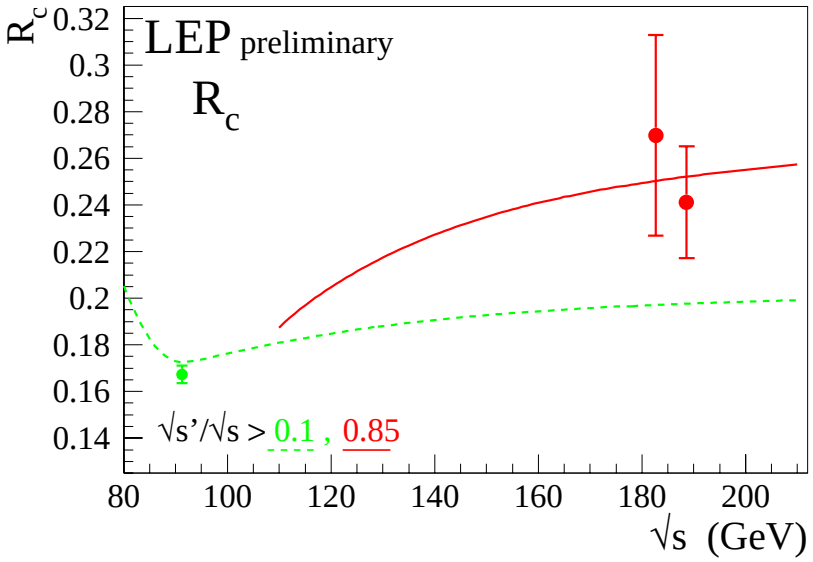
- Contact interactions
- Fermion size
- Extra dimensions, TeV strings, gravitons

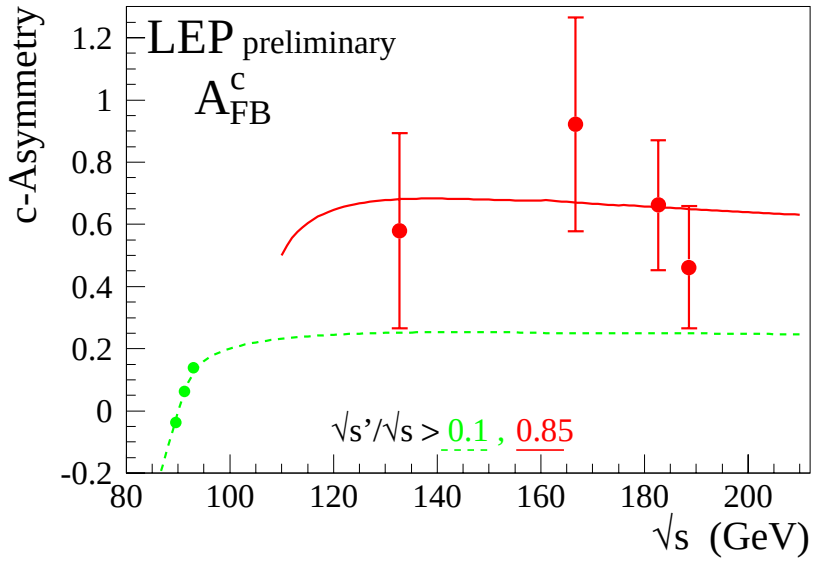

preliminary
LEP
$\sqrt{s'/s} > 0.85$
Forward-Backward Asymmetry
$e^+e^- \to \mu^+\mu^-(\gamma)$
$e^+e^- \to \tau^+\tau^-(\gamma)$
$A_{FB}^{meas} - A_{FB}^{SM}$
$\sqrt{s}$ (GeV)

s (again) the ratio of cross sections

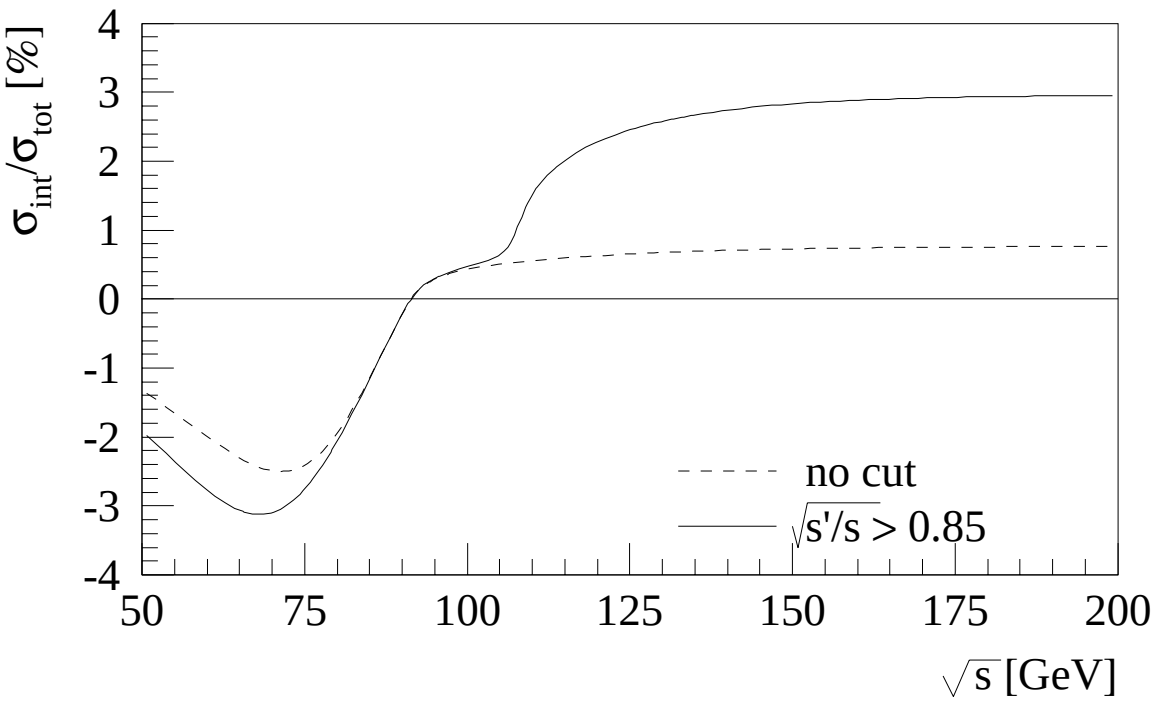








- Measure Interference between γ and Z (j_{had})

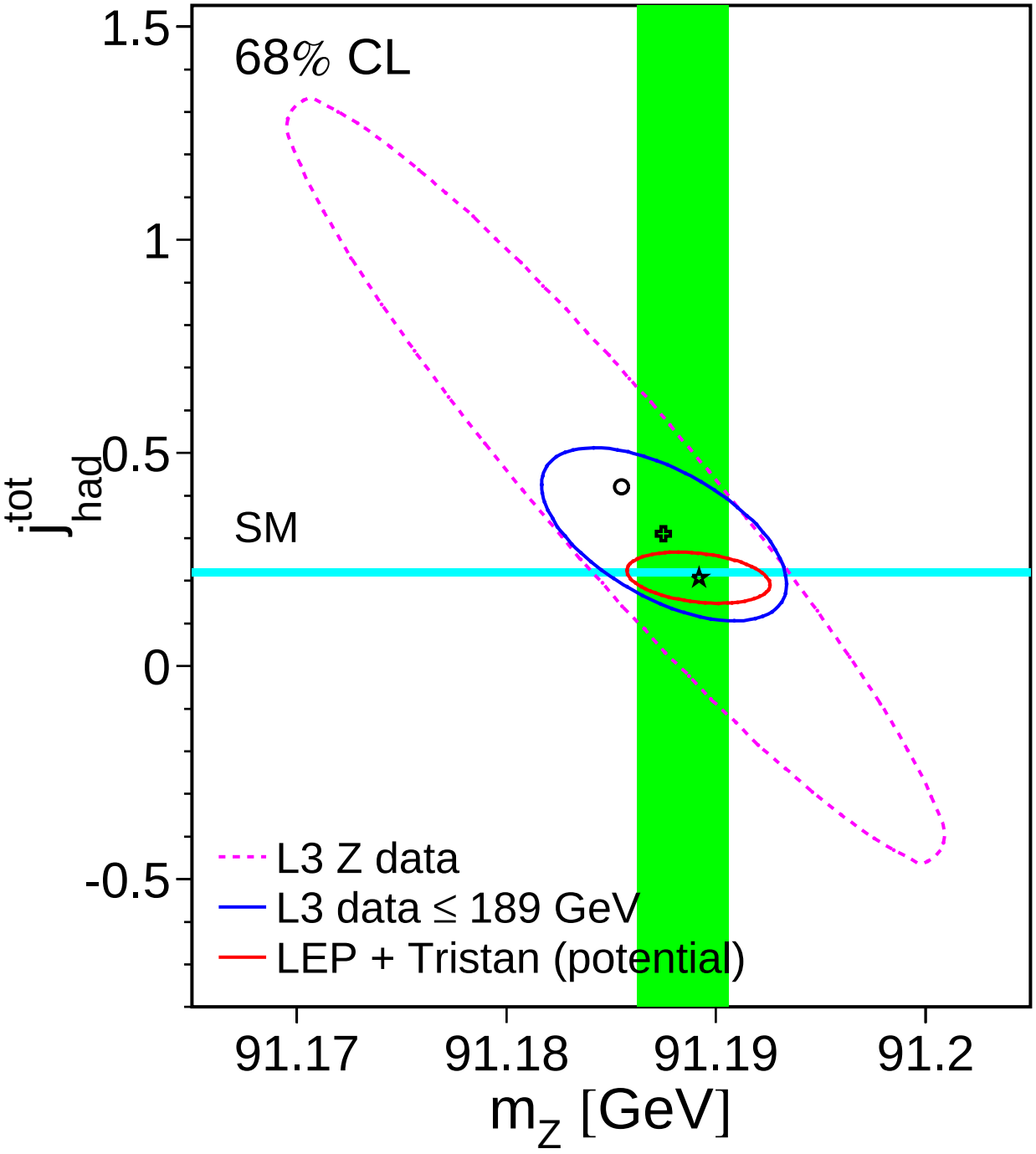


$$\sigma_a^0(s) = \frac{4}{3}\pi\alpha^2\left[\frac{g_f^a}{s} + \frac{j_f^a(s-\overline{m}_Z^2) + r_f^a\, s}{(s-\overline{m}_Z^2)^2 + \overline{m}_Z^2\overline{\Gamma}_Z^2}\right], \text{ for } a = \text{tot, fb,}$$

$$A_{fb}^0(s) = \frac{3}{4}\frac{\sigma_{fb}^0(s)}{\sigma_{tot}^0(s)}, \qquad \text{with} \qquad \sigma_{fb}^0 = \frac{4}{3}(\sigma_f - \sigma_b)\,.$$

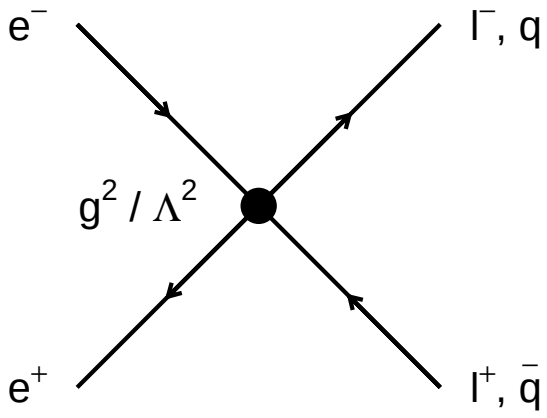
- Photon exchange
- Z-Boson exchange
- γ/Z interference

"Standard" fits: fix g_f^a and j_f^a ZFITTER, TOPAZ0
S-Matrix fits: fix g_f^a only ZFITTER, SMATASY



	M_Z[MeV]	j^{tot}_{had}	corr.
L3 Z data	91 185.2 $\pm$ 10.3	0.44 $\pm$ 0.59	-0.95
L3 $\leq$ 189GeV	91 187.5 $\pm$ 3.9	0.31 $\pm$ 0.13	-0.57
LEP + Tristan:	$\pm$ **2.3**	$\pm$ **0.04**	-0.28

$$\mathcal{L} = \frac{1}{1+\delta_{ef}} \sum_{i,j=\mathrm{L,R}} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma_\mu f_j),$$



g Coupling, by convention $g^2/4\pi = 1$

η_{ij} Helicity amplitudes, choose $|\eta_{ij}| = 0, 1$

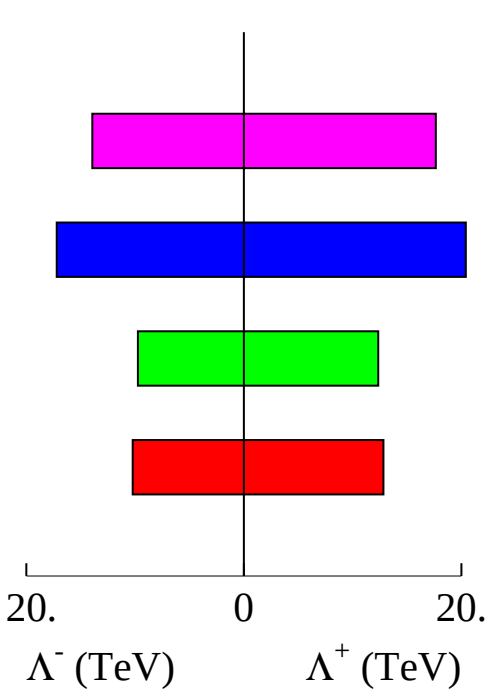
Λ Energy scale

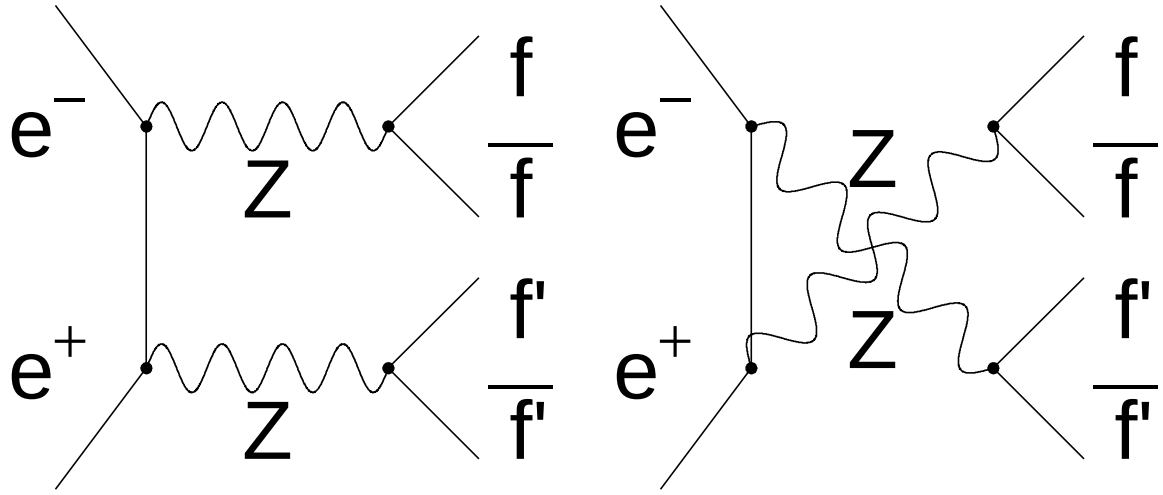
$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma^{\mathrm{SM}}}{d\cos\theta} + c_{\mathrm{int}}(s, \cos\theta)\frac{1}{\Lambda^2} + c_{\mathrm{ci}}(s, \cos\theta)\frac{1}{\Lambda^4}.$$

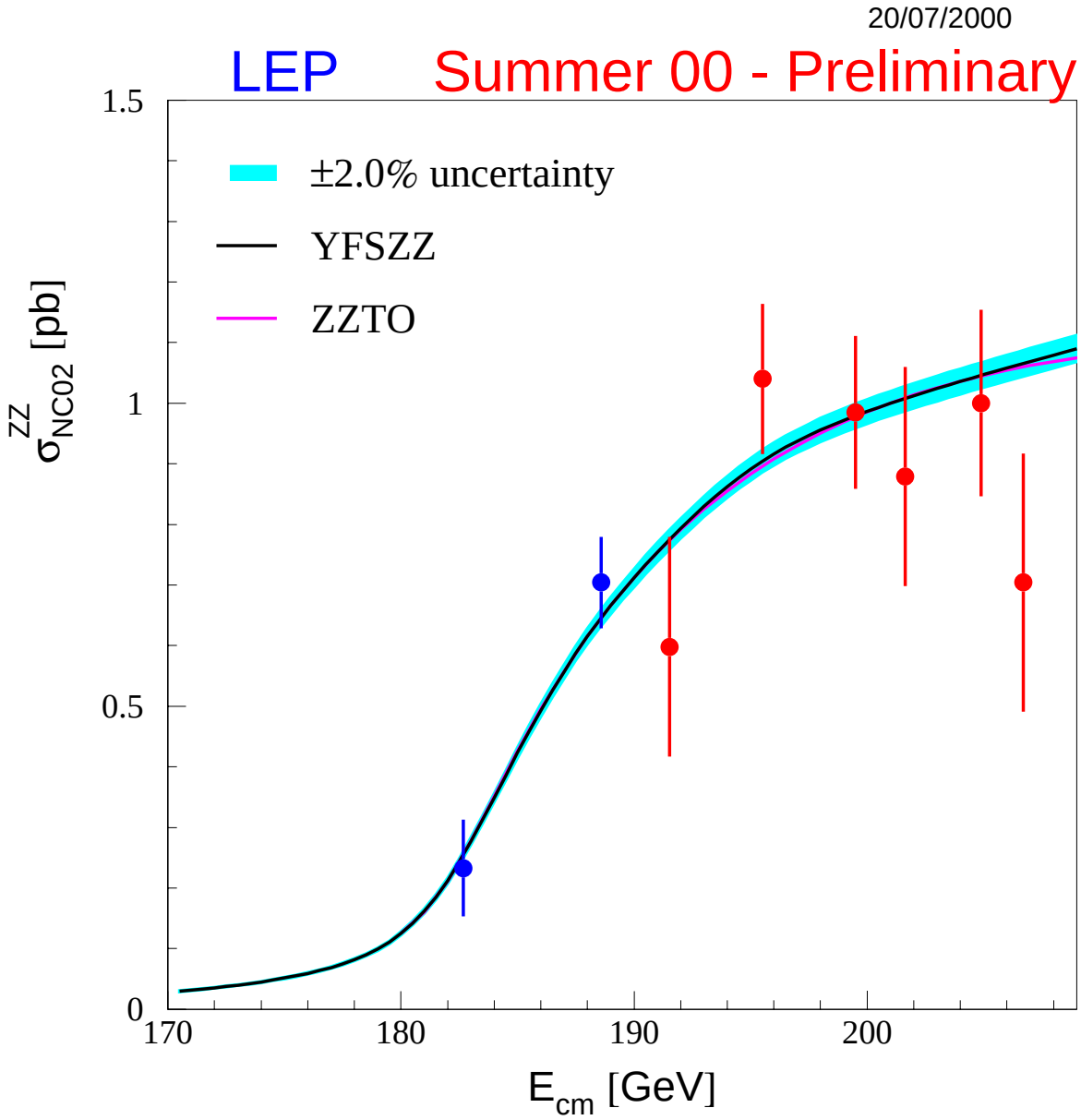
	η_{RR}	η_{LL}	η_{LR}	η_{RL}
AA	± 1	± 1	∓ 1	∓ 1
VV	± 1	± 1	± 1	± 1
RR	± 1	0	0	0
LL	0	± 1	0	0

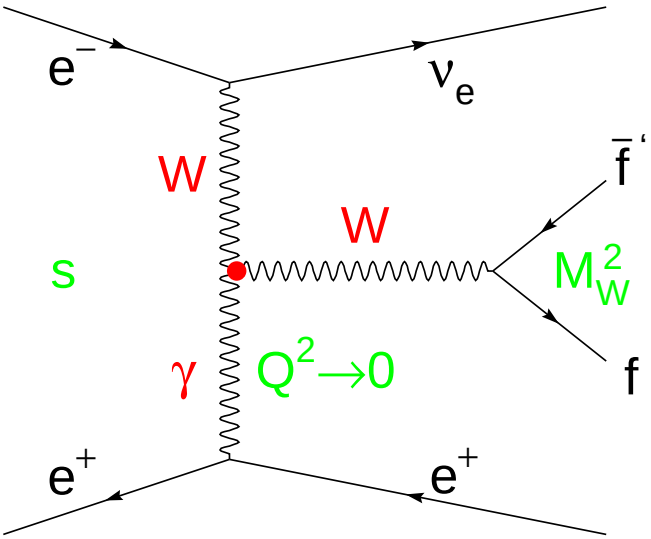
LEP Preliminary 130-202 GeV

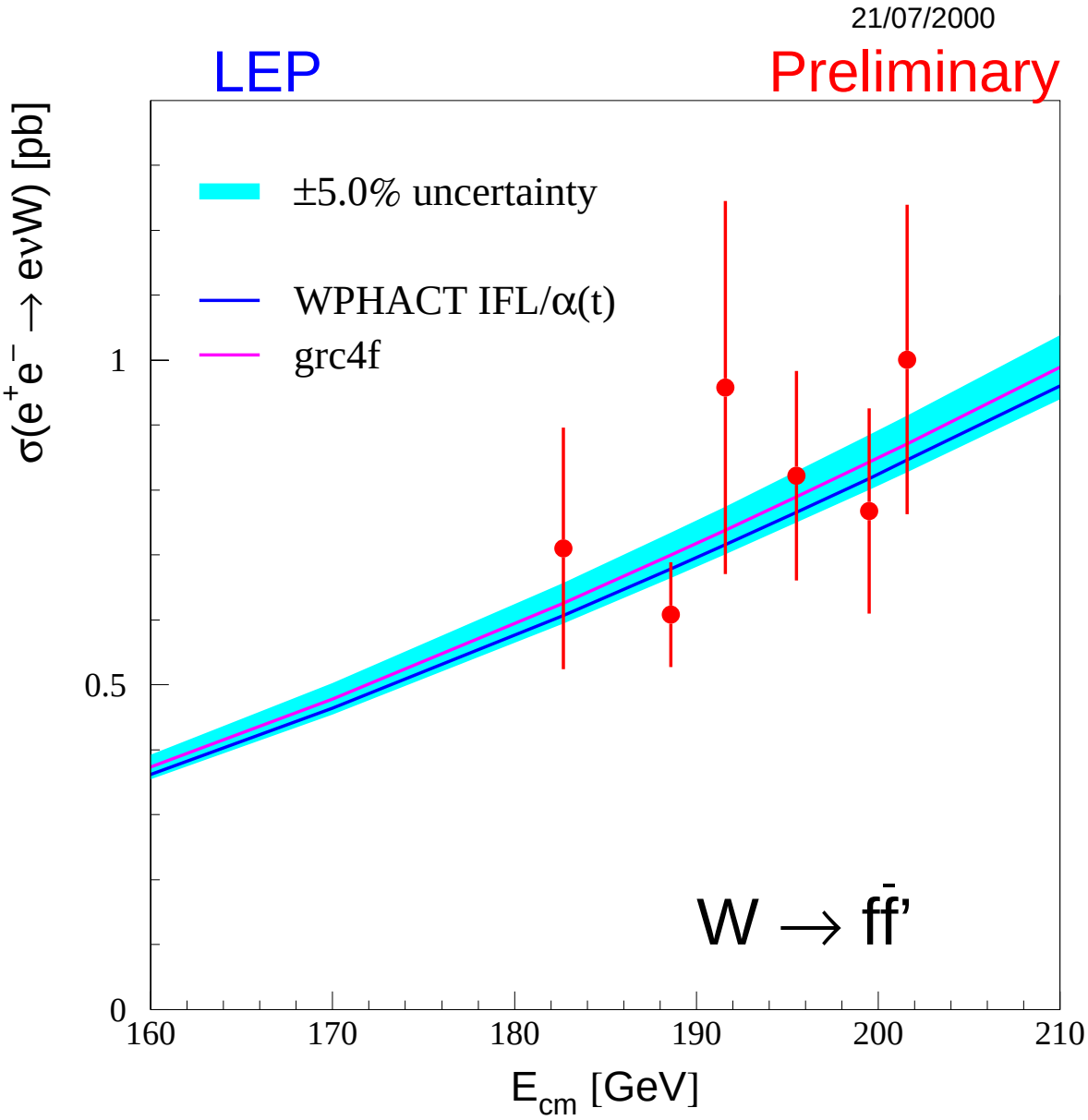
	Λ^-	Λ^+
AA	13.9	17.6
VV	17.2	20.4
RR	9.7	12.3
LL	10.2	12.8



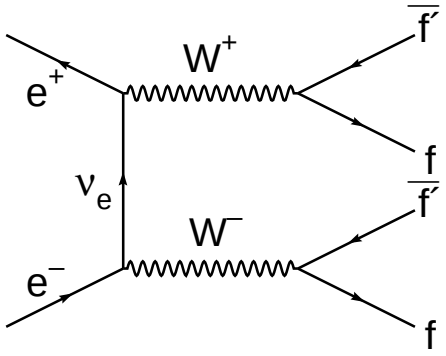

e⁻
e⁺
Z
Z
f
f
f'
f'
e⁻
e⁺
Z
Z
f
f
f'
f'

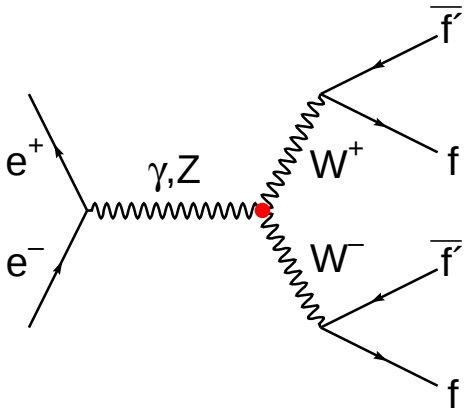

20/07/2000
LEP
Summer 00 - Preliminary
±2.0% uncertainty
YFSZZ
ZZTO
σ^{ZZ}_{NC02} [pb]
1.5
1
0.5
0
170
180
190
200
E_{cm} [GeV]


e⁻
νe
W
f̄'
W
s
M²W
γ
Q²→0
f
e⁺
e⁺

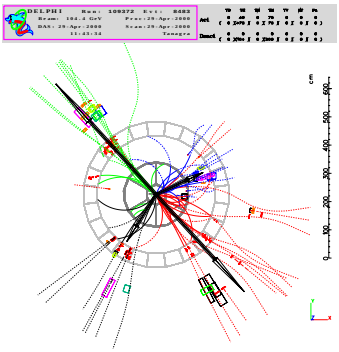

21/07/2000
LEP
Preliminary
±5.0% uncertainty
WPHACT IFL/α(t)
grc4f
σ(e⁺e⁻ → eνW) [pb]
1
0.5
0
160
170
180
190
200
210
E_cm [GeV]
W → ff̄'

- W-pair production at LEP



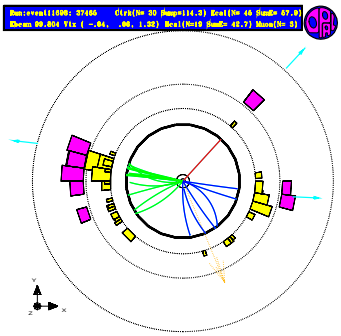


SM branchings $Br(W \to q\overline{q'}) = 67.6\%$
$Br(W \to l\overline{\nu}) = 10.8\%$ per lepton flavour



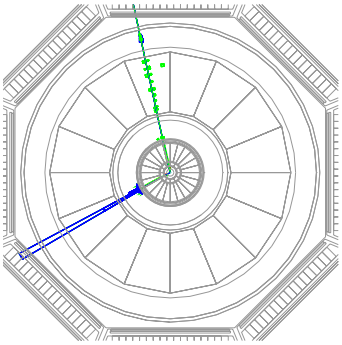
- Fully hadronic: 45.6% 4 jets

  High Multiplicity, balanced events



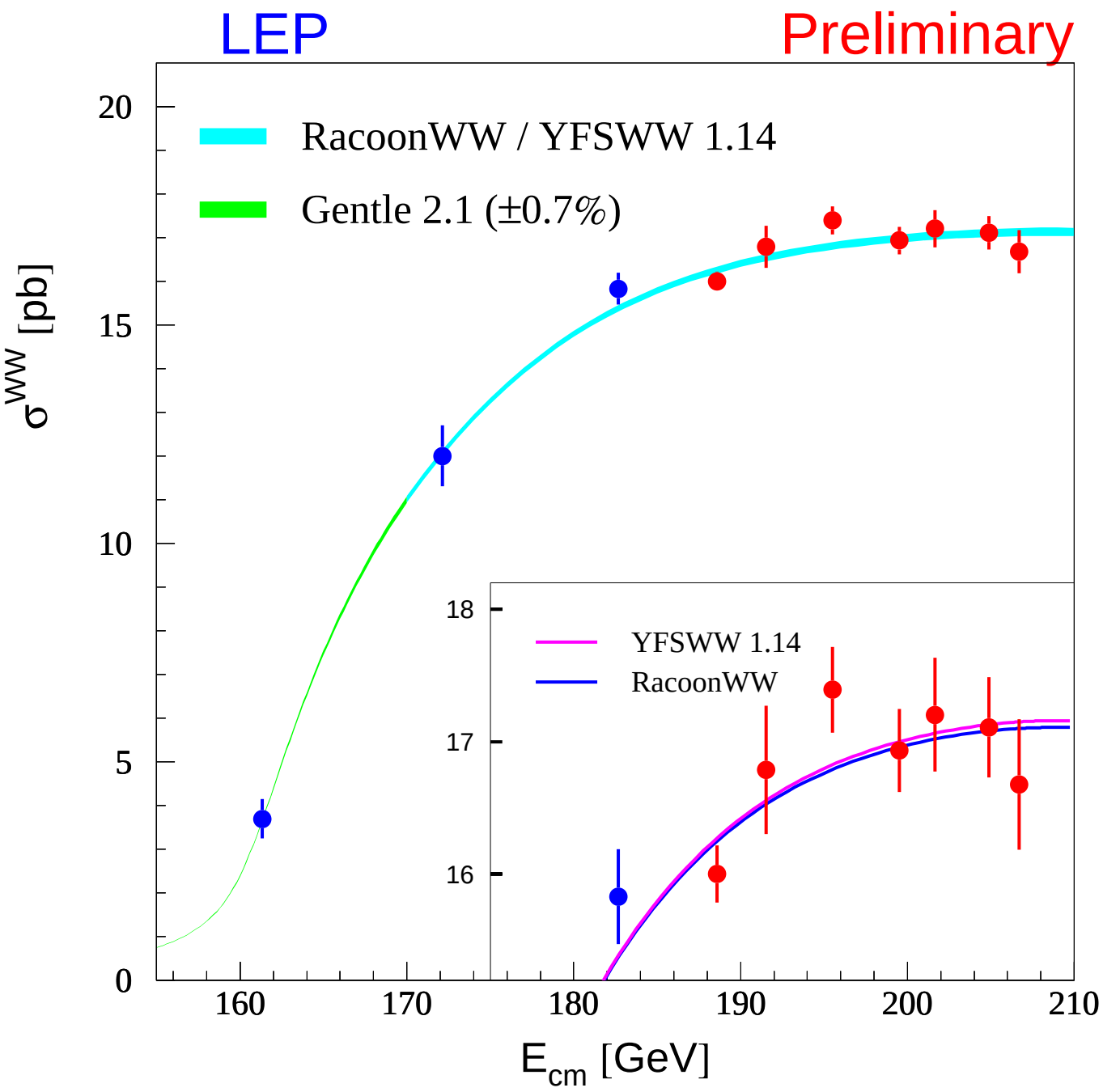
- Semileptonic: $3 \times 14.6\%$ 2 jets, 1 lepton

  Hadronic energy plus high energy lepton or narrow jet (τ)



- Fully leptonic: 10.6% 2 leptons

  Low multiplicity, acoplanar, missing energy



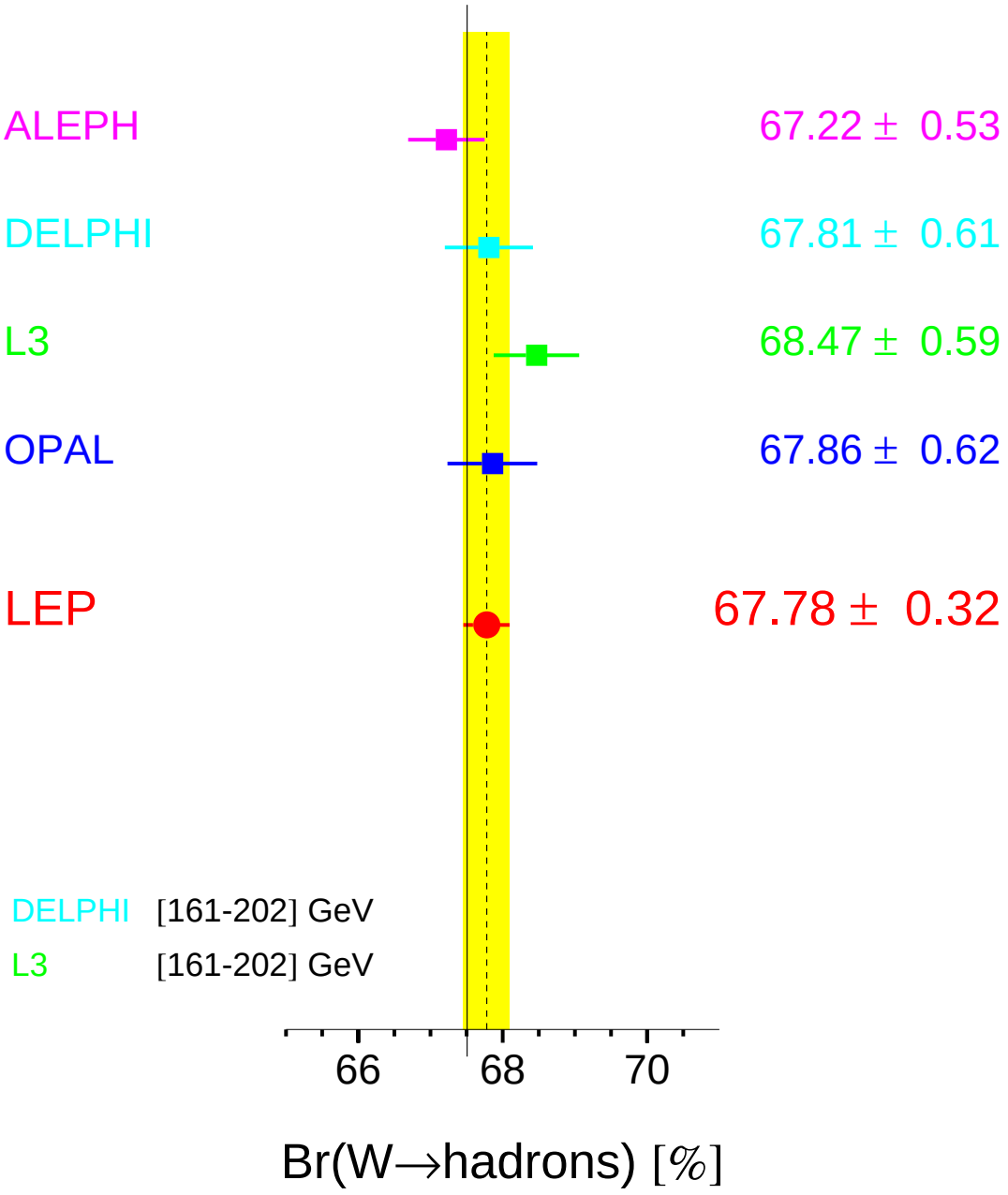
Excellent agreement with

- RacoonWW
- YFSWW

} at $E_{cm} > 170$ GeV

Summer 00 - Preliminary - [161-207] GeV

Br(W→hadrons) [%]



- Indirect determination of $|V_{cs}|$:

$$\frac{Br(W \to hadrons)}{1 - Br(W \to hadrons)} = \Sigma \left|V_{ij}^2\right| \left(1 + \frac{\alpha_s}{\pi}\right)$$

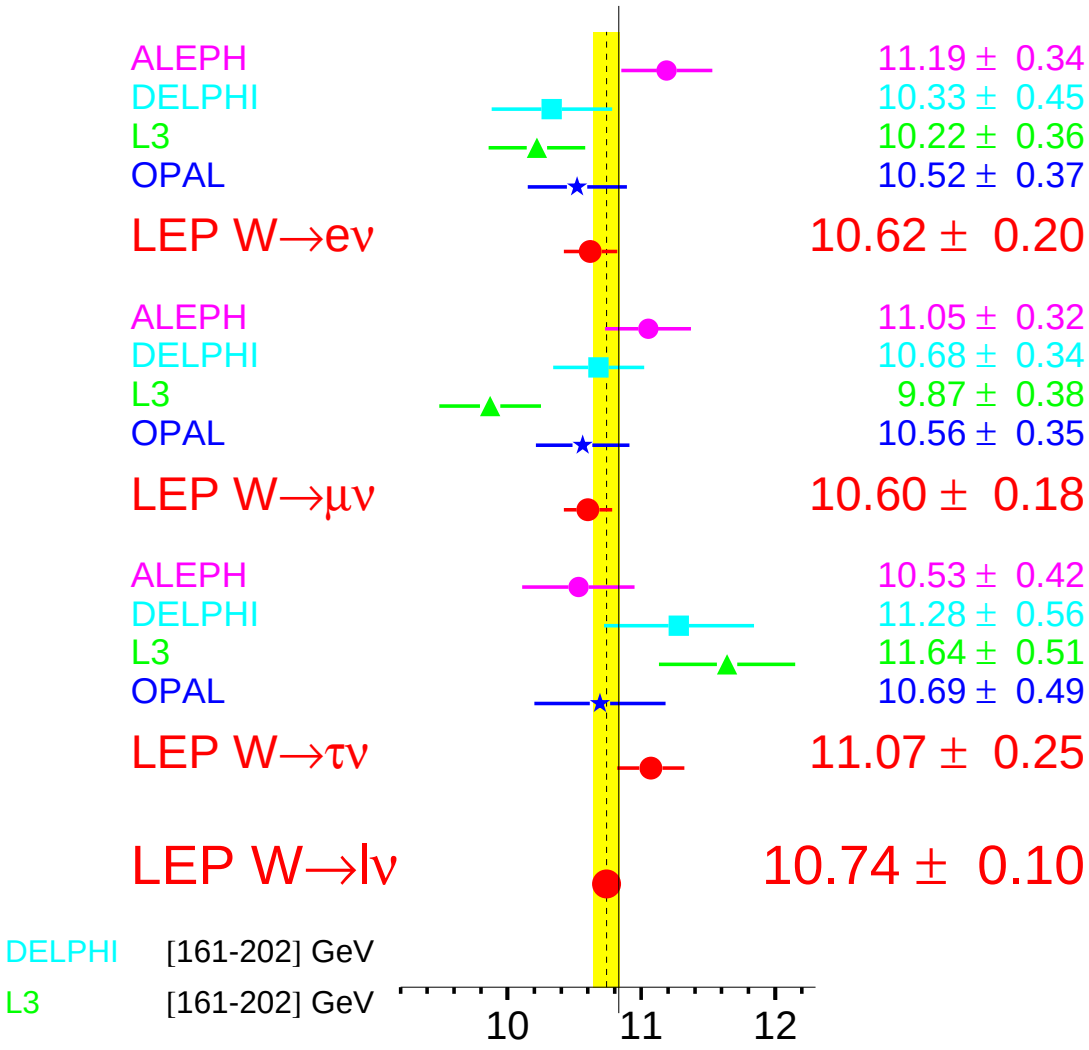
- Direct determination of $|V_{cs}|$ from tagged charm:

$$\text{OPAL}: \quad \frac{\Gamma(W \to cX)}{\Gamma(W \to had)} = 0.47 \pm 0.04 \pm 0.06$$

LEP	$\lvert V_{cs} \rvert$
Indirect	0.989 ± 0.016
Direct	0.95 ± 0.08

Summer 00 - Preliminary - [161-207] GeV

W Leptonic Branching Ratios



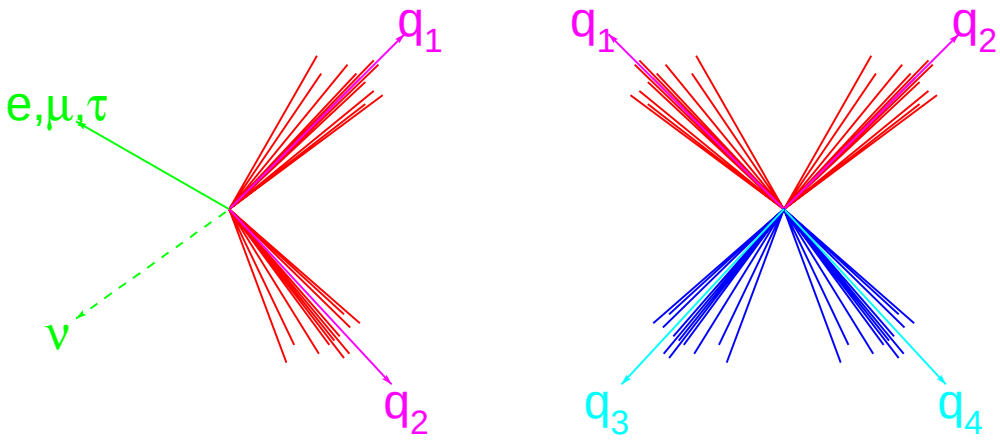
Indirect extraction from TEVATRON:

$Br(W \rightarrow e\nu)$ [%]

CDF 10.50 ± 0.30

D0 10.39 ± 0.35

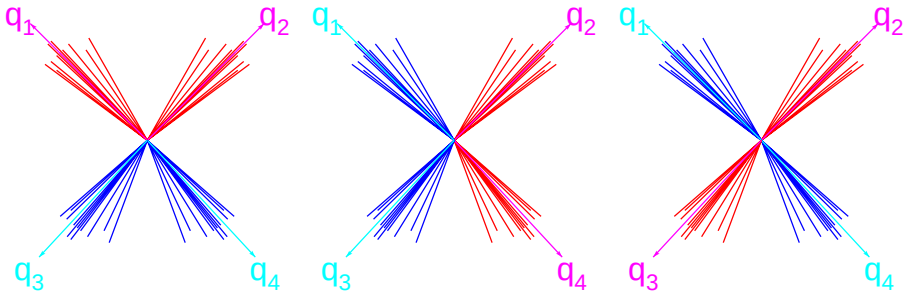
10.43 ± 0.25



- reconstruct lepton and jets
- impose kinematic constraints:

  E and $\vec{p}$ conservation $\longrightarrow$ 1C for qq$\ell\nu$, 4C for qqqq

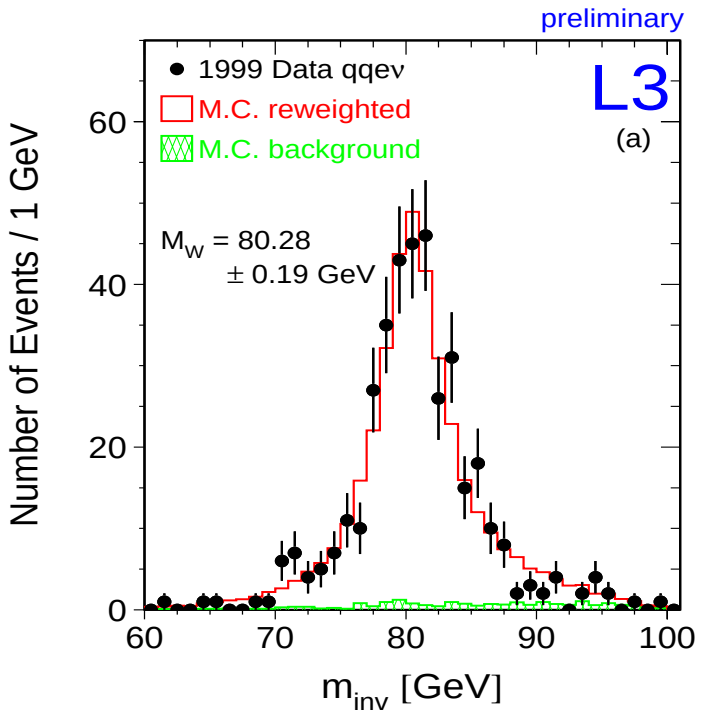
  equal masses of recontructed W's $\longrightarrow$ +1C
- special for qqqq events: jet pairing problem

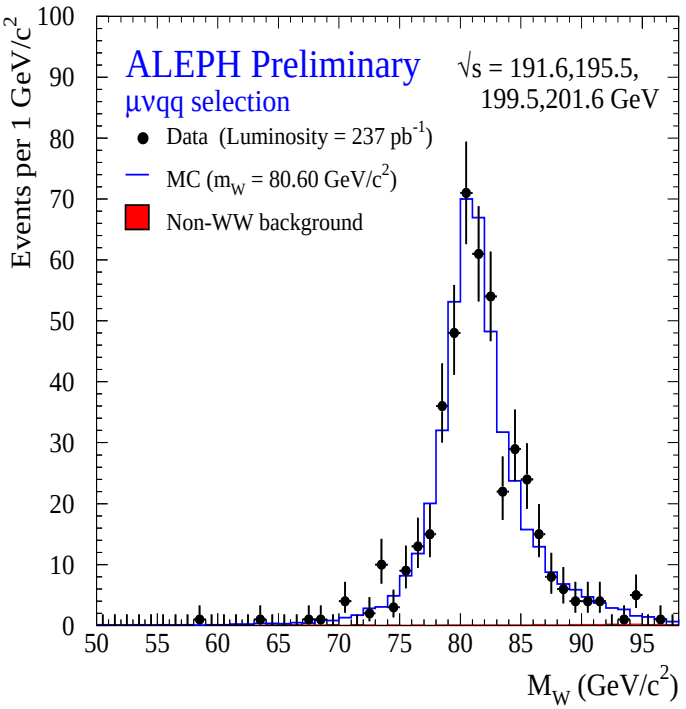


$\longrightarrow$ choose best pairing

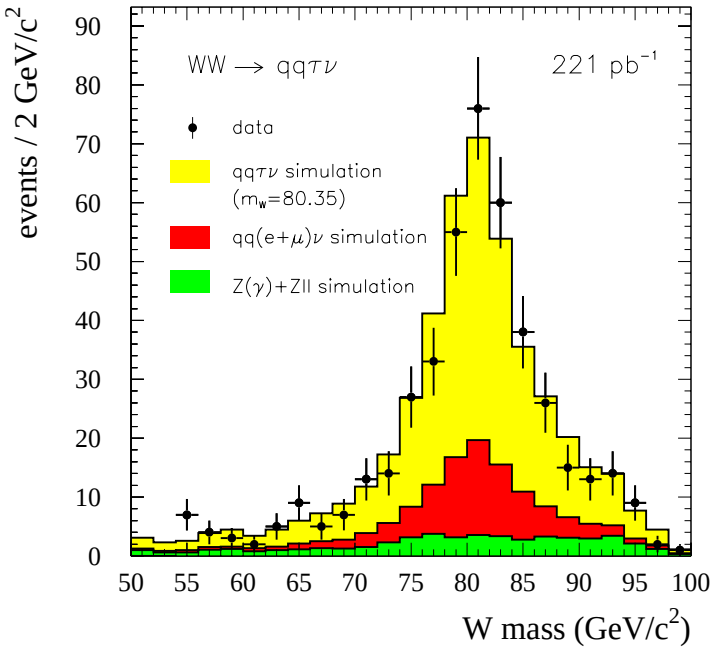
- also gluon radiation is taken into account

$\longrightarrow$ split into 4 and 5 jet sample (D,O)

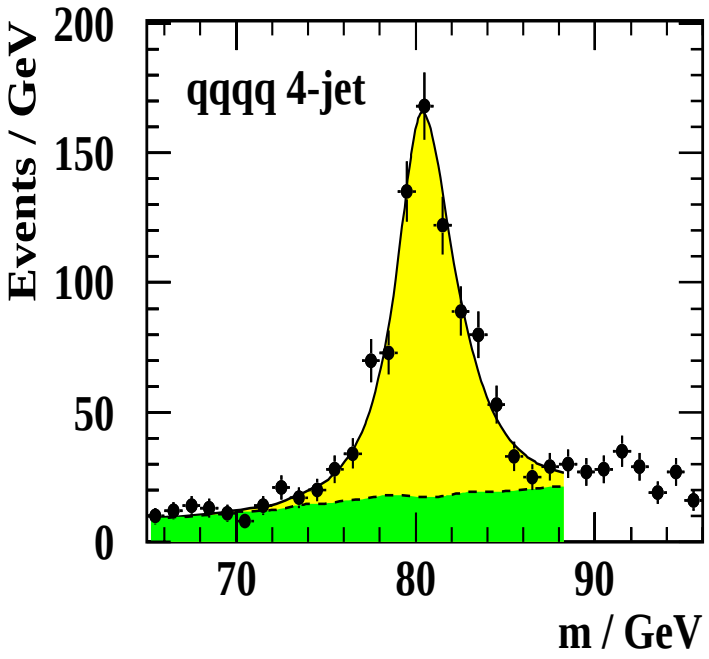




DELPHI preliminary

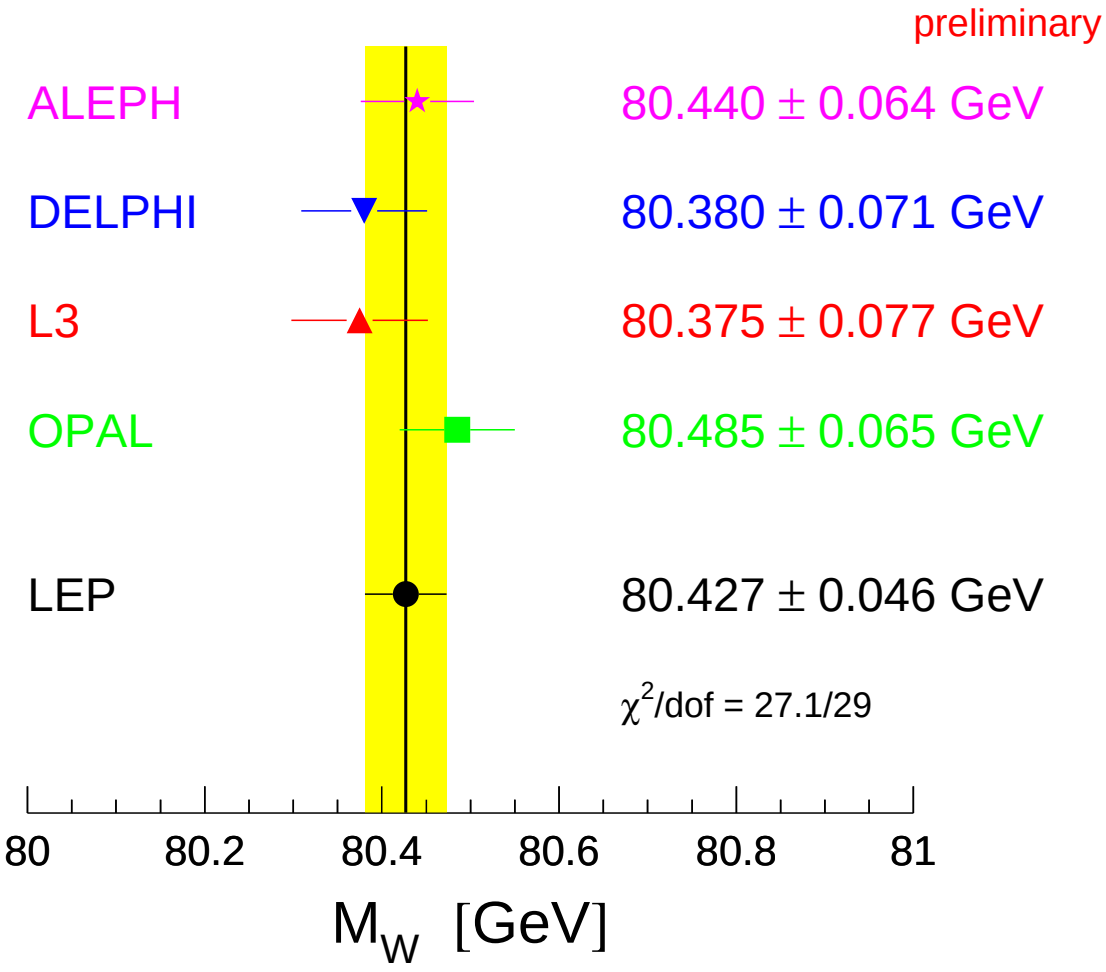


OPAL 192-202 GeV preliminary



→ compare reweighted Monte Carlo to data (A,L,O)
→ convolute differential cross-section with resolution function (D,O)
→ fit Breit-Wigner curve to measured mass spectrum (O)

- all LEP2 data until 1999 included:



- LEP value is a combination of individual measurements from the experiments for different channels and years
- contribution to total error from

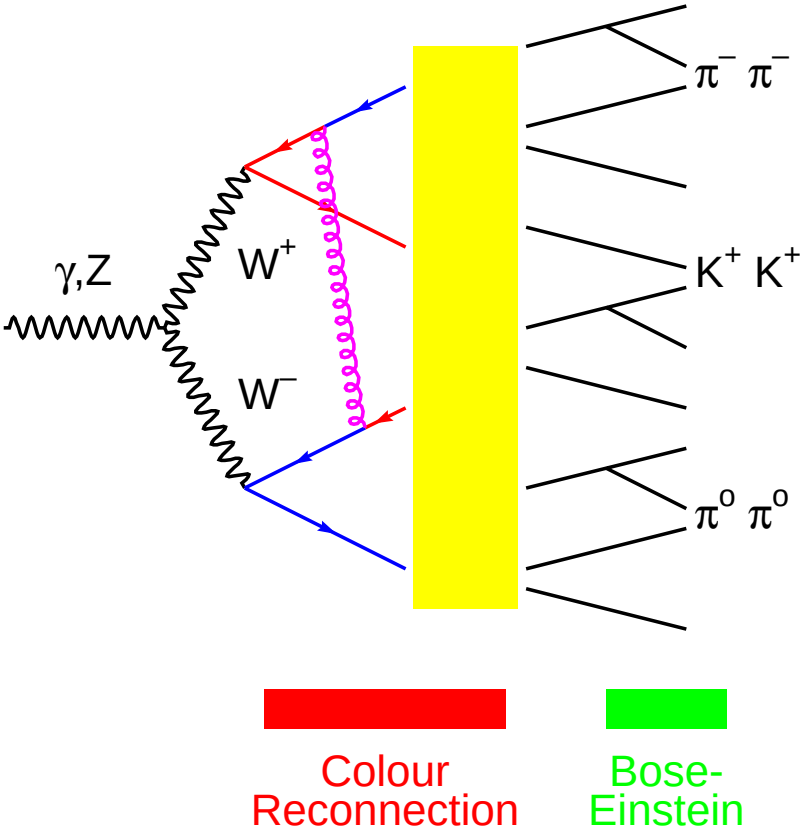
statistics:	30 MeV
systematics:	36 MeV

- LEP energy error $\Delta E_{beam} = 21$ MeV

$$\Rightarrow \Delta M_W = \frac{\Delta E_{beam}}{E_{beam}} \cdot M_W = 17 \text{ MeV}$$

- new LEP spectrometer $\rightarrow$ precision $\Delta E_{beam} < 15$ MeV (not yet achieved)

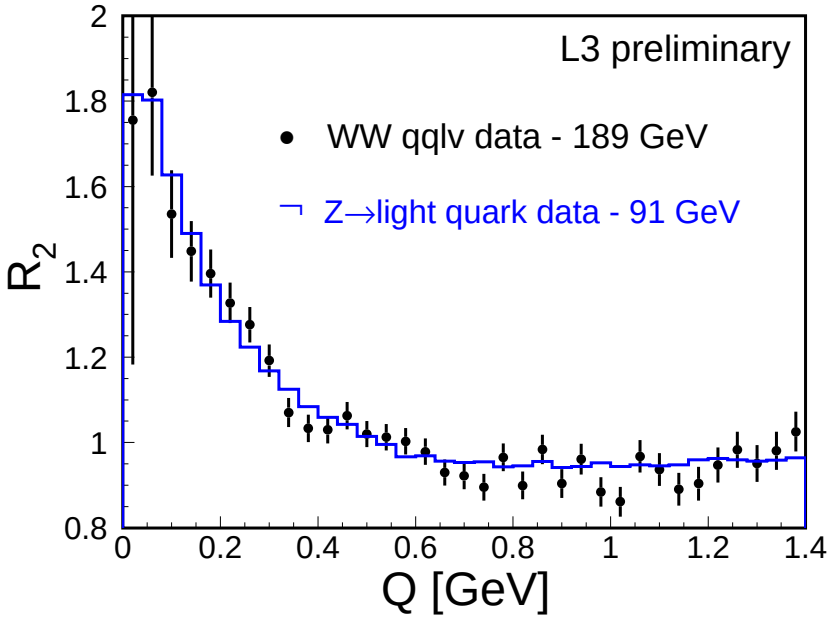
- Final State Interactions in qqqq events



- cross-talk affects reconstruction of invariant masses

Identical pions close in phase space:

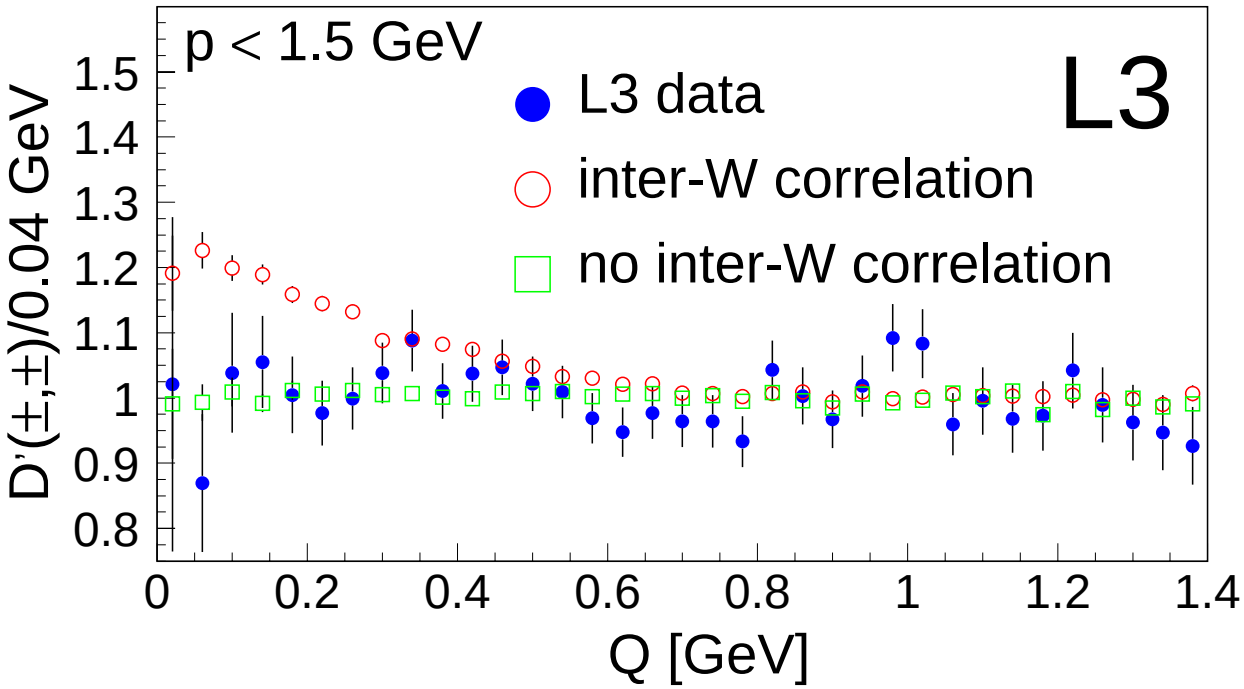
Q^2 = squared 4-momentum difference



Intra-W effects:

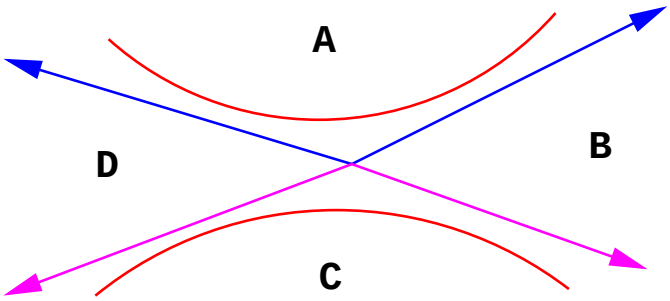
$W^{\pm} \simeq Z$ decays ($Z \not\to b\bar{b}$)

Cross talk in $W^+W^- \to q\bar{q}q\bar{q}$?



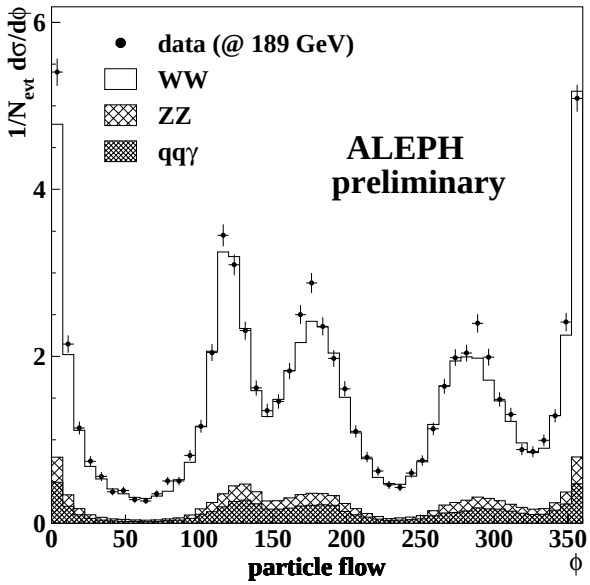
→ BE correlations only inside each W!?

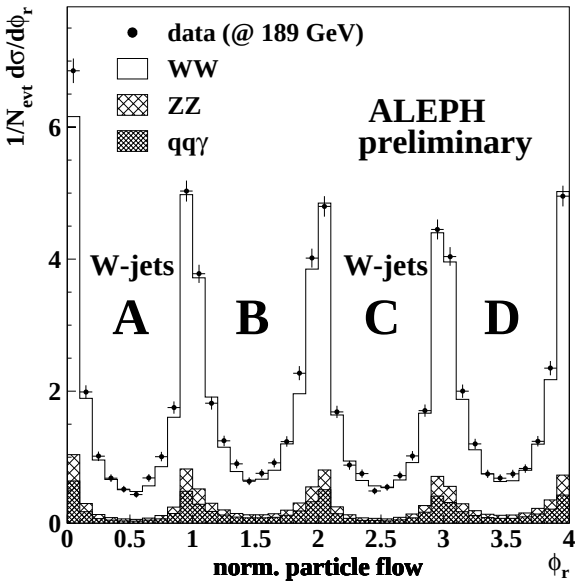
Compare particle flow between jets from

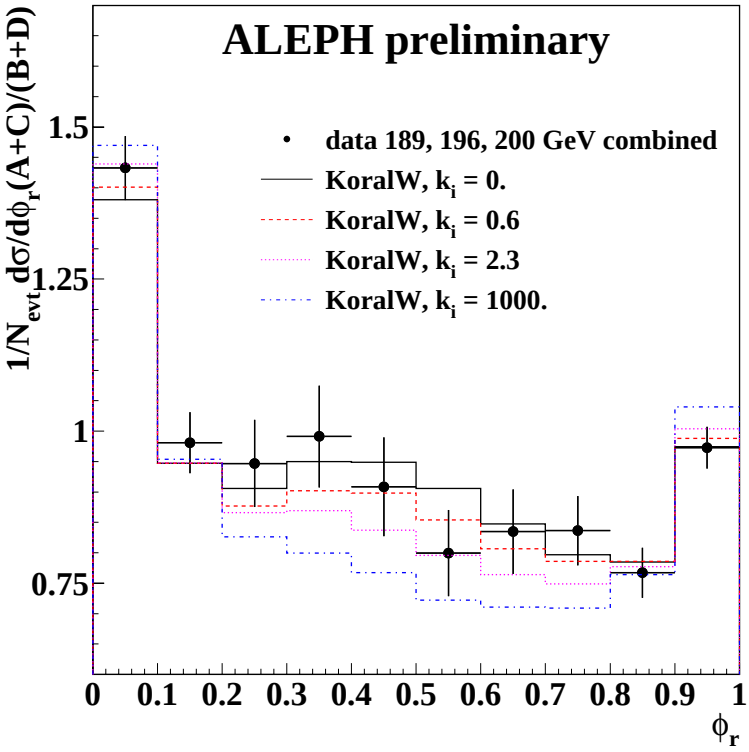


- same (A,C)
- different (B,D)

W-Boson





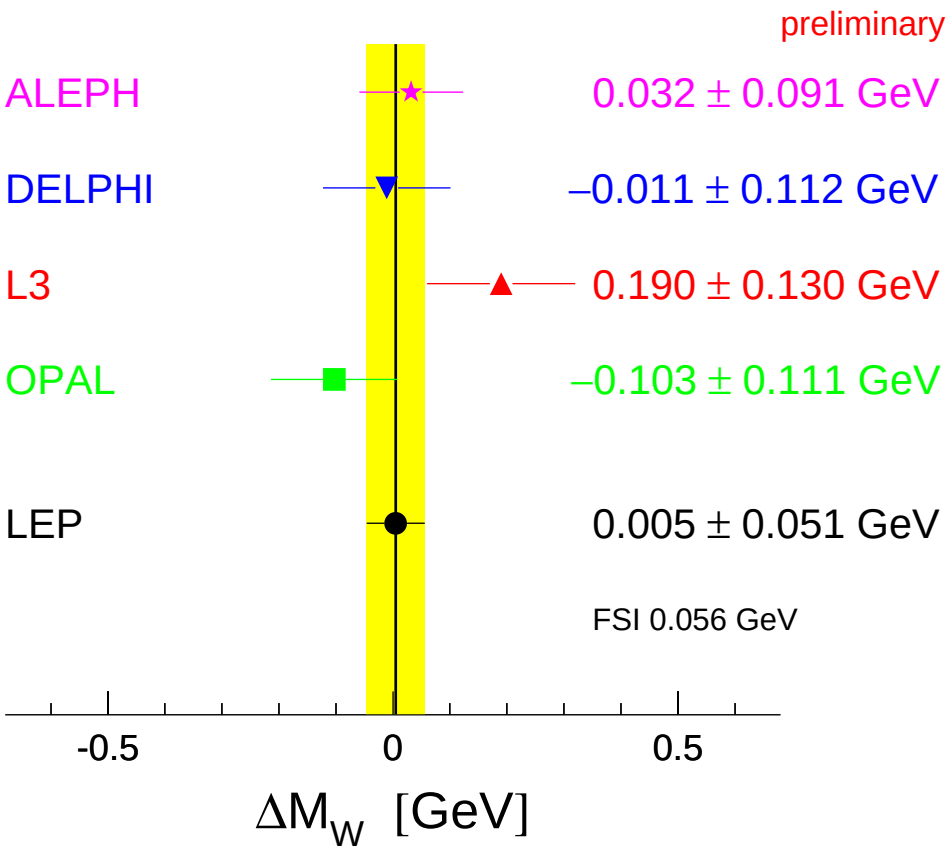


L3, ALEPH:

$$R = \frac{dn/d\phi(A+C)}{dn/d\phi(B+D)}$$

→ not yet statistically significant, but promising

- $\Delta M_W = m_{qqqq} - m_{qql\nu}$ probes possible effects of FSI



→ no indication for mass shift due to FSI

- FSI systematic error is estimated by comparing MC models

  for BE → with and w/o cross-talk

  for CR → SK I, SK II, SK II', ARIADNE I and II, HERWIG, GH

  all experiments are affected in the same way!

- error on qqqq due to BE: 25 MeV CR: 50 MeV

  statistical error component: 34 MeV (qqqq only)

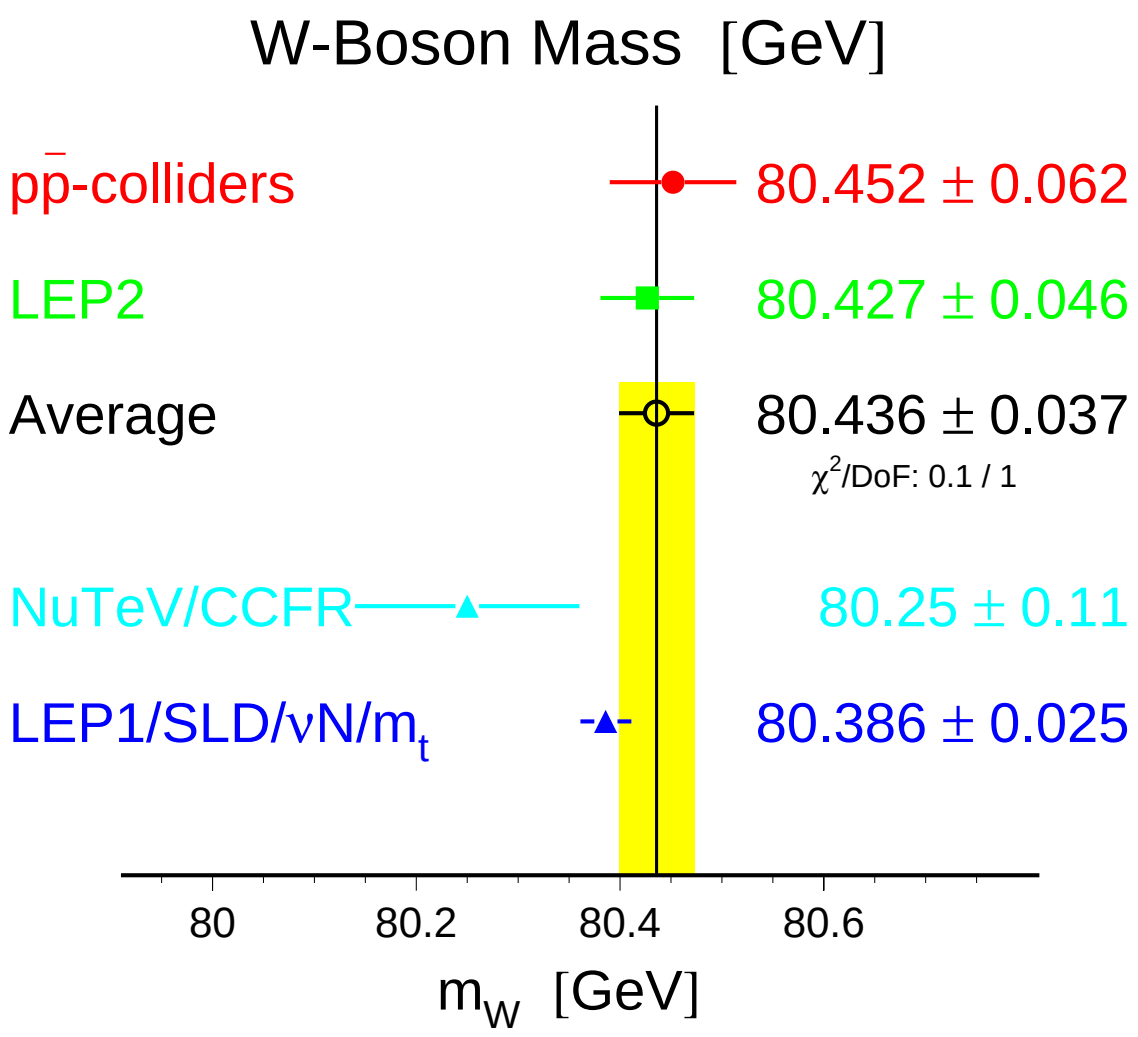
typical example

Source	Systematic Errors on M_W in MeV		
	$qq\ell\nu$	qqqq	Combined
Colour Reconnection	–	50	13
Bose-Einstein Correlations	–	25	7
LEP Beam Energy	17	17	17
ISR / FSR	8	10	8
Hadronisation	26	23	24
Detector Systematics	11	8	10
Other	5	5	4
Total Systematic	35	64	36
Statistical	38	34	30
Total	51	73	47

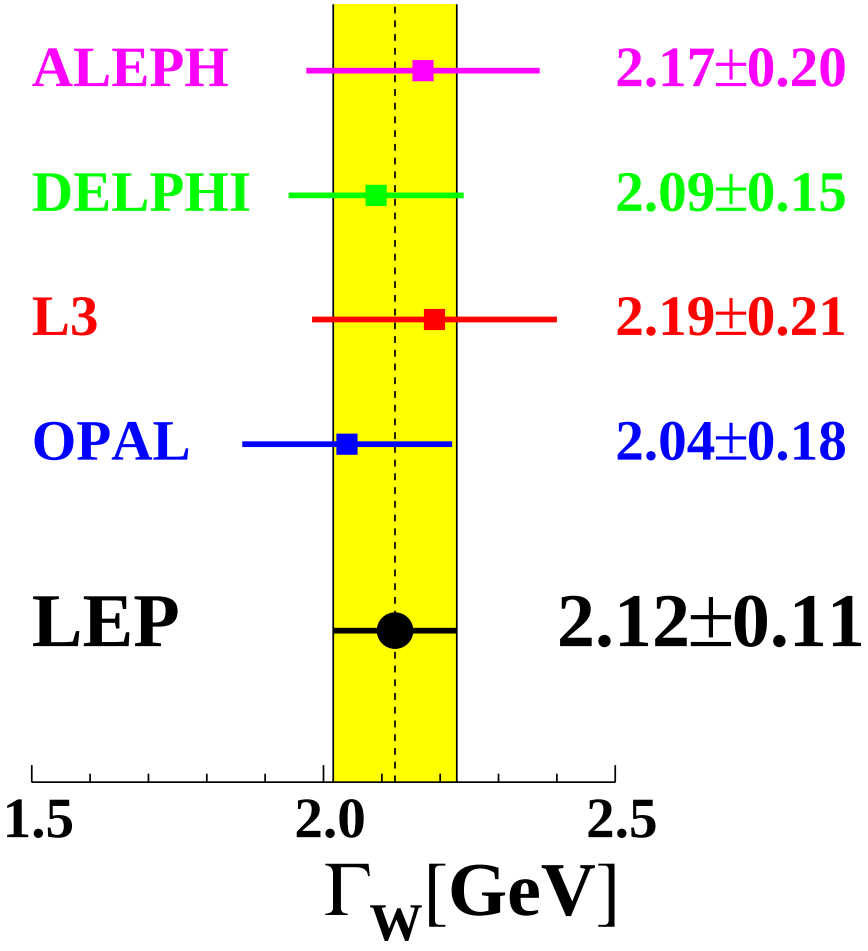
- due to FSI $\longrightarrow$ contribution to combined M_W measurement:

qqqq 27% and $qq\ell\nu$ 73%

- comparison with other W mass measurements:



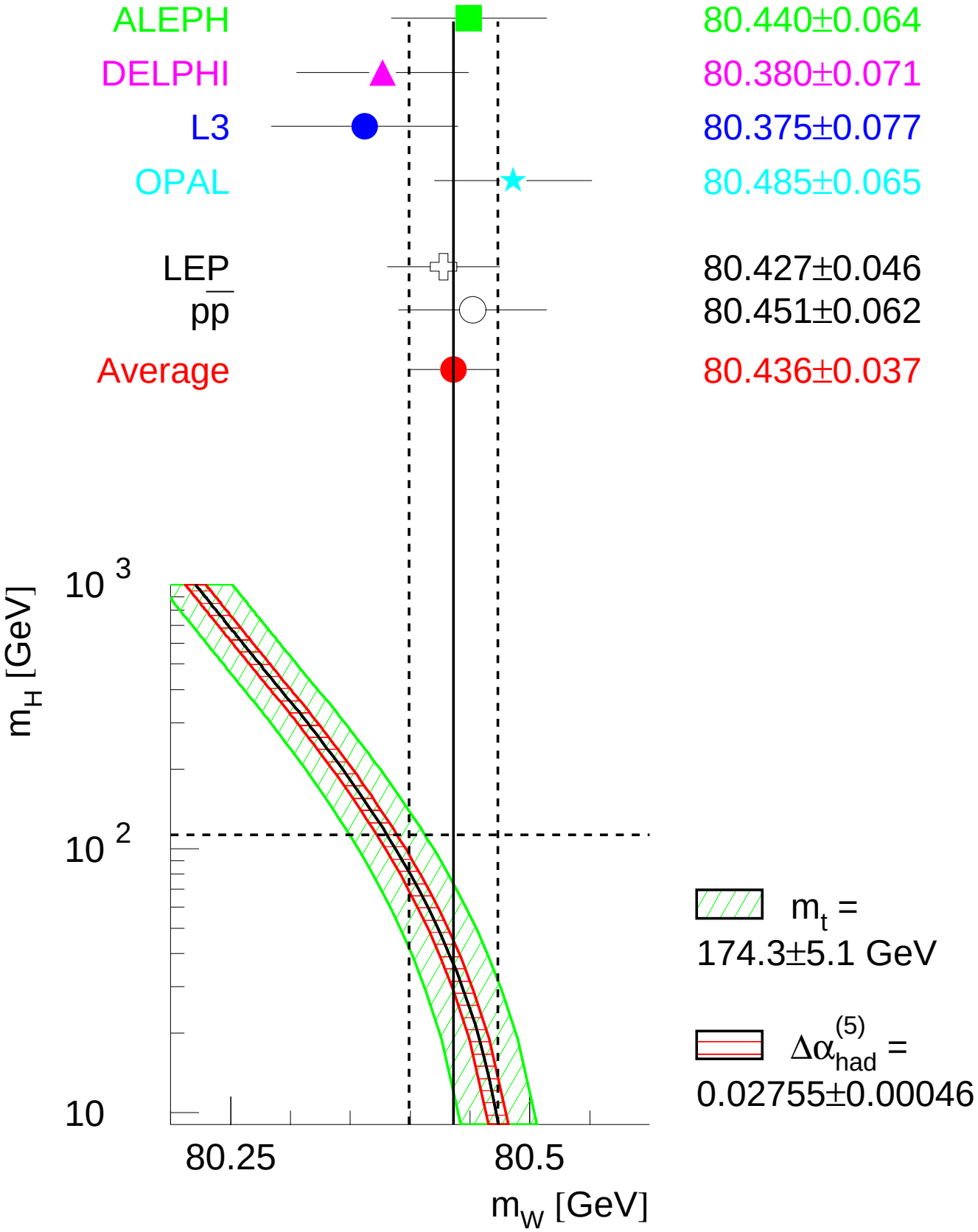
LEP Preliminary : Summer 2000



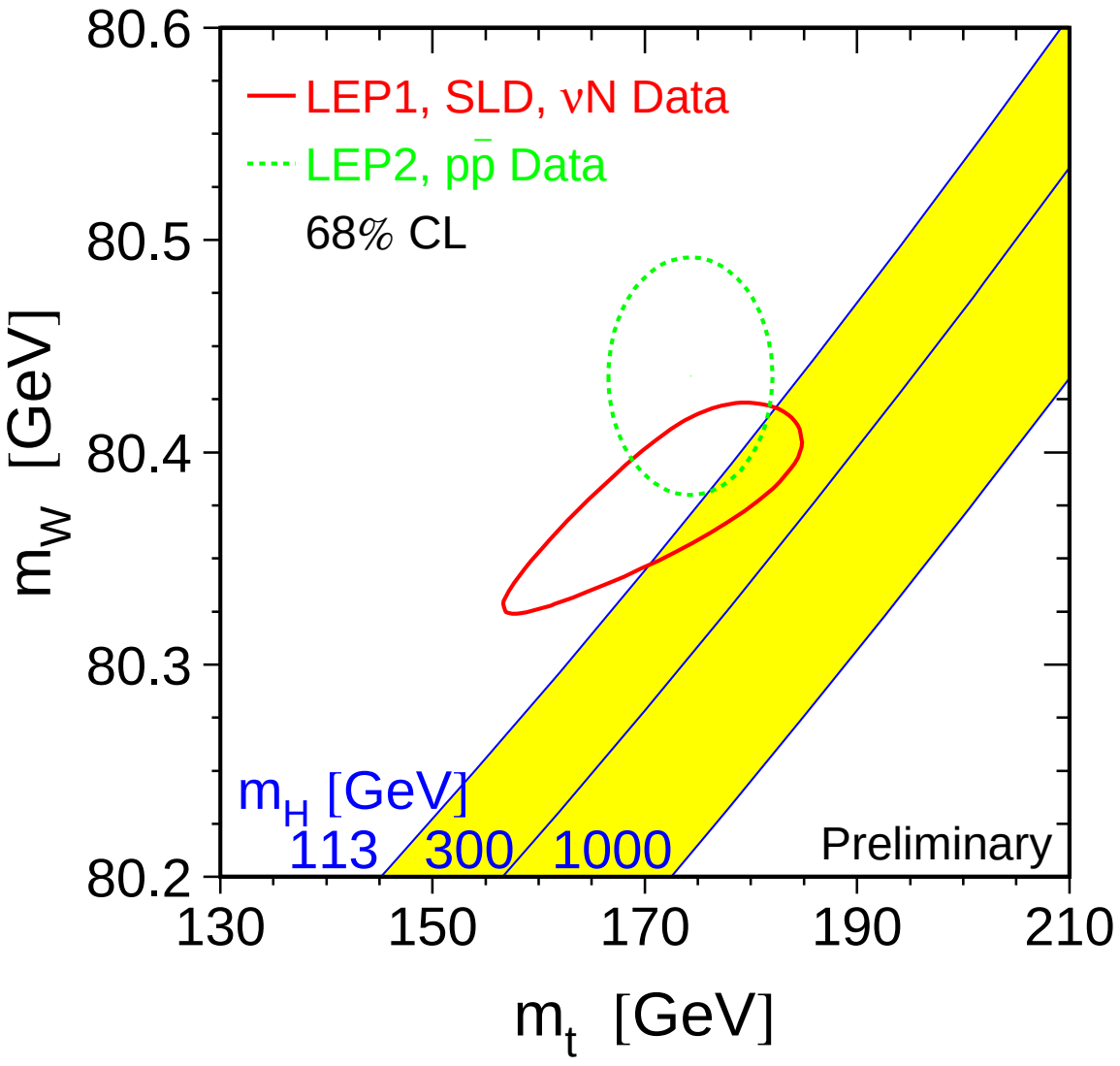
- compare direct width determination by CDF

$\Gamma_W = 2.06 \pm 0.13$ GeV

W-Boson Mass [GeV]



- compare direct M_W and M_t with fit to electroweak data:

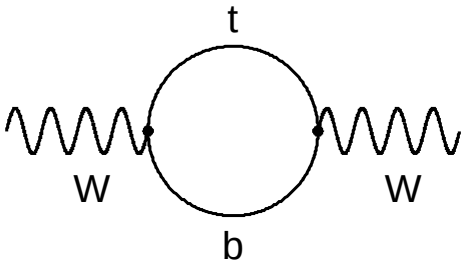


- from electroweak fits

with LEP data: $M_t = 179^{+13}_{-10}$ GeV

all data except direct M_W: $M_W = 80.386 \pm 0.025$ GeV

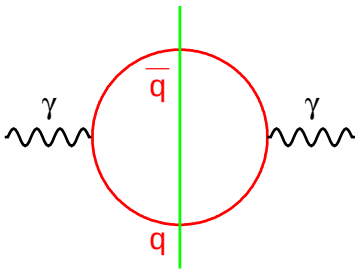
Standard Model parameter relations confirmed at 1-loop level



- $\alpha(M_Z^2)$ is important ingredient in EW fits $\rightarrow M_H$
- running of α:

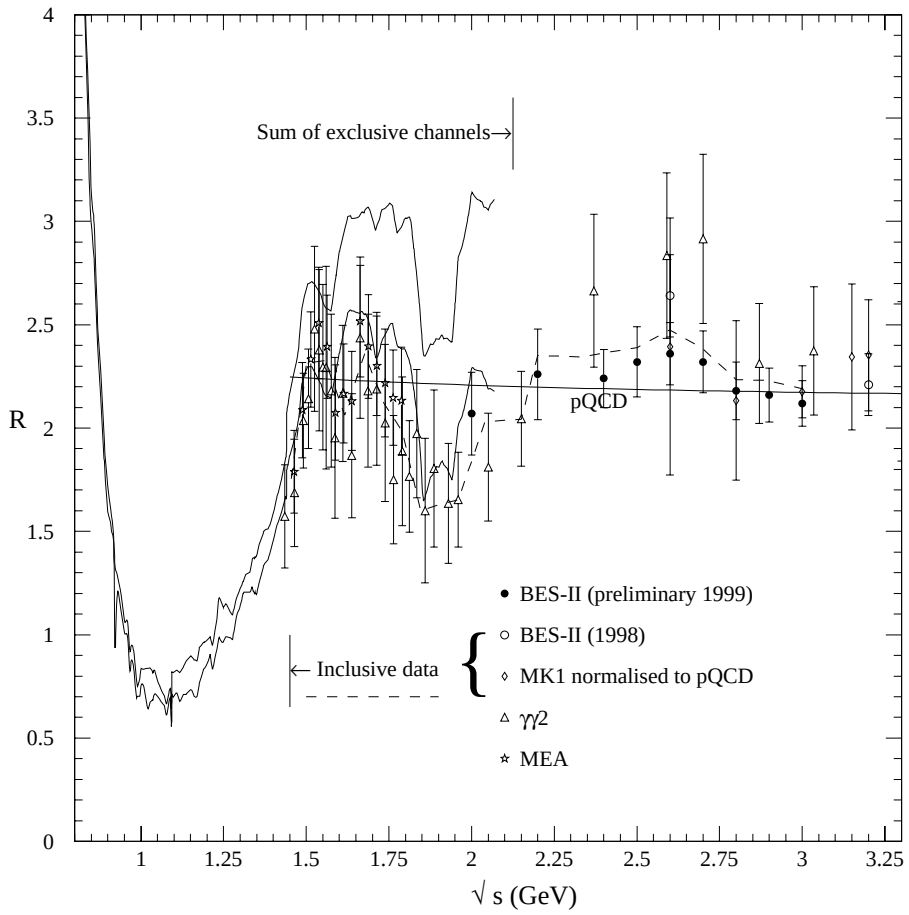
$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha_{lep}(s) - \Delta\alpha_{had}^{(5)}(s) - \Delta\alpha_{had}^{top}(s)}$$

- $\Delta\alpha_{lep}(s)$ known to 3-loop level
- important is contribution from $\Delta\alpha_{had}^{(5)}$
  $\rightarrow$ less precise

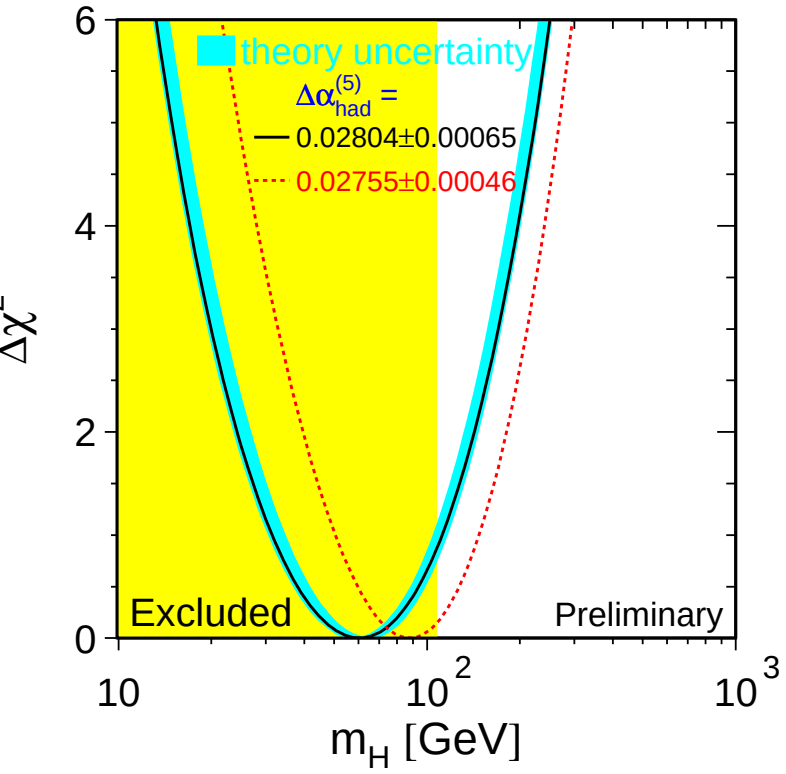


$$\Delta\alpha_{had}^{(5)}(s) \propto \int_{4M_\pi^2}^{\infty} \frac{R(s')\,ds'}{s'(s'-s)}$$

- the ratio $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$
  can be measured and calculated in perturbative QCD
- recent measurements by BES II are now included:



Mass of the Higgs Boson



$\Delta\alpha^{(5)}_{had}$	M_H [GeV]	$\log(M_H/\ \mathrm{GeV})$	M_H limit (95% C.L.)
0.02804 ± 0.00065	60^{+52}_{-29}	$1.78^{+0.27}_{-0.28}$	< 162 GeV
new BES included			
0.02755 ± 0.00046	88^{+60}_{-37}	$1.94^{+0.22}_{-0.24}$	< 203 GeV
new BES and pQCD			
0.02738 ± 0.00020	104^{+59}_{-39}	$2.02^{+0.19}_{-0.20}$	< 215 GeV

(Jegerlehner et al., Pietrzyk et al., Martin et al., includes new results on M_W by Tevatron and on heavy flavours by SLD)

- the new values of $\Delta\alpha^{(5)}_{had}$ yield
  - → a better error on $\log(M_H/\ \mathrm{GeV})$
  - → a better agreement with Higgs searches at LEP
- the Higgs boson is light . . . but heavier than

$M_H > 112.3$ GeV at 95% CL (limit from direct searches at LEP)

- Measurement of Fermion Pair Production in good agreement with Standard Model predictions
- Further improvement on M_Z, j_{had} within S-Matrix ansatz
- No new (contact) interactions below 10-20 TeV
- Cross sections for Single W, W^+W^-, ZZ agree as well

- LEP measures W mass and width with increased precision

$$M_W = 80.427 \pm 0.046 \text{ GeV}$$
$$\Gamma_W = 2.12 \pm 0.11 \text{ GeV}$$

. . . in perfect agreement with fit to electroweak data

- outlook on LEP M_W:

with 2000 data $\longrightarrow$ statistical error $\times$ 0.85

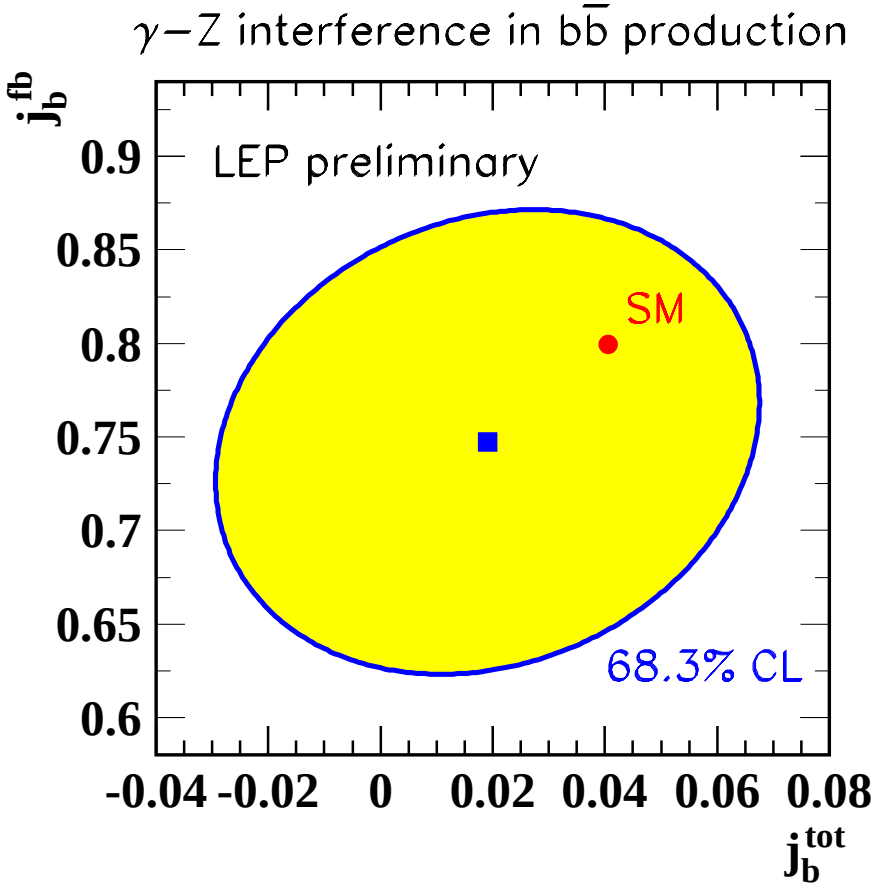
$\longrightarrow \delta M_W = 30 - 40$ MeV

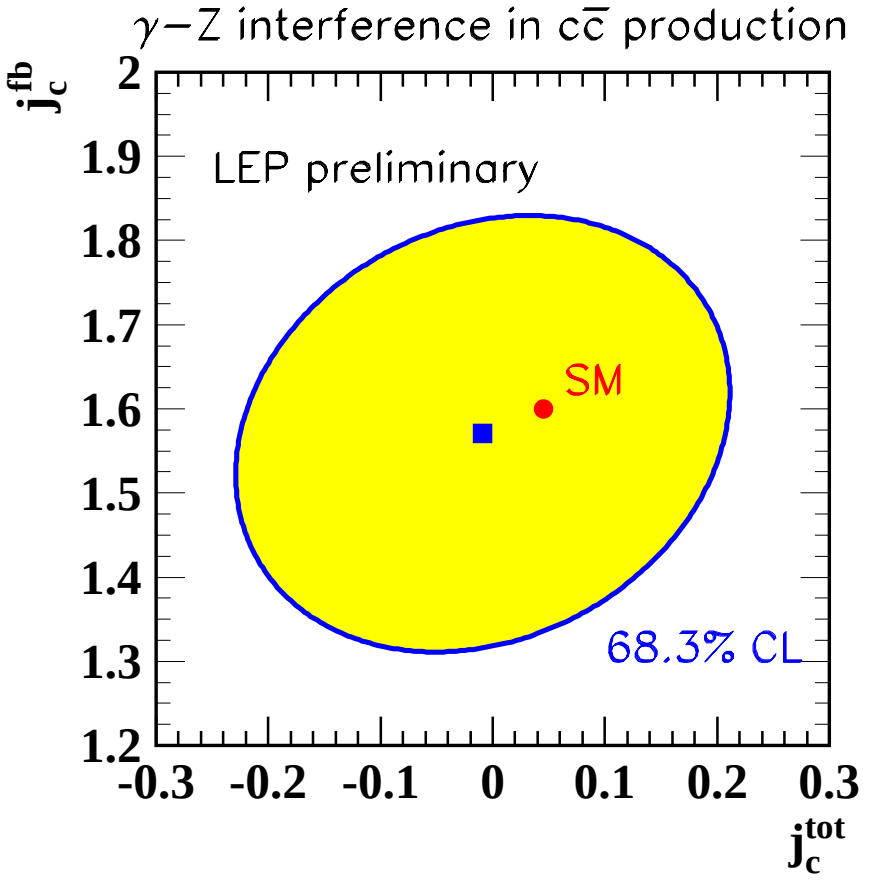
- there is progress going on in $\alpha(M_Z^2)$ determination
- although we are always looking for deviations . . .

The Standard Model works

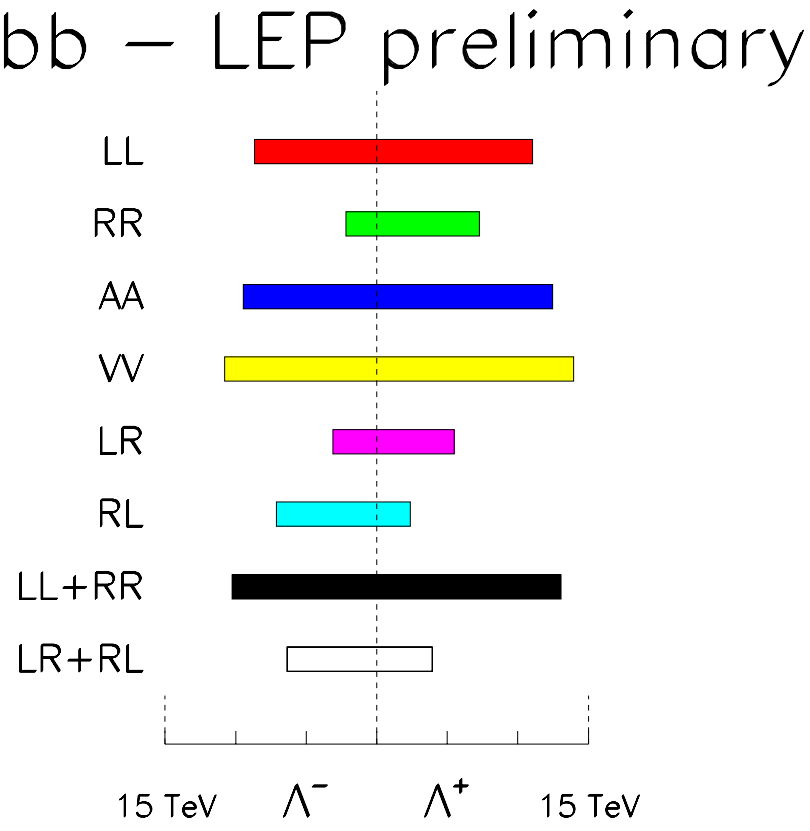
The Standard Model Higgs boson is light

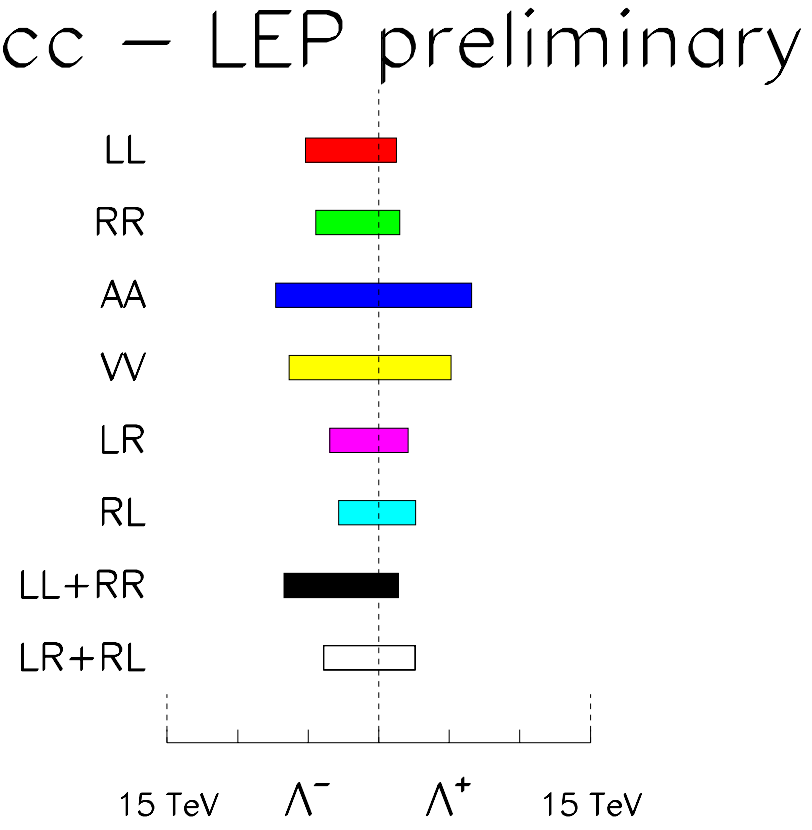
(and maybe already observed?)


γ−Z interference in bb̄ production
LEP preliminary
SM
68.3% CL
j_b^{fb}
j_b^{tot}
0.9
0.85
0.8
0.75
0.7
0.65
0.6
-0.04
-0.02
0
0.02
0.04
0.06
0.08


γ−Z interference in cc̄ production
LEP preliminary
SM
68.3% CL
j_c^{fb}
j_c^{tot}
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
-0.3
-0.2
-0.1
0
0.1
0.2
0.3

133 - 202 GeV


bb – LEP preliminary
LL
RR
AA
VV
LR
RL
LL+RR
LR+RL
15 TeV
Λ⁻
Λ⁺
15 TeV


cc – LEP preliminary
LL
RR
AA
VV
LR
RL
LL+RR
LR+RL
15 TeV
Λ⁻
Λ⁺
15 TeV