DELPHI results

@ the LEP Jamboree

22 July 2002

presented by
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on behalf of the **DELPHI Collaboration**

DELPHI today

- LEP stopped in November 2000
- Last data/MC processing before the last Jamboree

... What/how are we currently doing ?

- More than 50 papers in the pipeline
- About 60 notes to ICHEP02

... Lots of results in the fields of

- Searches
- EW physics
- QCD
- Heavy flavours

Results are:
new/preliminary/nearly-final/final
.... (see case by case)
Limits are at 95% CL

Still far too much material for a 30 minutes talk !

Abstracts for ICHEP

- **Beyond the SM (17)**

  l*, b', FCNC, FCNC c.i.

  SUGRA, GMSB, AMSB, RpV, sneutrino RpV, gluino, γ's+E_{mis}

  H flav blind, H inv, H char, H doubly char, H 2hdm

- **EW physics (17)**

  R_b, AFB^l_{bb}, AFB_{bb}, τ BR, τ lifetime, $\gamma\gamma \rightarrow \tau\tau$, ν_τ mass, LEP2 energy

  WW σ BR, W mass, ZZ, Zγ*, single boson, TGC, QGC,

  Neutral Higgs, collinear ev. in H

- **QCD hard interactions (6), soft interactions (8)**

  m_b, m_b in 4jet rate, event shape dist., α_s, mult. 3 jets, F^e

  CR, CR m_W, BE, mult., b hadronisation., fragm, F_2^γ, J/ψ

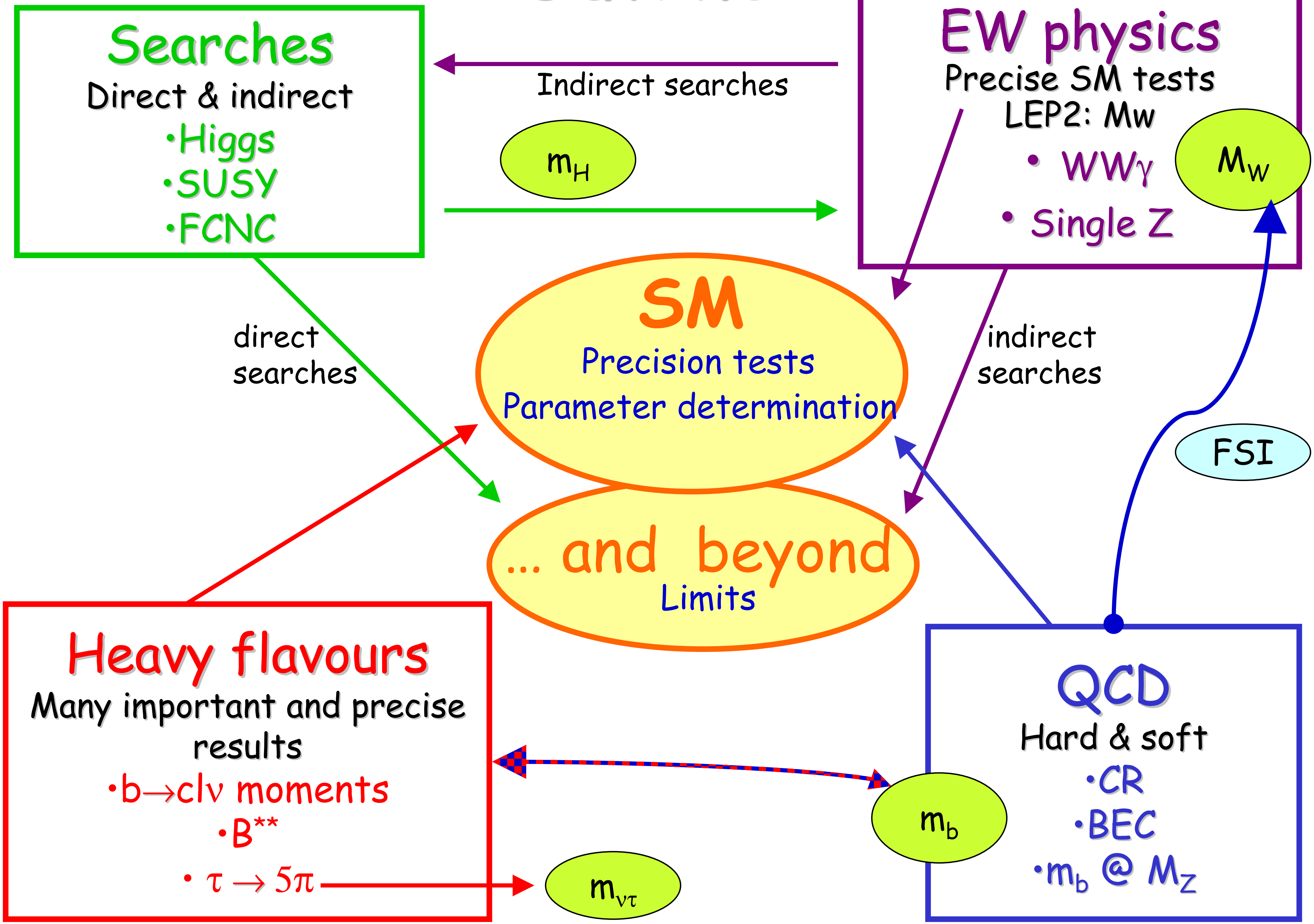
- **Heavy quark mesons and baryons (9)**

  btag, b fragm. func., τ_B, B oscill., Vcb, mom.b $\rightarrow X_c l\nu$, D**, B**, $\Xi_{c,b}$

- **Other (3)**

  f_1, η_c (Spectroscopy), μ bundles (Particle Astrophysics)

Outline

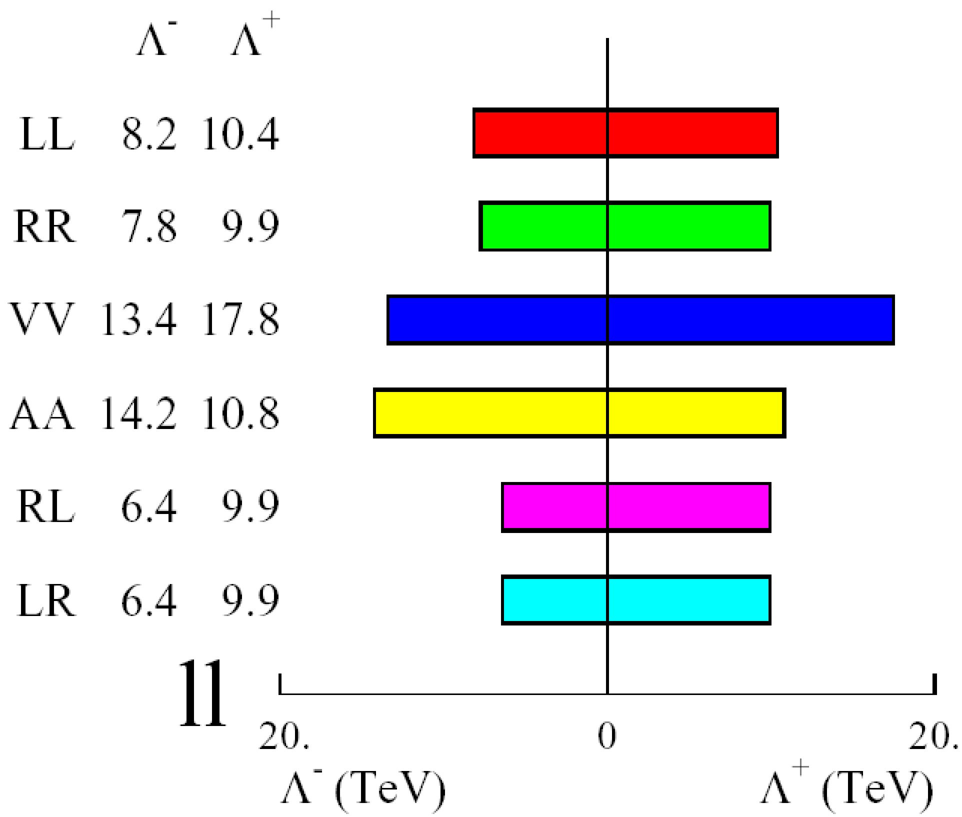

Searches
Direct & indirect
•Higgs
•SUSY
•FCNC
Indirect searches
m_H
EW physics
Precise SM tests
LEP2: Mw
• WWγ
• Single Z
M_W
direct searches
SM
Precision tests
Parameter determination
indirect searches
FSI
... and beyond
Limits
Heavy flavours
Many important and precise results
•b→clν moments
•B**
• τ → 5π
$m_{\nu\tau}$
m_b
QCD
Hard & soft
•CR
•BEC
•m_b @ M_Z

Searches @LEP

... and direct

- Limited E_{cm} range, but clean & complete
- ... We try to look everywhere:
  - Model-indep (topological)
  - Systematic exploration of models

Indirect...



contact interaction limits from $e^+e^- \to l^+l^-$

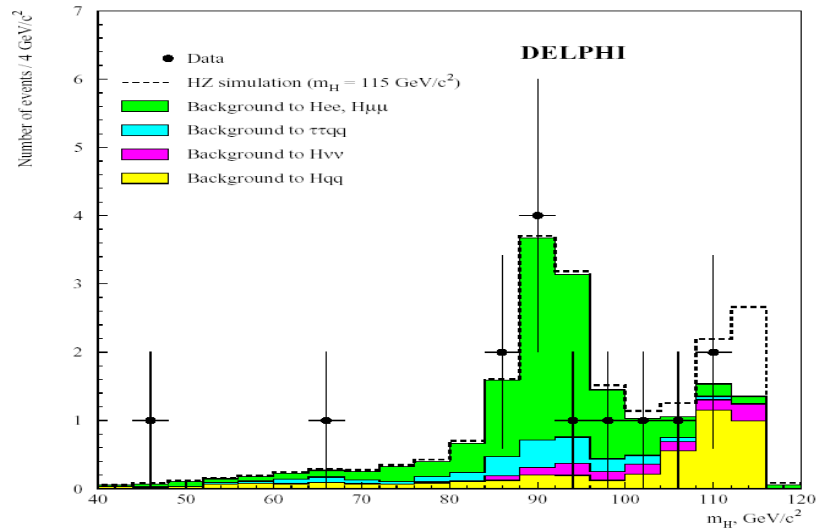
- Higgs
  - Standard
  - MSSM
  - 2HDM
  - Invisible
  - Doubly charged
- SUSY
  - SUGRA
  - GMSB
  - AMSB
  - RPV
- Other
  - FCNC
  - New fermions
  - Technicolor

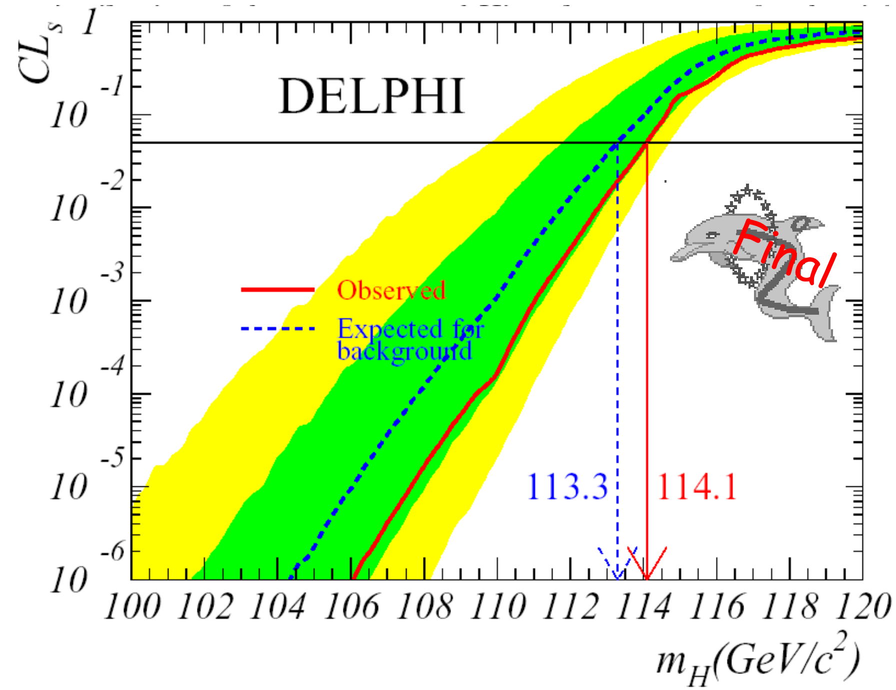
SM Higgs

Final(ly) !...

- Analyses stable... what's new ?
- m_H down to 12 GeV/c^2
- Final processing calibrations/alignment/btag tuning
- CL calculation procedures:
  - improved pdf derivation
  - new binning
  - new efficiency parameterisation
- From online to final E_{cm} files (–200 MeV)
- New signal MC
  - hZhA03+higher rate of b→bg
- New background MC
  - WPHACT / KK2f
  - gluon splitting (bb,cc), Vcb

Net effect –200 MeV/c^2

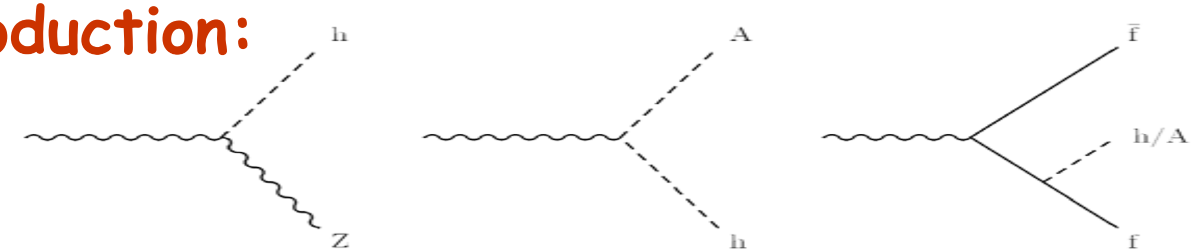




...LEP combination ! (Pierre's talk)

A different Higgs - 2HDM and beyond

Production:



Bjorken process   Pair production   Yukawa process

Higgs doublet mixing may suppress Bjorken and Pair prod, Yukawa may be enhanced

Different decay scenarios:

- Type I
- Type II, different mixings:
  - Dominant g,c
  - Dominant b,τ

Fermiophobic
Flavour Indep

Final states:

- 4b
- 4b+jets
- 6b
- 2b2τ
- 4τ

LEP1+LEP2 data

•Higgs cascades ($h \to AA$, $h \to AZ$, $A \to hZ$) considered

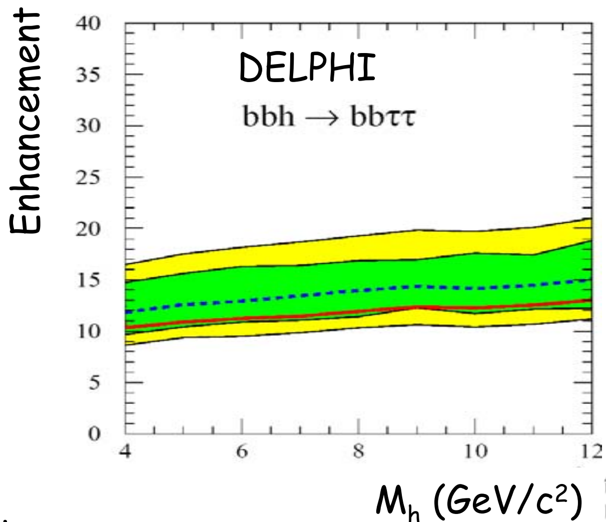
•Extra doublet do not increase number of available final states

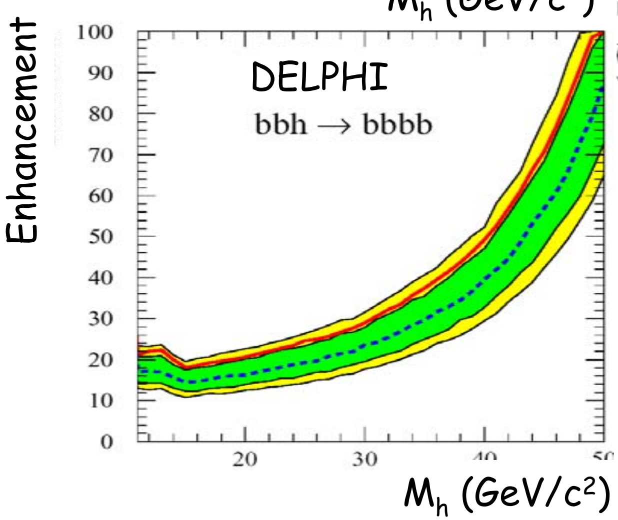
•Further details (production rates+BR) are model dependent

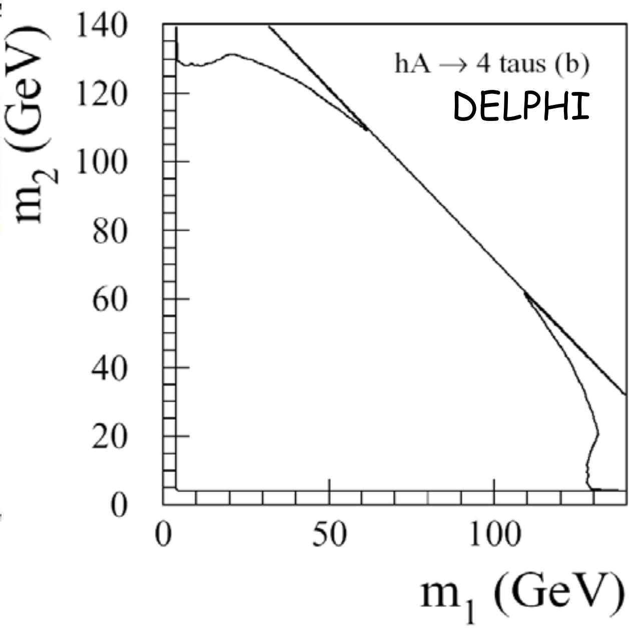
A different Higgs (II)

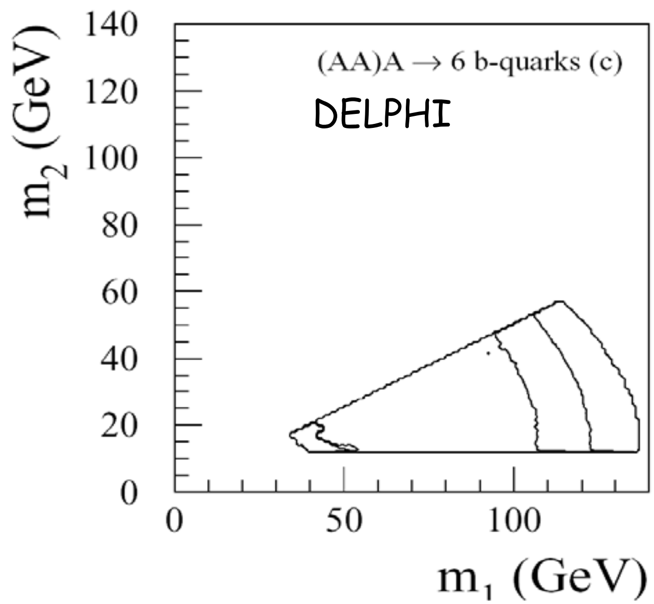
Emphasis on model independency: $\sigma \propto \sigma_0 \times BR \times C^2$

m_1	m_2	$C^2_{2b2\tau}$	m_1	m_2	$C^2_{2b2\tau}$	m_1	m_2	$C^2_{2b2\tau}$
11	4	≥ 1	60	6	0.021	40	10	0.006
20	4	0.005	70	6	0.016	50	10	0.013
30	4	0.006	11	8	≥ 1	60	10	0.029
40	4	0.007	20	8	0.004	70	10	0.029
50	4	0.021	30	8	0.004	11	12	≥ 1
60	4	0.038	40	8	0.006	20	12	0.004
70	4	0.183	50	8	0.014	30	12	0.006







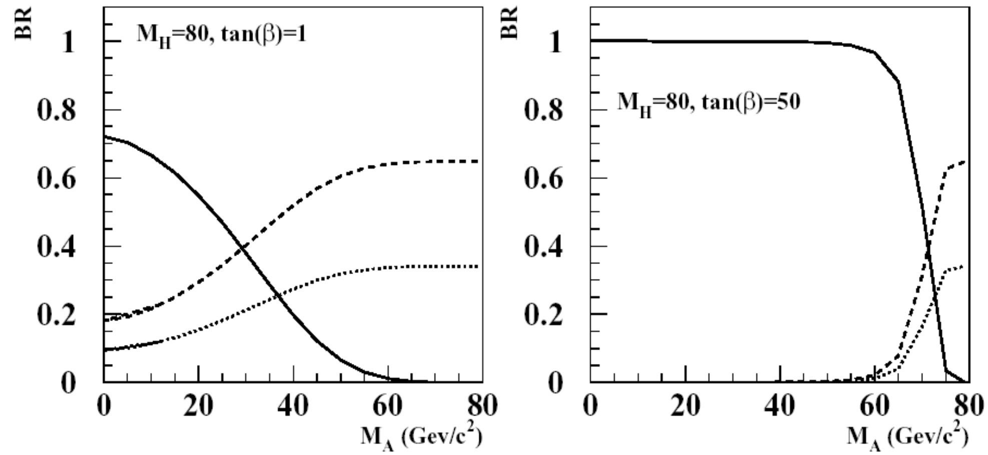


$e^+e^- \rightarrow H^+H^-$

... Still general 2HDM

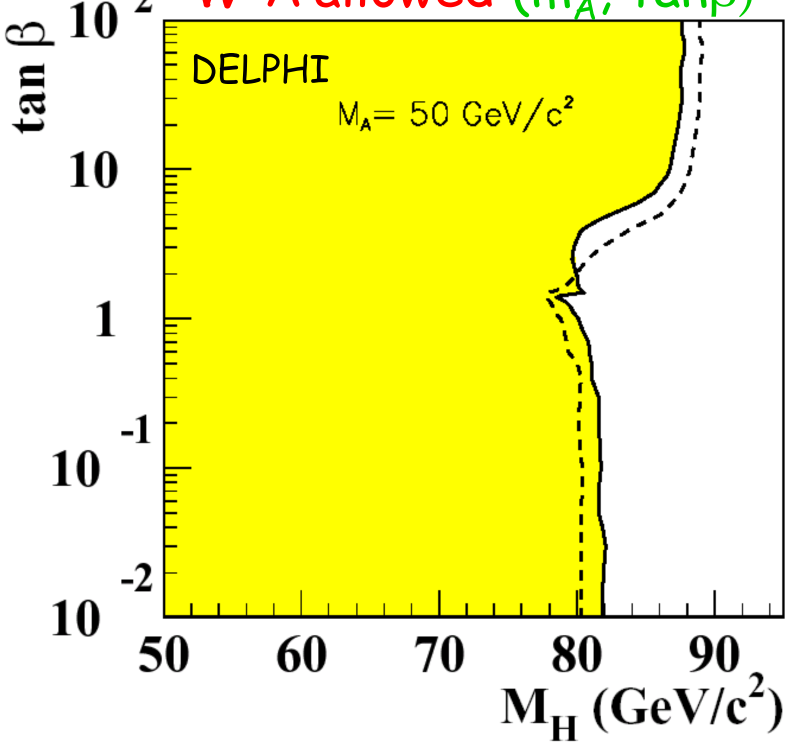
- Five different final states
  - $\tau\nu\tau\nu$, $cscs$, $cs\tau\nu$
  - W^*AW^*A, $W^*A\tau\nu$

  (BR very model dependent)

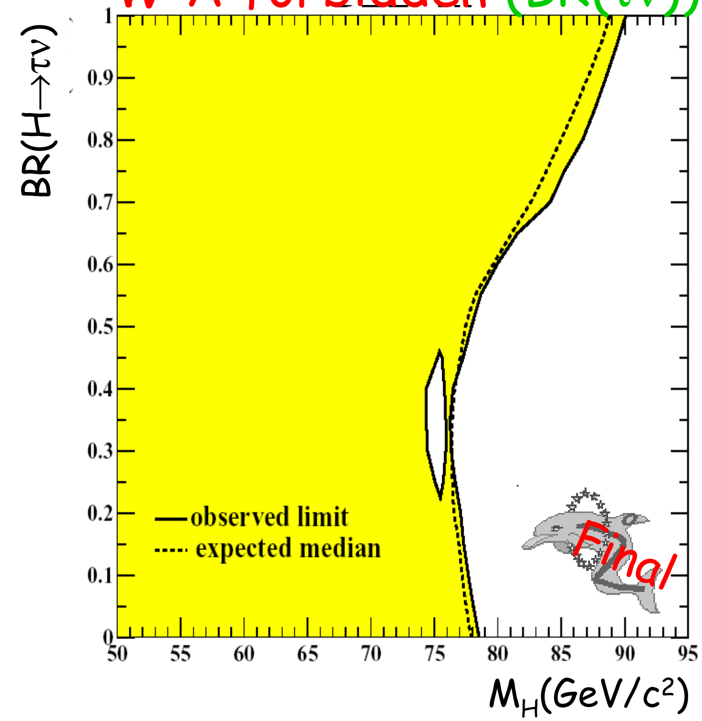


- 2 scenarios:

W^*A allowed (m_A, tanβ)

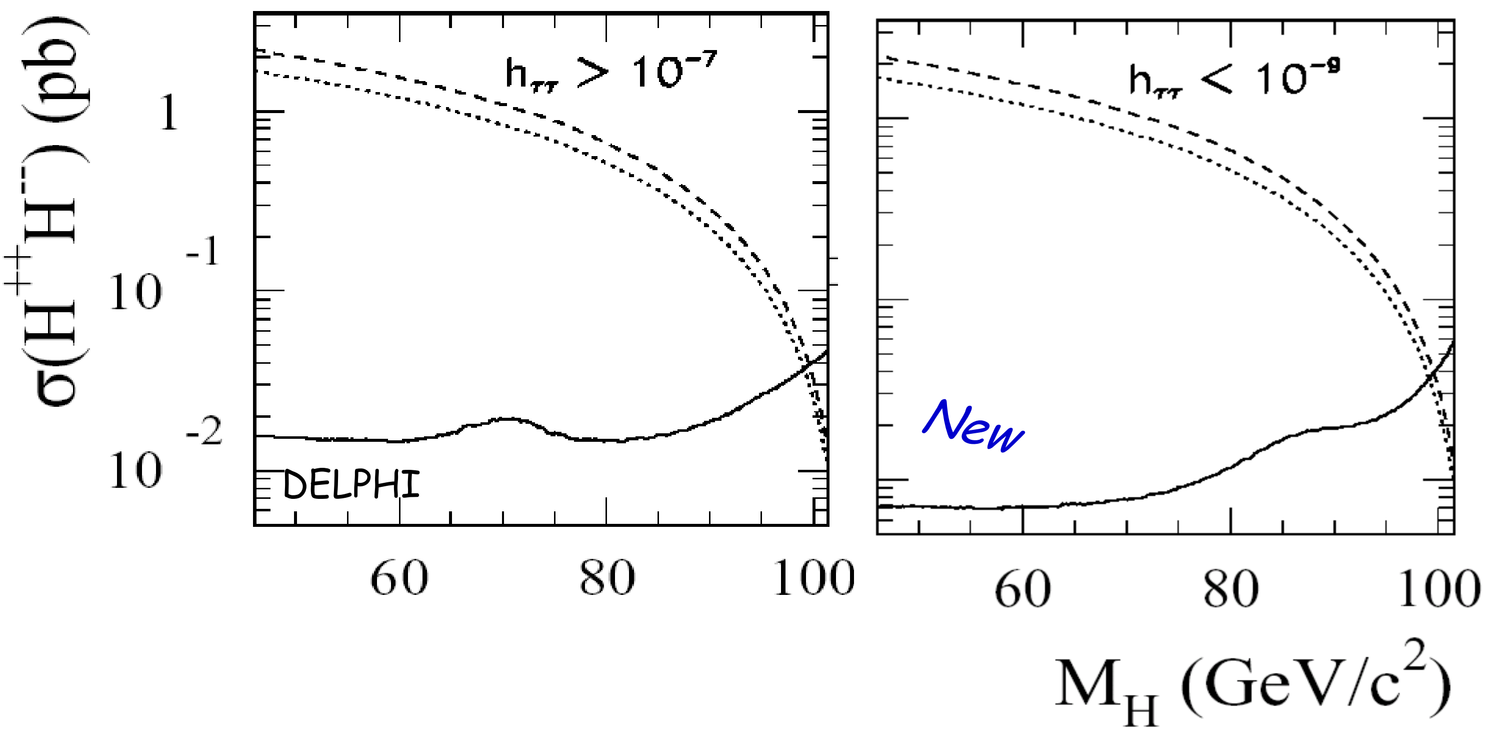


W^*A forbidden (BR($\tau\nu$))



H^{++}

- …e.g. Left-right symmetric models
  - Same sign lepton pair: $H^{\pm} \to \tau^{\pm}\tau^{\pm}$
  - Lifetime depends on $h\tau\tau$ Yukawa coupling
- Different analyses combined:
  - 4τ (prompt decay)
  - Kink+stable particle searches



Final

$M_H > 97.3\ GeV/c^2$

SUSY

- Searches for
- Charginos - Sleptons
- Neutralinos - Squarks

… Combining different searches:

Sparticles Higgs "Corners"

we can constrain:

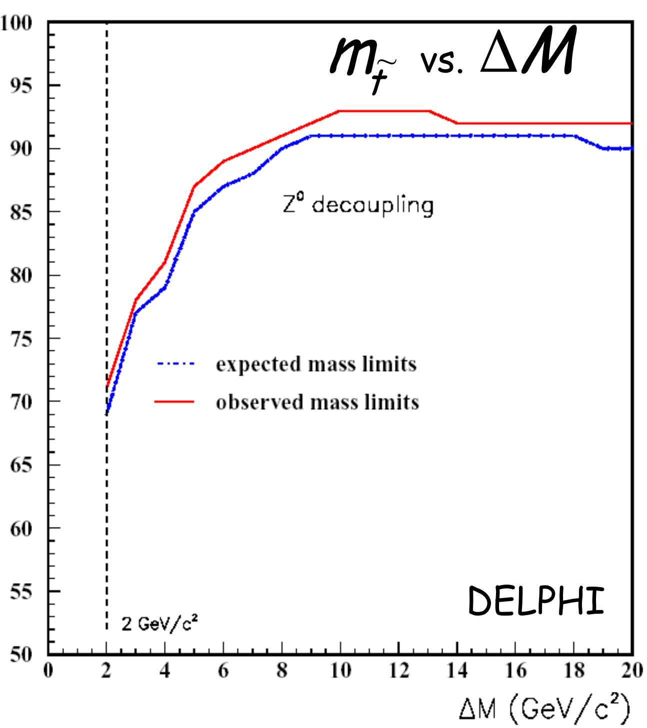
(M_2, μ) plane and smasses (M_{LSP})

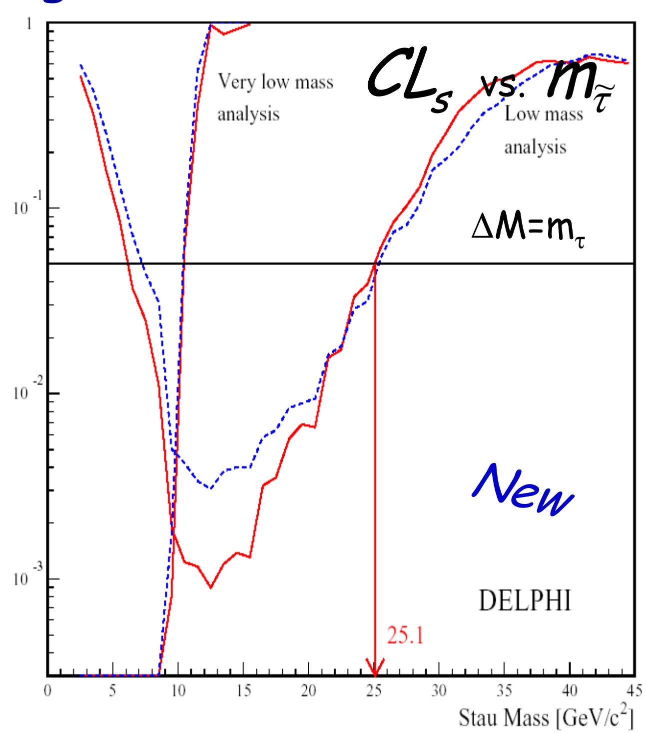
in specific scenarios e.g. CMSSM

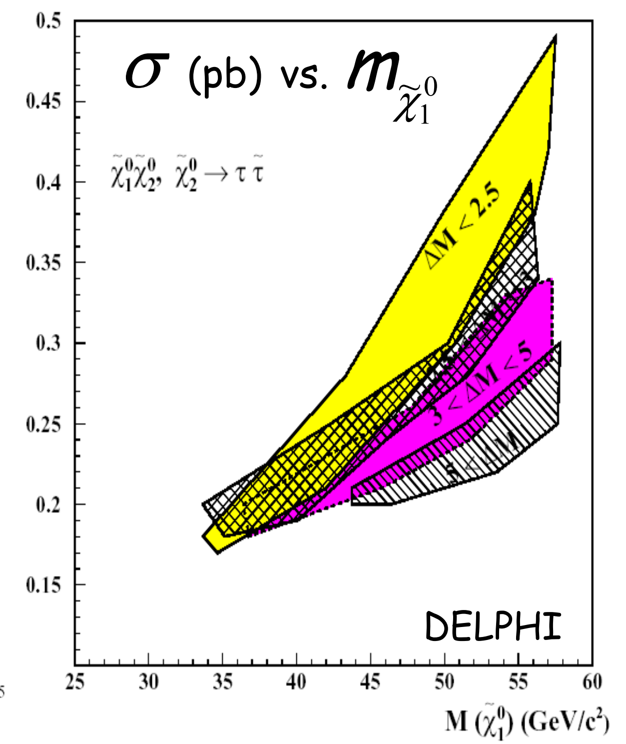
$$m_0, m_{1/2}, \tan\beta, \mu, A_\tau, A_b, A_t$$

- As much as possible model independent

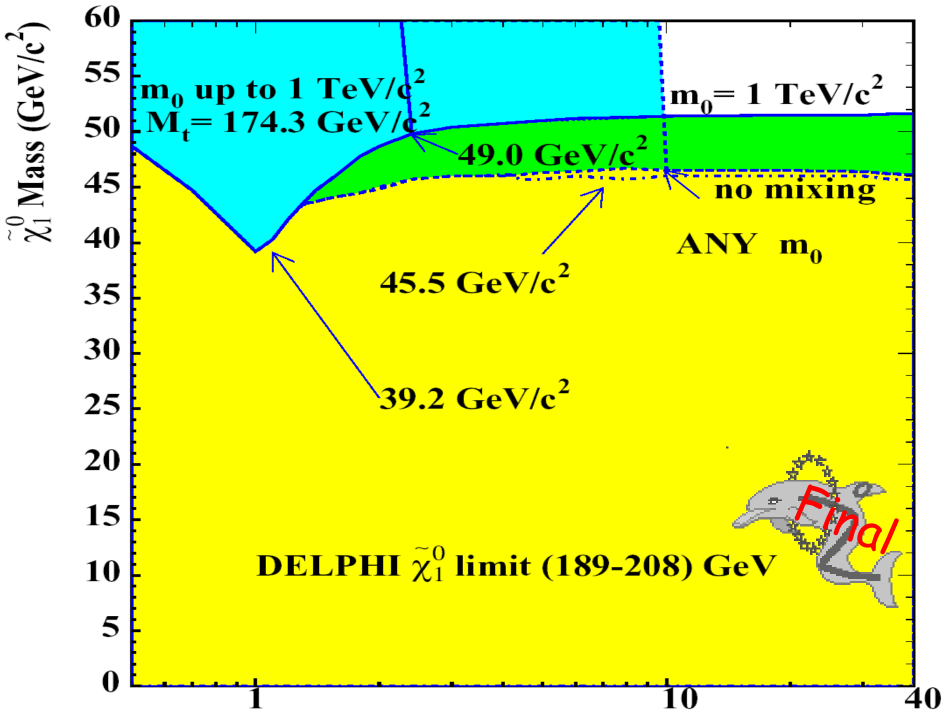
… different SUSY breaking schemes





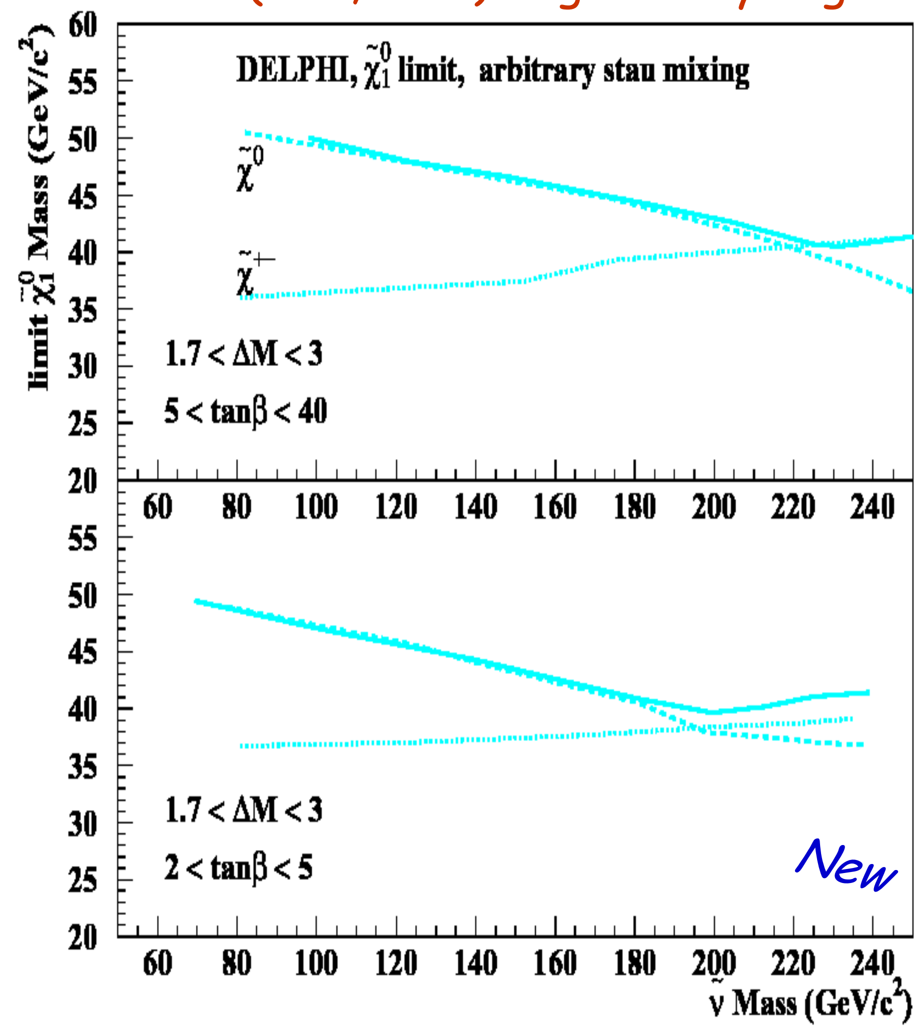


SUSY (II)



Conservative limit on m_{lsp}, valid for any τ mixing

model with mixing only in the stau sector maximises (LSP, stau) degeneracy region



- MSSM Higgs search in maximal M_{h0} scenario excludes low tanβ: $M_A \leq 1000$ GeV/c^2, $A_t - \mu/\tan\beta = \sqrt{6}$ TeV/c^2
- High m_0: $\tilde{\chi}^{\pm}, \tilde{\chi}^0$ (+ cascades!)
- Low m_0: $\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$
  - ΔM! $(\tilde{\chi}_1^{\pm}, \tilde{\nu})$ $(\tilde{\chi}_1^0, \tilde{\tau})$
  - mixing!
  - squark searches

SUSY (III)

$\tilde{\chi}_1^{\pm}$
- 102.7 (SUGRA high m_0, $\Delta M>10$)
- 75 (SUGRA, any ΔM)
- 94 (CMSSM any m_0, $\Delta M>3$)
- 102.5 (RPV-UDD and LLE)
- 100 (GMSB, stau NLSP)
- 96 (GMSB, co-NLSP)
- 75 (AMSB $\mu<0$)
- 68 (AMSB $\mu>0$)

$\tilde{\tau}$
- 82 (SUGRA $\Delta M>15$)
- 25 (SUGRA $\Delta M>m_\tau$)
- 86 (RPV-UDD, LLE, $\Delta M>5$)
- 82 (GMSB)
- 82 (AMSB $\mu<0$)
- 72 (AMSB $\mu>0$)

$\tilde{\chi}_1^0$
- 49 (CMSSM, high m_0, max mix)
- 46 (CMSSM, any m_0, no mix)
- 39.2 (CMSSM, any m_0, no H lim)
- 38 (RPV-UDD, LLE)
- 89 (GMSB)
- 75 (AMSB $\mu<0$)
- 68 (AMSB $\mu>0$)

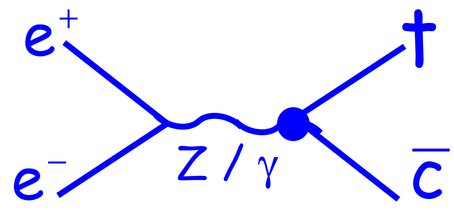
$\tilde{\nu}$
- 85 (RPV-UDD,LLE)
- 127 (AMSB $\mu<0$)
- 98 (AMSB $\mu>0$)

$\tilde{b}$
- 76 (SUGRA $\Delta M>7$)
- 78 (RPV, $\Delta M>5$)

$\tilde{t}$
- 92 (SUGRA $\Delta M>10$)
- 71 (SUGRA $\Delta M>2$)
- 77 (RPV, $\Delta M>5$)

FCNC…?

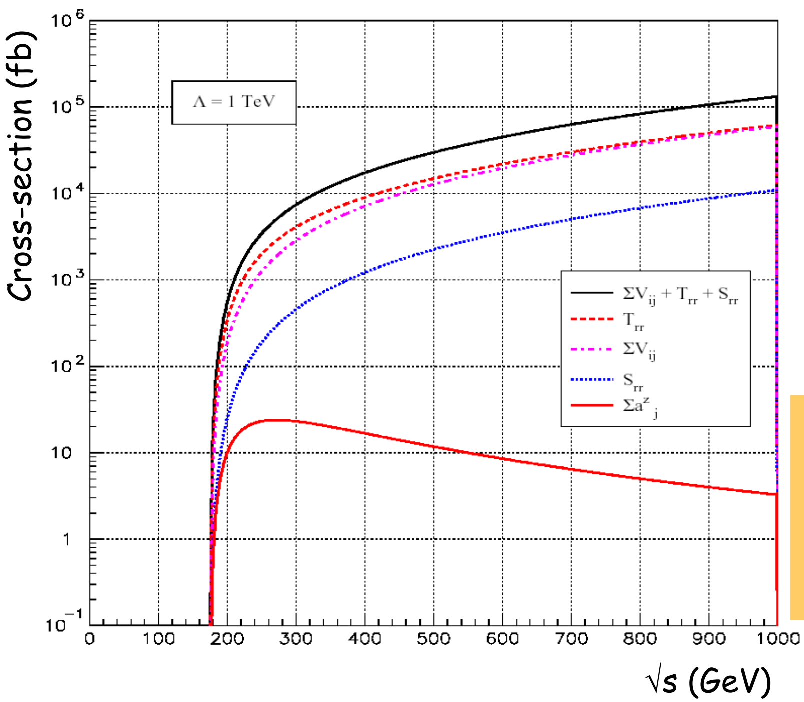
Single top



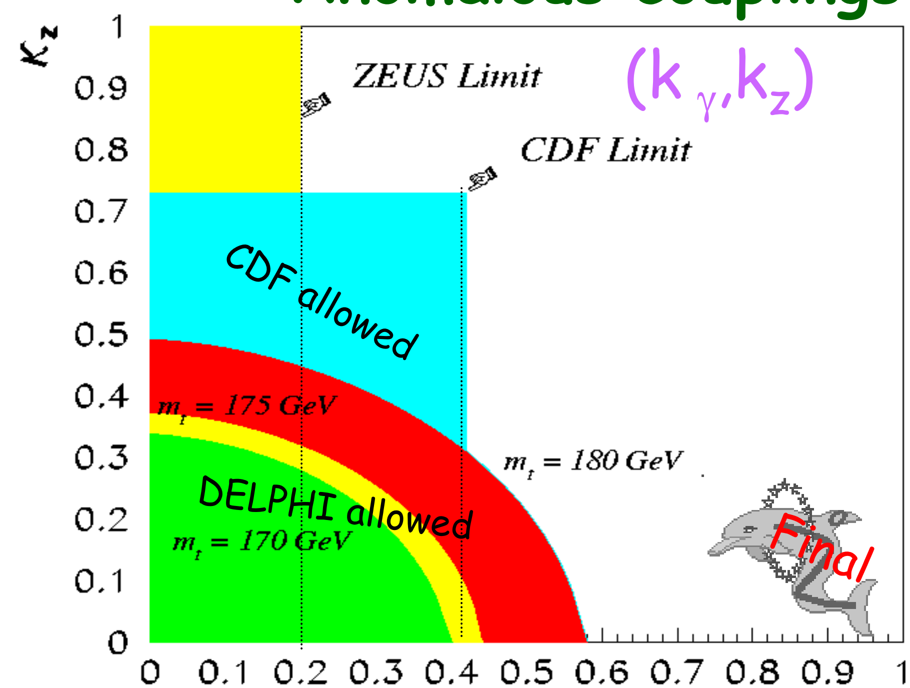
.. Much suppressed in the SM (10^{-13})

- **Contact interactions**

$$\sigma \propto \frac{s}{\Lambda^4}\ f(S^2_{RR}, V^2_{RR}, T^2_{RR}, \ldots)$$



- **Anomalous couplings**



Larger uncertainty from top mass

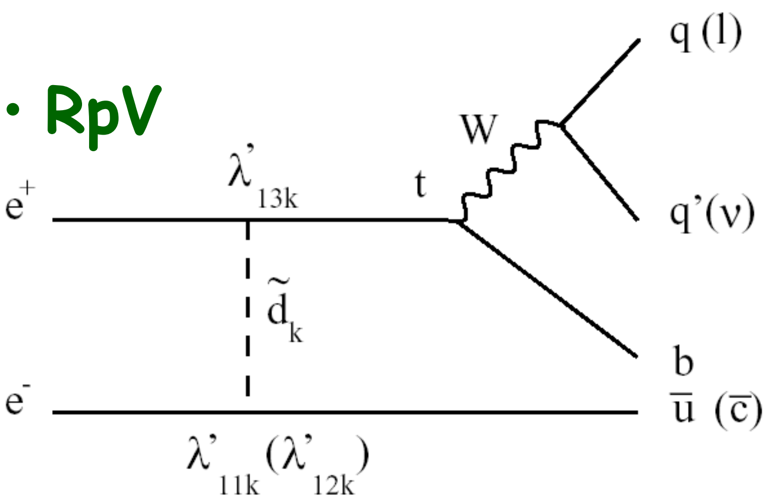
LEP combined result will be updated

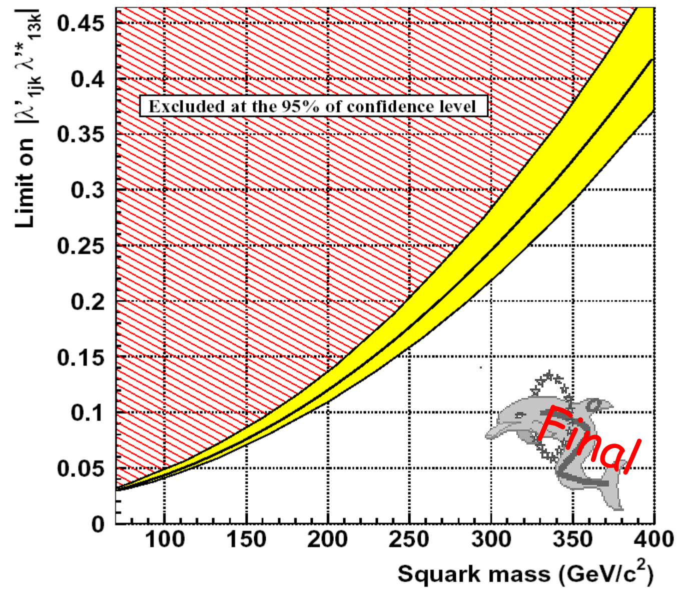
Limits on Λ for different non-zero 4-f couplings

L (GeV)	All but axial	Tensor	Vector	Scalar	Axial
Observed	1312	1143	986	604	473
Expected	1423	1253	1069	660	510

FCNC in more "exotic" scenarios

- **RpV**



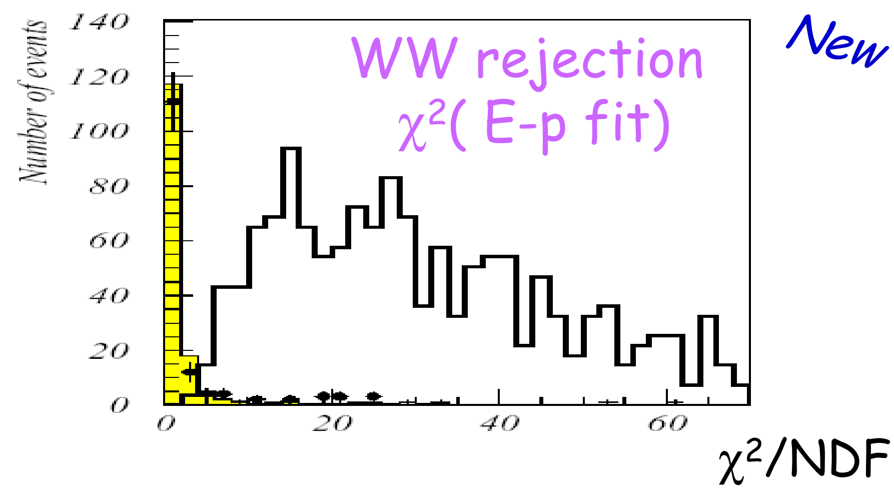


$\sigma < 0.11$ pb

- **A fourth generation quark**

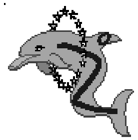
- Pair production (m~100 GeV/c²)
- FCNC decay $b' \rightarrow bZ$
- Final states bqqbνν, bllbνν
- Other Z decay modes to be included

- Low energy b jets
- Very large Emis



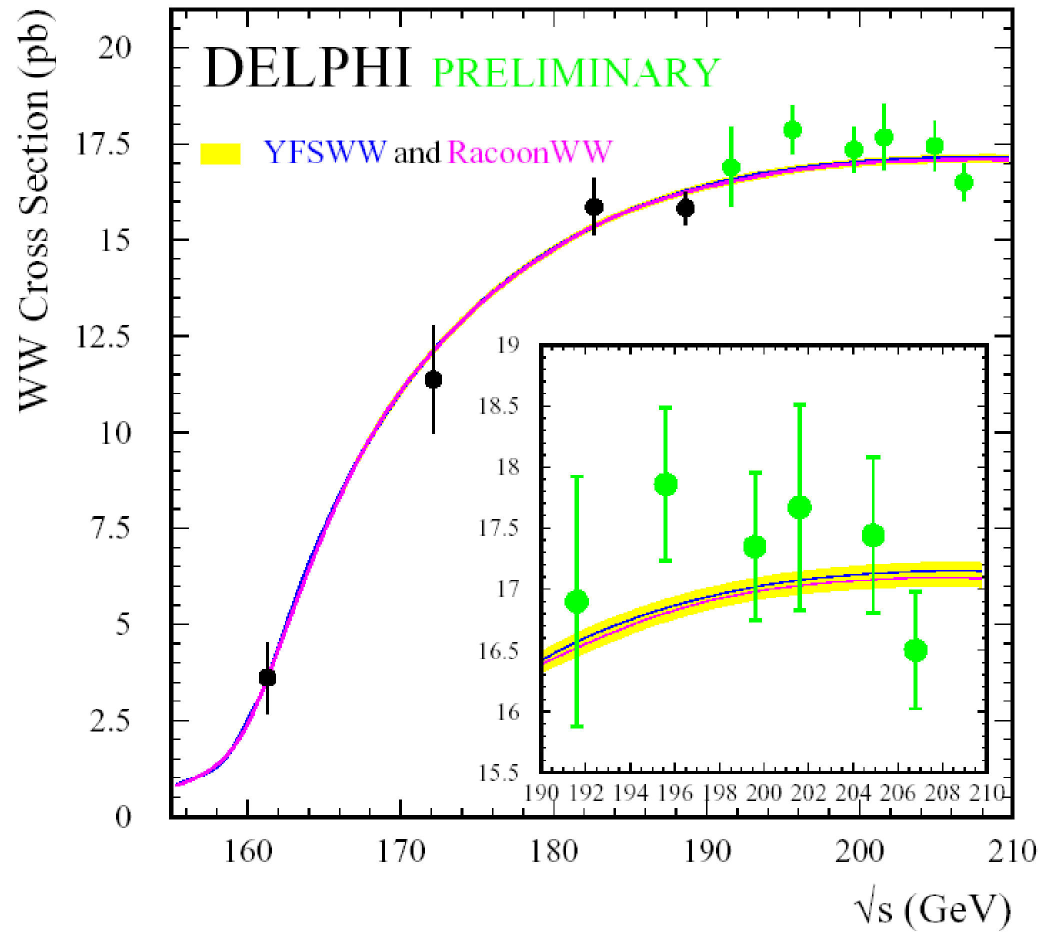
$\sigma \times BR(b' \rightarrow bZ)^2 < 0.21$ pb (0.26 pb exp.)

EW physics @ LEP



From the beginning, the main goal of LEP.
Many precision tests of the SM
and indirect limits on new physics.

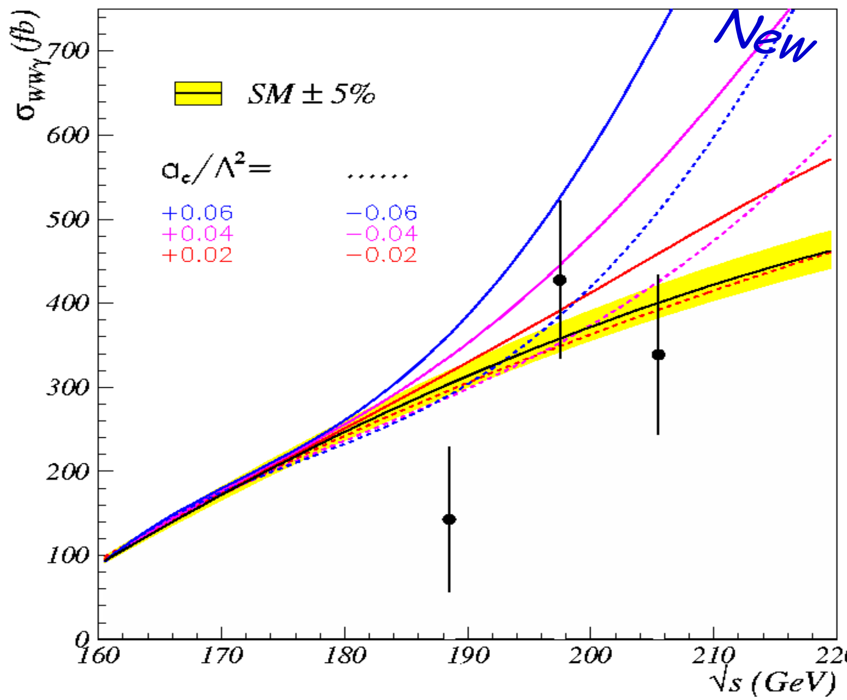
- 2-fermion & 2-photon
  - Cross-sections
  - Asymmetries
- WW & ZZ
  - W mass
  - Cross-sections and BR
- Single boson
  - W & Z ←
- Anomalous couplings
  - TGC
  - QGC ←
- $Z\gamma^*$



QGC with $e^+e^- \rightarrow WW\gamma$

- $E_\gamma > 5$ GeV
- $|\cos\theta_\gamma| < 0.95$
- $\cos\alpha_{isol} < 0.9$

- WW at LEP: extensive studies,
  - Agreement with SM, (σ_{WW}, TGC)
  - High E_{cm} & Lum: WWγ !



- Hard, central, isolated γ:
  - All processes contribute (ISR/FSR/WSR)
  - Enhance possible anomalous contributions

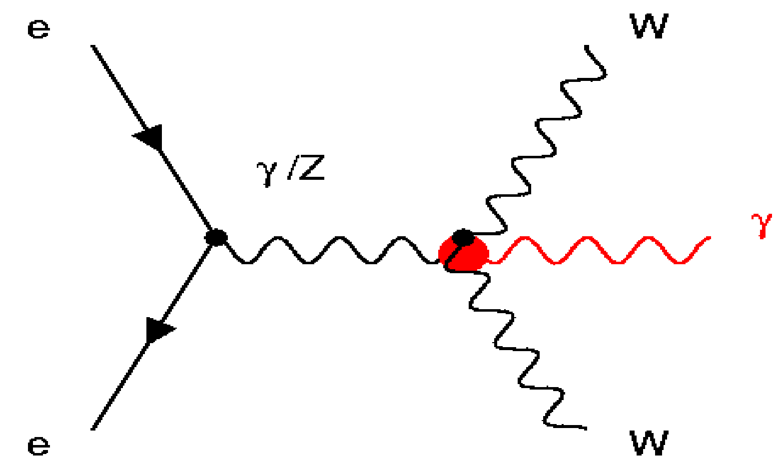
- Final states:
  - WW→qqqq, WW→qqlν
- Radiation description is crucial:
  - WPHACT+YFSWW+...
  - EEWWG (anomalous QGC)

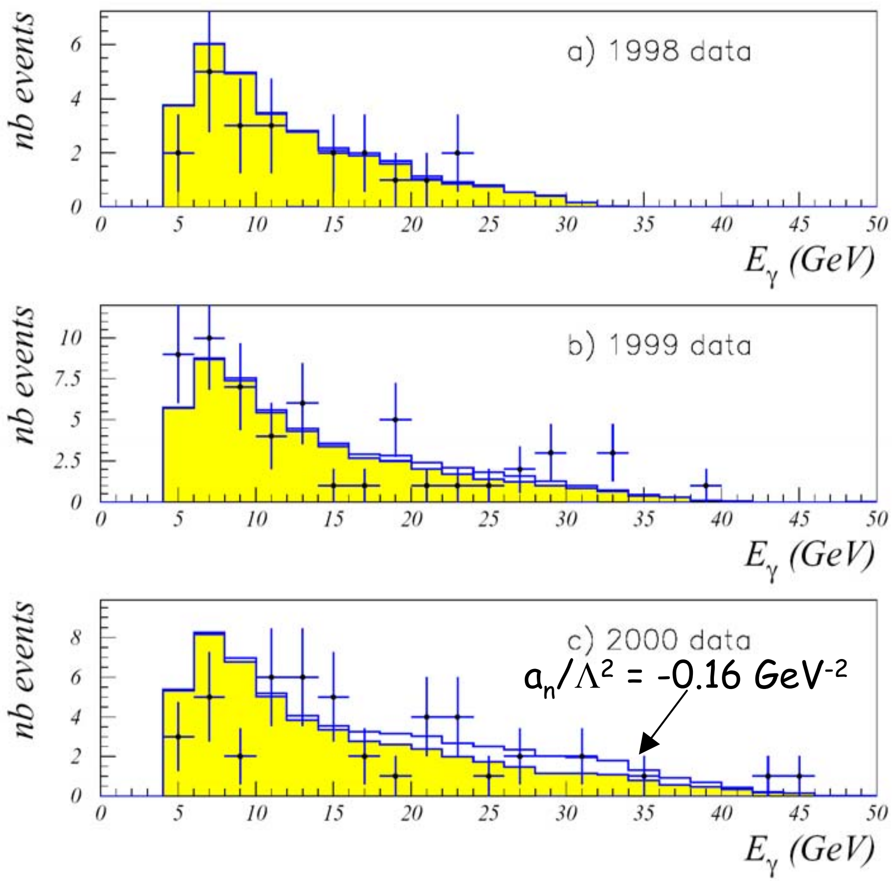
- γqqμν: P≈80% ε≈50%
- γqqqq: P≈50% ε≈40%

•Dominated by statistics: LEP combination !

Anomalous QGC ?

- Negligible at LEP2 in SM
- Contact interactions ?
- Parameterised by set of operators (those affecting TGC are excluded)





- increase σ_{tot}
- distort $E\gamma$ spectrum
- sensitivity increases with E_{cm}

$-0.018\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < +0.018\ \mathrm{GeV}^{-2}$

$-0.057\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < +0.030\ \mathrm{GeV}^{-2}$

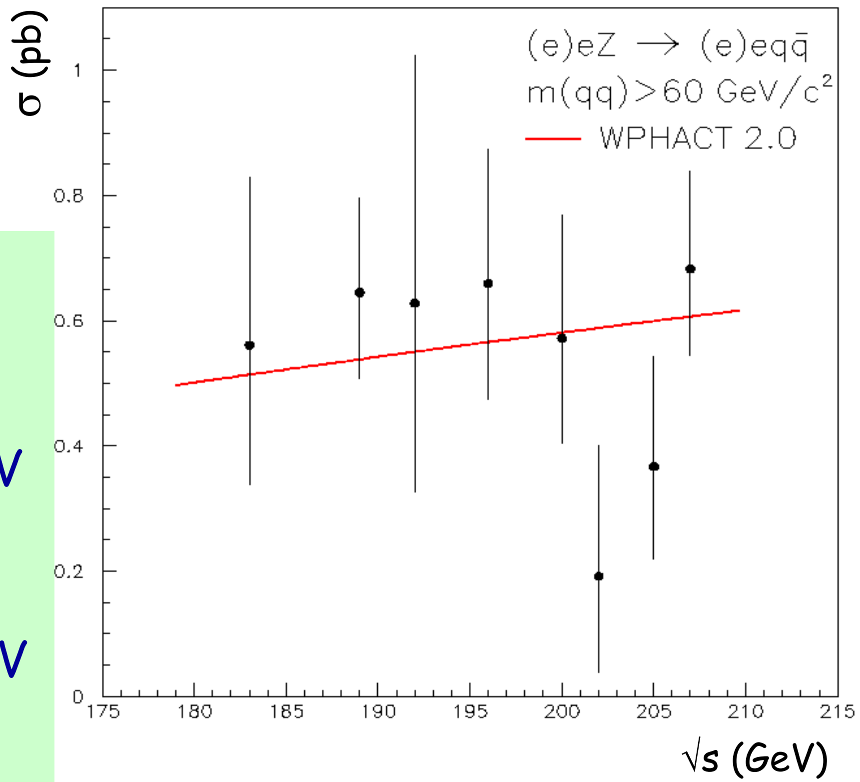
$-0.16\ \mathrm{GeV}^{-2} < a_n/\Lambda^2 < +0.12\ \mathrm{GeV}^{-2}$

$e^+e^- \to Zee$

	Data	MC tot	Zee
qqee	151	150	107
μμee	13	8.3	7.6

Final state: $e^+e^-f\bar{f}, (f = q, \mu)$

... different contributions



Signal definition (common LEP):

- mff > 60 GeV/c2
- $\cos\theta_{e+} < -0.98$, $-0.98 < \cos\theta_{e-} < 0.5$, $E_{e-} > 3$ GeV (if visible electron)
  or
- $\cos\theta_{e-} > +0.98$, $-0.5 < \cos\theta_{e+} < 0.98$, $E_{e+} > 3$ GeV (if visible positron)

(z axis along electron beam)

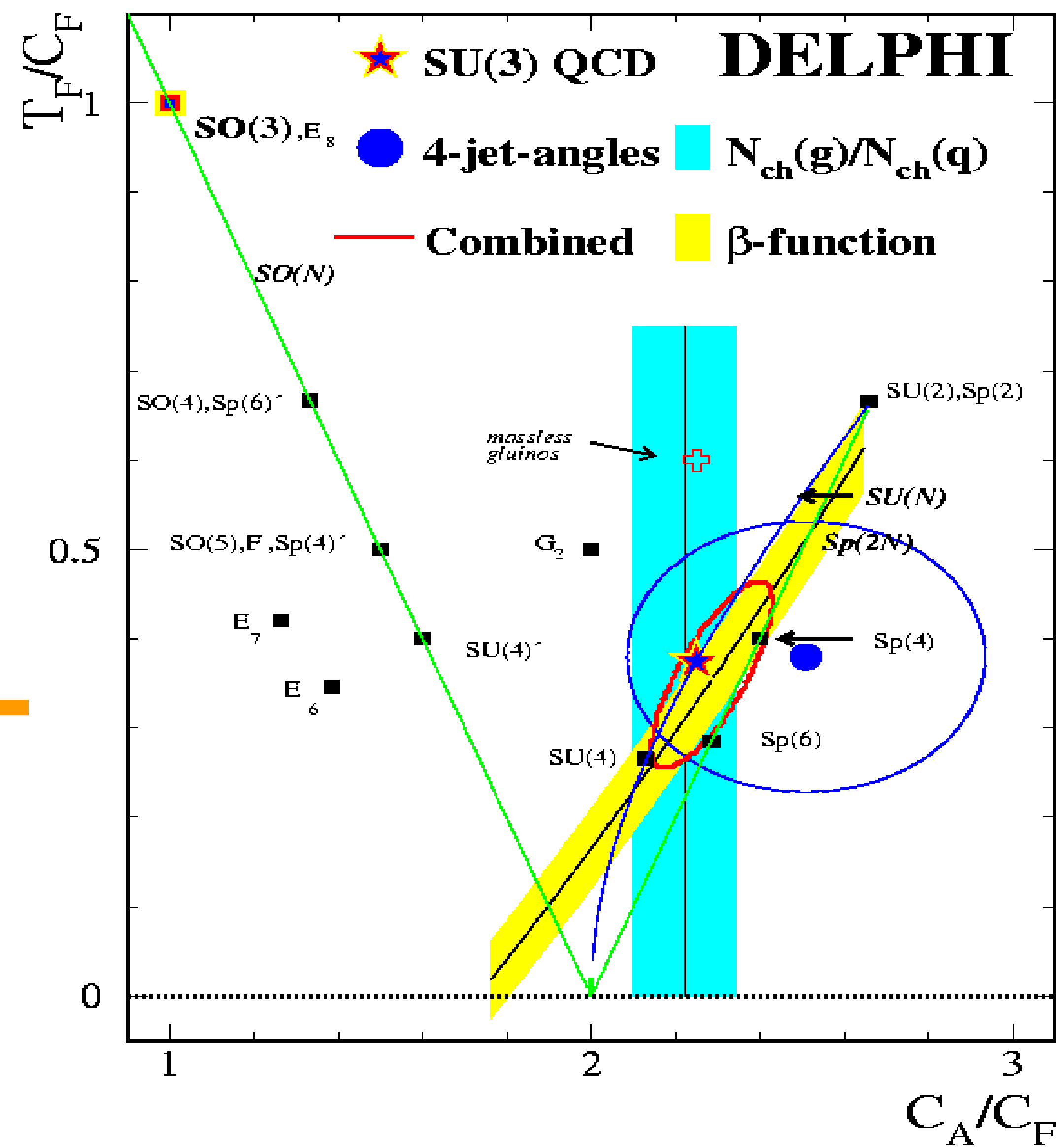
... enhanced single Z contribution

- Agreement with SM
- Dominated by statistics
- LEP combination !

QCD @ LEP

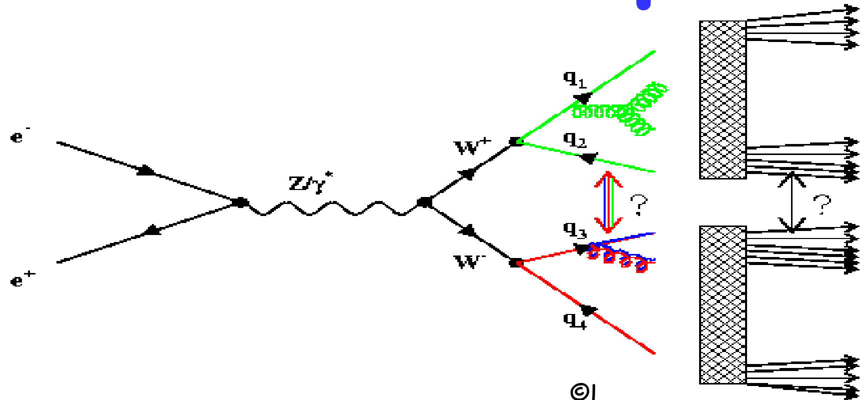
Detailed studies, much greater precision, many beautiful tests and insight to the structure of QCD

- Hard …
  - α_s running
  - m_b running
  - Gauge structure
  - Event shape
  - Jet rates
- … And soft
  - Colour reconnection
  - B-E correlations
  - Multiplicities
  - Quark & gluon jets
  - Fragmentation functions
- $\gamma\gamma$-physics



Colour Reconnection in WW→4q

- Probes hadronisation dynamics in space & time !
- *Affects W mass measurement*



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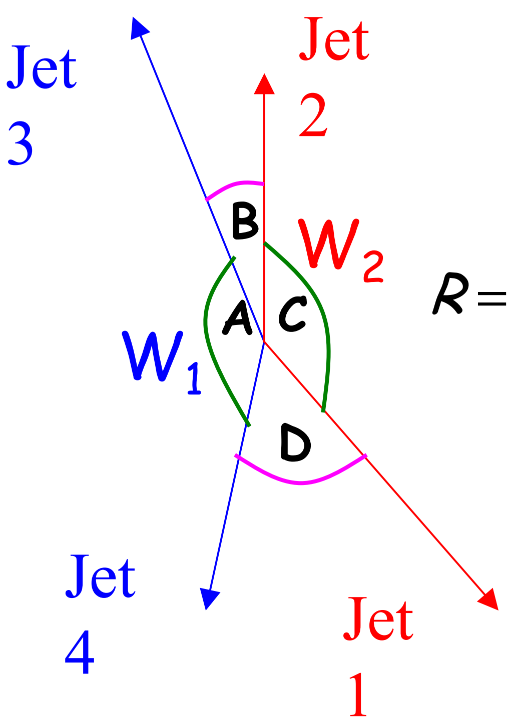
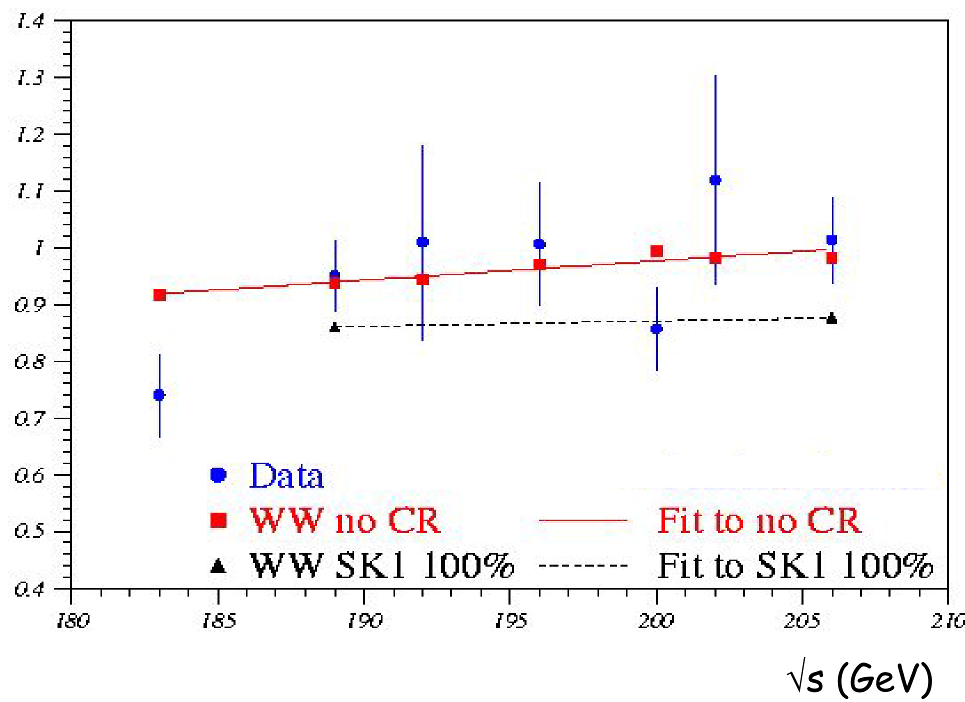
Particle Flow Method

Exploit changes in particles distribution in inter W regions

Events with well-defined regions: low efficiency

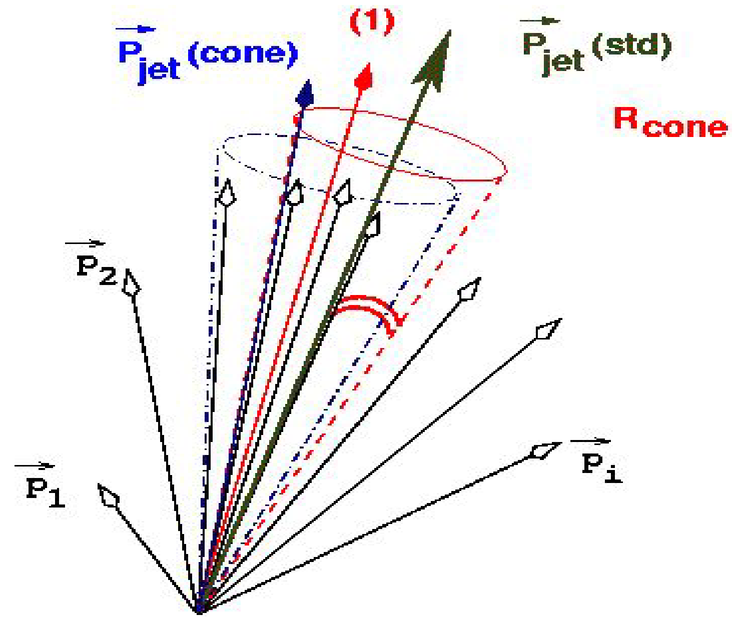


$$R=\frac{\int_{0.2}^{0.8}\frac{1}{N_{ev}}\frac{dn}{d\Phi}d\Phi(A+C)}{\int_{0.2}^{0.8}\frac{1}{N_{ev}}\frac{dn}{d\Phi}d\Phi(B+D)}$$



CR from ΔM_W

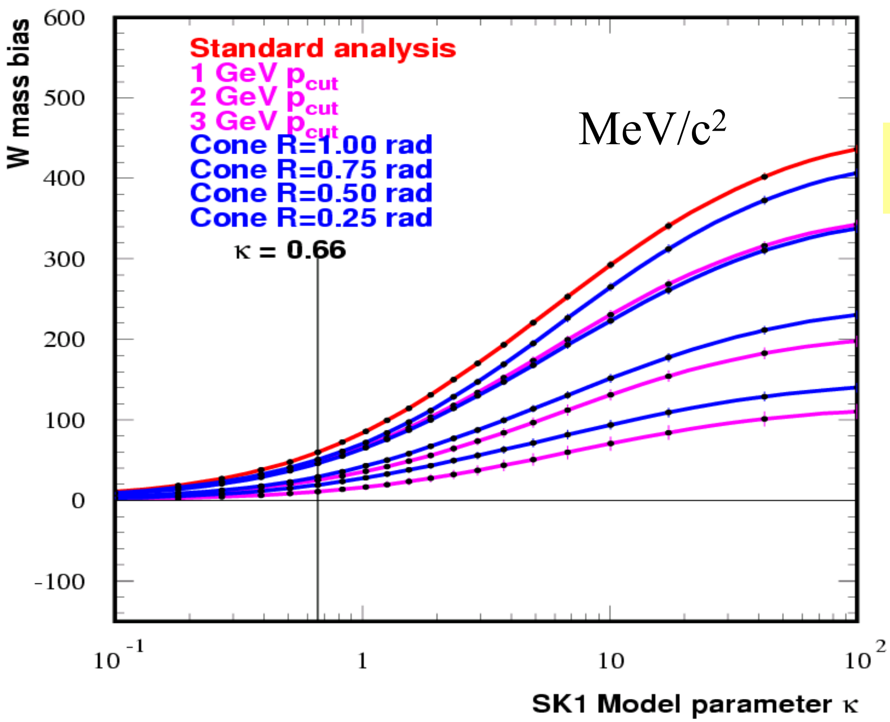
Use different dependence of M_W estimators on CR (k@SKI):



Two m_W estimators :

- Standard (rather complex estimator)
- Cone-like (neglect info of some particles)

Calibration: remove intrinsic bias (k=0)

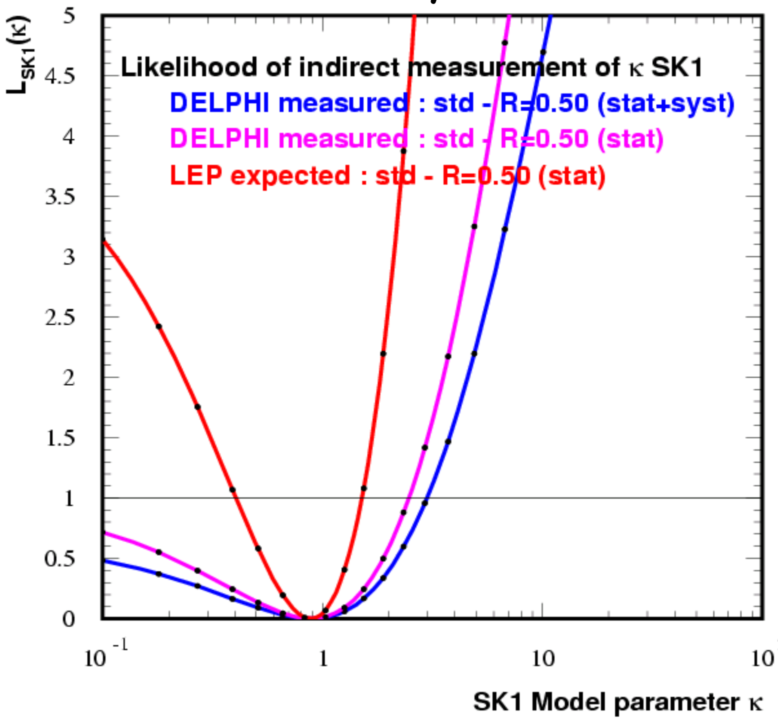


$$\Delta M_W(std, R_{cone} = 0.5 rad) = 36 \pm 36 \pm 25\ MeV/c^2$$

- Compare with model prediction for each k ...

CR (III)

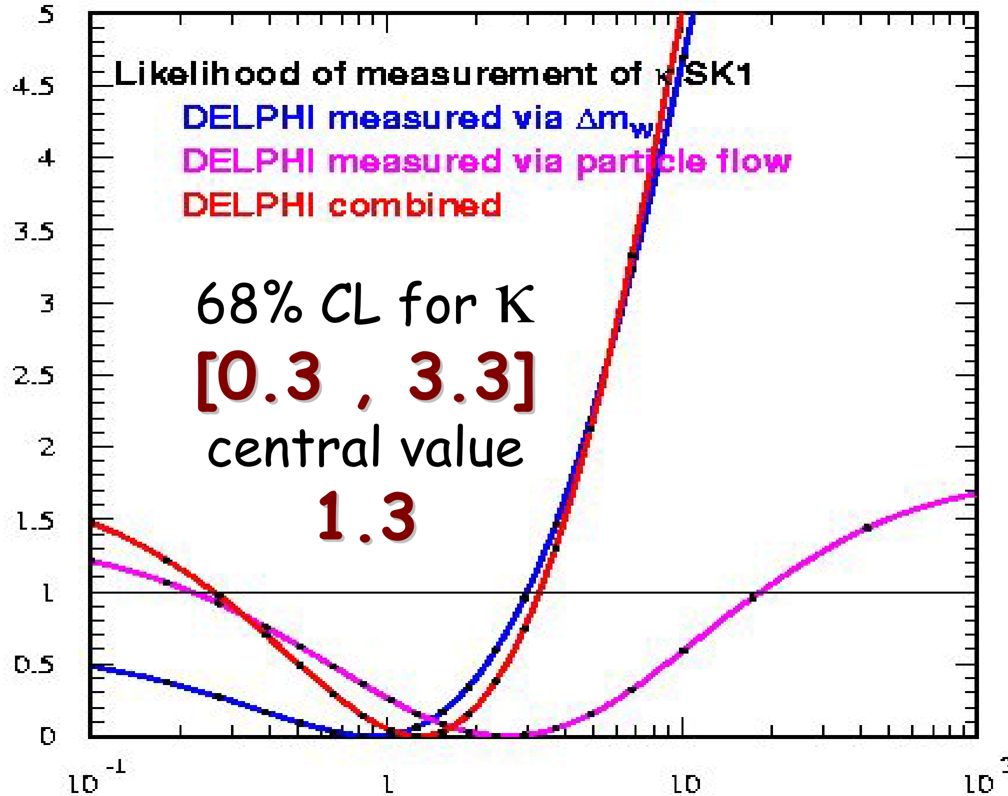
Effect of systematics:



Source	MeV/c²
Fragmentation	10
$\sqrt{s}$ dependence ⊕ bck.	10
Energy flow in jet	11
BEI-BEA	8
BEO-BEI	16

Combination of the two methods

(assuming no correlation)



- Compatible with no or small CR !
- LEP combination !

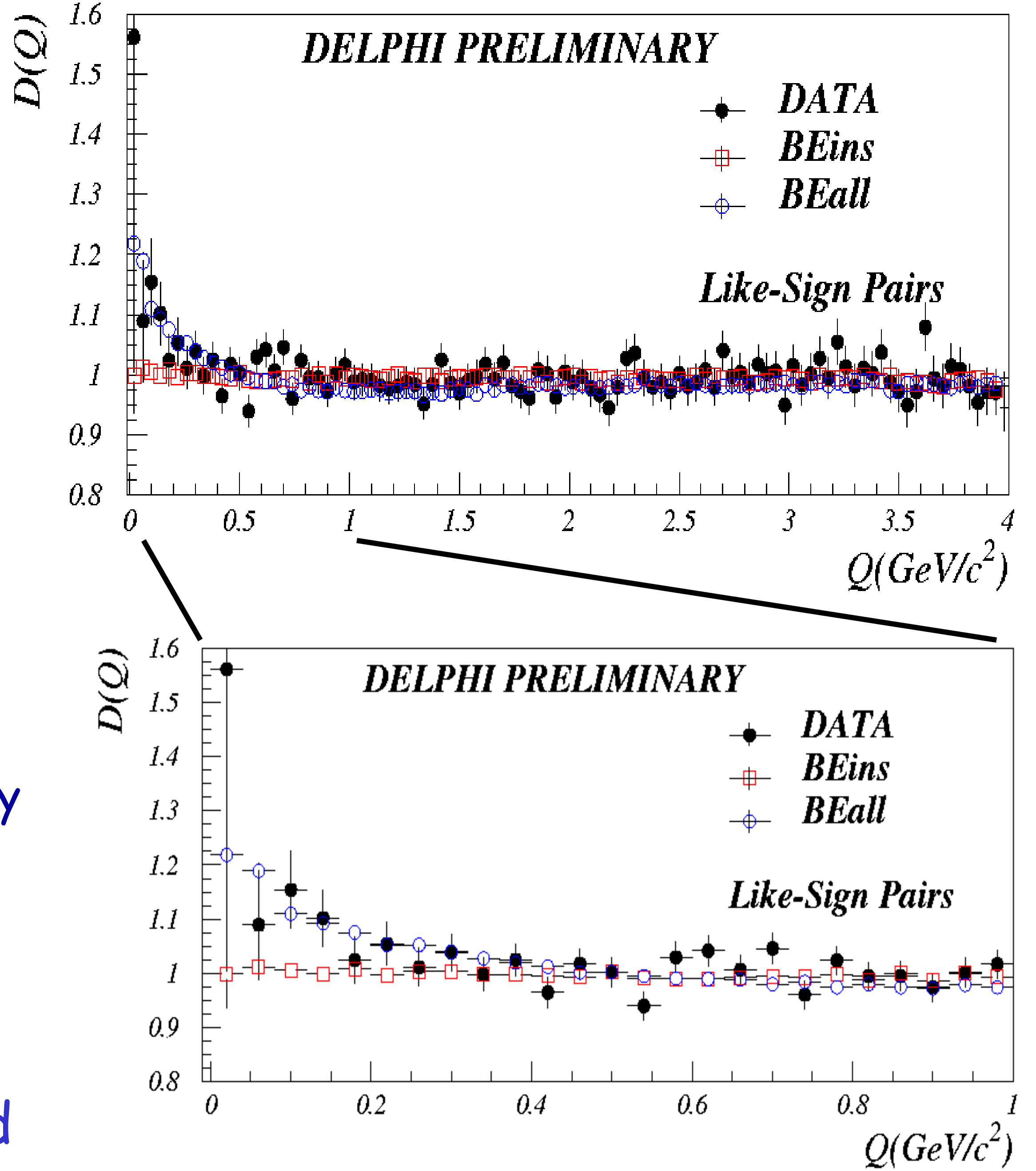
Bose-Einstein correlations

... between π's

of different W's in

WW→4q

$$D(Q) = \frac{4q - back}{2(2q) + mix}$$

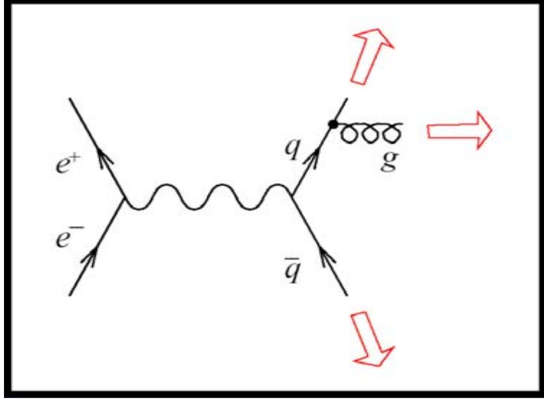


What changed ?

- Data/MC final processing
- Analysis optimisation: higher eff. for same purity
- Background subtraction: from 4 jet events @ Z

... being finalised

m_b @ M_Z



Massive quarks radiate less gluons than light quarks...

... mass effects @ LEP energies:

- Negligible for more inclusive observables ($m_b^2/M_Z^2 < 0.3\%$)
- Some sensitive variables (e.g. jet rates, new scale $(m_b^2/M_Z^2)/Y_{cut}$)

- Measured observable for extracting m_b:

$$R_3^{b\ell}(y_c) = \frac{\Gamma_{3j}^{Z\to b\bar{b}g}(y_c) / \Gamma_{tot}^{Z\to b\bar{b}}(y_c)}{\Gamma_{3j}^{Z\to \ell\bar{\ell}g}(y_c) / \Gamma_{tot}^{Z\to \ell\bar{\ell}}(y_c)}$$

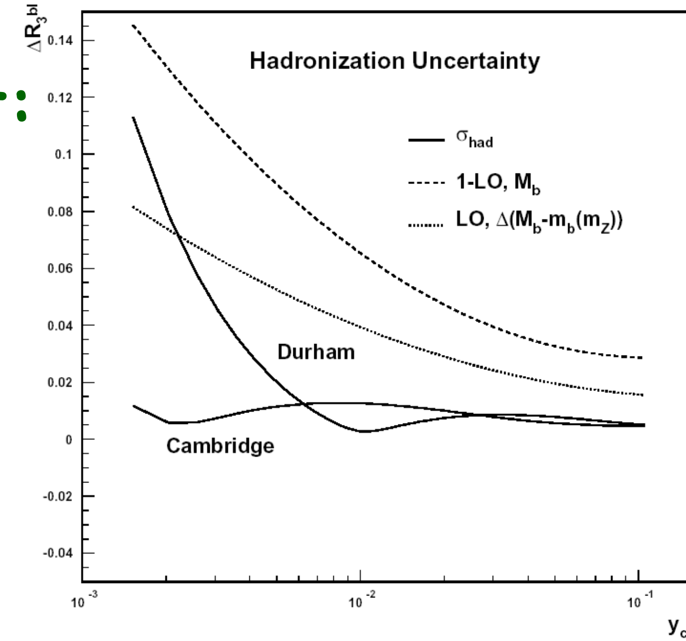
ℓ = light quark

- Calculations including mass effect at NLO performed for b/l ratios:

$$R_3^{b\ell}(y_c) = 1 + r_b(\mu)\cdot\left(b_I(y_c, r_b(\mu)) + \frac{\alpha_s(\mu)}{\pi} b_{II}(y_c, r_b(\mu))\right)$$

function b_I and b_{II} in reference; $r_b(\mu) = m_b^2(\mu)/M_Z^2$

m_b (II)

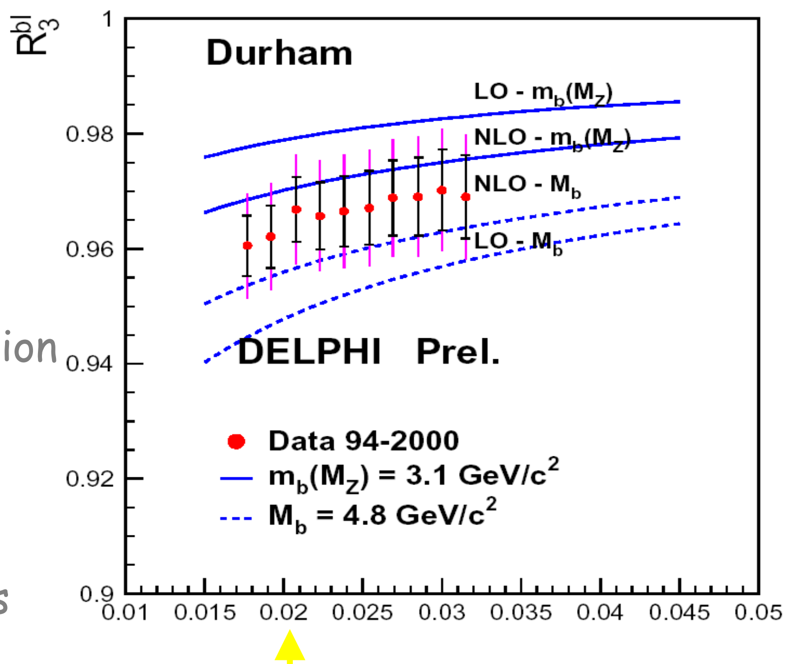


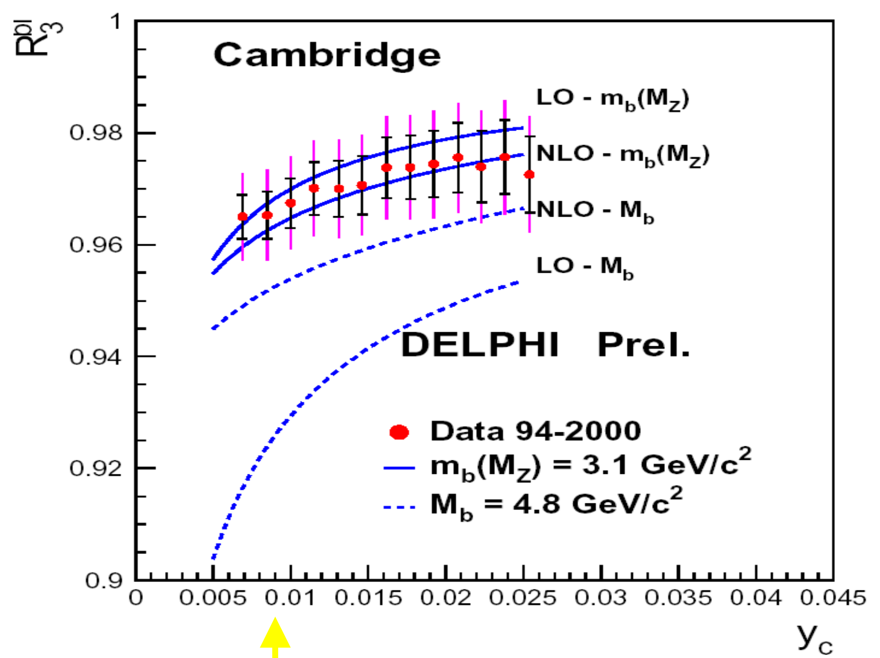
•Improvements w.r.t. '97 measurement:

- •Reduced theoretical uncertainty: Cambridge
- •Reduced fragmentation uncertainty
- •Better treatment of masses (Pythia)
- •Better understanding of b and l tagging
- •Some more data

•Results of R_3^{bl} at parton level:

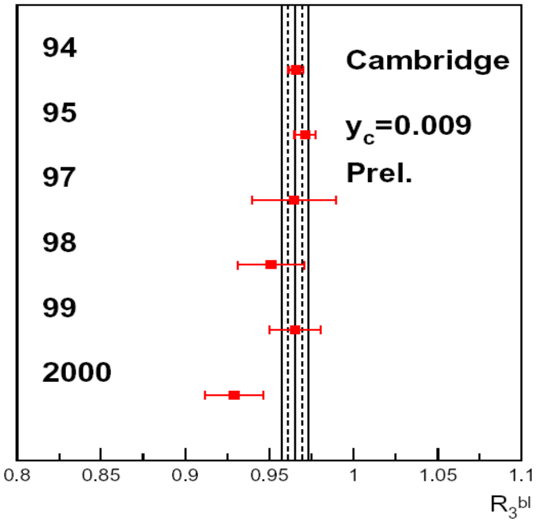
Detector
+
Hadronisation model
+
Gluon splitting corrections





m_b (III)

Stability:



- **Cambridge:**

$$m_b(M_Z) = 2.82 \pm 0.19(stat)^{+0.31}_{-0.33}(syst) \pm 0.06(theo)\ \mathrm{GeV}/c^2$$

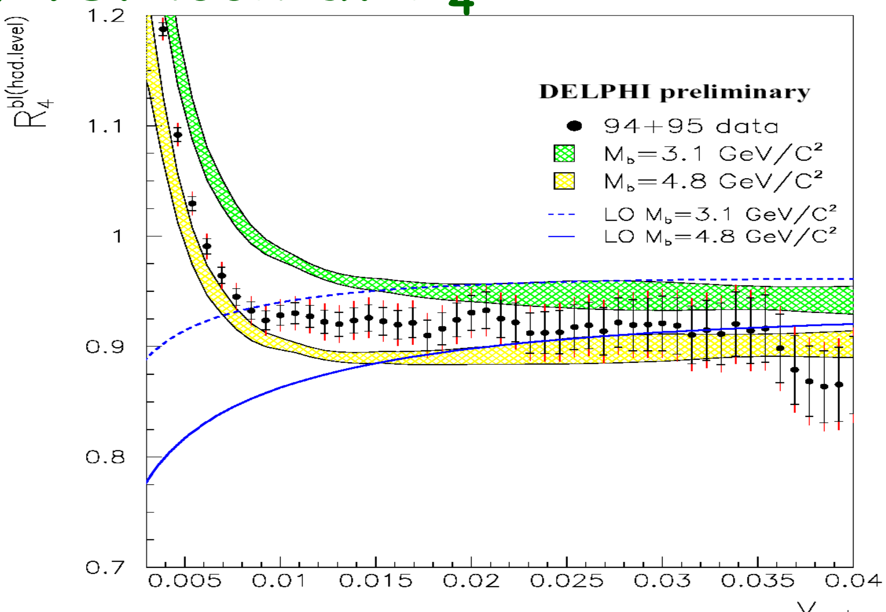
- **Durham:**

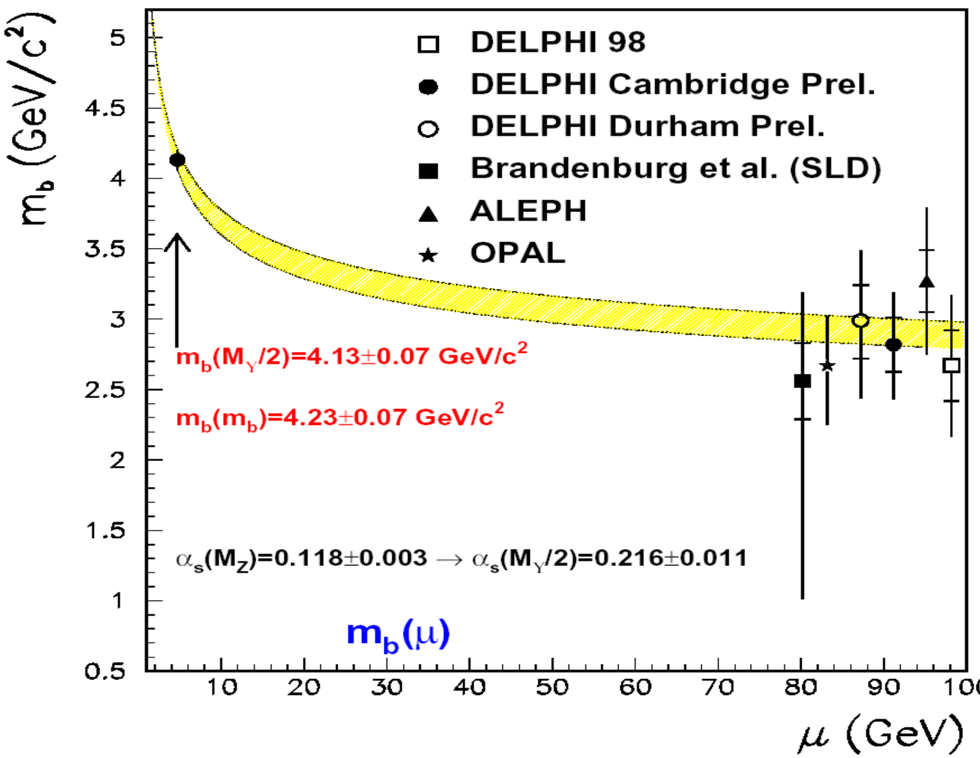
$$m_b(M_Z) = 2.99^{+0.25}_{-0.27}(stat)^{+0.34}_{-0.37}(syst) \pm 0.28(theo)\ \mathrm{GeV}/c^2$$

$$m_b(M_\Upsilon/2) - m_b(M_Z) = 1.31^{+0.37}_{-0.40}\ \mathrm{GeV}/c^2$$

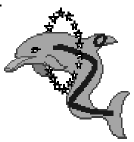
$$\alpha_s^b / \alpha_s^\ell = 1.001 \pm 0.004(stat) \pm 0.007(syst) \pm 0.002(theo)$$

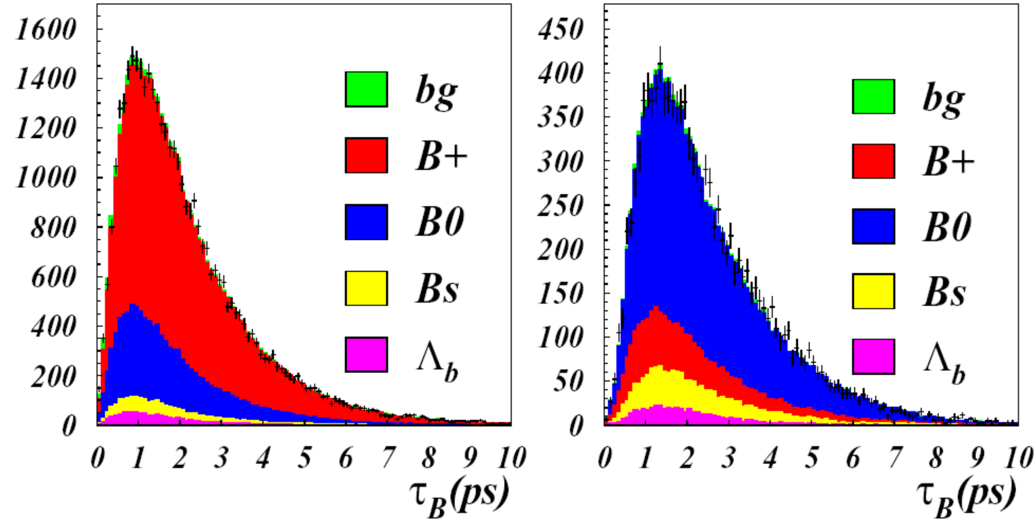
First look at R_4^{bl}:





Heavy flavours @LEP

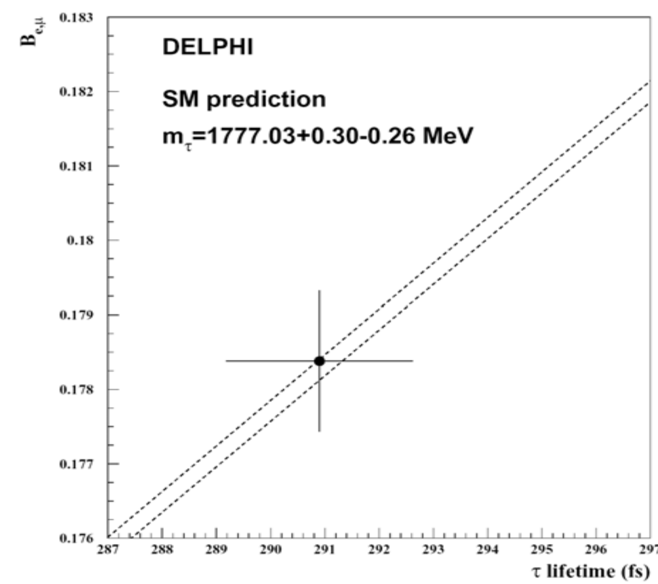




- B physics…
  - Lifetimes
  - Oscillations
  - Leptonic and hadronic moments
  - Spectroscopy
  - V_{cb}
- τ physics…
  - Lifetime
  - Branching fractions
  - ν_τ mass

Vertex detectors & b-tagging at LEP !

Still some unique and most precise results



Moments in B semileptonic decays

- V_{cb}, V_{ub} govern B decay rate ⟹ crucial for SM tests
- Experiment: $b \to c \ell \overline{\nu}_\ell$ BR & lifetime (1-2%)

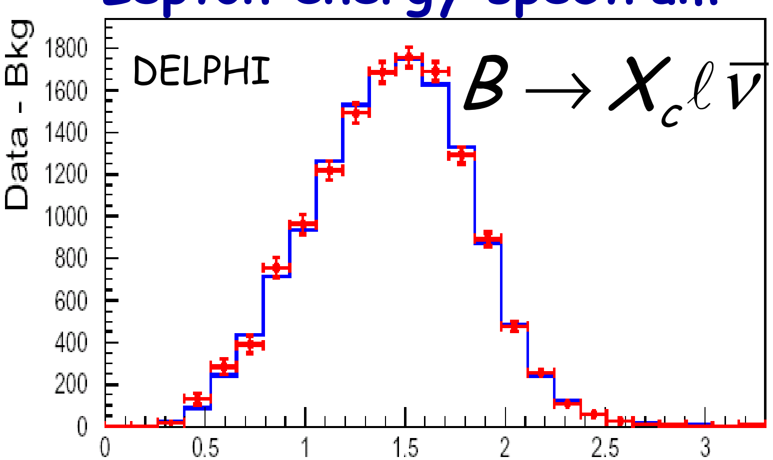
... dominant theory uncertainty from input parameters:

- quark masses m_b, m_c
- kinematics of quarks in hadrons λ_1

... But there is more info in our data !

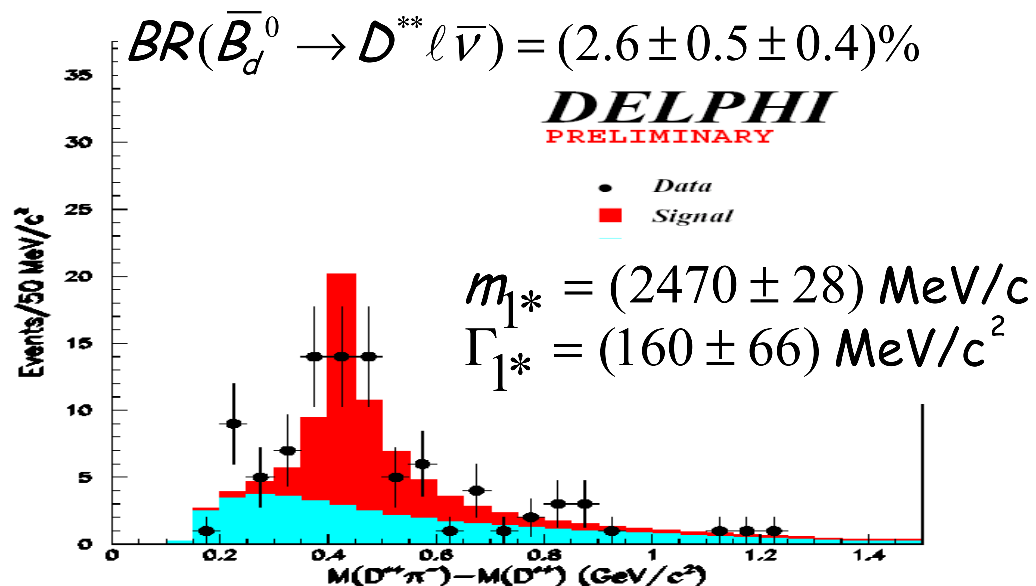
moments (n=1,2,3) of distribution: $M_n \equiv M_n(m_b, m_c, \lambda_1)$

Lepton energy spectrum:



High energy:
sensitivity to full lepton spectrum

Hadronic mass distribution

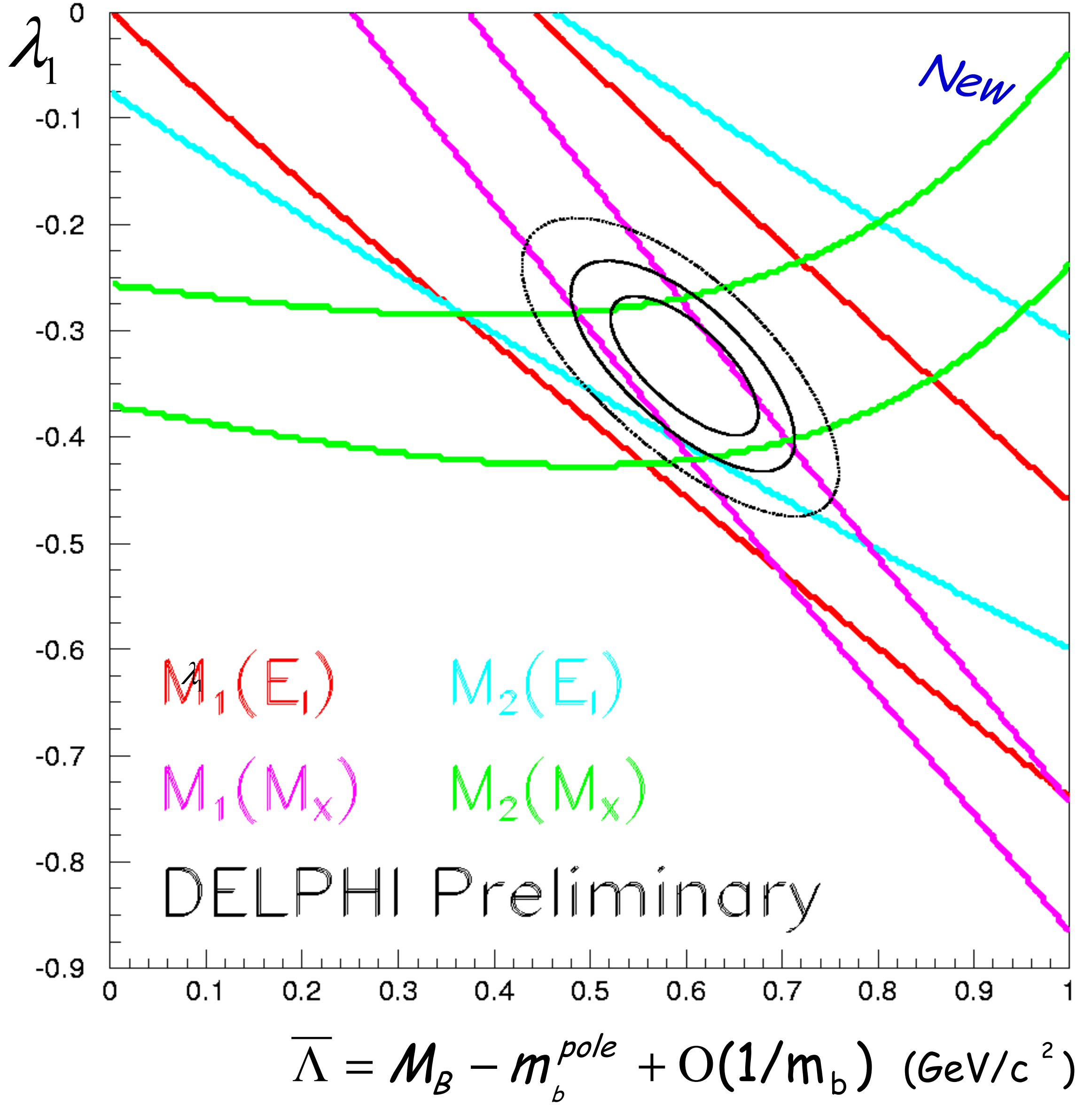


Moments (II)

... Combining
the 2 analyses:

M(E_l)
lepton spectrum moments
M(M_x)
D** hadronic mass moments

... We can constrain
(Λ,λ_1) plane



$$\overline{\Lambda} = (0.59 \pm 0.05(stat) \pm 0.05(syst) \pm 0.12(m_b^3, \alpha_s))\ GeV$$

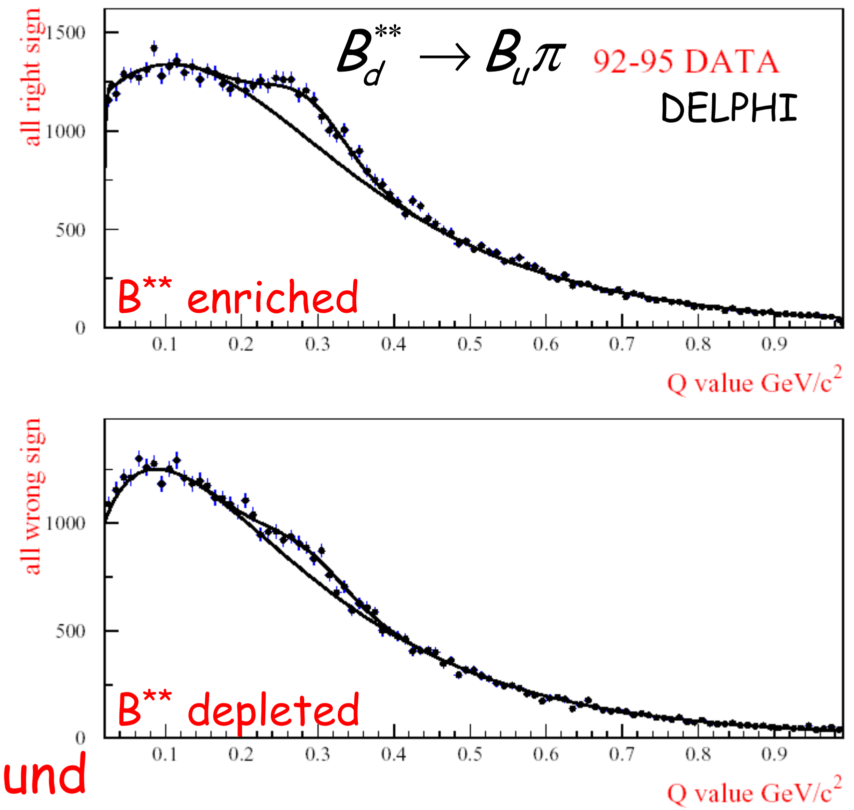
$$\lambda_1 = (-0.33 \pm 0.05(stat) \pm 0.05(syst) \pm 0.16(m_b^3, \alpha_s))\ GeV^2$$

$B^{**}_{(s)} \to B^{(*)}\pi(K)$

- Searching for orbitally excited B
  - Measurement of production rates B_u^{**}, B_d^{**}
  - Narrow and broad states
  - Upper limits in production rates $\Sigma_b^{(*)}, B_s^{**}$

Analyses:

- Larger data sample
- Significantly improved tracking, calorimetry and tagging algorithms
- B tag
- b charge tag, sec. vertex charge tag
- Inclusive B momentum reconstruction
- Particle ID (kaons and pions, RICH+TPC)



- Significantly reduce dependence on MC description of background:

- Simultaneous fit to signal and background on data ("Soft" analysis)
- Work at high purity ("NN" analysis)

Q value definition:
$Q=M(B,\pi)-M_B-M_\pi$

B**

Some Results:

Narrow states only:

Width compatible with experimental resolution

Data prefer small mass splitting

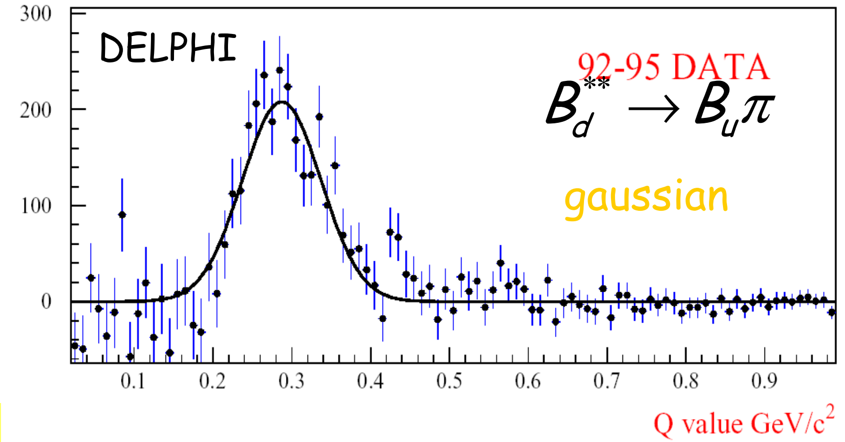
$$\sigma_{\bar{B}^{**}_{u,d}} / \sigma_b = (0.098 \pm 0.007(\text{stat}) \pm 0.012(\text{sys}))$$

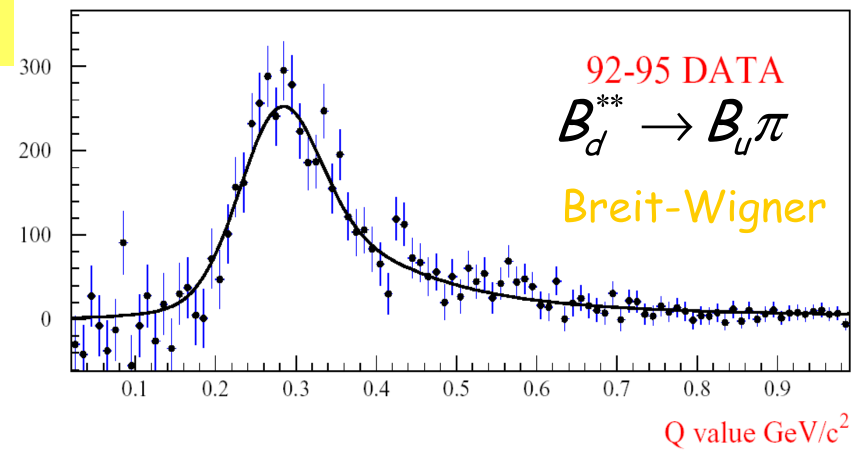
... Some evidence for broad states

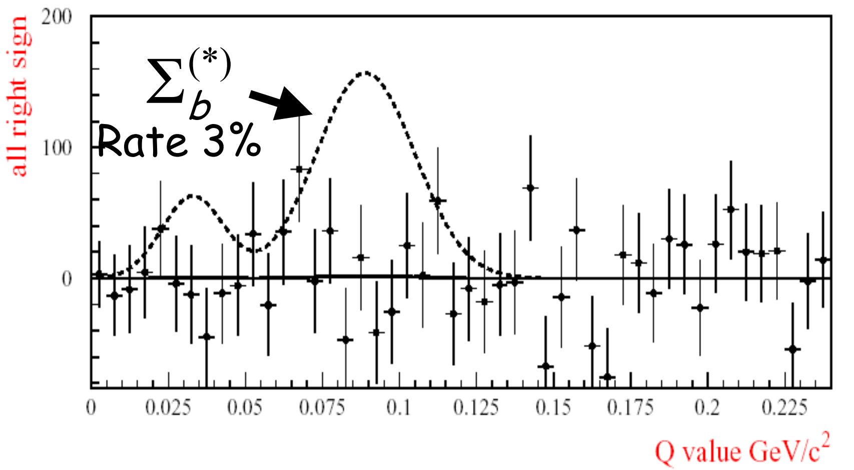
Upper limits $\Sigma_b^{(*)}, B_s^{**}$

(assuming narrow and Q<150 MeV)

$$\sigma_{\Sigma_b^{(*)}} / \sigma_b , \sigma_{\bar{B}_s^{**}} / \sigma_b < 0.015 \text{ at 95\% CL}$$



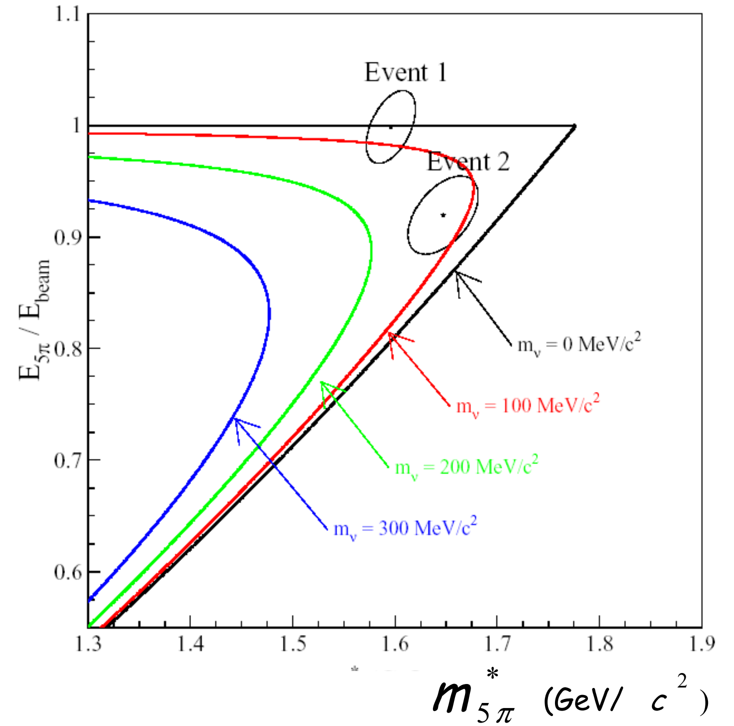




$\tau \to 5\pi$

... kinematic of $\tau^{\pm} \to 3\pi^{\pm} 2\pi^{\mp} \overline{\nu_{\tau}} (\nu_{\tau})$: info on ν_τ mass !

Can be seen as a 2-body decay: $\tau^{-} \to h^{-} \nu_{\tau}$



Undetected ν:

- θ_τ unknown, but: $E_h^{\min,\max} = \gamma(E_h^* \pm \beta p_h^*)$
- invariant mass: $m^*_{5\pi} < m_\tau$

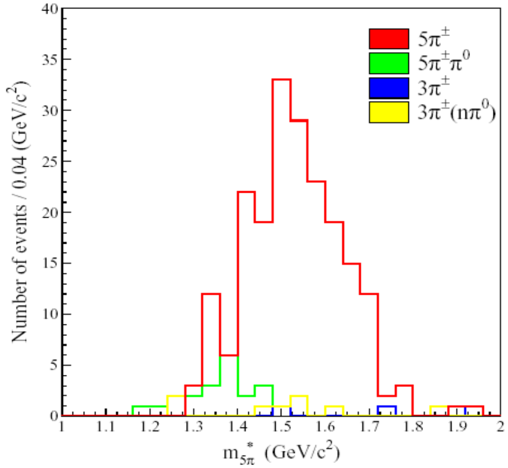
...2D distribution of the 2 variables fitted to obtain a limit on $m\nu_\tau$

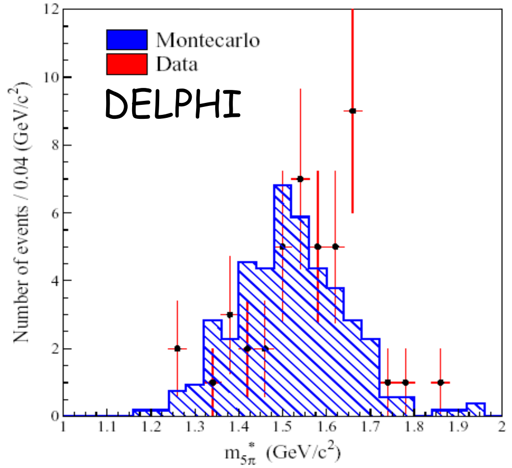
Select $Z \to \tau\tau$ "1-prong 5-prong"...

Data: 47 events ($P \approx 76\%$)

- Fit region: $m^*_{5\pi} > 1.6$ GeV, $E_{5\pi}/E_{beam} > 0.85$

15 events in data



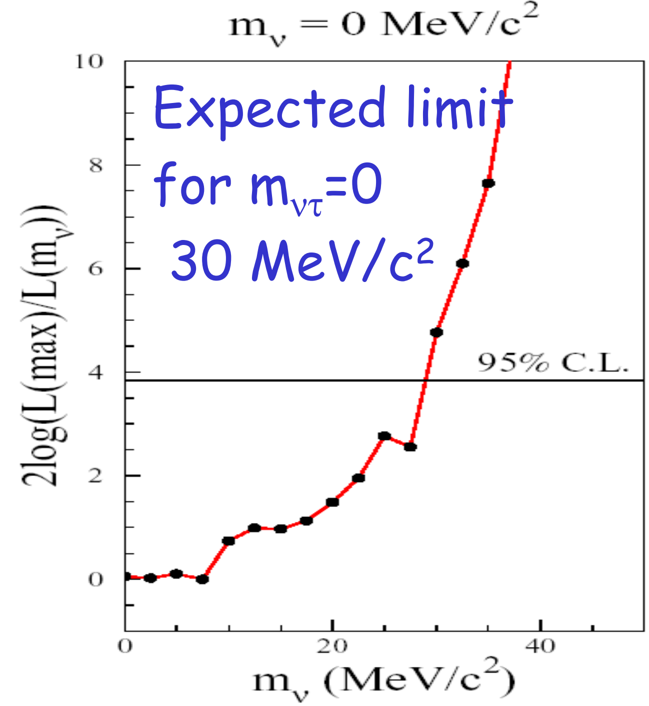


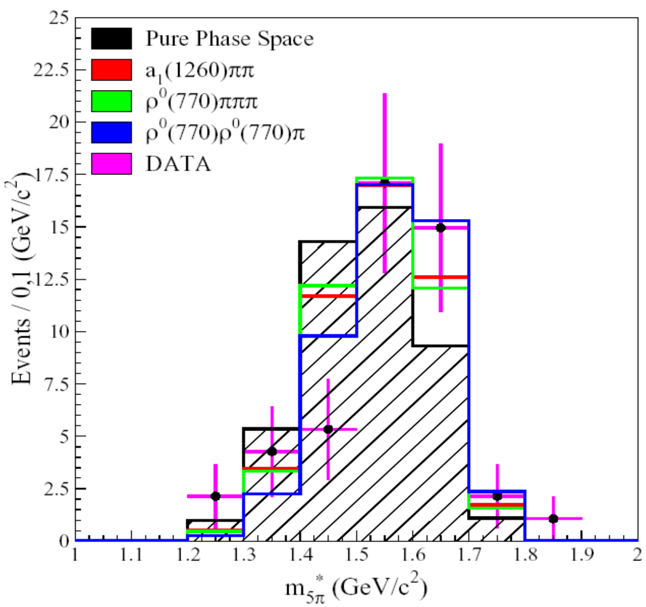
$\tau \rightarrow 5\,\pi$

$$L = \prod_{i=1}^{N_{obs}} P(m_i^*, E_i \mid m_{\nu_\tau}) = \alpha L_{sig} + (1-\alpha) L_{bgd}$$

P = Probability of each event in the ($m_{5\pi}$,$E_{5\pi}/E_{beam}$) plane
$\otimes$ Experimental resolution $\otimes$ Selection efficiency

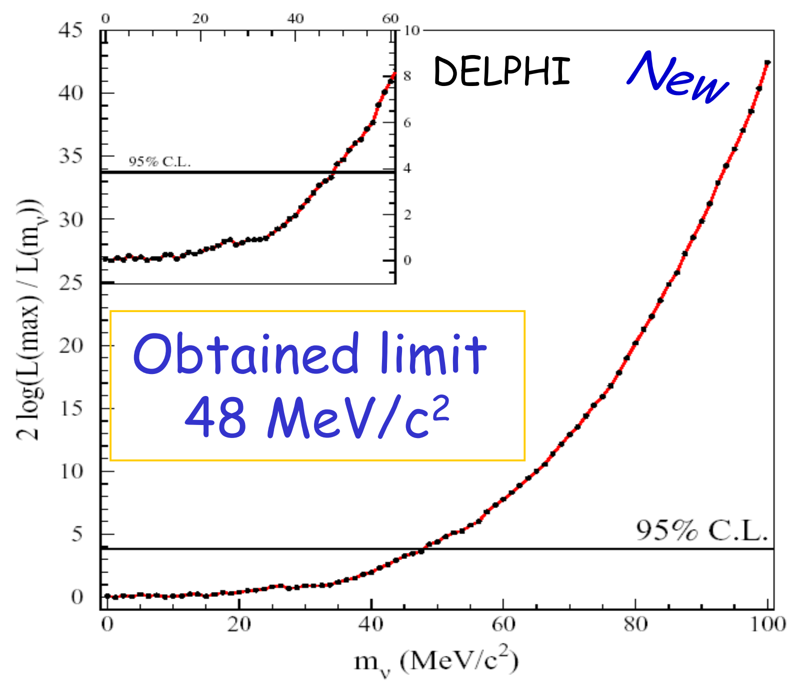
- Method tested for different input masses





...systematics

Effect	Source
Exp. Resol	2.5
Mass calib	1.0
Fit region	0.7
m_τ	0.3
E_{beam}	0.1
Hadr mass	4.0



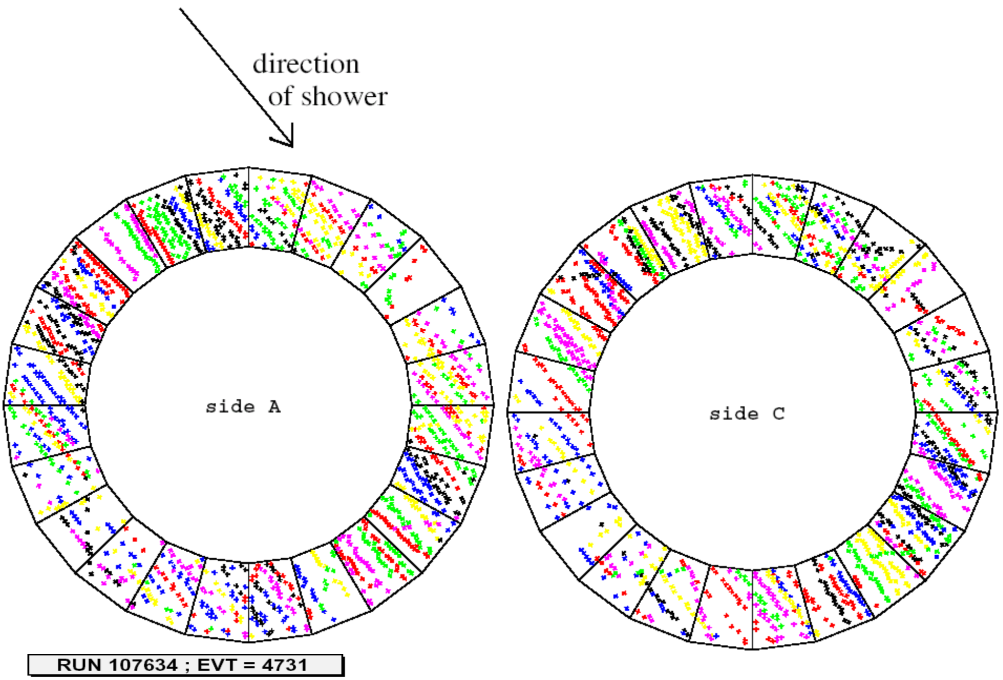
Intermediate structure of the decay:
conservative pure phase space taken

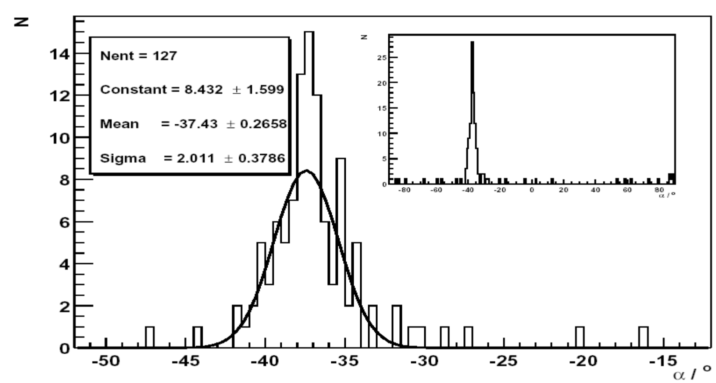
Cosmic muon bundles!

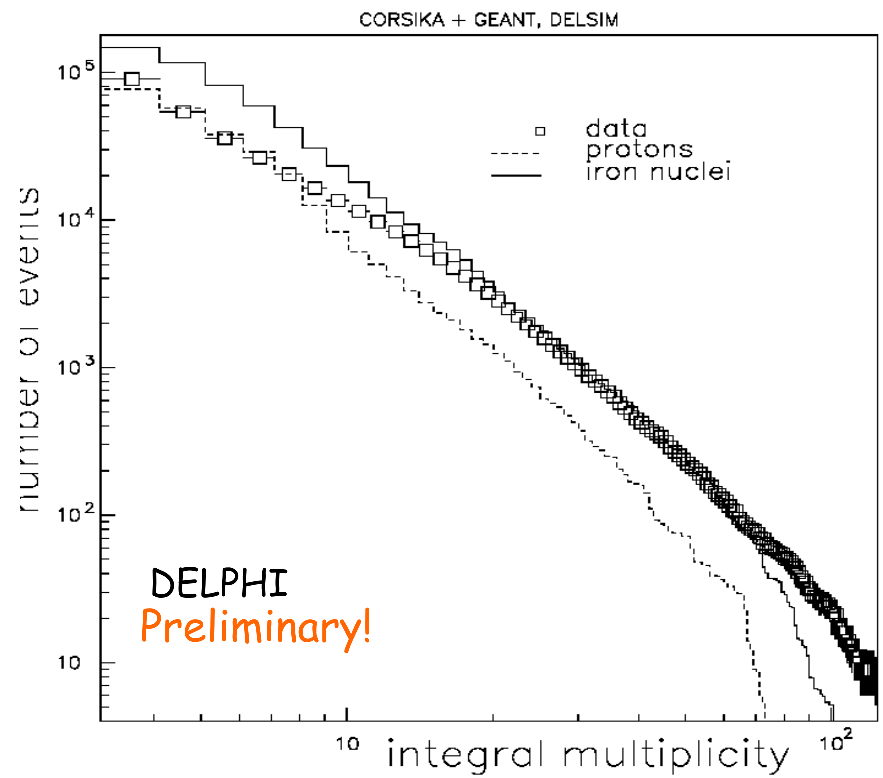
... few experiments with intermediate momentum threshold and good spatial resolution...

DELPHI cosmics:

- Depth ~ 100 m, Pcut ~ 50 GeV/c
- HCAL + μ chambers +TOF (trigger)
- Run time T_{eff}=1.6 10^6 s







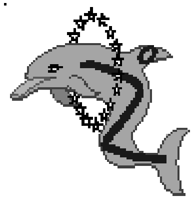
Possible excess at high multiplicities

Underground data yields new 'handle' !

Next: more extensive MC

What's left to be done ?

... **Best possible use of our data !**



Results/publications

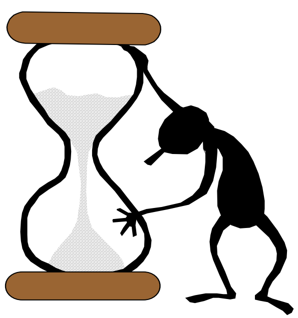
... Impressive set of results @ LEP
- often better precision than expected
- Some will stay for a long time !

final papers must do justice to many years of hard work by many people
- Excellent machine performance !!
- High quality results
- Complete interpretations
- Some "summary papers"

Data

The clean LEP data will be useful! (model testing, generator tuning, education, ...)

... Try to keep it easily available
- C++ analysis structure (IDEA)
- "Team ntuples" - high level info shared and kept by different groups



... Still lots of activity

more than 50 Papers and Theses

many ongoing LEP Combinations

and still some new analyses... !