Electroweak and Higgs Physics

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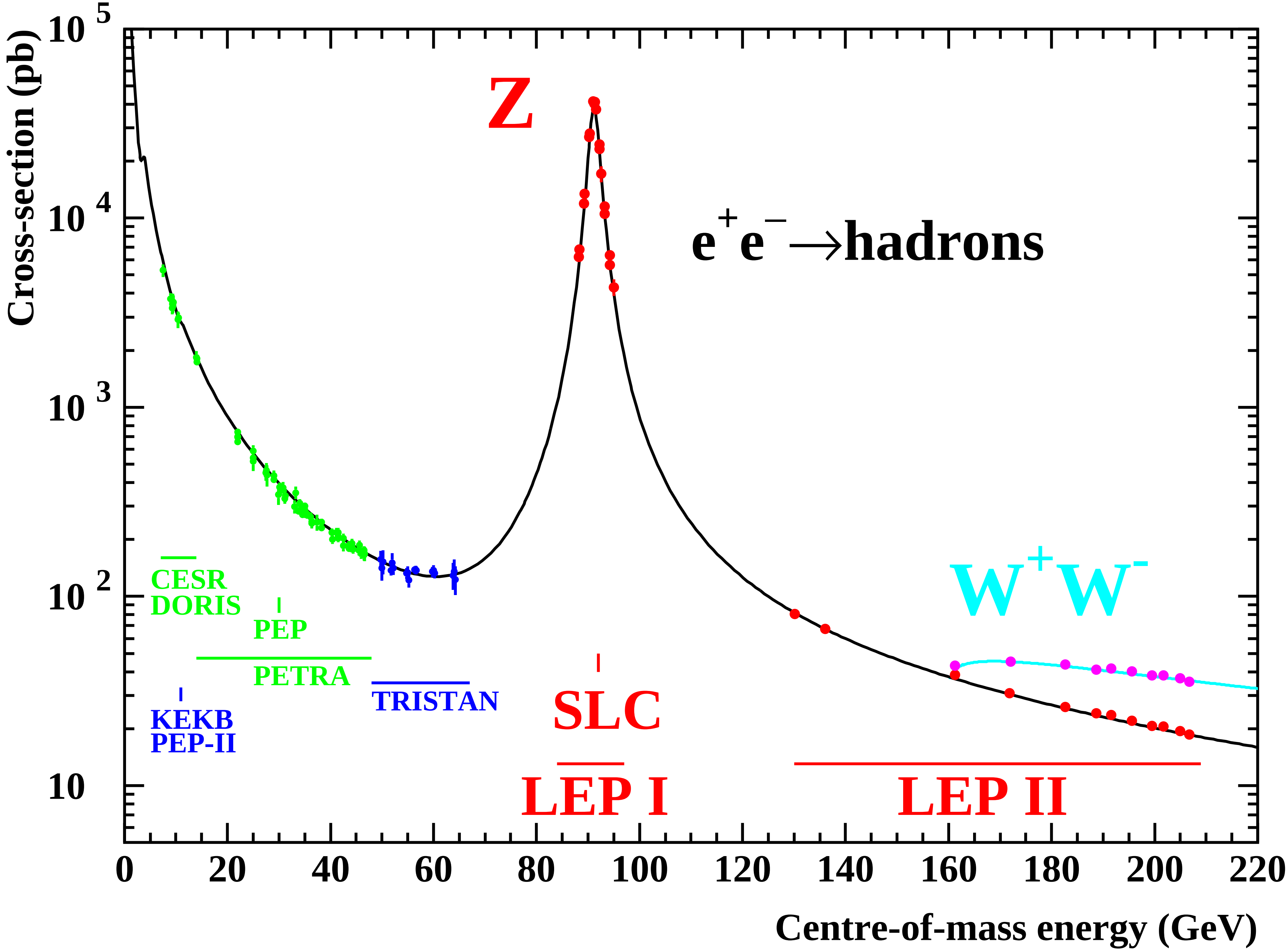
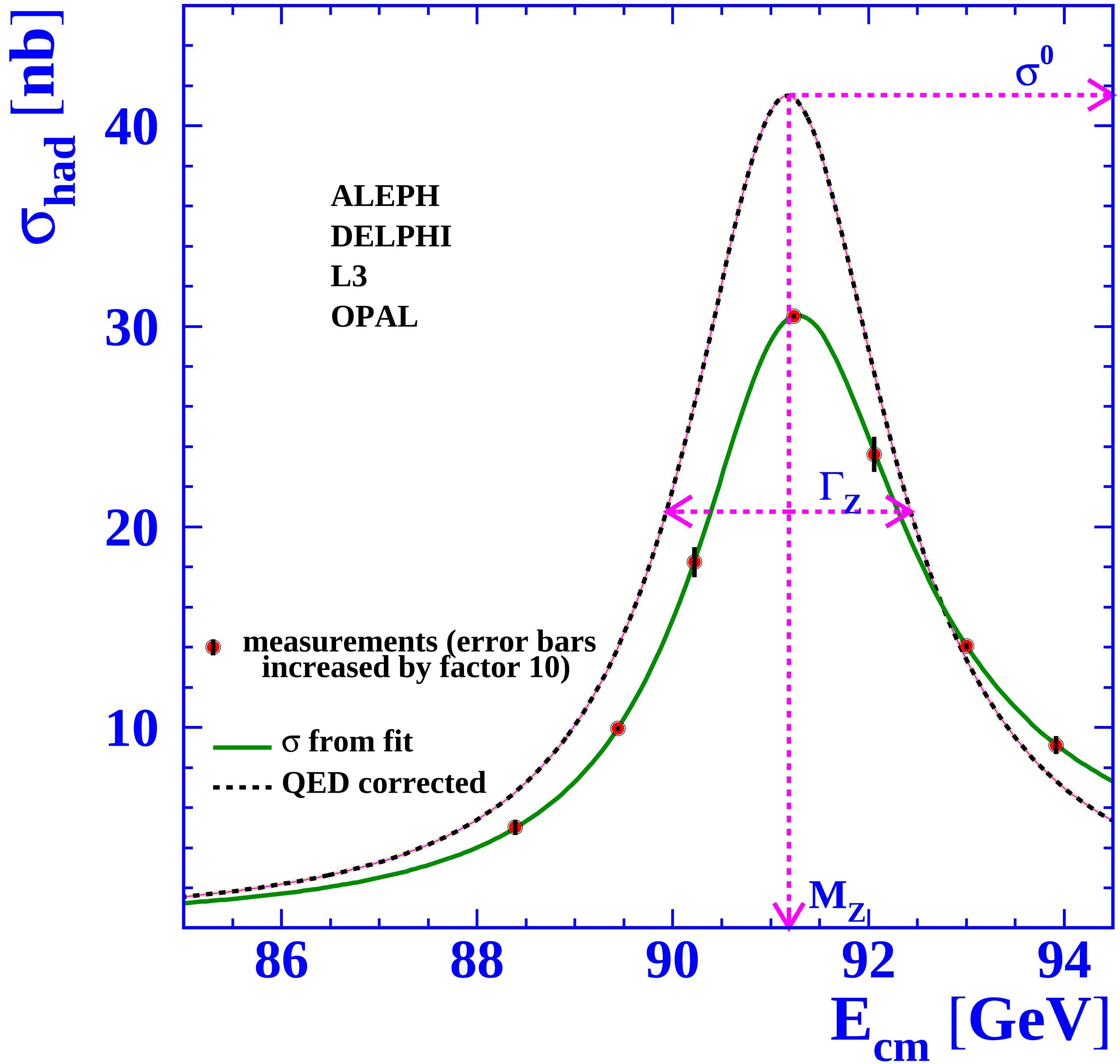
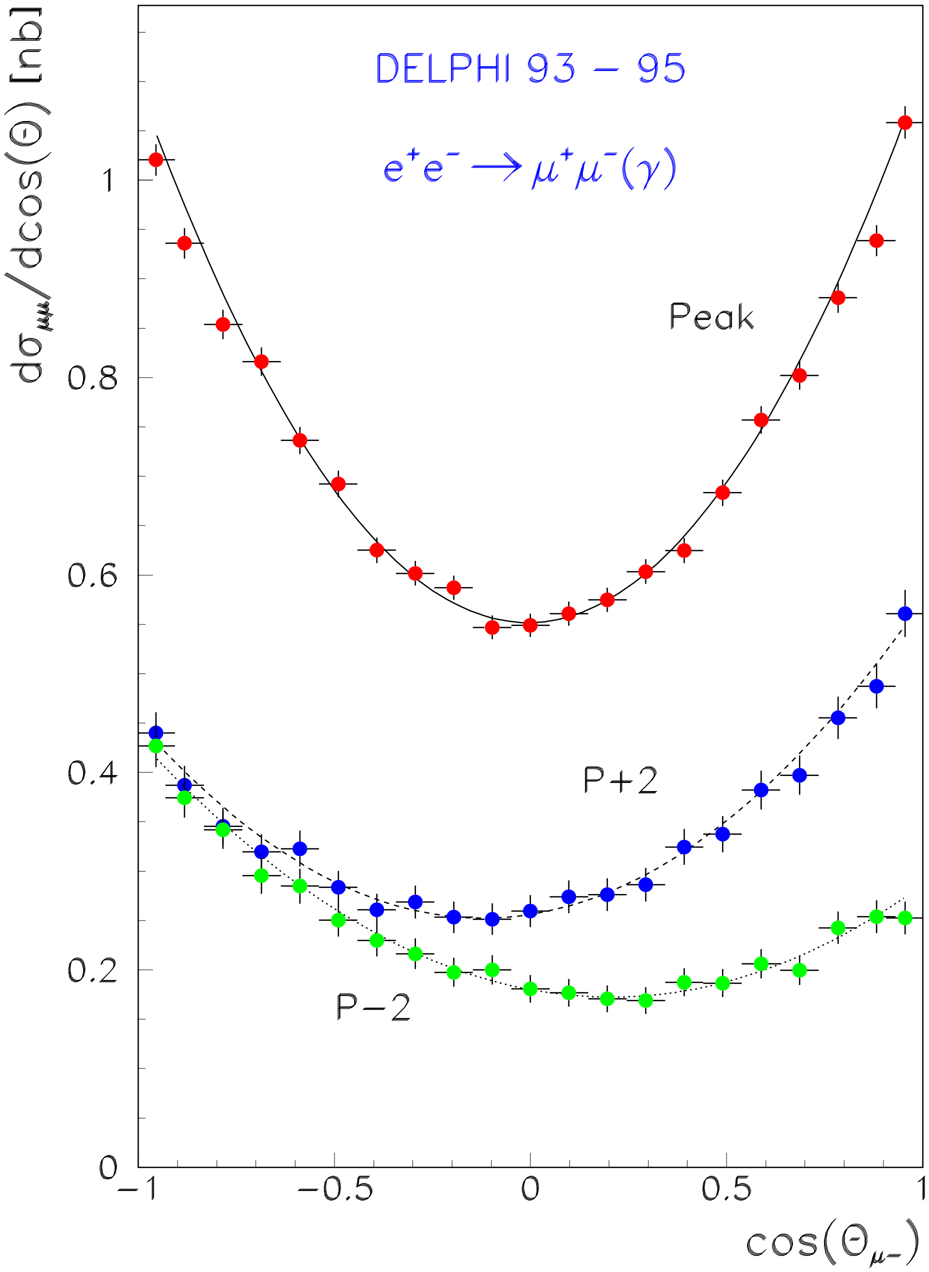
Isospin and hypercharge of SM-fermions

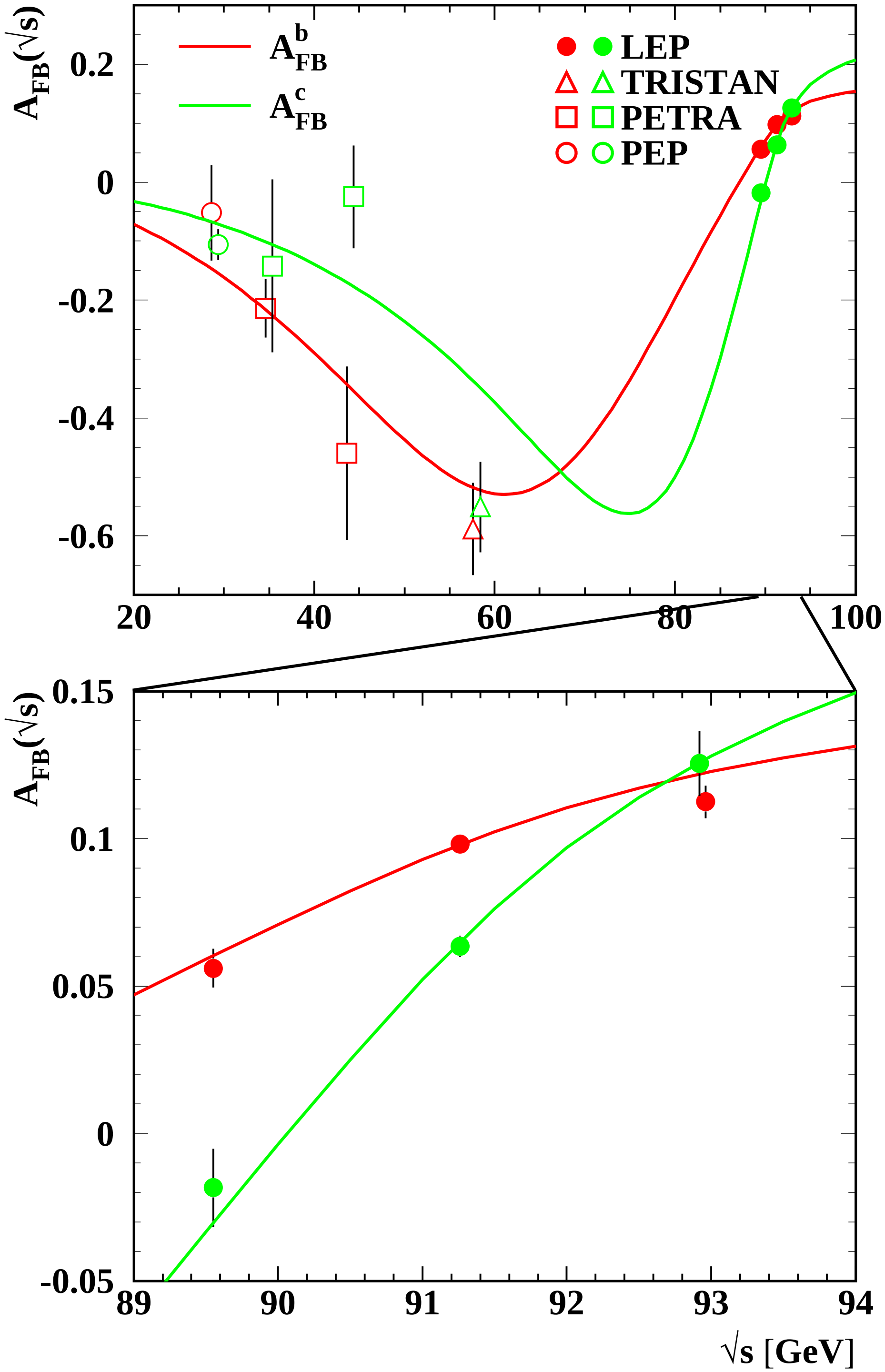
	I_3	Y	Q
ν_L	$+\frac{1}{2}$	-1	0
e_L	$-\frac{1}{2}$	-1	-1
ν_R	0	0	0
e_R	0	-2	-1
u_L	$+\frac{1}{2}$	$+\frac{1}{3}$	$+\frac{2}{3}$
d_L	$-\frac{1}{2}$	$+\frac{1}{3}$	$-\frac{1}{3}$
u_L	0	$+\frac{4}{3}$	$+\frac{2}{3}$
d_L	0	$-\frac{2}{3}$	$-\frac{1}{3}$

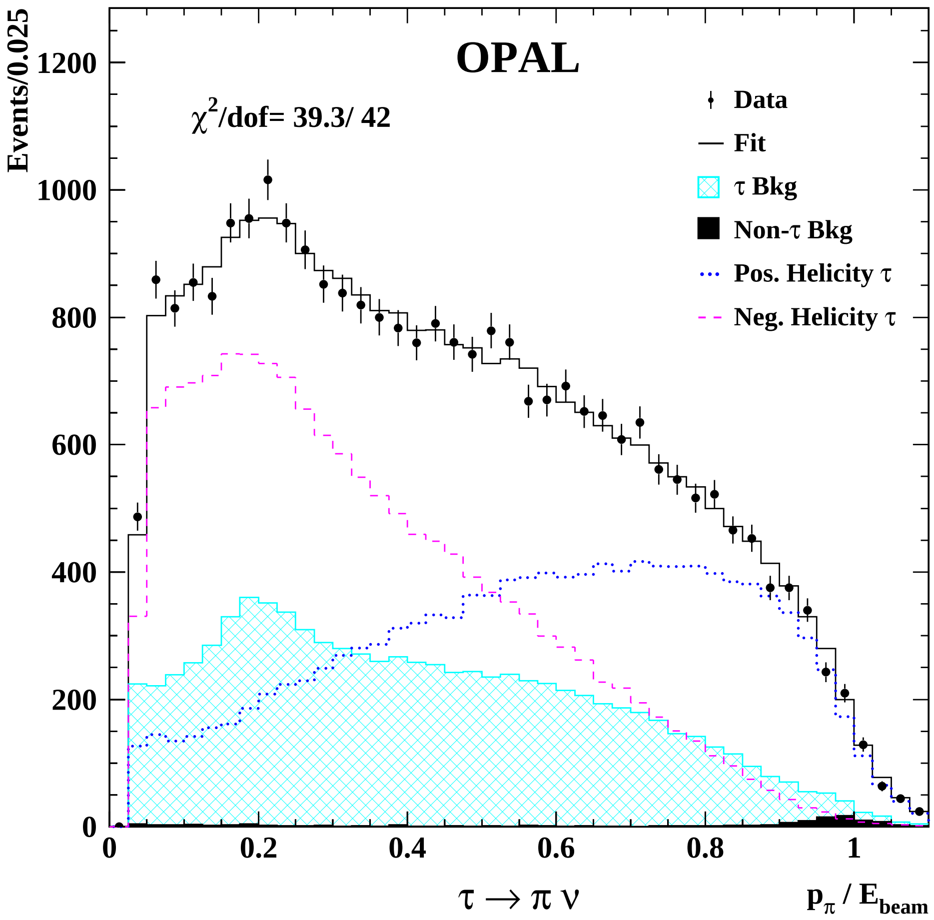

Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z
e+e−→hadrons
W+W-
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

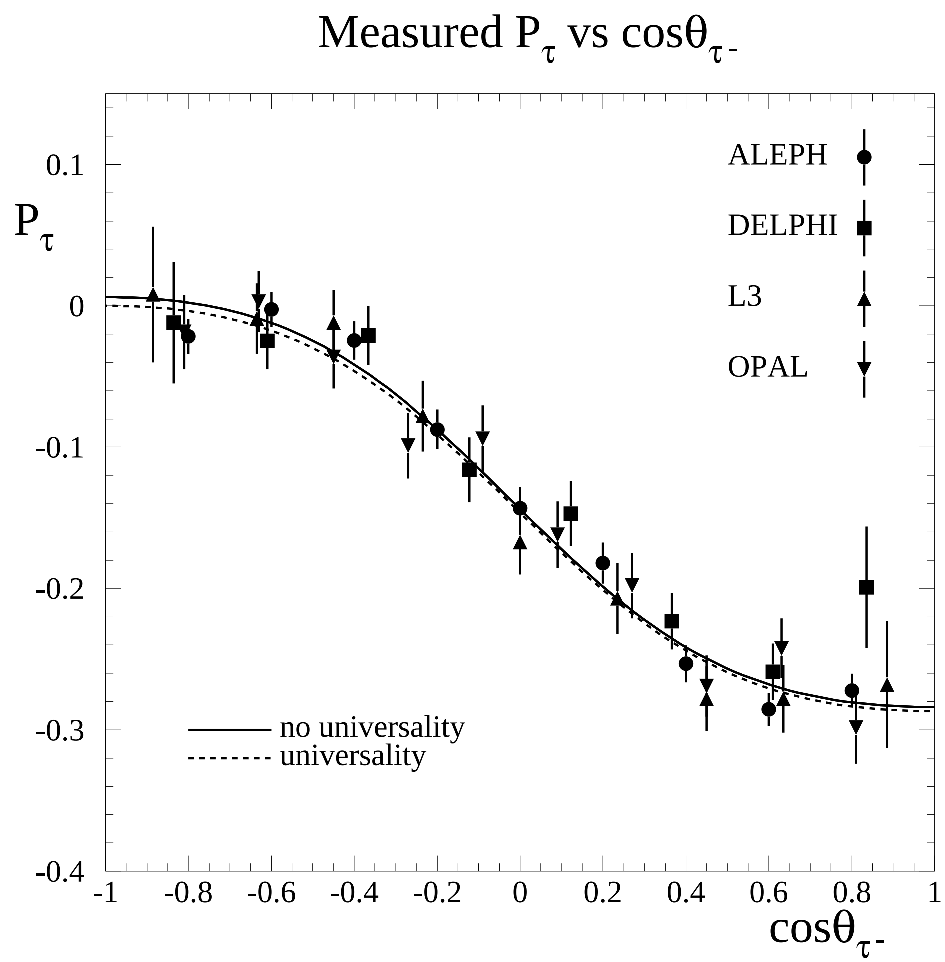


σ_had [nb]
40
30
20
10
ALEPH
DELPHI
L3
OPAL
σ⁰
Γ_Z
M_Z
measurements (error bars increased by factor 10)
σ from fit
QED corrected
86
88
90
92
94
E_cm [GeV]


DELPHI 93 – 95
$e^+e^- \to \mu^+\mu^-(\gamma)$
Peak
P+2
P−2
$d\sigma_{\mu\mu}/d\cos(\Theta)$ [nb]
$\cos(\Theta_{\mu-})$


A_{FB}^b
A_{FB}^c
LEP
TRISTAN
PETRA
PEP
$A_{FB}(\sqrt{s})$
$\sqrt{s}$ [GeV]

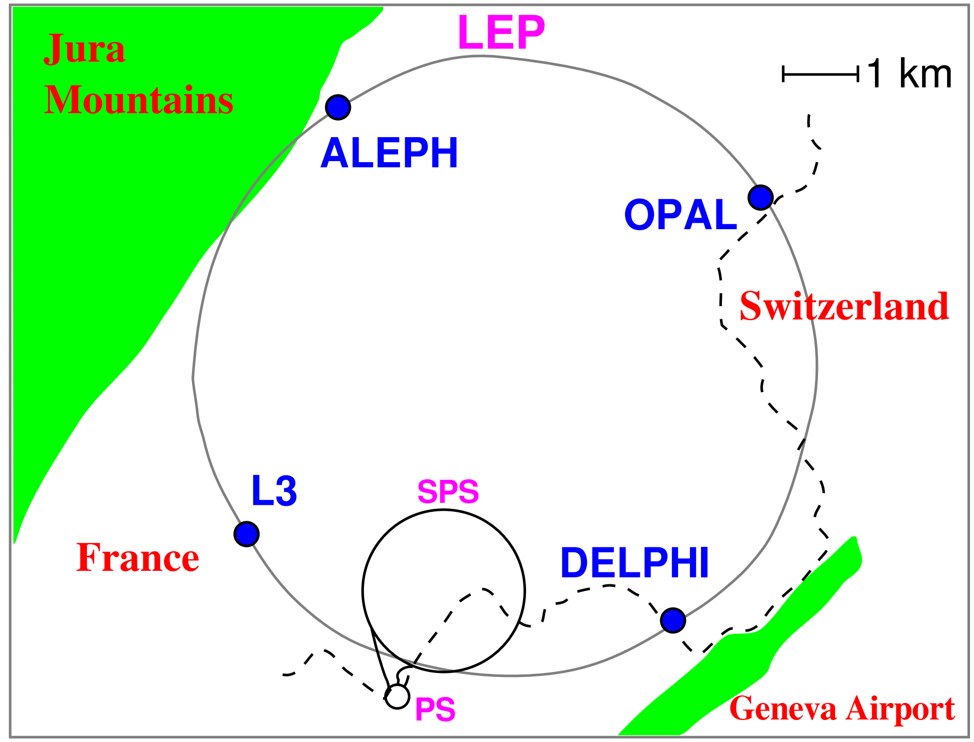

OPAL
χ^2/dof= 39.3/ 42
Data
Fit
τ Bkg
Non-τ Bkg
Pos. Helicity τ
Neg. Helicity τ
Events/0.025
τ → π ν
p_π / E_{beam}


Measured P_τ vs $\cos\theta_{\tau^-}$
P_τ
ALEPH
DELPHI
L3
OPAL
no universality
universality
$\cos\theta_{\tau^-}$

Machines for precision electroweak physics

LEP:

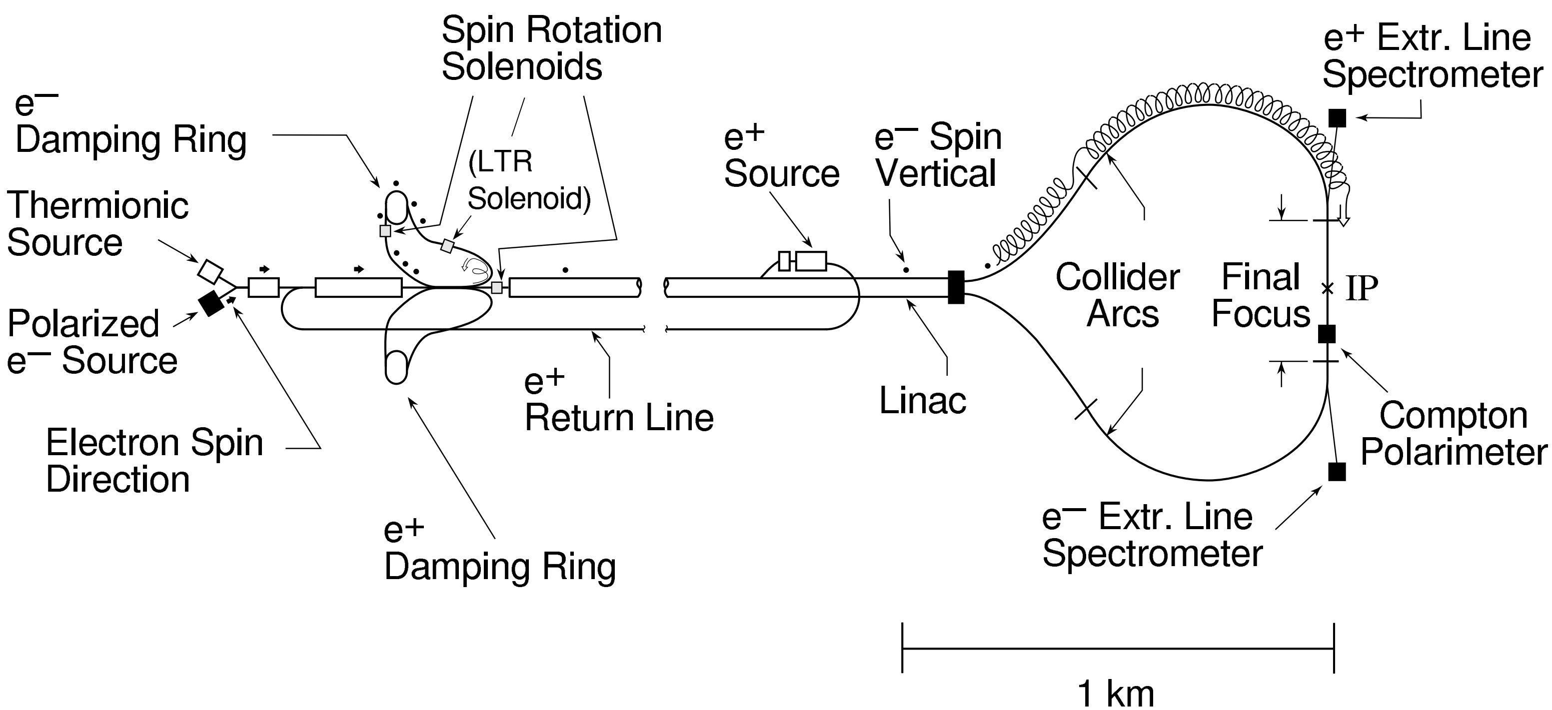
- e^+e^- ring at CERN (in the now-LHC tunnel)



- 1989-1995 running at or close to the Z-peak
  - 17000000 recorded Z-decays
  - 30% luminosity taken off-peak for Z-mass and width
  - beam energy precision of $2 \cdot 10^{-5}$
- 1996-2000 running above W-pair threshold
  - $\sim 700\ \text{pb}^{-1}$ per experiment at $161\,\text{GeV} < \sqrt{s} < 207\,\text{GeV}$
  - ➡ ~ 12000 W-pairs per experiment
  - Higgs sensitivity up to $m_{\text{H}} = 115\,\text{GeV}$

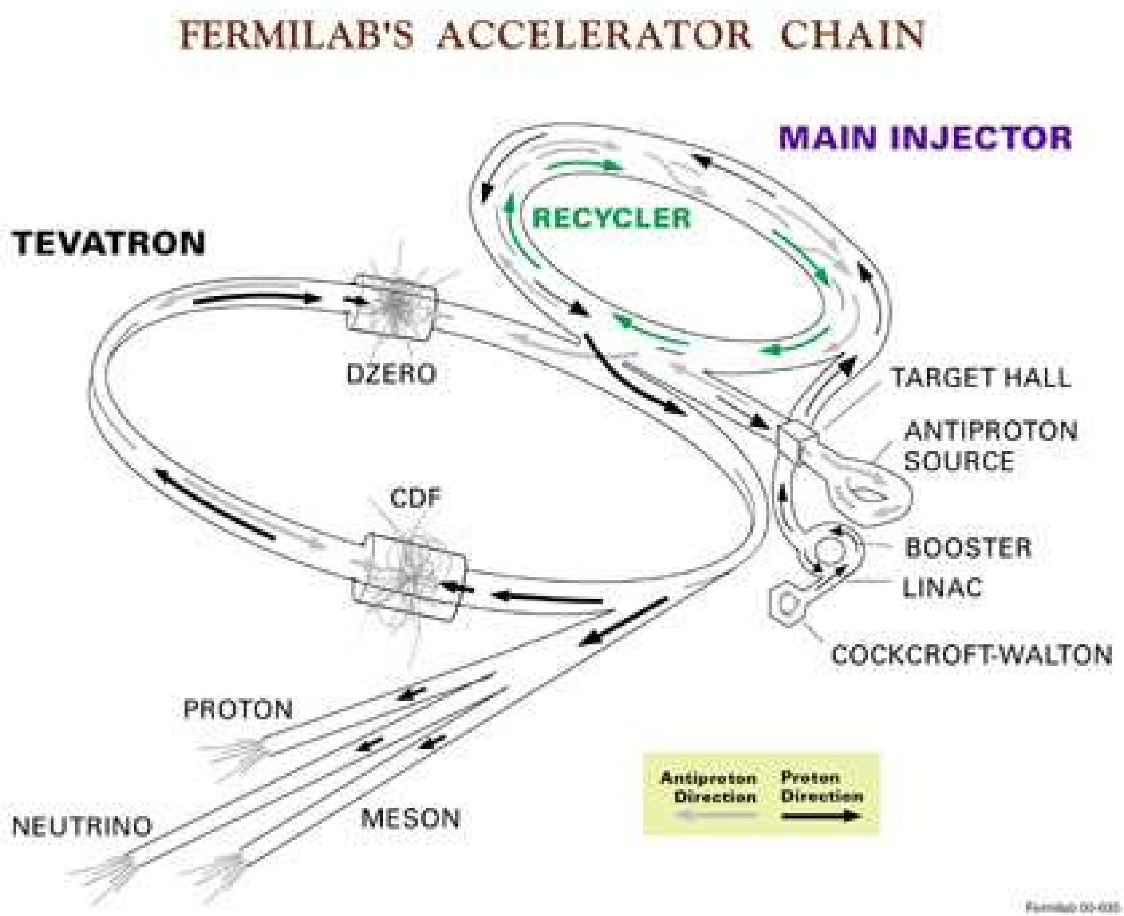
SLC:

- Linear collider at SLAC, running on the Z-pole from 1989 to 1998
- Only 500000 Z-decays recorded
- However up to 80% beam polarisation known to 0.5%
- Small bean size and beam pipe allowed for superb b-tagging



Tevatron:

- $p\bar{p}$ collider at Fermilab
- $\sqrt{s} = 1.96\,\text{TeV}$, $\int \mathcal{L} \approx 6\ \text{fb}^{-1}$ up to now
- Access to t, W, H



The Z lineshape

- LEP was scanning around the Z-peak to measure the resonance parameters
- Cross section:

$$\sigma = \frac{N_{meas} - N_{bg}}{\epsilon \mathcal{L}}$$

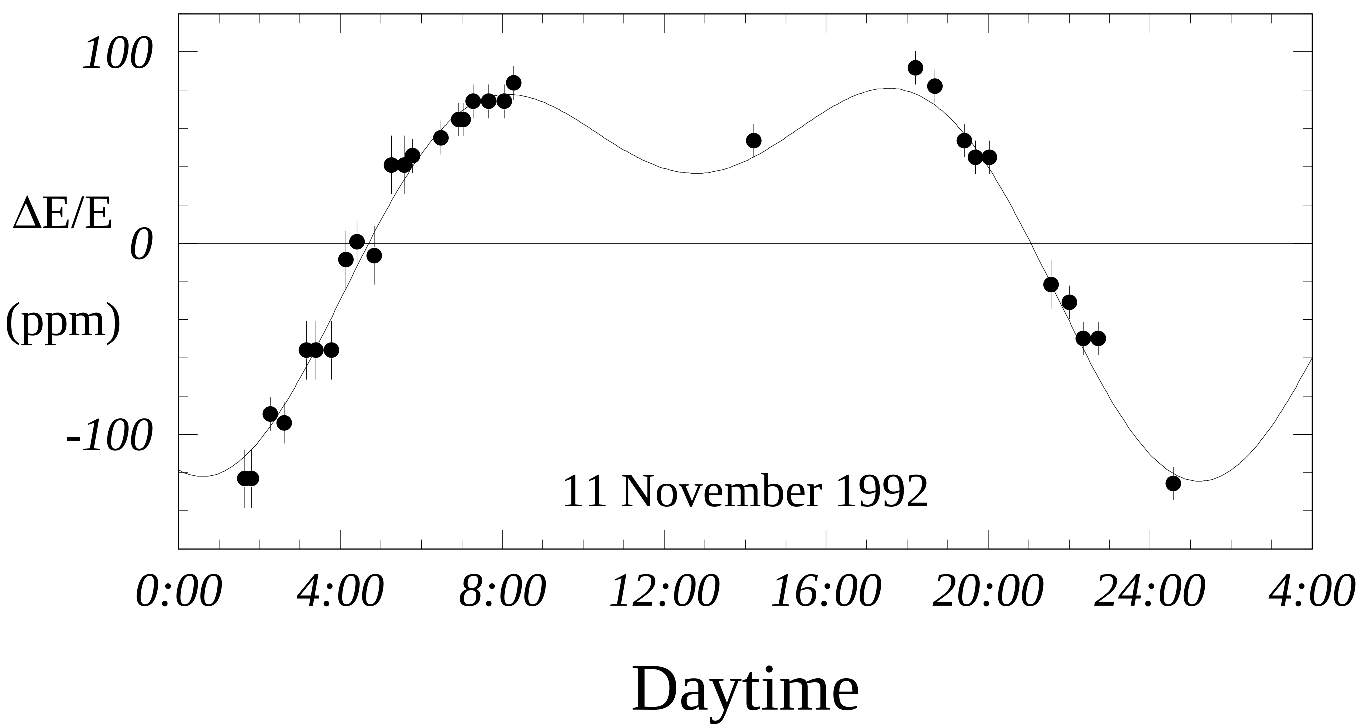
- Need to
  - count events
  - calculate efficiency and background
  - measure luminosity
  - measure beam energy

Measurement of the beam energy

At the end of each off-peak fill the beam energy was measured by resonance depolarisation $(\Delta E_b \approx 0.2\,\mathrm{MeV})$

Corrections have to be applied for:

- RF-status (few MeV, anticorrelated between experiments)
- earth-tides $(< 15\,\mathrm{MeV}$ from moon and sun)

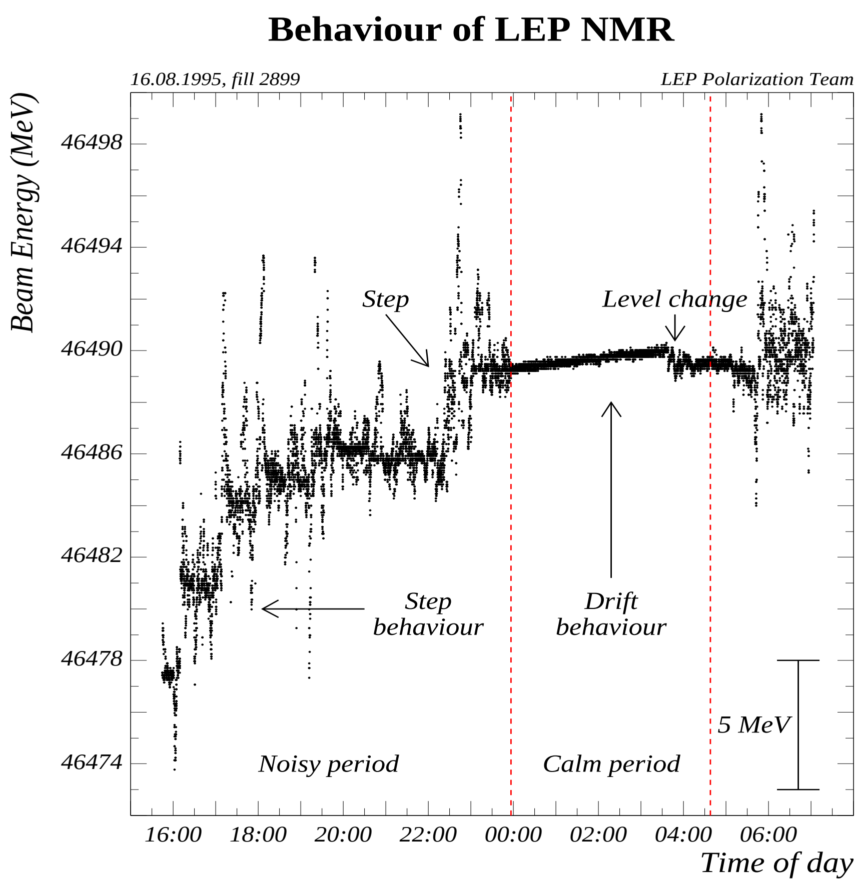


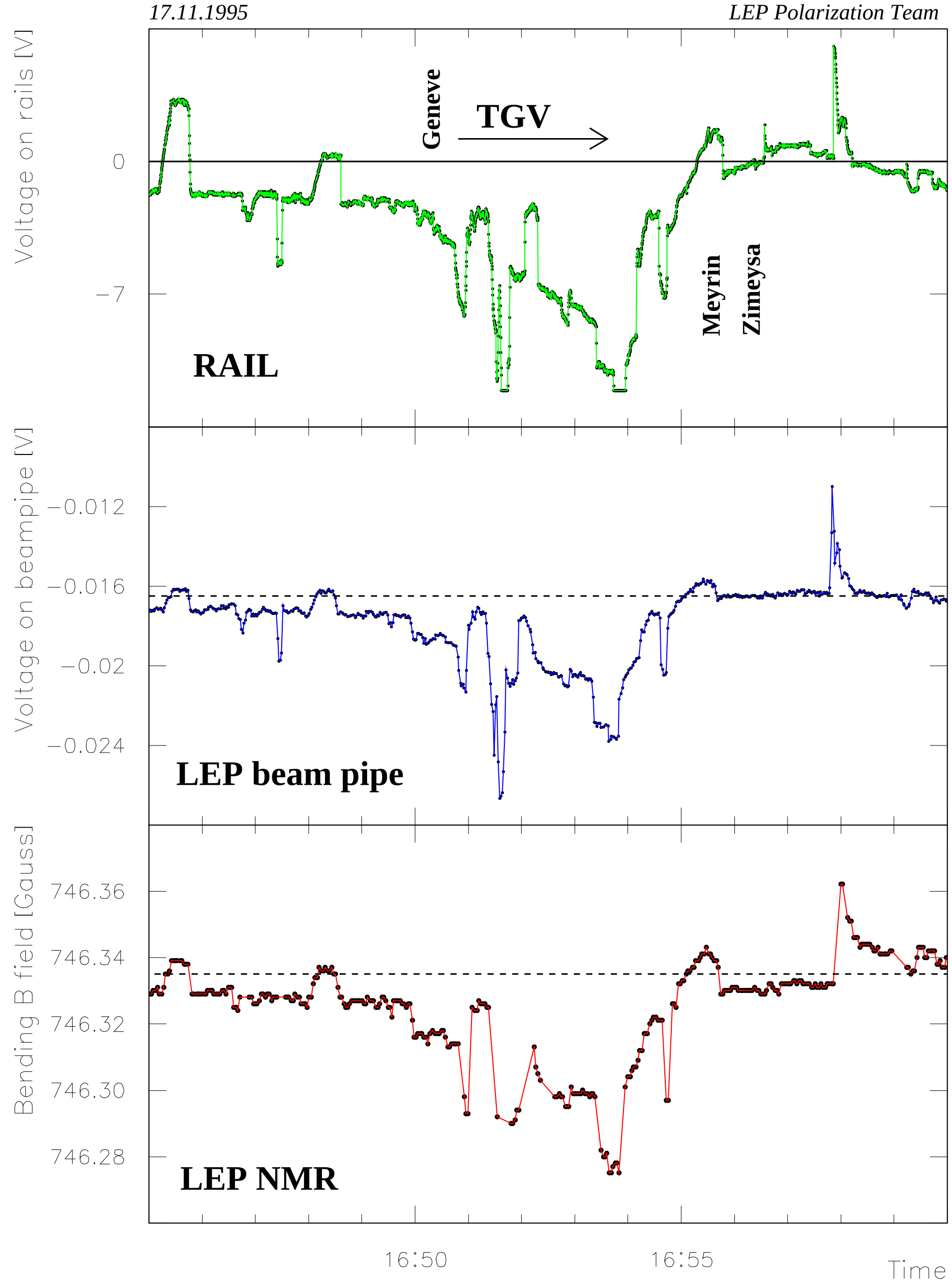
- Hysteresis in the dipole magnets

  time dependence of beam energy:

  – ∼ 10 MeV/ 4 hours during the day

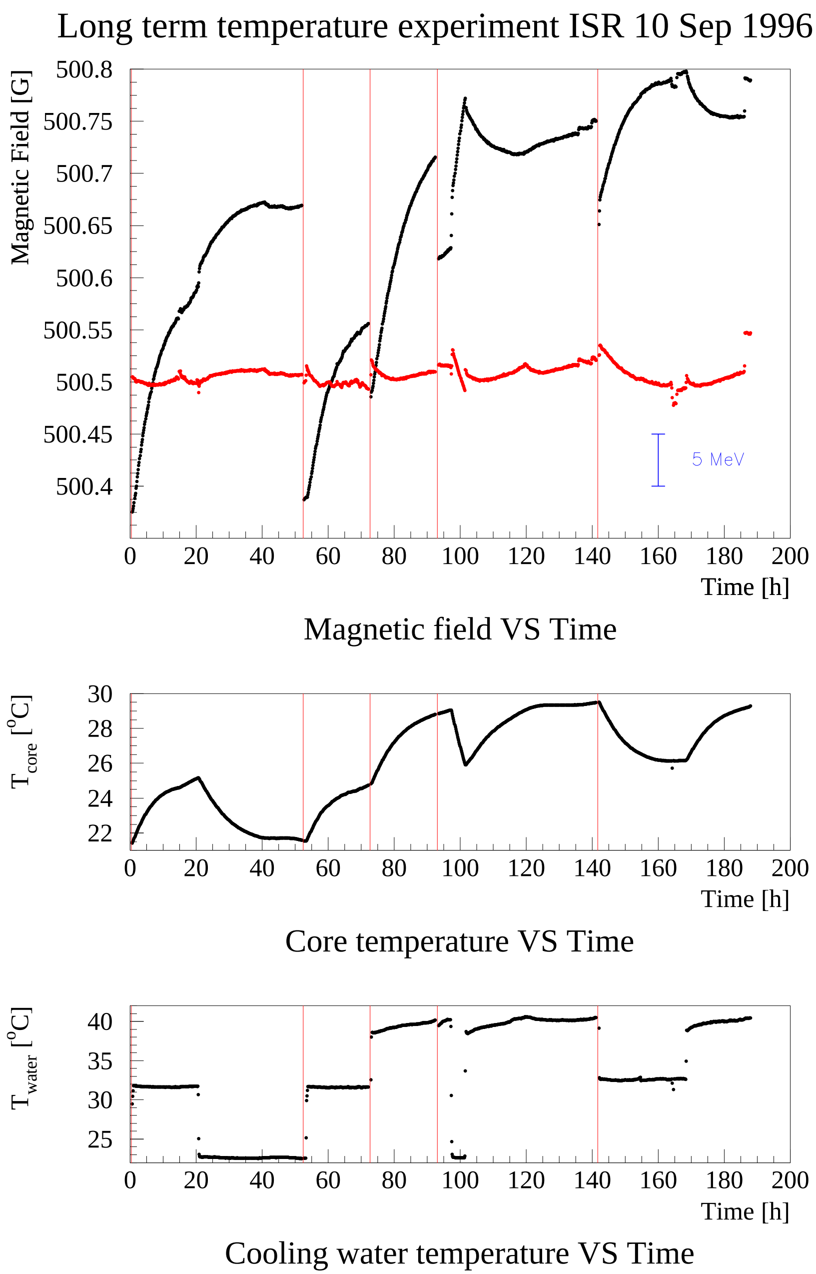
  – ∼ 0 in the night





due to trains between Geneva and Bellegarde

and complicated temperature dependence of the magnets

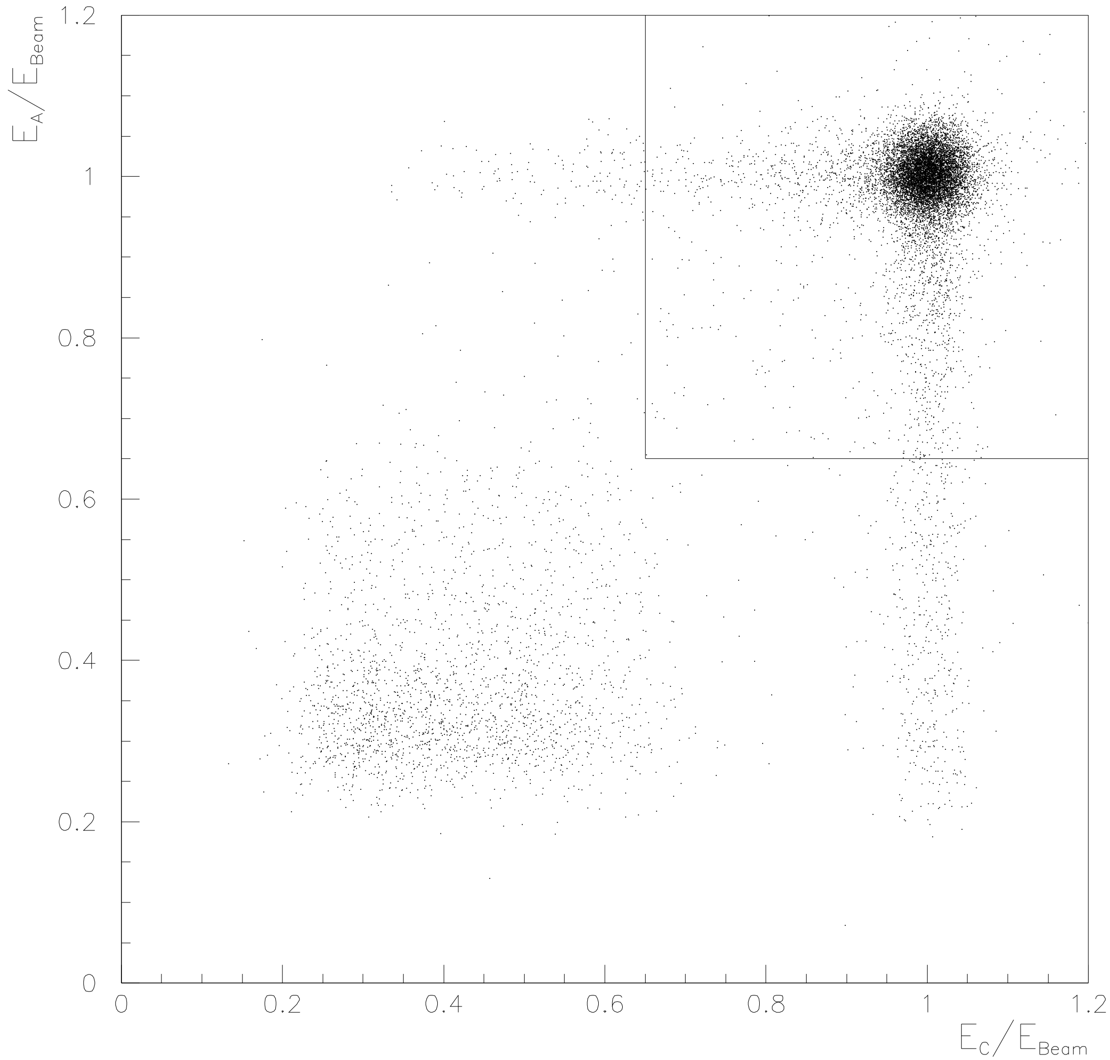


Total uncertainty from beam energy:

$$\Delta m_Z = 1.5\,\mathrm{MeV}$$
$$\Delta\Gamma_Z = 1.5\,\mathrm{MeV}$$

Measurement of the luminosity

- In principle luminosity can be calculated from machine parameters
- However, if a gauge reaction is available with known cross section, luminosity can be obtained much more precise from this
- Bhabha scattering ($e^+e^- \rightarrow e^+e^-$) at low angles is, apart from small corrections, a pure QED process with a large cross section
  $\longrightarrow$ Ideal for luminosity determination
- Typical LEP acceptance:
  $30\,\mathrm{mrad} < \theta < 180\,\mathrm{mrad}$
- Total cross section above θ_{min}: $\sigma \propto 1/\theta^3_{\mathrm{min}}$
- Need to know very precisely the lower acceptance cut ($\sim 20\mu$m is needed for $< 0.1\%$ error)
- Efficiency/background not a problem

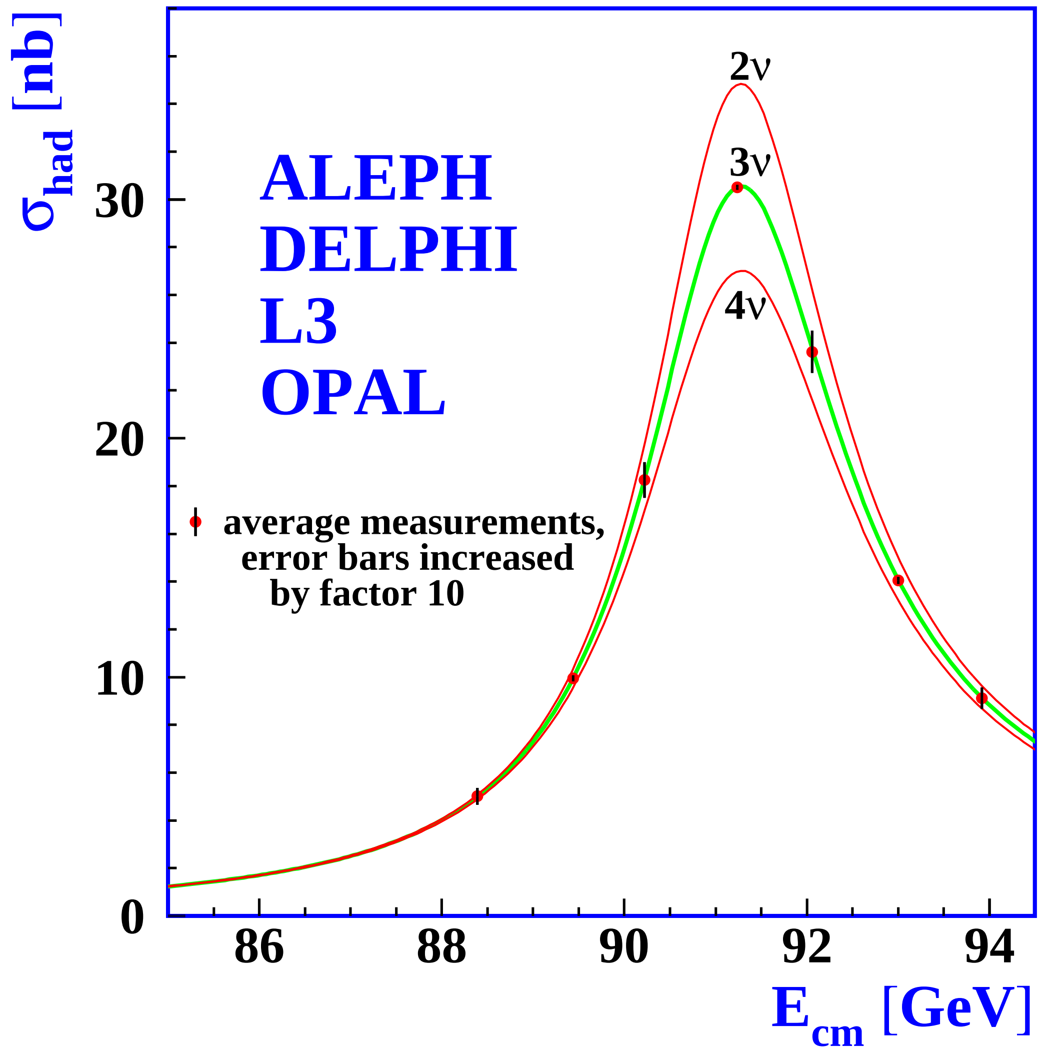


Experimental accuracy: $\approx 0.1\%$

Theoretical accuracy: $\approx 0.11\%$

Results:

$$m_Z = 91.1867 \pm 0.0021\,\mathrm{GeV}$$
$$\Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}$$
$$\Gamma_{\mathrm{had}} = 1744.2 \pm 2.0\,\mathrm{MeV}$$
$$\Gamma_e = 83.92 \pm 0.12\,\mathrm{MeV}$$
$$\Gamma_\mu = 83.99 \pm 0.18\,\mathrm{MeV}$$
$$\Gamma_\tau = 84.08 \pm 0.22\,\mathrm{MeV}$$
$$\Gamma_l = 83.99 \pm 0.09\,\mathrm{MeV}$$
$$\Gamma_{\mathrm{inv}} = 499.2 \pm 1.5\,\mathrm{MeV}$$



Taking $\Gamma_\nu/\Gamma_\ell = 1.991 \pm 0.001$ from the Standard Model yields

$$N_\nu = 2.984 \pm 0.008$$

There exist exactly three fermion generations with $m_\nu < 45\,\mathrm{GeV}$ in the universe!

Measurements of $\sin^2 \theta^l_{eff}$

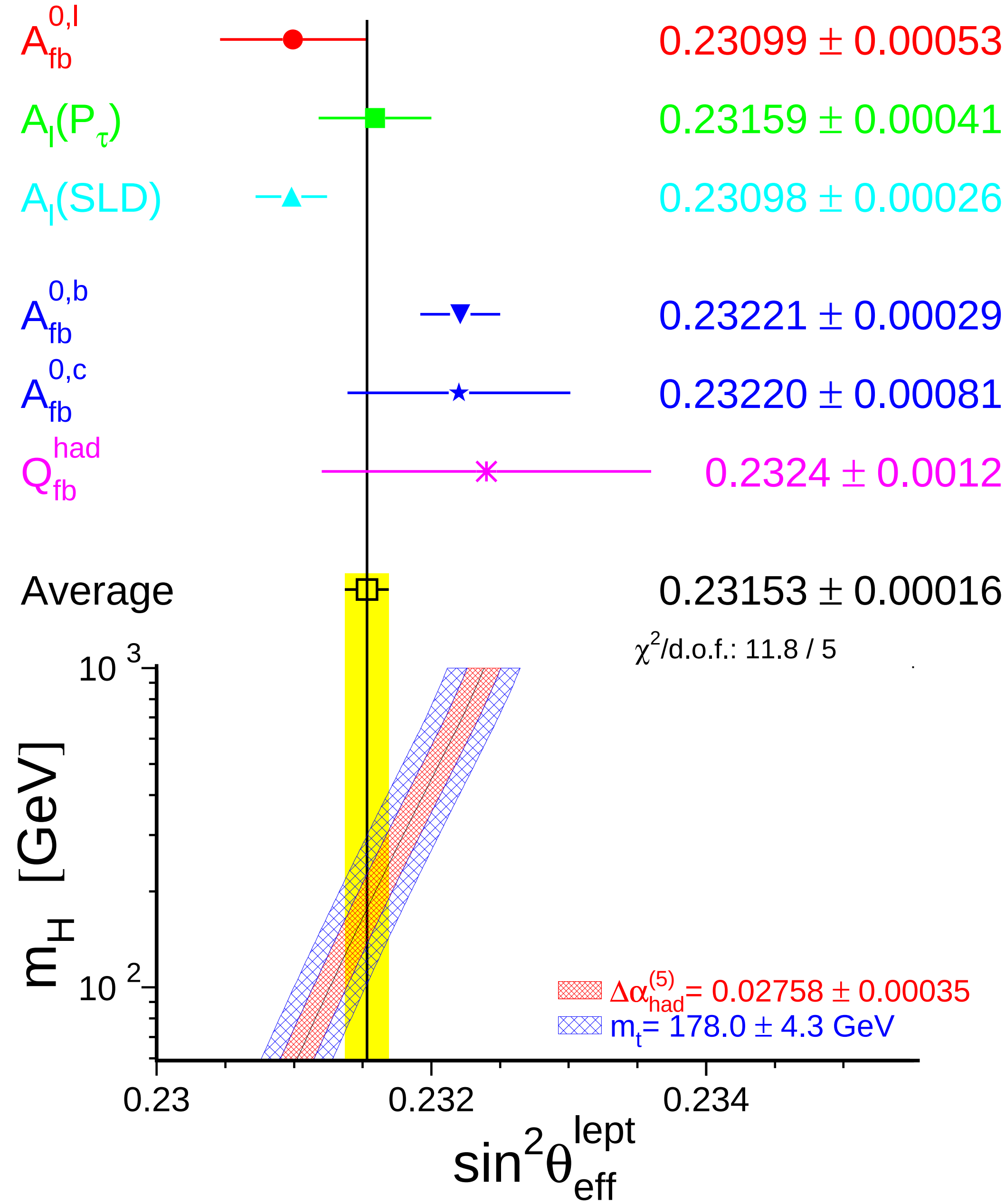
LEP

- Forward-backward asymmetry of μ, τ, (e)
- Forward backward asymmetry of b- and c-quarks
- τ-polarisation and its angular dependence

SLD

- left-right asymmetry with polarised beams
- (polarised forward-backward asymmetries)

$\sin^2 \theta^l_{eff}$ measurements at LEP/SLC

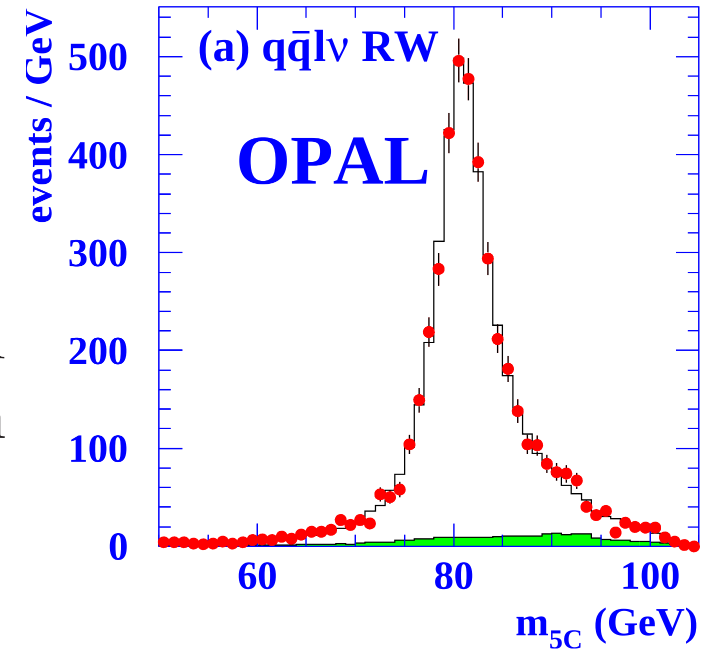


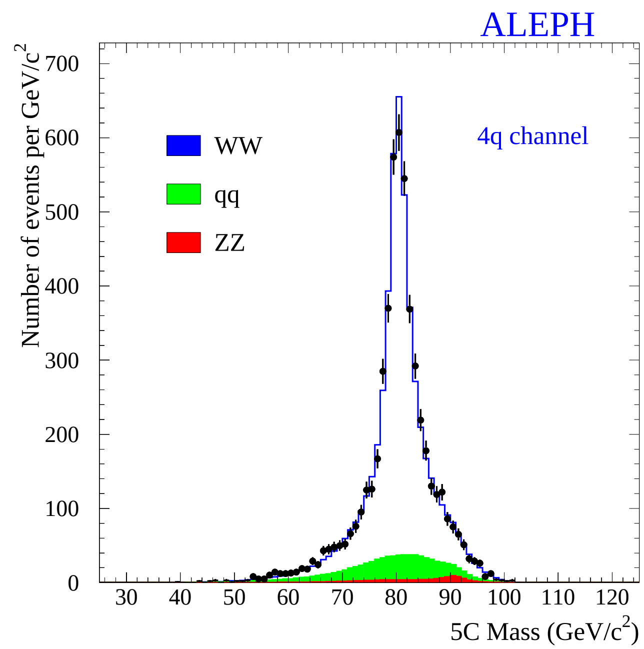
- Very precise measurement
- However marginal agreement between A_{LR} and A^b_{FB}
- No convincing physics explanation found
- Assume that it is a statistical fluctuation

W-mass measurements

LEP

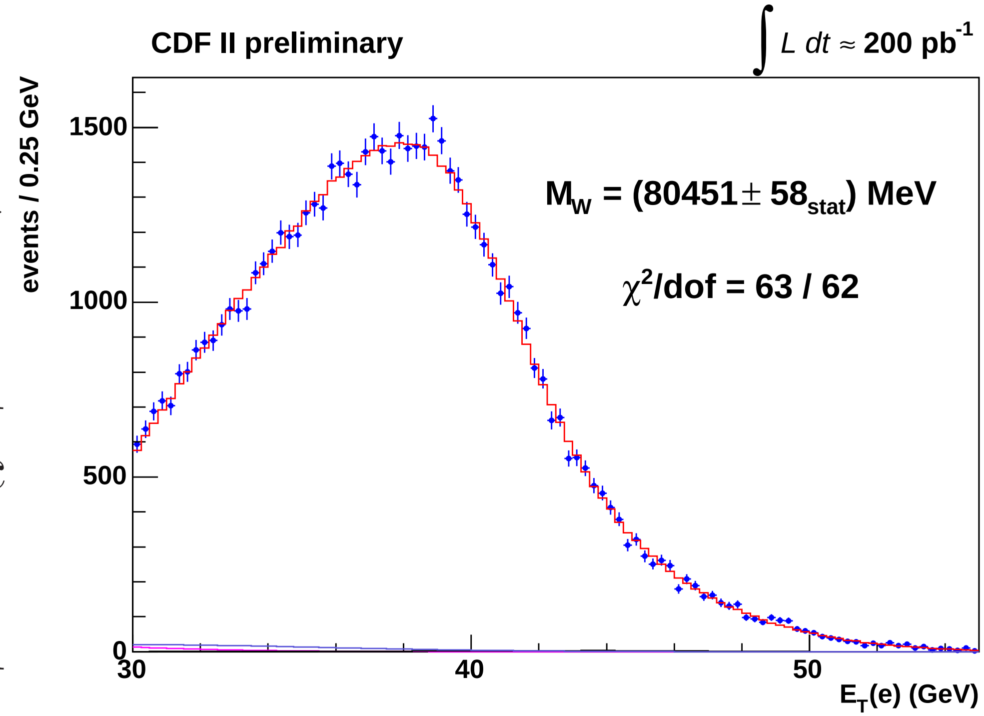
- $\sim$ 10000 W-pairs /experiment
- $\sim$ 45% mixed ($WW \to \ell\nu qq$ decays
  - for $\ell = \mu, e$ ν can be reconstructed from energy-momentum constraint $\Rightarrow$ clean measurement with good precision
- $\sim$ 45% $WW \to$ 4-jet decays
  - full information available
  - limited jet resolution can be improved with constrained fit
  - some problems with jet-pairing
  - still experimentally most precise measurement
  - however significant uncertainty from colour reconnection

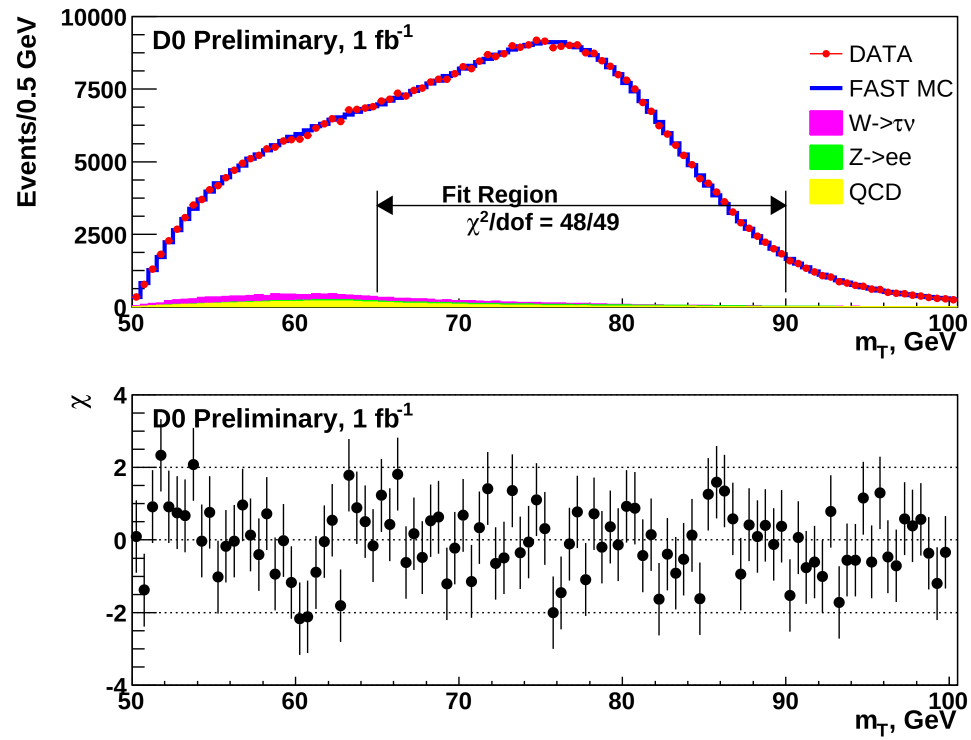




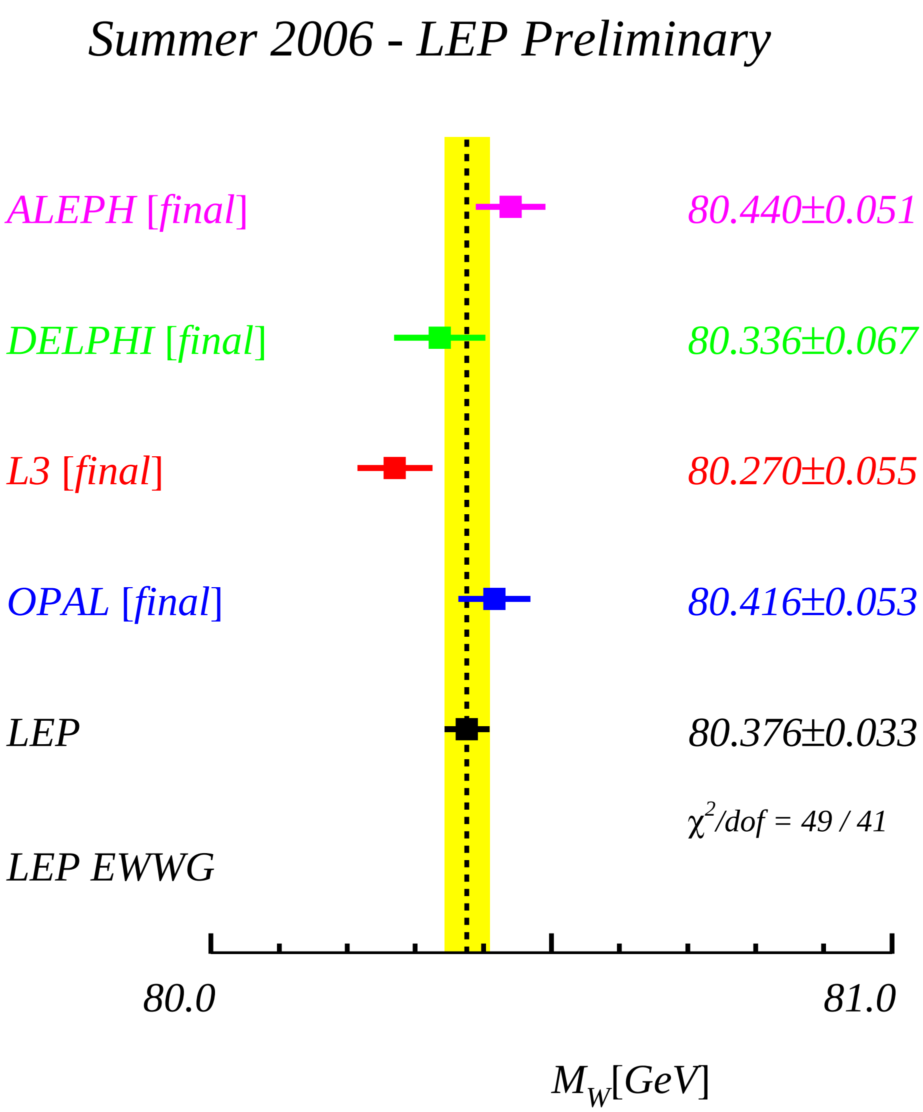
Tevatron:

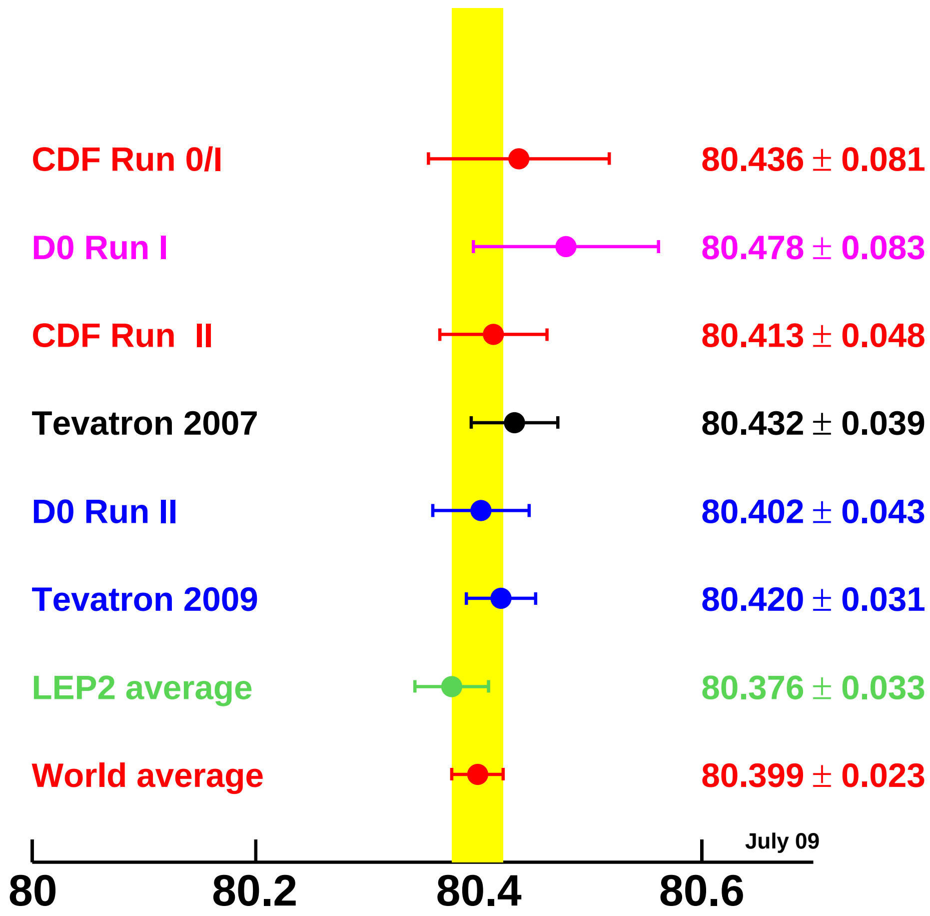
- Large statistics from $q\bar{q}' \to W \to \ell\nu$
- Only transverse ν momentum can be reconstructed using hadronic recoil
- Main uncertainty from lepton energy-scale
- Can be calibrated using Z-production ➡ limited by statistics
- m_W can be measured from lepton transverse momentum or from transverse mass
- Precision now at same level as LEP





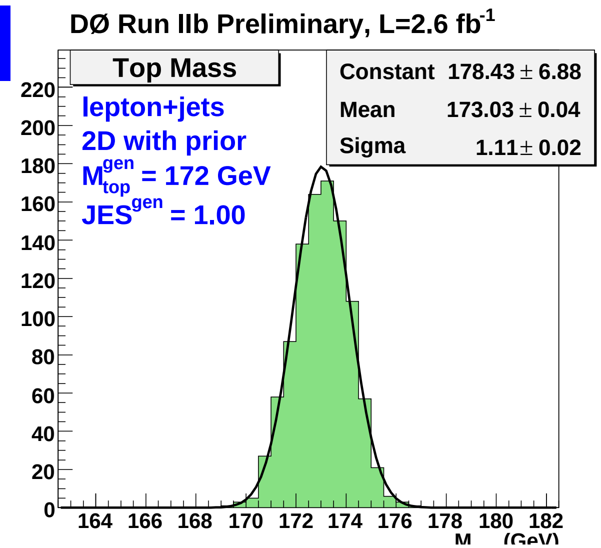
m_W combination

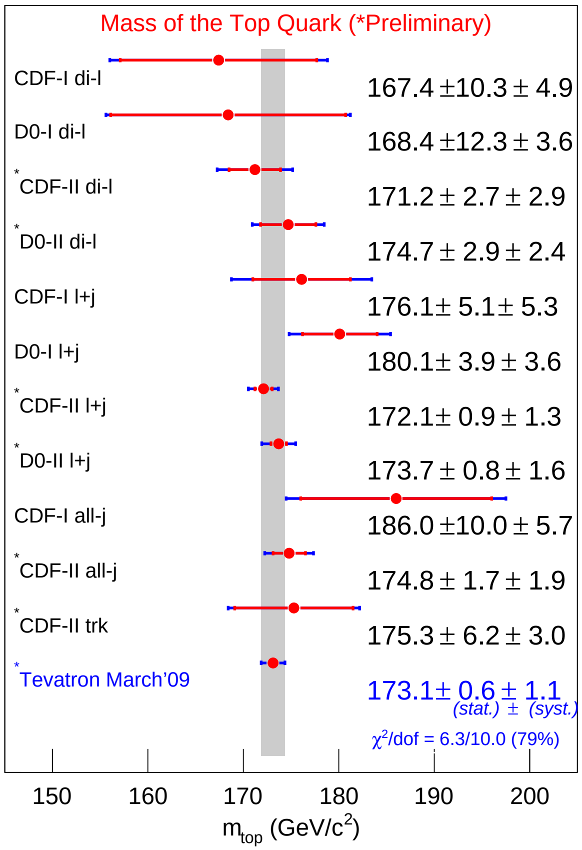




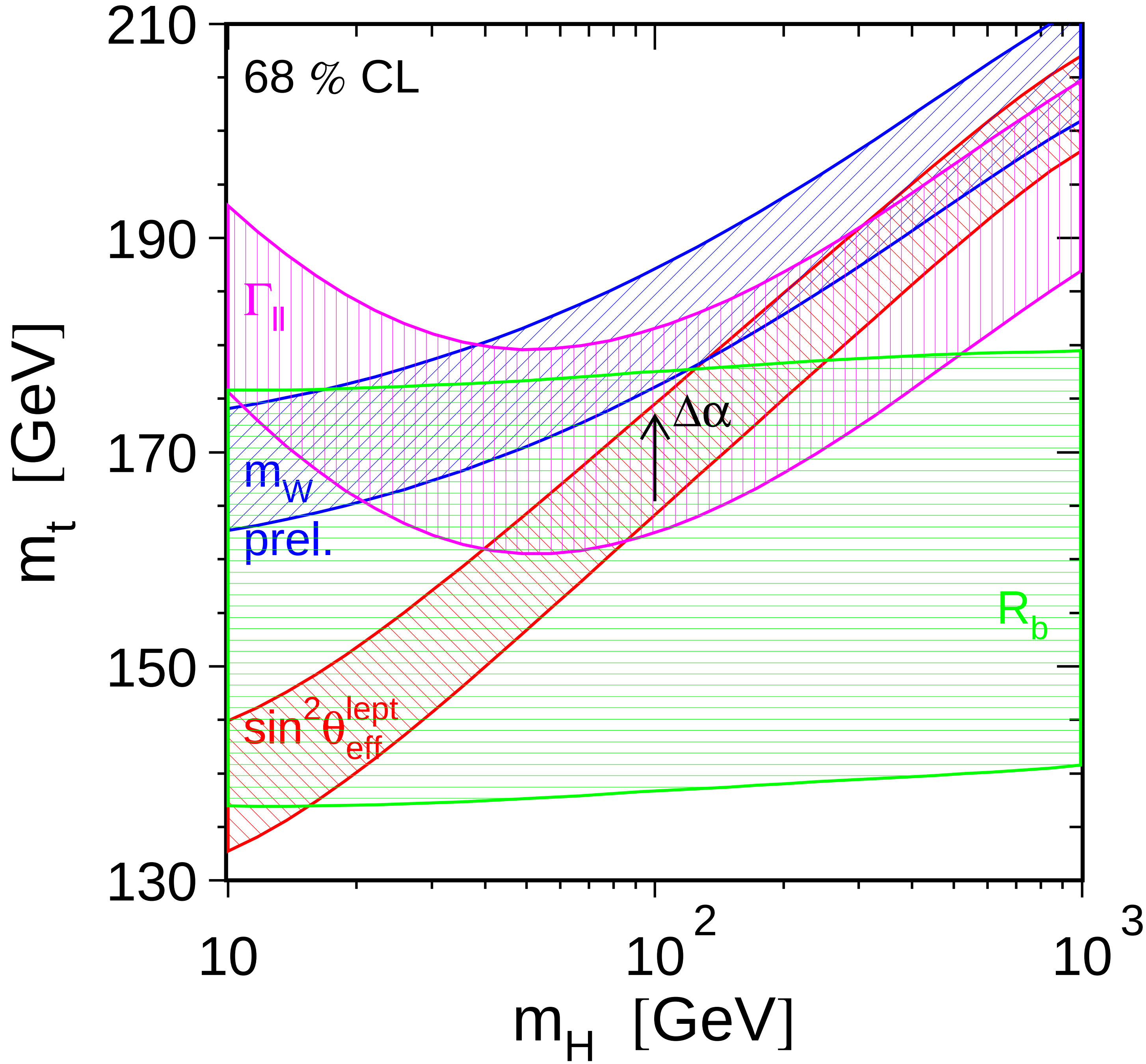
The top-quark mass

- The top mass enters only at 1-loop level
- However the dependence is quadratic and at percent-level measurement is needed to match the other observables
- Tevatron measurement on the 1 GeV level from reconstruction of the top-quarks
- Open issues:
  - colour reconnection effects: first estimates indicate 0.5 GeV uncertainty, included in world average
  - mass definition: could also be around 0.5 GeV, not yet included





$m_{\mathrm{H}} - m_{\mathrm{H}}$ bands allowed by the different observables

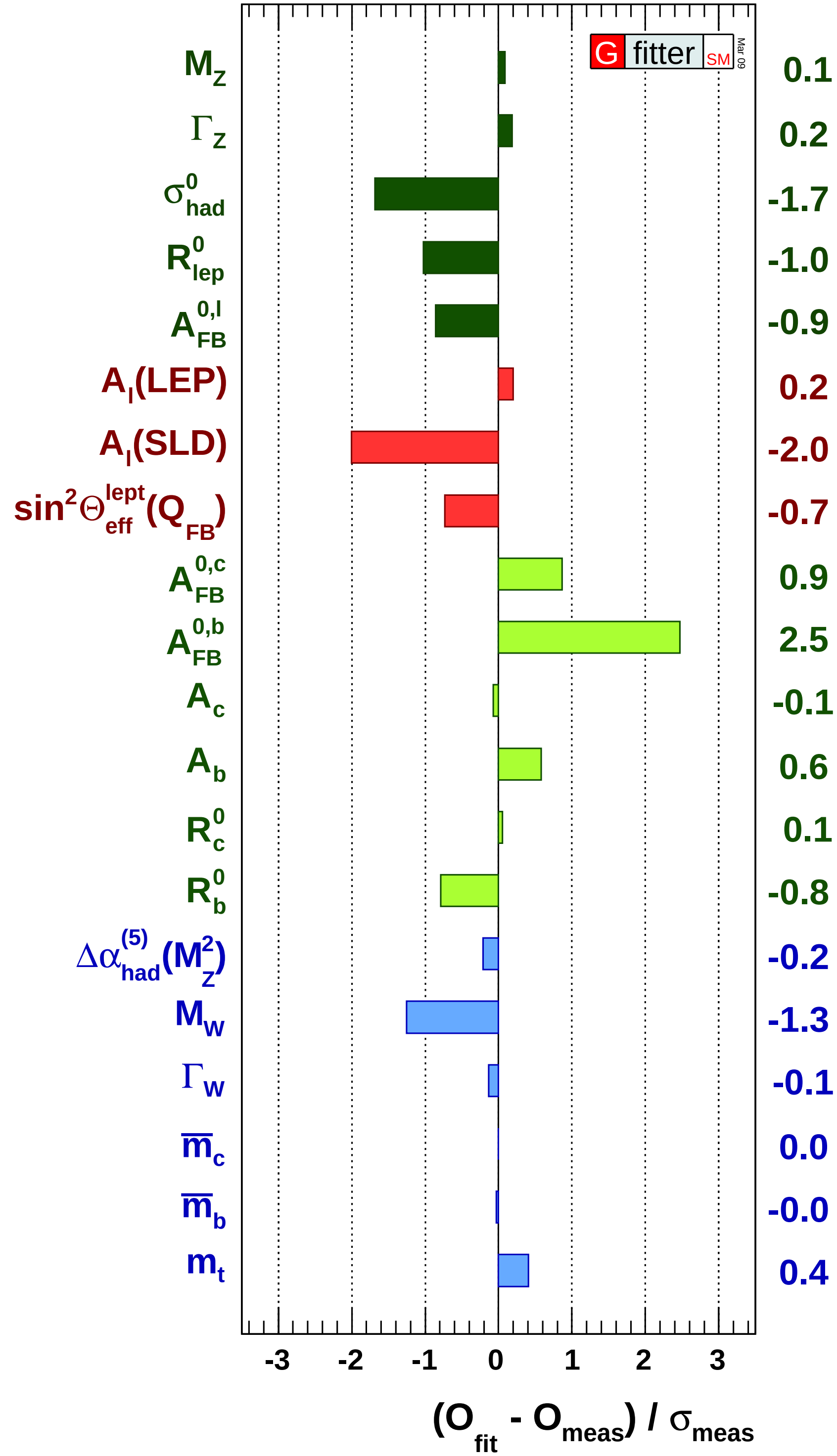


Result of the SM fit:

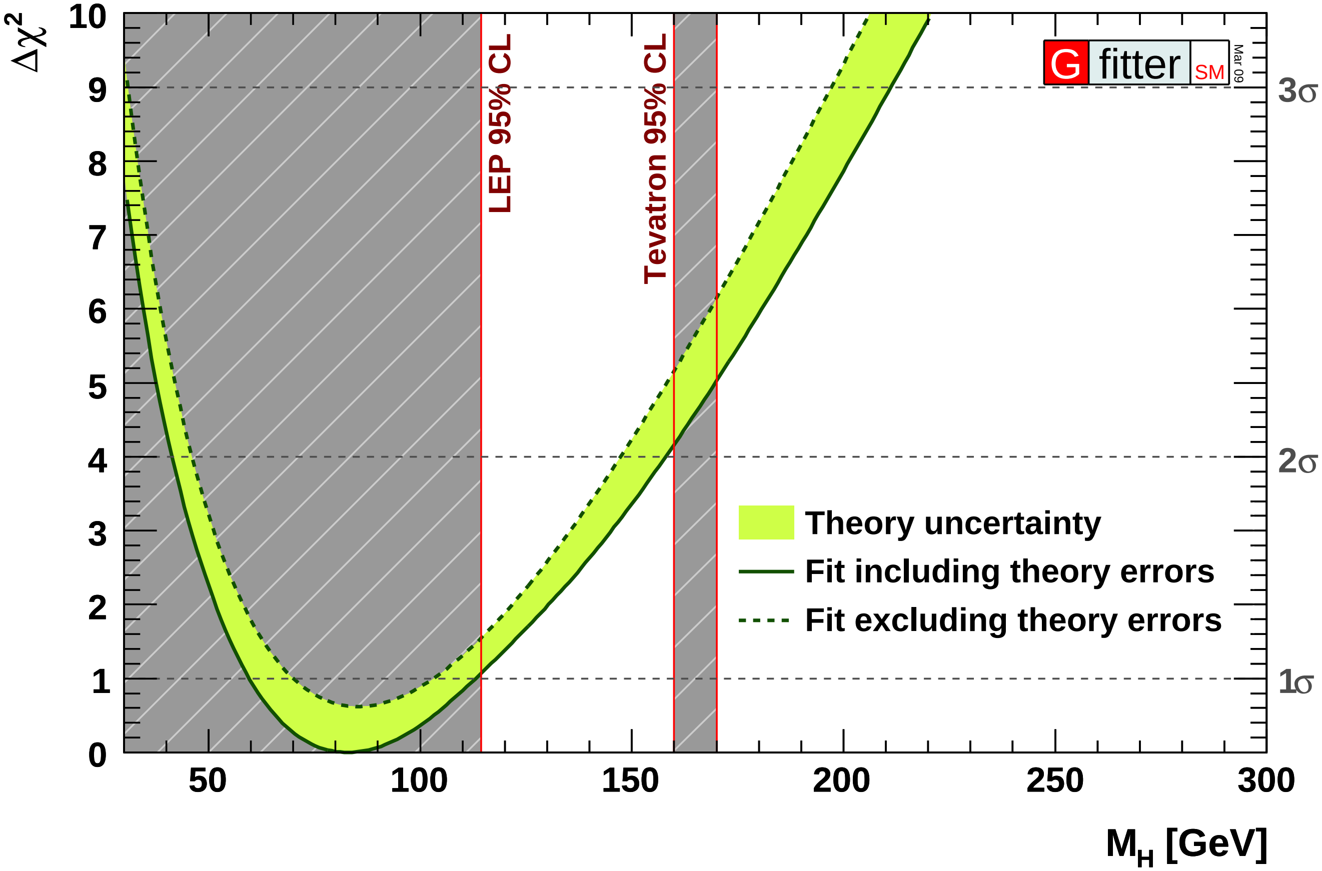
$$\begin{aligned} m_{\rm H} &= 83^{+30}_{-23}\,\text{GeV} \\ m_{\rm t} &= 173.2 \pm 1.2\,\text{GeV} \\ \alpha_s(m_{\rm Z}) &= 0.1192 \pm 0.0028 \\ \Delta\alpha^{(5)}_{\rm had}(m_{\rm Z}) &= 0.02772 \pm 0.0022 \end{aligned}$$

$\chi^2/ndf = 16.4/13 \quad \Rightarrow \text{Prob} = 23\%$

- Overall good agreement of data with SM
- Largest deviation 2.5σ ($A^{\rm b}_{\rm FB}$) not unexpected

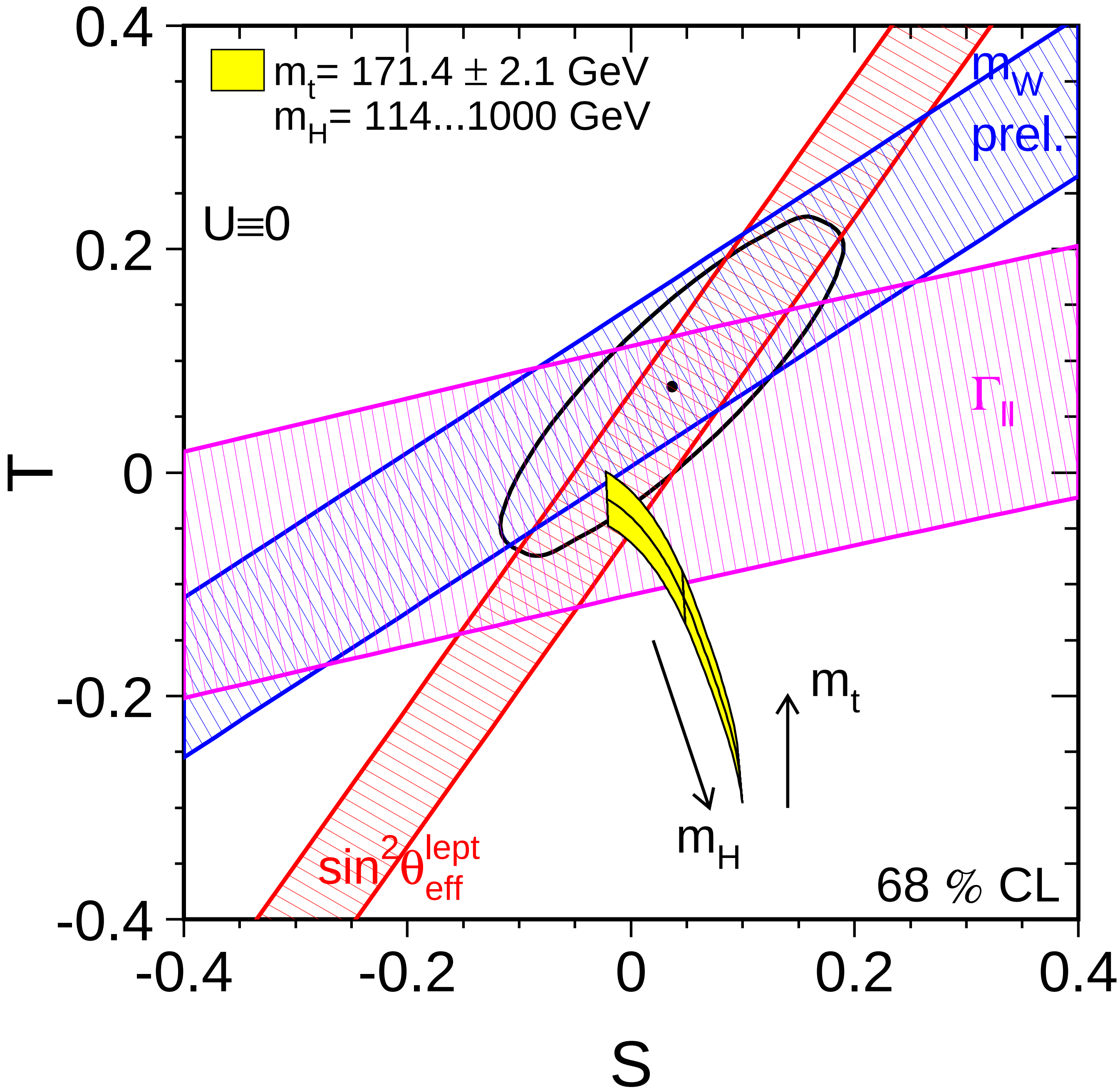


Higgs limit from the SM fit

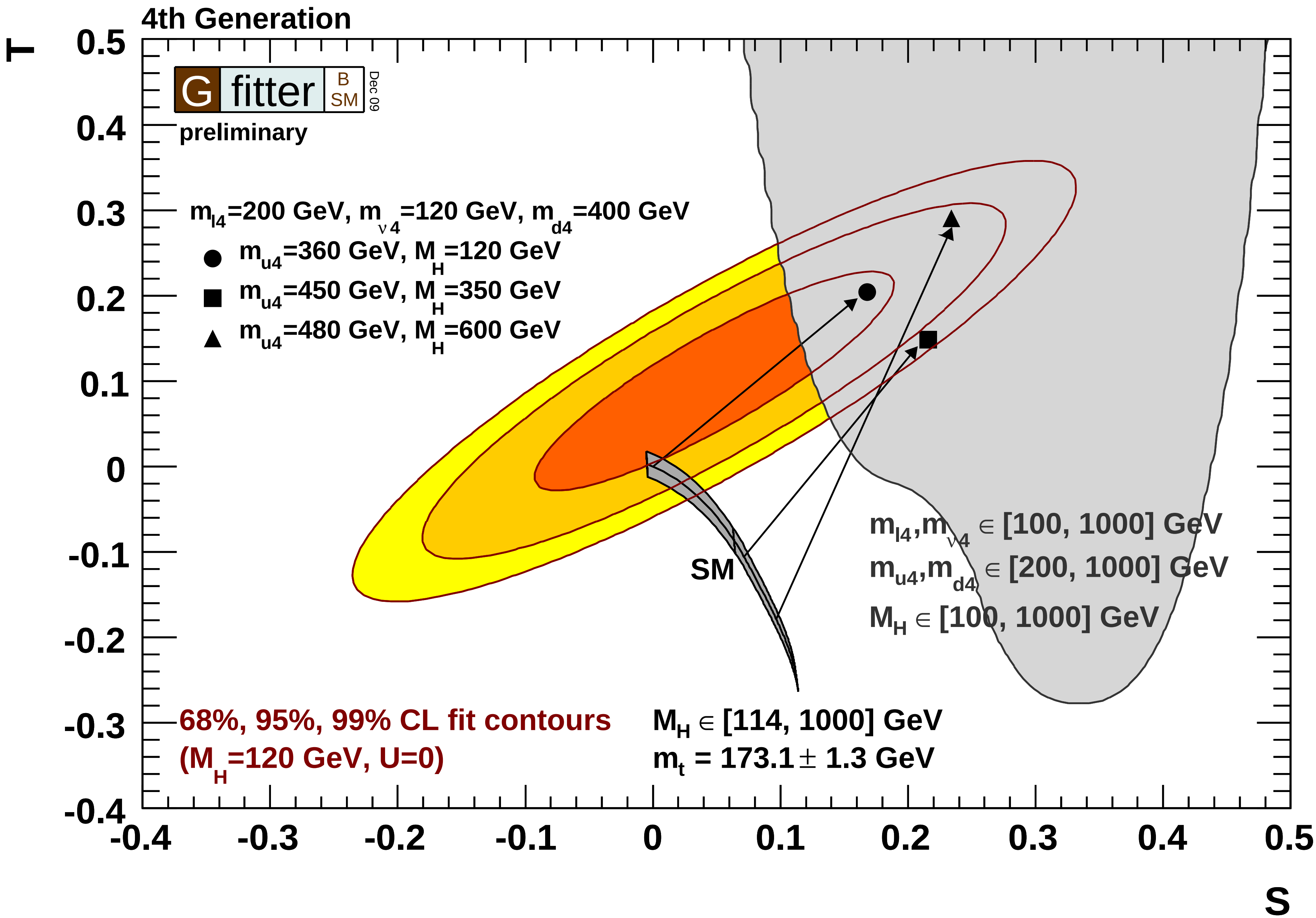


$$m_{\mathrm{H}} \lesssim 160\,\mathrm{GeV} \text{ at } 2\sigma$$

ST contours for the different observables

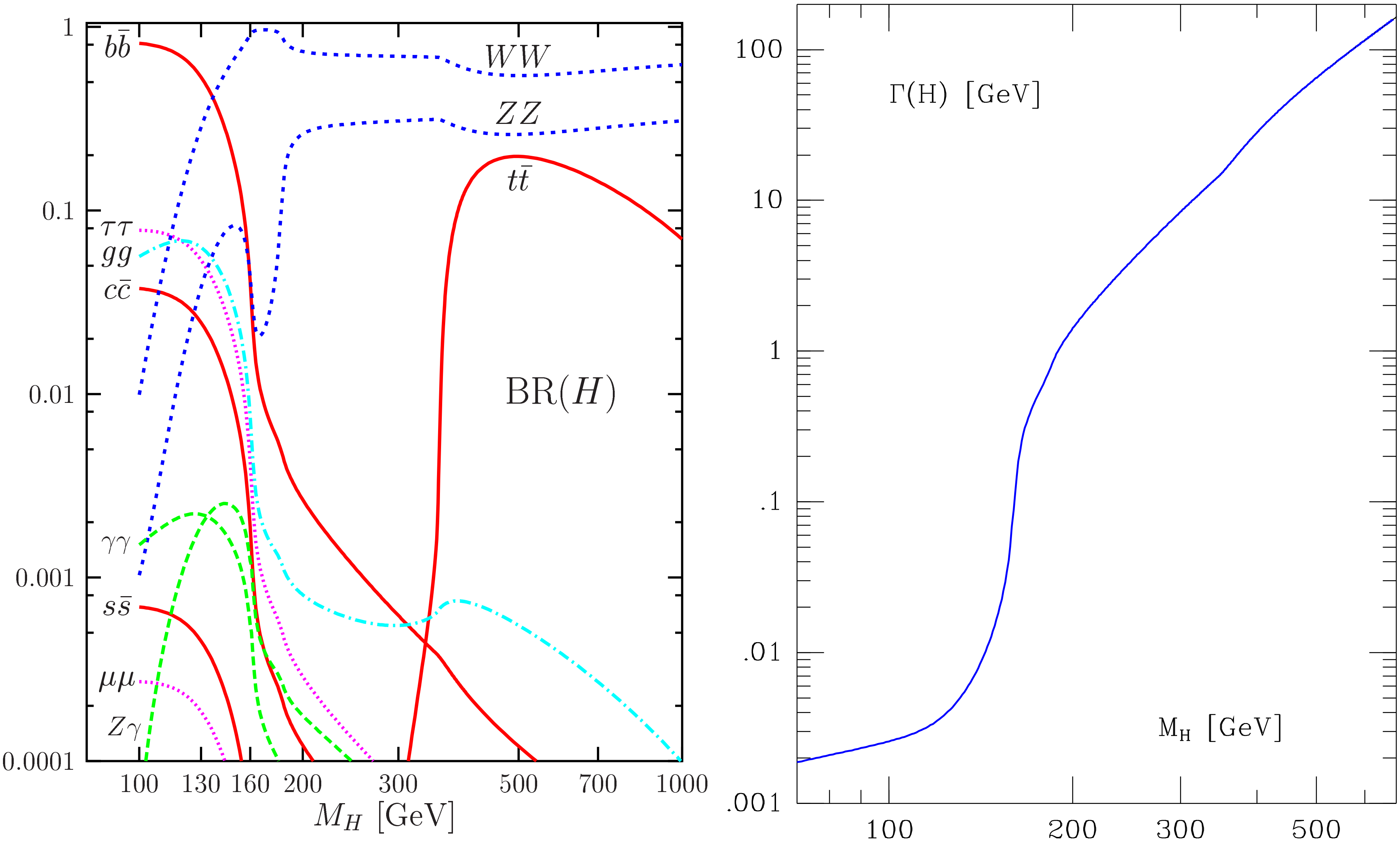


ST in a 4th generation scenario

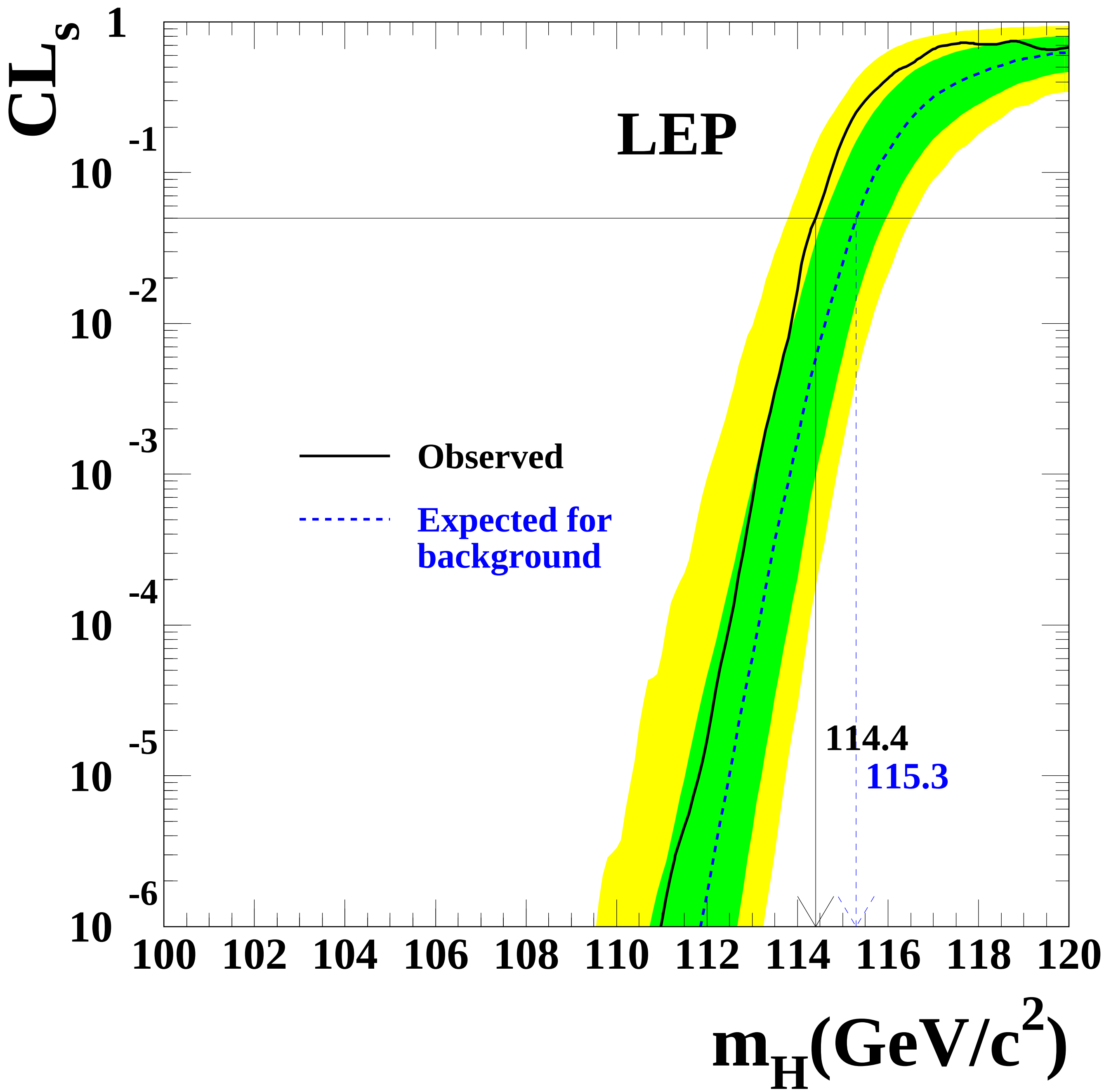


Higgs physics

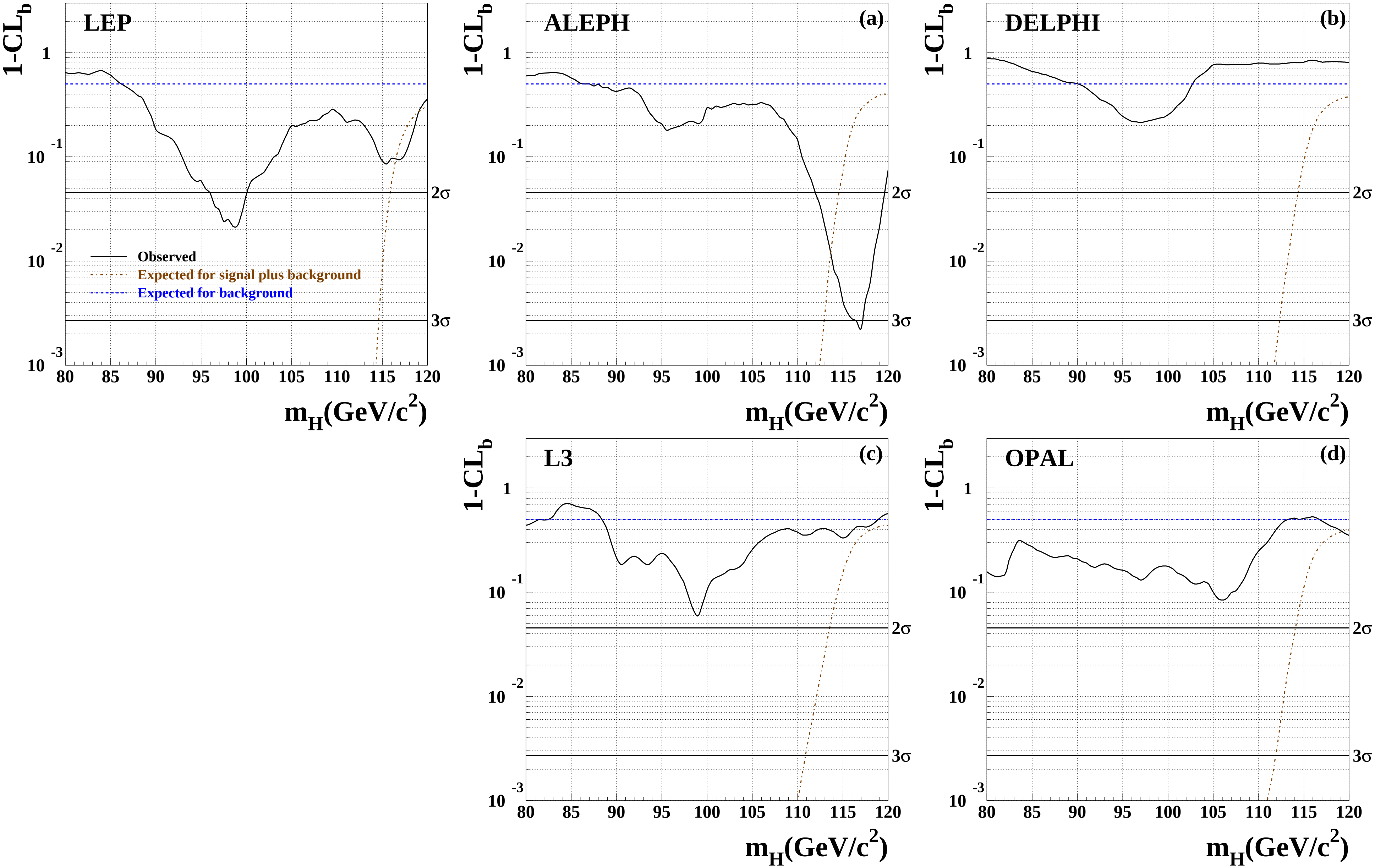
Higgs branching ratios and total width in the SM



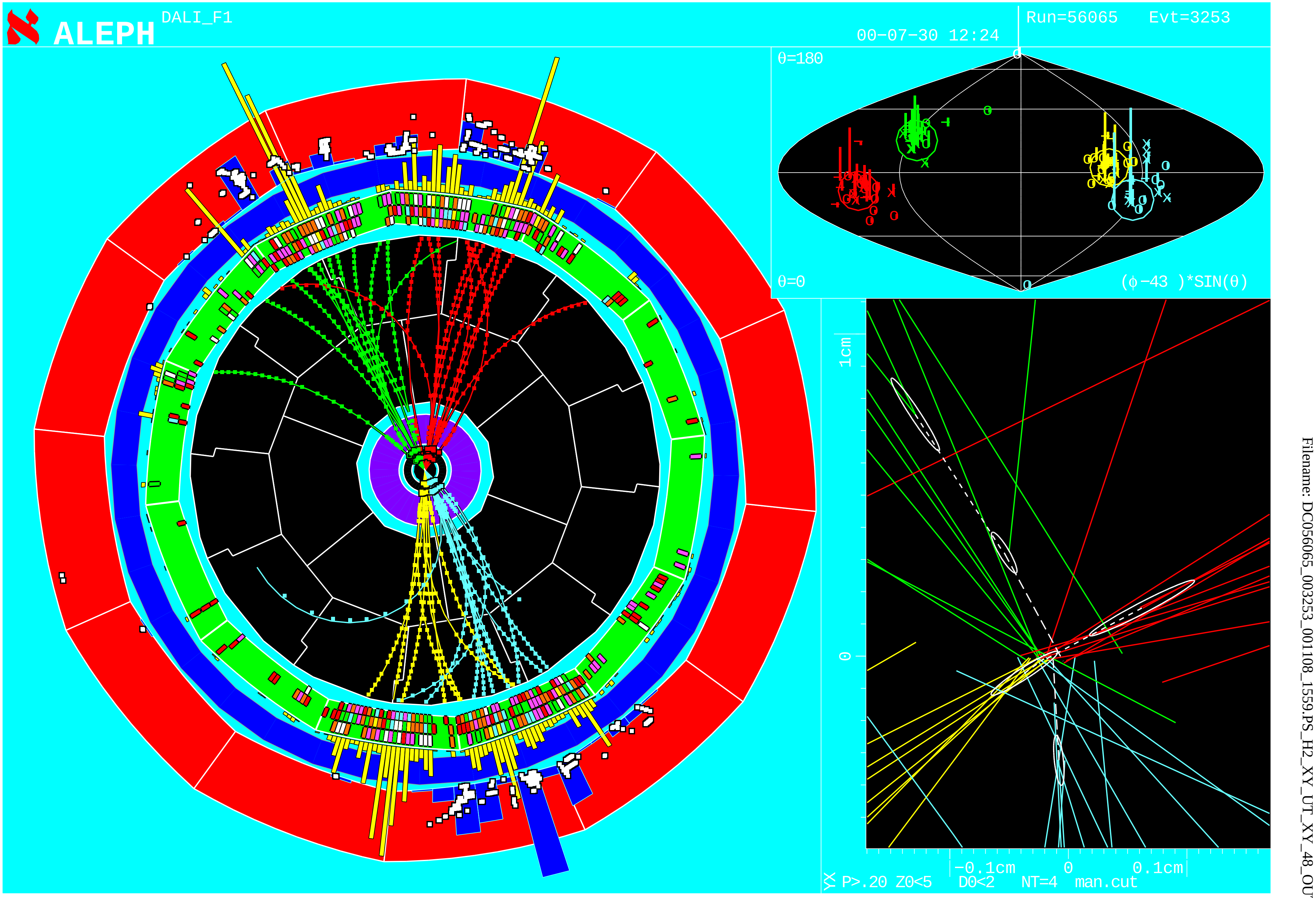
Combined Higgs limit of the LEP experiments



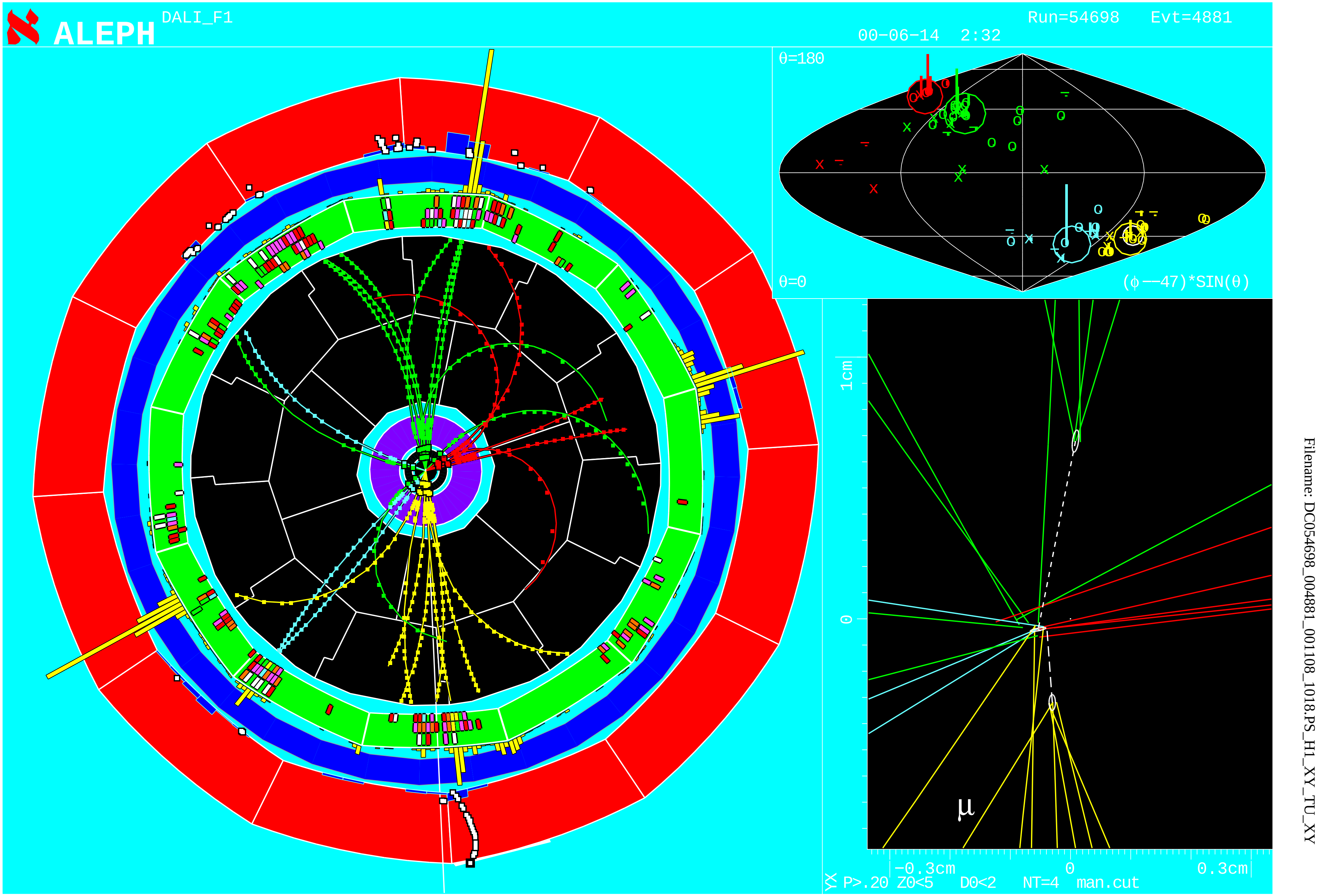
Background compatibility of the Higgs searches



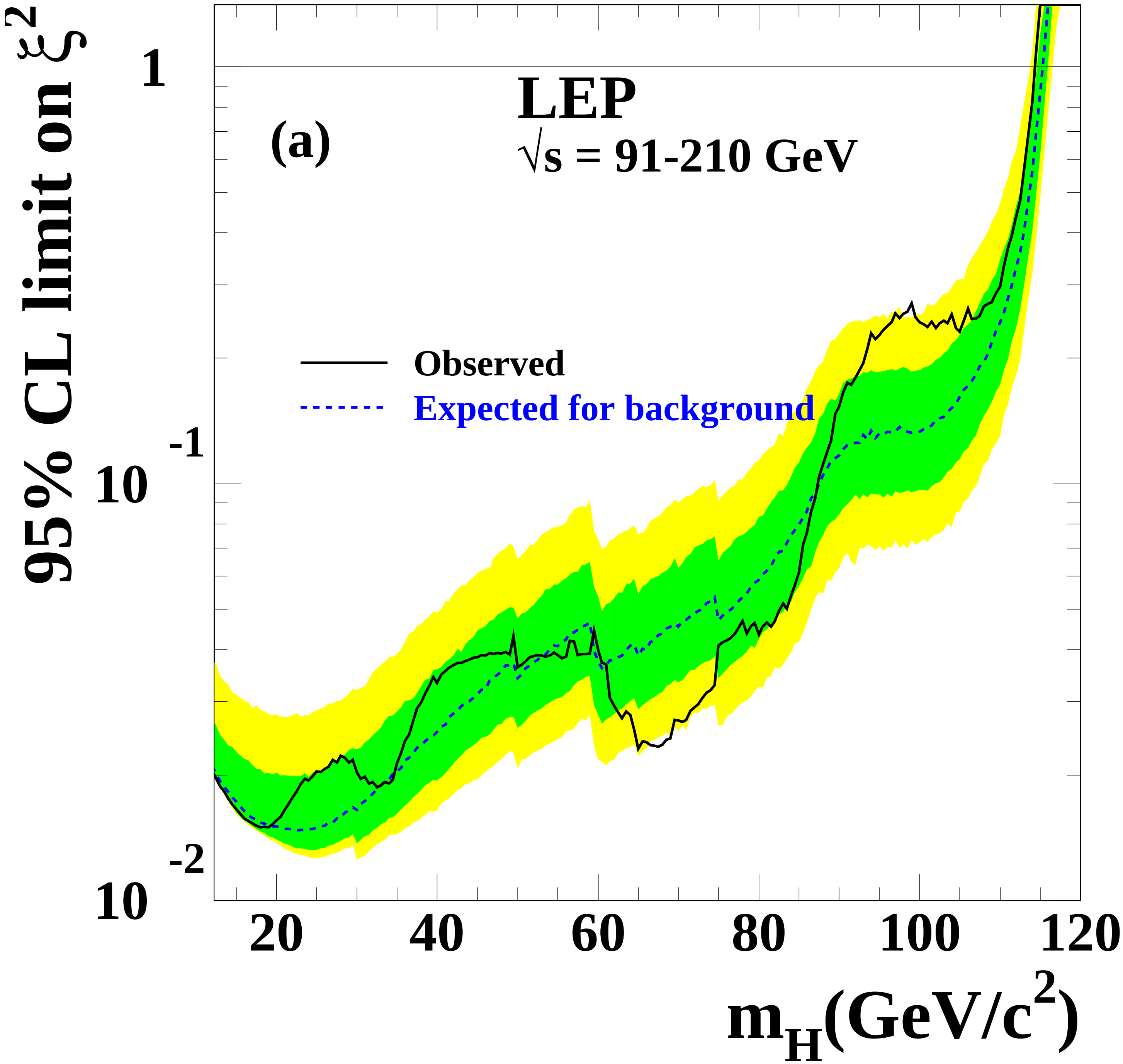
ALEPH Higgs candidate



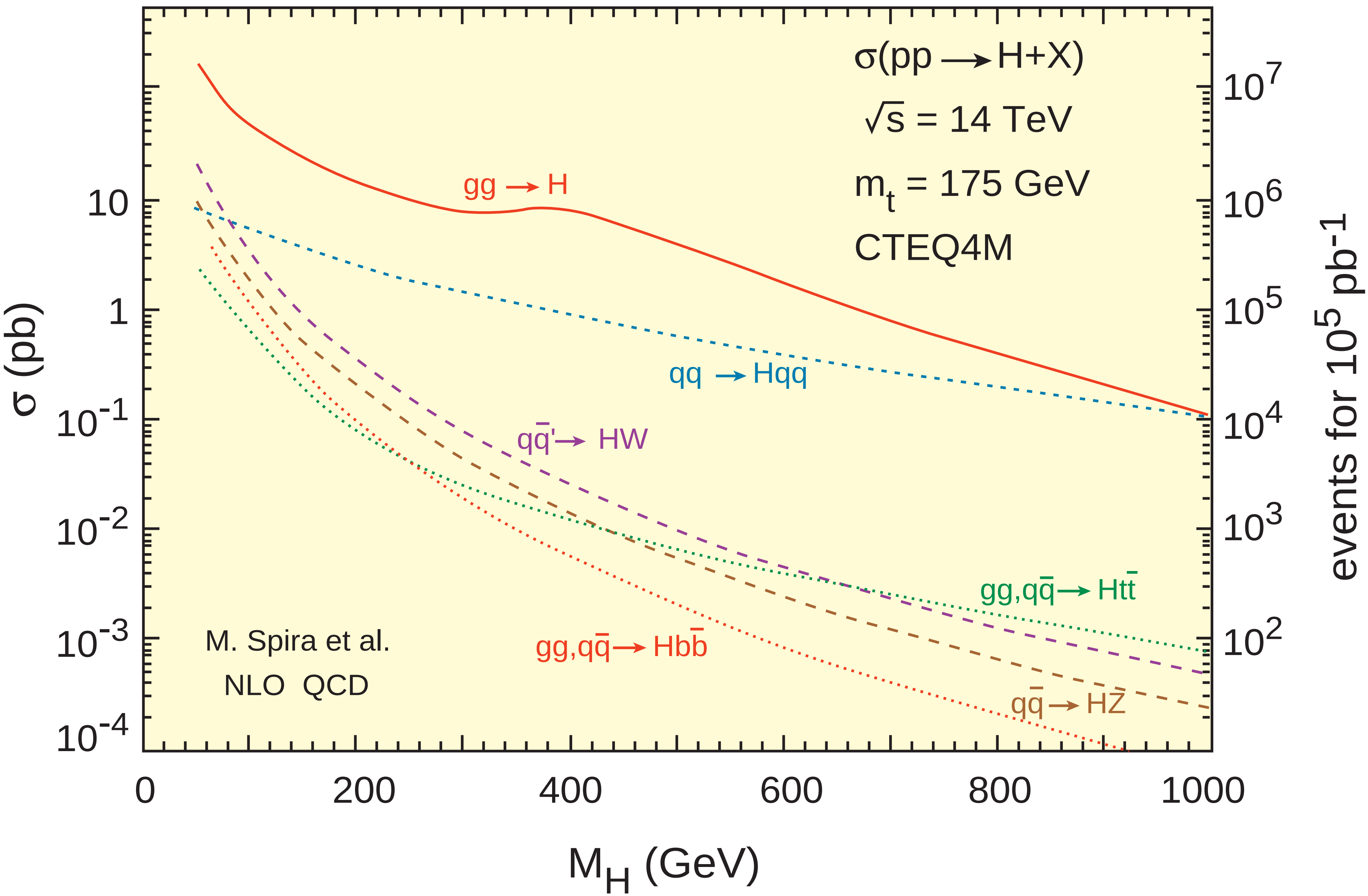
Another ALEPH Higgs candidate



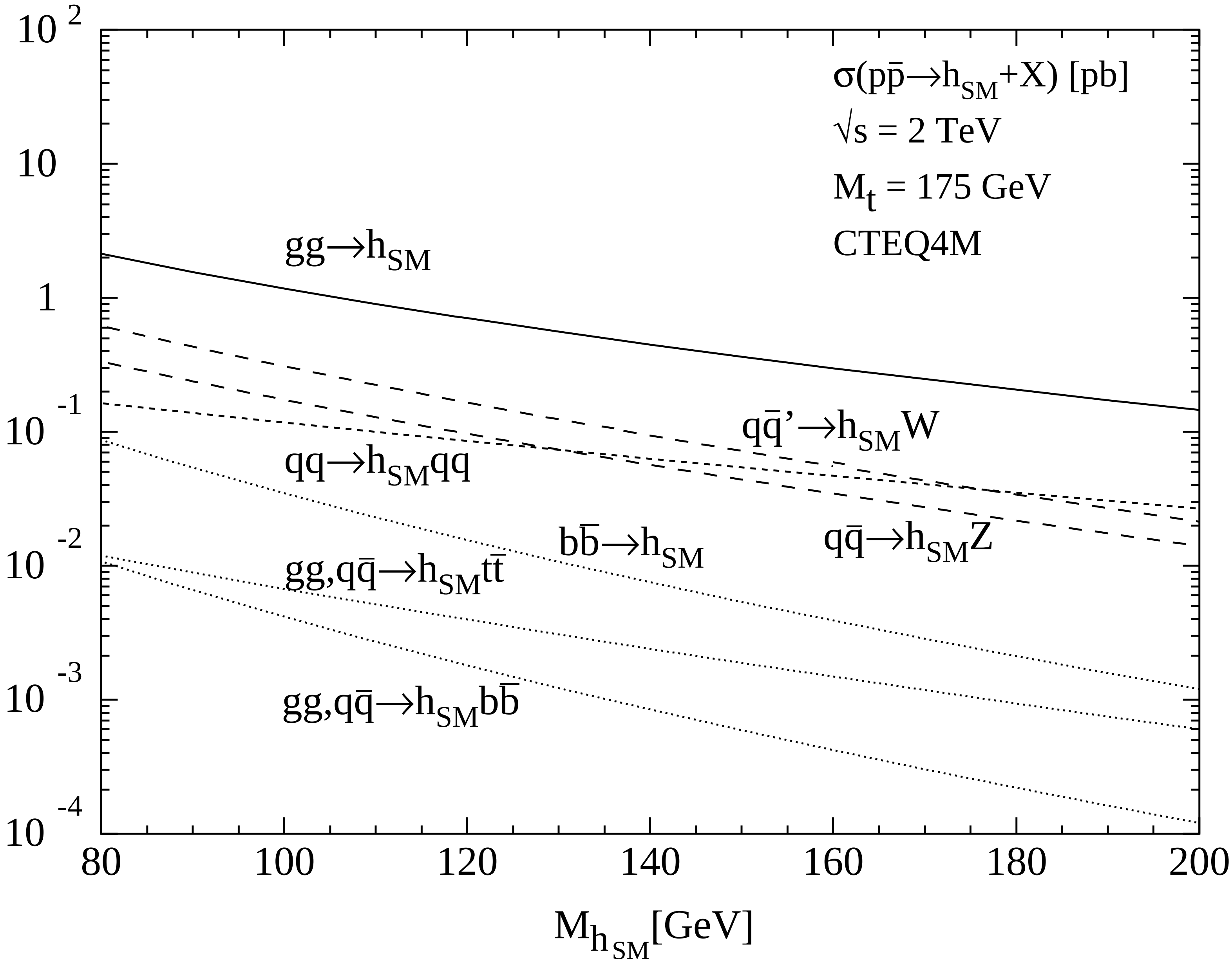
LEP limit on $g(ZZH)^2$

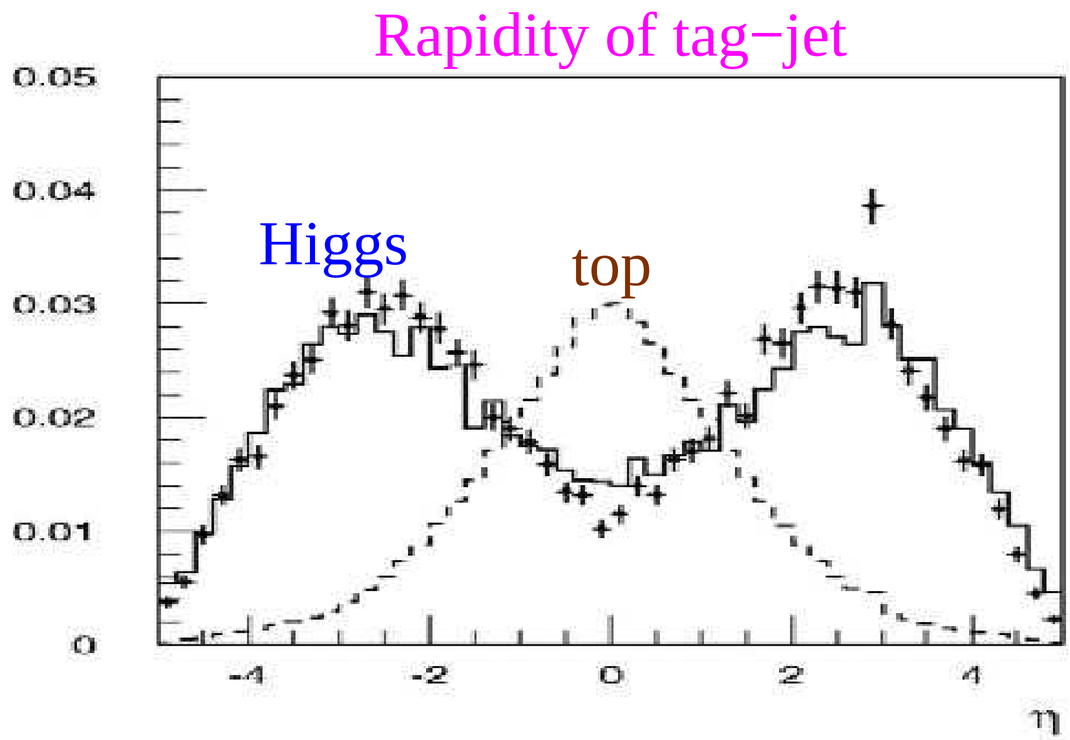


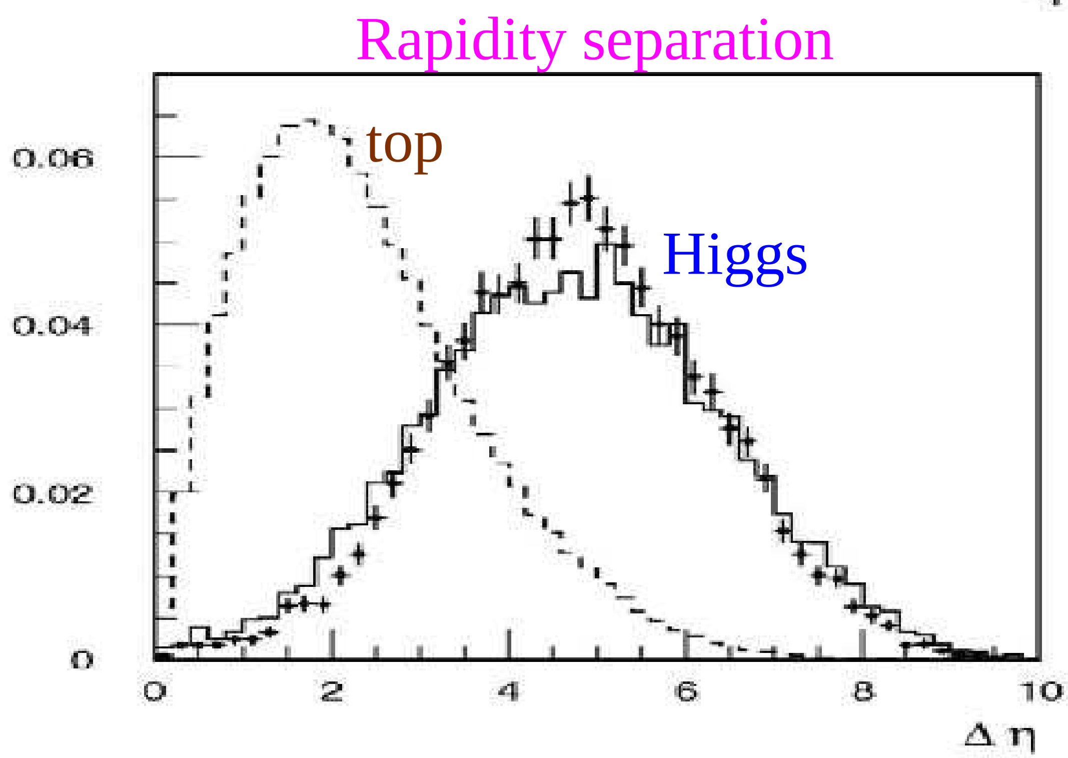
Higgs cross section at the LHC



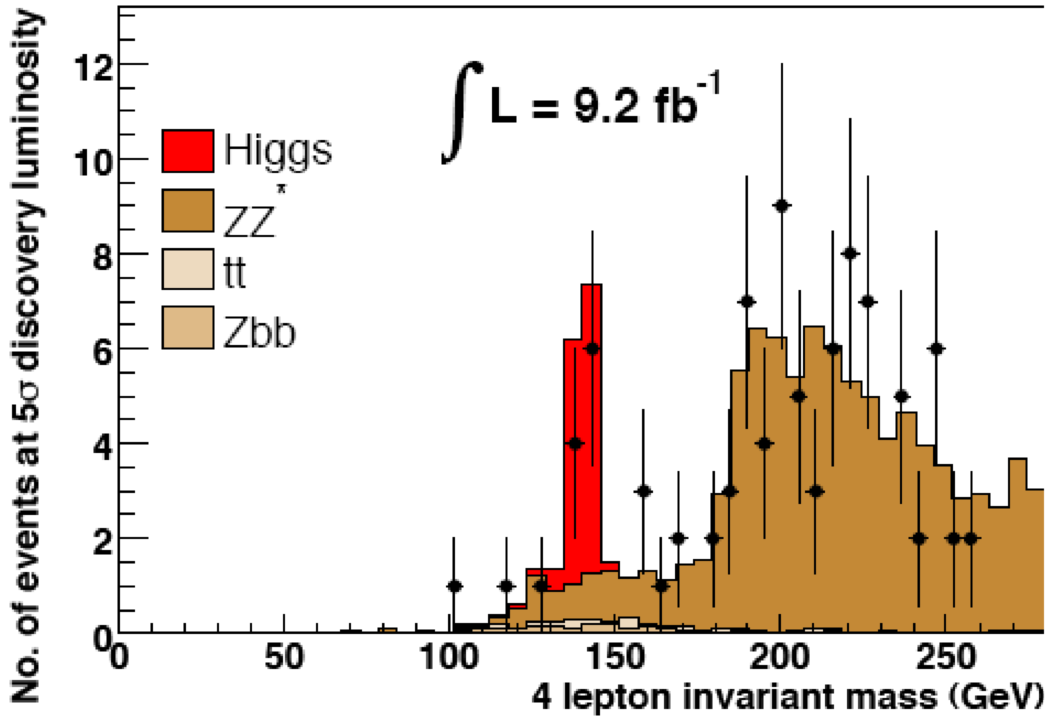
Higgs cross section at the Tevatron



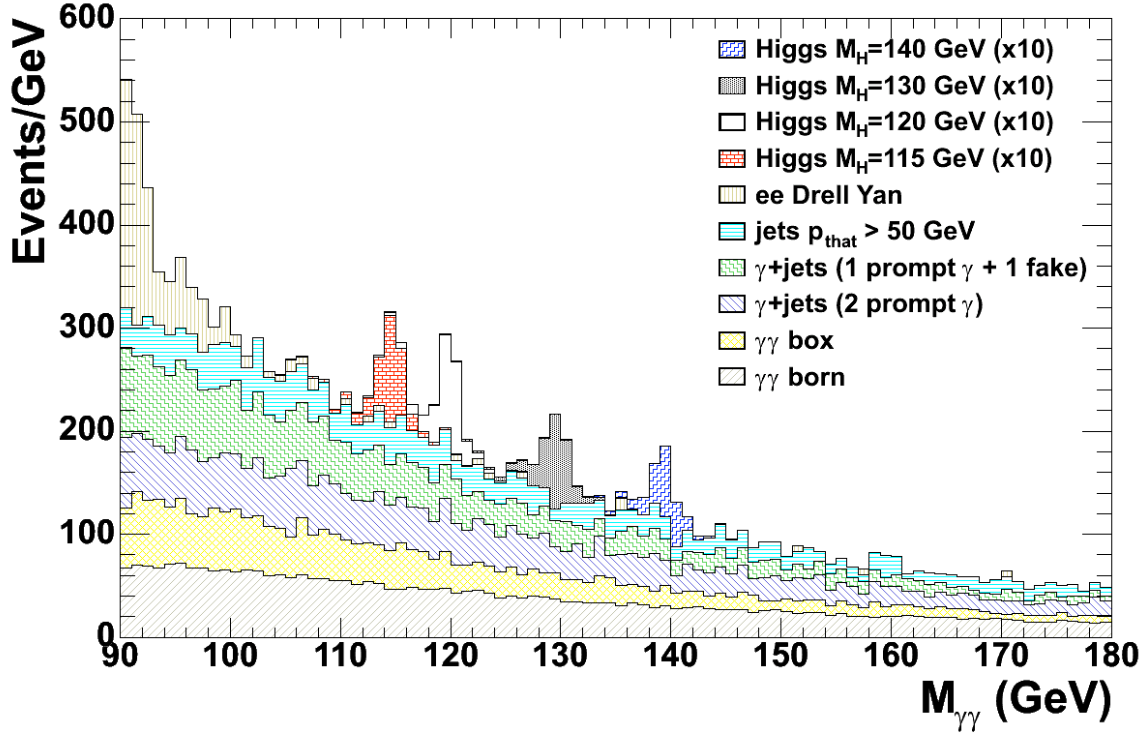

Rapidity of tag−jet
0.05
0.04
0.03
0.02
0.01
0
Higgs
top
-4
-2
0
2
4
η


Rapidity separation
0.06
0.04
0.02
0
top
Higgs
0
2
4
6
8
10
Δ η

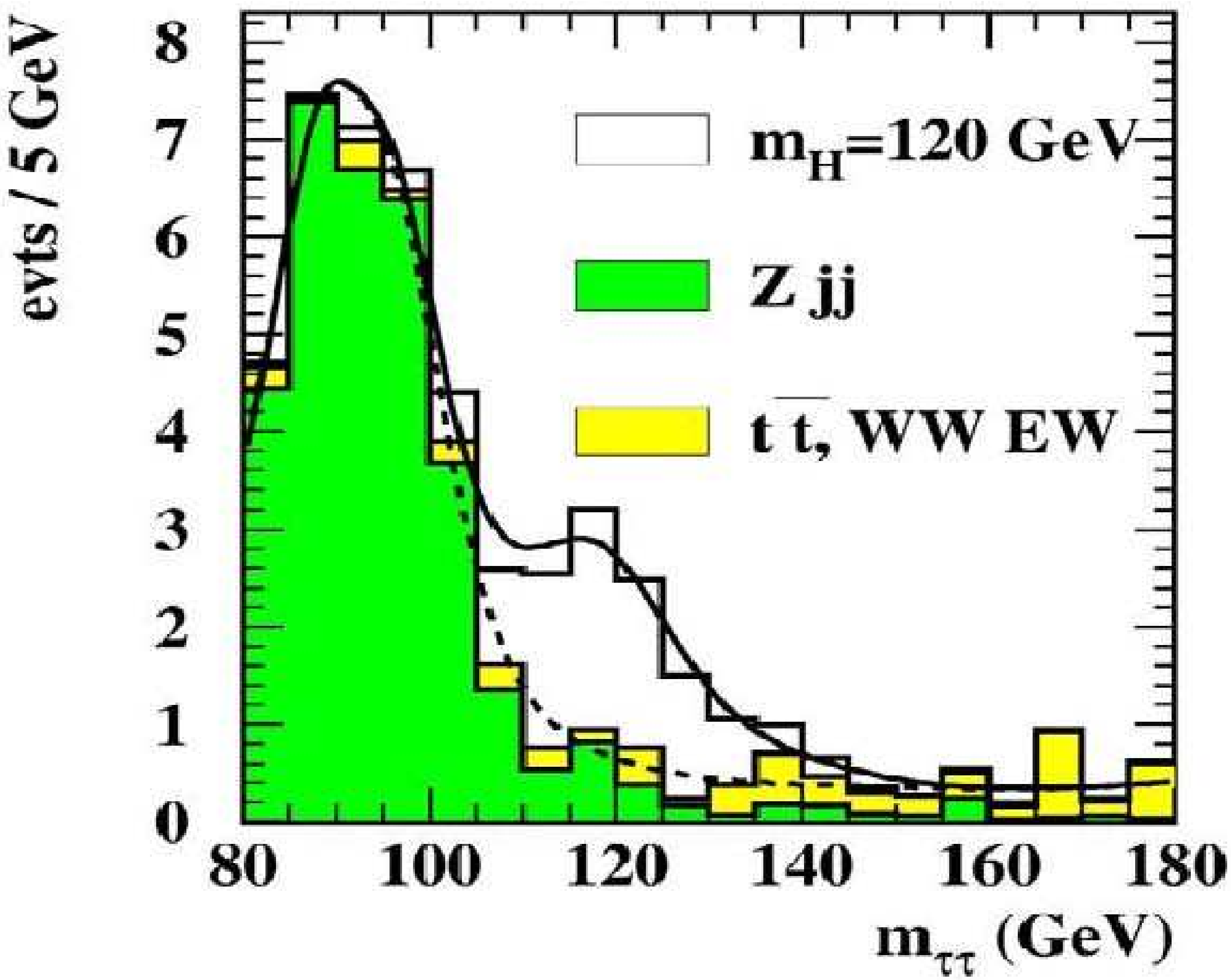
$H \to ZZ$ at the LHC



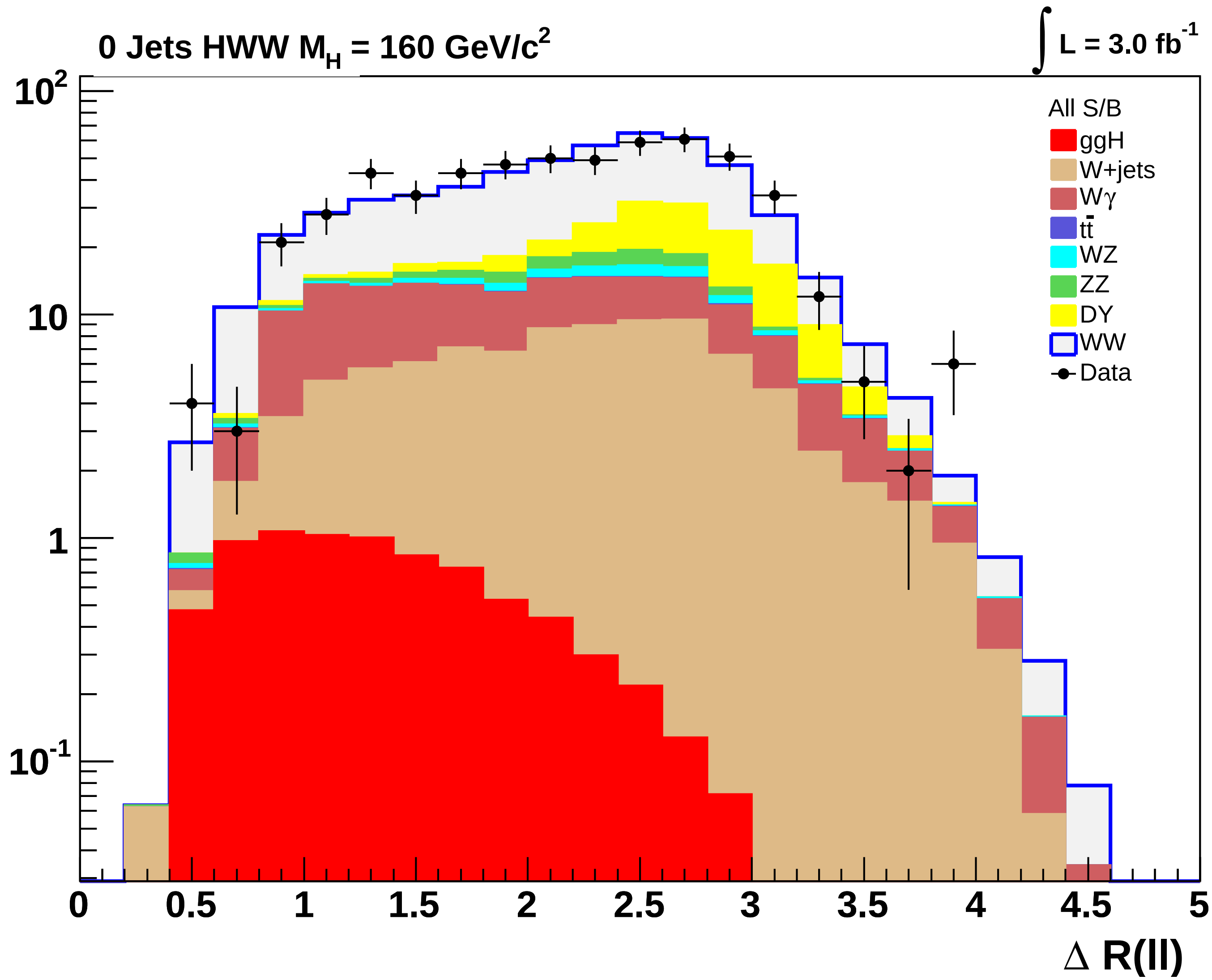
$H \to \gamma\gamma$ at the LHC



m_{H} reconstruction from $Hqq \to \tau^+\tau^- qq$



ΔR for lepton pairs from $H \to WW$



Higgs searches at the Tevatron

Light Higgs:

- Main decay to $b\bar{b}$
- Main channel $gg \rightarrow H \rightarrow b\bar{b}$ hopeless
- Possible channels $WH \rightarrow \ell\nu b\bar{b}$, $ZH \rightarrow \ell\ell b\bar{b}$, $ZH \rightarrow \nu\nu b\bar{b}$,

Medium Higgs

- $gg \rightarrow WW \rightarrow \ell\nu\ell\nu$ becomes accessible
- In addition some signal from $WH \rightarrow \ell\nu\ell\nu + ...$

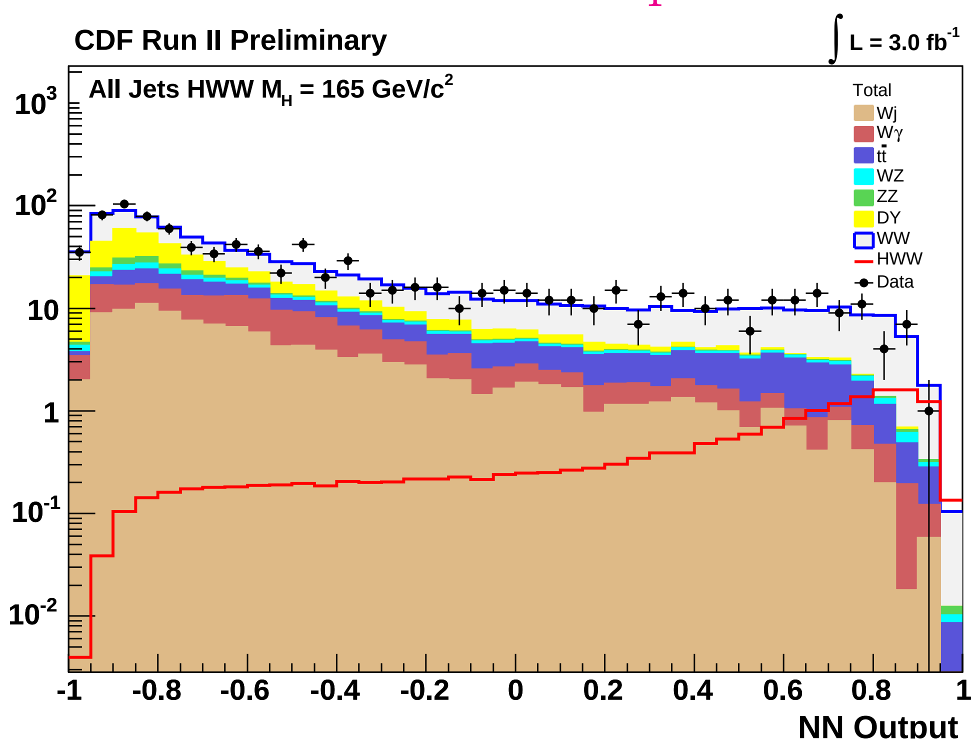
Heavy Higgs ($m_{\mathrm{H}} > 200\,\mathrm{GeV}$)

- No chance because cross section too low

Search for $gg \to WW \to \ell\nu\ell\nu$

- Many variables with low separation power
- E.g. leptons correlated because of Higgs spin (=0)
- Combined with multivariate techniques, here NN
- Small signal under huge bg, WW and Drell-Yan dominant

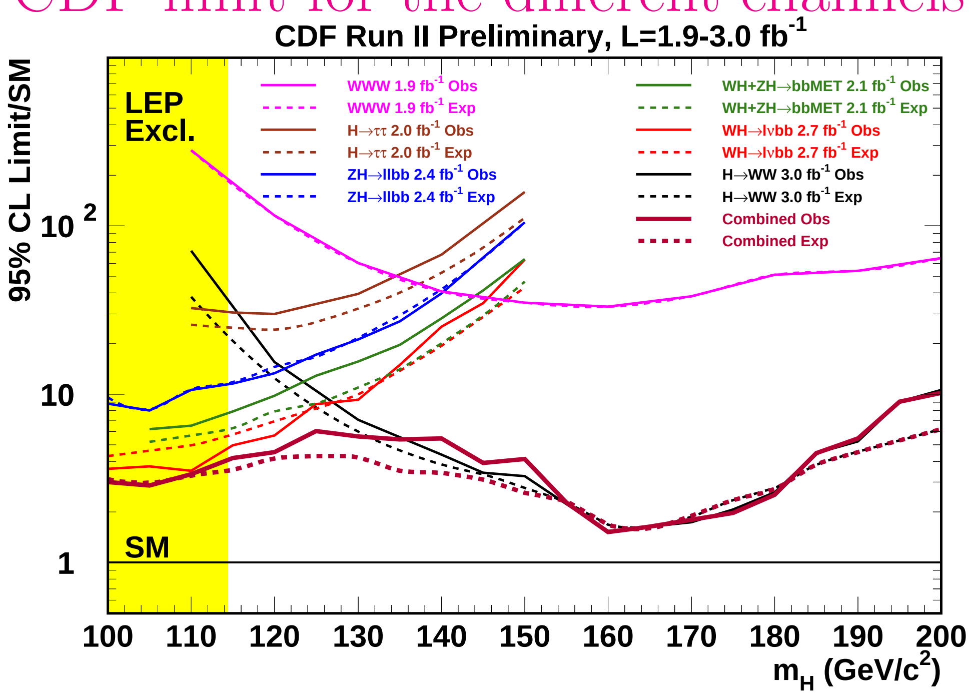
Neural Net output



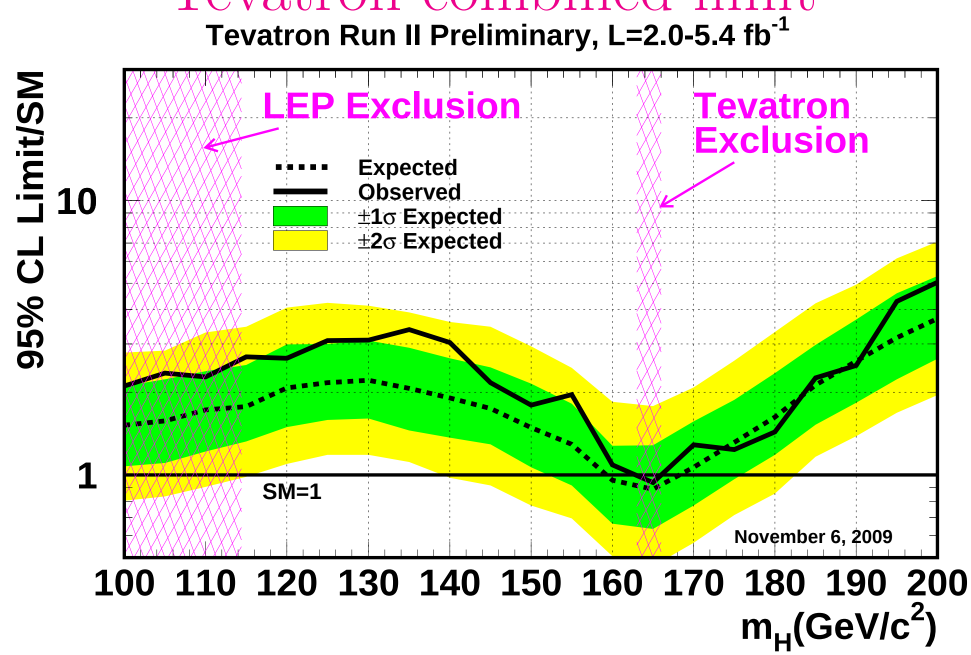
Results

- Low mass region dominated by $WH \to \ell\nu b\bar{b}$ and $WH, ZH \to \mathrm{MET}\, b\bar{b}$
- Higher masses only $H \to \ell\nu\ell\nu$
- Exclusion at low masses still around $2-3\sigma(SM)$
- At $163\,\mathrm{GeV} < m_\mathrm{H} < 166\,\mathrm{GeV}$ SM-Higgs excluded!

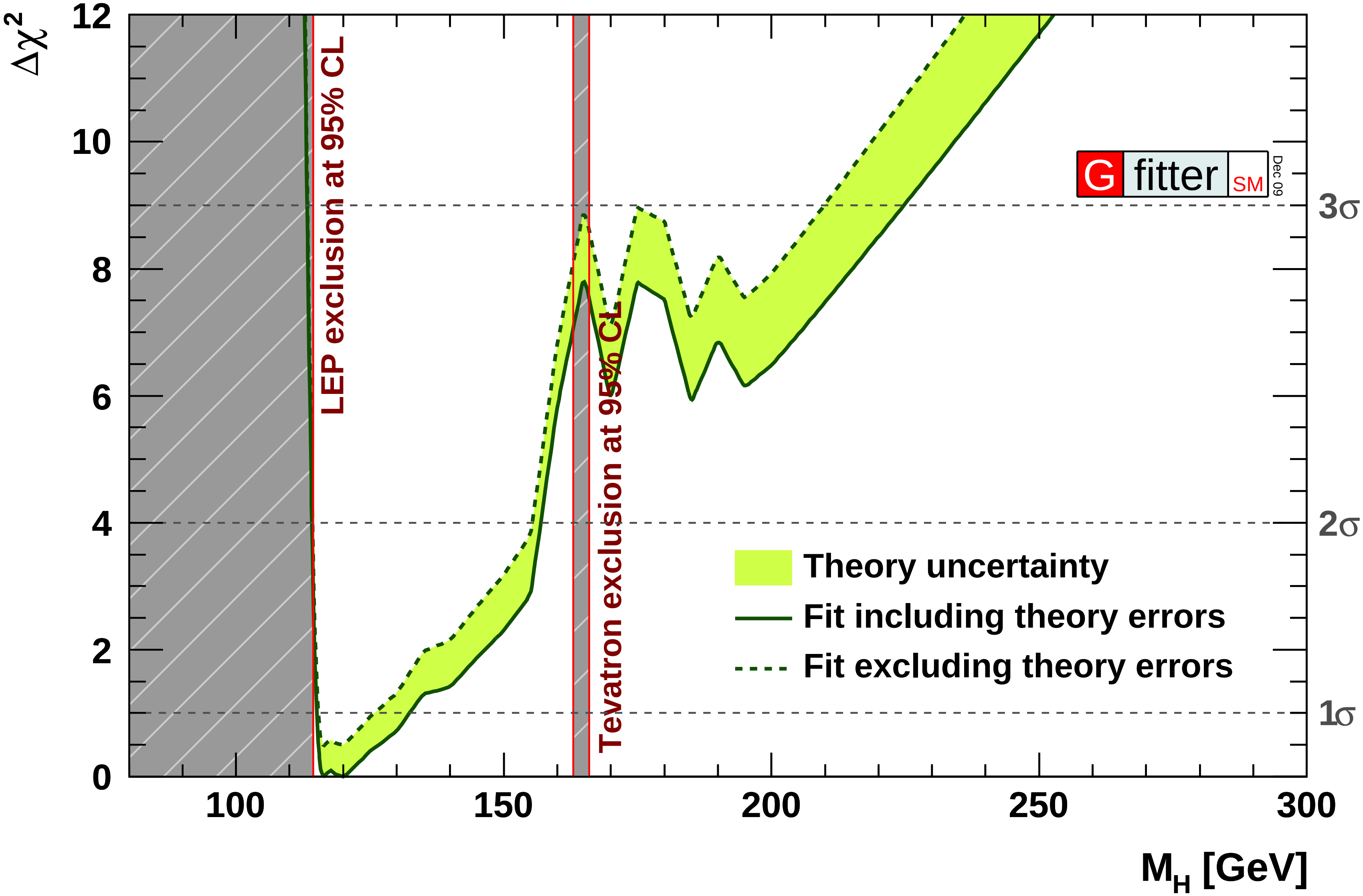
CDF limit for the different channels



Tevatron combined limit



Global electroweak fit including Higgs searches

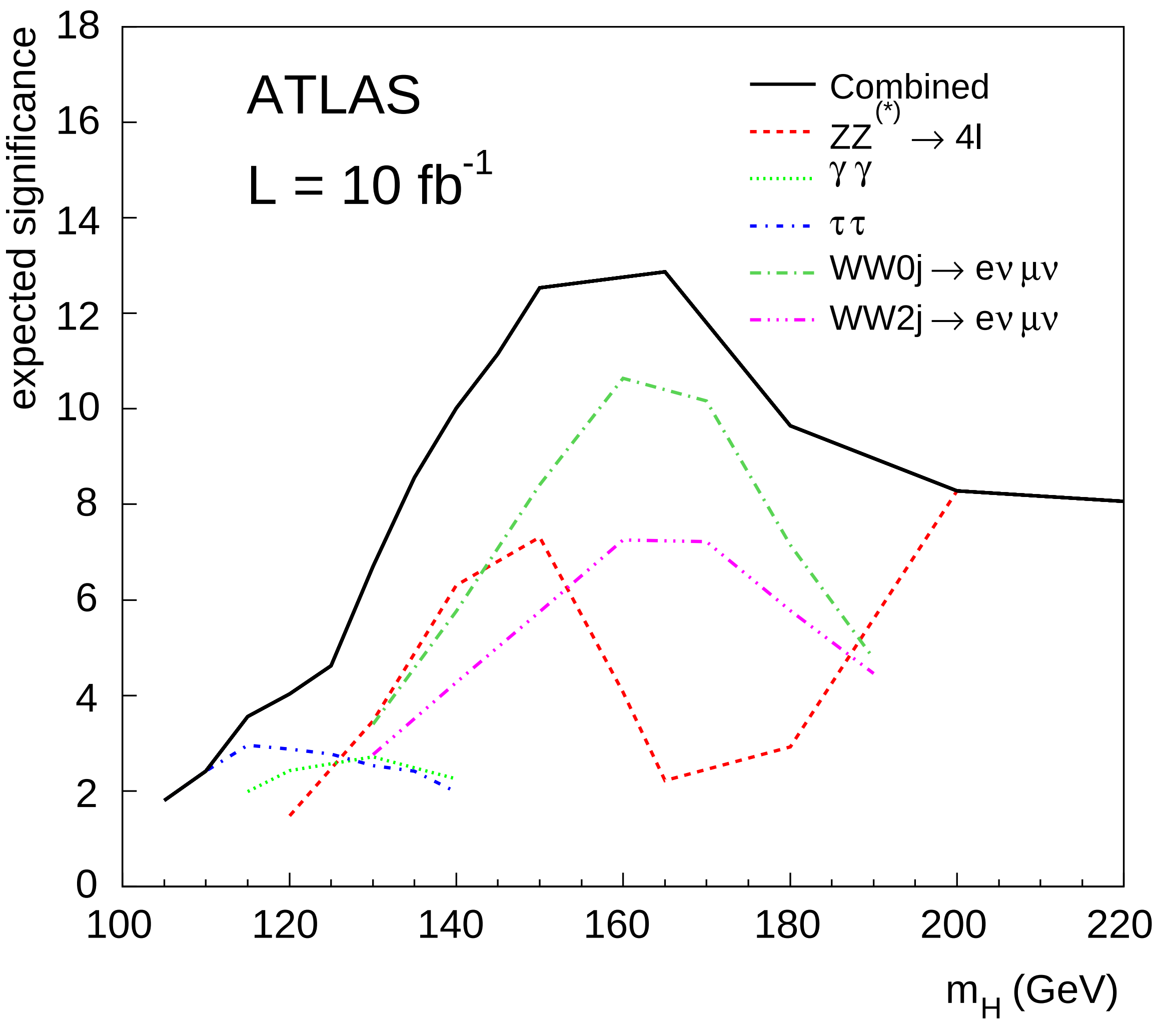


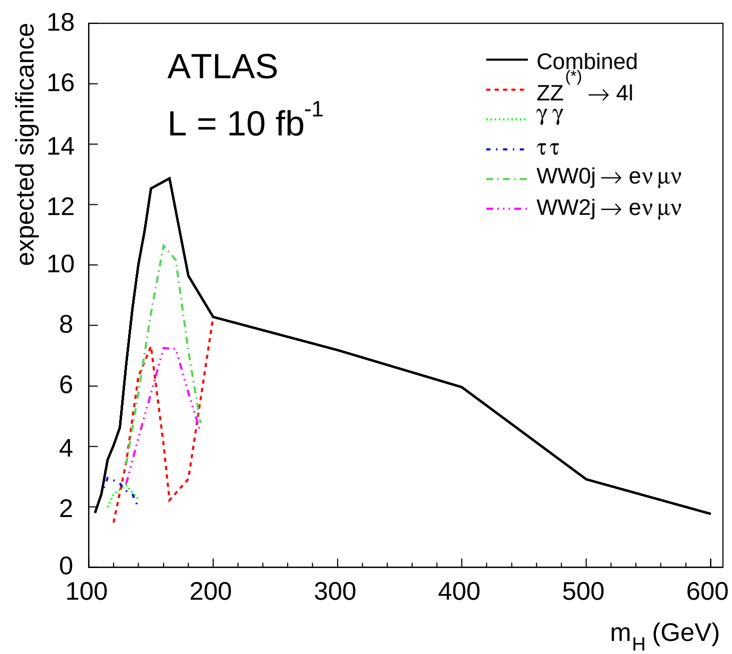
Within SM $m_{\mathrm{H}} < 160\,\mathrm{GeV}$ strongly favoured

Higgs searches at the LHC

- Easiest channel: $H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$: sensitive for $120\,\mathrm{GeV} < m_{\mathrm{H}} < 160\,\mathrm{GeV}$ and $m_{\mathrm{H}} > 180\,\mathrm{GeV}$
- $170\,\mathrm{GeV}$ hole can be more than filled with $H \to WW$
- Low masses can be probed with $H \to \gamma\gamma$ and $H \to \tau\tau$ in fusion channel
- Unfortunately the most probable region is the most difficult
- Nevertheless the Higgs can be discovered in the full region with 100 fb^{-1}

ATLAS Higgs search expectations for 10 fb^{-1} at 14 TeV



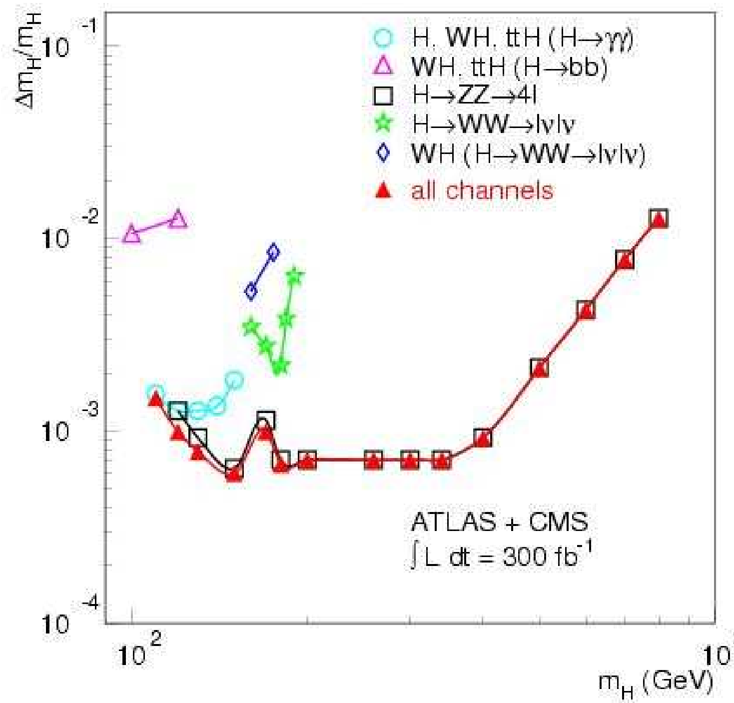


Higgs properties

LHC has discovered a particle compatible with a Higgs, what can be measured?

Mass:

Modes with complete Higgs reconstruction ($H \to \gamma\gamma$, $H \to ZZ \to 4\ell$) allow mass measurement with 0.1% precision.

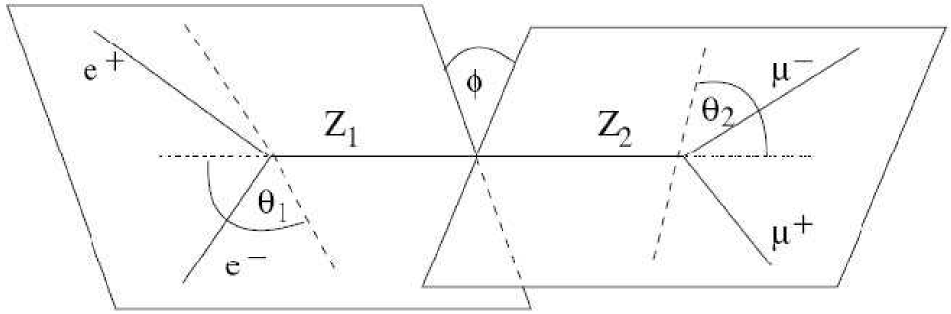


Spin:

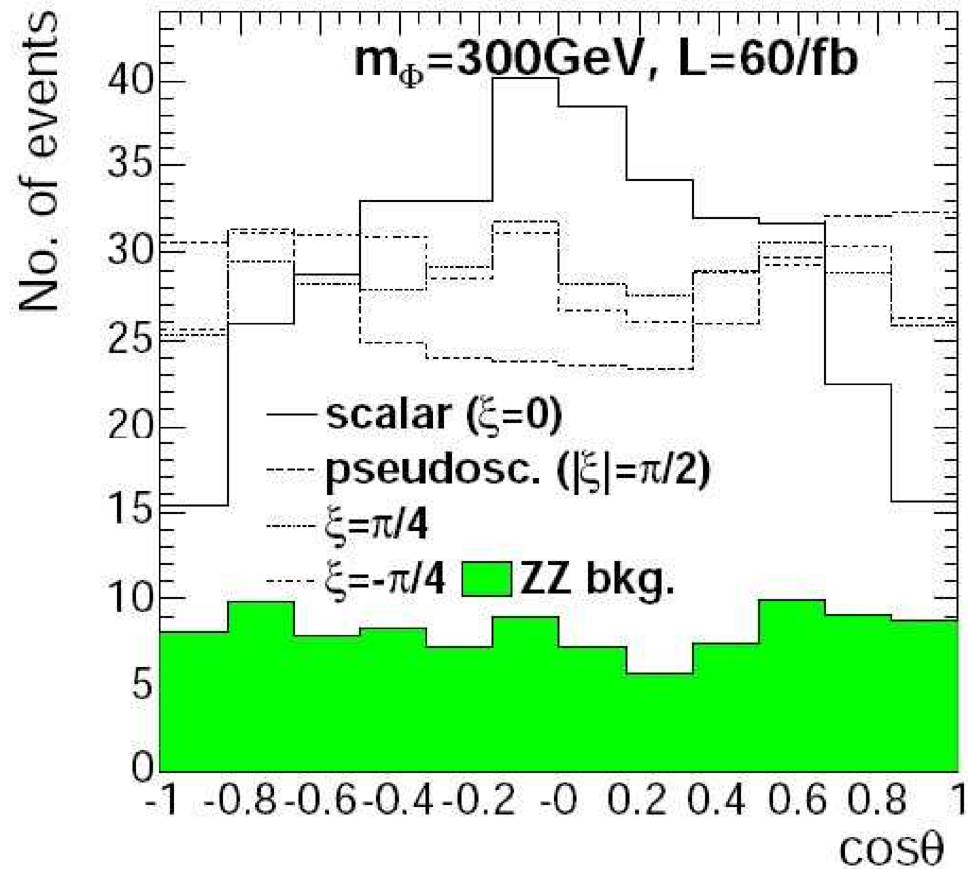
Coupling Hvv forbidden if H has spin 1 and v is massless vector particle (e.g. g or γ) (angular momentum conservation and Pauli principle)

➡ visibility of $H \to \gamma\gamma$ or $gg \to H$ excludes spin 1

If $H \to ZZ \to 4\ell$ is visible spin/CP can be obtained from decay angle distributions:

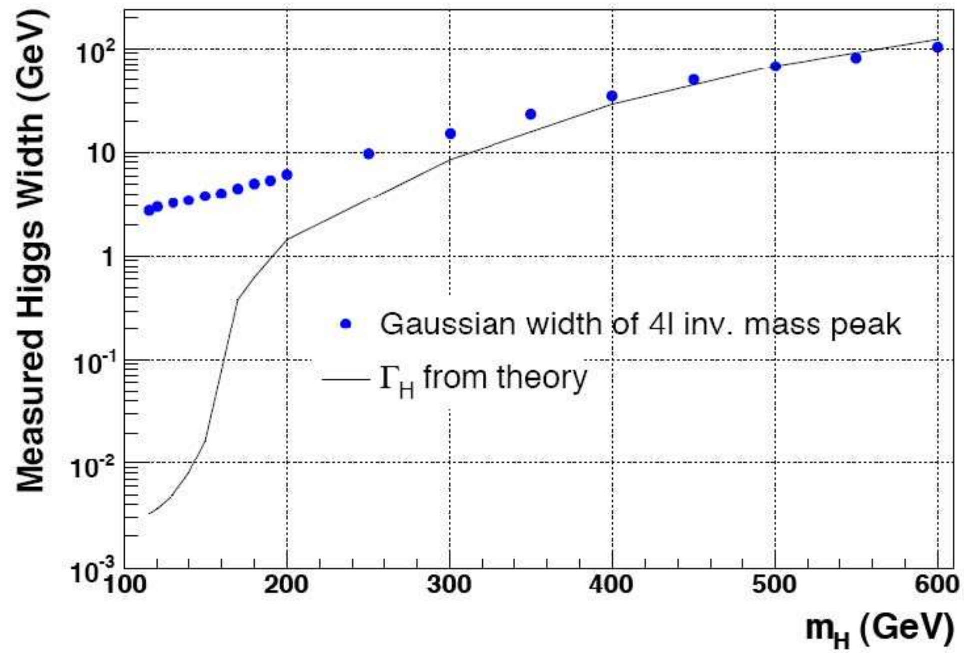


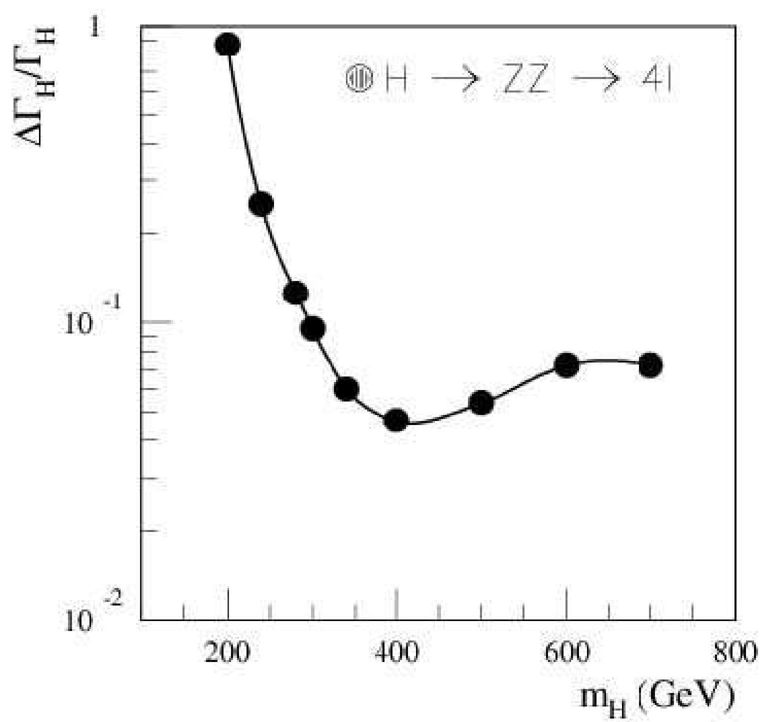
- Take $H \to ZZ \to 2e2\mu$
- Add CP odd coupling to SM coupling with strength $\tan\xi/m_V^2$
- Most backgrounds can be suppressed by cuts
- Can distinguish the extreme cases



The width of the Higgs

- For a light Higgs the width is much smaller than the detector resolution
- If $m_H > 2m_W$ the width gets much larger and can be measured

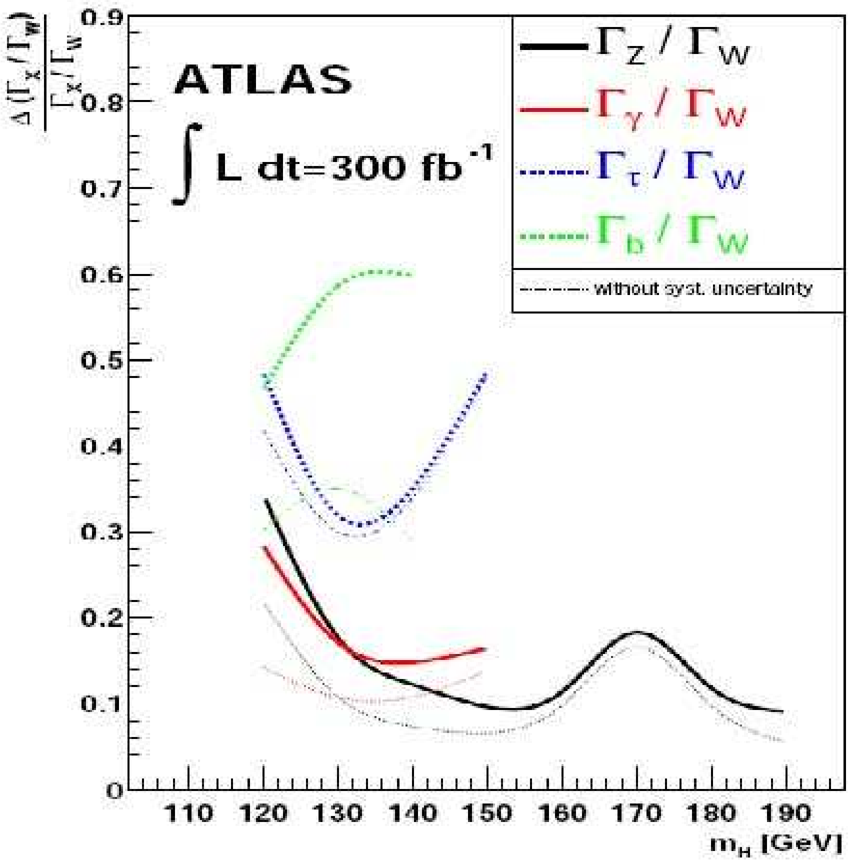




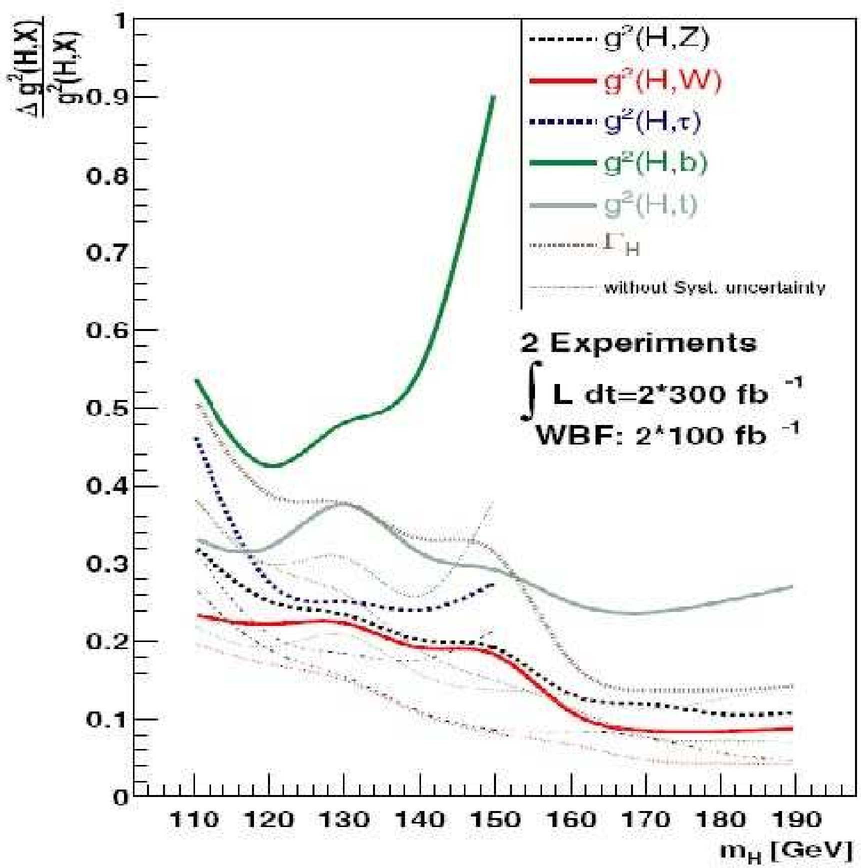
For $m_H > 200\,\text{GeV}$ a precision < 10% is possible

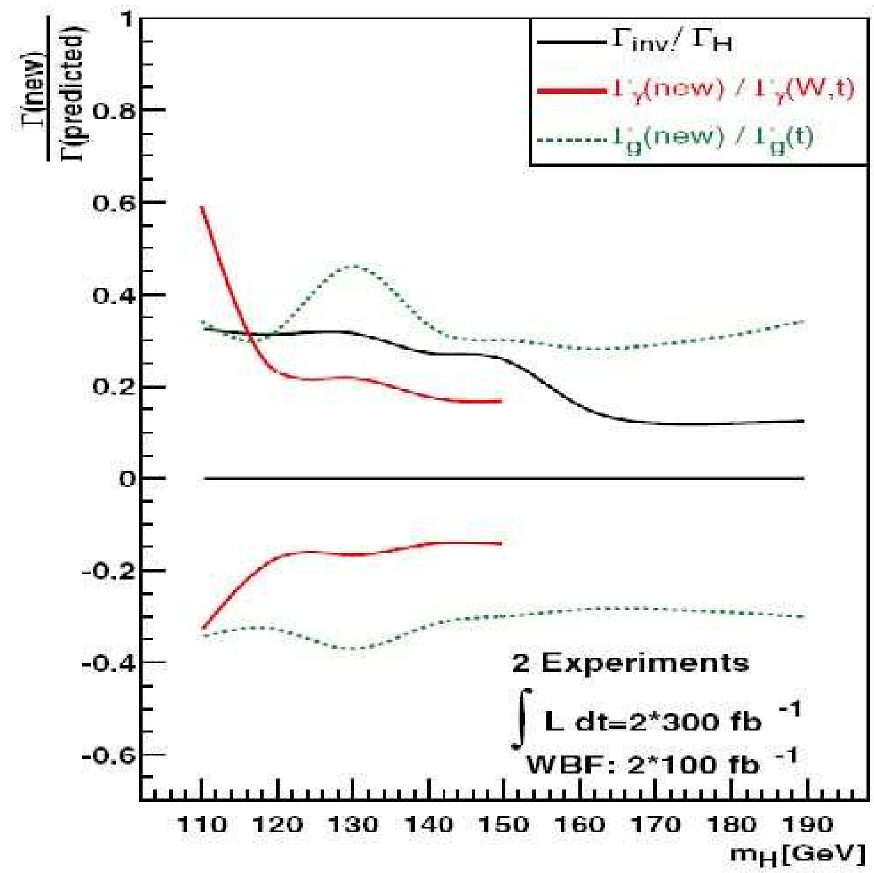
Higgs couplings

- $\sigma \times BR \propto \frac{\Gamma_{prod}\Gamma_{dec}}{\Gamma_H}$
- Ratios of production rates measure ratios of partial widths
- Can obtain ratios of decay widths with > 10% accuracy



- For absolute partial widths need additional assumptions.
- Precisions of couplings depend on assumptions
- Minimal assumption $\Gamma_V < \Gamma_V^{SM}$ $V = W, Z$
- Again precision $> 10 - 20\%$
- Better precision with additional assumptions





The future of Higgs physics

- If a roughly SM like Higgs exists LHC will find it
- However the parameter determination at LHC is marginal
- This could be improved by a future e^+e^- collider
- Two LC projects are under study

  ILC LC in superconducting technology. 1st stage $\sqrt{s} \leq 500\,\mathrm{GeV}$, upgradable to 1 TeV.

  CLIC LC in two-beam technology $\sqrt{s} \leq 3\,\mathrm{TeV}$
- A LC could be e.g. the next project at CERN following the LHC

Questions to be answered for the Higgs

SM−like Higgs at LHC ?

1 doublet

- SM
- little Higgs
- mixed with Radion

2 doublets

- 2HDM
- MSSM

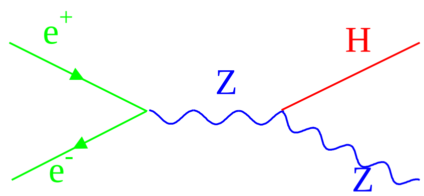
2doublets+x

- NMSSM
- XMSSM

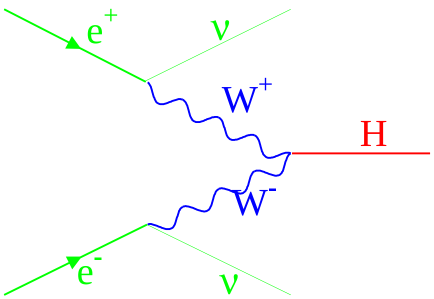
Composite Higgs (Technicolour)
Special role of top quark
(little Higgs, top−colour)
...

- Main production at e^+e^- colliders

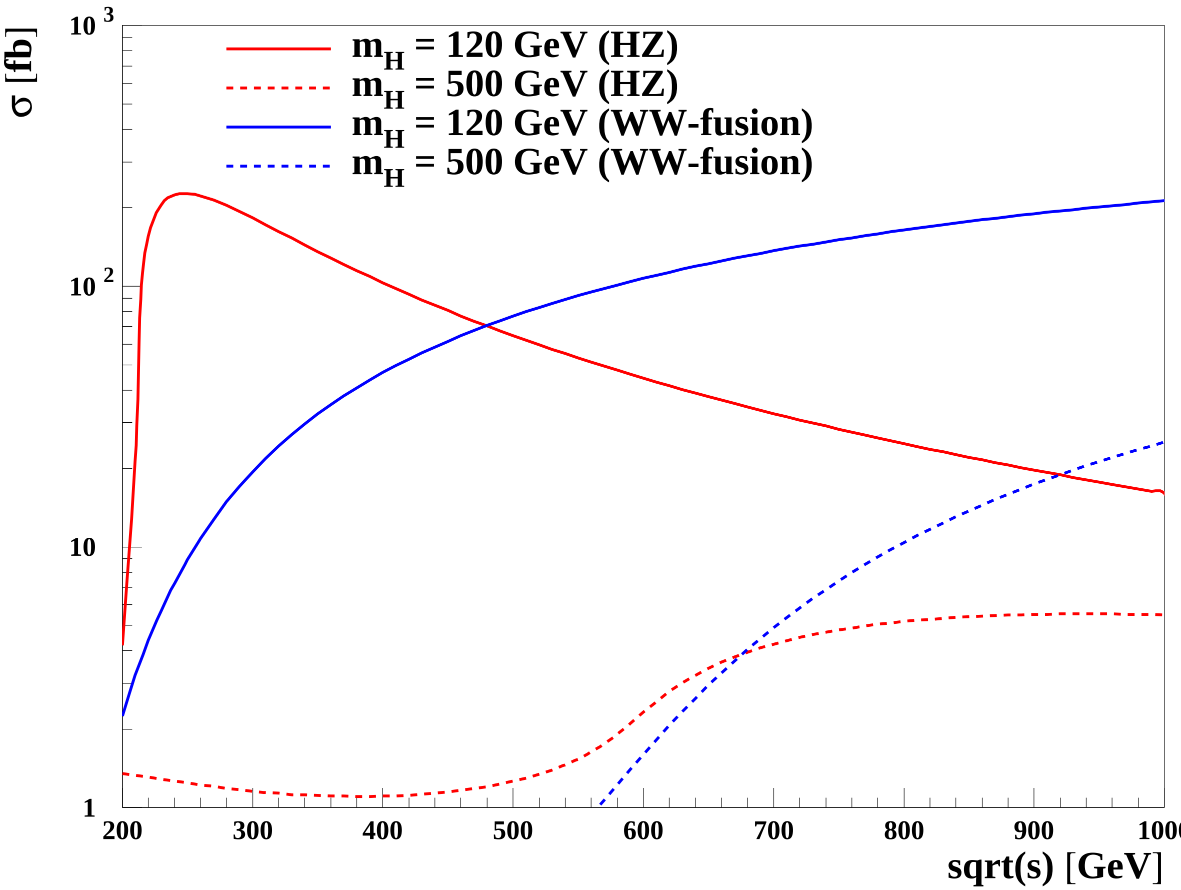
Higgsstrahlung



W-fusion



- Cross section:



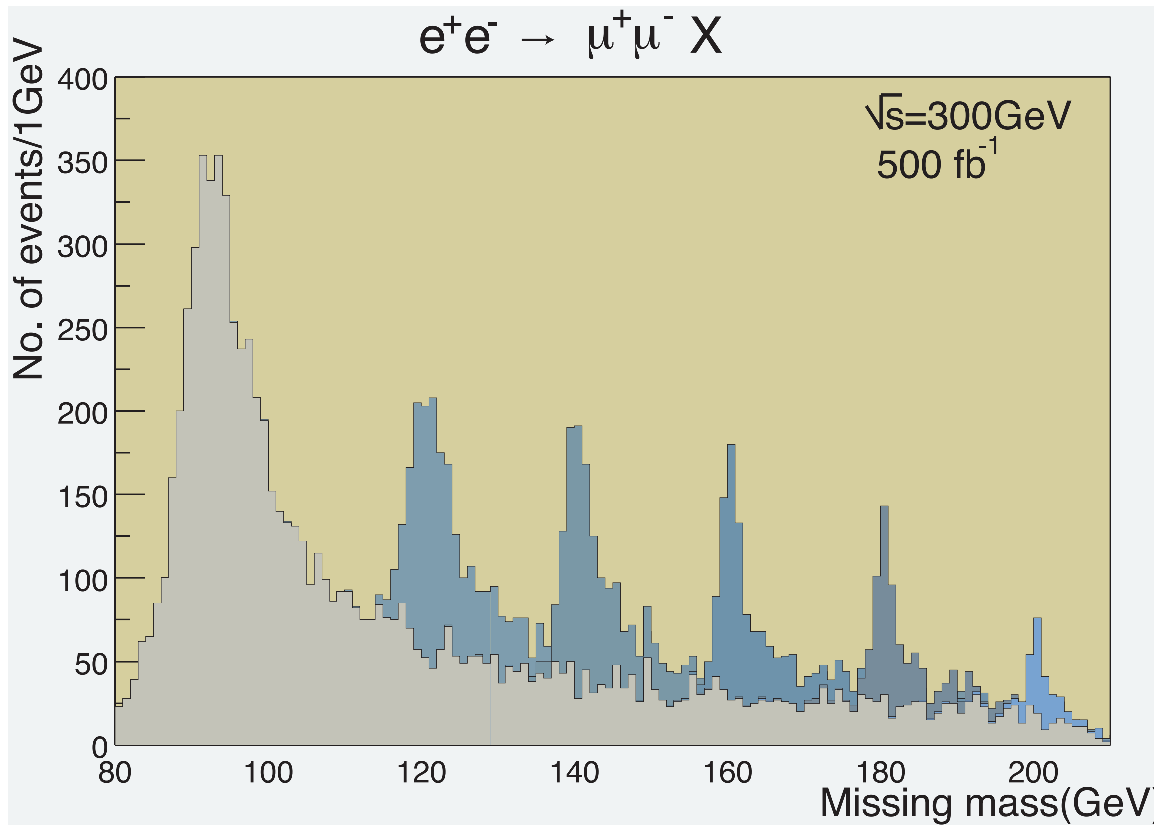
First key measurement: Unbiased $e^+e^- \to HZ$ measurement from recoil mass

- Select events $e^+e^- \to ZX$ with $Z \to \ell^+\ell^-$
- Can see Higgs peak in recoil-mass spectrum without any link to Higgs decay products

➠ Unbiased measurement of HZZ coupling

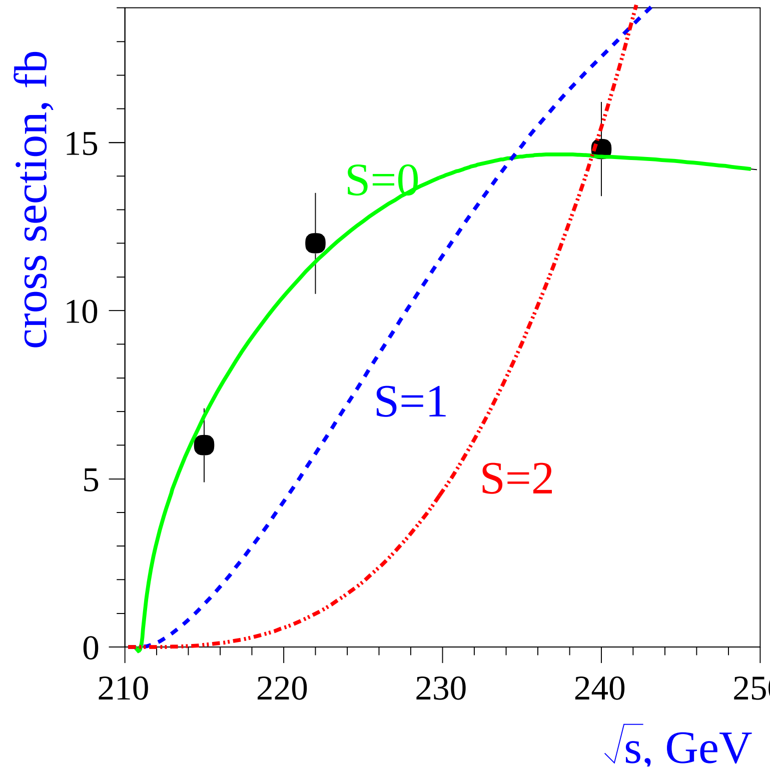
➠ Unbiased basis for Higgs branching ratios

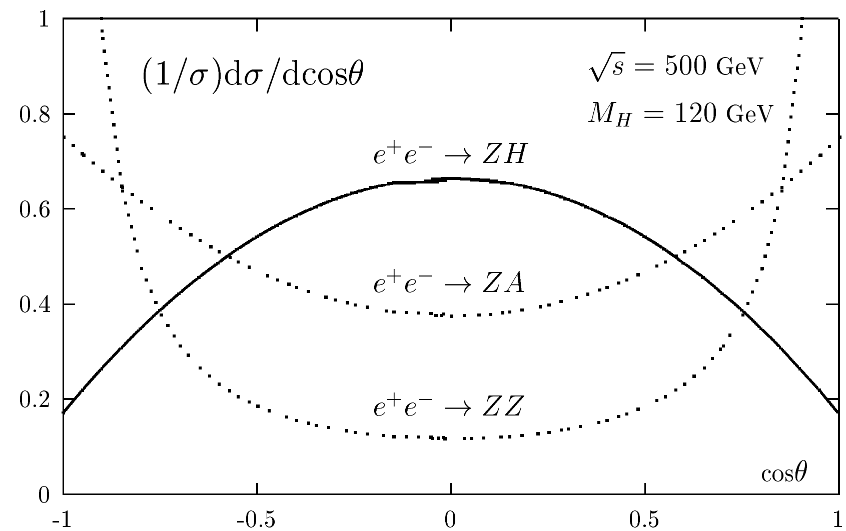
- Measurement best at cross section maximum $\sqrt{s} \approx m_{\rm H} + m_{\rm Z} + 40\,{\rm GeV}$
- However possible in a rather wide energy range



Higgs quantum numbers

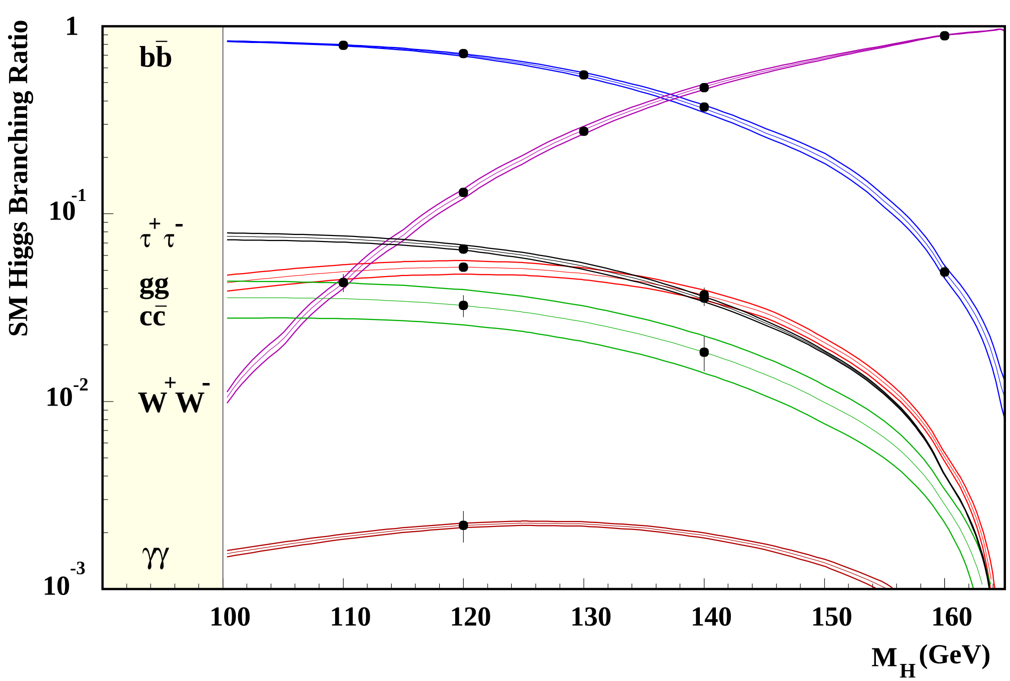
- The Higgs spin can be measured from a threshold scan
(few remaining ambiguities can be figured out from angular correlations of the decay products)
- CP can be measured from spin correlations in $H \to \tau\tau$

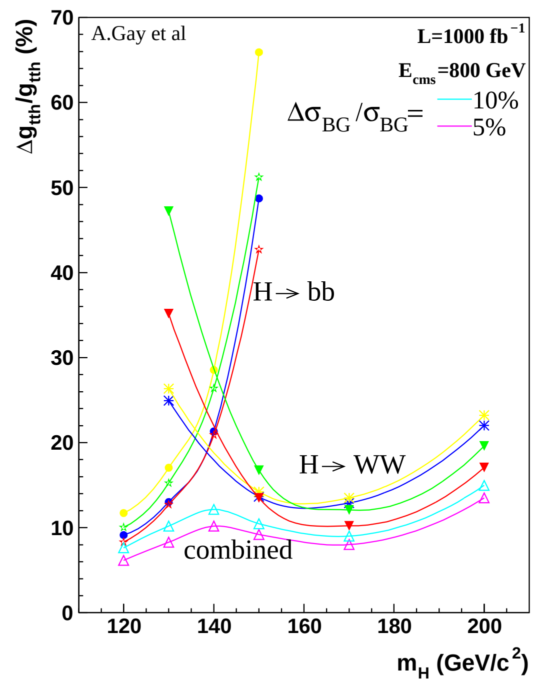




Higgs couplings

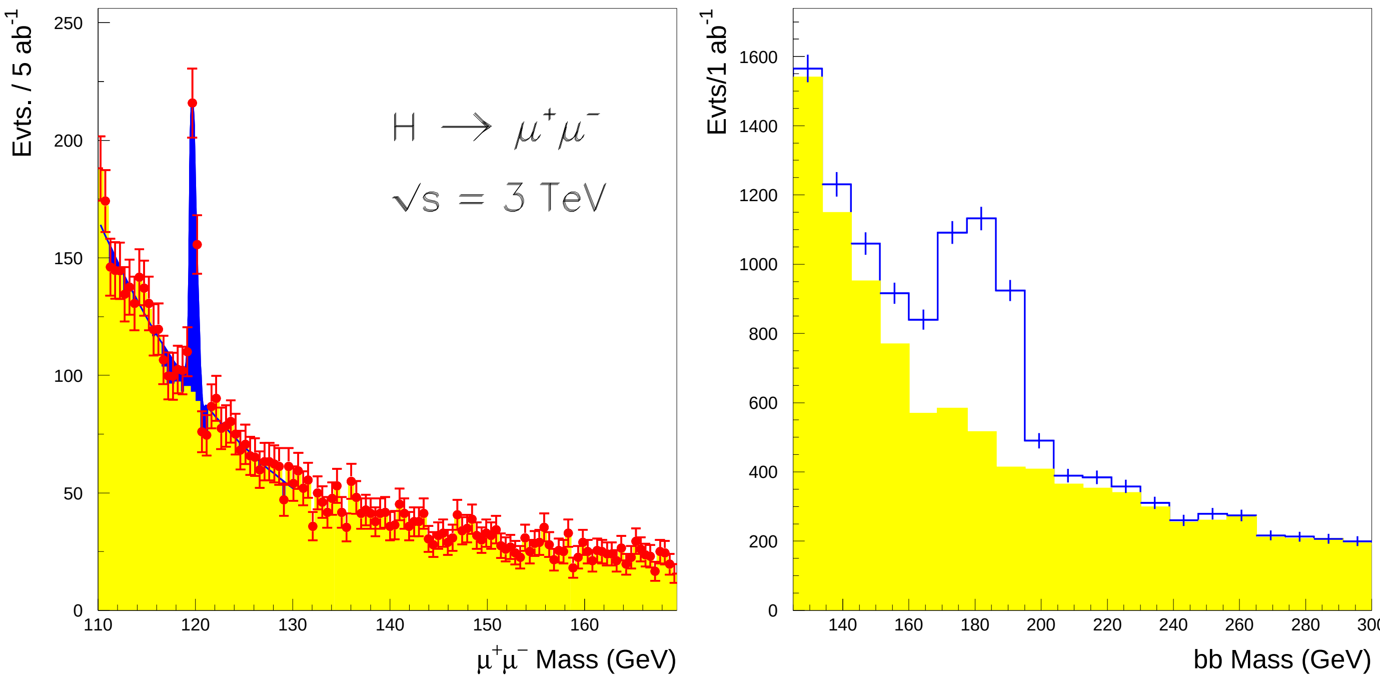
- The HZZ coupling can be directly obtained on the 3% level from the recoil measurement
- If the Higgs is reasonably light ($m_{\mathrm{H}} \lesssim 140\,\mathrm{GeV}$) the branching ratios to many fermions can be measured with good accuracy
- $H\mathrm{b\bar{b}}$ remains visible up to around $m_{\mathrm{H}} \lesssim 200\,\mathrm{GeV}$
- The $\mathrm{t\bar{t}}H$ coupling can be measured from $\mathrm{t\bar{t}}H$ final states





Advantage of high energy (CLIC): fusion cross section rises

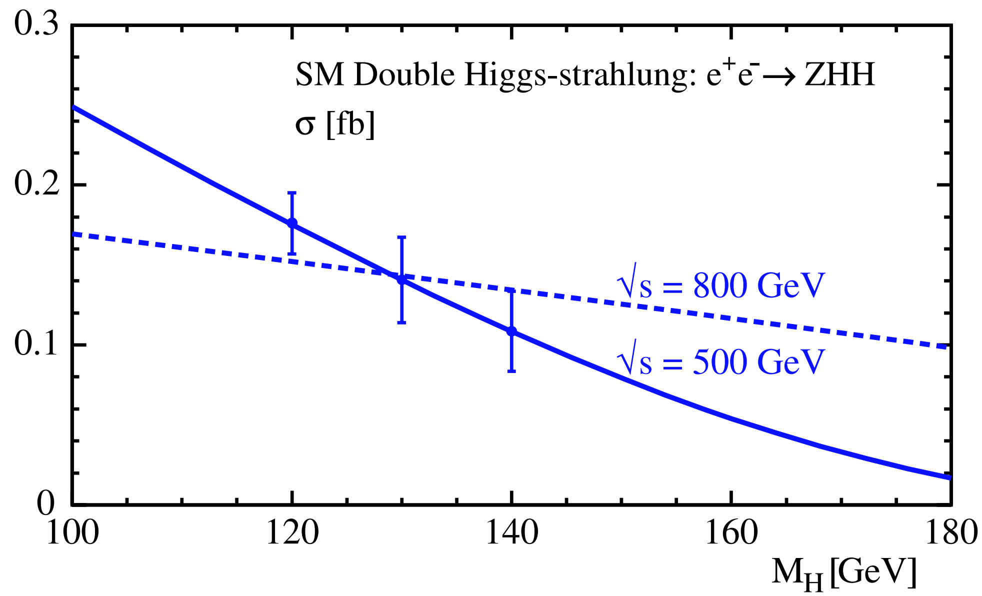
$\Rightarrow$ rare decays can be measured with better precision

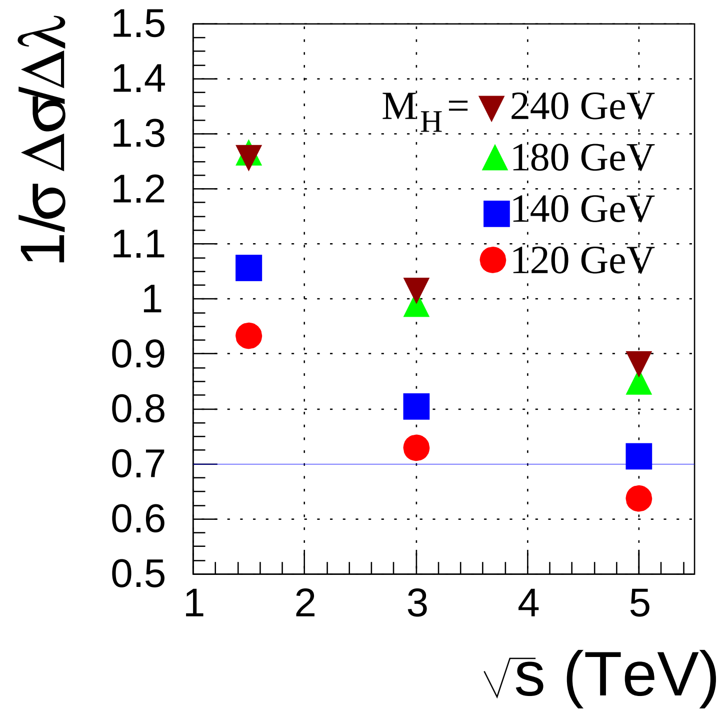


- $H \rightarrow \mu^+\mu^-$: 4.2% precision for $m_{\mathrm{H}} = 120\,\mathrm{GeV}$
- $H \rightarrow \mathrm{b\bar{b}}$: 3.4% precision for $m_{\mathrm{H}} = 220\,\mathrm{GeV}$

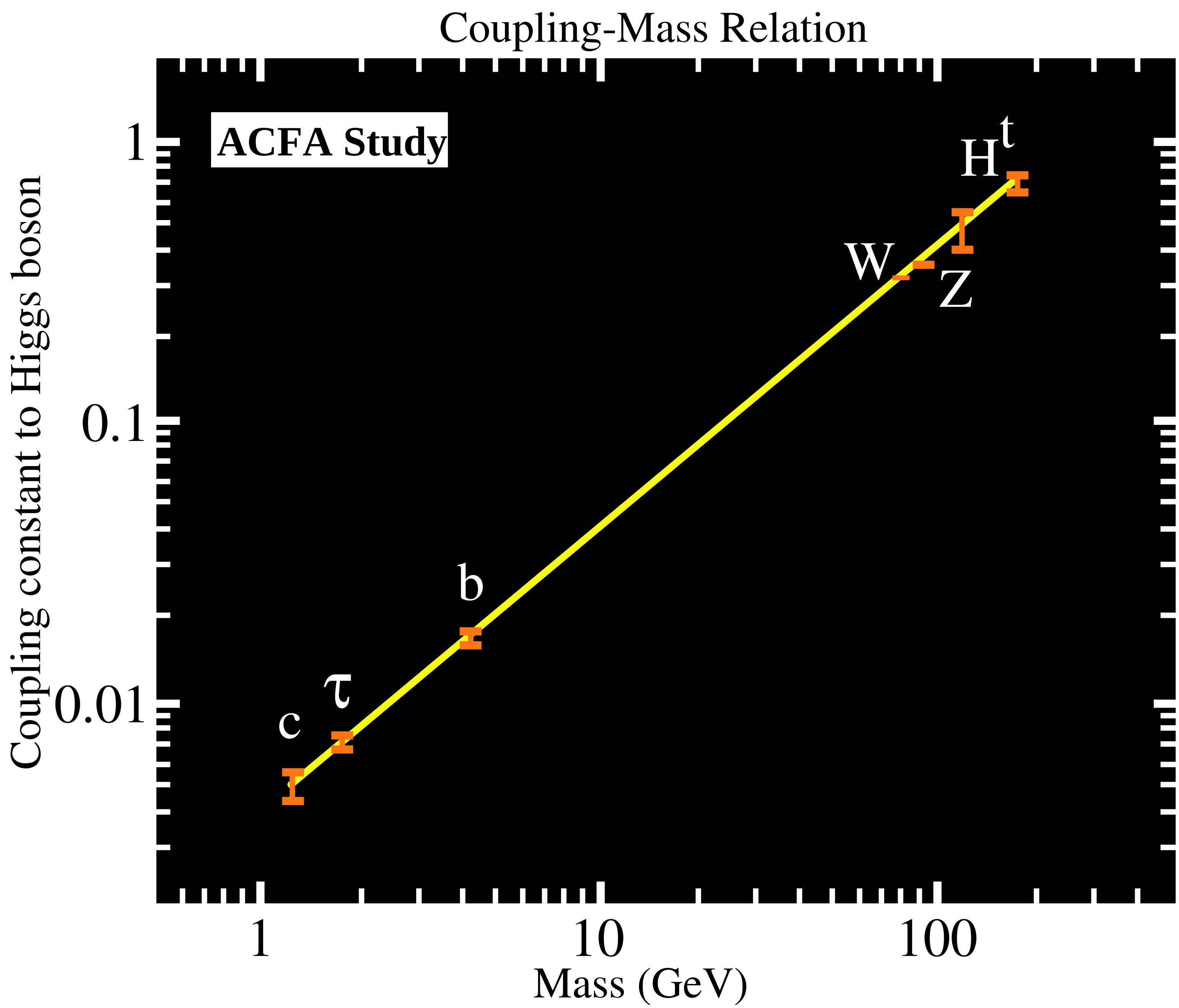
The Higgs self-coupling

- The HHH coupling can be measured from ZHH events at $\sqrt{s} = 500\,\text{GeV}$ and $\nu\nu HH$ events at $\sqrt{s} \sim 1\,\text{TeV}$
- Studies up to now use $H \to \text{b}\bar{\text{b}}$
- Combining both energies gives $\Delta\lambda_{HHH} = 12\%$ for $m_\text{H} = 120\,\text{GeV}$ degrading with higher Higgs masses
- For higher energies the larger cross section gets partly compensated by a lower sensitivity
  ➡ significant gain only for heavier Higgses



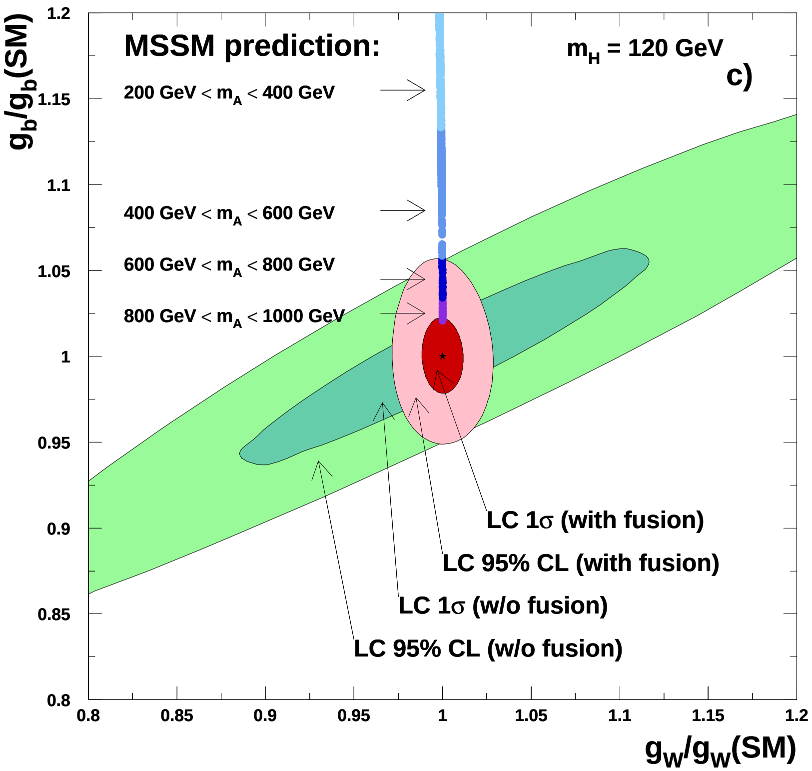


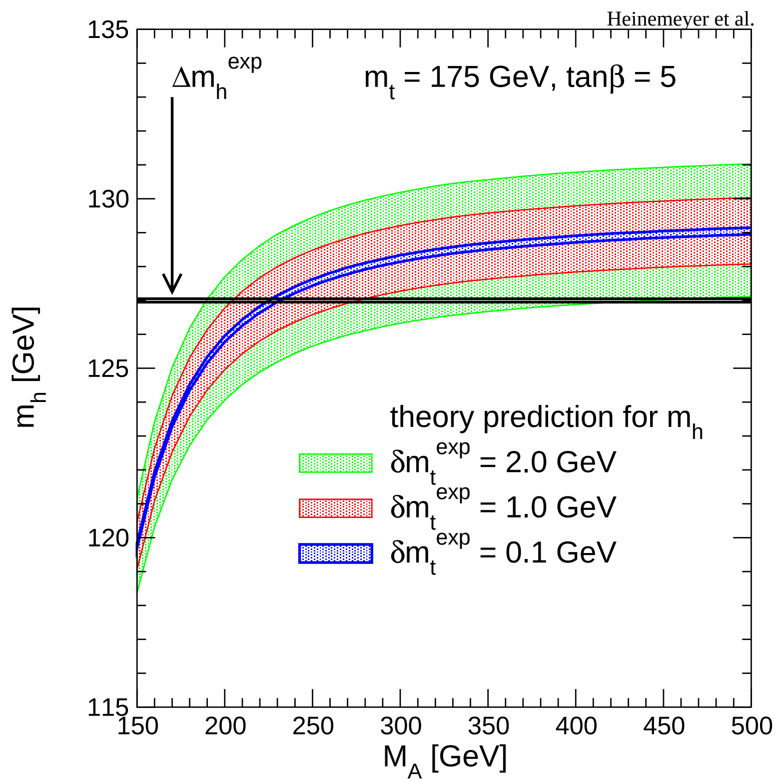
This can show that the Higgs really couples to mass



Applications of precision Higgs measurements

- Many coupling measurements lead way to new physics looking at patterns
- In a model (SUSY) precision couplings allow measurements of model parameters
- Similarly mass measurements allow determination of model parameters

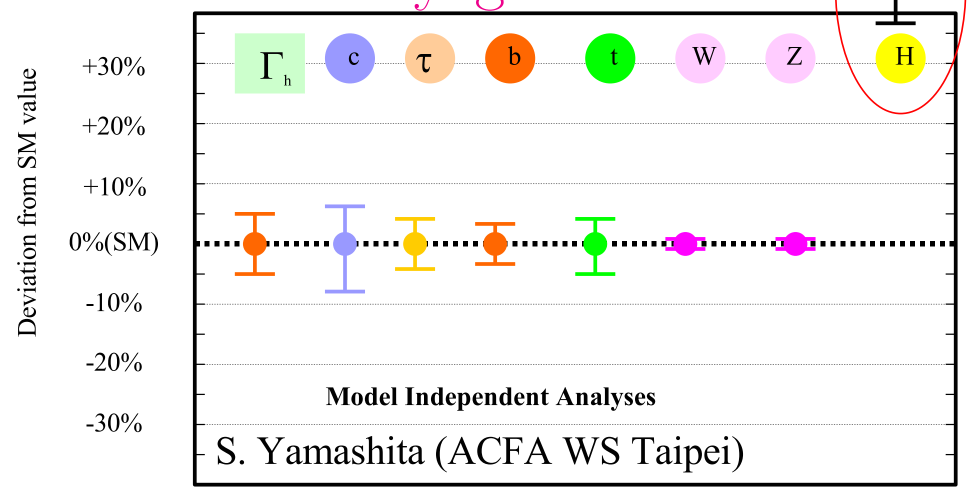




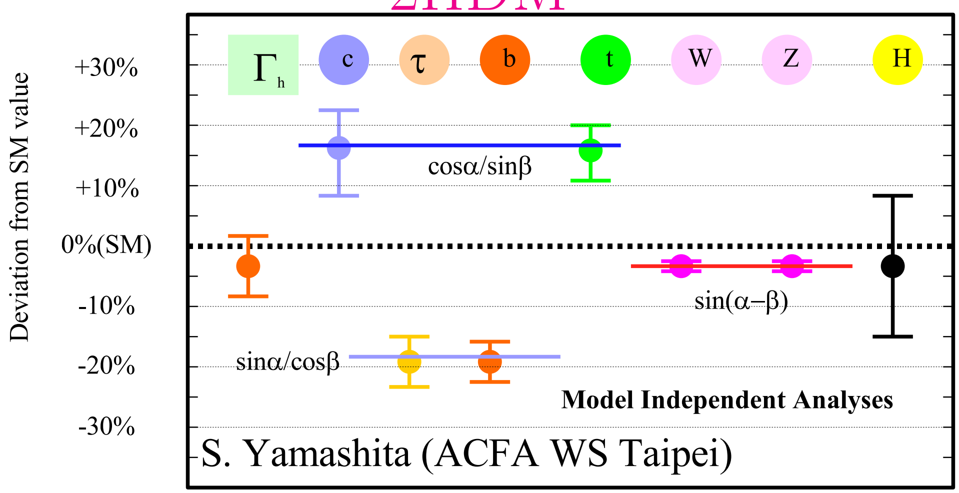
Applications of precision Higgs couplings

The Higgs-coupling measurements allow for a powerful distinction between models

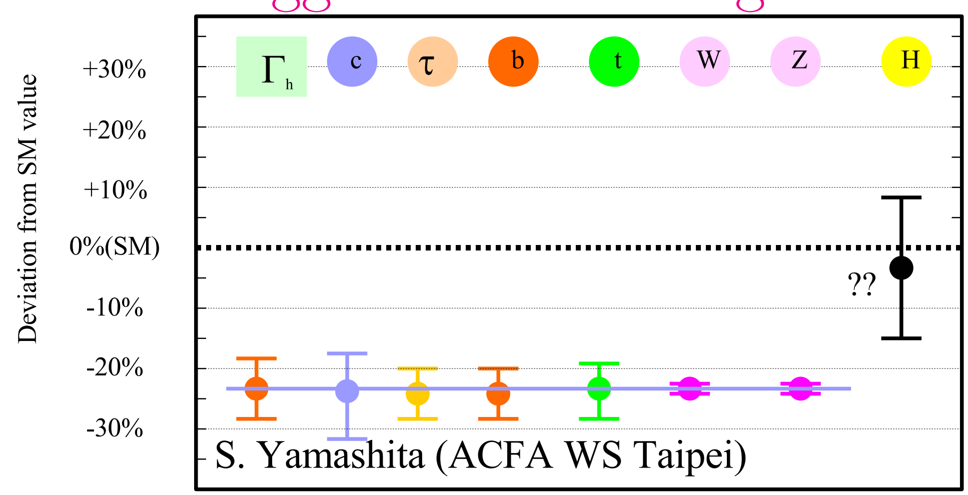
Baryogenesis



2HDM



Higgs-Radion mixing



Problems with the EW theory

The hierarchy problem

- Contributions from loop-corrections to Higgs mass with cutoff Λ

$$m_{\rm H}^2 = (m_{\rm H}^0)^2 + \frac{3\Lambda^2}{8\pi^2 v^2}\left[m_{\rm H}^2 + 2m_{\rm W}^2 + m_{\rm Z}^2 - 4m_{\rm t}^2\right]$$

➡ Higgs mass naturally at cutoff scale ($= m_{Planck}$???)

- Enormous fine-tuning required to keep Higgs at weak scale

Dark matter

- We have many pieces of evidence that there is more matter in the universe than we can see (flatness of the universe, structure of galaxies, rotation curves around galaxies)
- This matter cannot be baryonic (contradiction to big-bang-nucleosynthesis)

➡ We need a new form of matter that is not in the Standard Model

Baryogenesis

- The universe started in a matter-antimatter symmetric phase
- To generate the matter-antimatter asymmetry we need (Sacharov): baryon-number violation, CP-violation, out of equilibrium conditions
- The SM contains baryon-number violation in a non-perturbative way
- It also contains CP-violation in the CKM matrix
- Detailed calculations show that the CP violation is not sufficient to explain the observed asymmetry

Conclusions

- The electroweak Standard Model describes a vast amount of data with very good precision
- The Higgs boson is still missing, but data indicate that its mass is $115 - 160\,\mathrm{GeV}$
- However there are significant problems with this model that require new physics