The LEP experience:
Combining the Higgs boson searches of the four LEP experiments

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The LEP Higgs Working Group

- Created in 1997 (3 years before the end of LEP)
- Membership: from ALEPH, DELPHI, L3, OPAL
- Mandate: statistically combine the LEP Higgs data
  … for the most precise *LEP "legacy"*

Remember: … end of year 2000 … excitement …
ALEPH : "hint" for a possible Higgs with mass of about 115 GeV … Clarification was expected from combining all LEP data

The physics programme

- SM Higgs boson: H^0
- MSSM : h^0, H^0, A^0 … "benchmark models"
- 2HDM: H^+, H^-
- Exotica: $H^0 \rightarrow \gamma\gamma$, $H^0 \rightarrow$ *invisible* ($\chi^0\chi^0$)

Today's discussion restricted to the SM Higgs case

- What data are available ? … in what form ?
- Will the data be available – in a few years – for combining with *Tevatron* and *LHC* data ?

(The 115 GeV mass region is still interesting … Global SM fits to electroweak data "predict" a Higgs boson in that range !)

Answer : a careful "yes"

- The data are available … *but were not created with long-term preservation and re-use in mind*
- Highly specific, model-dependent, form …
  reuse limited to the same models (SM, or similar)
- High-level "objects" … can be combined only with equivalent objects from other experiments …
  calls for "standardization" of inputs
- Ancillary information … for re-use … available
  - *data descriptors*
  - *"insider knowledge" … people still available*

LEP Higgs Working Group "Sociology"

Halfway between "competition" and "cooperation"

- Spirit of … *limited openness*
- No insight into each-other's "kitchen" … *no possibility of mutual cross-checking* ⇒ *some tension*
- Data provided: *just the bare minimum necessary for a precisely defined and highly model-dependent purpose*

The exchange did not happen with "preservation for later re-use" in mind ⇒ *limited scope of potential re-utilization*

Individual searches

- *ALEPH, DELPHI, L3, OPAL* … different technologies …
  … but similar performances ⇒ Contributing with roughly equal "weight"

- *Signal processes* … search "channels" … *b-tag !*
  $e^+e^- \rightarrow Z^0\ H^0 \rightarrow bb, \tau^+\tau^-$
  ↳ $qq, \nu\nu, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

- *Kinematic range* … $M_H^{max} = E_{cm} - M_Z = 209-91 = 118$ GeV
  … but cross-section rapidly decreasing with increasing m_H

- *Background processes* … well-known SM processes
  … allowing nearly-perfect modelling

Selection procedures

- *Pre-selection* … against machine-related and most abundant physics backgrounds ($\gamma\gamma$-proc., $qq\gamma$)

- *Main selection* … against other SM processes (WW, ZZ, …)
  - different for each experiment and for each search channel
  - simple cuts, likelihoods, neural networks …)

  ⇒ *Discriminating variable … G*

- *Detailed Monte Carlo simulation* … of signal and background processes … as "seen" by the detectors

Individual selections adjusted and repeated routinely at each new collider energy ⇒ *individual publications*

Input provided for the statistical combination

At each new machine energy and for each search channel …

- The number of selected "candidate events" … $\mathcal{N}_{obs}$
- For each candidate event …
  - The reconstructed Higgs boson mass … $m^{\mathcal{H}}_{rec}$
  - The value of the optimal *discriminating variable* … $\mathcal{G}$

  ⇒ the *observed* event configuration in the $(m^{\mathcal{H}}_{rec}, \mathcal{G})$ plane

- Detailed Monte Carlo simulation … in the same plane *(binned)*
  - the *expected* background configuration … "b_i"
  - the *expected* signal configuration …

    … *for a list of hypothetical Higgs masses* … "$s_i(m_{\mathcal{H}})$"

The lack of standardization

The inputs were not provided in a standard, ready-to-use format … in particular, different formats *(binned histograms, fitted functions …)* were used by the four experiments to provide the expected (Monte Carlo) populations, i.e. the b_i and $s_i(m_{\mathcal{H}})$ distributions, in the $(m_{\mathcal{H}}^{rec}, \mathcal{G})$ plane

⇒ … a great deal of – avoidable – analysis power and computional power for the *pre-treatment* of the inputs (inter– and extrapolations, smoothing …)

Could / should have been done better !

Hypothesis testing … "frequentist" approach

Comparison of the *observed* event configuration in the

$(m^{\mathcal{H}}_{rec}, \mathcal{G})$ *plane* to the *expected* configurations for …

- the SM *background* hypothesis … *"b"*
- the SM *signal+backgd* hypothesis … *"s+b"…* (various m_H)

"Test statistic" … $Q = \mathcal{L}_{s+b} / \mathcal{L}_b$

$$-2\ ln\ Q(m_H) = 2\ s_{tot} - 2\ \sum N_i\ ln\,[1 + s_i(m_H)/b_i\,]$$

- Highest discrimination between the "b" and "s+b"
- Approximating … $\Delta\chi^2 = \chi^2_b - \chi^2_{s+b}$
- Sum over individual event "weights" …

allowing to study the "weight" of individual events contributing to a potential signal

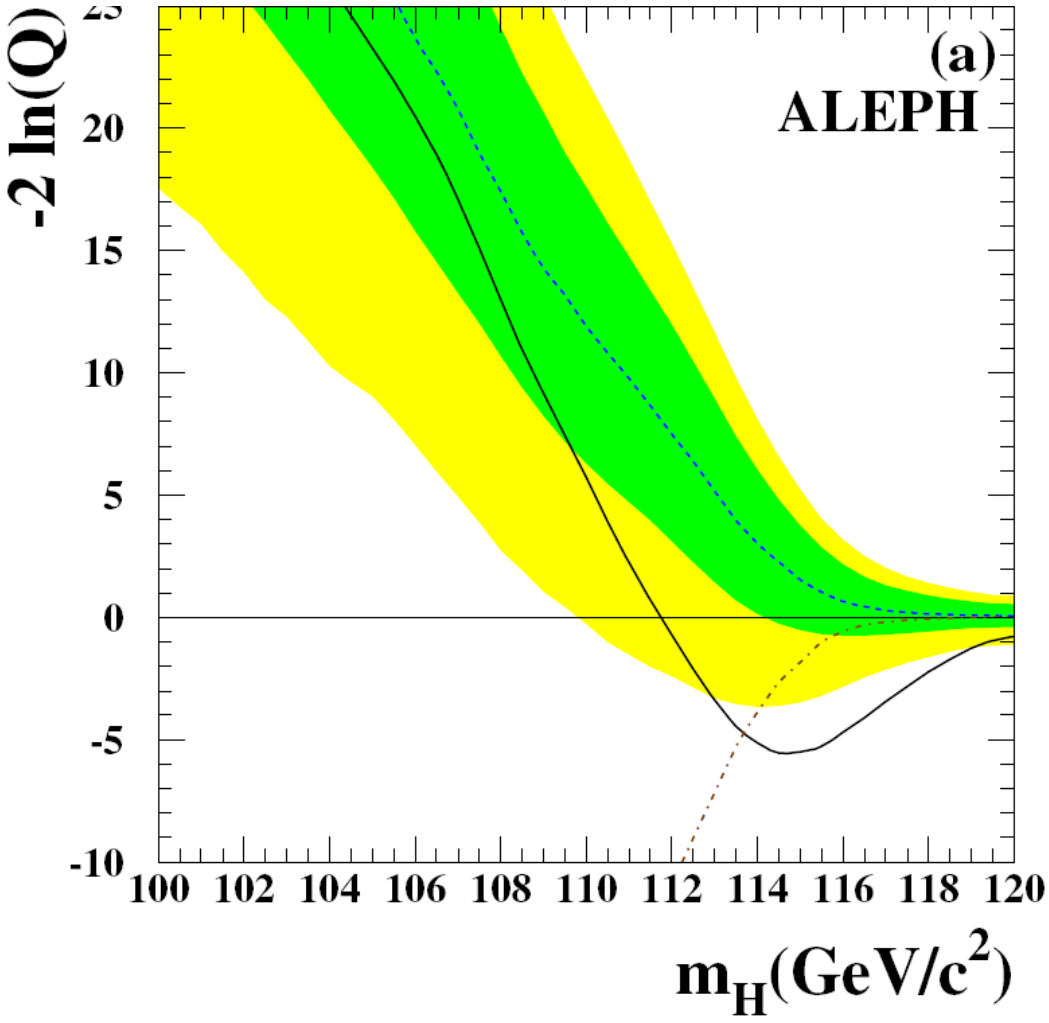
Test statistic … vrs hypothetical Higgs mass

..... "b" hypothesis, with 1σ and 2σ bands

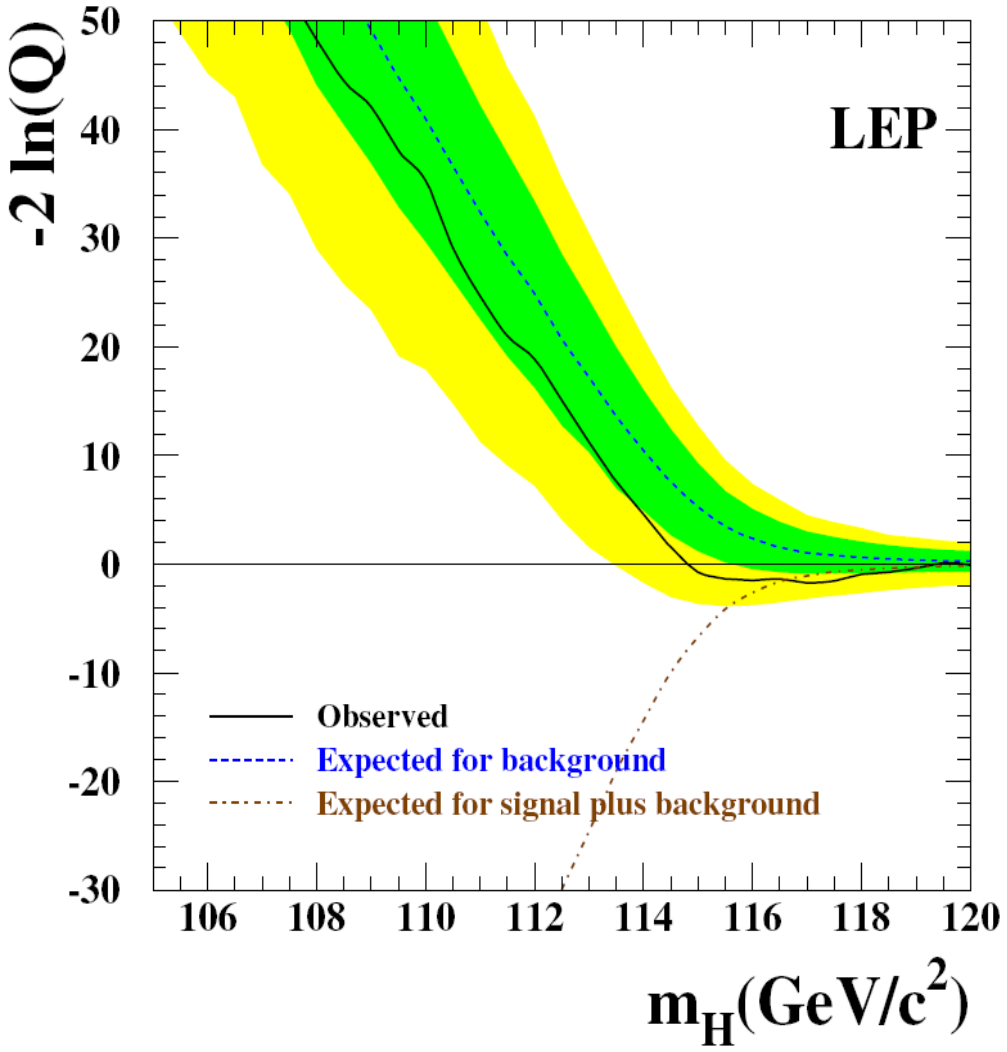
–·–·– "s+b" hypothesis

—— *Observation (negative values: "s+b" hypothesis is preferred)*

ALEPH claim …
3σ "evidence" for a Higgs signal with $m_H \simeq 115$ *GeV*



LEP-combined test statistic … "legacy"



- Exclusion of a Higgs boson with mass less than *114.4 GeV* (at 95% c.l.)
- Residual "hint" … in the 115 – 117 GeV mass region with a significance reduced to *1.7σ*

Phys. Lett. B 565 (2003) 61–75

LEP-data … at two levels of abstraction

Inputs provided … "for" the LEP combination

- the *observed* event distribution and …
- the *expected* density distributions b_i and $s_i(m_{\mathcal{H}})$
  … in the $(m_{\mathcal{H}}^{rec}, G)$ plane

Results generated … "by" the LEP combination

- $-2\ln Q$ plots … *for the signal- and backgd hypotheses*
- the corresponding *confidence levels* : CL_s *and* CL_b

… *Provided in ready-to-use numerical form*

Discussion … Conclusion

- Data provided by the four LEP experiments … just the bare minimum … for a rather short-sighted, limited, model-dependent usage …

  Result: potential of re-use … strongly restrained (limited to the same theoretical framework)

- Lack of "standardization" … at the input level

  Result: sophisticated software … (interpolation, smoothing) … "insider knowledge" … person- and computer power … required

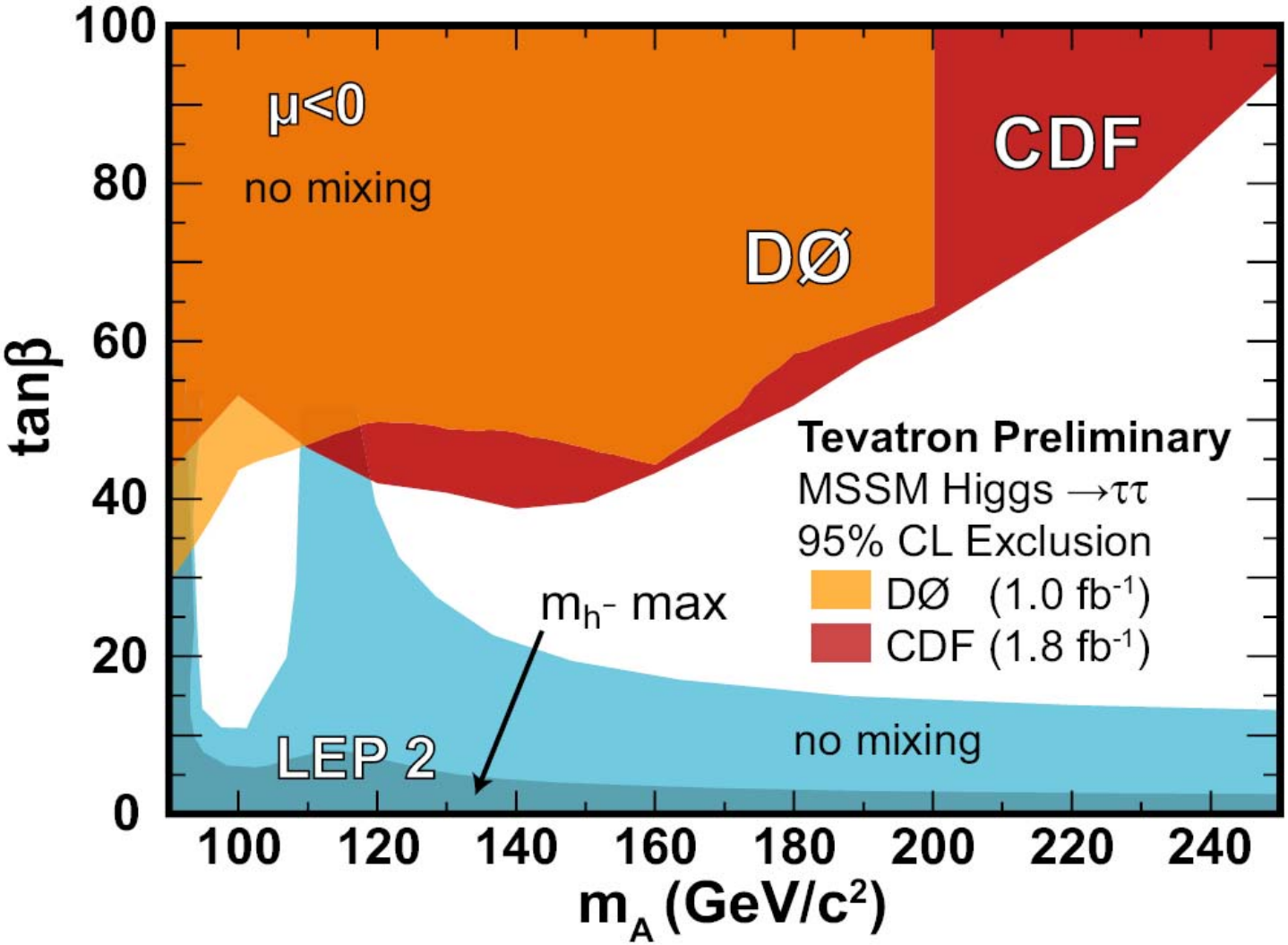
- **But**: The data is there, packaged, stored and documented … together with the necessary software … (people involved still active) …

  … relatively easy to re-use with future data (Tevatron, LHC)

LEP data re-used … Combined with Tevatron data

-> mass exclusion plots

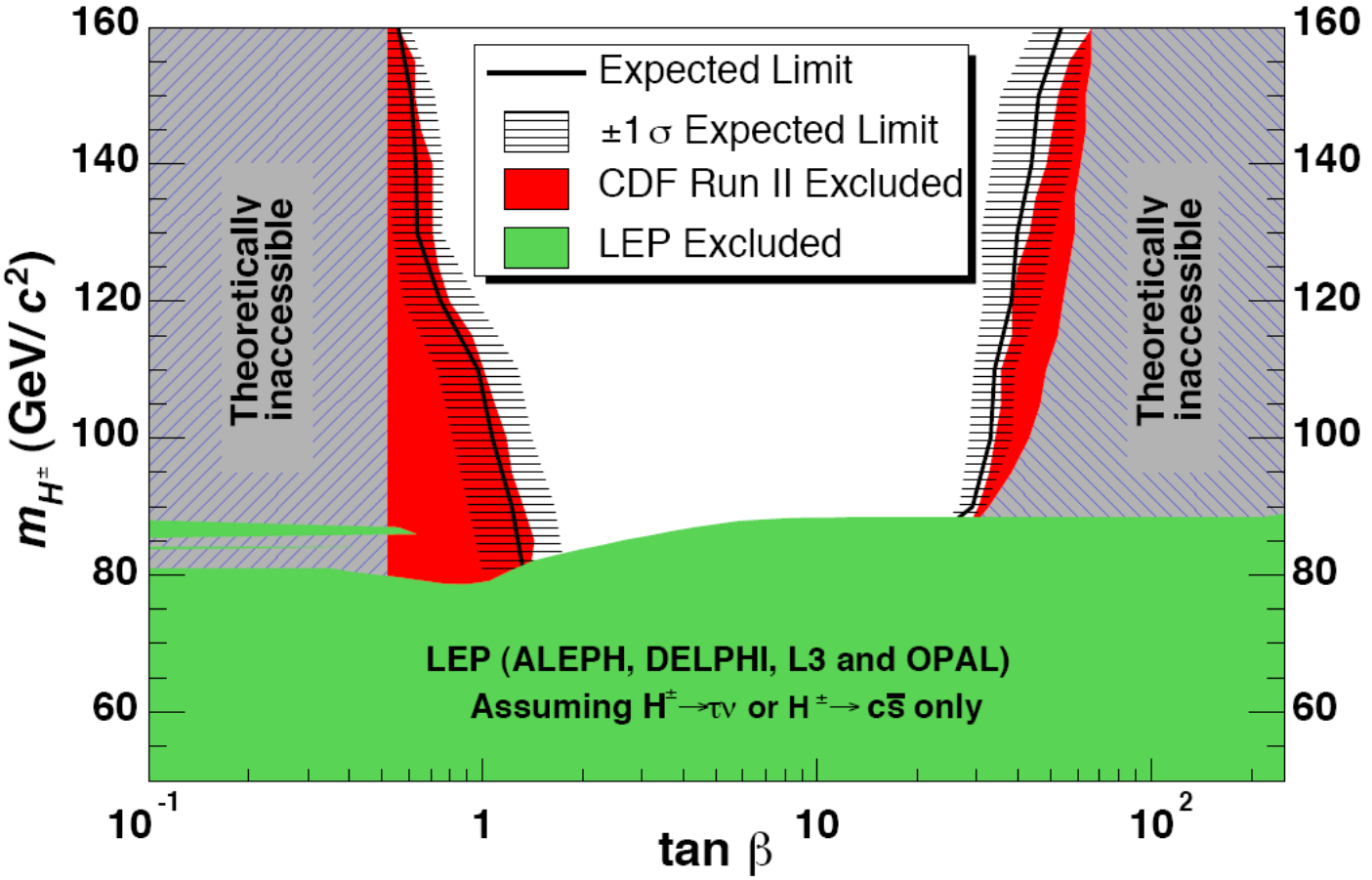
Example: MSSM *(Source: PDG 2008)*



… *other example:* *LEP – Tevatron Charged Higgs searches*

… *after parameter transformations*

(Source: PDG 2008)



More sophisticated re-use of combined LEP data

"Gfitter – Revisiting the Global Electroweak Fit of the Standard Model and Beyond"

H. Flaecher et al., arXiv:0811.0009, CERN-OPEN-2008-024, DESY-08-160, Nov. 2008

Uses the stored *-2 ln Q* curves and derived confidence levels form the LEP combination *(available in numerical form)*

… together with similar high-level objects from precision electroweak measurements of *LEP, SLD, Tevatron* …

to further constrain the parameters of the SM (and beyond)

Lessons for the future …

Preservation effort should be better prepared and planned *right from the beginning* of the experiment, in order to achieve … a broader scope

- *More model-independence …*

  … for more versatility in possible re-use

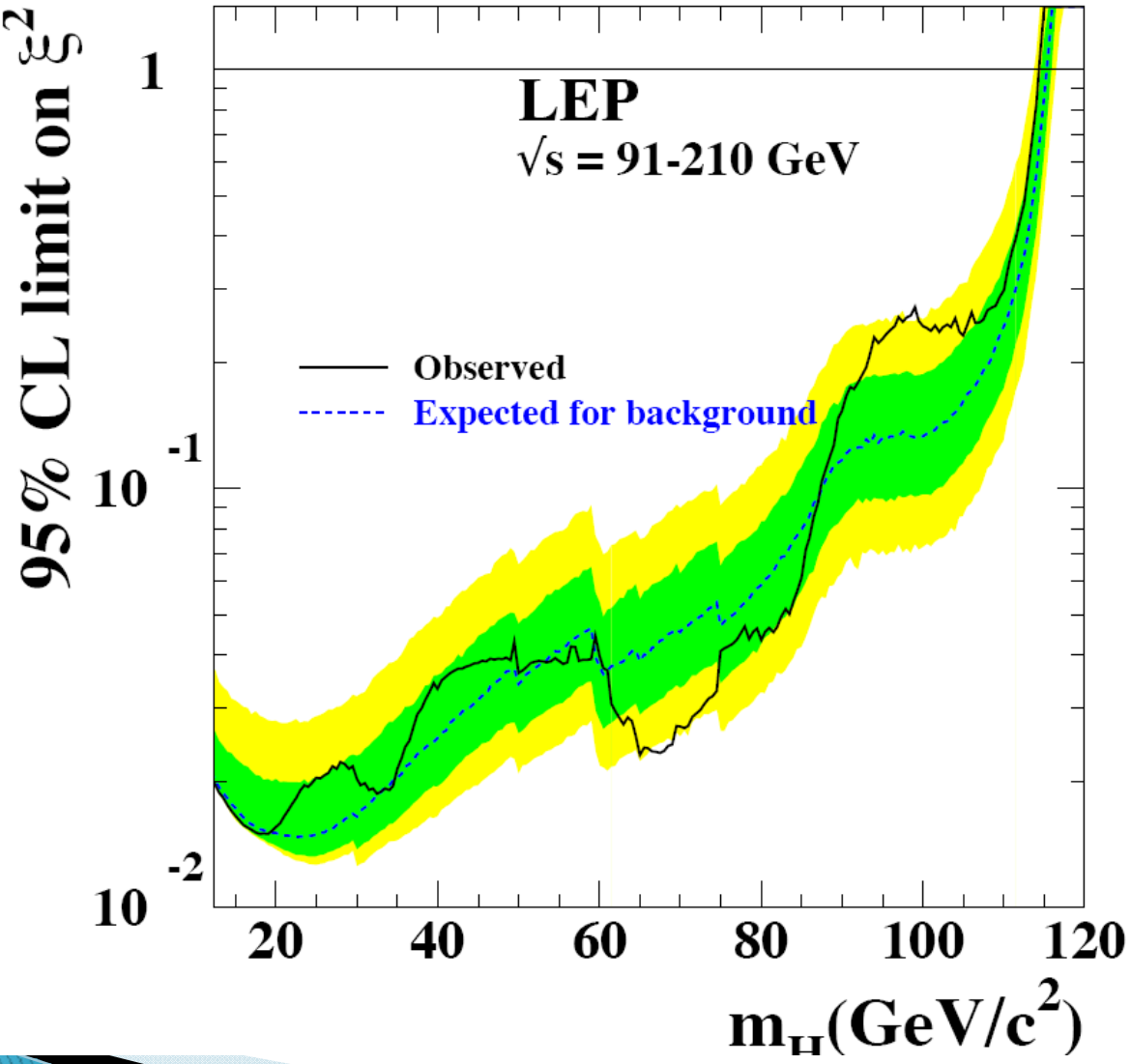
- *More standardization …*

  … for simplicity of access and … to avoid strong dependence on "insider" knowledge

Preservation should be regarded as an integral part of the data taking effort

Reserve slides

Model-independent bound on HZZ coupling $(g/g_{SM})^2$

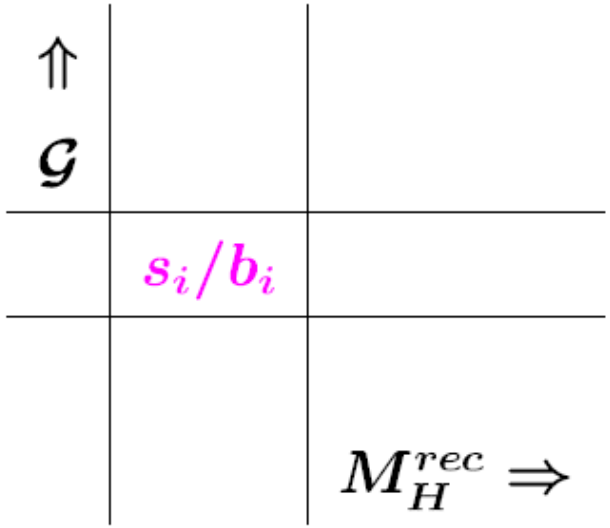


(1) INPUTS ... for each "channel" ... binned in two discriminating variables (both contribute to the search sensitivity)

- Reconstructed Higgs mass M_H^{rec}
- Global variable $\mathcal{G}$ ... containing b-tag, kinematics, jet-properties ...

In each bin i ...

- Bkgd. (MC) b_i
- Signal (MC) $s_i(m_H)$ for "test-mass" m_H
- Nbr of candidates N_i



MC estimates of $s_i(m_H)$ and b_i take into account the exp'tal details (e.g. E_{cm}, lumi, signal eff., mass-resol., bkgds ...)

For "test-mass" m_H ...

(2) LIKELIHOOD TEST ... "sig + bkgd" $\Longleftrightarrow$ "bkgd"

$$-2\ln Q(m_H) = 2s_{tot} - 2\sum N_i \ln[1 + s_i(m_H)/b_i]$$

$Q(m_H) = \mathcal{L}(s+b)/\mathcal{L}(b)$ "test-statistic"

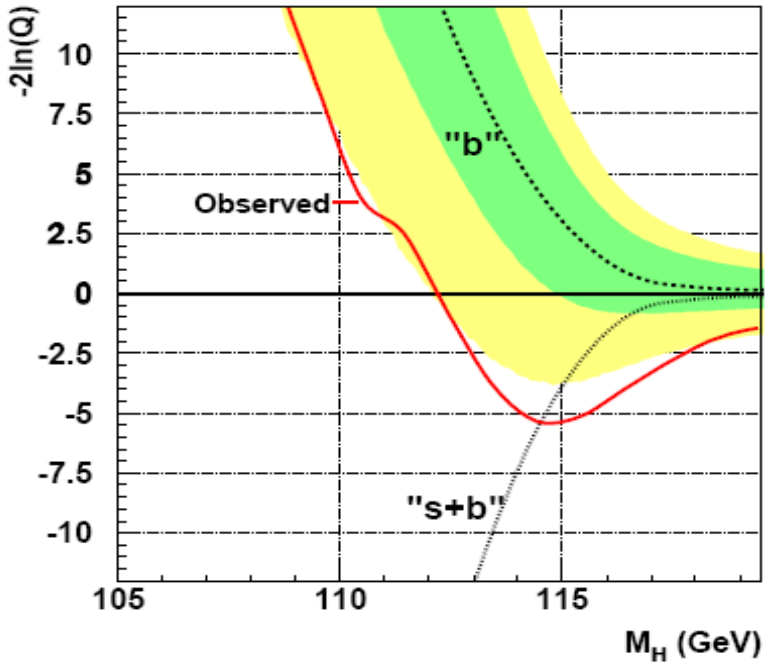
to rank the observed event configuration

between "$s+b$" and "b" hypotheses

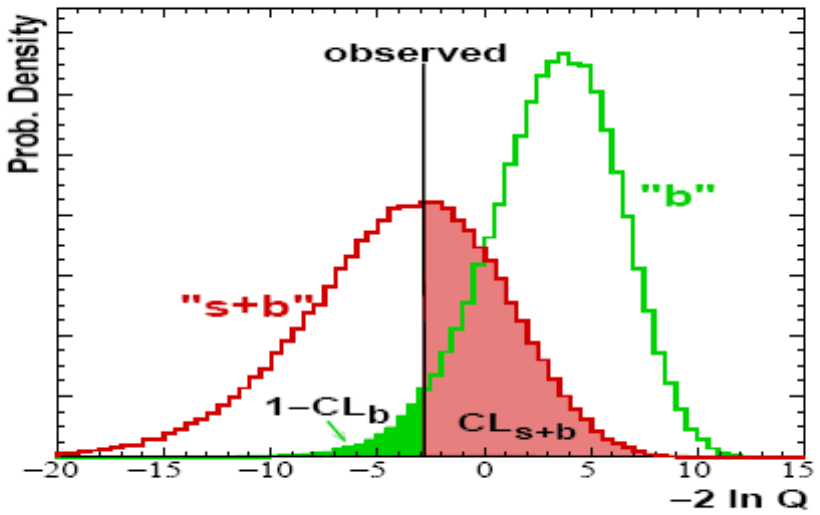
For arbitrary test-mass m_H ... and replacing the data set by

ficticious MC sets of "$s+b$" and "b" configurations

$\Rightarrow$ expected curves ... and statistical spread



(3) CONFIDENCE LEVELS ...



- $1 - CL_b$ ... a measure of incompatibility with "b"

  Given an ensemble of "b" experiments ...

  probability to obtain an event configuration less bkgd-like

  than the observed event configuration

$1 - CL_b$	0.32	0.046	2.7×10^{-3}	6.3×10^{-5}	5.7×10^{-7}
	$1\,\sigma$	$2\,\sigma$	$3\,\sigma$	$4\,\sigma$	$5\,\sigma$

- CL_{s+b} ... a measure of incompatibility with "$s + b$"

  $CL_s = CL_{s+b}/CL_b$ $\Rightarrow$ lower bound on Higgs mass

Confidence ... 1-CL_b