Karlsruhe Institute of Technology

Searches for the Higgs Boson Before the Advent of the LHC

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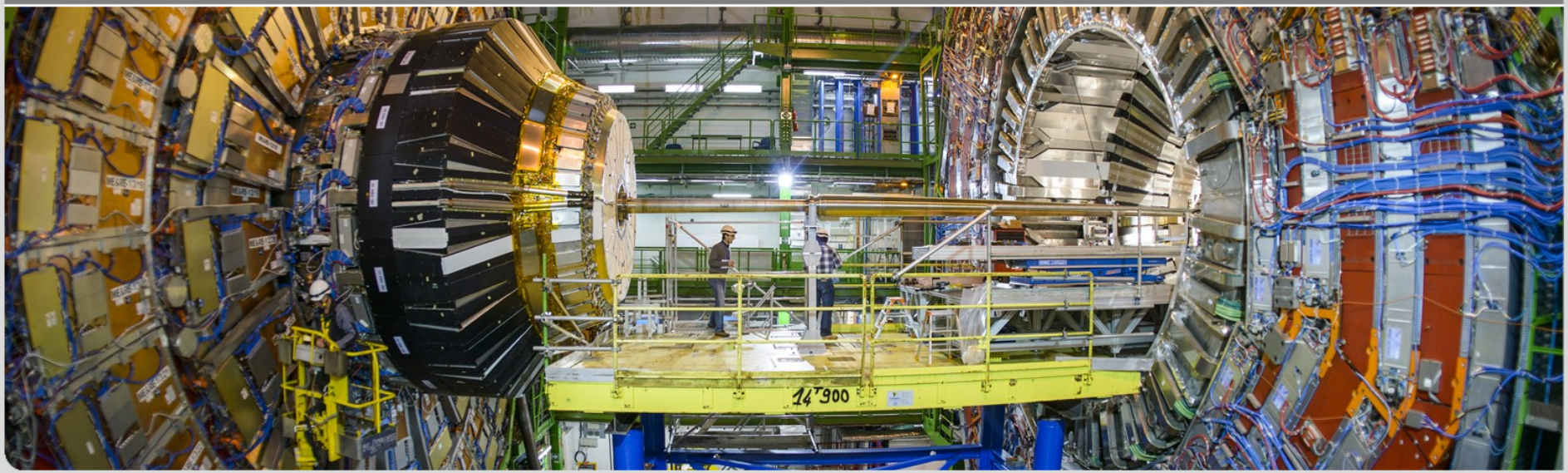
17. June 2016

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



Schedule for today

- What was the main production mechanism of Higgs bosons at LEP?
- What was the highest center of mass reached at LEP and to what reach on m_H does this correspond to?

3 Direct Higgs boson searches @ the Tevatron

2 Direct Higgs boson searches @ LEP

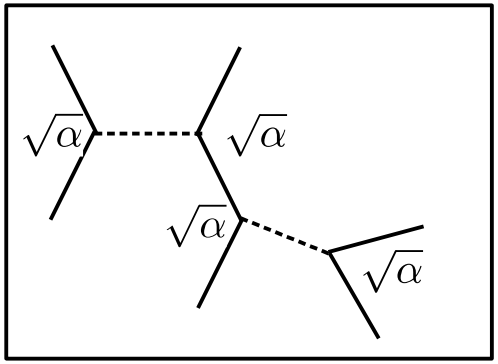
1 Indirect constraints on m_H from high precision EWK observables

Order α^2 diagrams (QED)

- We have only discussed contributions to $\mathcal{S}_{fi}$, which are of order α^1 in QED. (e.g. LO $ee \to ee$ scattering) .

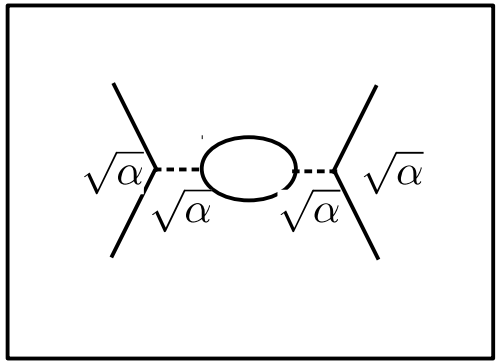
- Diagrams which contribute to order α^2 would look like this:

Additional legs:



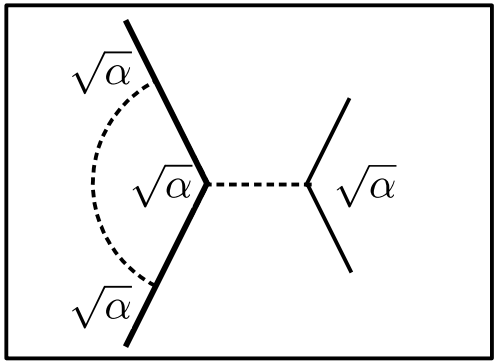
- LO term for a $2 \to 4$ process.
- NLO contrib. for the $2 \to 2$ process.
- Opens phasespace.

Loops:



(in propagators or legs)

- Modifies (effective) masses of particles ("running masses").



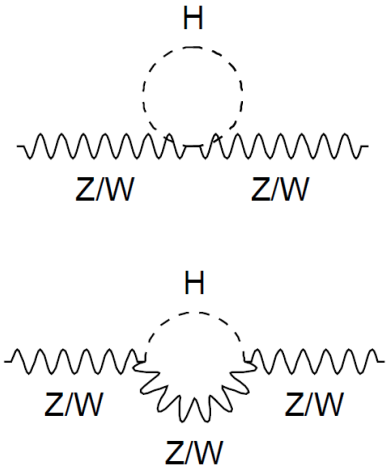
(in vertices)

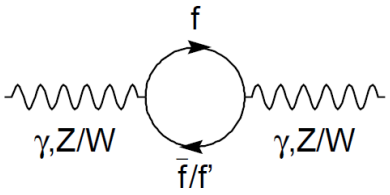
- Modifies (effective) couplings of particles ("running couplings").

Higher orders and precision observables

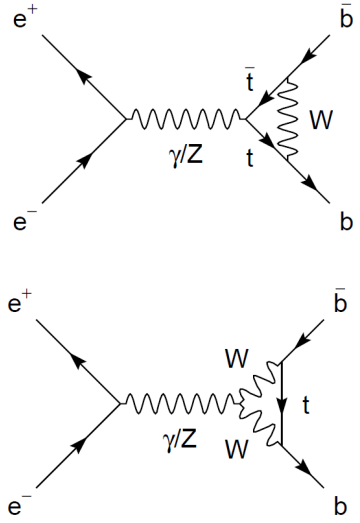
- Particles, which cannot be directly observed at lower energy scales, still have influence on observables, due to higher order corrections in loops.

The Higgs/*top* in propagator loops:





The *top* in vertex loops:



- Introduce direct dependencies of (measurable) effective vector boson masses and couplings on m_H & m_t.

Higher order corrections to m_W

- Higher order corrections to m_W :

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-4\frac{\alpha\pi}{\sqrt{2}G_F m_Z^2}\cdot\frac{1}{1-\Delta r}}\right) \qquad \Delta r = \Delta\alpha + \Delta r_W$$

$$\Delta\alpha = \Delta\alpha_{\text{lep}} + \Delta\alpha_{\text{top}} + \Delta\alpha^{(5)}_{\text{had}}$$

$$\Delta r_W(m_t, m_H) \simeq \frac{\alpha}{\pi \sin^2\theta_W}\left(-\frac{3}{16}\frac{\cos^2\theta_W}{\sin^2\theta_W}\frac{m_t^2}{m_W^2} + \frac{11}{24}\log\left(m_H/m_Z\right)\right)$$

(1-loop precision)

$\propto m_t^2$

$\propto \log(m_H)$

- Effects set in at $\mathcal{O}(\alpha^2) \approx \mathcal{O}(10^{-4})$ → high precision needed on observables and theoretical prediction!

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(1-loop precision)

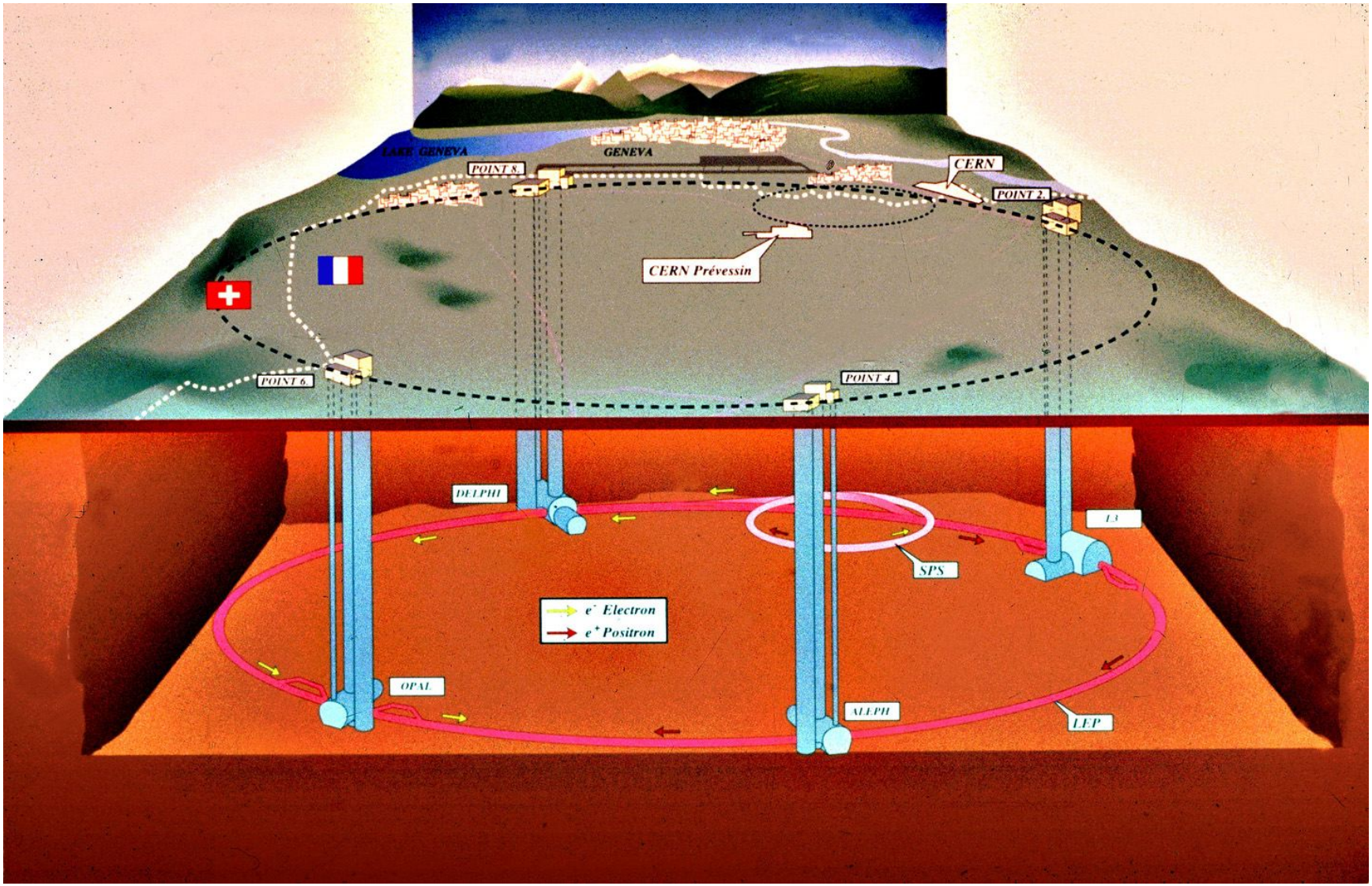
$\propto m_t^2$

$\propto \log(m_H)$

Largest theoretical uncertainty.

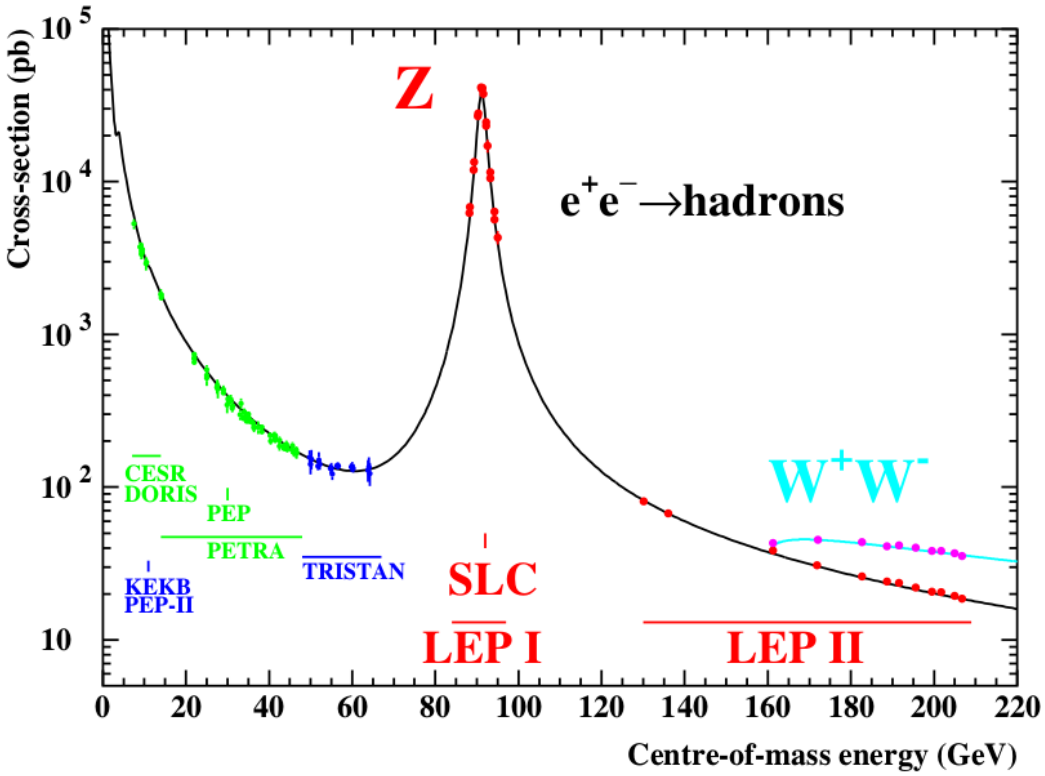
- Effects set in at $\mathcal{O}(\alpha^2) \approx \mathcal{O}(10^{-4})$ → high precision needed on observables and theoretical prediction!

High precision measurements @ LEP & SLAC



High precision observables @ LEP

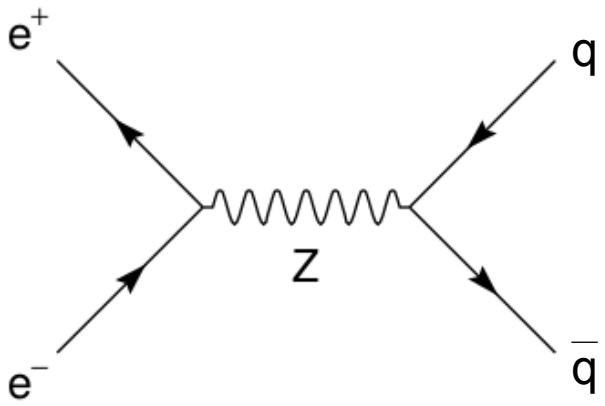
- High precision measurements made at $\sqrt{s} = m_Z$ during LEP-I run period:

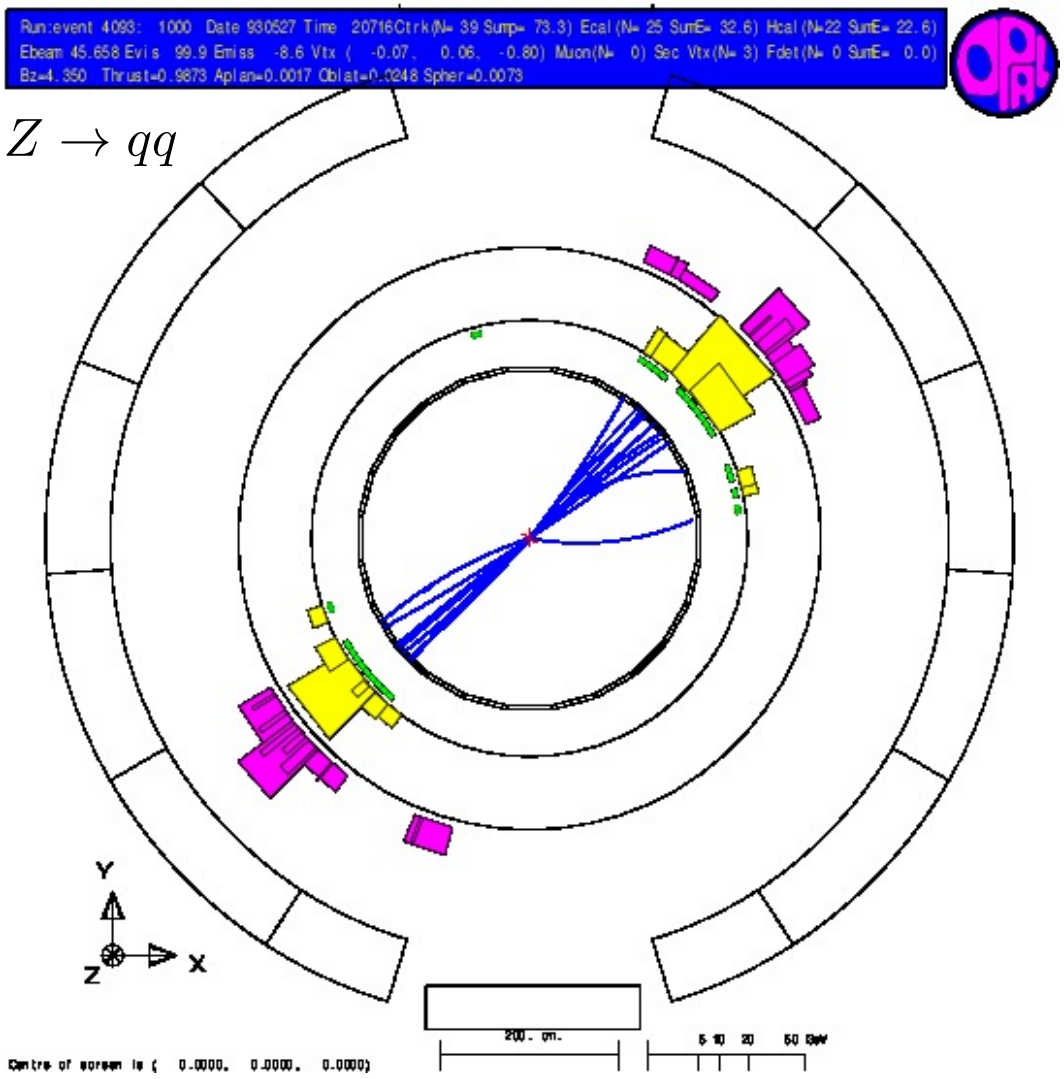


Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8
		202.1

- $15 \cdot 10^6$ $Z \to qq$ events
- $1.7 \cdot 10^6$ $Z \to \ell\ell$ events

Typical $Z \to qq$ event @ LEP



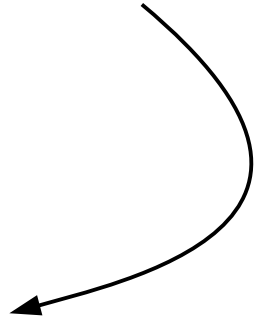


Z-pole electroweak precision observables

Pseudo-Observable	Measured Value		
$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$	0.02758	$\pm$	0.00034
m_Z [GeV]	91.1875	$\pm$	0.0021
Γ_Z [GeV]	2.4952	$\pm$	0.0023
σ^0_{had} [nb]	41.540	$\pm$	0.037
R^0_l	20.767	$\pm$	0.025
R^0_b	0.21629	$\pm$	0.00066
R^0_c	0.1721	$\pm$	0.0030
$A^{0,l}_{FB}$	0.0171	$\pm$	0.0010
$A^{0,b}_{FB}$	0.0992	$\pm$	0.0016
$A^{0,c}_{FB}$	0.0707	$\pm$	0.0035
$\sin^2\theta^{\text{lep}}_{\text{eff}}$	0.2324	$\pm$	0.0012
$\mathcal{A}_l(\mathcal{P}_\tau)$	0.1465	$\pm$	0.0033
$\mathcal{A}_b$	0.923	$\pm$	0.020
$\mathcal{A}_c$	0.670	$\pm$	0.027
$\mathcal{A}_l(\text{SLD})$	0.1513	$\pm$	0.0021

(as of hep-ex/0509008)

- 14(+1) observables.
- Precision between $\mathcal{O}(10^{-5})$ for m_Z & $\mathcal{O}(10^{-2})$ for $\mathcal{A}_l(\text{SLD})$ (including theoretical uncertainties).
- Exploit dependencies $\propto m_t^2$ and $\propto \log(m_H)$ of higher orders via relations in m_W and $\sin\theta_{\text{eff}}$.



NB: Using similar relations with the same dependencies as shown on slide 5f for m_W.

$\Delta\alpha^5_{\mathrm{had}}(m_Z)$ as additional "observable"

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(as of hep-ex/0509008)

- $\Delta\alpha^5_{\mathrm{had}}(m_Z)$ as obtained from independent measurements at lower energies.

Z-pole observables

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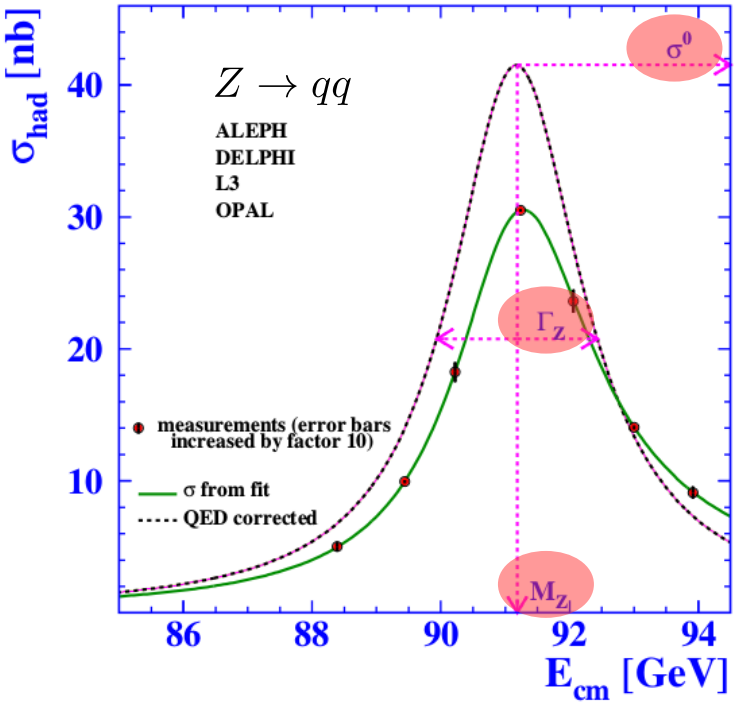

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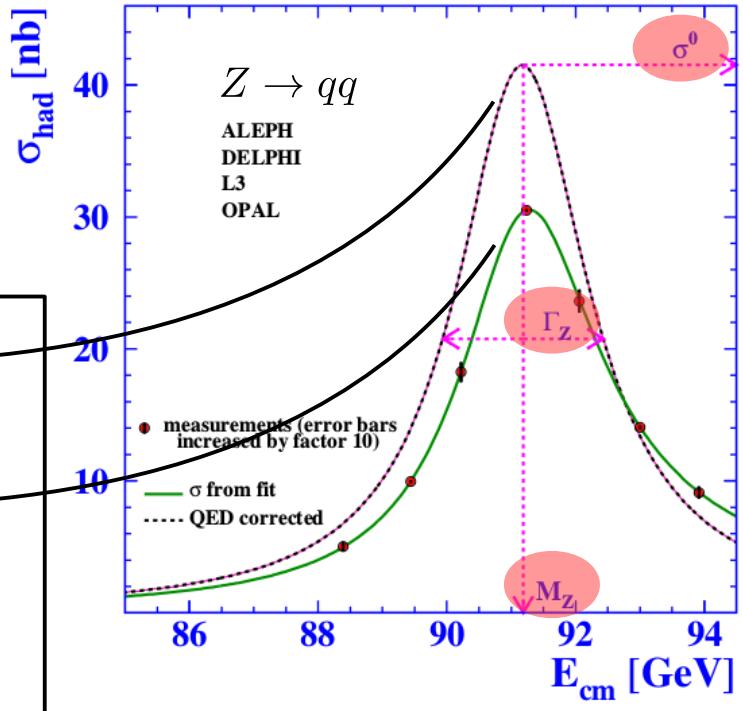
A_l			0.0033
A_b			
A_c	0.670	$\pm$	0.027
$\alpha_s(m_Z^2)$	0.1185	$\pm$	0.0021

(as of hep-ex/0509008)

After correction for HO effects.

Actual measurement.



- ISR up to $\mathcal{O}(\alpha^3)$.
- FSR up to $\mathcal{O}(\alpha_s^3)$ and $\mathcal{O}(\alpha \cdot \alpha_s)$.
- ISR FSR interference effects up to $\mathcal{O}(\alpha)$.
- Since corrections are sizable these variables are referred to as “pseudo-observables”.

Partial decay widths

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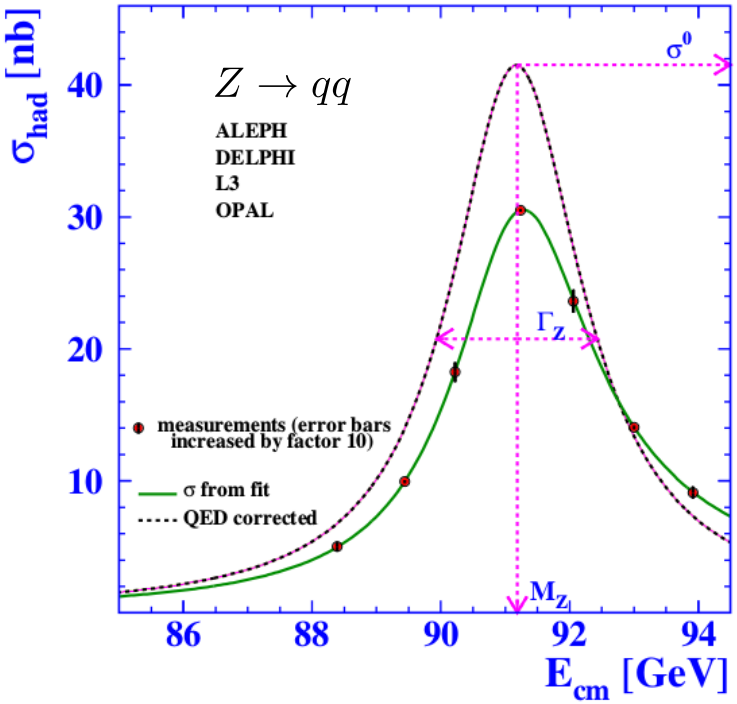

Ratios of partial decay widths:

$$R^0_\ell = \frac{\Gamma^0_{\rm had}}{\Gamma_{\ell\ell}} \qquad R^0_c = \frac{\Gamma_{cc}}{\Gamma^0_{\rm had}} \qquad R^0_b = \frac{\Gamma_{bb}}{\Gamma^0_{\rm had}}$$

$$\Gamma^0_{\rm had} = \frac{\sigma^0_{\rm had} m_Z^2}{12\pi} \cdot \frac{\Gamma_Z^2}{\Gamma_{ee}}$$

Asymmetries (→ sensitive to $\sin\theta_{\mathrm{eff}}$)

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(as of hep-ex/0509008)

- Z boson has different coupling to left- and right-handed fermions.
- Leads to:
  - net polarization in final states.
  - different rates on polarized beams.

$$\mathcal{A}_f = \left.\frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}\right|_f = \left.\frac{2 g_V g_A}{g_V^2 + g_A^2}\right|_f$$

$$\left.\frac{g_V}{g_A}\right|_f = 1 - 4|Q_f|\sin^2\theta_{\mathrm{eff}}$$

$$A^{0,f}_{FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$\langle\mathcal{P}^0_\tau\rangle = -\mathcal{A}_\tau$$

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Forward-Backward Asymmetry

(as of hep-ex/0509008)

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Left-Right Asymmetry

(as of hep-ex/0509008)

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$$\mathcal{A}_f = \left.\frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}\right|_f = \left.\frac{2 g_V g_A}{g_V^2 + g_A^2}\right|_f$$

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Asymmetries (forward backward, exclusive)

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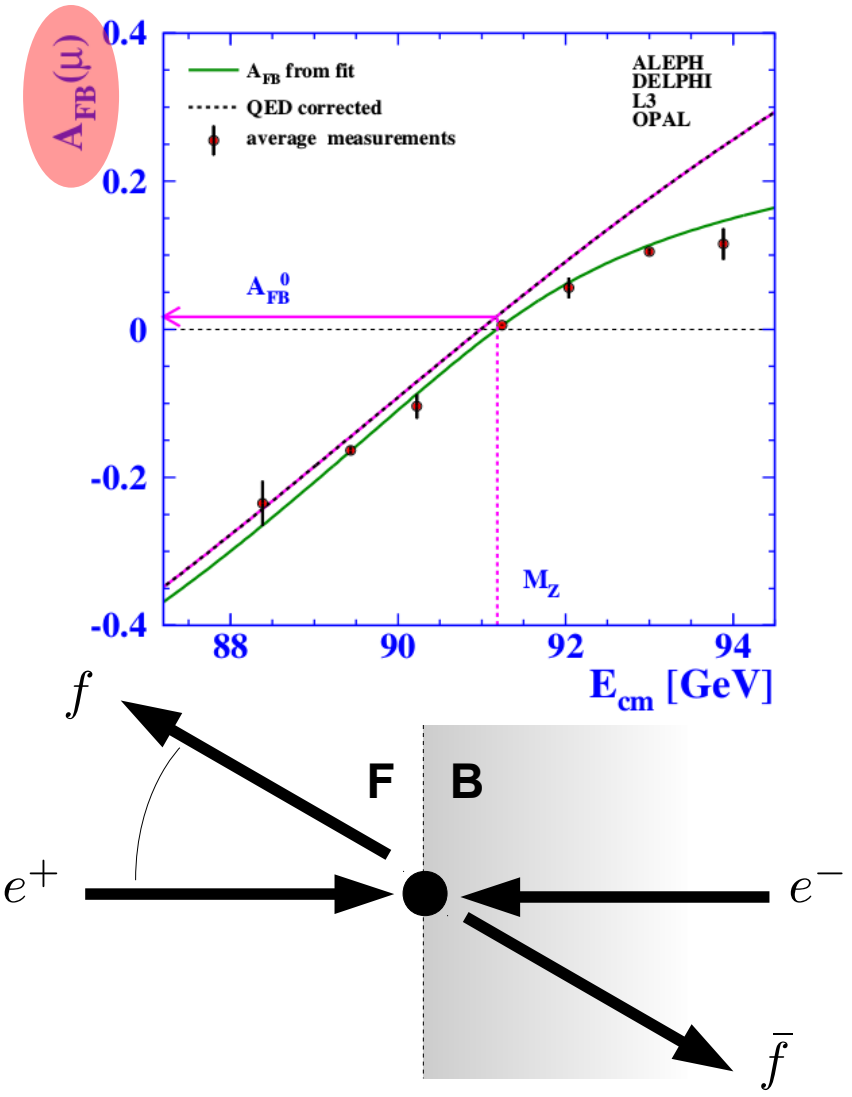

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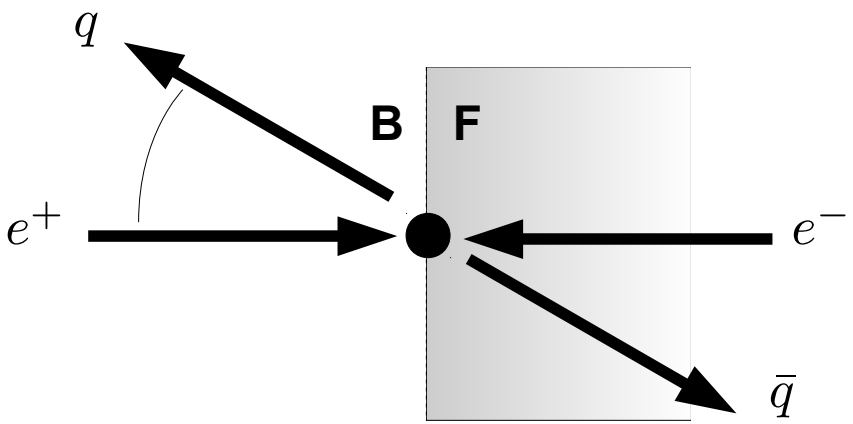
$\mathcal{A}_l$(SLD)	0.1513	$\pm$	0.0021

(as of hep-ex/0509008)

- Determined from inclusive hadronic forward-backward charge asymmetry measurements at LEP.
- Usually directly expressed in terms of $\sin^2\theta^{\rm lep}_{\rm eff}$.

e.g. determined by jet charge



Asymmetries (left-right couplings from τ polarization)

Pseudo-Observable	Measured Value		
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	0.02758	$\pm$	0.00034
m_Z [GeV]	91.1875	$\pm$	0.0021
Γ_Z [GeV]	2.4952	$\pm$	0.0023
$\sigma^0_{\rm had}$ [nb]	41.540	$\pm$	0.037
R^0_l	20.767	$\pm$	0.025
R^0_b	0.21629	$\pm$	0.00066
R^0_c	0.1721	$\pm$	0.0030
$A^{0,l}_{FB}$	0.0171	$\pm$	0.0010
$A^{0,b}_{FB}$	0.0992	$\pm$	0.0016
$A^{0,c}_{FB}$	0.0707	$\pm$	0.0035
$\sin^2\theta^{\rm lep}_{\rm eff}$	0.2324	$\pm$	0.0012
$\mathcal{A}_l(\mathcal{P}_\tau)$	0.1465	$\pm$	0.0033
$\mathcal{A}_b$	0.923	$\pm$	0.020
$\mathcal{A}_c$	0.670	$\pm$	0.027
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(as of hep-ex/0509008)

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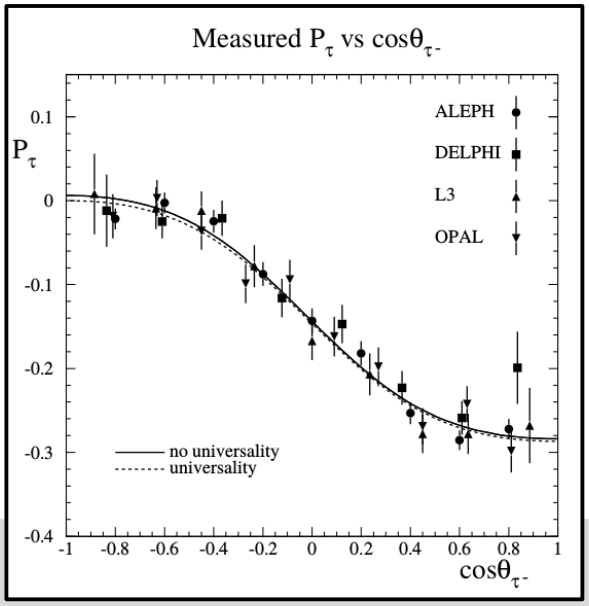
Example: $\tau^- \to \pi^- \nu_\tau$



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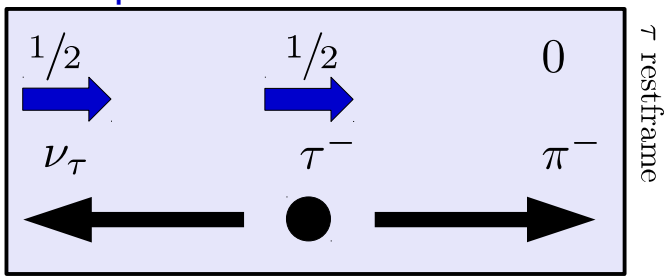

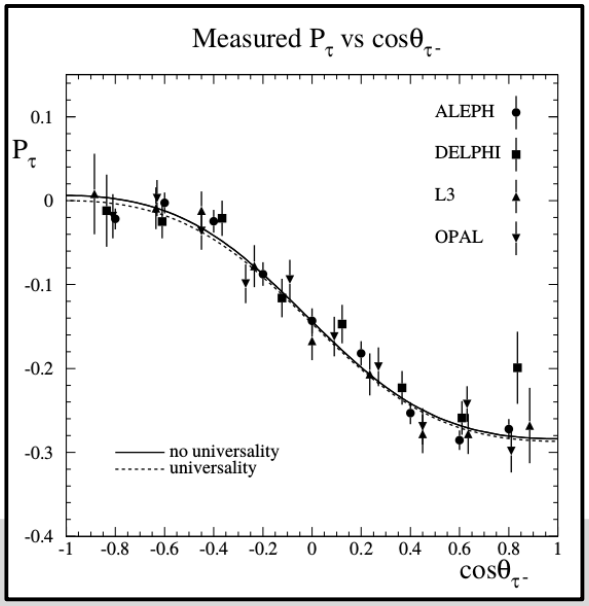

Asymmetries (left-right couplings @ SLD/SLAC)

Pseudo-Observable	Measured Value		
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	0.02758	$\pm$	0.00034
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$\sigma^0_{\rm had}$ [nb]	41.540	$\pm$	0.037
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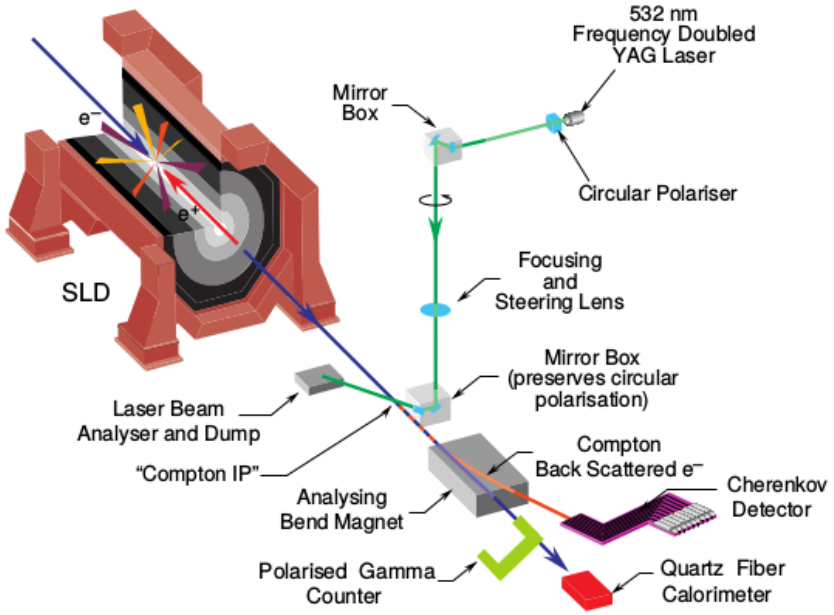
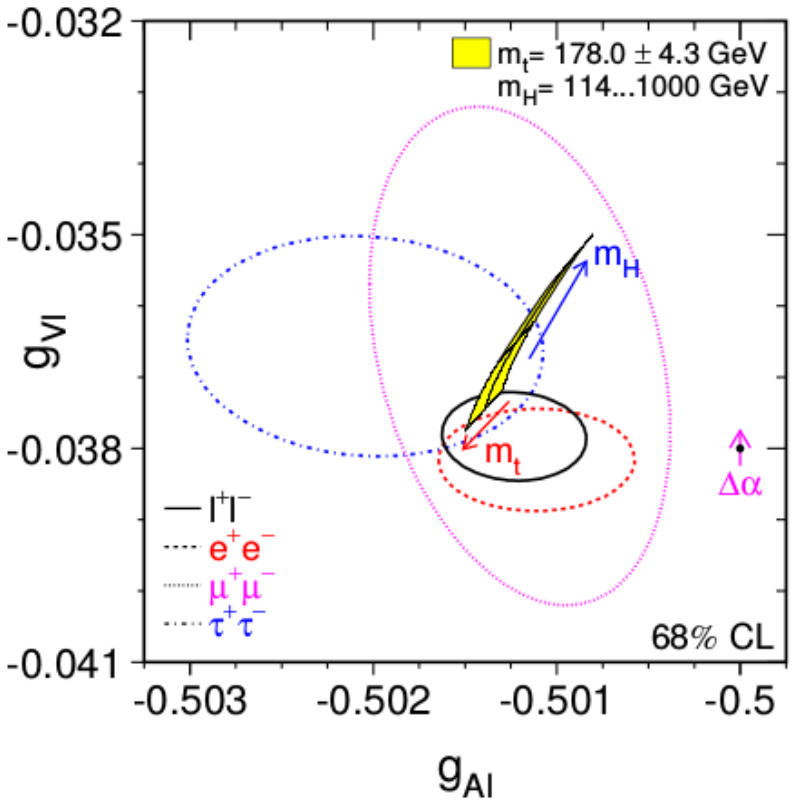
(as of hep-ex/0509008)

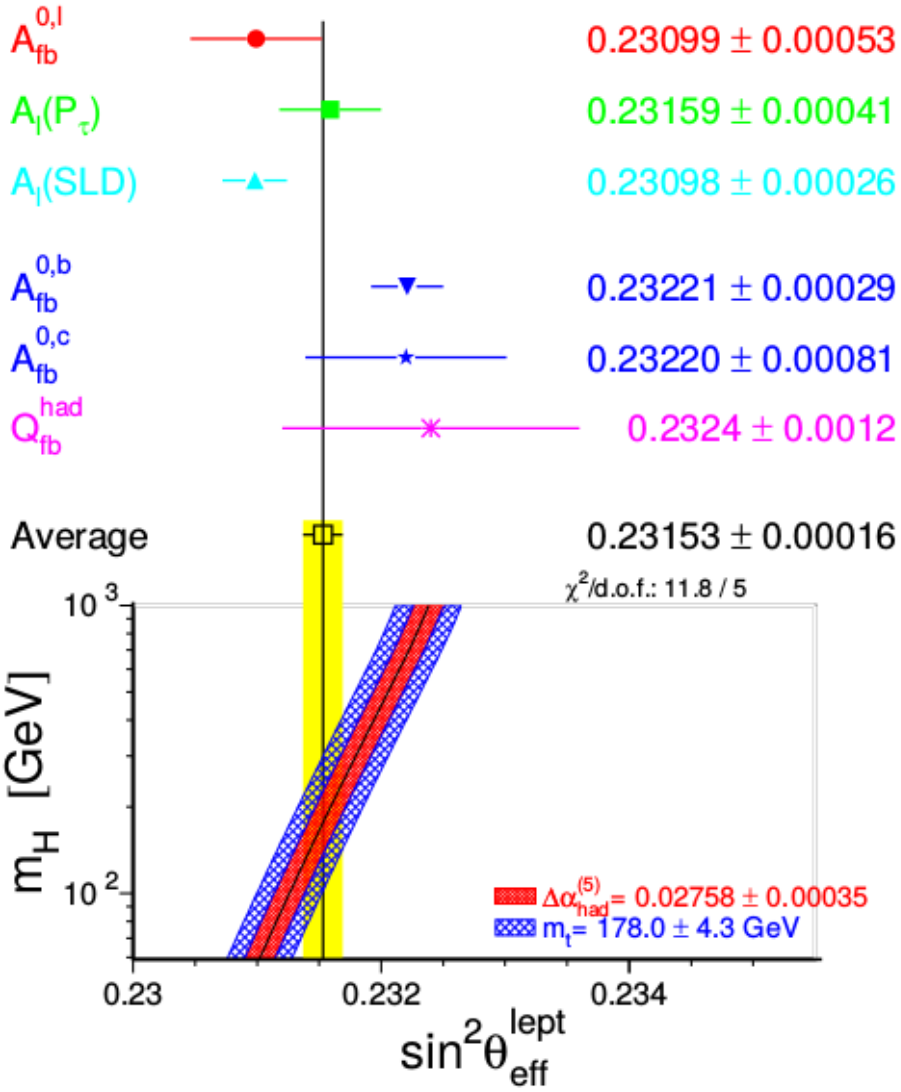
- Measured with polarized e^+ beam with the SLD experiment at SLAC.



Asymmetries (sensitivity to m_t and m_H)

- Lepton universality.
- Light Higgs boson preferred.

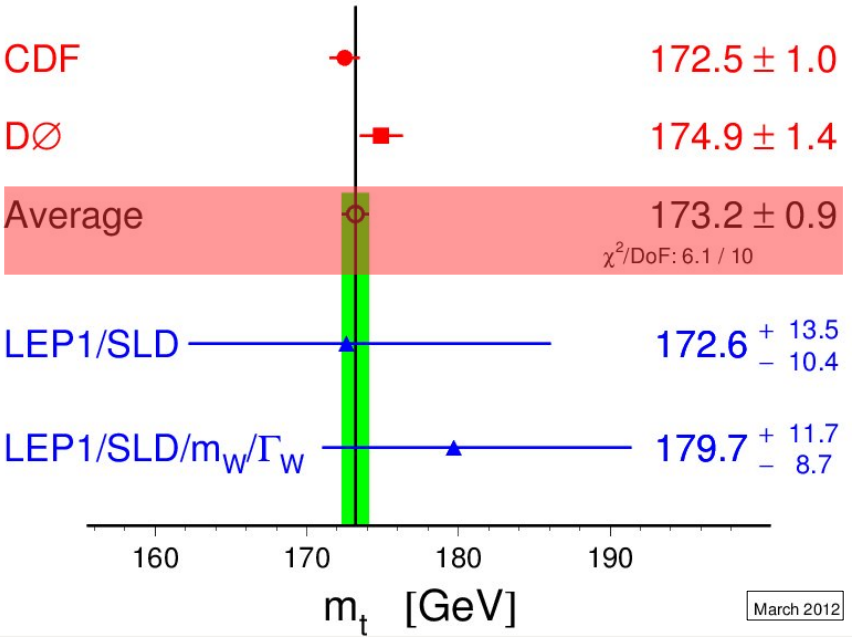


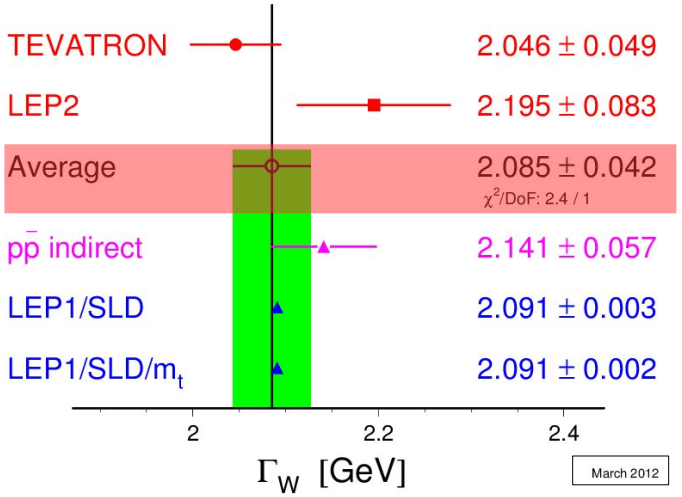


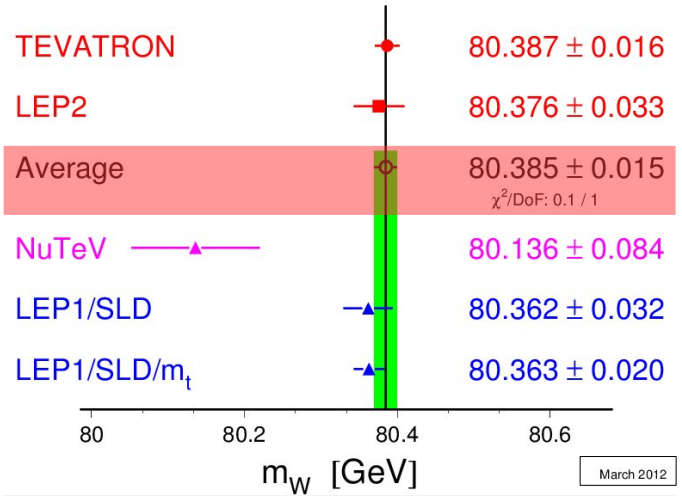
Additional measurements for maximal sensitivity

Pseudo-Observable	Measured Value
m_W [GeV]	80.385 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
m_t [GeV]	173.2 ± 0.9

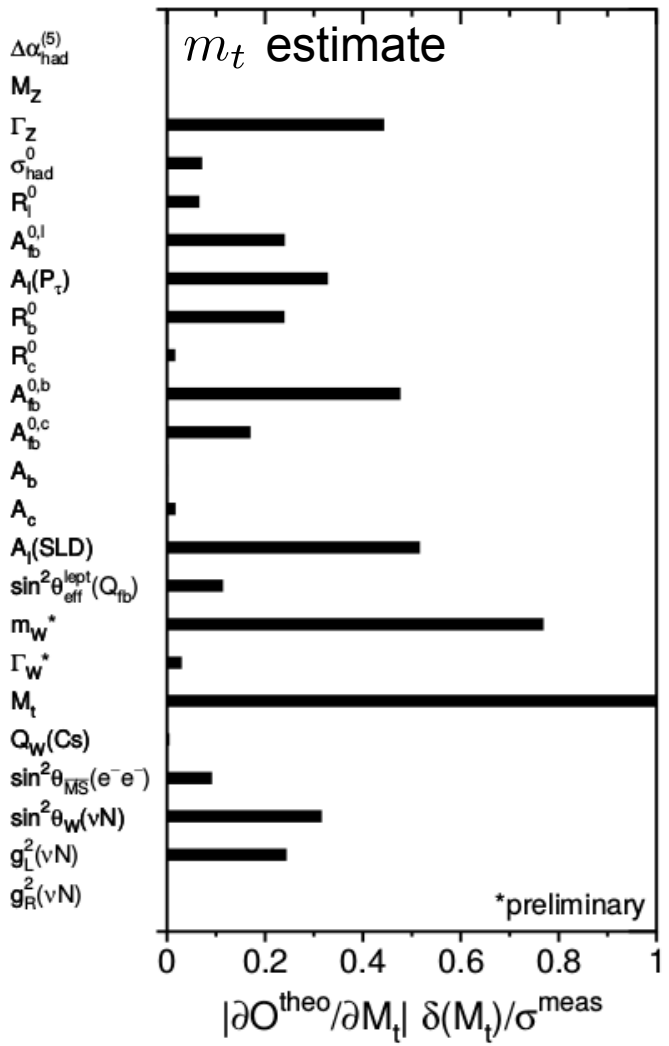
(as of March 2012)

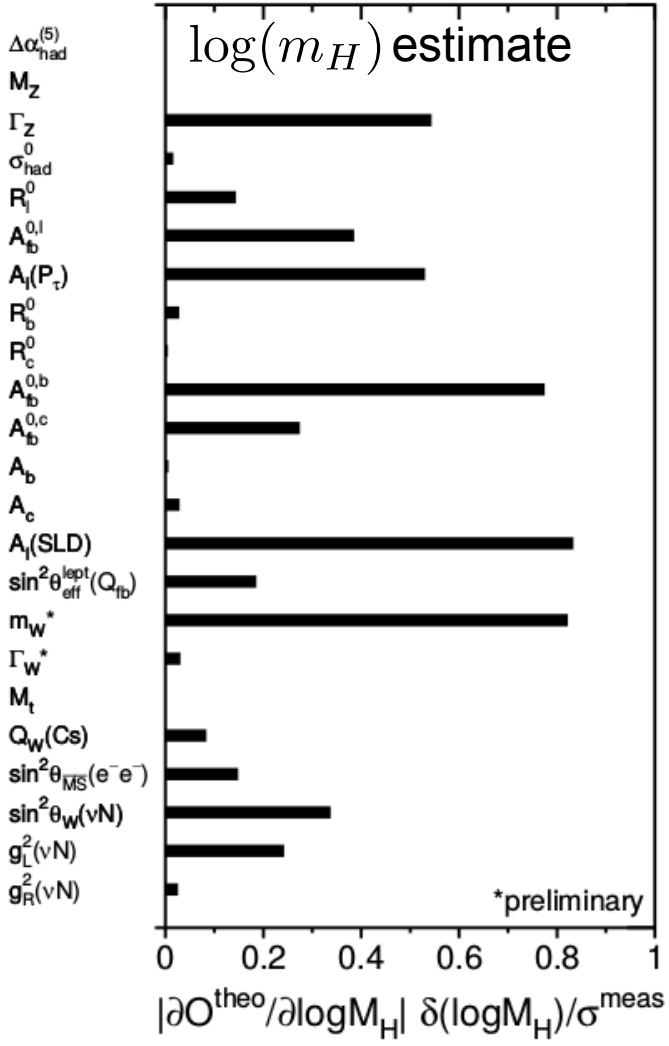






Sensitivity (sensitivity to m_t and m_H)





Chose typical uncertainties.

Parameter estimate

- Five parameter χ^2 fit:

Parameter	Best Fit Value	$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	$\alpha_s(m_Z)$	m_Z	m_t	$\log(m_H/\mathrm{GeV})$
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	0.02759 ± 0.00035	1.0				
$\alpha_s(m_Z)$	0.1190 ± 0.0027	−0.04	1.0			
m_Z	91.1874 ± 0.0021	−0.01	−0.03	1.0		
m_t	173 ± 11.5	−0.03	0.19	−0.07	1.0	
$\log(m_H/\mathrm{GeV})$	2.05 ± 0.385	−0.29	0.25	−0.02	0.89	1.0

Fit of Z-pole observables only: [1]

$\chi^2/ndof = 16/10$

$\mathcal{P}(\chi^2) = 9.9\%$

(2005)

Fit of Z-pole observables + m_W, Γ_W, m_t : [2]

$\chi^2/ndof = 16.9/13$

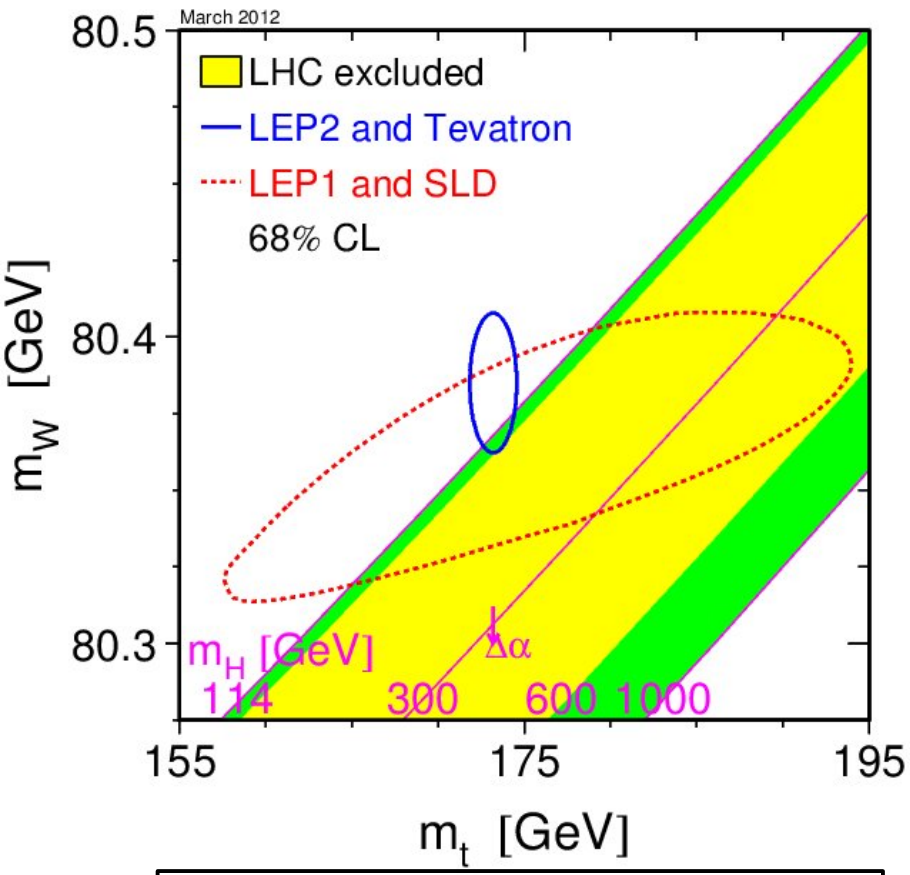
$\mathcal{P}(\chi^2) = 20.2\%$

(2012)

[1] (as of hep-ex/0509008)

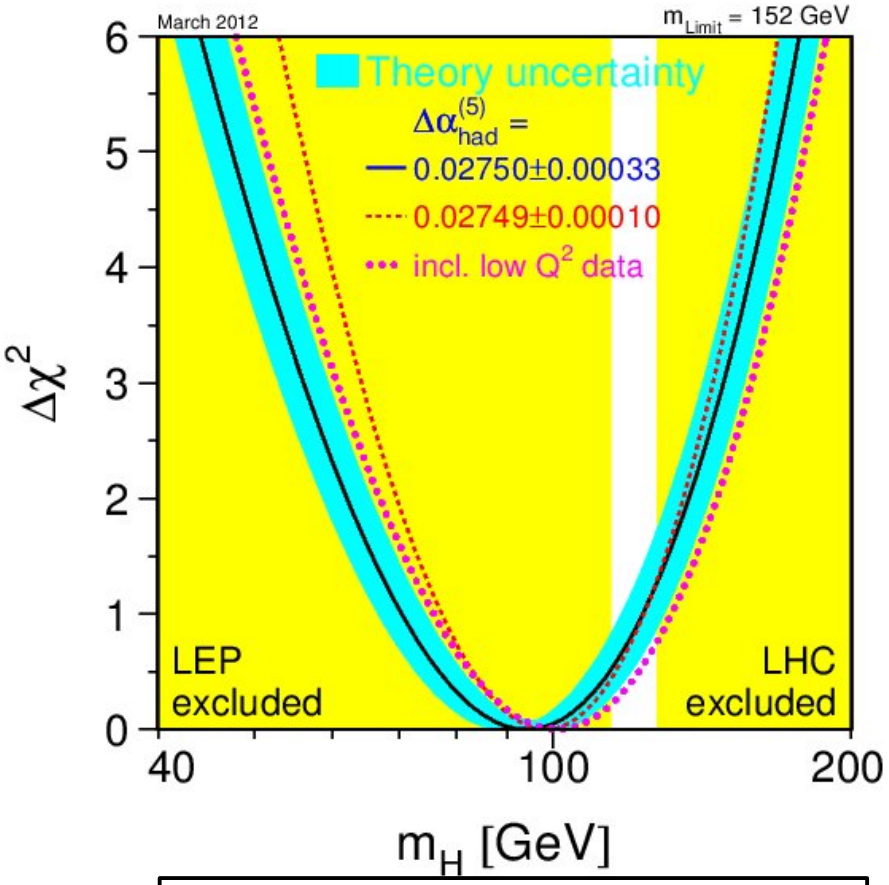
[2] http://lepewwg.web.cern.ch/LEPEWWG/winter12_results

Main result



Z-pole + m_W + Γ_W:

$m_t = 178.1 \pm^{10.9}_{7.8}$ GeV

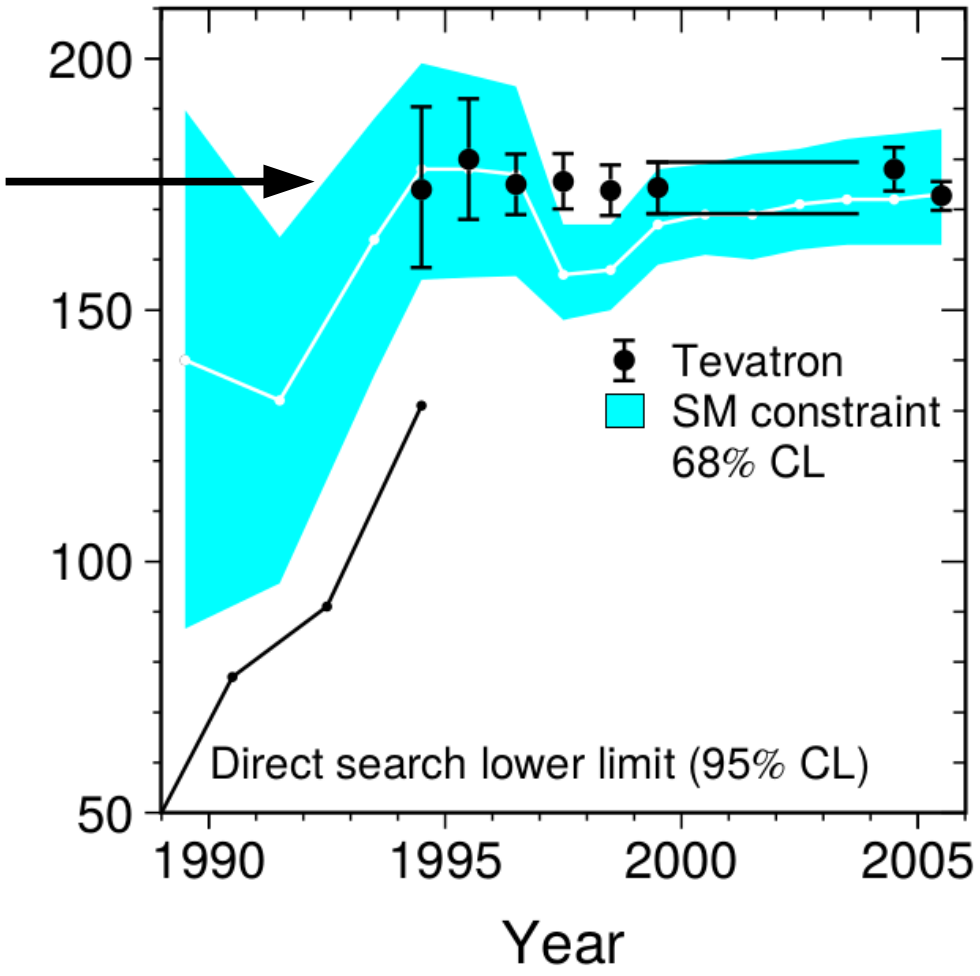


Z-pole + m_W + Γ_W + m_t:

$m_H = 98 \pm^{25}_{21}$ GeV

Pre-discovery constraints on m_t & m_H

- Consistency checks of the SM turned out as great success:
- Constraints on m_t spot on with direct measurements before discovery!
- Constraints on m_H in good agreement with direct measurements before discovery!



Direct searches

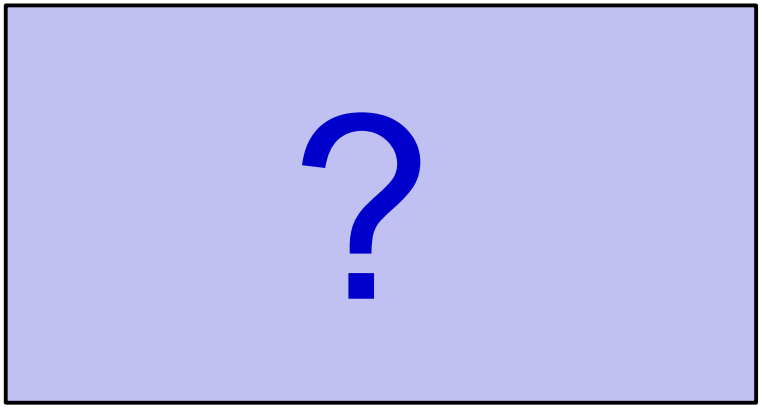
Higgs Boson...

Google-Suche Auf gut Glück!

Google.de angeboten auf: English

Direct searches @ LEP

- Main production mode in e^+e^-:



- Higgs boson couples to mass.
- Strongest coupling to heaviest objects.

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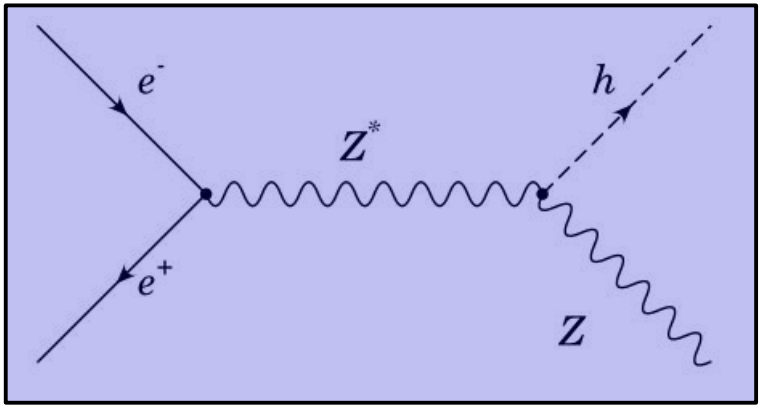

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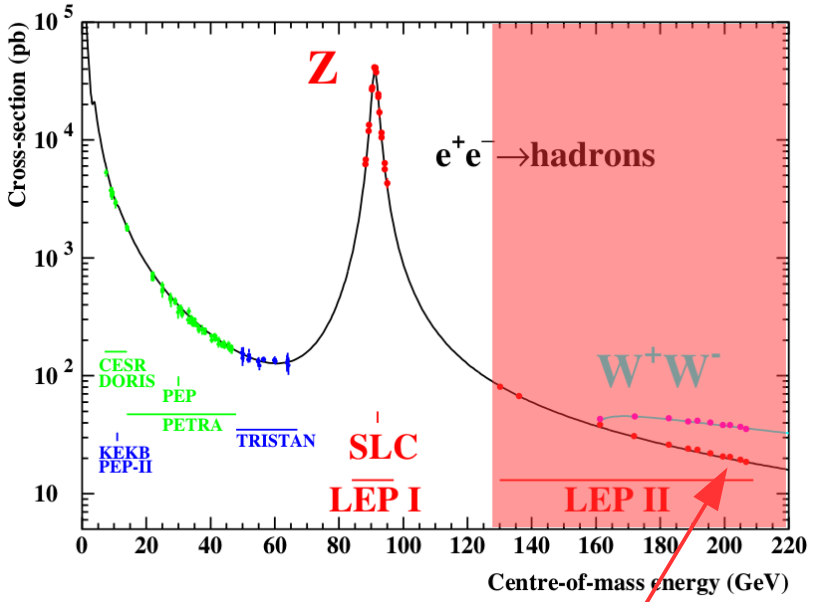
Integrated luminosities in pb^{-1}					
	ALEPH	DELPHI	L3	OPAL	LEP
$\sqrt{s} \geq 189$ GeV	629	608	627	596	2461
$\sqrt{s} \geq 206$ GeV	130	138	139	129	536



Year	1996		1997	1998	1999				2000	
E_{CM} nominal [GeV]	161	172	183	189	192	196	200	202	205	207

What was the maximal reach on m_H at LEP?

Direct searches @ LEP

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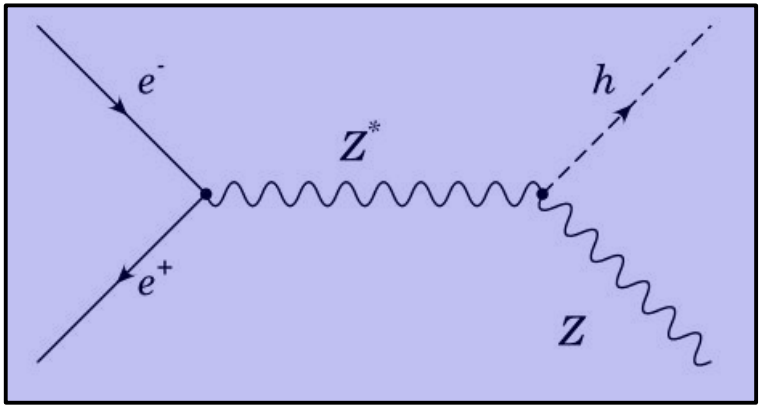

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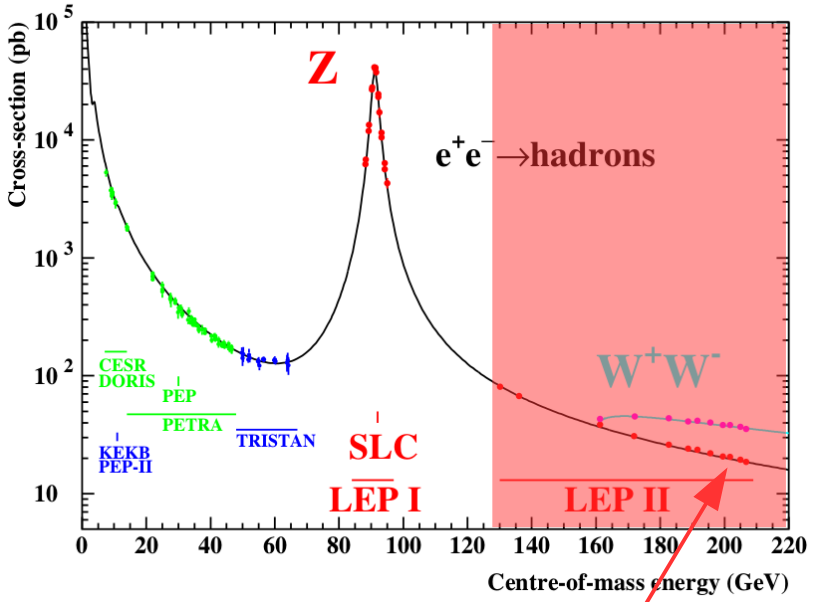

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What was the maximal reach on m_H at LEP? ⟶ $m_H \approx 117$ GeV

Test statistic (LEP, remember from last lecture)

$$\mathcal{L}_{s+b} = \prod_{k=1}^{N} \left(\frac{(s_k+b_k)^{n_k}}{n_k!} e^{-(s_k+b_k)} \cdot \prod_{j=1}^{n_k} \frac{s_k S_k + b_k B_k}{s_k + b_k} \right)$$

$$\mathcal{L}_b = \prod_{k=1}^{N} \left(\frac{b_k^{n_k}}{n_k!} e^{-b_k} \cdot \prod_{j=1}^{n_k} \frac{b_k B_k}{b_k} \right)$$

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$$q = -2 \ln Q = 2 \sum_{k=1}^{N} \left(s_k - \sum_{j=1}^{n_k} \ln \left(1 + \frac{s_k S_k}{b_k B_k} \right) \right)$$

What values of Q (and q) correspond to more signal/background like?

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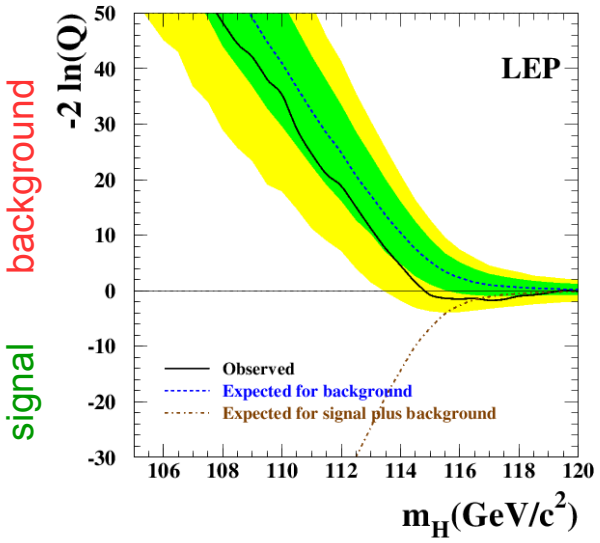

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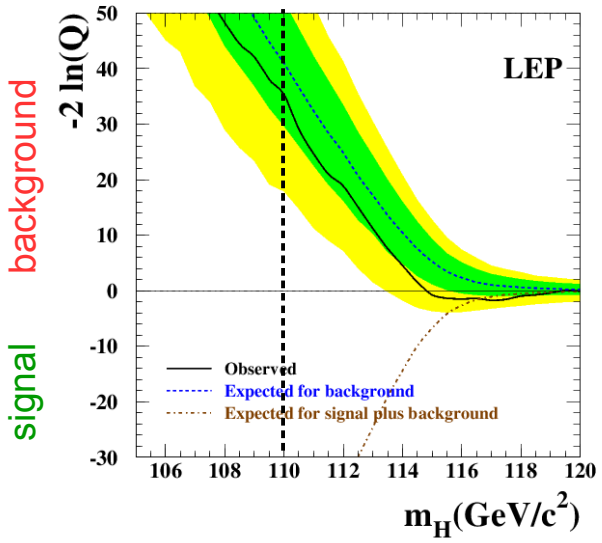

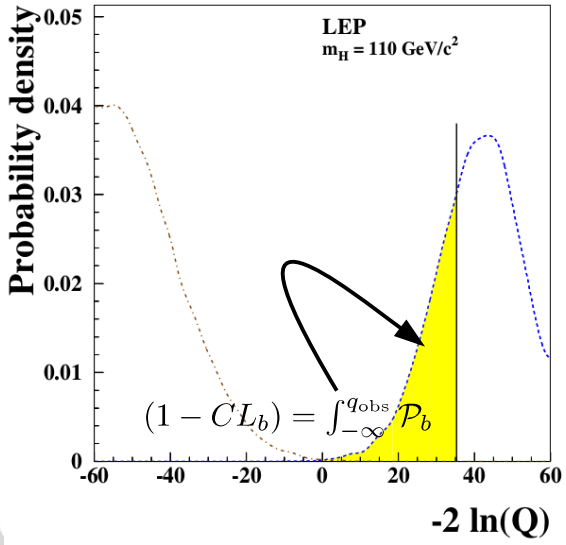

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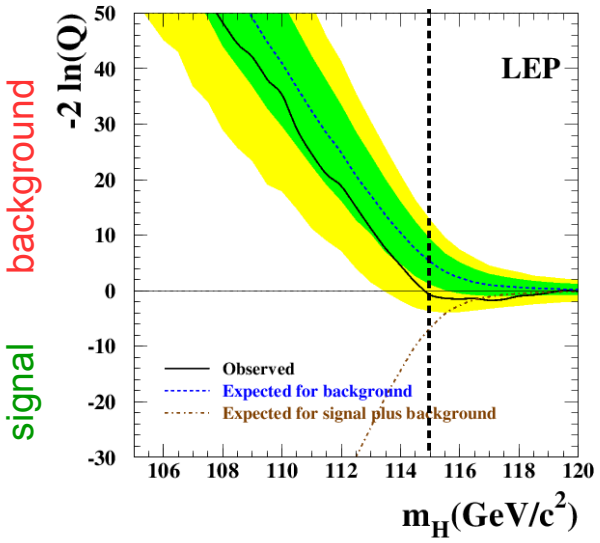

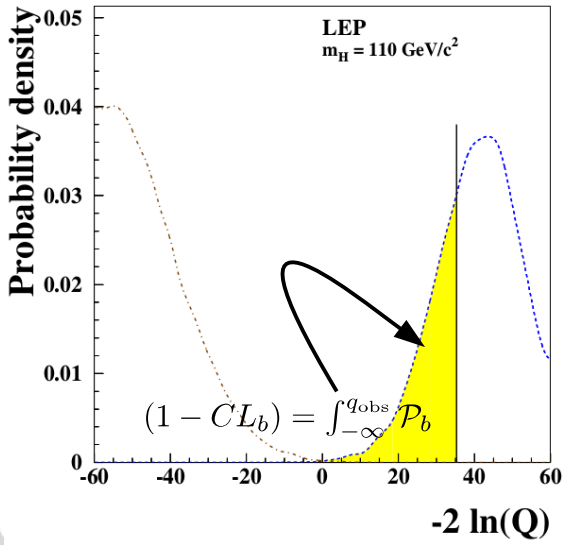

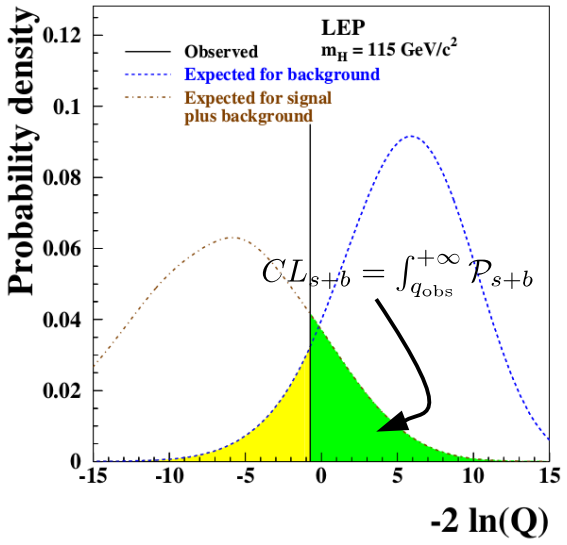

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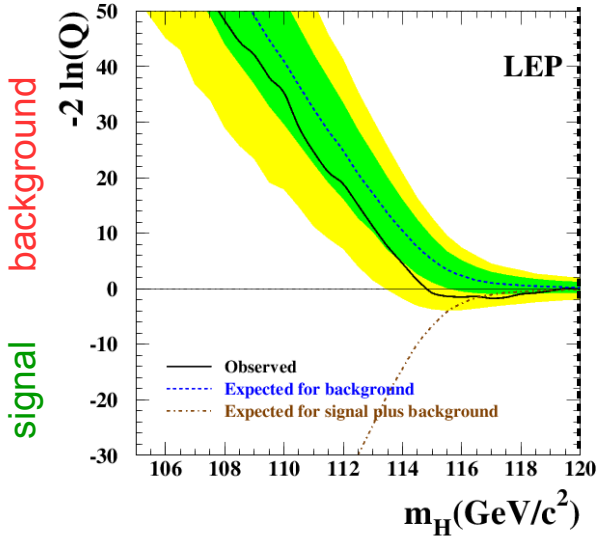
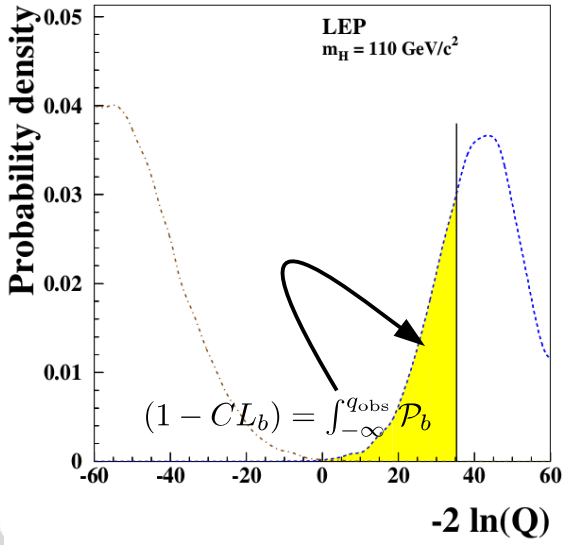
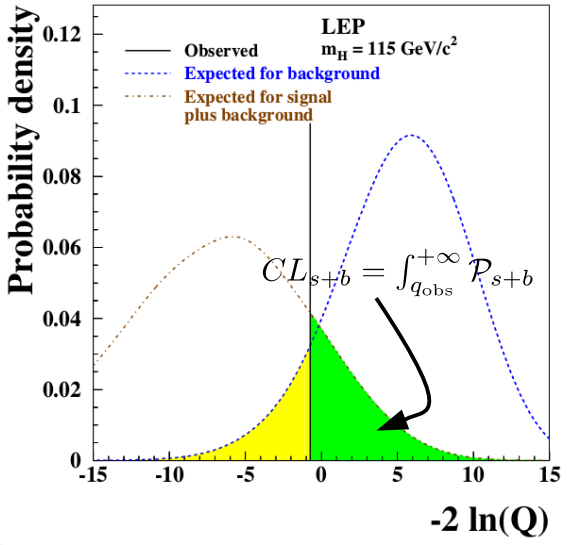
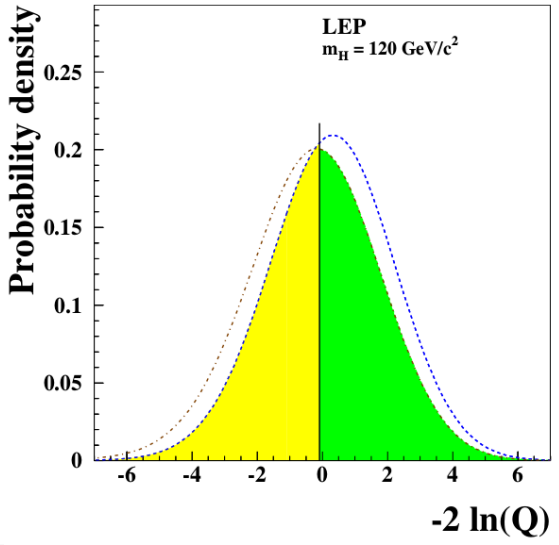


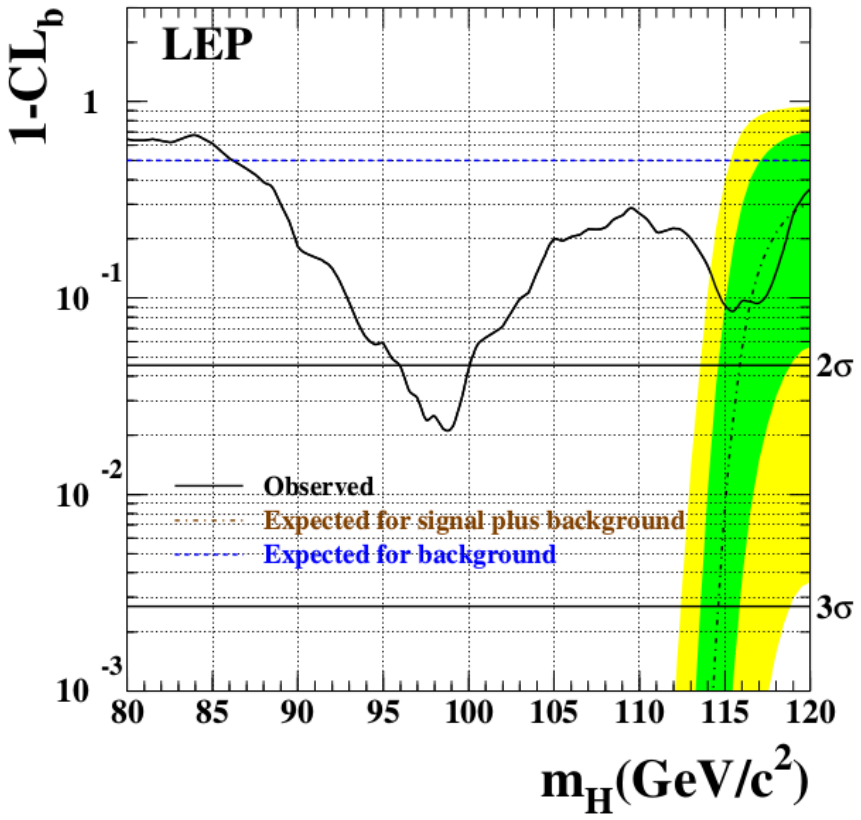




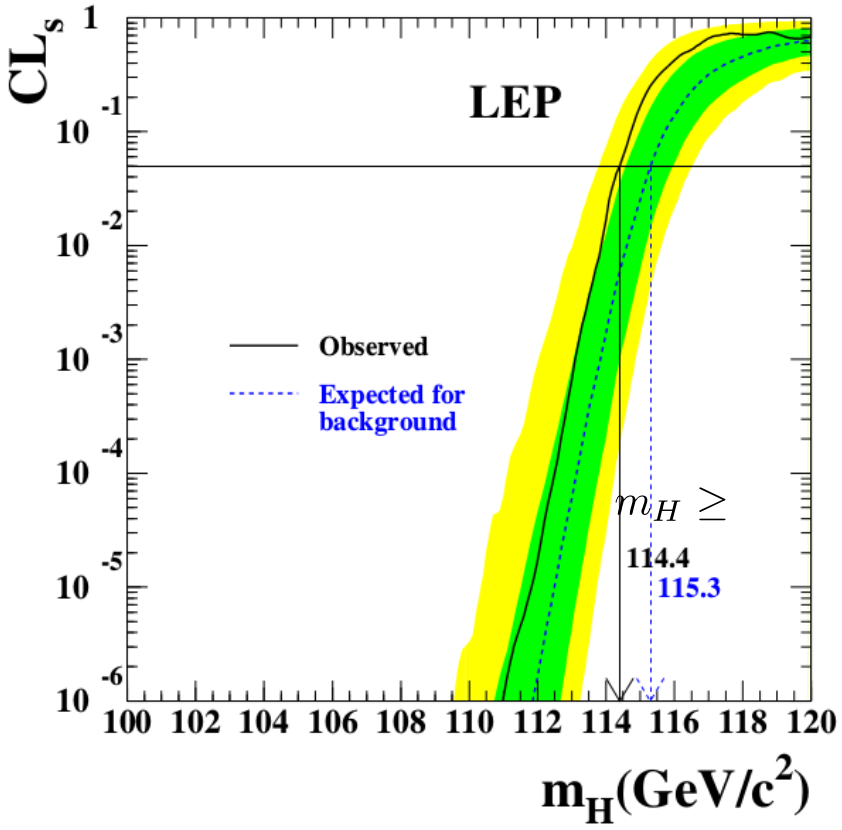


Result (final word from LEP)

p-value:



CL_s-limit ($CL_s = \frac{CL_{s+b}}{CL_b}$):

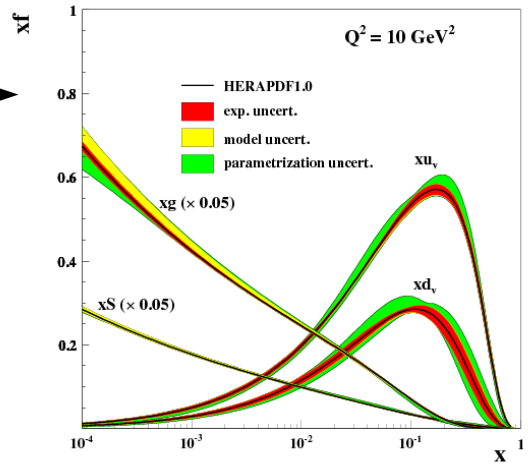


- No signal observed! There is a 2σ effect, but this is not compatible with the SM.

Direct searches @ Tevatron

- Also @ Tevatron searches have been conducted at $\sqrt{s} = 1.96\ \mathrm{TeV}$:
- Luminosity: $\mathcal{L}_{\mathrm{int}} \leq 10\ \mathrm{fb}^{-1}$

$\langle x \rangle = ?$

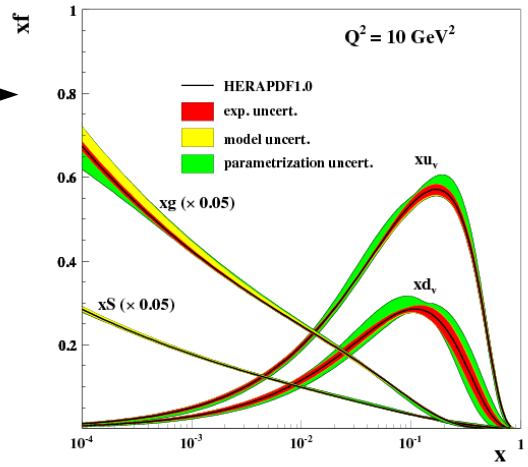


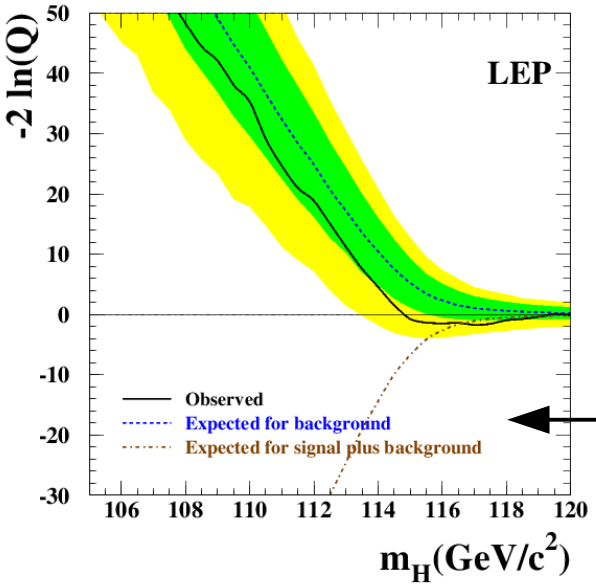
Direct searches @ Tevatron

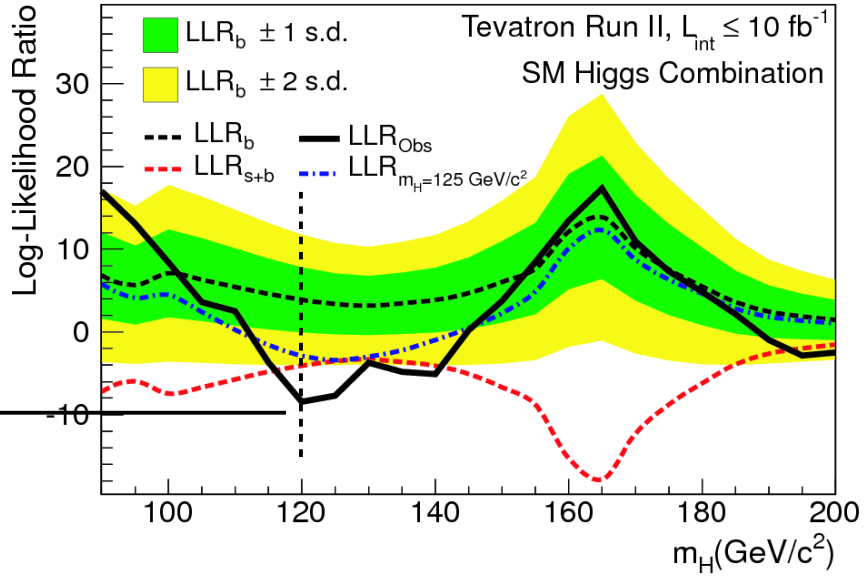
- Also @ Tevatron searches have been conducted at $\sqrt{s} = 1.96$ TeV:
- Luminosity: $\mathcal{L}_{\text{int}} \leq 10\ \text{fb}^{-1}$

NB: Production/decay modes:
$gg \to H$, $q\bar{q} \to H$, $q\bar{q} \to VH$, $q\bar{q} \to t\bar{t}H$
$H \to b\bar{b}$, $\tau\tau$, WW, ZZ, $\gamma\gamma$

$$\langle x \rangle = \frac{80\ \text{GeV} + 125\ \text{GeV}}{1\,960\ \text{GeV}} \approx 0.10$$

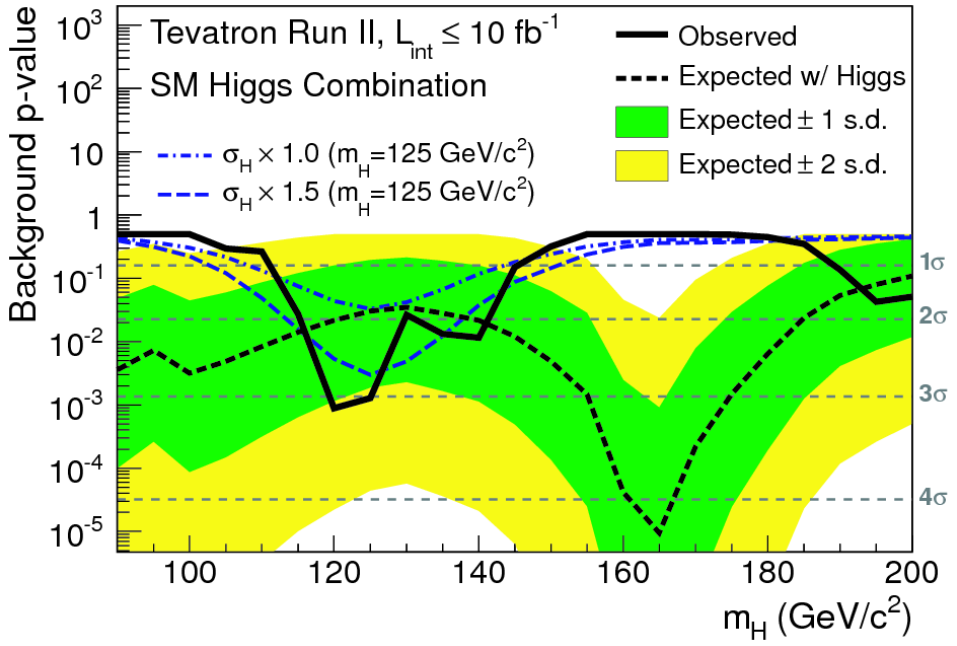




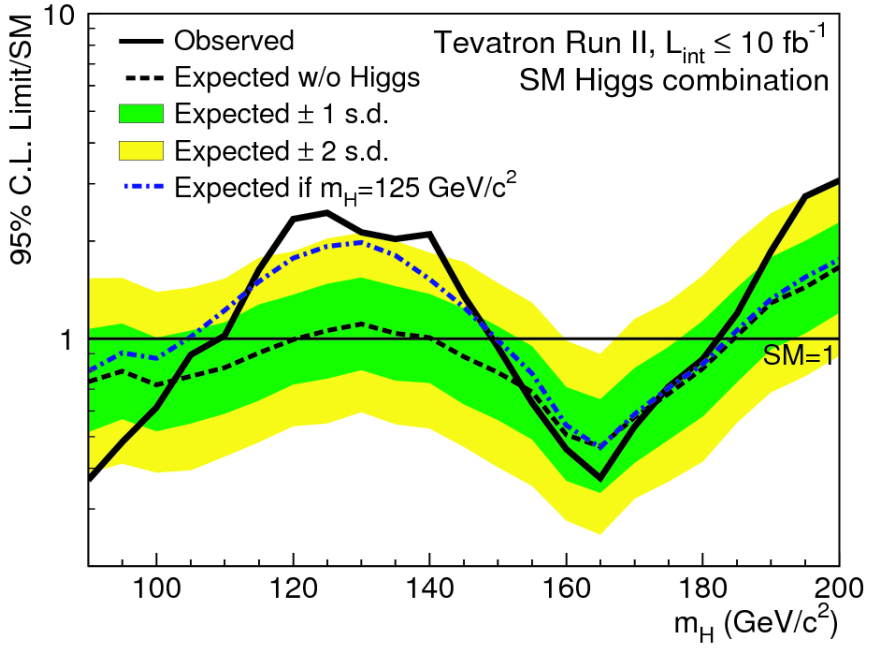


Result (final word from Tevatron)

p-value:



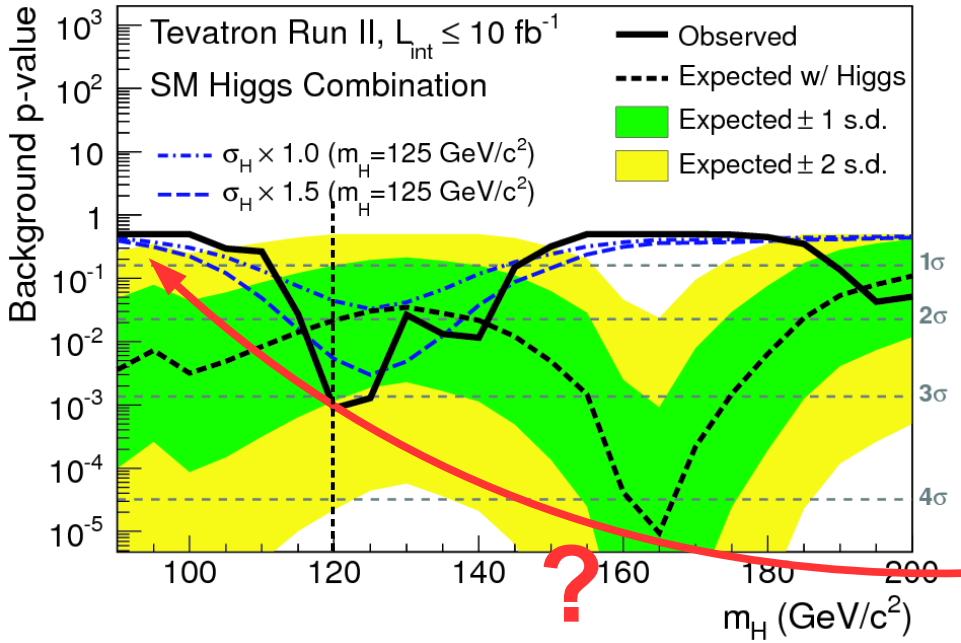
CL_s-limit ($CL_s = \frac{CL_{s+b}}{CL_b}$):

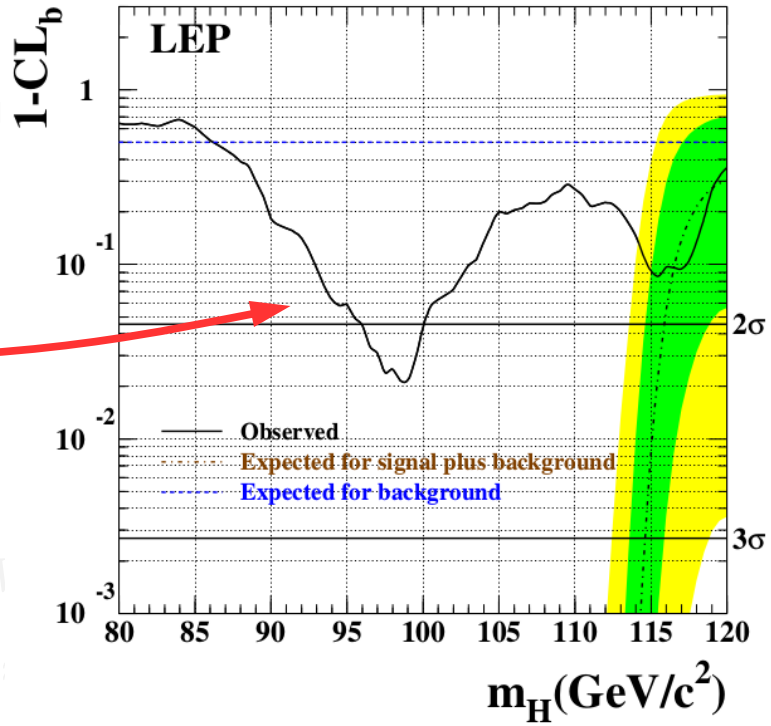


- Sensitivity of Tevatron results driven by $q\bar{q} \to VH,\ H \to \bar{b}b$.
- $\gtrsim 3\sigma$ evidence for a Higgs boson around $m_H \approx 120$ GeV, $\approx 1.5\sigma_{\mathrm{SM}}$.

Result (final word from Tevatron)

p-value:





- Sensitivity of Tevatron results driven by $qq \to$
- $\gtrsim 3\sigma$ evidence for a Higgs boson around m_H

Concluding Remarks

- The hunt for the Higgs boson had begun in the LEP-II era already.
- We had already good hints where to expect the Higgs (according to the SM) from high precision Z-pole measurements.
- Direct searches @ LEP and @ Tevatron remained inconclusive, since the Higgs boson was out of reach.
- 2010 the dishes were set for the final round...
- Next week we will discuss the computing exercises. The week after Andrew Gilbert will discuss with you the discovery at the LHC and what we know about the new particle up to today.

Backup