Moderne Experimentalphysik III: Hadronen und Teilchen (Physik VI)

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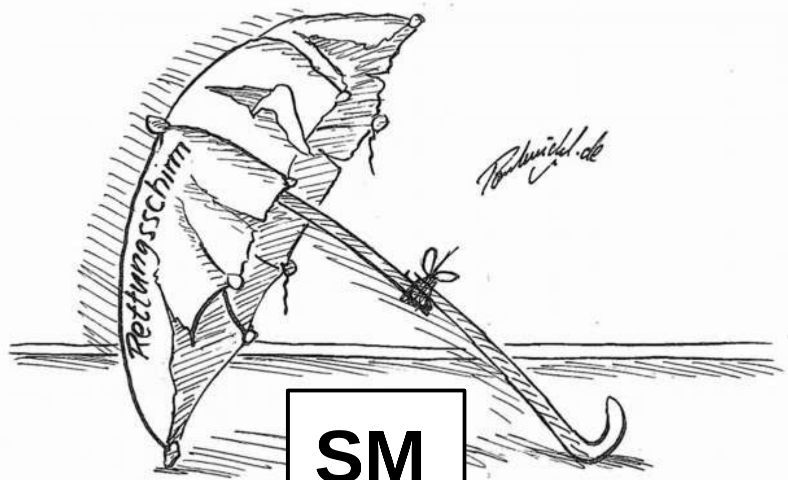
28. Juni 2018

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IETP) – PHYSICS FACULTY

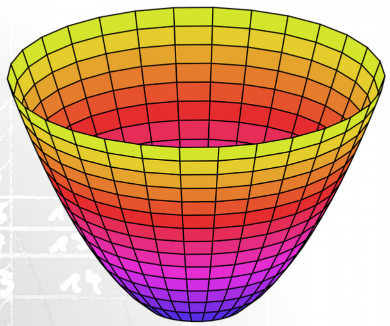
Wie kann eine Symmetrie zur gleichen Zeit erhalten und gebrochen sein?



SM

Problem: lokale Eichsymmetrien in Lagrangedichte sind durch massive Teilchen explizit gebrochen

Spontane Symmetrie-brechung:



$$f(x,y) = x^2 + y^2$$

$$x = r\cos\varphi$$

$$y = r\sin\varphi$$

$$f(x,y)\big|_{r,\varphi} = r^2\left(\cos\varphi^2 + \sin\varphi^2\right) = r^2$$

$$\tilde{f}(x,y) = (x-1)^2 + (y-1)^2$$

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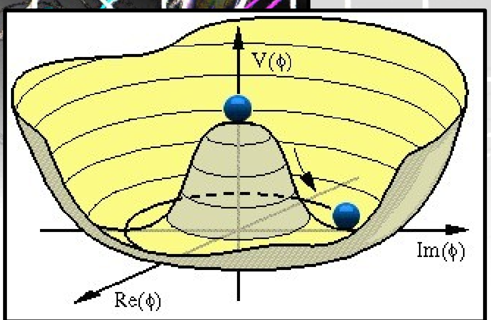
("hidden symmetry")



Führe Potential ein das den Grundzustand des Universums aus der Symmetrieachse der Bewegungsgleichungen zwingt.

→ Teilchenmasse als Kopplung an nicht verschwindenden Vakuumerwartungswert.

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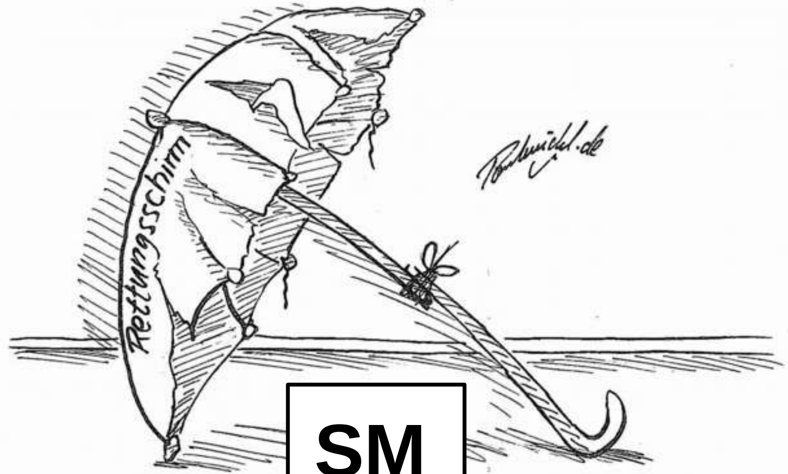

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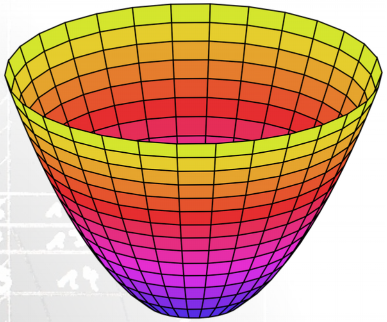

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Erinnerung:

$$f_{H\to ff} = i\frac{m_f}{v} \qquad \text{(Fermions)}$$

$$f_{H\to VV} = i\frac{2m_V^2}{v} \qquad \text{(Heavy Bosons trilinear)}$$

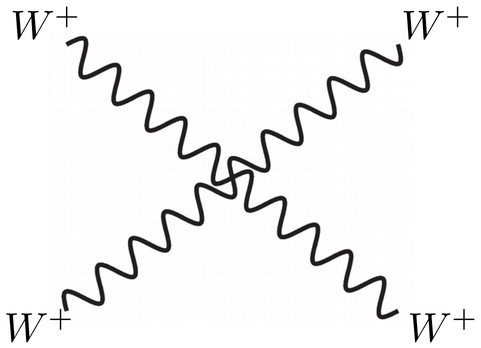
$$f_{HH\to VV} = i\frac{2m_V^2}{v^2} \qquad \text{(Heavy Bosons quartic)}$$

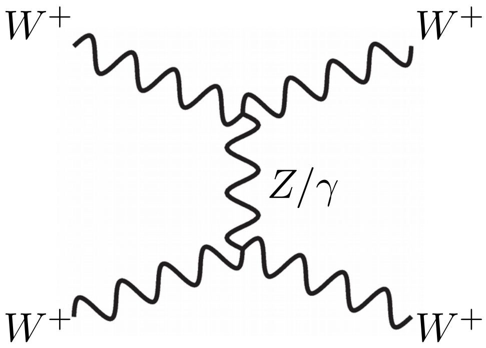
$$f_{H\to HH} = i\frac{3m_H^2}{v} \qquad (H\ \text{Boson trilinear})$$

$$f_{HH\to HH} = i\frac{3m_H^2}{v^2} \qquad (H\ \text{Boson quartic})$$

Higgs sector in the light of (tree-level) unitarity

- Unitarity problem demonstrated for $W^+W^+ \to W^+W^+$ scattering:





$$\mathcal{M}_{gauge} = -g^2 \frac{s}{4m_W^2} + \mathcal{O}(s^0)$$

constraint

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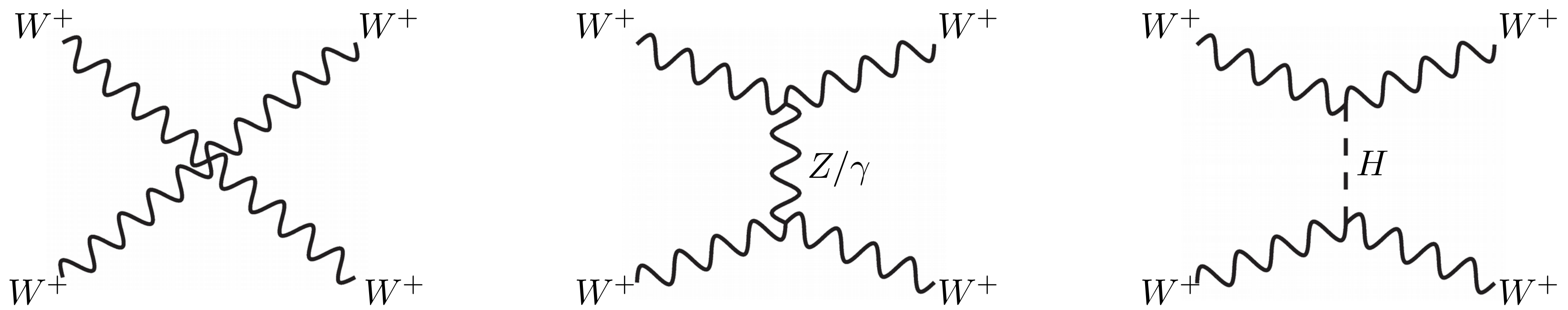


$$\mathcal{M}_{gauge} = -g^2 \frac{s}{4m_W^2} + \mathcal{O}(s^0)$$

constraint

$$\mathcal{M}_H = g_{HWW}^2 \frac{s}{m_W^4} + \mathcal{O}(s^0)$$

$$g_{HWW} = \frac{2m_W^2}{v} = g \cdot m_W$$

with: $v = \frac{2m_W}{g}$

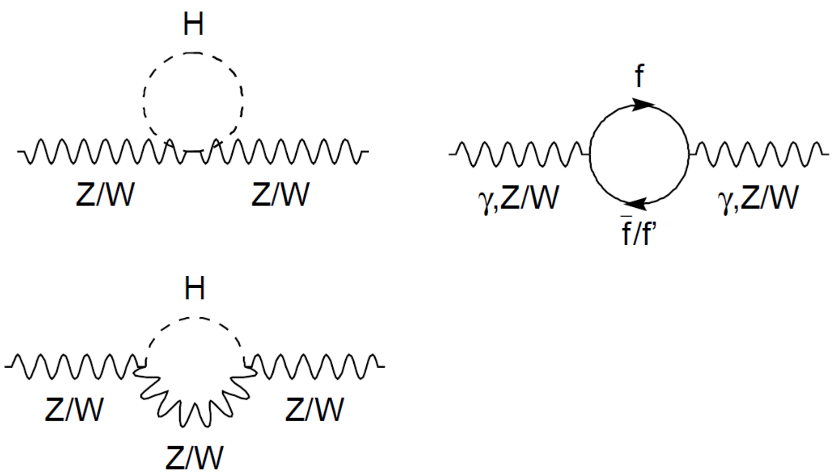
Exact cancellation of **divergent behavior** only if scalar exchange particle has coupling of type $\propto m_W^2$.

- Any additional contribution to this process should preserve this cancellation.

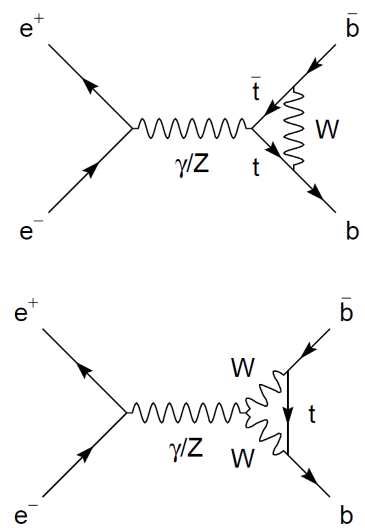
Higher orders and precision observables

- 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 :

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

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

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

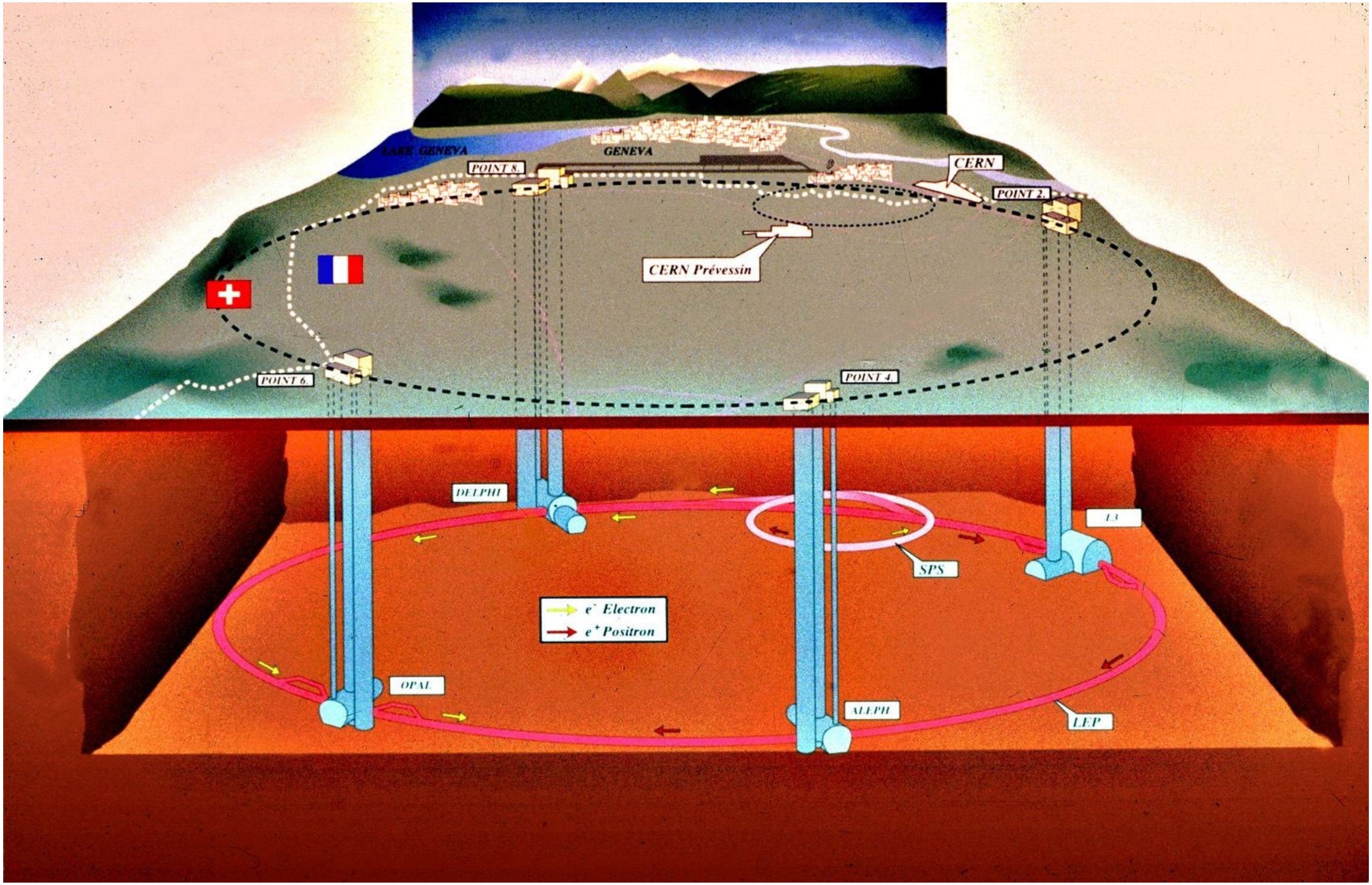
(1-loop precision)

$\propto m_t^2$

$\propto \log(m_H)$

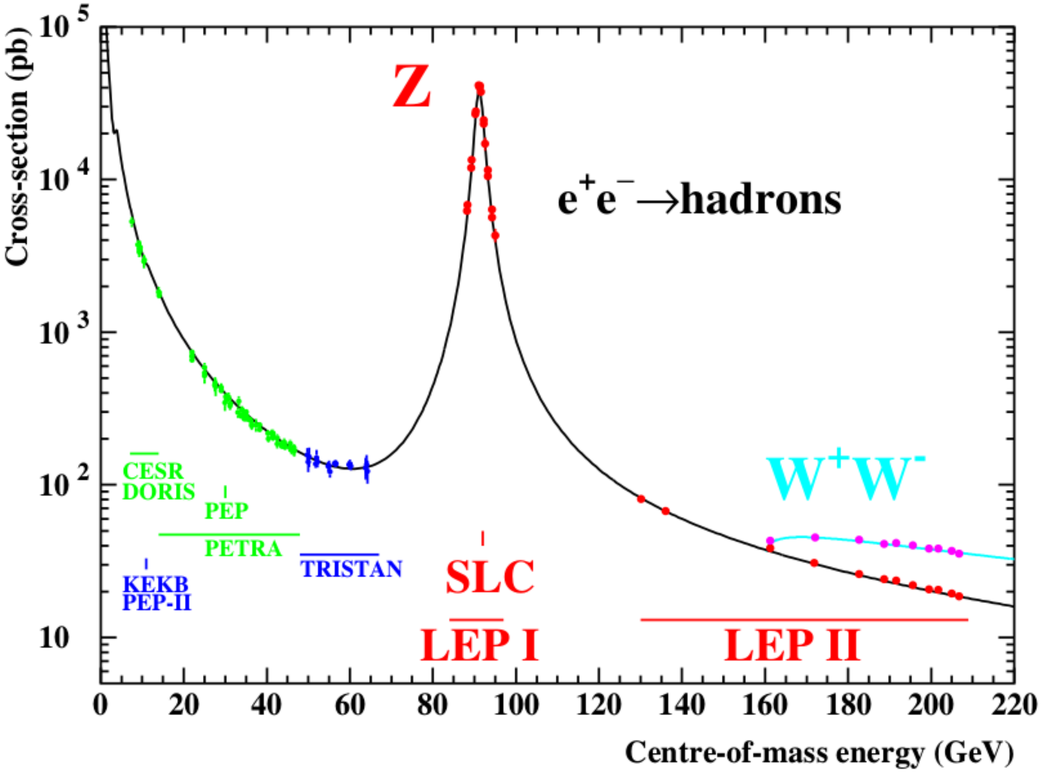
- Effects set in at $\mathcal{O}(\alpha^2) \approx \mathcal{O}(10^{-4})$ → high precision needed on observables and theoretical prediction!

High precision measurements @ LEP & SLAC



High precision observables @ LEP

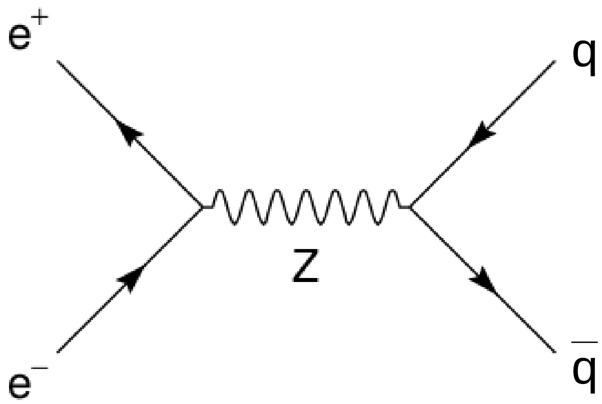
- High precision measurements made at $\sqrt{s} = m_Z$ during LEP-I run period:



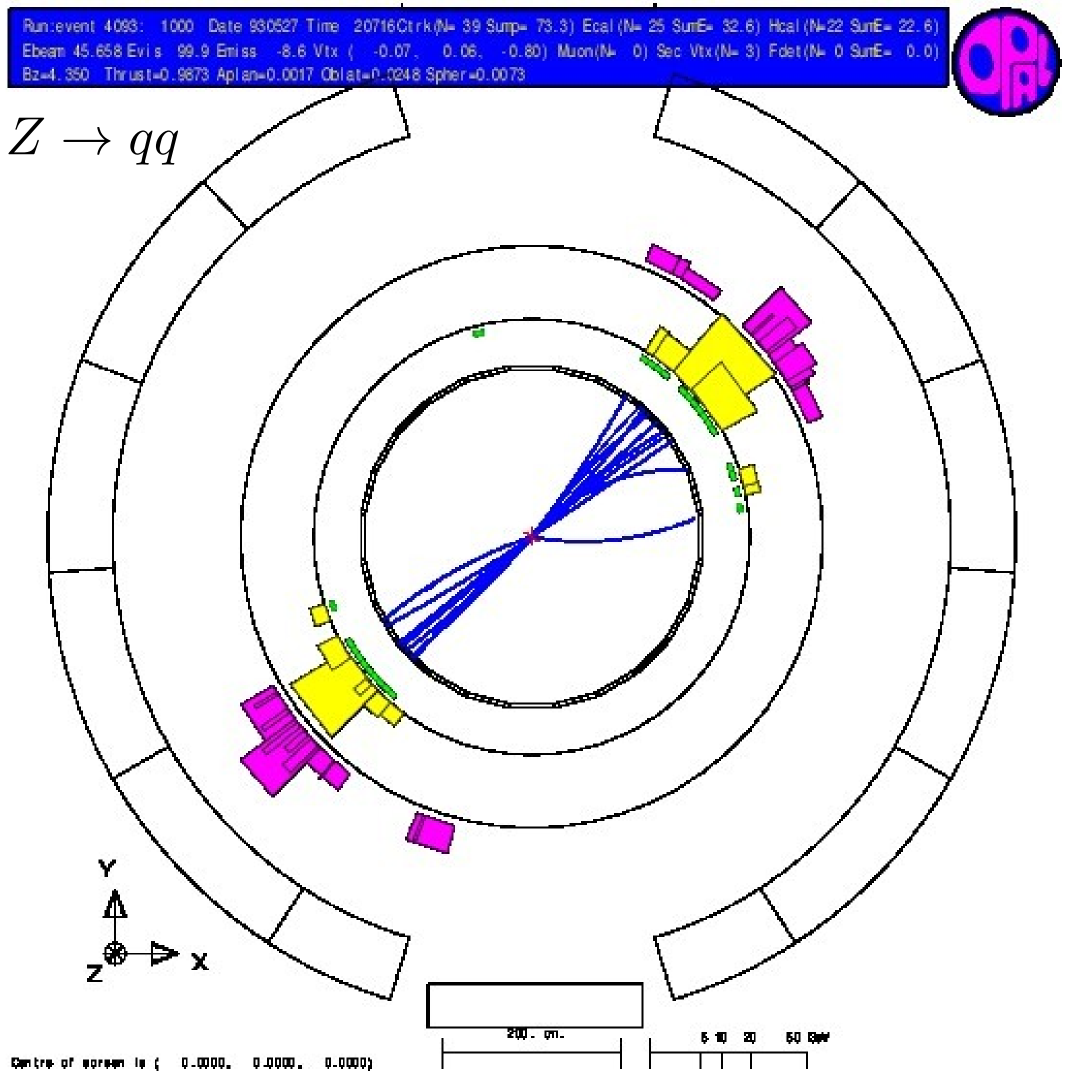
Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8
		202.1

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

Typical $Z \to qq$ event @ LEP



$Z \to qq$



Z-pole electroweak precision observables

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

(as of hep-ex/0509008)

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

NB: Using similar relations with the same dependencies as shown for m_W.

Parameter estimate

- Five parameter χ^2 fit:

Parameter	Best Fit Value	$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$	$\alpha_s(m_Z)$	m_Z	m_t	$\log(m_H/\text{GeV})$
$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$	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	
$\log(m_H/\text{GeV})$	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)

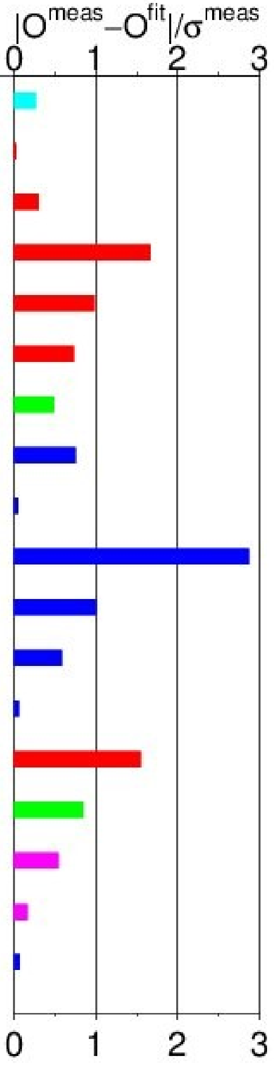
Fit of Z-pole observables + m_W, Γ_W, m_t: [2]

$\chi^2/ndof = {}^{16.9}/_{13}$

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

(2012)

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

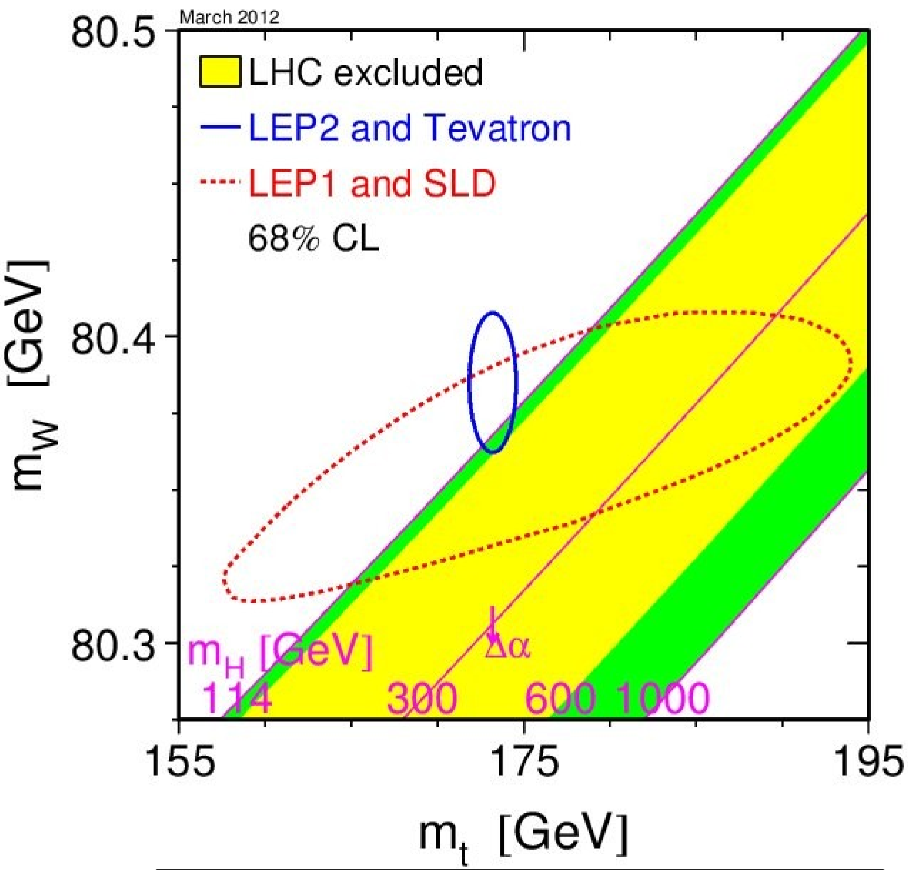


March 2012

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

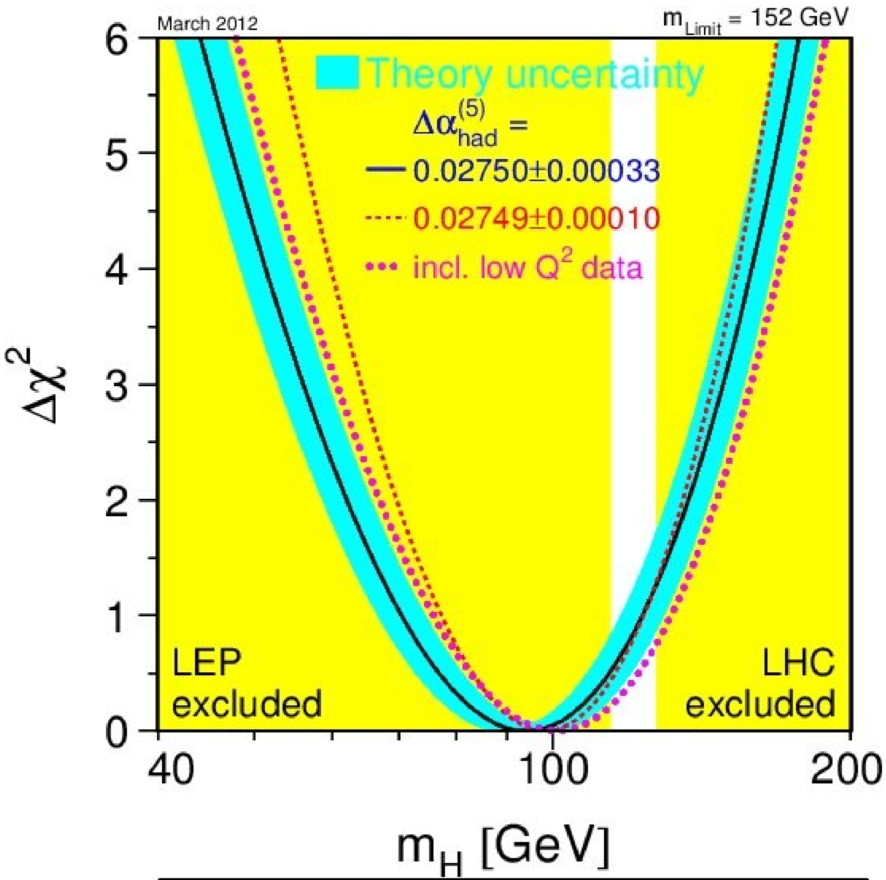
[2] http://lepewwg.web.cern.ch/LEPEWWG/winter12_results

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

Direkte Higgs Suchen und Entdeckung

Direkte Suche bei LEP-II

- **Hauptproduktion** in e^+e^-:

?

- Higgs Boson koppelt an Masse.
- Kopplung am stärksten für schwerste Objekte.

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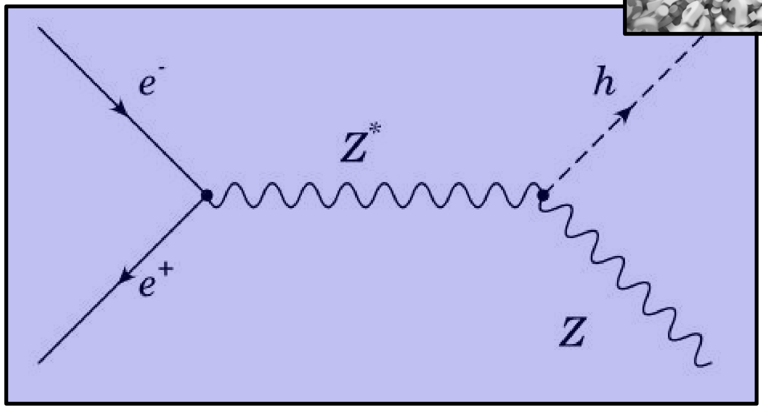

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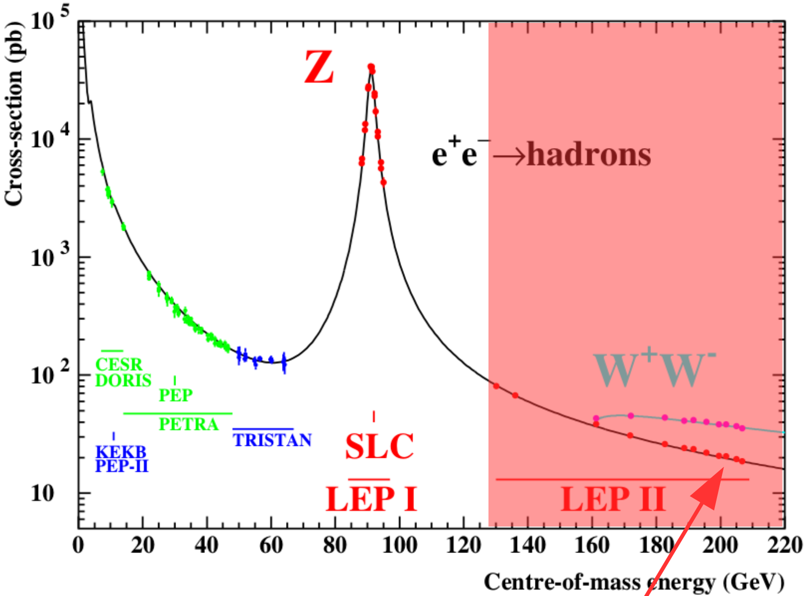

Year	1996		1997	1998	1999				2000	
E_{CM} nominal [GeV]	161	172	183	189	192	196	200	202	205	207

Direkte Suche bei LEP-II

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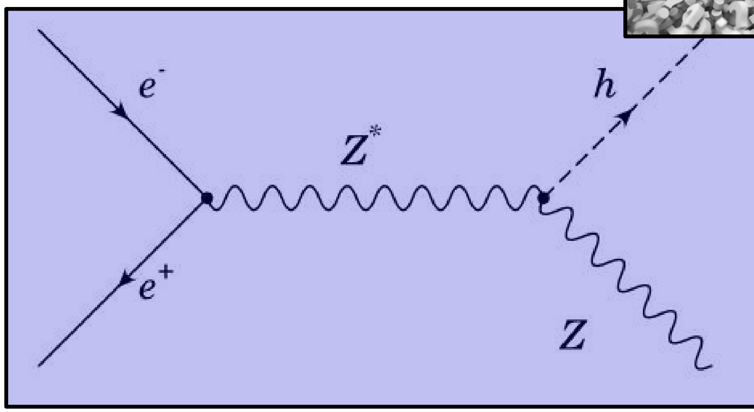
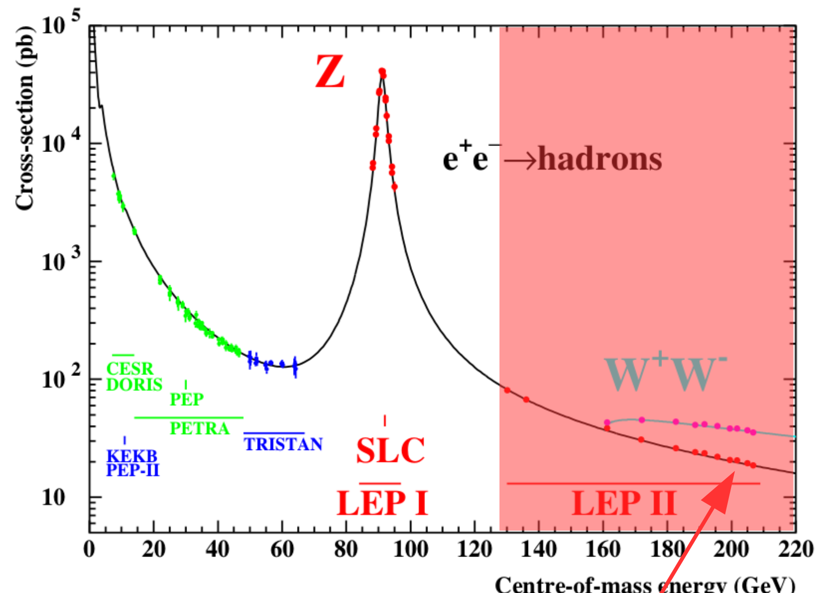


Wie groß war die maximale Reichweite der LEP-Experimente in m_H?



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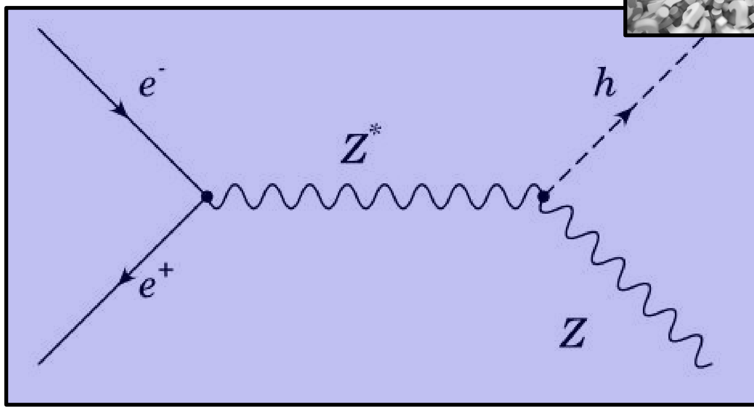

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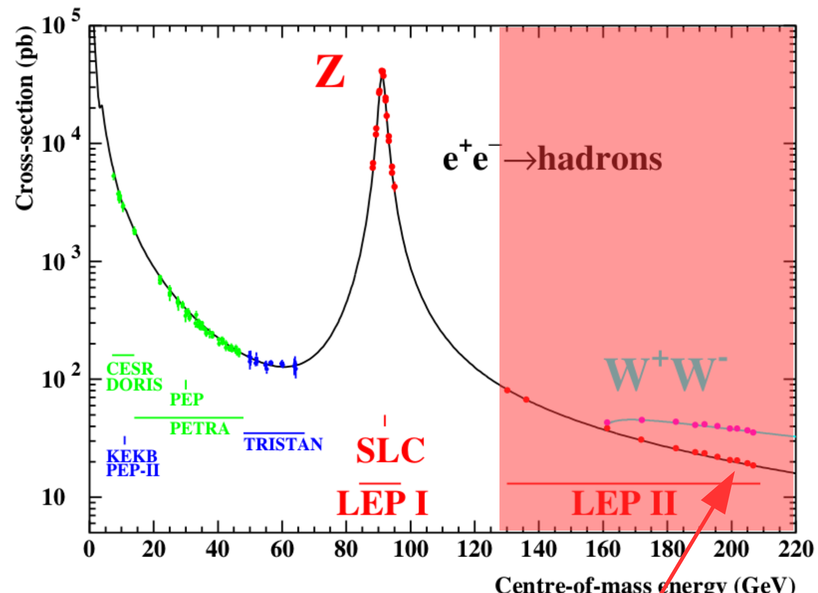
Zu vergleichen mit Folien 9 und 10

Wie groß war die maximale Reichweite der LEP-Experimente in m_H? $\approx 117\ \mathrm{GeV}$



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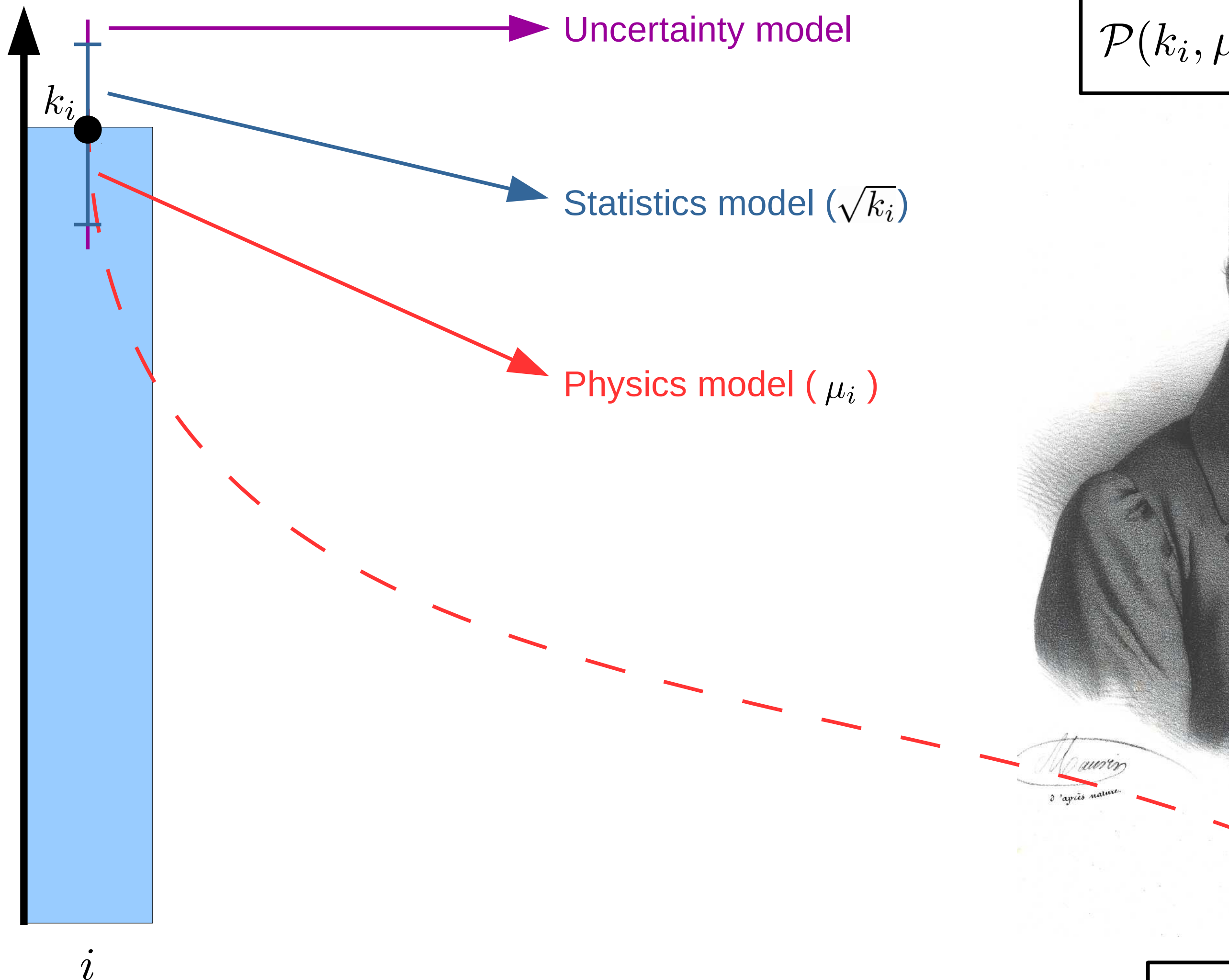
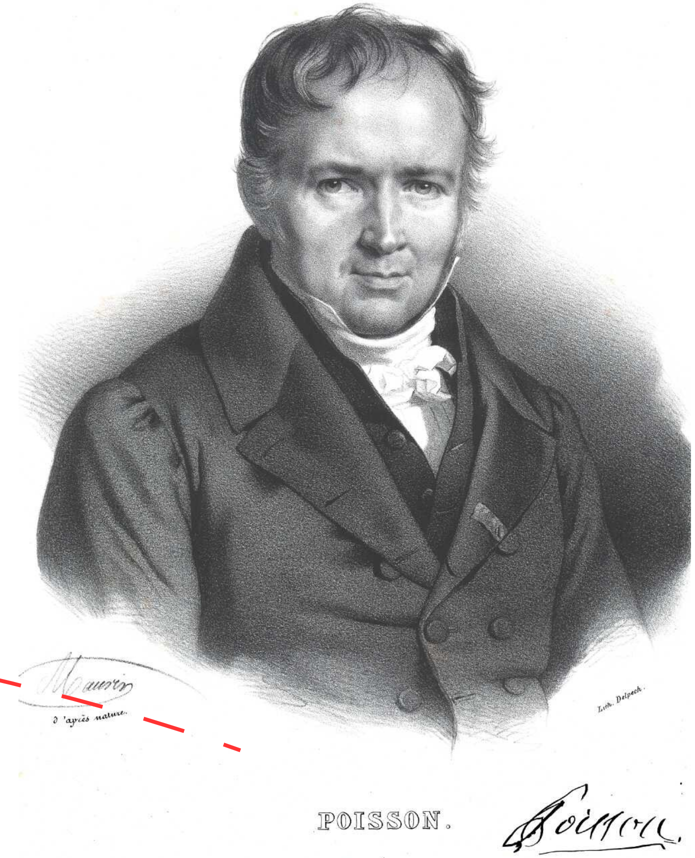
Models in counting experiments

$$\mathcal{P}(k_i, \mu_i) = \frac{\mu_i^{k_i}}{k_i!} e^{-\mu_i}$$

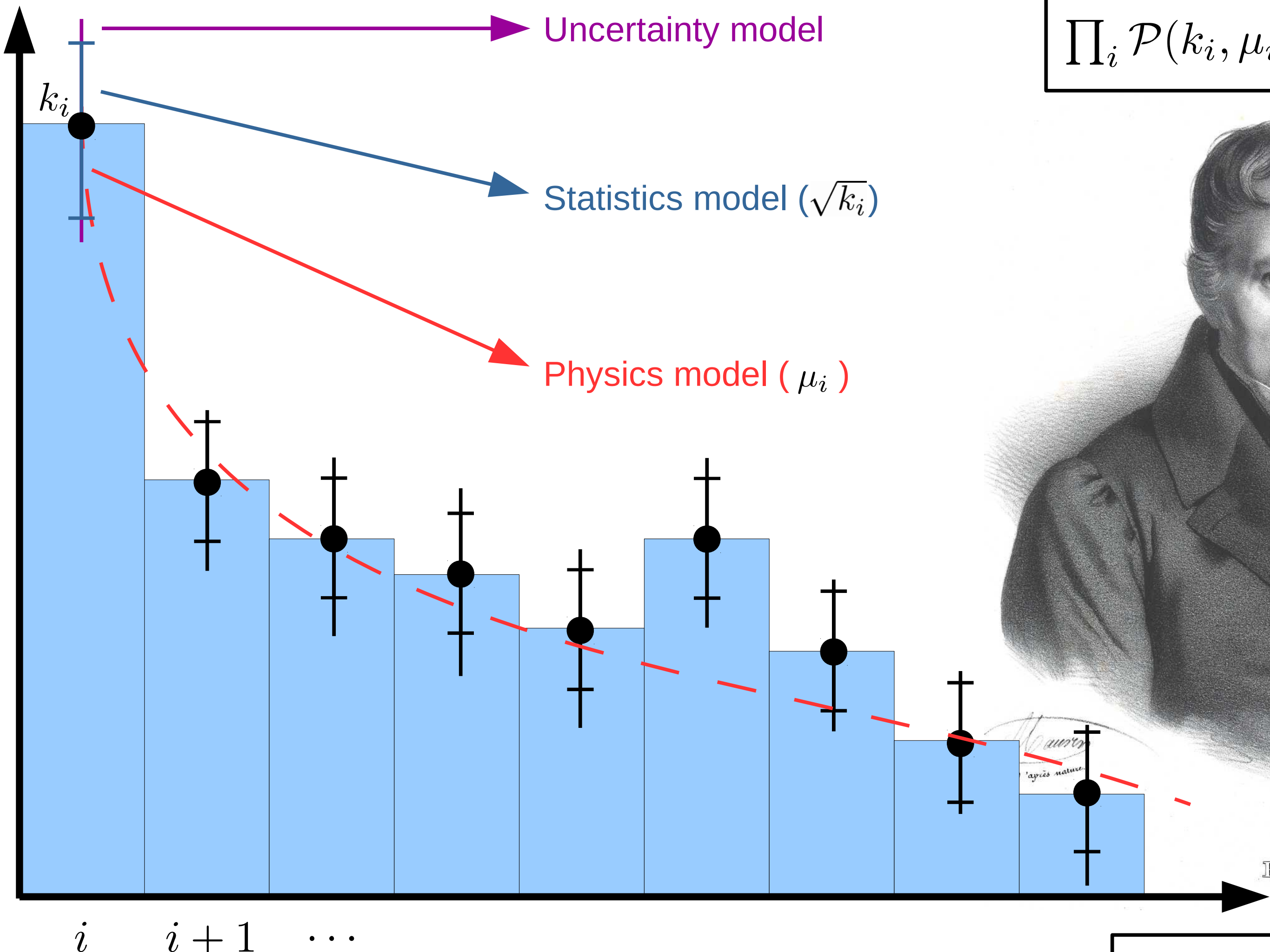


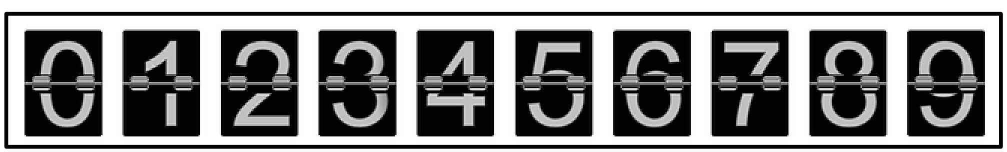


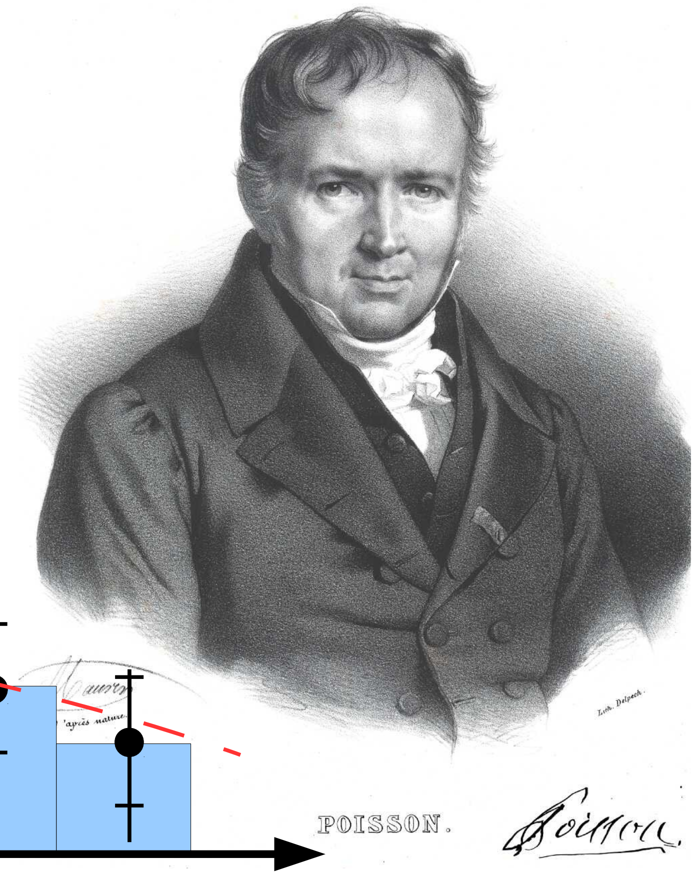
Siméon Denis Poisson
(21.07.1781 – 25.04.1840)

From one to many...

$$\prod_i \mathcal{P}(k_i, \mu_i) = \prod_i \frac{\mu_i^{k_i}}{k_i!} e^{-\mu_i}$$







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Model building (likelihood functions)

- Likeliness of a model to be true quantified by *likelihood function* $\mathcal{L}(\{k_i\},\{\kappa_j\})$.

$$\prod_i \mathcal{P}(k_i,\mu_i) = \prod_i \frac{\mu_i^{k_i}}{k_i!} e^{-\mu_i}$$

$\{\kappa_j\}$ → model parameters.

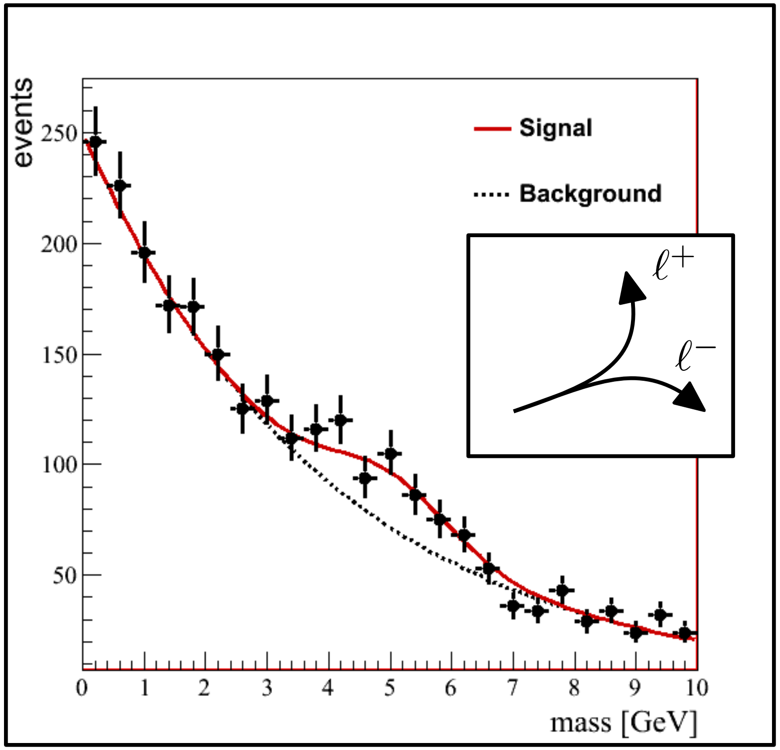
$\{k_i\}$ → measured number of events (e.g. in bins *i*).

- Simple example:
signal on top of known background in a binned histogram:

$$\mathcal{L}(\{k_i\},\{\kappa_j\}) = \prod_i \underbrace{\mathcal{P}(k_i,\mu_i(\kappa_j))}$$

Product of *pdf*s for each bin (Poisson).

$$\mu_i(\kappa_j) = \underbrace{\kappa_0 \cdot e^{-\kappa_1 x_i}}_{\text{background}} + \underbrace{\kappa_2 \cdot e^{-(\kappa_3 - x_i)^2}}_{\text{signal}}$$



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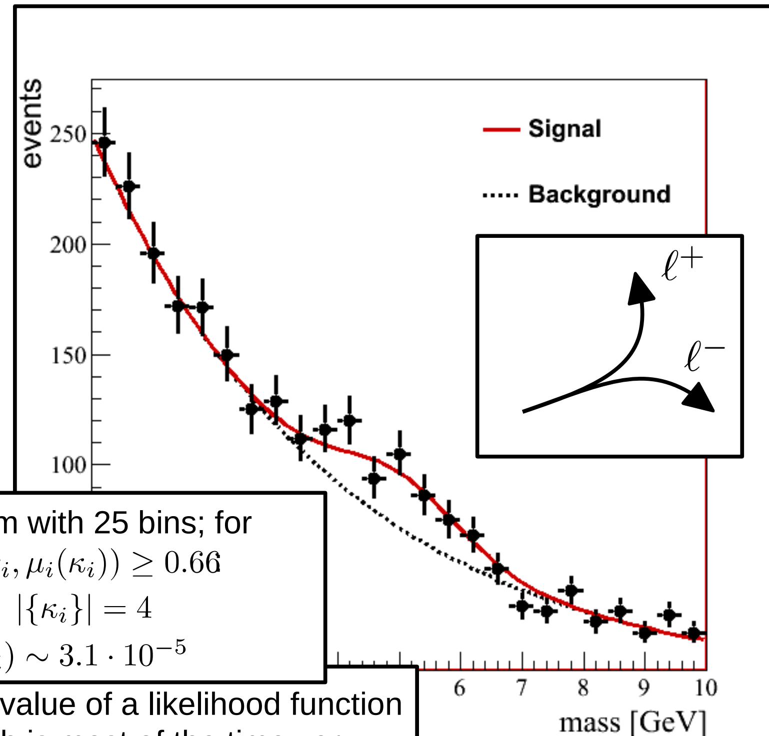


EX: histogram with 25 bins; for each bin $\mathcal{P}(k_i,\mu_i(\kappa_i)) \geq 0.66$

$|\{k_i\}| = 25 \quad |\{\kappa_i\}| = 4$

$\prod \mathcal{P}(k_i,\mu_i(\kappa_i)) \sim 3.1 \cdot 10^{-5}$

NB: a value of a likelihood function as such is most of the time very close to zero, and w/o a reference in general w/o further meaning.

Example: test statistics (LEP ~2000)

- Test signal (H_1, for fixed mass, m, and fixed signal strength, μ) vs. background-only (H_0).

pdf's for nuisance parameters modified according to Bayes theorem.

$$\mathcal{L}(n|\,b(\kappa_j)) = \prod_i \mathcal{P}(n_i|b_i(\kappa_j)) \times \prod_j \mathcal{C}(\kappa_j|\tilde{\kappa}_j)$$

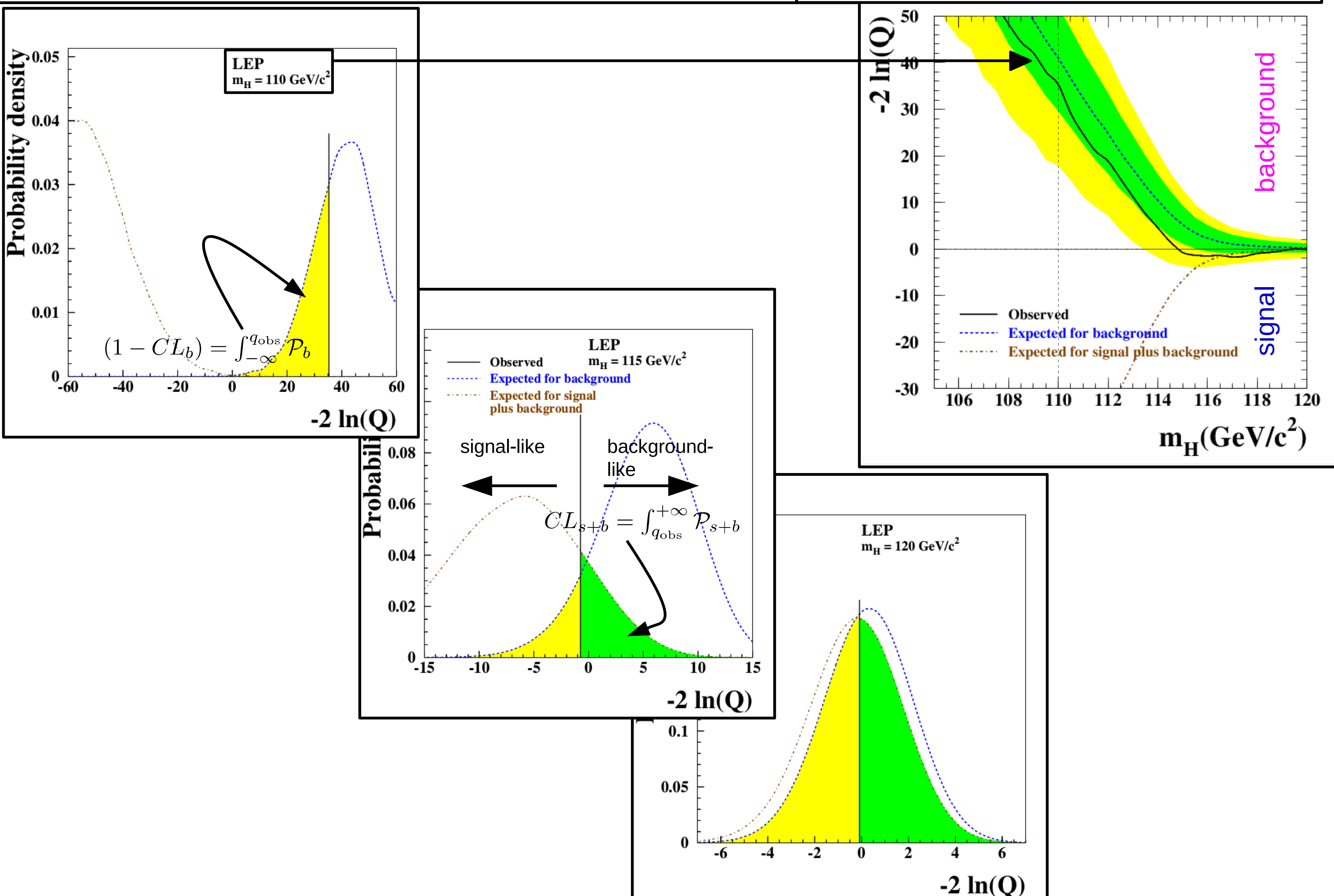
$$\mathcal{L}(n|\,\mu s(\kappa_j) + b(\kappa_j)) = \prod_i \mathcal{P}(n_i|\mu s_i(\kappa_j) + b_i(\kappa_j)) \times \prod_j \mathcal{C}(\kappa_j|\tilde{\kappa}_j)$$

$$q_\mu = -2\ln\left(\frac{\mathcal{L}(\,n|\mu s+b)}{\mathcal{L}(\,n|b)}\right), \quad 0 \leq \mu$$

nuisance parameters $\tilde{\kappa}_j$ integrated out before evaluation of q_μ (→marginalization).

Example: test statistics (LEP)

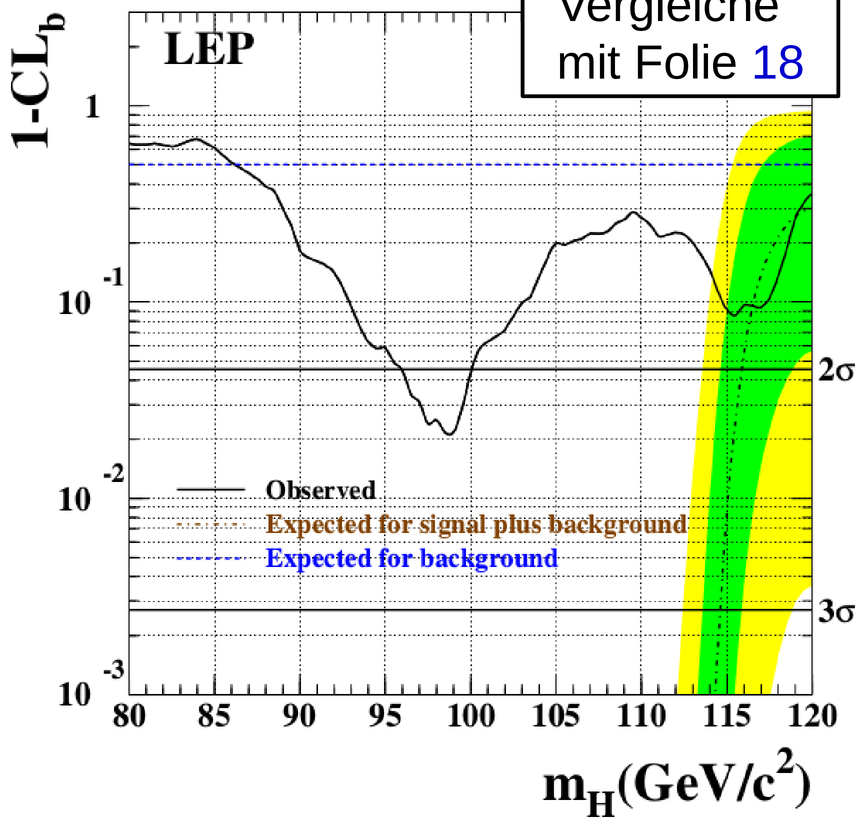
$$q_\mu = -2\ln\left(\frac{\mathcal{L}(n|\mu s+b)}{\mathcal{L}(n|b)}\right), \quad 0 \le \mu$$



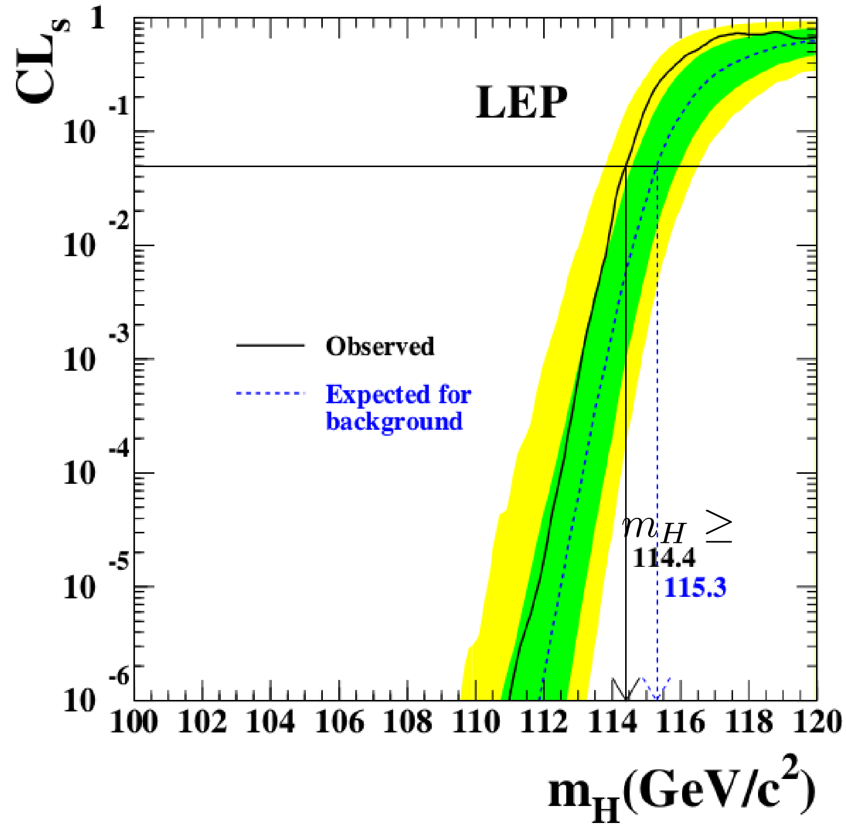
Ergebnis LEP-II

- **p-Wert** (Untergrundkompatibilität) :

Vergleiche mit Folie 18



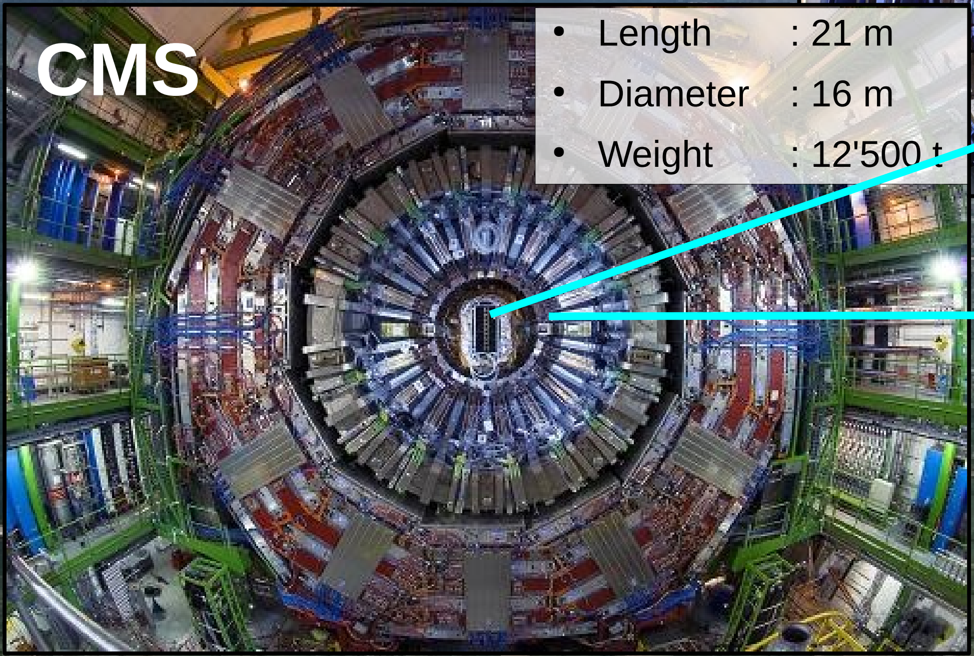
- **Limit auf Masse** (@ 95% CL):



- **Kein Signal** beobachtet

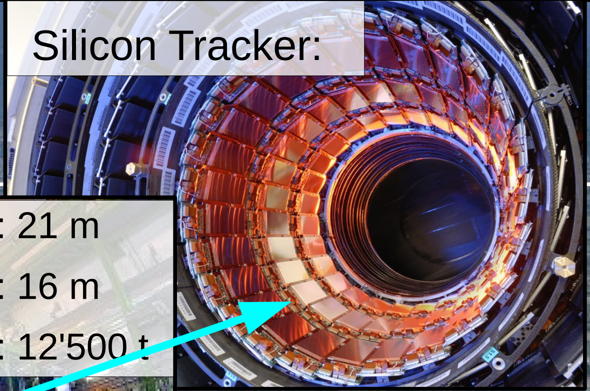
- Untere Schranke auf Masse: $m_H > 114.4$ GeV (@ 95% CL)

Direkte Suche am LHC

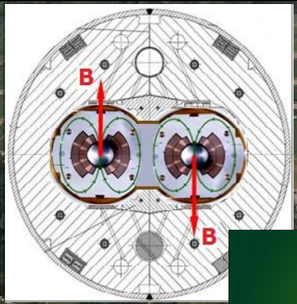


- Length : 21 m
- Diameter : 16 m
- Weight : 12'500 t

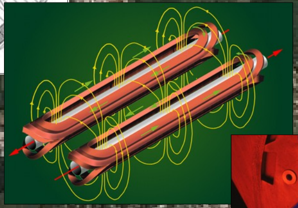
Silicon Tracker:



Electromagnetic Calo:

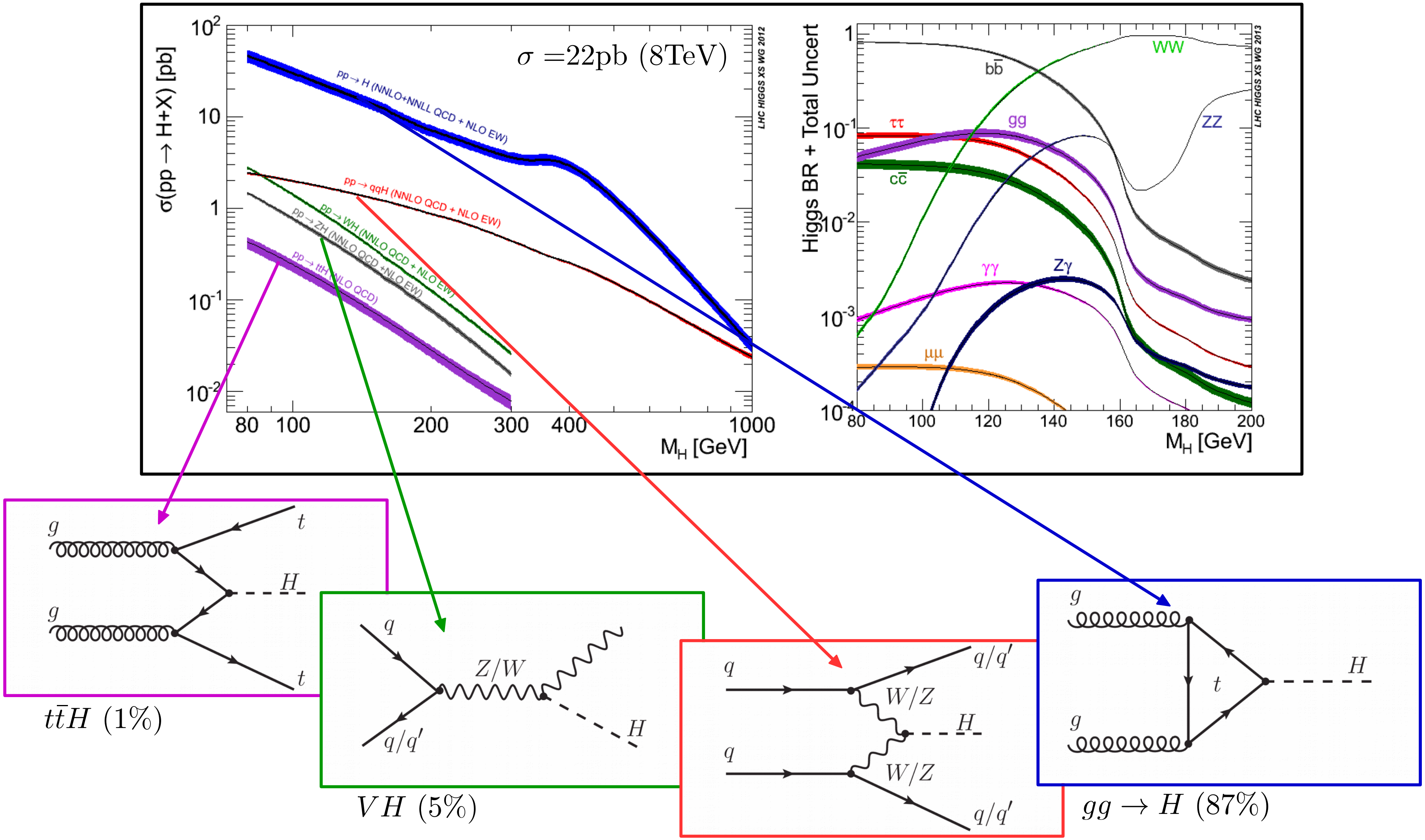


- 8.3 T
- 11.8 kA
- 160 cyc



- Energy density 500 kJ/m.
- Tension 200'000 t/m.

Produktion und Zerfall



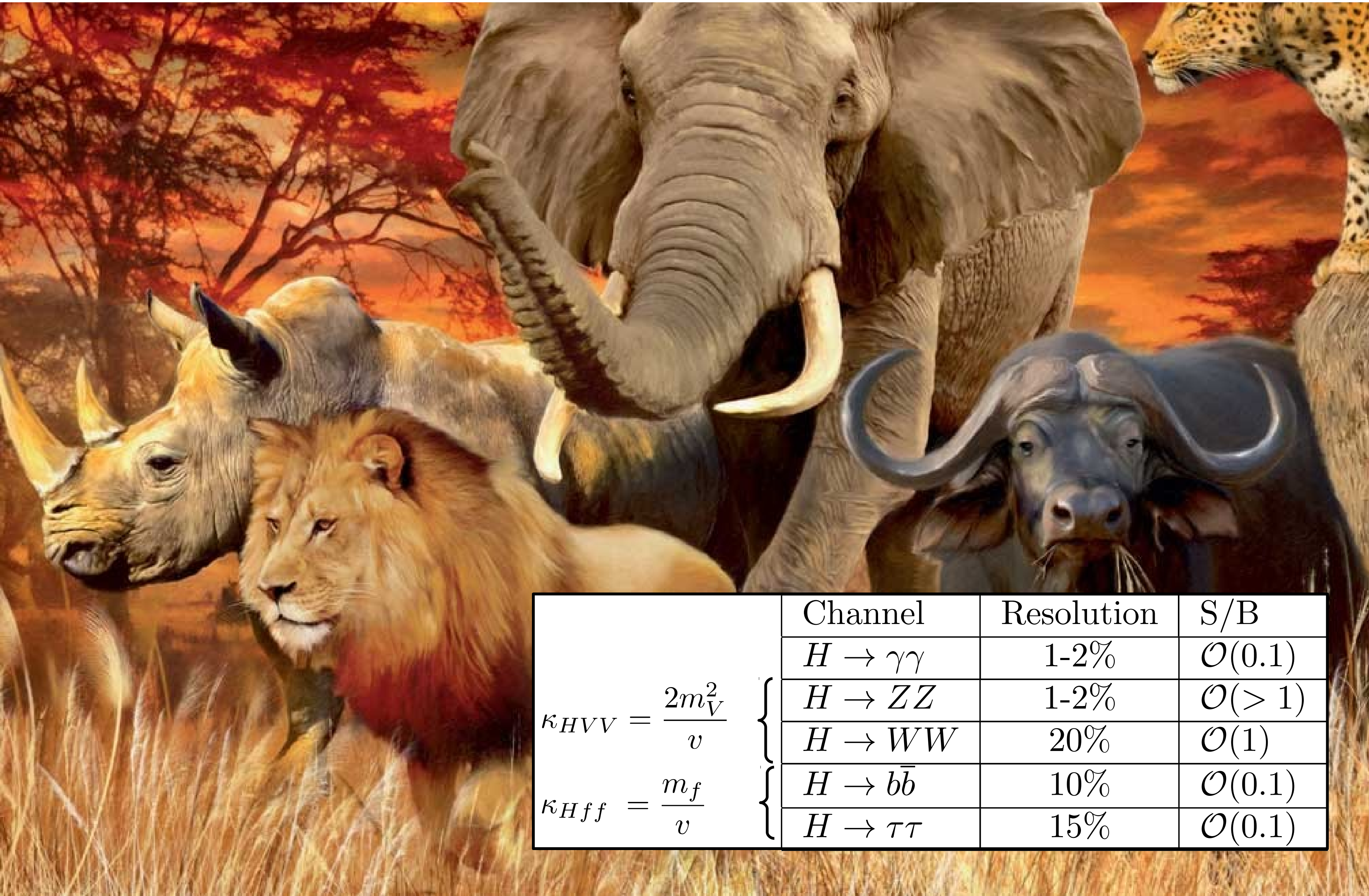
$t\bar{t}H$ (1%)

VH (5%)

$qq \to H$ (7%)

$gg \to H$ (87%)

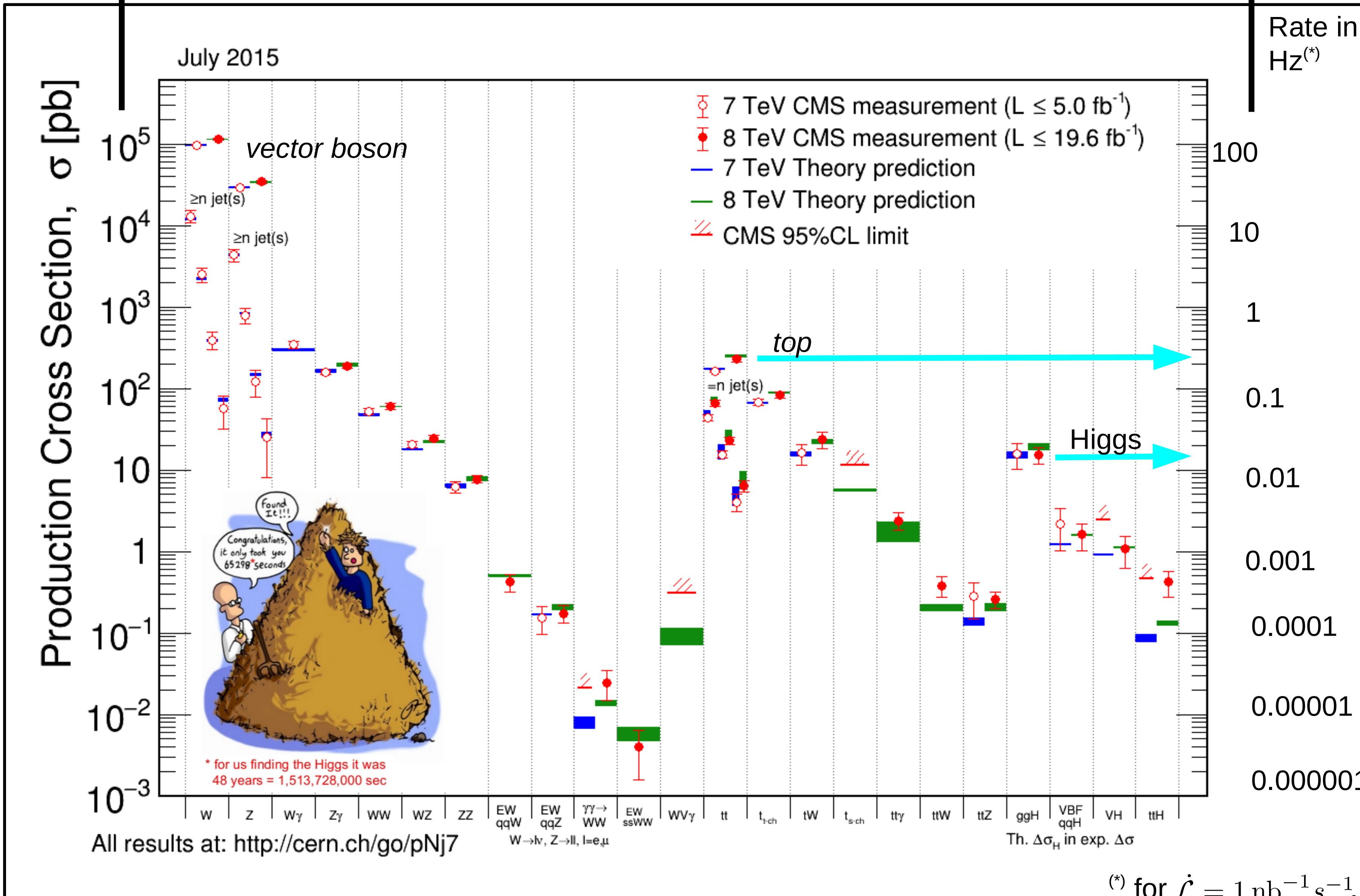
Wichtigste Zerfallskanäle am LHC



	Channel	Resolution	S/B
	$H \to \gamma\gamma$	1-2%	$\mathcal{O}(0.1)$
$\kappa_{HVV} = \frac{2m_V^2}{v}$	$H \to ZZ$	1-2%	$\mathcal{O}(> 1)$
	$H \to WW$	20%	$\mathcal{O}(1)$
$\kappa_{Hff} = \frac{m_f}{v}$	$H \to b\bar{b}$	10%	$\mathcal{O}(0.1)$
	$H \to \tau\tau$	15%	$\mathcal{O}(0.1)$

10^{11} $\sigma_{incl}(pp)$ 10^8

Die Herausforderung

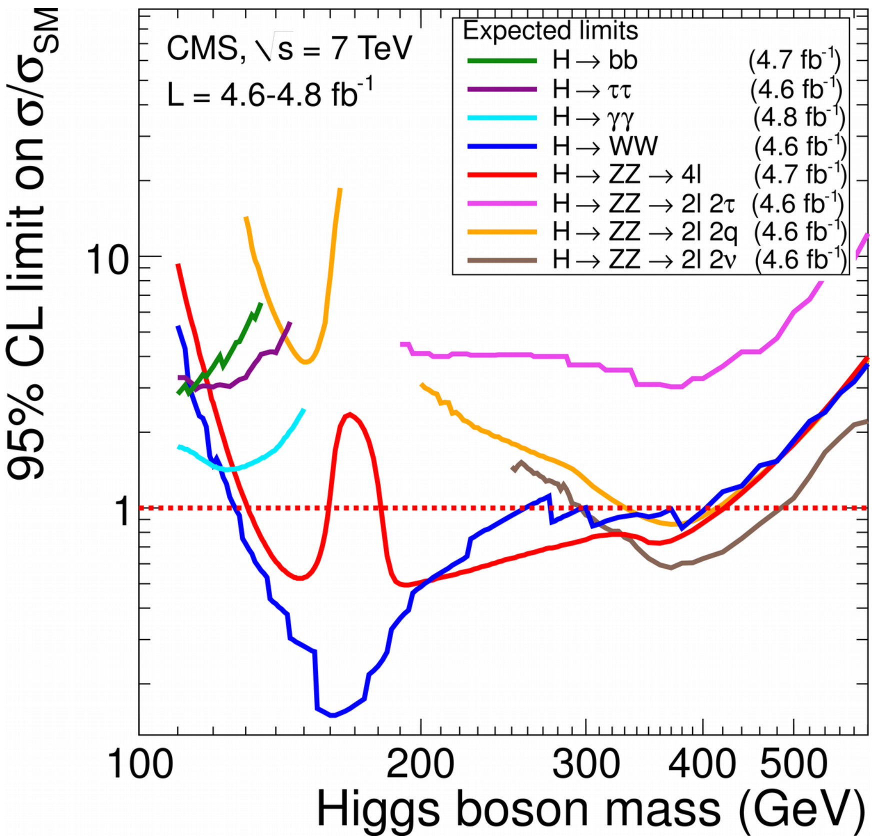


Verlauf der Suche bis Mitte 2012

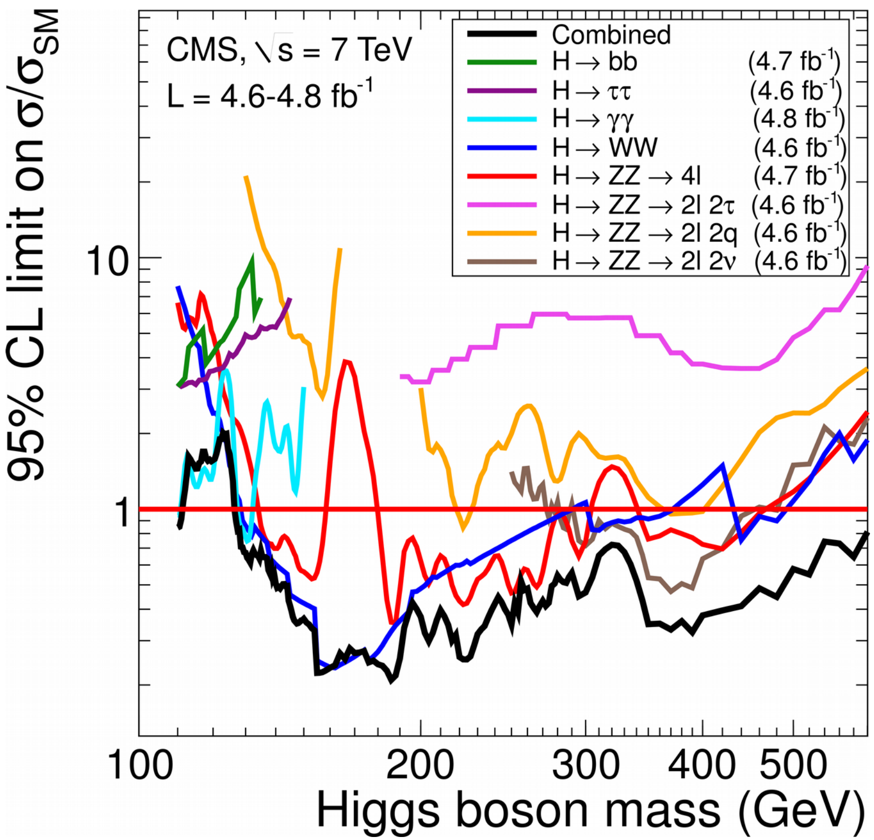
Anm: ausgeschlossen sind alle Bereiche oberhalb der Kurven

- Ausschluß des SM bis auf **engen Massenbereich** des Higgs Bosons

- Erwartete (Ausschluß-)Sensitivität:

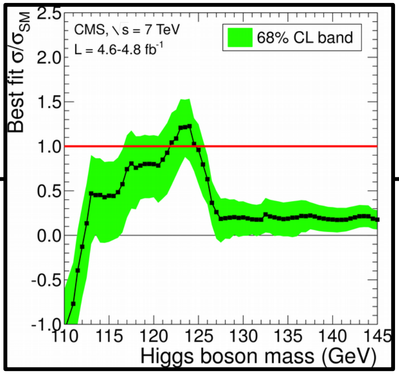


- Beobachteter Massenausschluß:



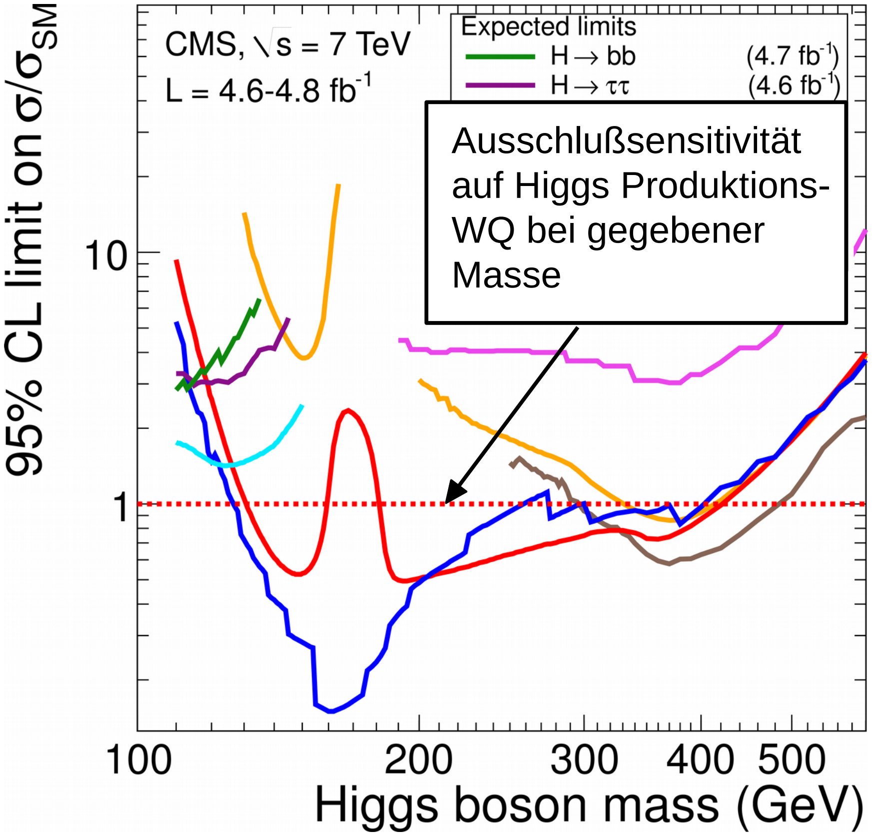
Verlauf bis Mitte 2012

Signalstärke aus Anpassung an Daten

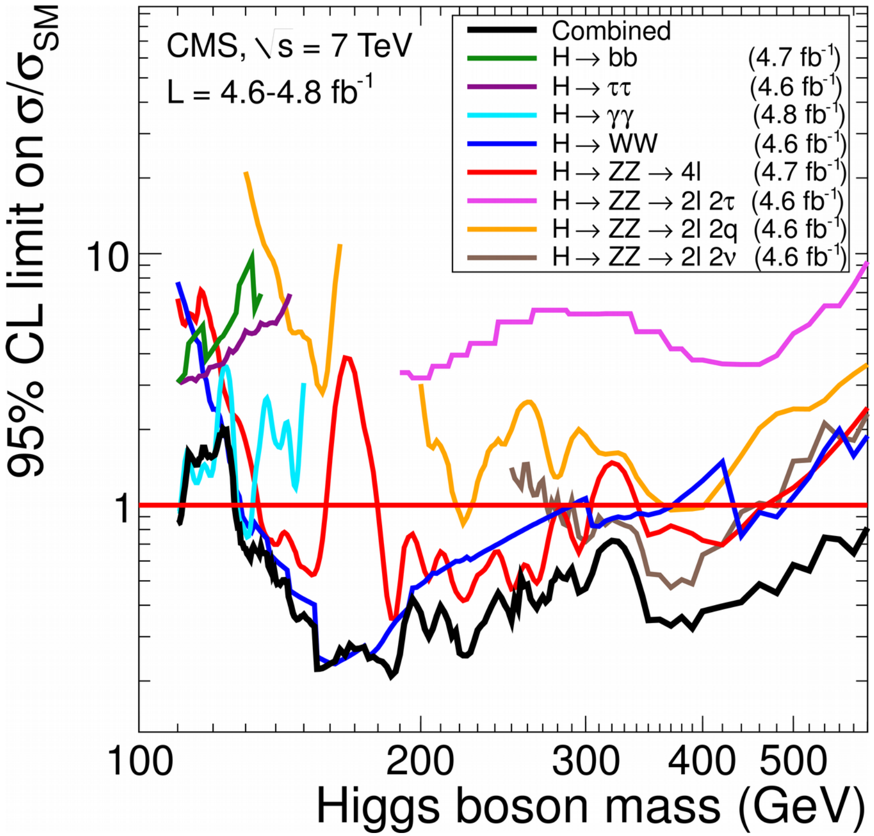


- Ausschluß des SM bis auf **engen Massenbereich** des Higgs Bosons

- Erwartete (Ausschluß-)Sensitivität:

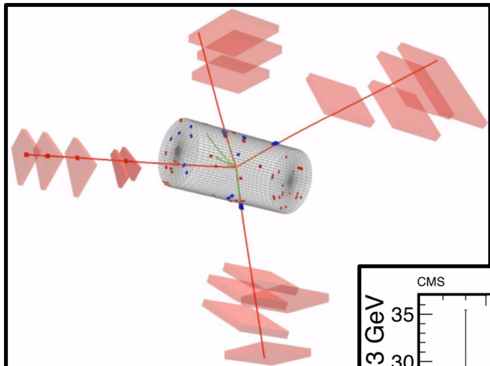


- Beobachteter Massenausschluß:

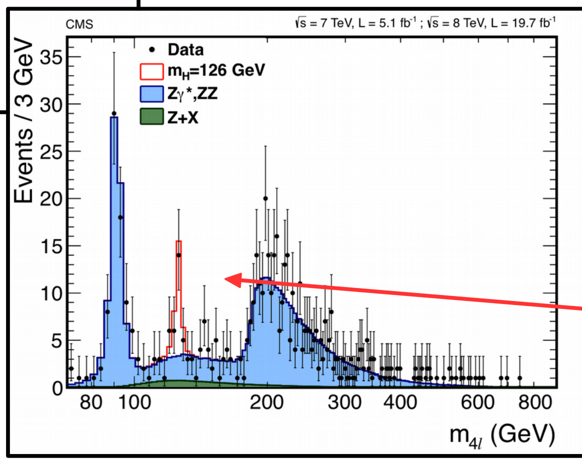


Die Entdeckung

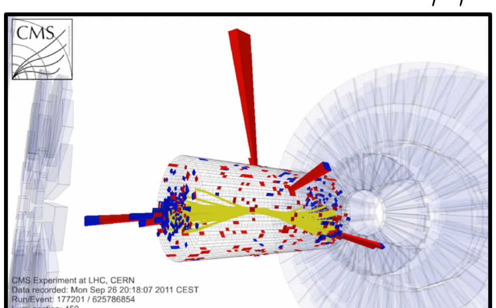
- **Klare Beobachtung** in bosonischen Zerfallskanälen
- Fermionische Kanäle noch nicht klar, weil noch nicht sensitiv genug (→ erfolgte etwas später)

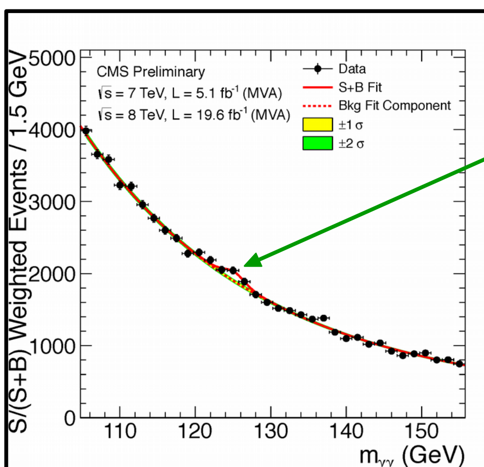


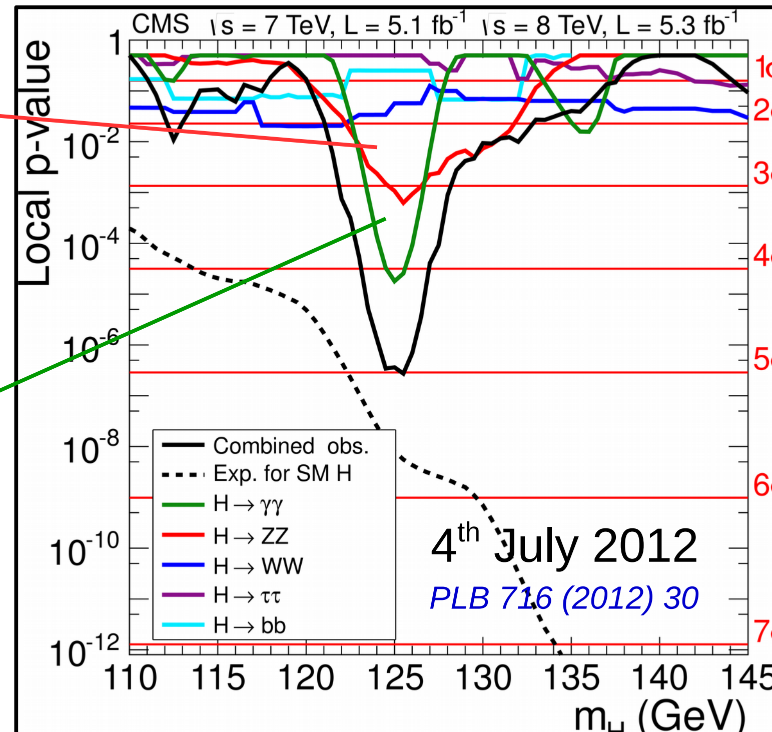
$H \to ZZ \to 4\ell$



$H \to \gamma\gamma$





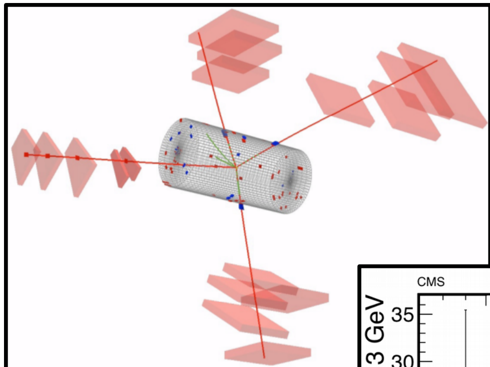


Die Entdeckung

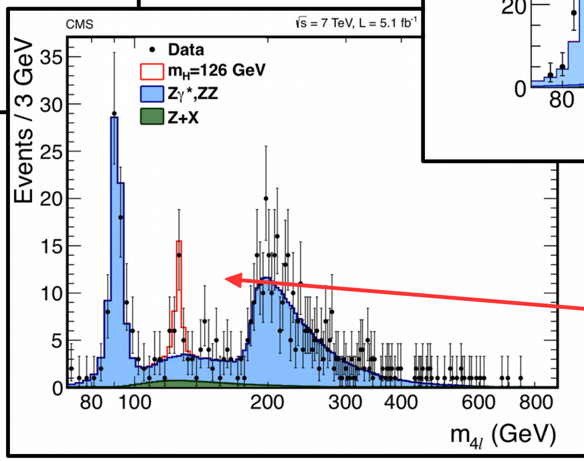
bosonischen

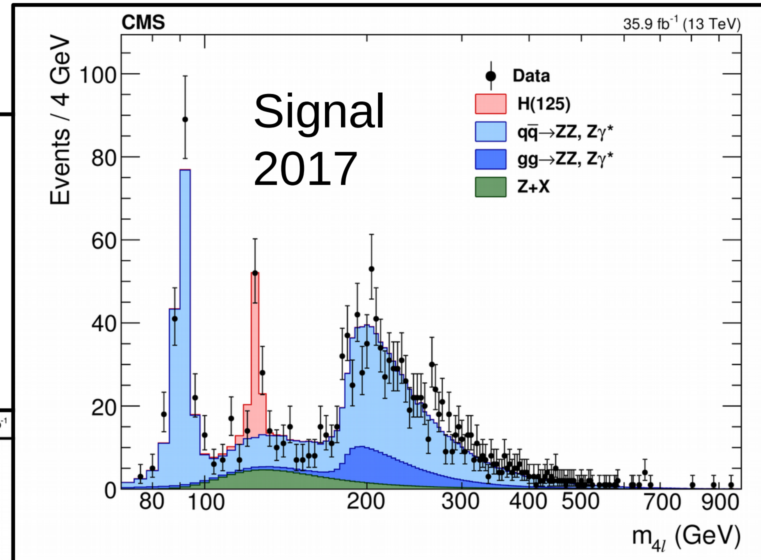
och nicht klar,

genug (→

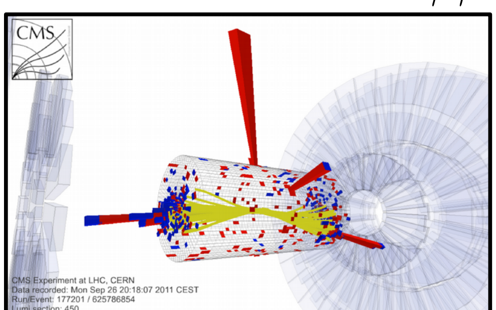


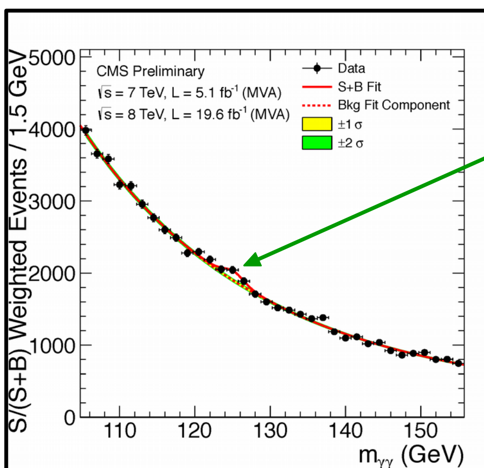
$H \to ZZ \to 4\ell$

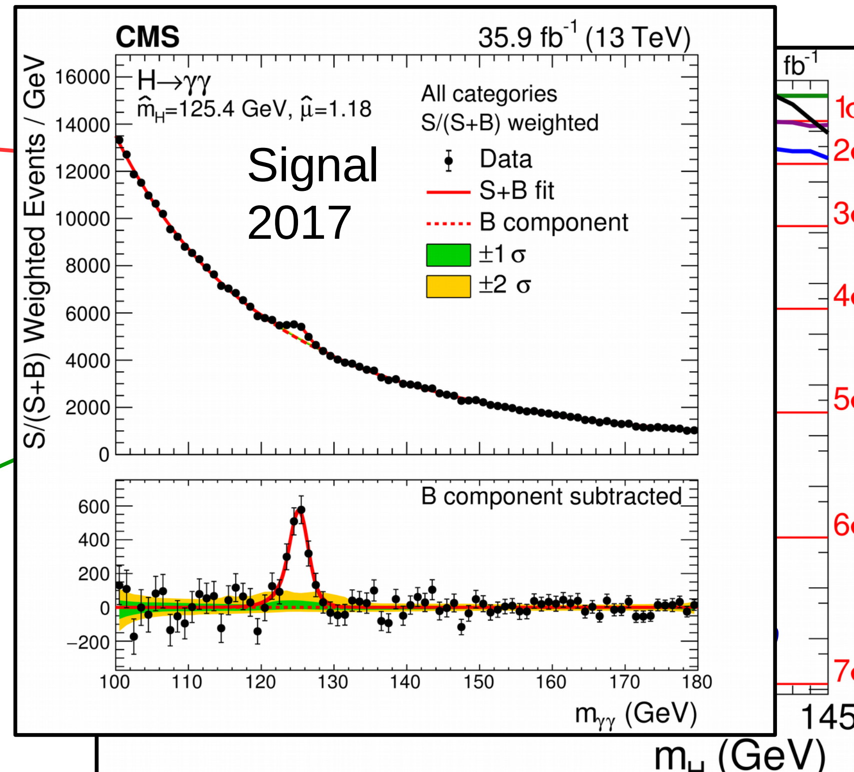




$H \to \gamma\gamma$

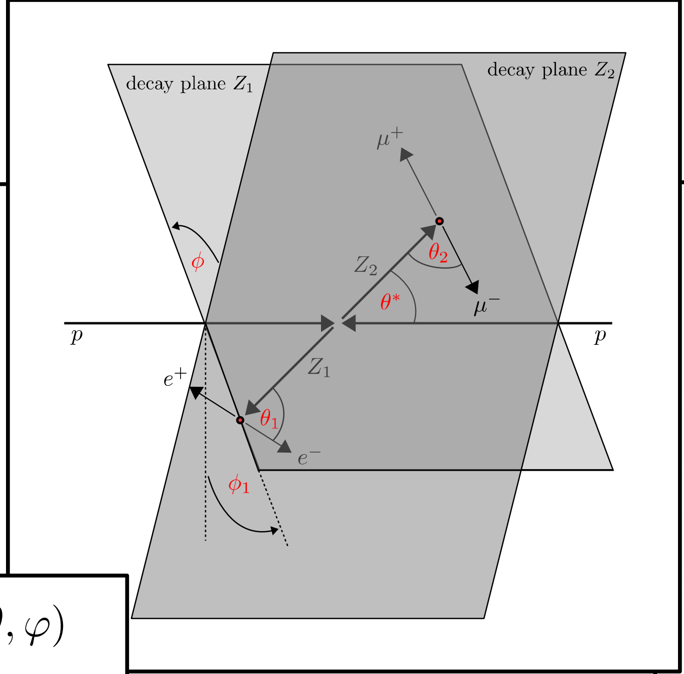


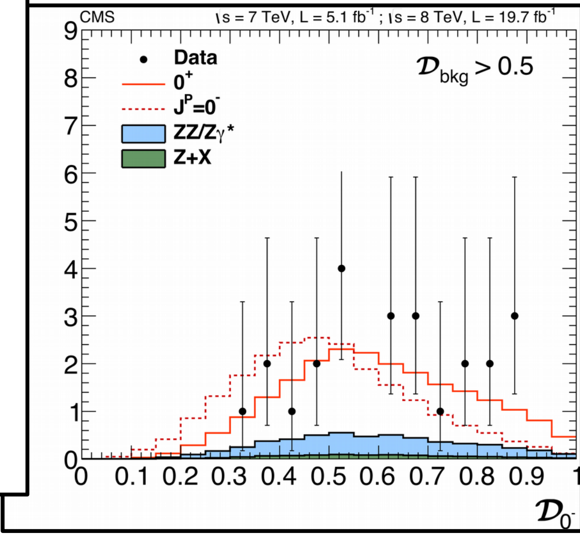




Spin & CP

- Golden decay channel: $H \to ZZ \to 4\ell$

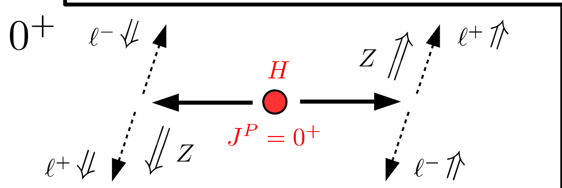




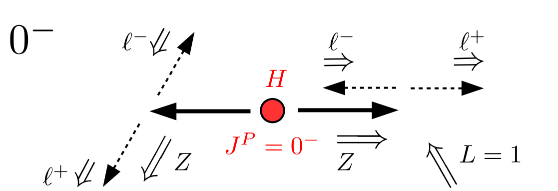
PRD 89 (2014) 092007

$$P(Y_L^m(\theta,\varphi)) = (-1)^L \cdot Y_L^m(\theta,\varphi)$$

$$P(4\ell) = (-1)^L(-1)^2(+1)^2 = (-1)^L$$

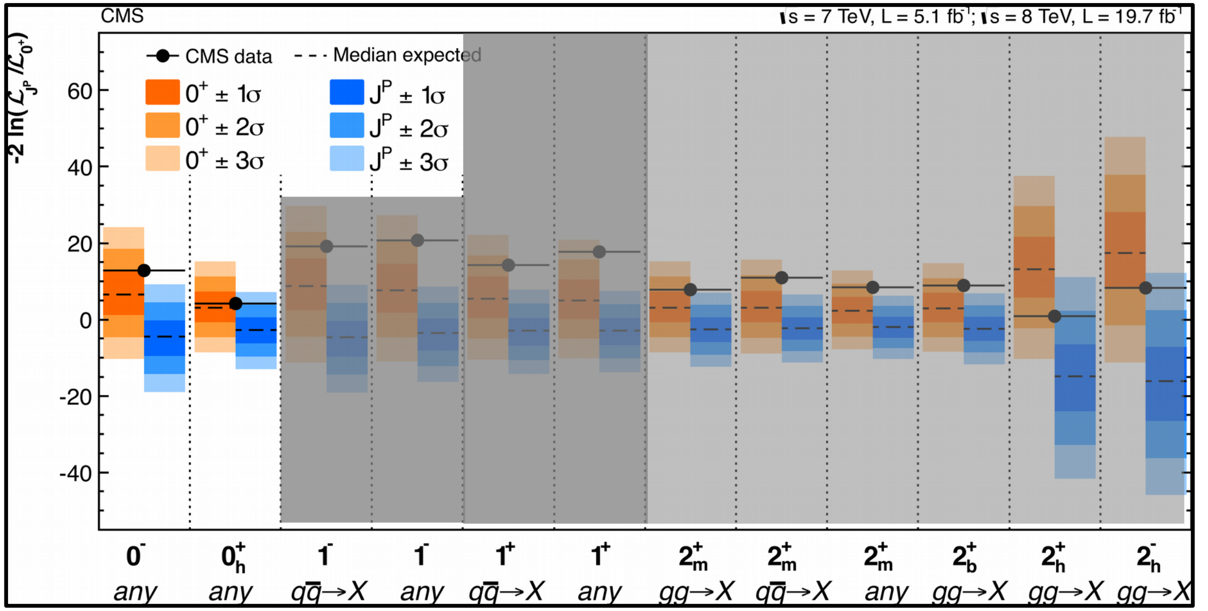


$$|0,0\rangle = \sqrt{\tfrac{1}{3}}|1,\ \ 1\rangle \otimes |1,-1\rangle - \sqrt{\tfrac{1}{3}}|1,0\rangle \otimes |1,0\rangle + \sqrt{\tfrac{1}{3}}|1,-1\rangle \otimes |1,\ \ 1\rangle$$



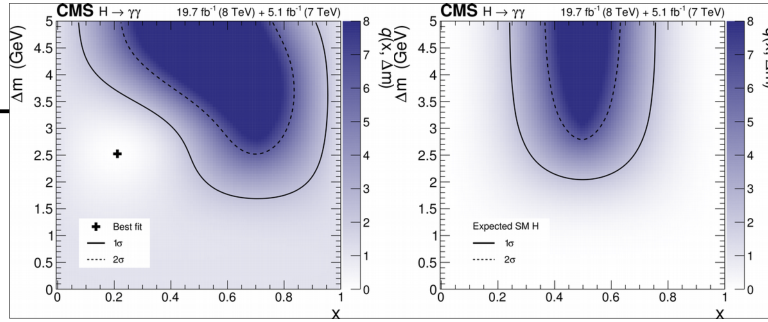
$$|1,\pm1\rangle = \sqrt{\tfrac{1}{2}}|1,\pm1\rangle \otimes |1,0\rangle - \sqrt{\tfrac{1}{2}}|1,0\rangle \otimes |1,\pm1\rangle$$

Test of pure **spin hypotheses** (based on $\mathcal{O}(50)$ evts):



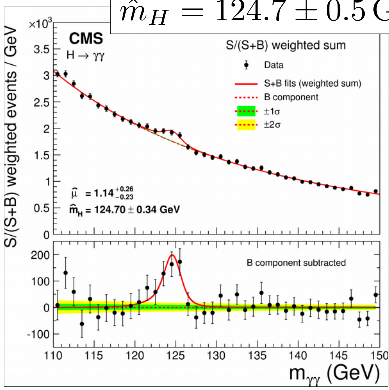
Compatibility

Second close-by resonance in $H \to \gamma\gamma$?



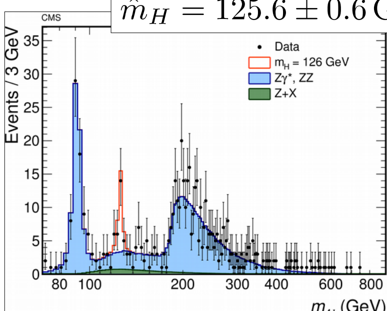
EPJ C 74 (2014) 3076

Coupling across production modes or decay channels:



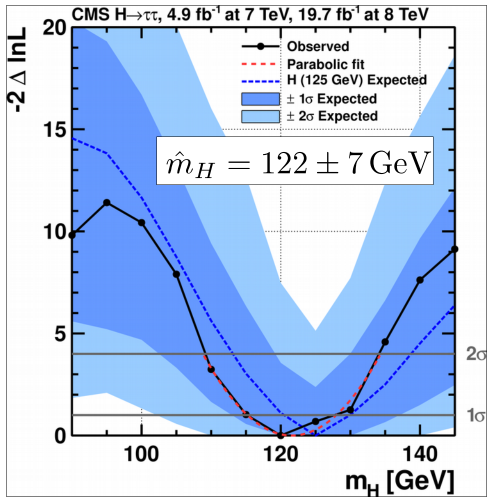
$\hat{m}_H = 124.7 \pm 0.5\,\text{GeV}$

EPJ C 74 (2014) 3076



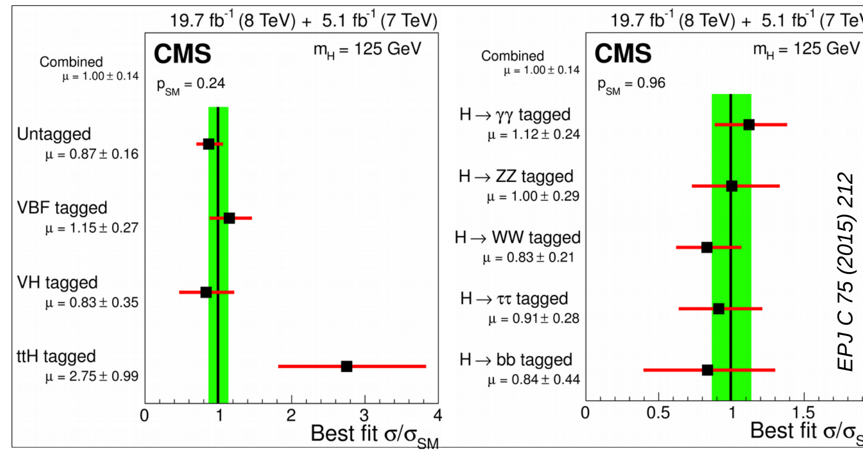
$\hat{m}_H = 125.6 \pm 0.6\,\text{GeV}$

PRD 89 (2014) 092007

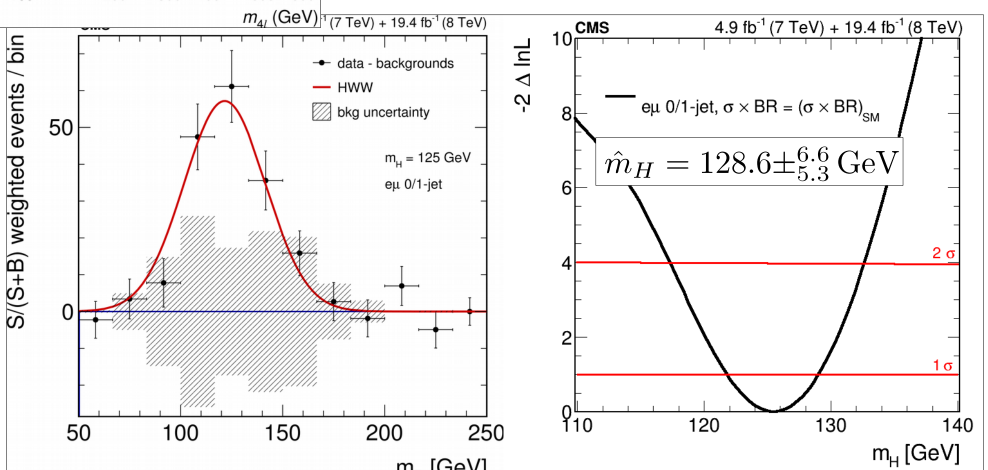


$\hat{m}_H = 122 \pm 7\,\text{GeV}$

JHEP 05 (2014) 104



EPJ C 75 (2015) 212



$\hat{m}_H = 128.6^{+6.6}_{-5.3}\,\text{GeV}$

JHEP 01 (2014) 096

Overall coupling consistency:

- Event categories : 227
- Nuisance parameters: $\mathcal{O}(2500)$
- 16 MB binary file of stat. model (~145 MB in human readable form).

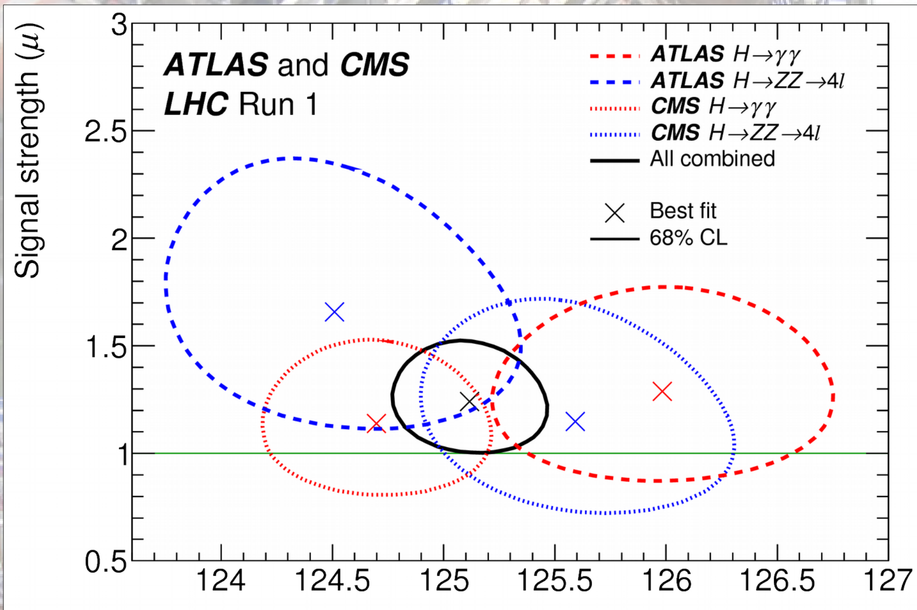
$\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.14$

$p\text{-value} = 84\%$

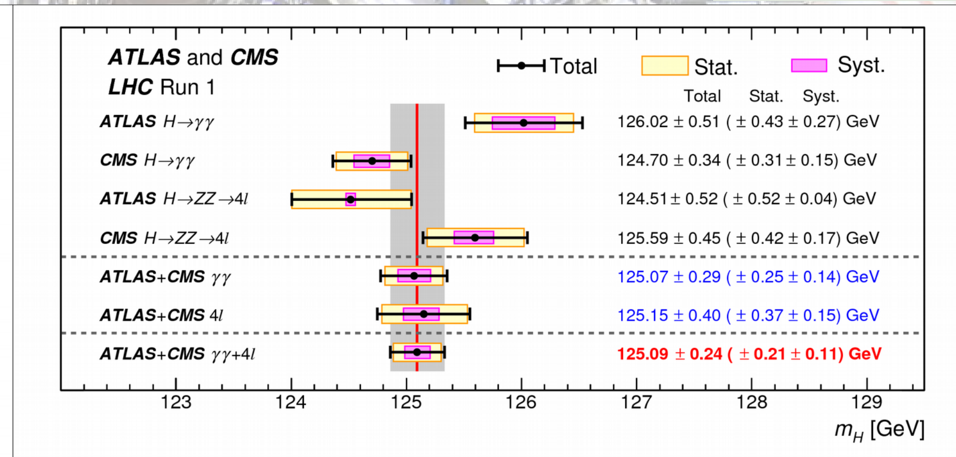
EPJ C 75 (2015) 212

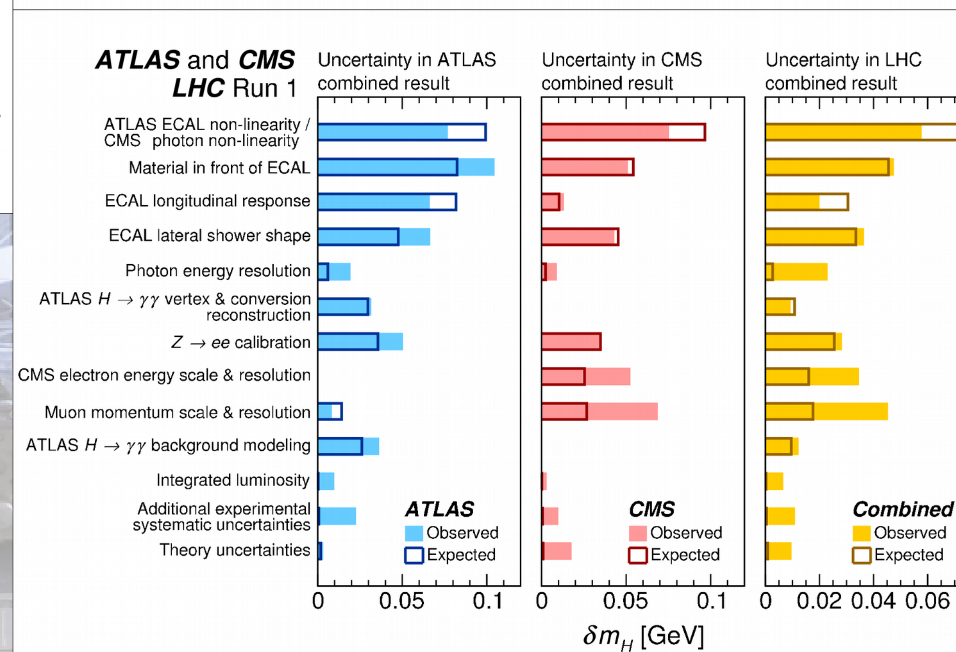
Mass

- ATLAS+CMS **LHC run-1 combination**:



PRL 114 (2015) 191803





$$125.06 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})\ \text{GeV}$$

Coupling structure

CMS-PAS-HIG-15-002

- Event categories : 574
- Nuisance parameters: 4268

$\mu = \sigma/\sigma_{SM} = 1.09 \pm 0.11$

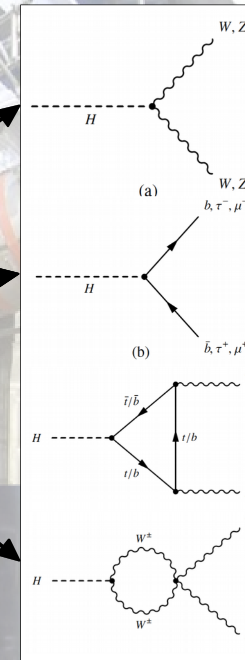
- ATLAS+CMS **LHC run-1 combination**:

Considered production modes:

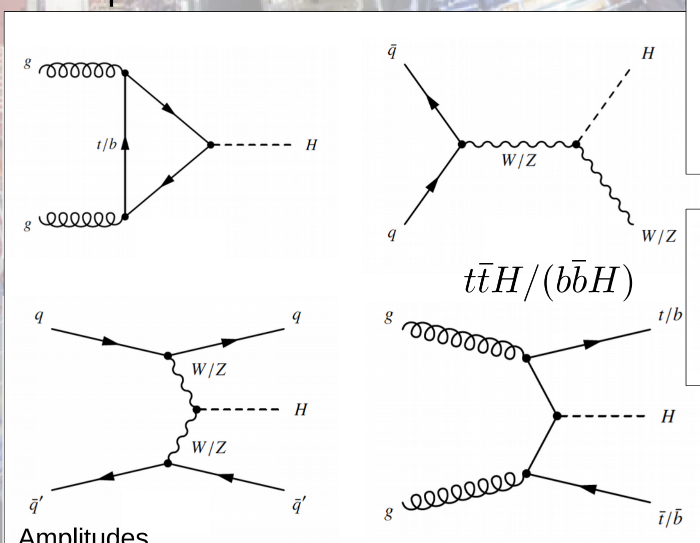
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
[$ggZH$]	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

Considered decay channels:

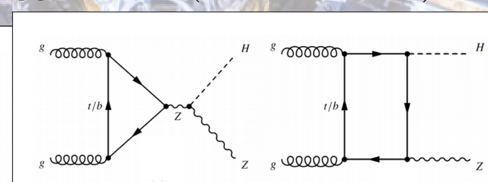
Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

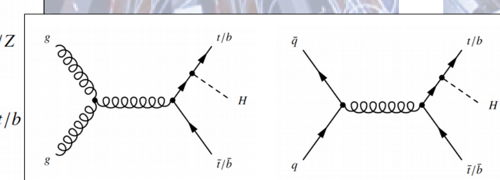


Main production modes:

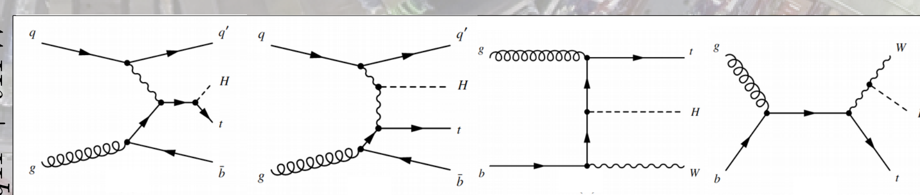


$gg \to ZH$ (10% to $ZHbb$)

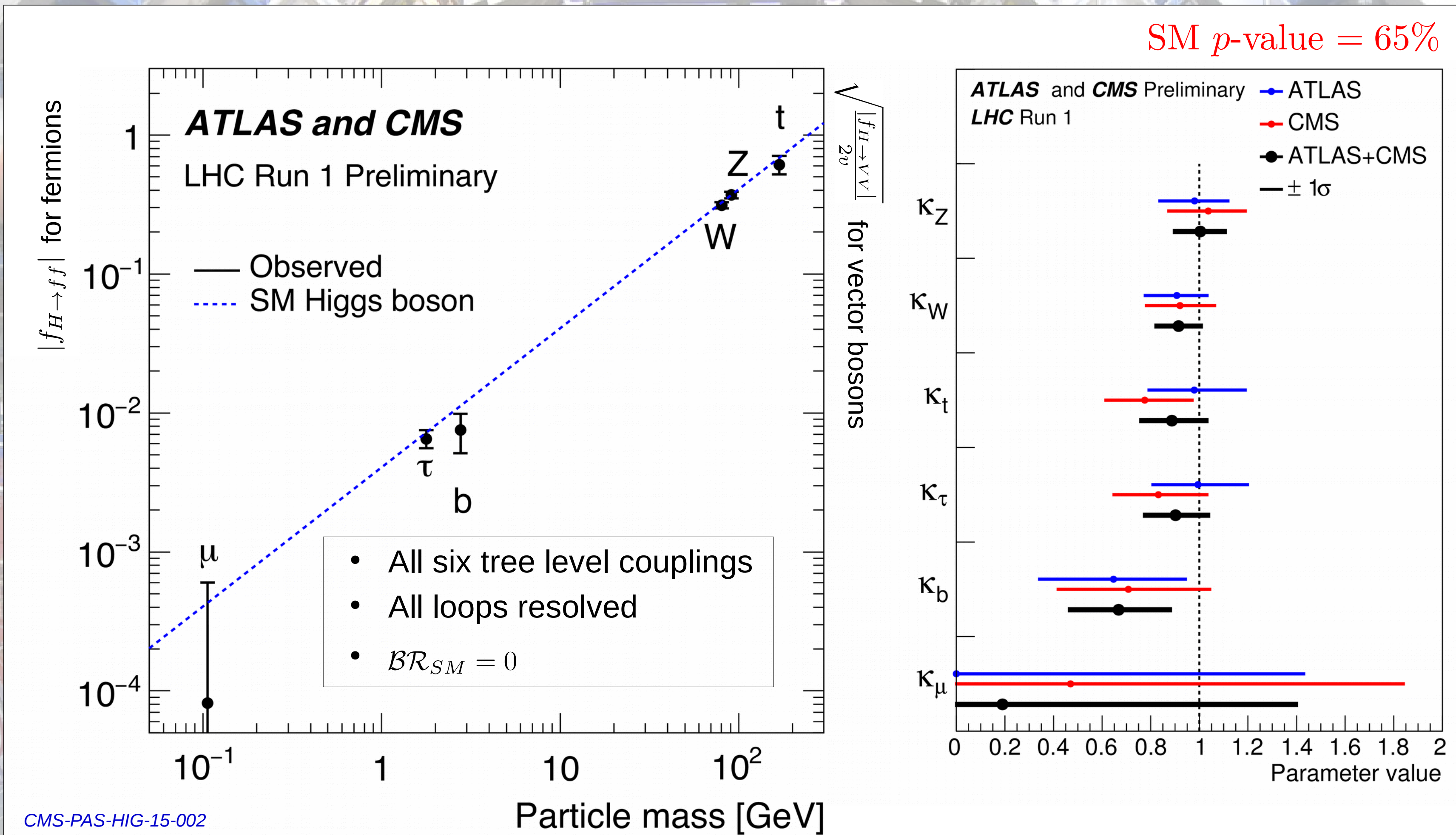




$tqH + tHW$



"Money plot"



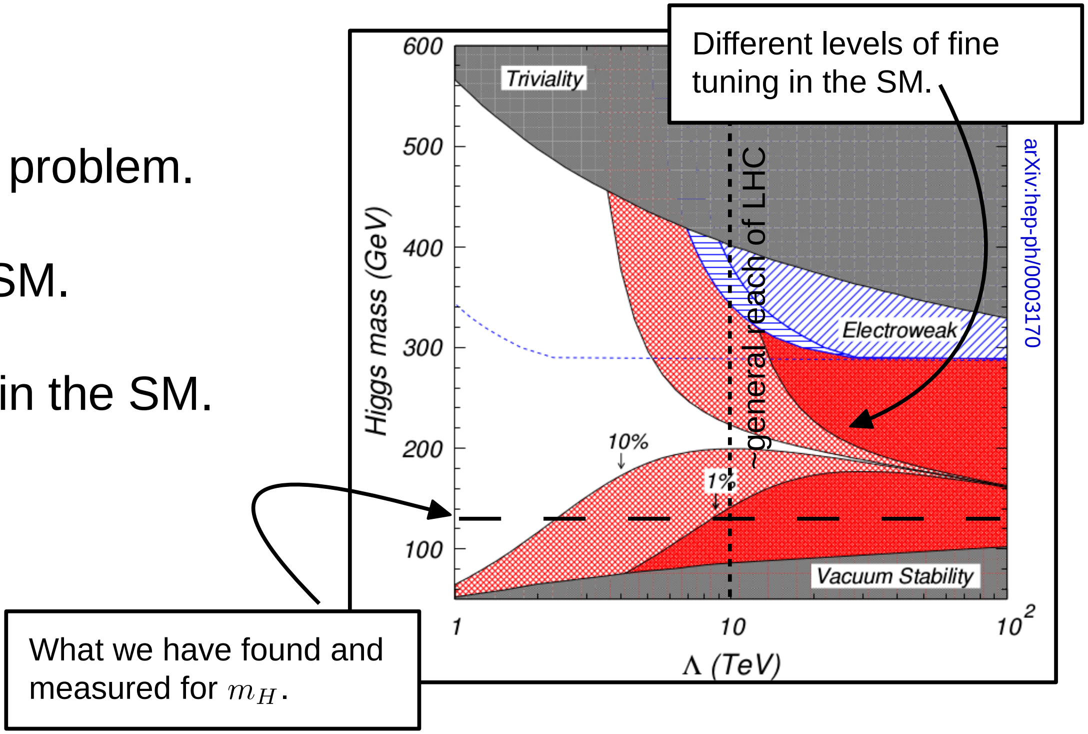
$$|f^{\text{obs}}_{H\to ff}| = \kappa_f \cdot |f^{\text{SM}}_{H\to ff}| = \kappa_f \cdot \frac{m_f}{v} \qquad f = \mu, \tau, b, t$$

$$\sqrt{\frac{|f^{\text{obs}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \sqrt{\frac{|f^{\text{SM}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \frac{m_V}{v} \qquad V = W, Z$$

Within measurement accuracy **unique scaling** as expected within the SM.

Why the Higgs boson still is not THE Higgs boson [1]

- Gravity is not included in the SM.
- The SM suffers from the hierarchy problem.
- Dark matter is not included in the SM.
- Neutrino masses are not included in the SM.
- There are known deviations from the SM expectation in $a_\mu \equiv \frac{g_\mu - 2}{2}$ (3.6σ unresolved).



- There must be physics beyond the SM!
- At what scale does it set in?
- (How) Does it influence the Higgs sector?

[1] Arguments taken from S. Heinemeyer (HH Higgs workshop 2014)

Gliederung der Vorlesung

YOU ARE HERE

Vorlesung:	Vorlesungstag:	Übungsblatt:
VL-01 Einheiten, Relativistische Kinematik	Di 17.04.2018	-
VL-02 Teilchenstreuung	Do 19.04.2018	-
VL-03 Wirkungsquerschnitt	Di 24.04.2018	Blatt-01
VL-04 Teilchenbeschleunigung	Do 26.04.2018	-
Vorlesung fällt aus	Di 01.05.2018	Blatt-02
VL-05 Teilchennachweis durch Ionisation	Do 03.05.2018	-
VL-06 Elektromag. WW und Schauer	Di 08.05.2018	Blatt-03
Vorlesung fällt aus	Do 10.05.2018	-
VL-07 Detektoren der Teilchenphysik	Di 15.05.2018	Blatt-04
VL-08 Symmetrien und Erhaltunsästze	Do 17.05.2018	-
VL-09 Fundamentale Teilchen und Kräfte im SM	Di 22.05.2018	Blatt-05
VL-10 Diskrete Symmetrien des SM	Do 24.05.2018	-
VL-11 Teilchenzoo: vom Hadron zum Quark	Di 29.05.2018	Blatt-06
Vorlesung fällt aus	Do 31.05.2018	-
VL-12 Farbladung und QCD	Di 05.06.2018	Blatt-07
VL-13 Phänomenologie der schwachen WW	Do 07.06.2018	-
VL-14 Theorie der elektroschwachen WW	Di 12.06.2018	Blatt-08
VL-15 Higgs Mechanismus	Do 14.06.2018	-
VL-16 SM: Quarksektor	Di 19.06.2018	Blatt-09
VL-17 Top: Entdeckung und Eigenschaften	Do 21.06.2018	-
VL-18 Higgs: Entdeckung und Eigenschaften	Di 26.06.2018	-
VL-19 Neutrinophysik	Do 28.06.2018	-

Backup