Az ATLAS és CMS legújabb Higgs-adatai és elméleti interptretálásuk

Elméleti Fizikai Szeminárium,
MTA WIGNER FK RMKI,Budapest

Zoltan Kunszt , ITP, ETH, Zurich
22 March 2013

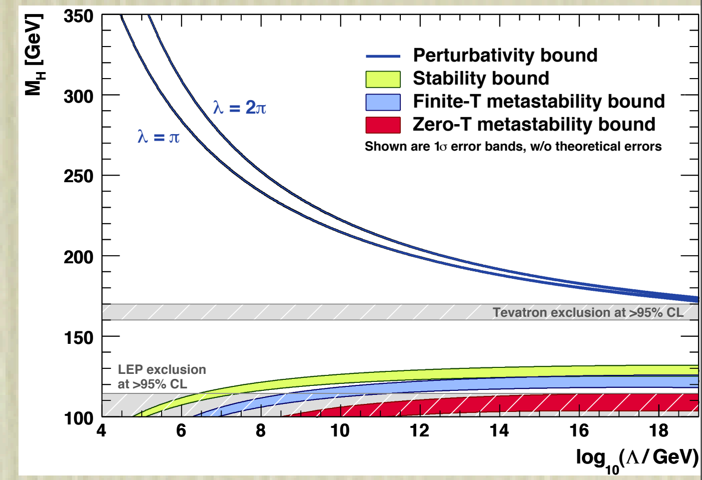
1. Fundamental scalars with fine tuning
2. Supersymmetric standard model
3. Composite Higgs

PART II:

EXPERIMENT AND PHENOMENOLOGY

Historical comments on Higgs-phenomenology

Development of the Higgs-phenomenology



Theoretical Constraints on Higgs Mass:

Unitarity, triviality, stability of the Higgs-potential

$$M_H < 0.7 - 1.0 \text{ TeV}$$

Slow start for phenomenology:

Neutron-electron scattering, nuclear $0^+ - 0^+$ transitions,

neutron-nucleon scattering, emission from starts $M_H > 18$ MeV

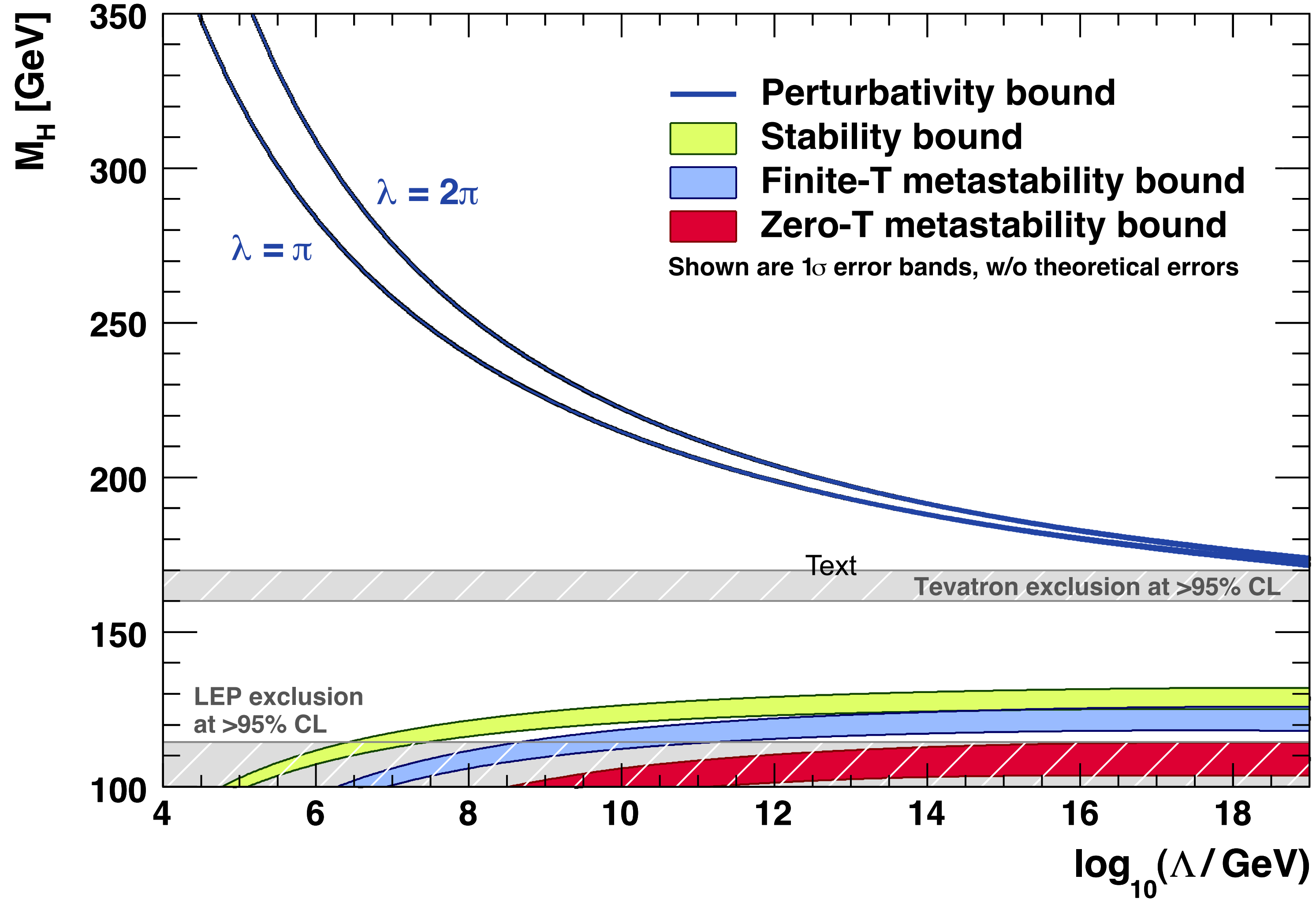
Higgs Boson on the Experimental Agenda:

$$\mathbf{J/\Psi} \rightarrow \gamma + \mathbf{H} \quad \text{and} \quad \mathbf{\Upsilon} \rightarrow \gamma + \mathbf{H}$$

LEP: $\mathbf{e}^+ + \mathbf{e}^- \rightarrow \mathbf{Z} + \mathbf{H}$ and $\mathbf{Z} \rightarrow \mathbf{H} + \mu^+\mu^-$ Ellis, Gaillard, Nanopoulos, 1976, Bjorken. 1978

SSC, LHC: **The Higgs Hunter's Guide**
John F. Gunion (UC, Davis), Howard E. Haber (UC, Santa Cruz), Gordon L. Kane (Michigan U.), Sally Dawson (Brookhaven). Jun 1989

Theoretical Constraints on Higgs Mass



Stability of the Higgs potential
Triviality of the scalar theory
Unitarity

Higgs-phenomenology started very slowly

- Emission from stars:

  $M_H > 0.7\ m_e$ (Sato & Sato, 1975)

- Neutron-electron scattering:

  $M_H > 0.7$ MeV (Rafelski, Muller, Soff & Greiner; Watson & Sundaresan; Adler, Dashen & Treiman; 1974)

- Neutron-nucleus scattering:

  $M_H > 13$ MeV (Barbieri & Ericson, 1975)

- Nuclear $0^+ - 0^+$ transitions:

  $M_H > 18$ MeV (Kohler, Watson & Becker, 1974)

A Phenomenological Profile of the Higgs Boson

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

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We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Higgs Boson on the Experimental Agenda

- Searches at LEP:

  (EG, Yellow report 76-18)

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

  (EGN 76, Ioffe & Khoze 78,

  Lee, Quigg & Thacker 77)

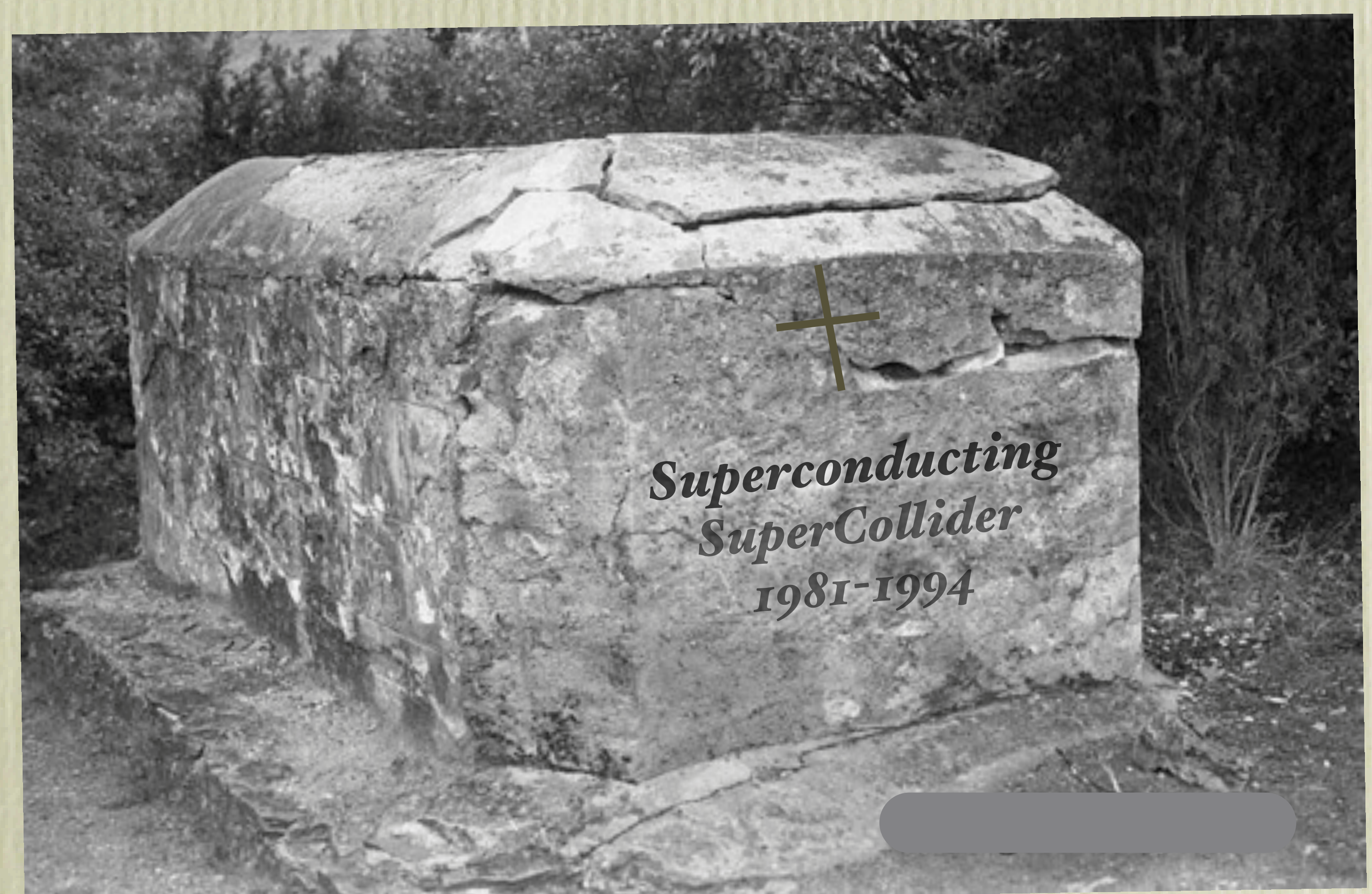
- $Z \rightarrow H + \mu^+\mu^-$

  (EG 76, Bjorken 1978)

- $M_H > 114.4$ GeV

The SSC and LHC proposals

SSC put forward in 1981
Building in the period 1986-1993
In 1993 it was terminated by Al Gore



Weinberg: biggest science policy mistake....

1984 For the community it all started with the CERN – ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel

1987 La Thuile Workshop

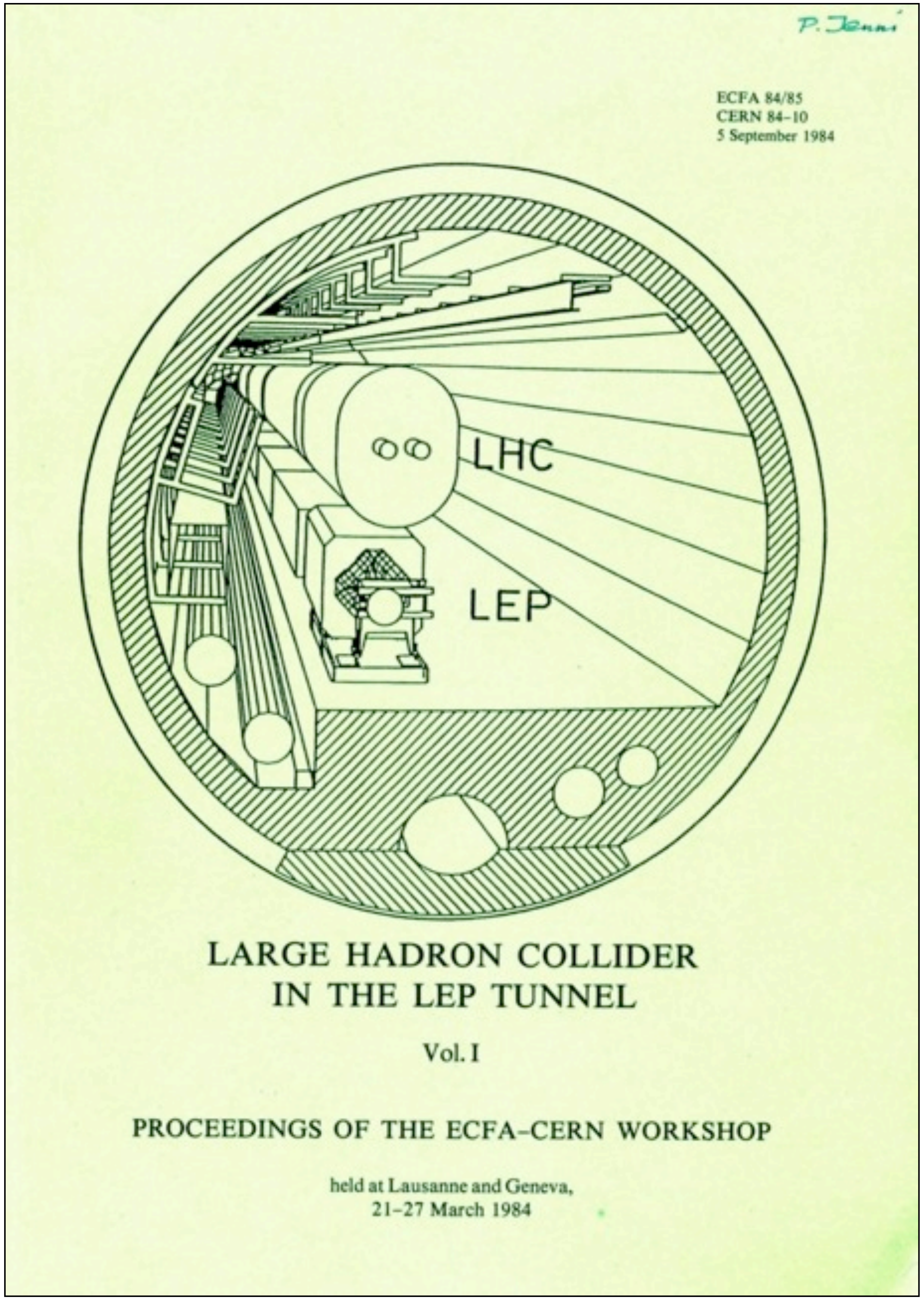
(Many LHC colleagues were already involved in this WS set up by Carlo Rubbia as part of the Long Range Planning Committee: a clear evolution started for detectors away from a 4μ iron-ball experiment towards multi-purpose detectors…)

1989 ECFA Study Week in Barcelona for LHC instrumentation

1990 Large Hadron Collider Workshop Aachen (ECFA)

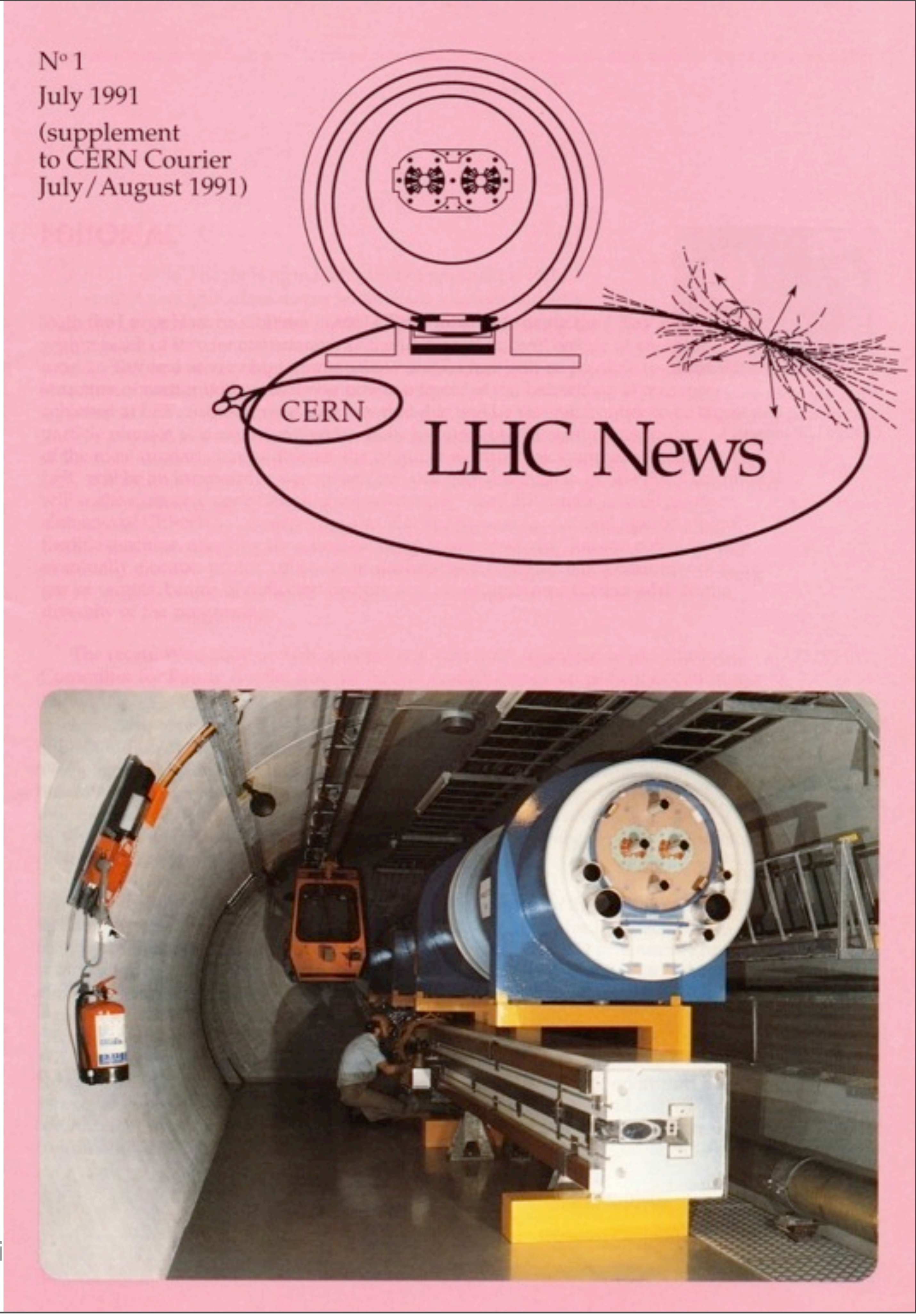
1992 CERN – ECFA meeting 'Towards the LHC Experimental Programme' in Evian

ATLAS and CMS became reality with Letters of Intent (LoI), submitted on 1st October 1992, 20 years ago



1991 December CERN Council: 'LHC is the right machine for advance of the subject and the future of CERN' (thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002



The two-stage approval of LHC was understood to be modified in case sufficient CERN non-member state contributions would become available

A lot of LHC campaigns and negotiations took place in the years 1995 - 1997, including also the experiments

Japan, Russia, India, Canada and the USA were agreeing in that phase to contribute to the LHC

(Israel contributed all along to the full CERN programme and LHC)

1997

December Council approved finally the single-stage 14 TeV LHC for completion in 2005

Delivery of the last dipole for the LHC injection lines from Russia (15th June 2001), with L Maiani and A Skrinsky in the centre

La Thuile and Geneve 7-13 January 1987

Main question: linear electron-positron collider or proton-proton collider?
Answer: Large Hadron Collider at 16 TeV with multi-purpose detectors.

$$E_{\text{total}} = 16 \text{ TeV !}$$

La Thuile and Geneve 7-13 January 1987

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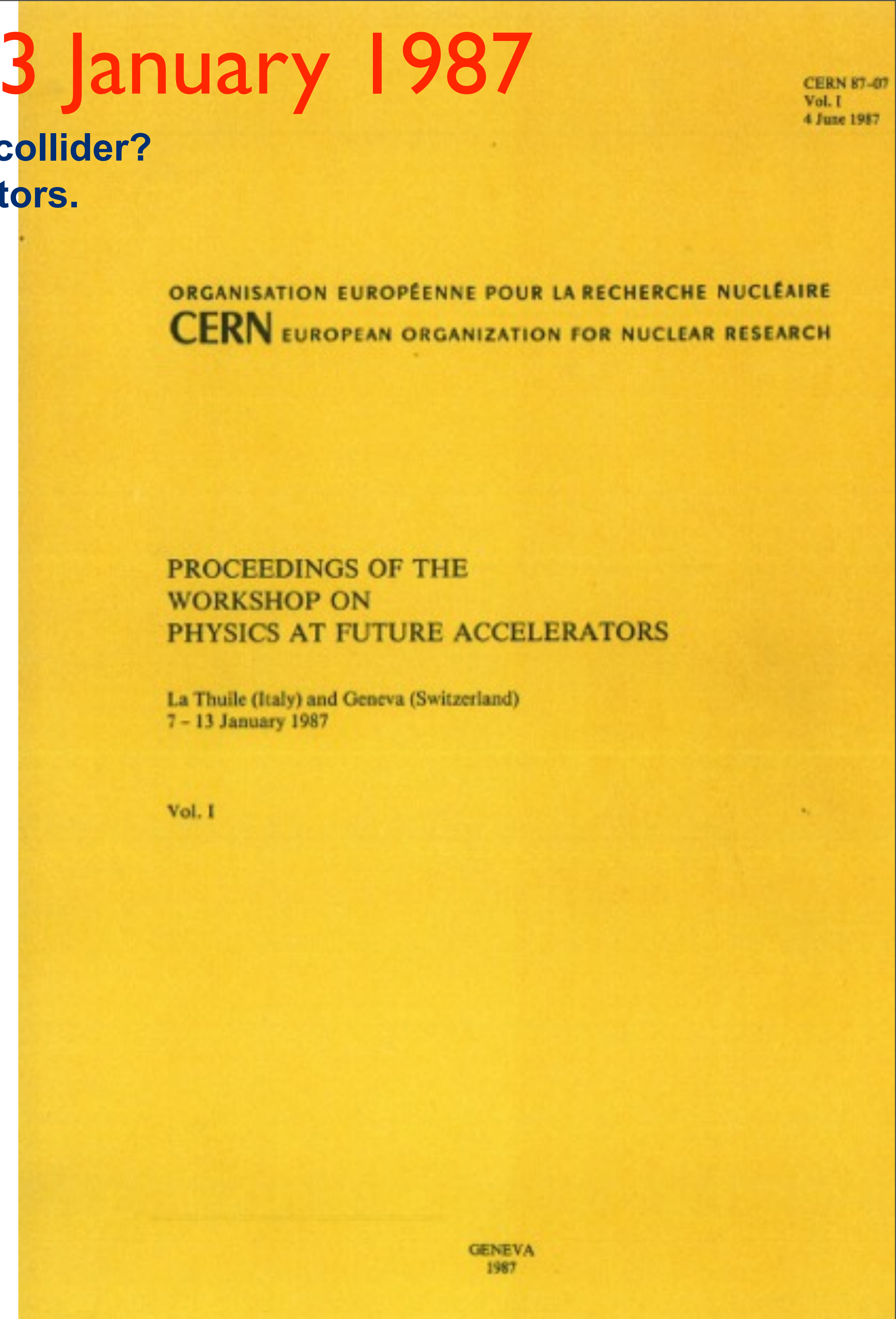
CERN 87-07
Vol. I
4 June 1987

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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PROCEEDINGS OF THE
WORKSHOP ON
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Working groups and conveners

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Physics	
1. Standard Model	G. Altarelli and D. Froidevaux
2. Beyond the Standard Model	J. Ellis and F. Pauss
3. Large cross-sections	Z. Kunszt and W. Scott
Detectors	
Jet detector	T. Åkesson
Vertex detector and tracking	D.H. Saxon
Particle identification	F. Palmonari
Triggering and data acquisition	J.R. Hansen
Interaction regions	J.E. Augustin, W. Kienzle and W. Bartel

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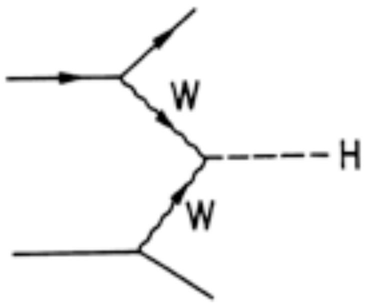
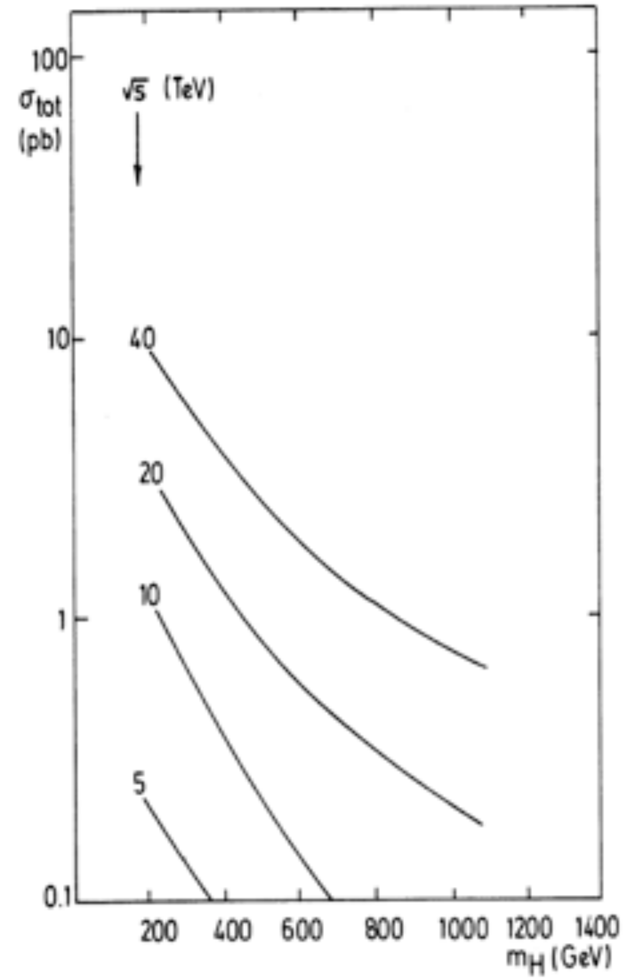

W
W
H

Fig. 18


σ_{tot}
(pb)
$\sqrt{s}$ (TeV)
100
10
1
0.1
40
20
10
5
200
400
600
800
1000
1200
1400
m_H (GeV)

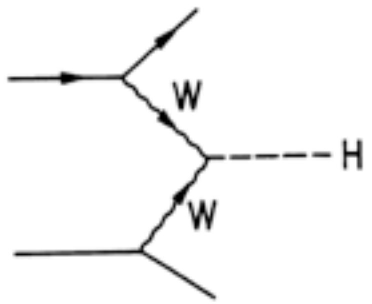
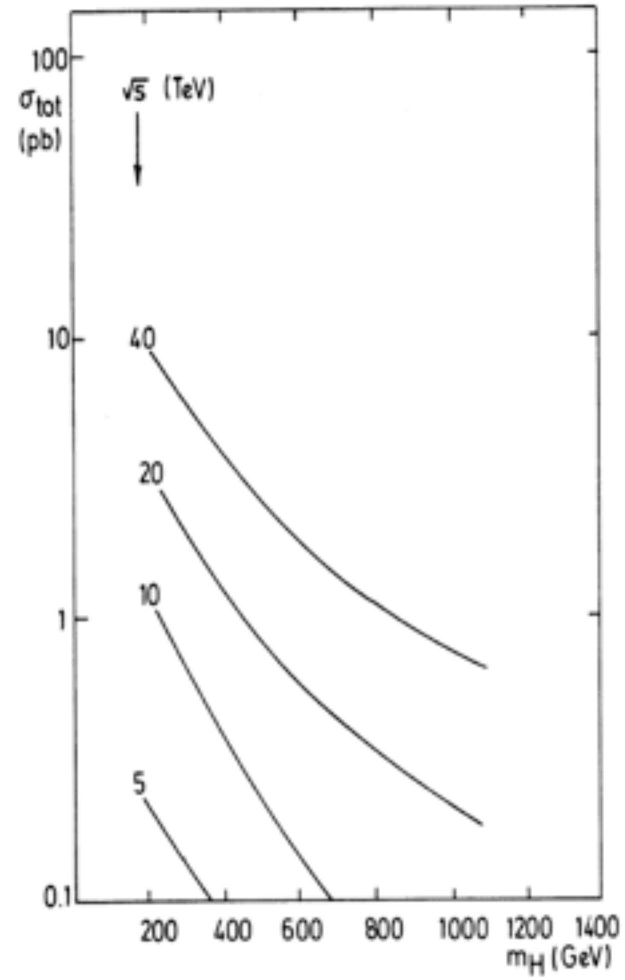
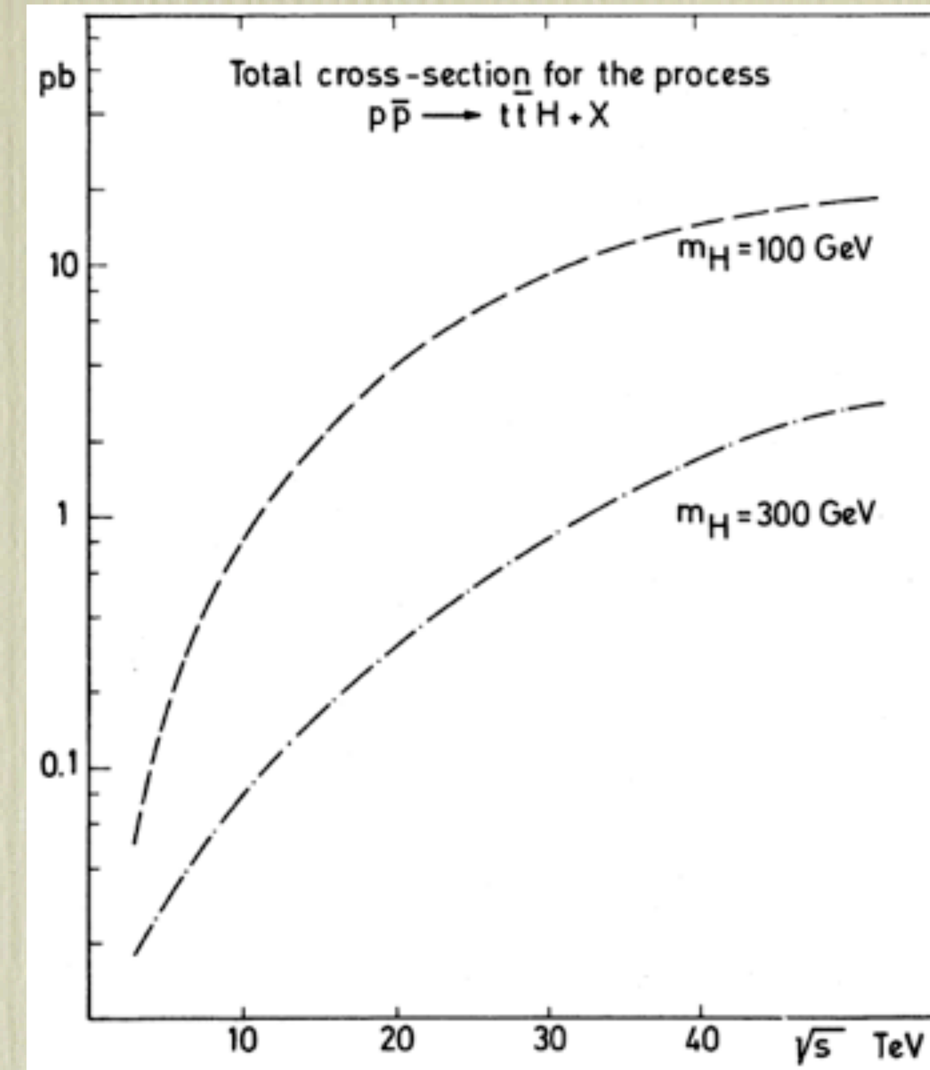

W
W
H

Fig. 18


σ_{tot} (pb)
$\sqrt{s}$ (TeV)
100
10
1
0.1
40
20
10
5
200
400
600
800
1000
1200
1400
m_H (GeV)


pb
Total cross-section for the process
$p\bar{p} \longrightarrow t\bar{t}H + X$
10
1
0.1
m_H = 100 GeV
m_H = 300 GeV
10
20
30
40
$\sqrt{s}$ TeV

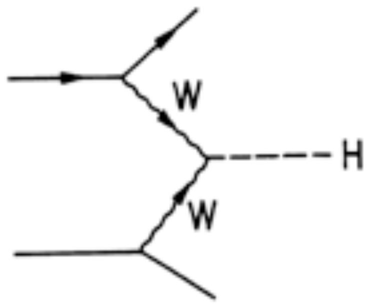
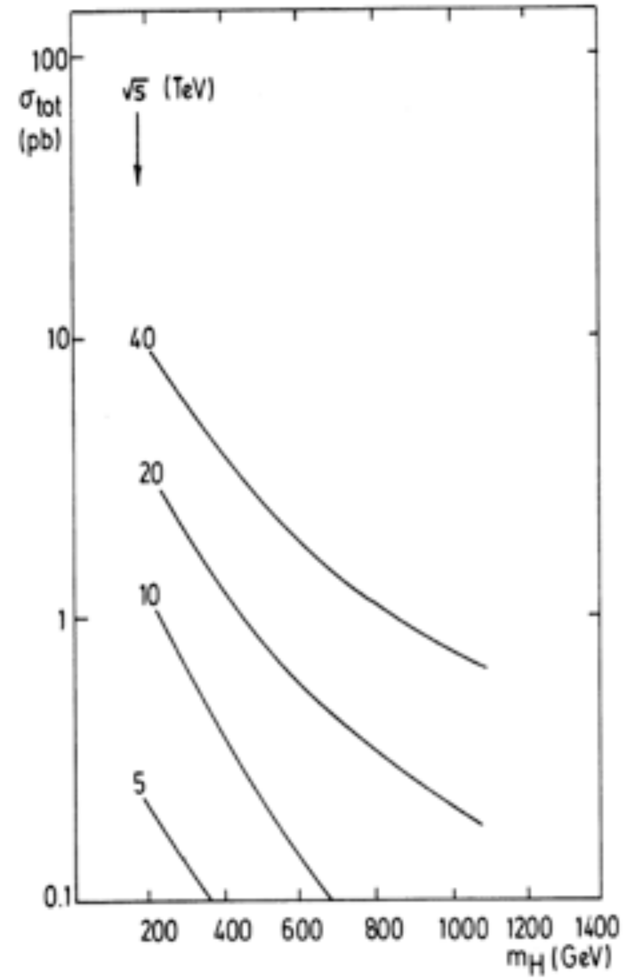

W
W
H

Fig. 18


σ_{tot} (pb)
$\sqrt{s}$ (TeV)
100
10
1
0.1
40
20
10
5
200
400
600
800
1000
1200
1400
m_H (GeV)

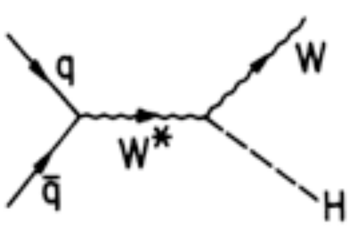
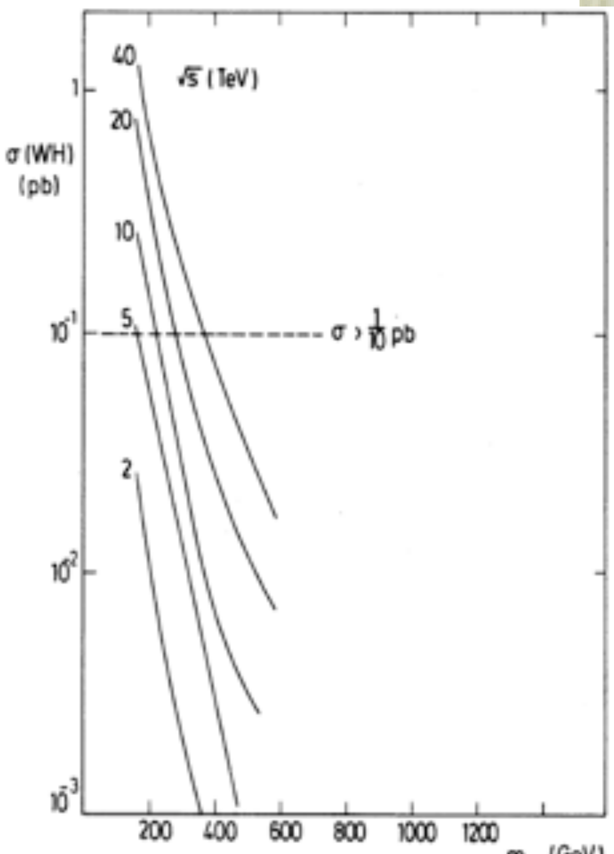
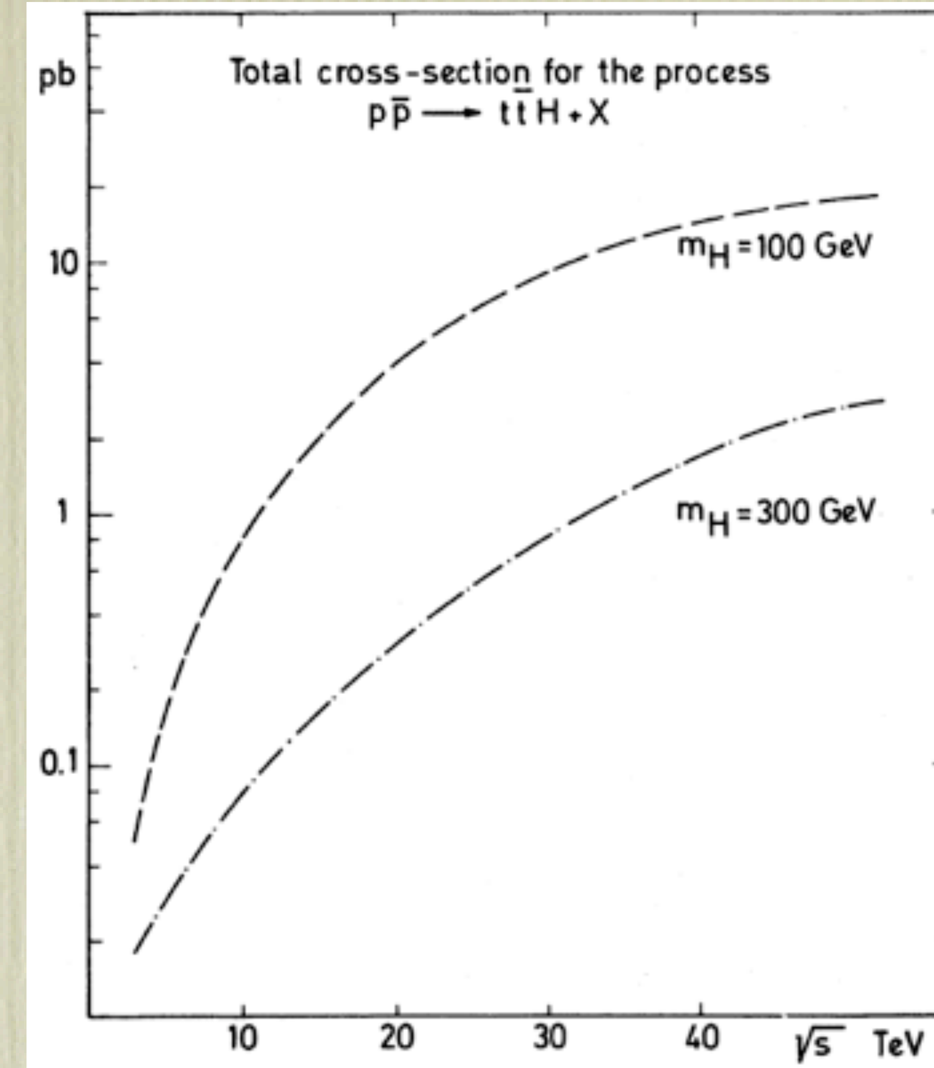

q
$\bar{q}$
W^*
W
H

Fig. 21


σ (WH) (pb)
$\sqrt{s}$ (TeV)
1
10^{-1}
10^{-2}
10^{-3}
40
20
10
5
2
$\sigma > \frac{1}{10}$ pb
200
400
600
800
1000
1200
m_H (GeV)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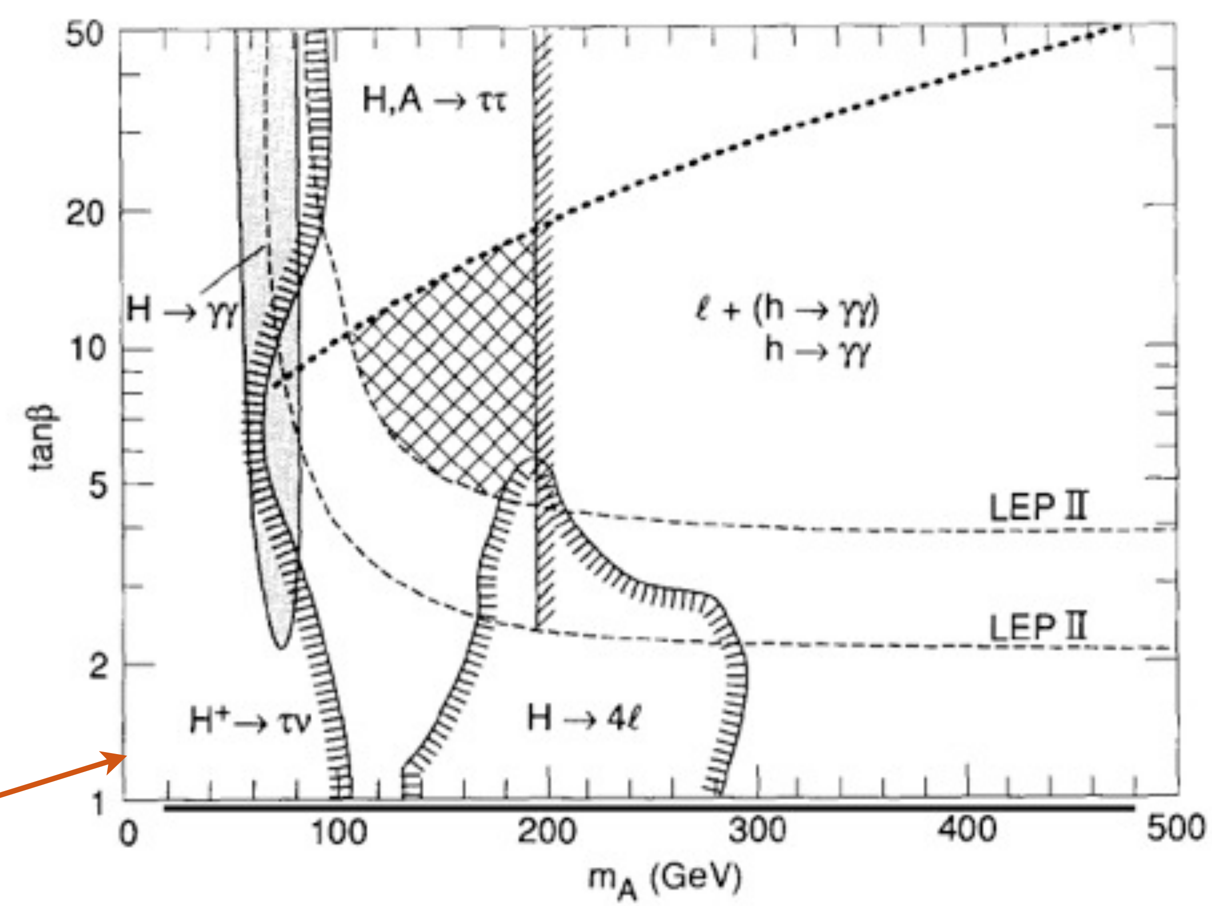
pb
10
1
0.1
m_H = 100 GeV
m_H = 300 GeV
10
20
30
40
$\sqrt{s}$ TeV

1990 Large Hadron Collider Workshop Aachen (ECFA)

A5. Higgs physics 427

Superb electromagnetic calorimeter is needed to suppress jet background



The Standard Model Higgs at the LHC: Branching rations and cross-sections, *Z. Kunszt and W.J. Stirling*

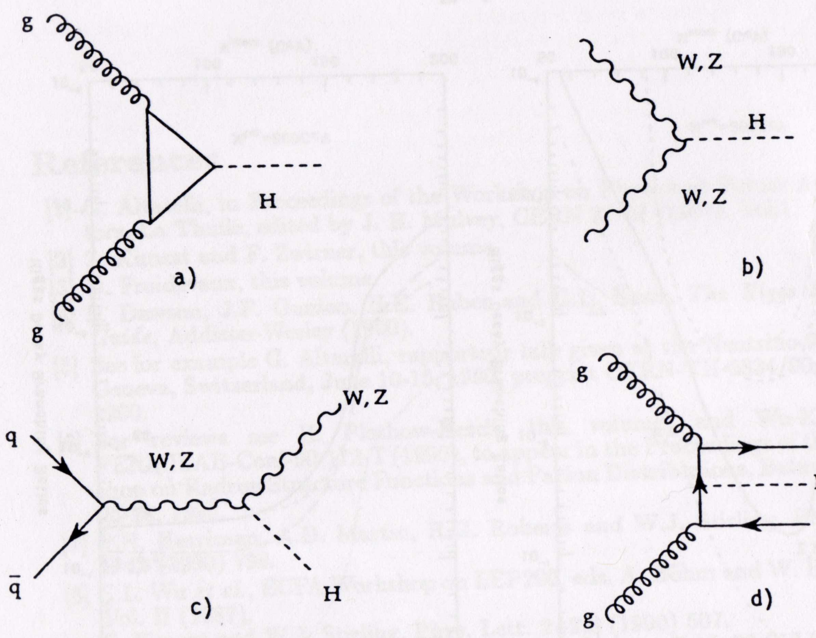


Fig. 5

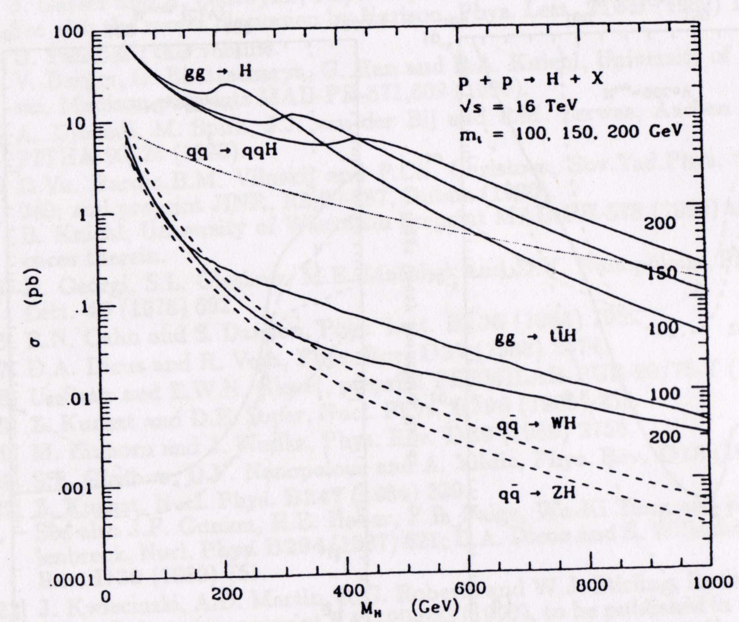


Fig. 6

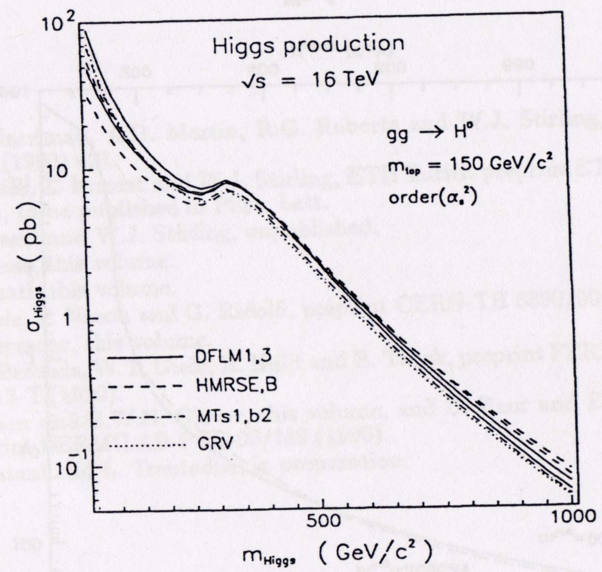


Fig. 7

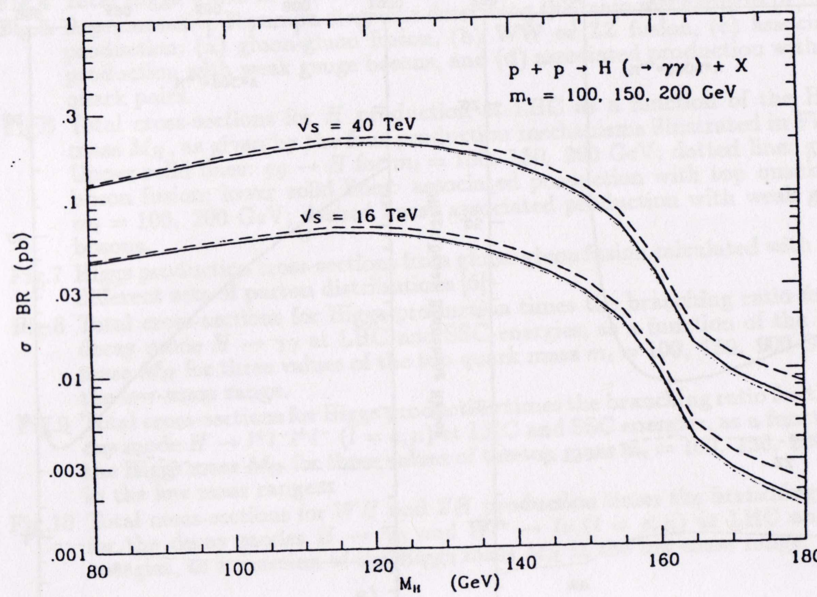


Fig. 8

Higgs phenomenology is more and more in the focus of many projects

NLO, NNLO corrections

Experimental simulations

MC descriptions

PROCEEDINGS OF THE WORKSHOP ON STANDARD MODEL PHYSICS (AND MORE) AT THE LHC

CERN 2000–004
9 May 2000

CONVENERS

QCD Group:

S. Catani
M. Dittmaier
D. Soper
J. Stirling
S. Tapprogge

Top Group:

M. Beneke
I. Efthymiopoulos
M. Mangano
J. Womersley

Electroweak Group:

S. Haywood
P. Hobson
W. Hollik
Z. Kunszt

Beauty Production Group:

P. Nason
G. Ridolfi
O. Schneider
G. Tartarelli
P. Vikas

Beauty Decays Group:

P. Ball
R. Fleischer
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Higgs-keltés:

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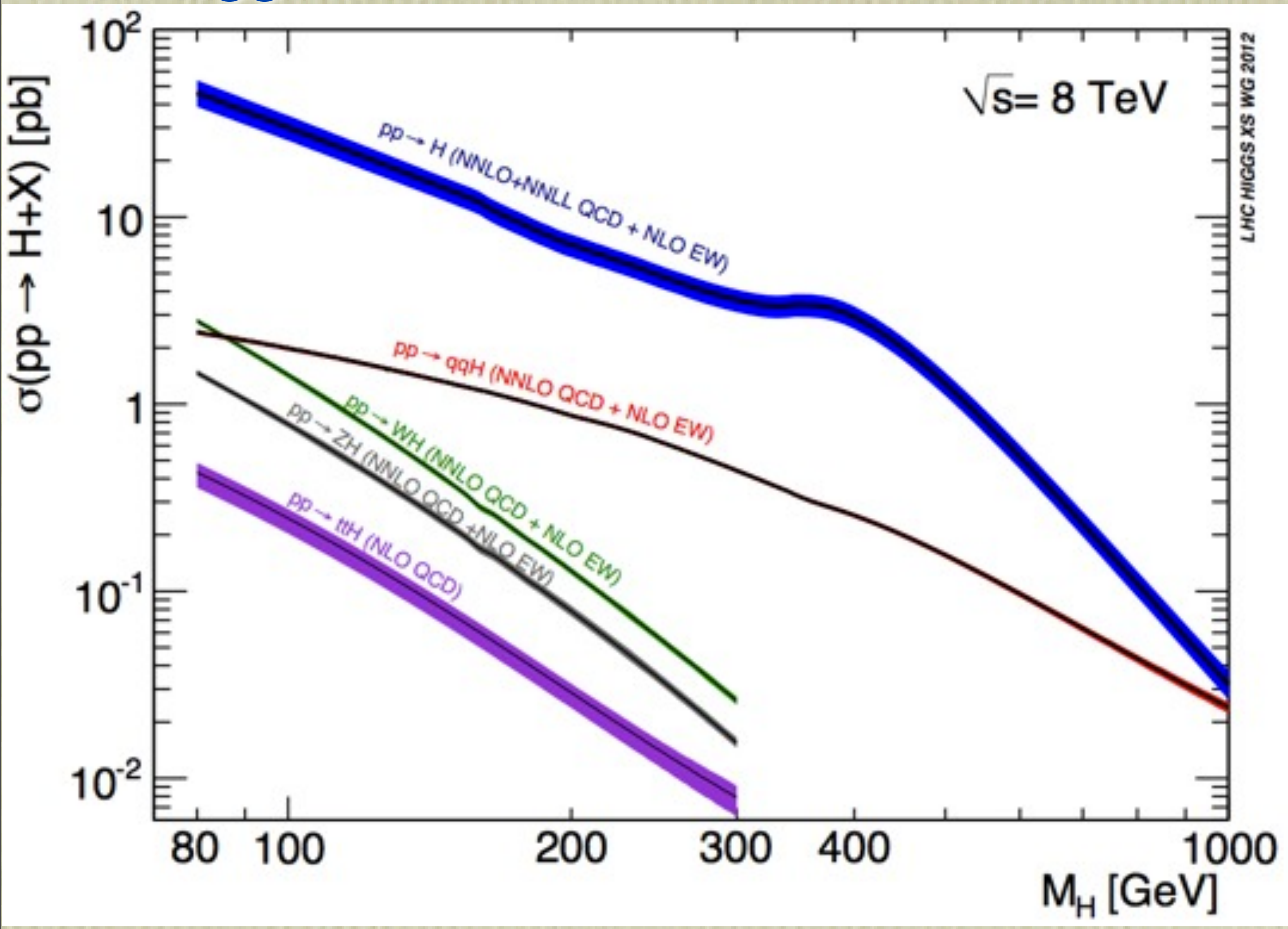

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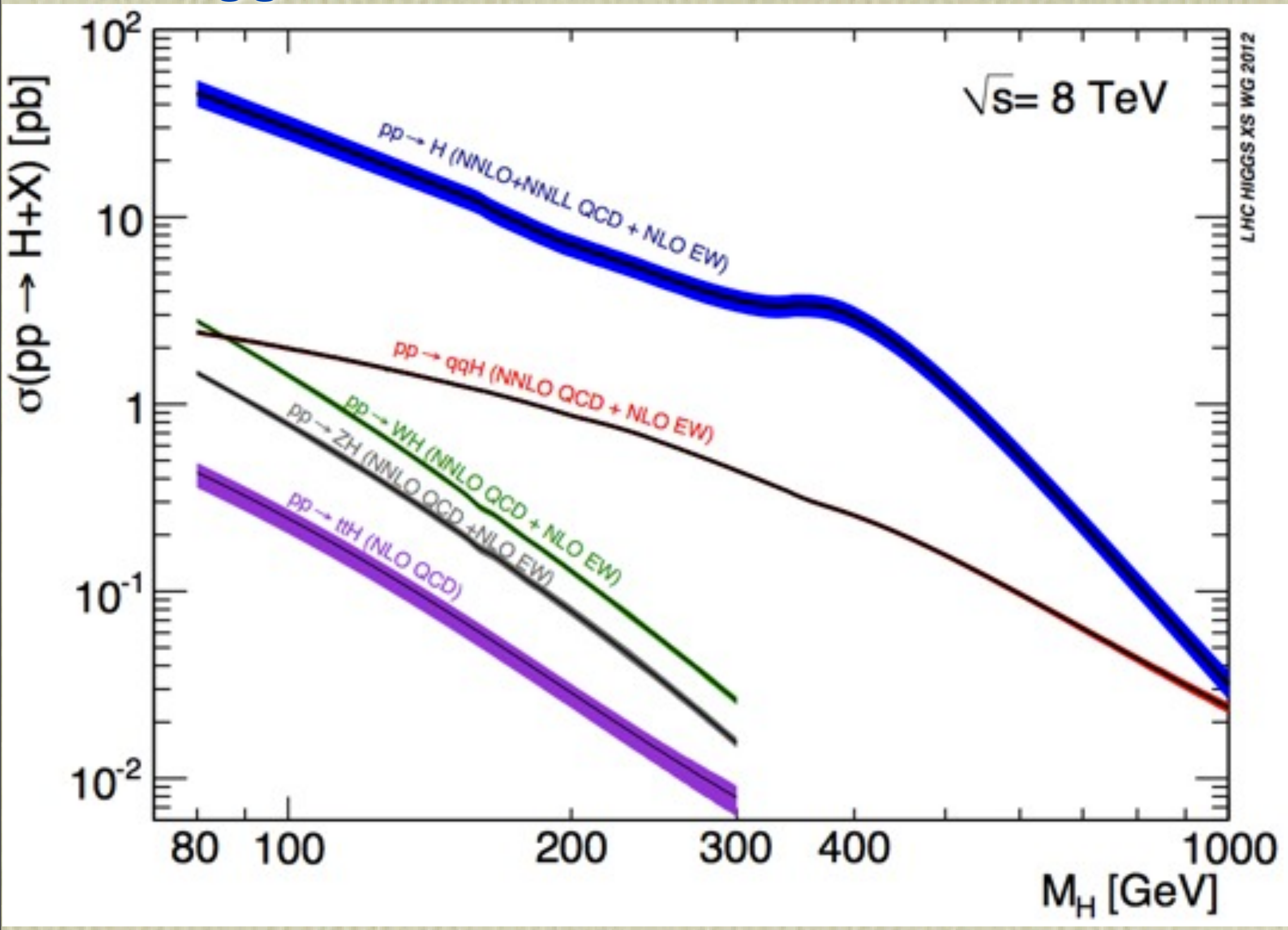
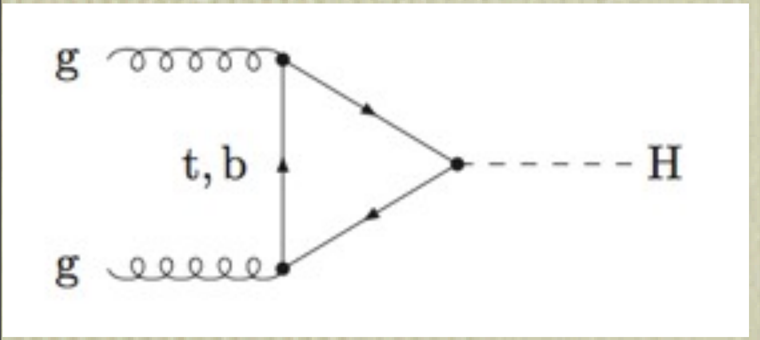
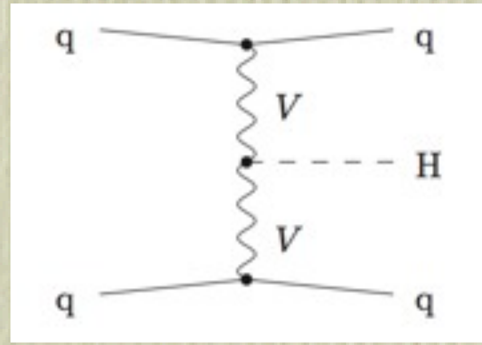


gluon fusion



vector boson fusion



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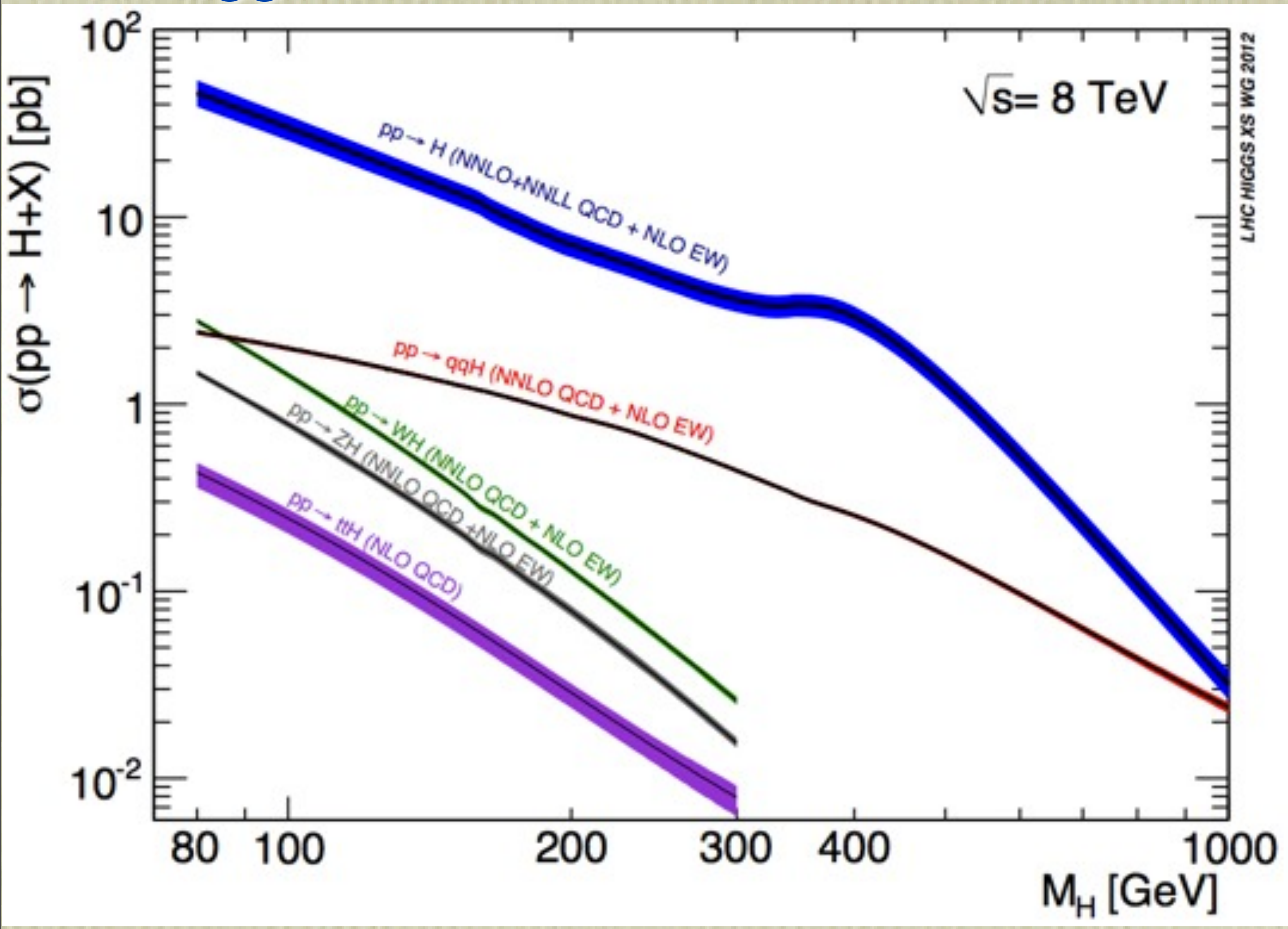

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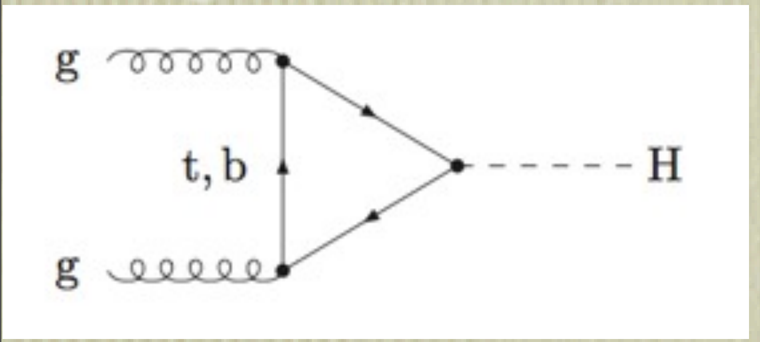

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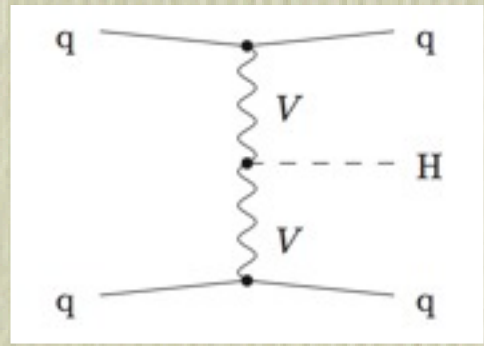

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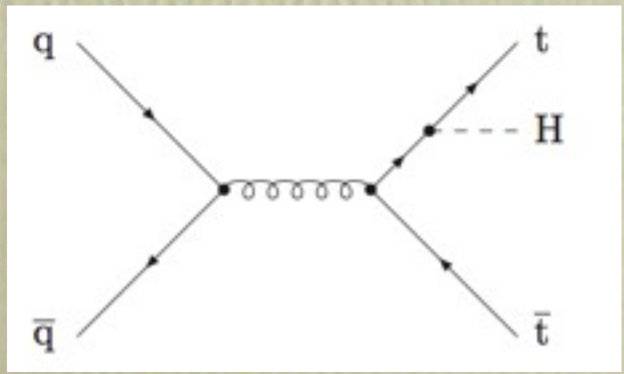
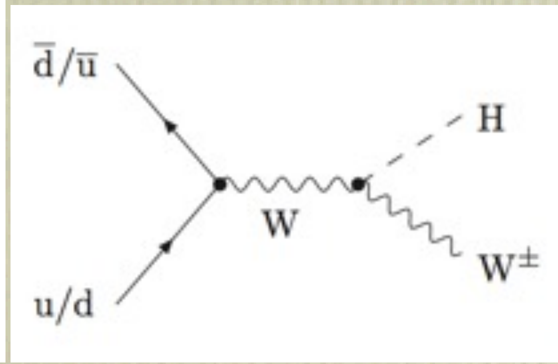


associate production



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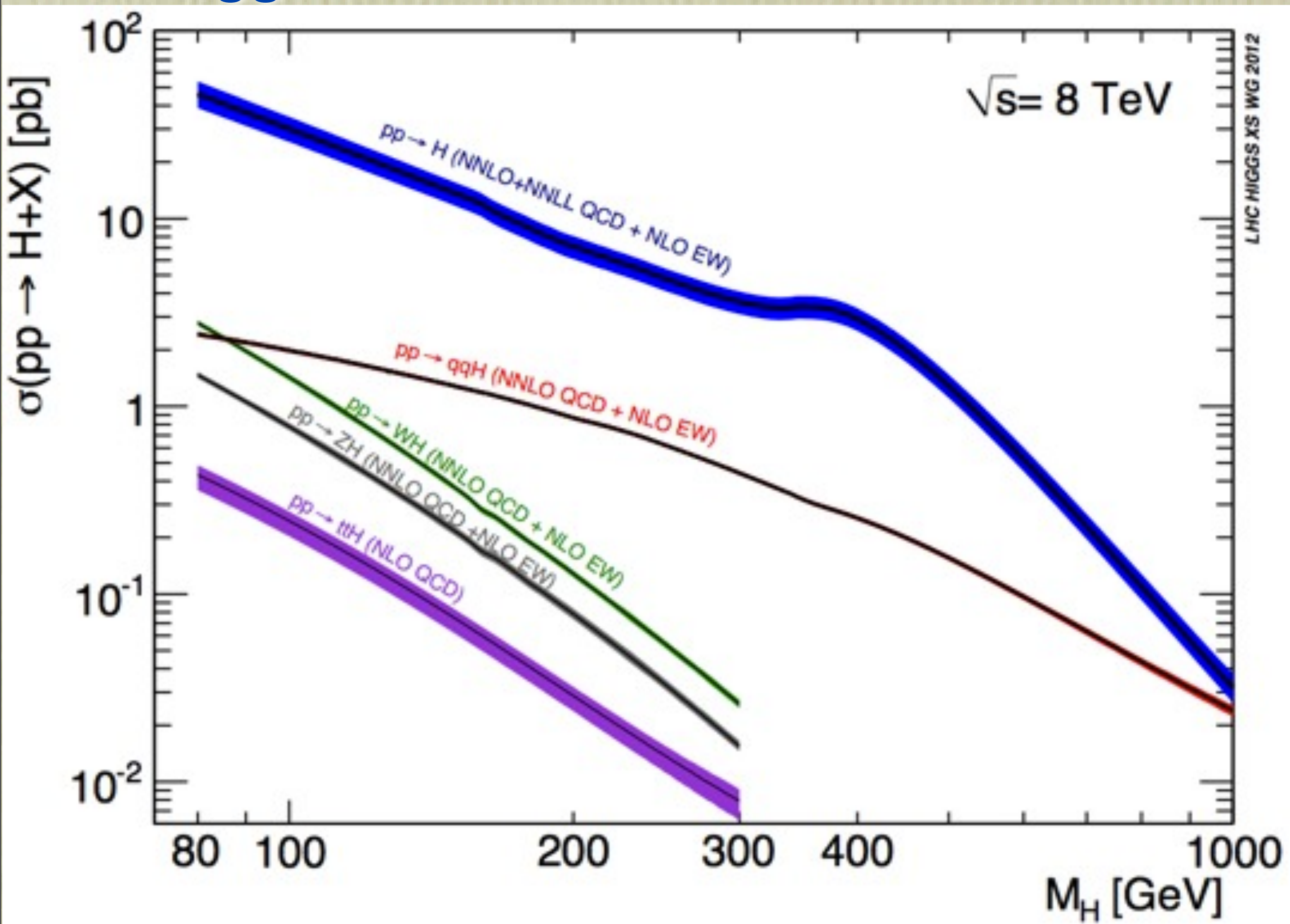

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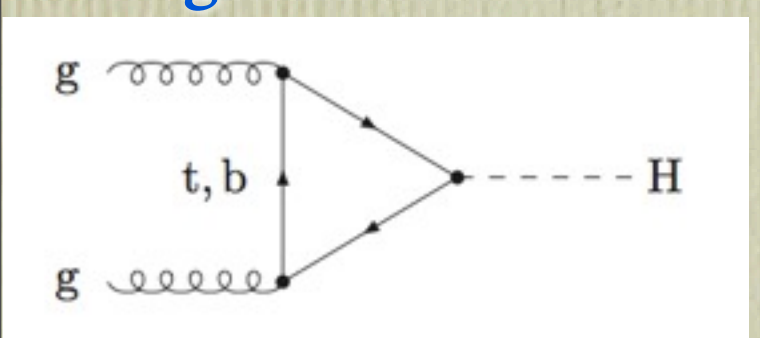
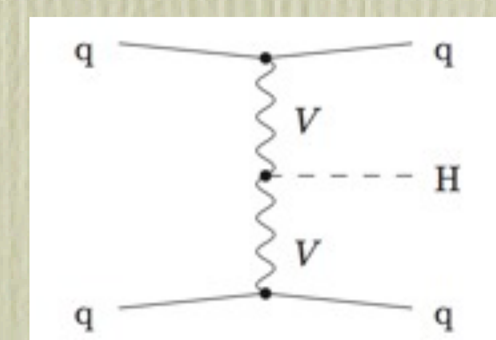


vector boson fusion



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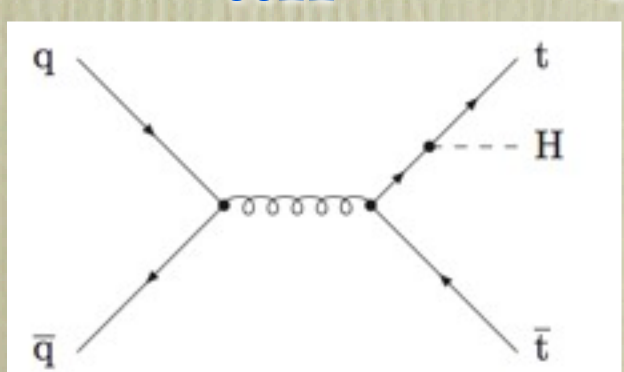

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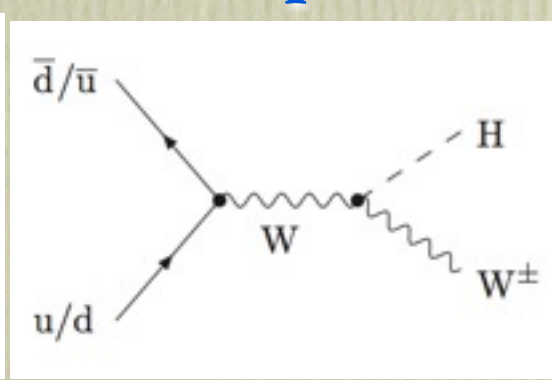
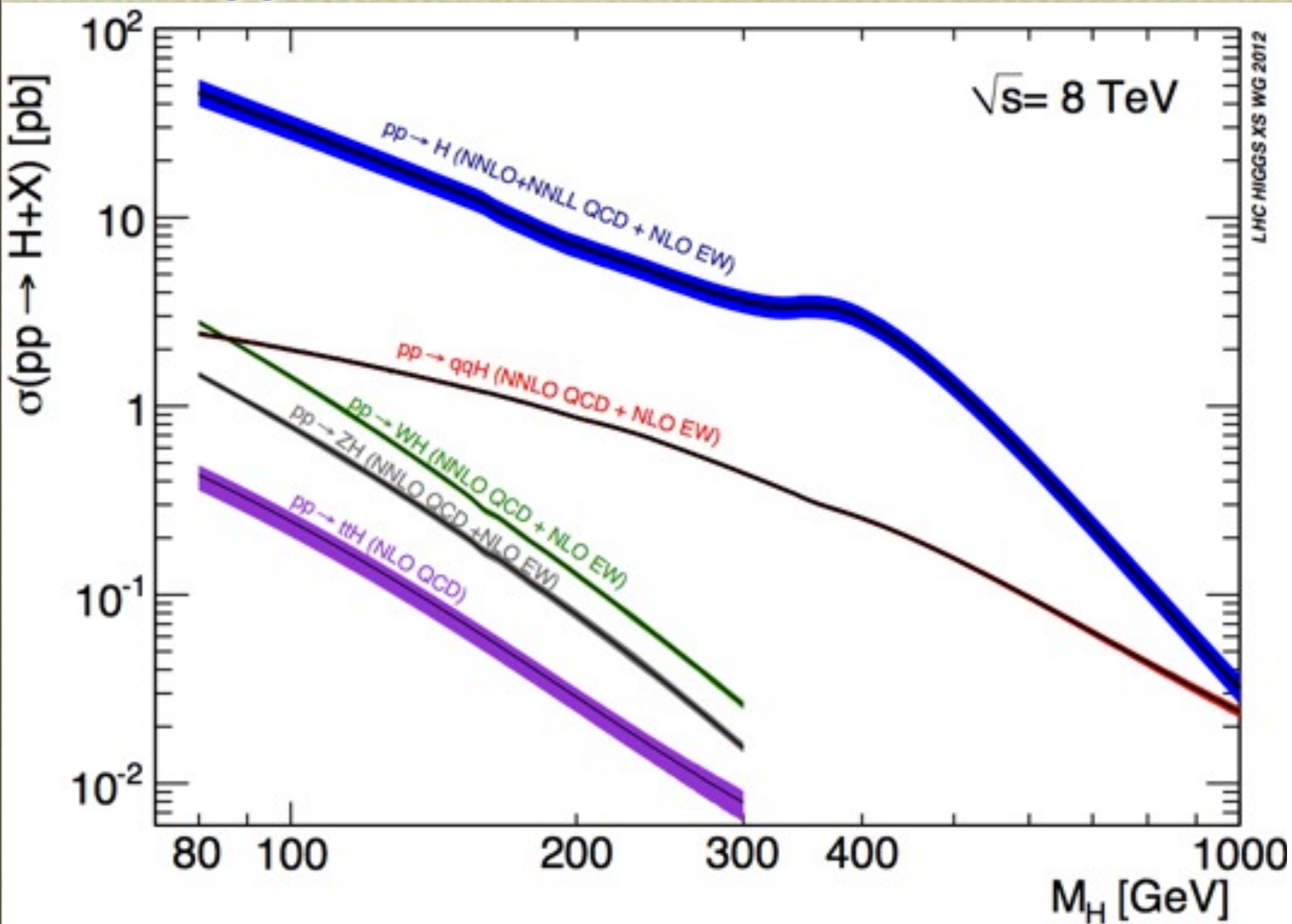


Higgs bomlási modusok:

Higgs-keltés:



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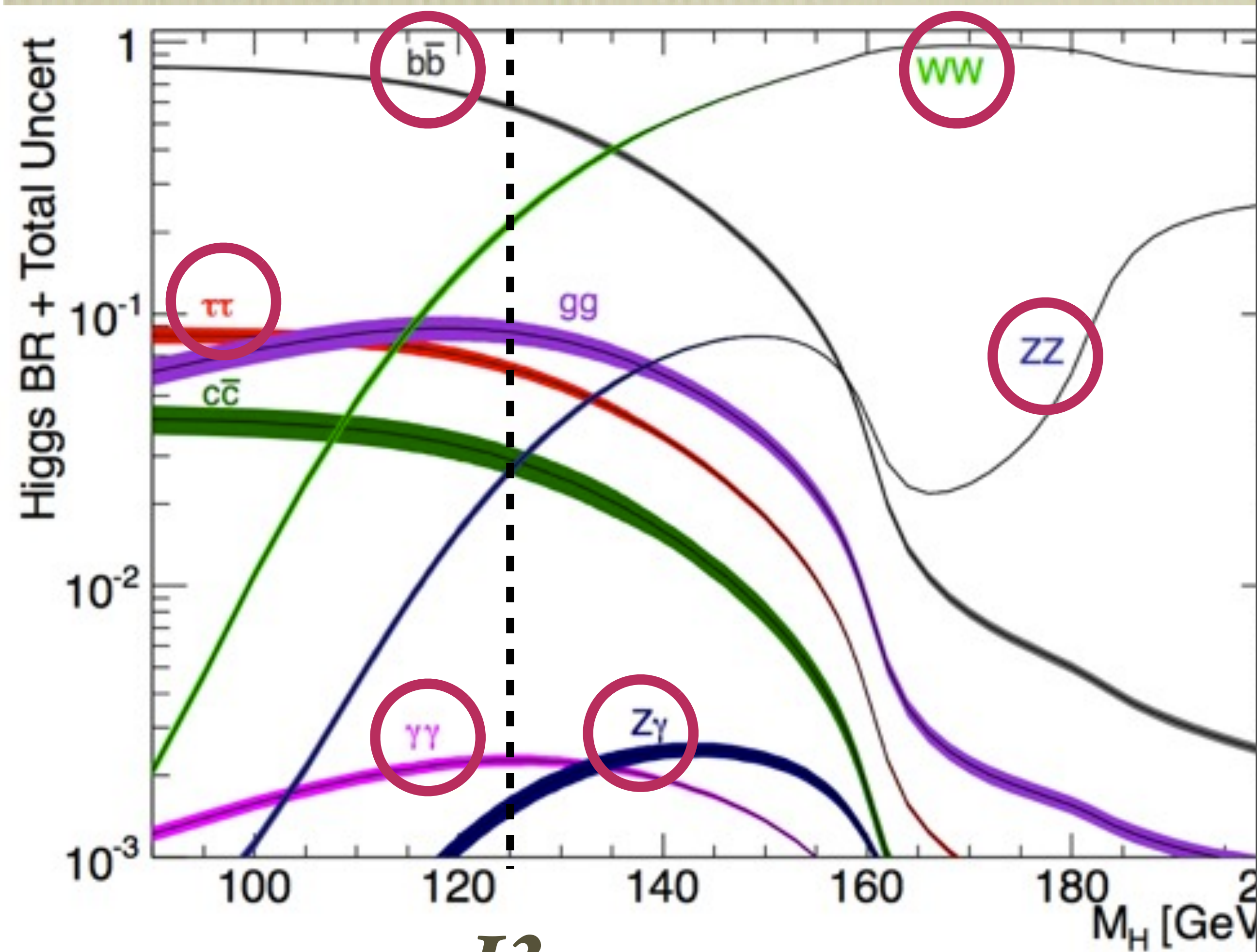

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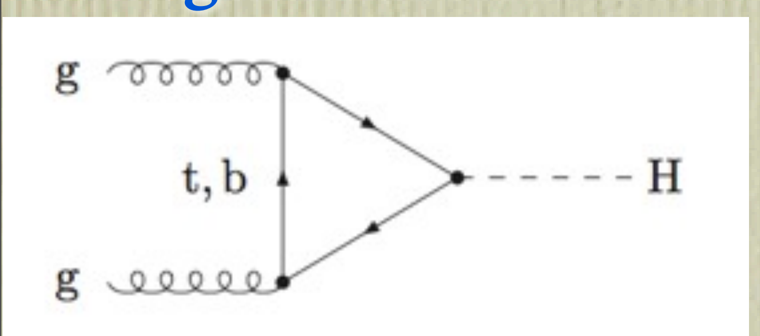
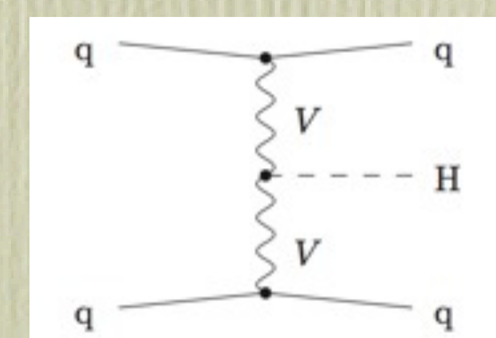
gluon fusion



vector boson fusion



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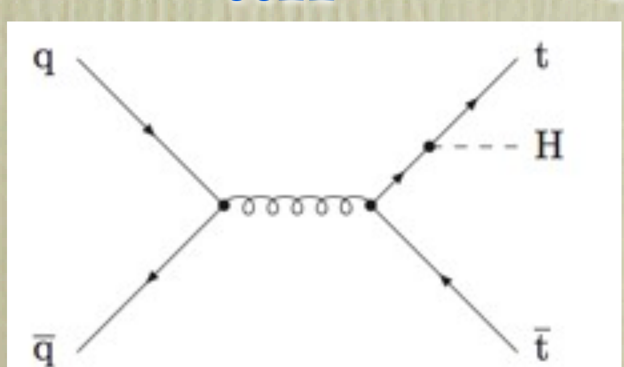
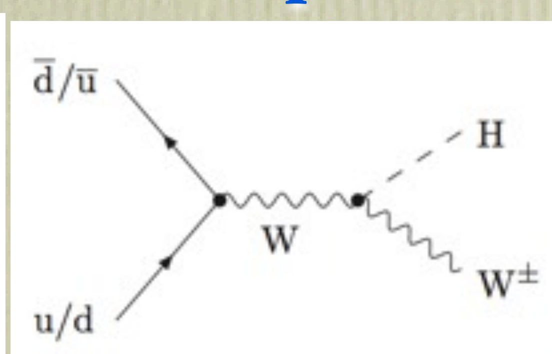
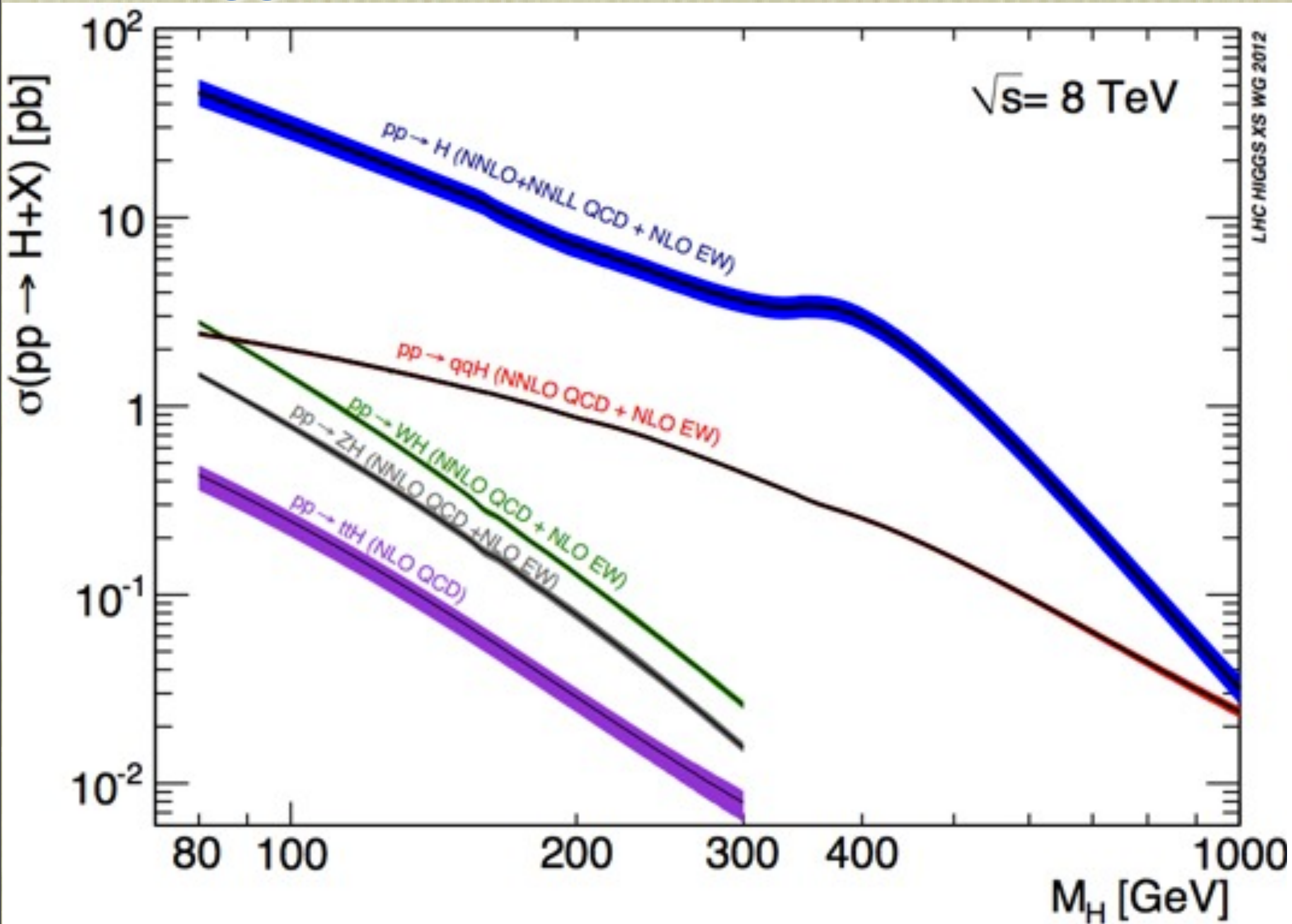


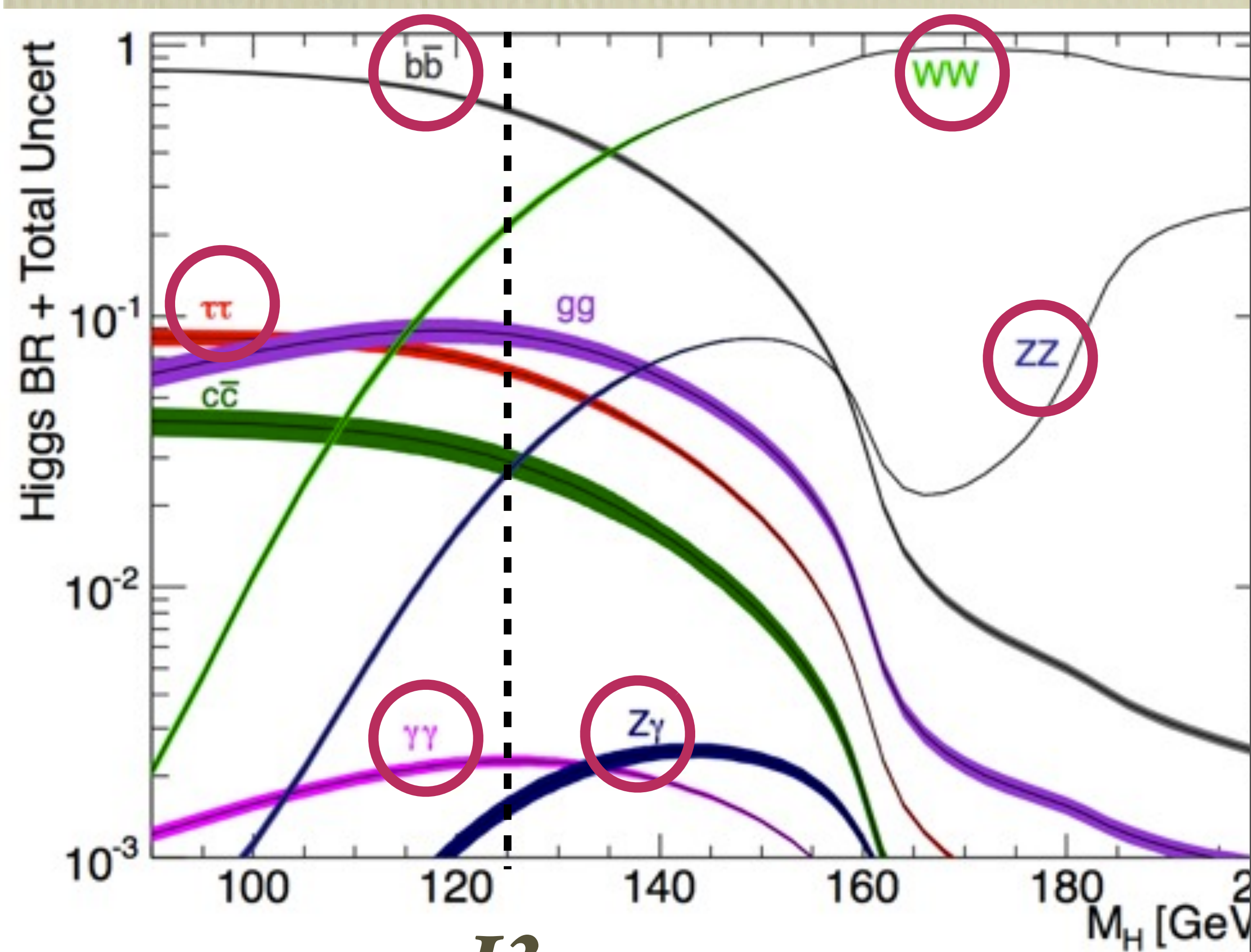
associate production



Higgs-keltés:

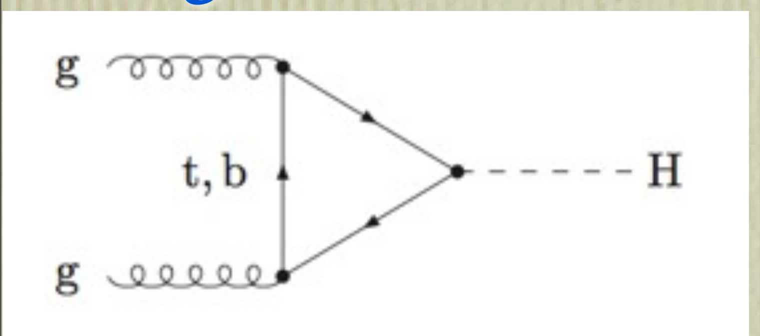


Higgs bomlási modusok:

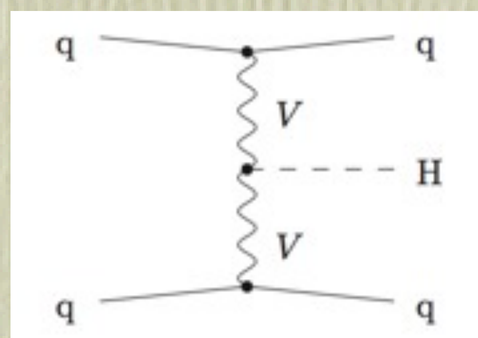


12

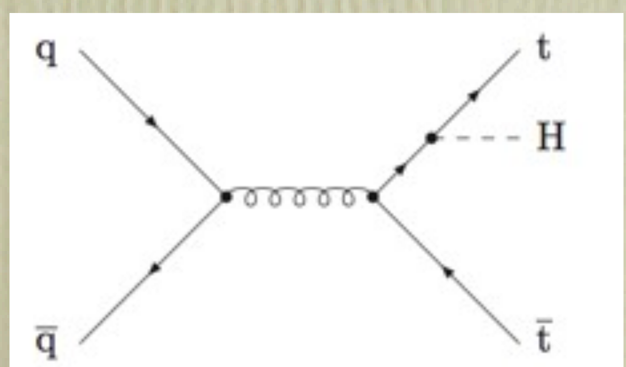
gluon fusion



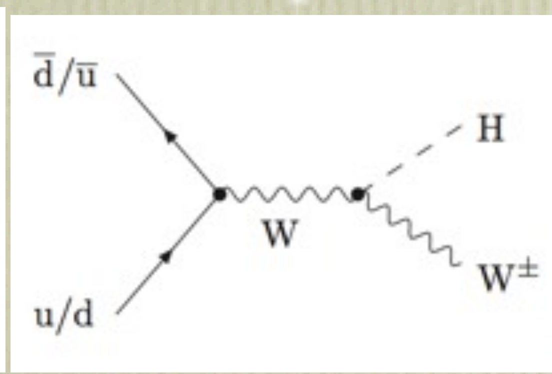
vector boson fusion



ttH



associate production

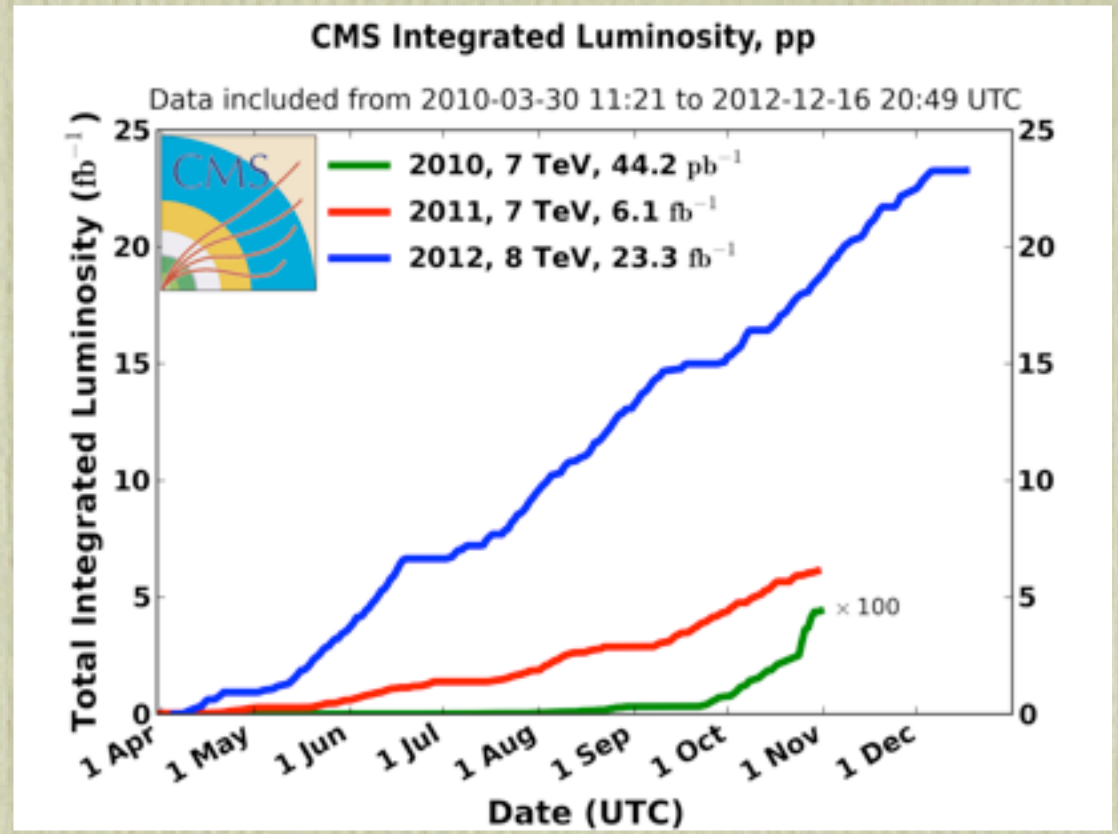


Adatok analizálva:

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^{(*)}$
- $H \rightarrow W^{+}W^{-}$
- $H \rightarrow bb$
- $H \rightarrow \tau^{+}\tau$

The LHC and the detectors perform beyond expectations!

The LHC and the detectors perform beyond expectations!



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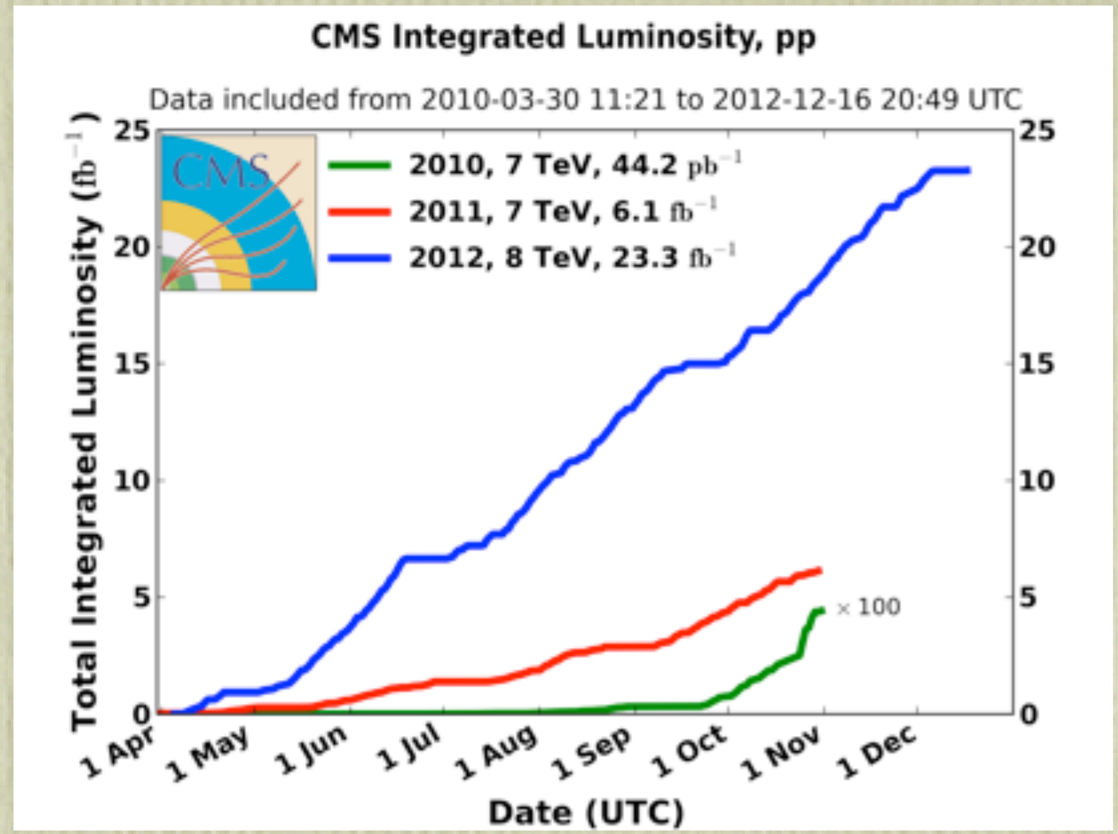

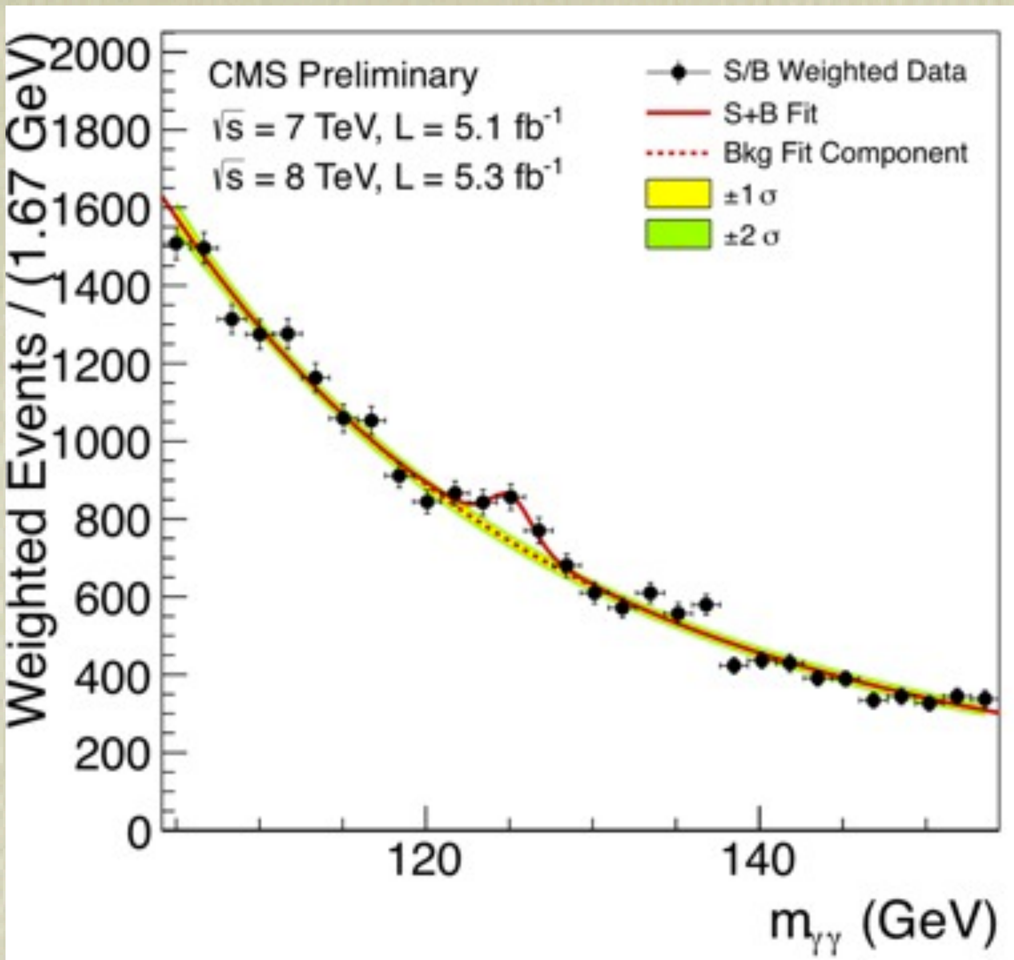

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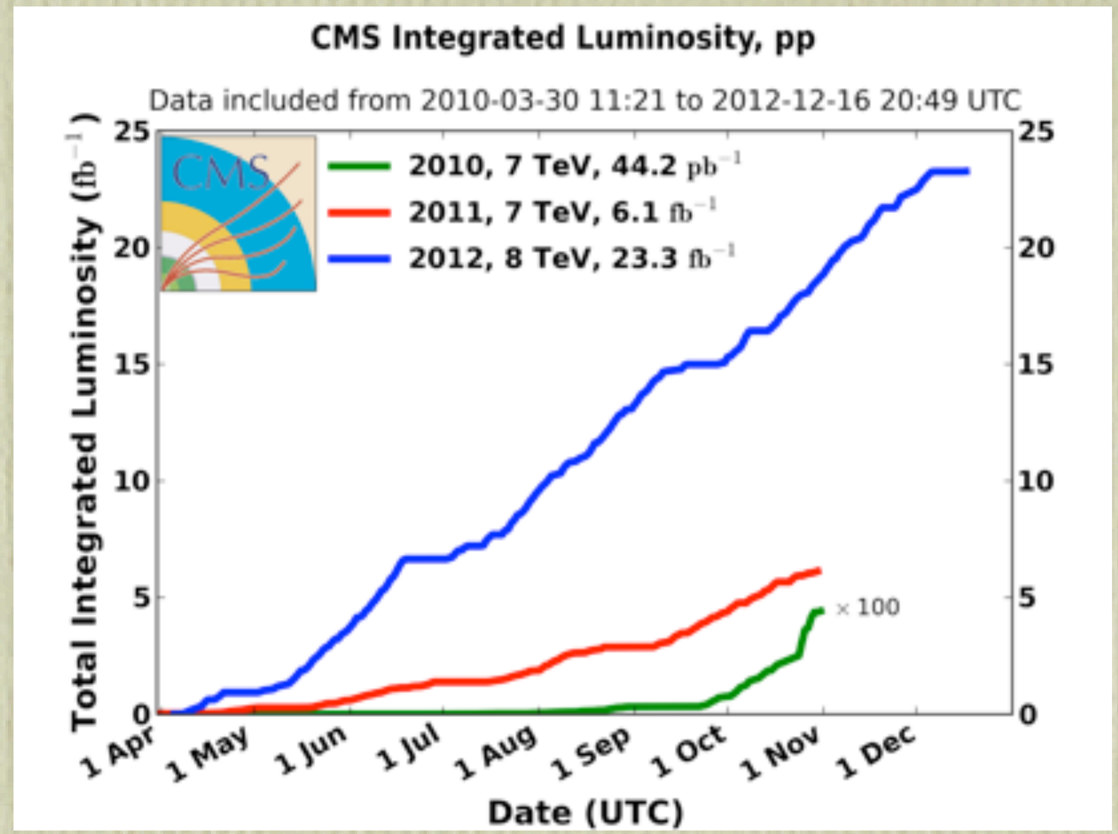

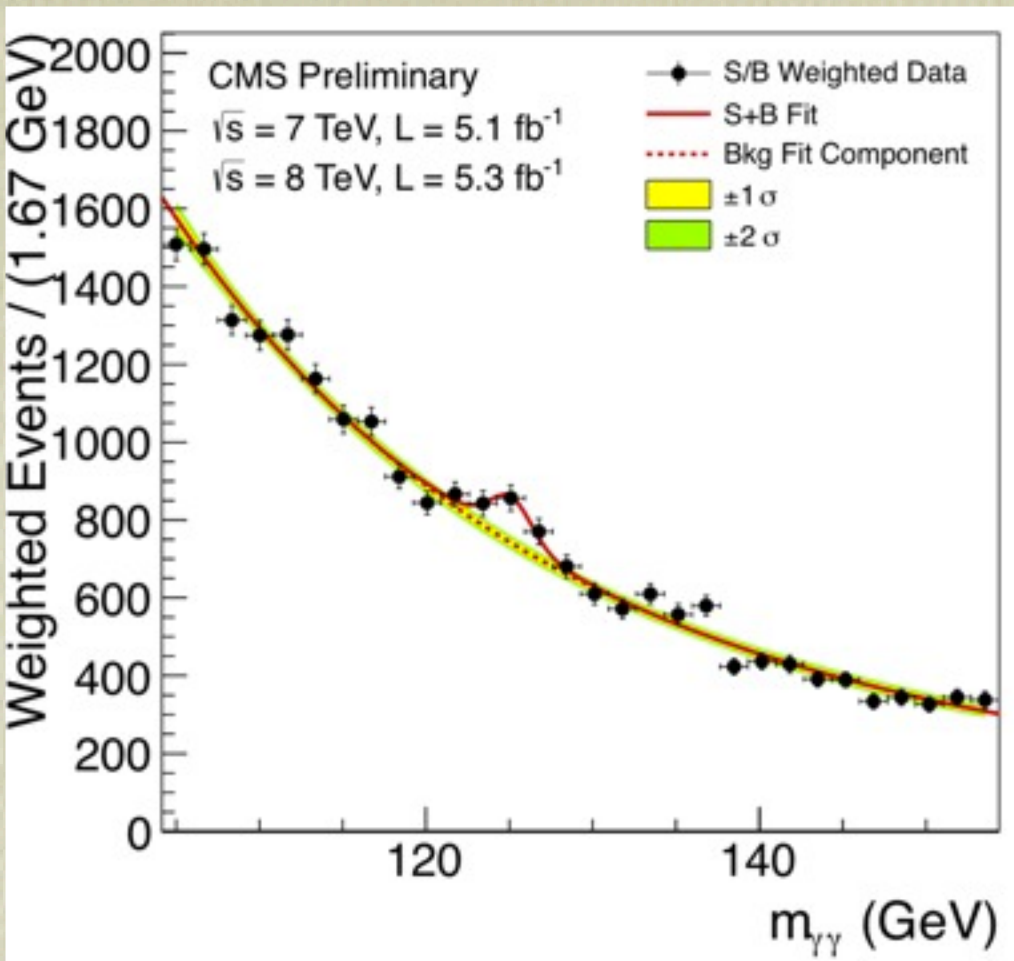

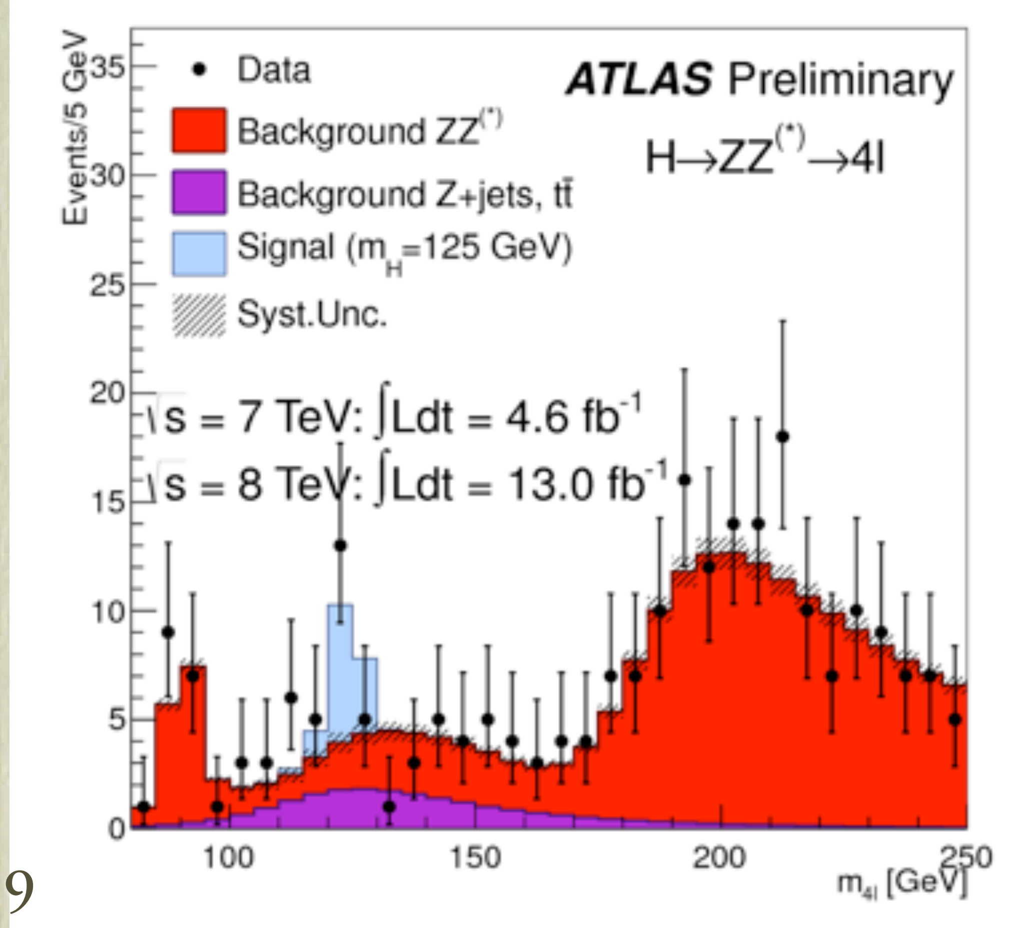

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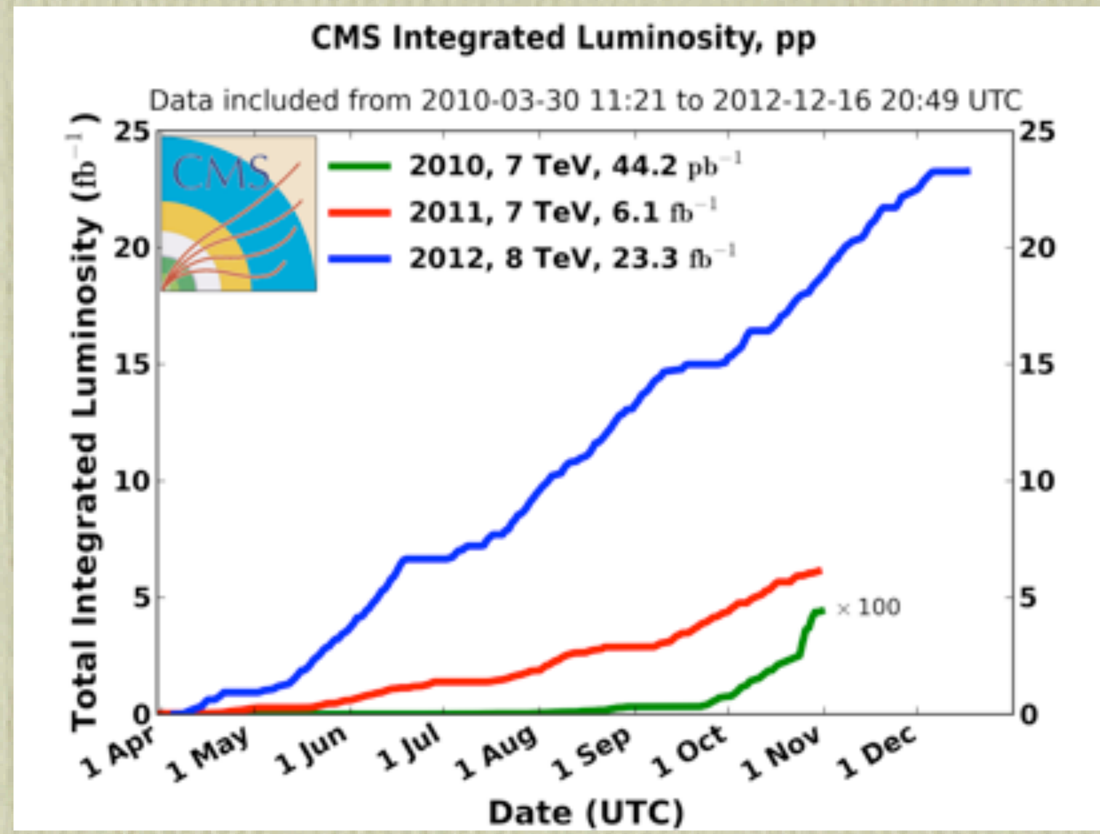
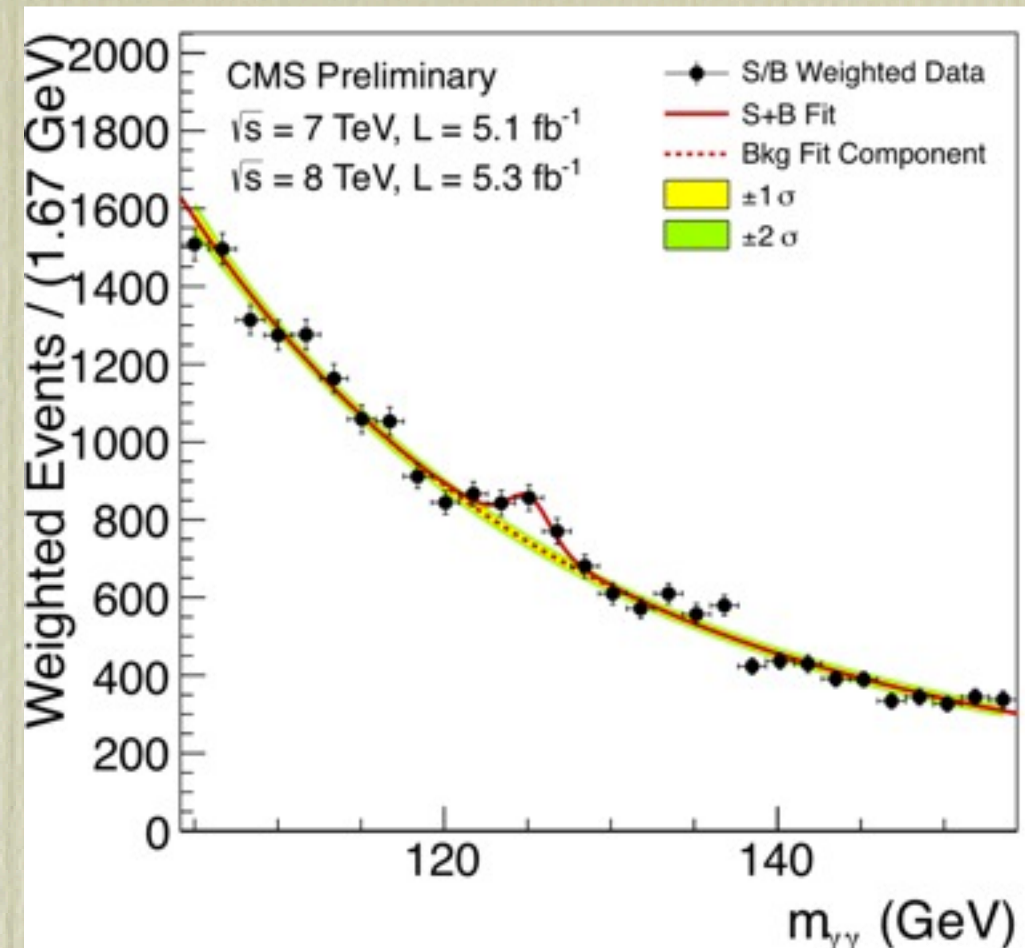
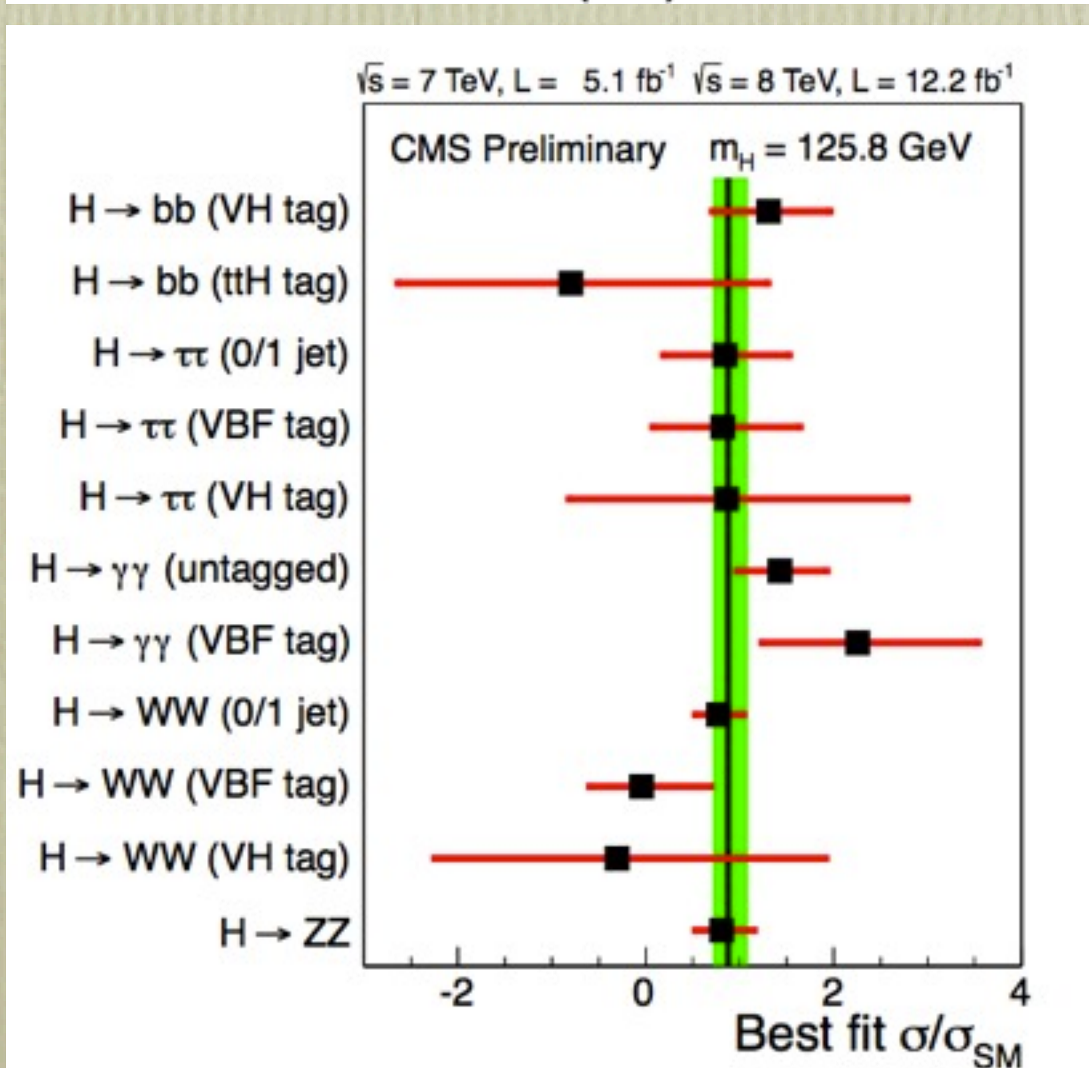
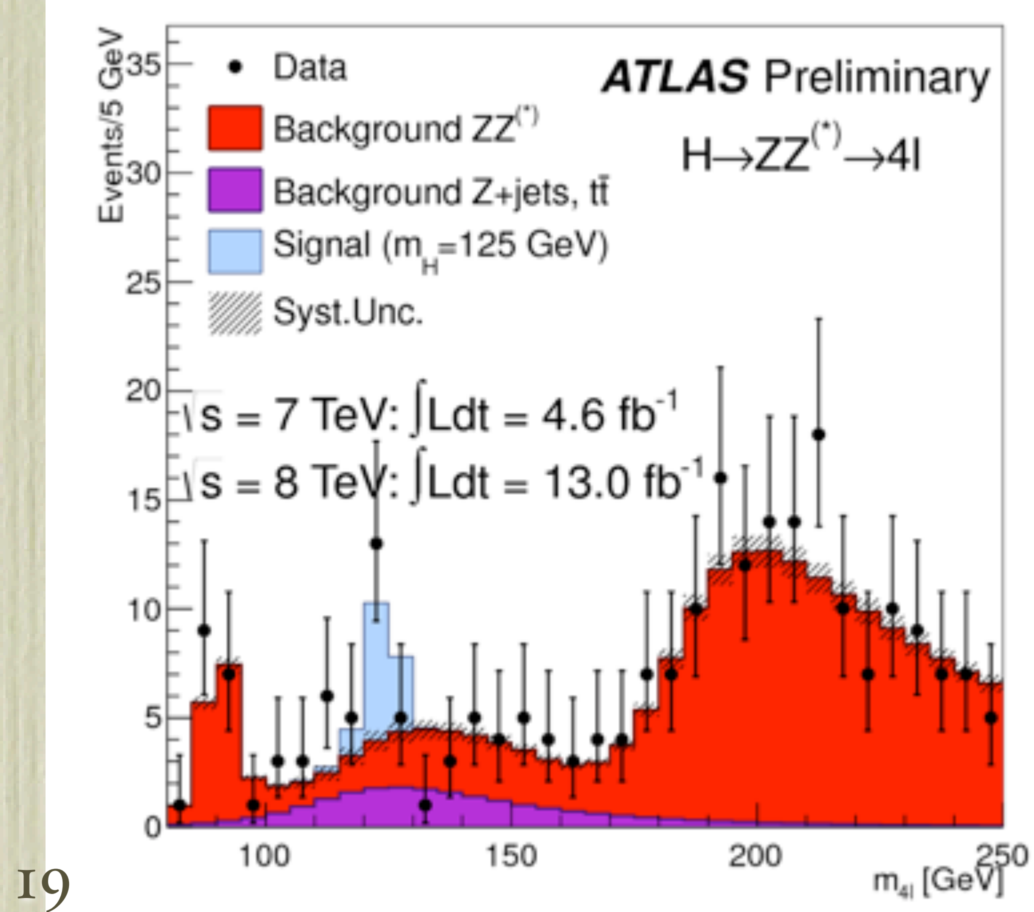








ATLAS

Updated results in H→γγ channel and property measurements **New**

Updated results in H→ZZ(*)→4l channel and property measurements **New**

Analysis in H→WW(*)→lνlν channel with 13 fb-1 of 8 TeV data

First results on H→Zγ channel **New**

High-mass BSM Higgs searches in diboson states **New**

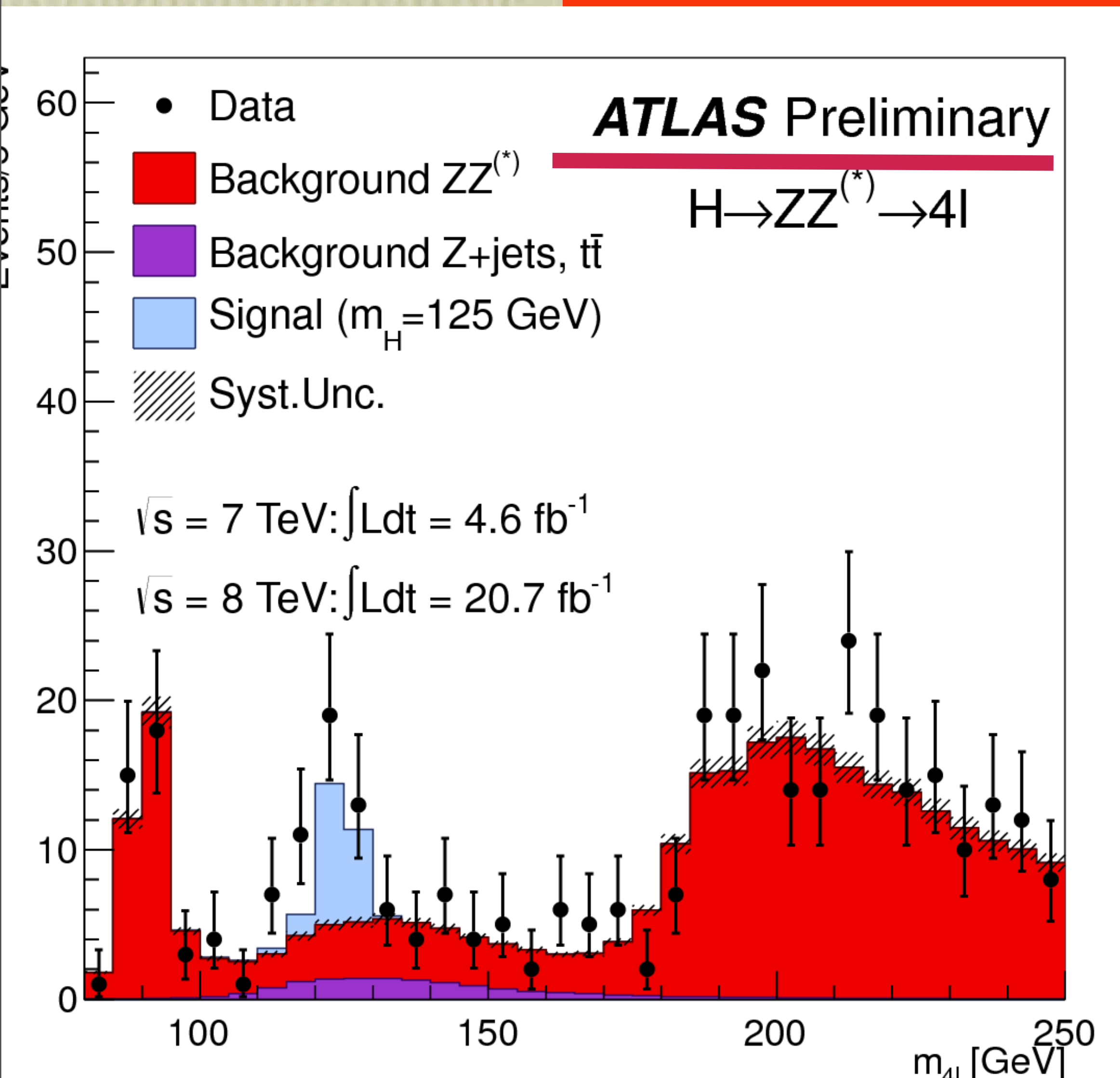
Color code:

- Red: new update, shown today
- Blue: no new update, briefly shown today
- Green: no new update, some information in back-up slides

- High sensitivity analyses:
  - $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$
  - $\mathrm{H} \to \mathrm{WW} \to 2\ell 2\nu$
  - $\mathrm{H} \to \gamma\gamma$
- Other analyses at low masses:
  - $\mathrm{WH} \to \mathrm{WWW} \to 3\ell 3\nu$
  - $\mathrm{W/ZH} \to qq'2\ell 2\nu$
  - $\mathrm{H} \to \mathrm{Z}\gamma$
- High mass analyses:
  - $\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\nu$
  - $\mathrm{H} \to \mathrm{ZZ} \to qq'2\ell$
  - $\mathrm{H} \to \mathrm{WW} \to qq'\ell\nu$
- Two analyses also very high performing at high mass:
  - $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$, including $H \to \mathrm{ZZ} \to 2\ell 2\tau$
  - $\mathrm{H} \to \mathrm{WW} \to \ell\nu\ell\nu$

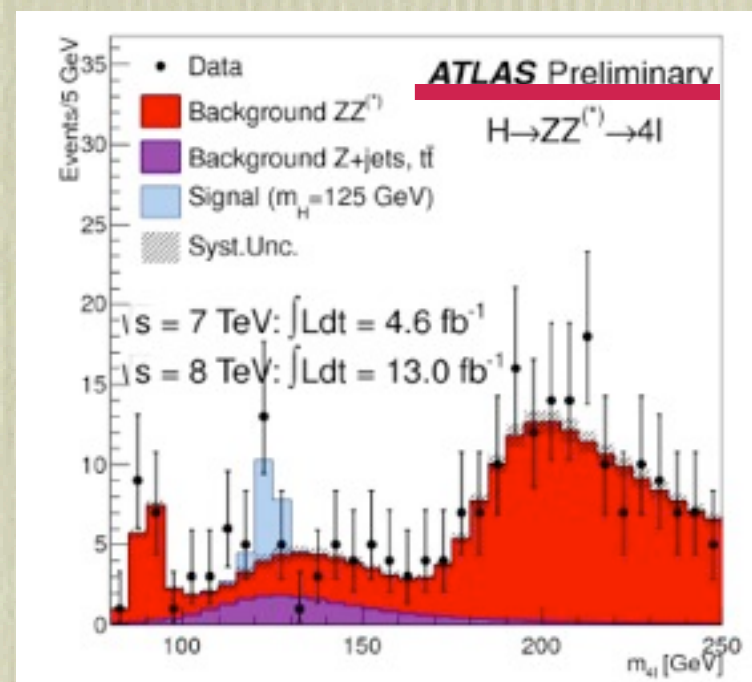
Zürich, January 7 and Moriond March 9

$H \to ZZ^{(*)} \to$ 4 leptons



Signal (125 +/- 5 GeV): 18 events
Expected : 8.3 background+ 9.9 events
Observed local significance: 4.1σ
Expected local significance: 3.1σ

Expected 4-lepton mass resolution (sigma) 1.6-2.4 GeV (4μ to $4e$)
Mass distribution shown in 5 GeV bins! (now also in 2.5 GeV bins!)
data transparency still missing (no detailed table given)!



Fitted mass : $m_H = 124.3 \pm 0.7$
Signal strength : $\hat{\mu} = 1.6 \pm 0.4$

peak excess for new data disturbingly low: around 121-122±1? GeV!
(110-115-120-125-130-135 GeV with 3 - 9 - 12 - 7 - 4 - 4 events/bin)

compared to CMS (March 2013):
Mass= 125.8 ± 0.5 (stat) ± 0.2 (syst.) GeV
and $\mu = 0.91 \pm 0.3$ (0.24)

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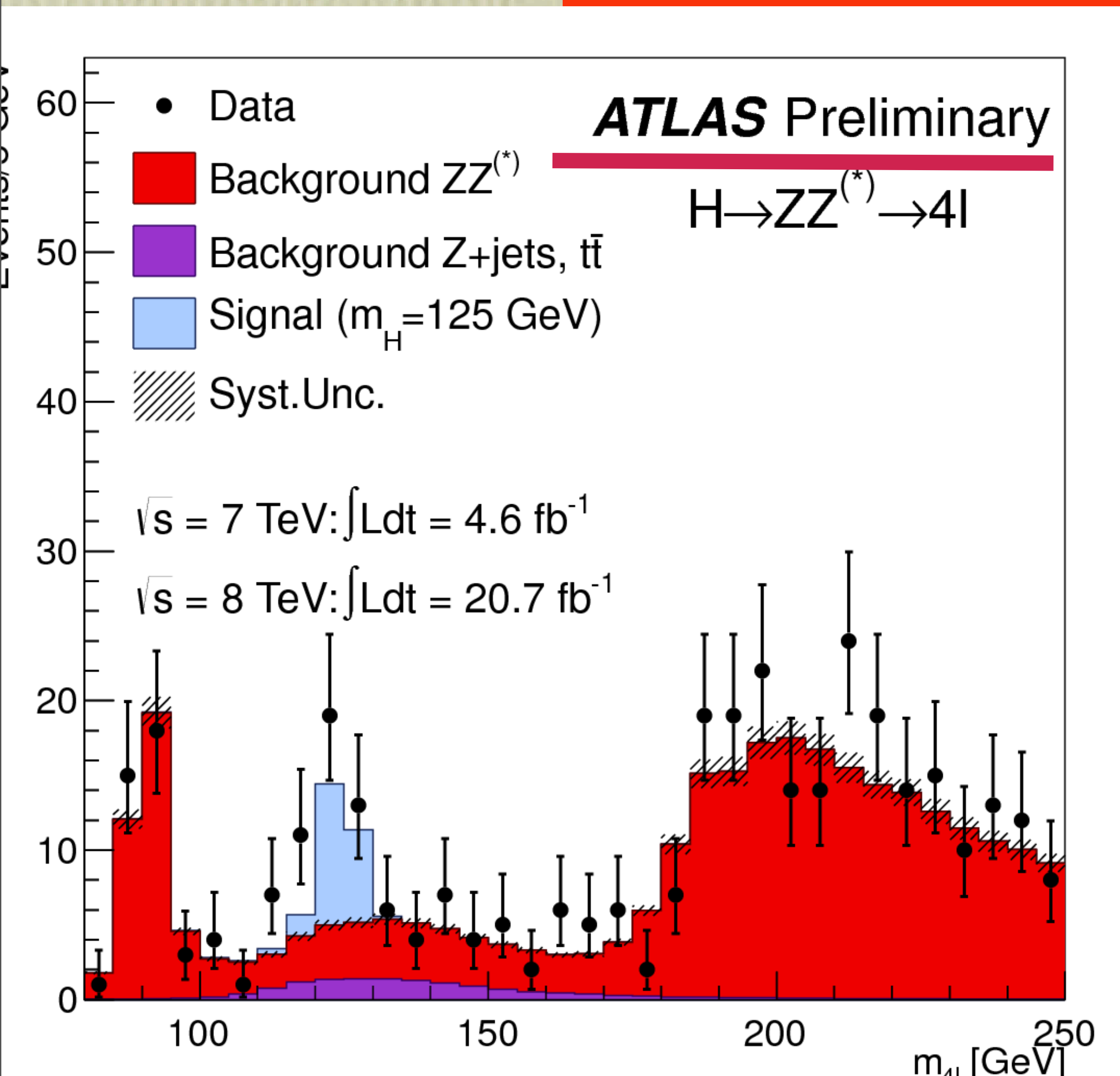

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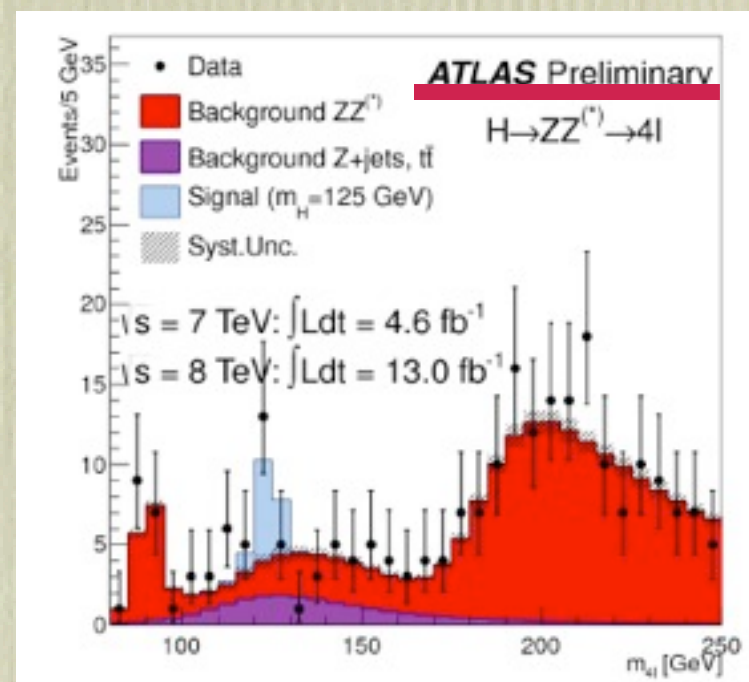

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Mass mesurement: $m_H = 123.5 \pm 0.9\ (stat)\ ^{+0.4}_{-0.2}\ (syst)$ GeV
Signal strength: $\hat{\mu} = 1.3 \pm 0.4$

peak excess for new data disturbingly low: around 121-122±1? GeV!
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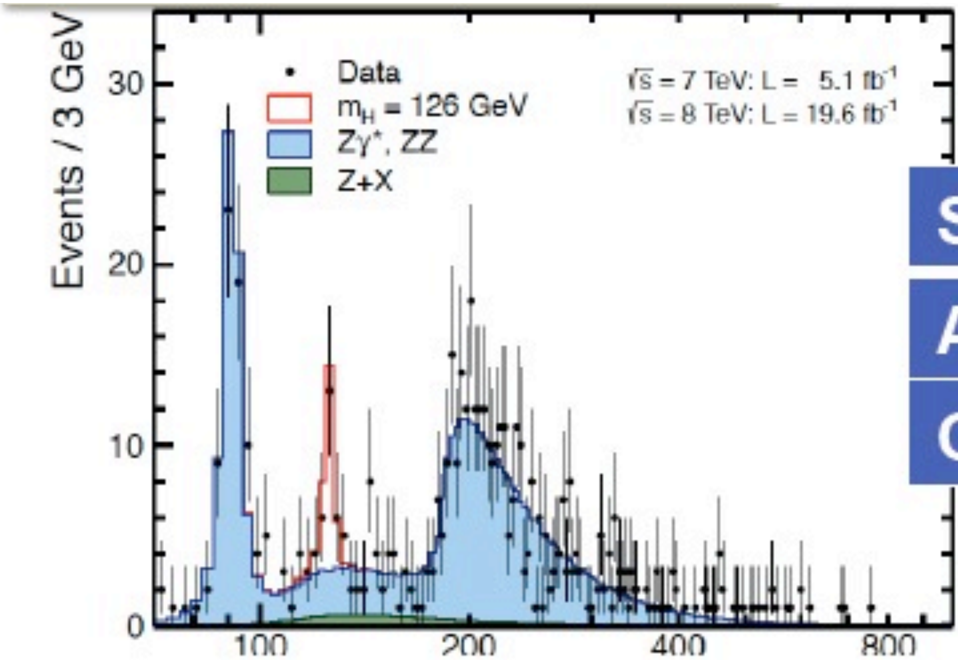
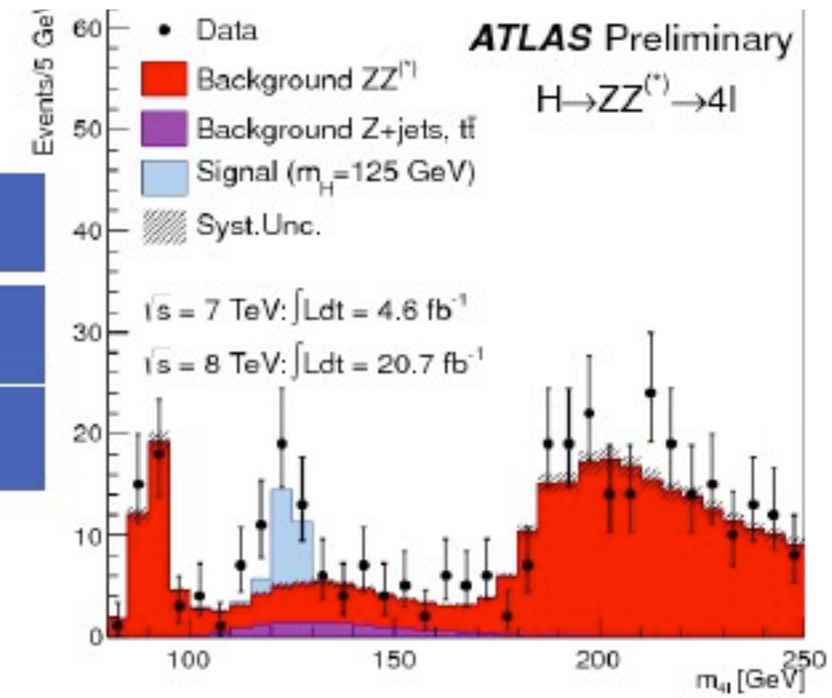
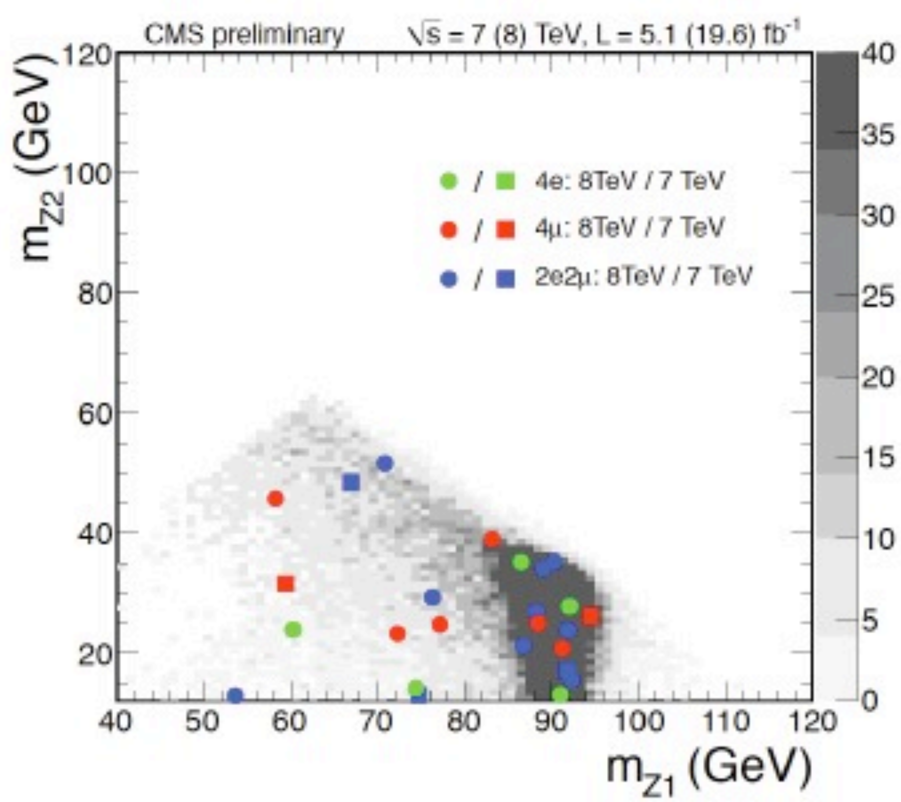
Moriond March 9

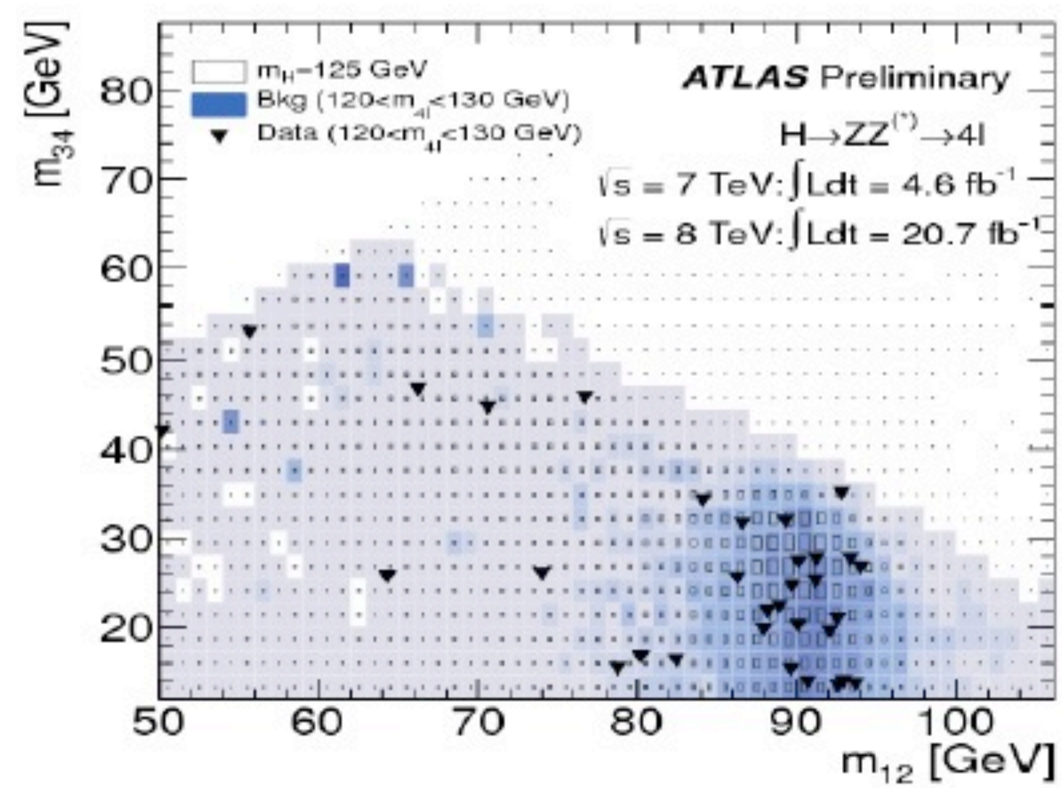


Sign/Exp	Exp	Obs
ATLAS	4.4 σ	6.6 σ
CMS	6.7 σ	7.2 σ

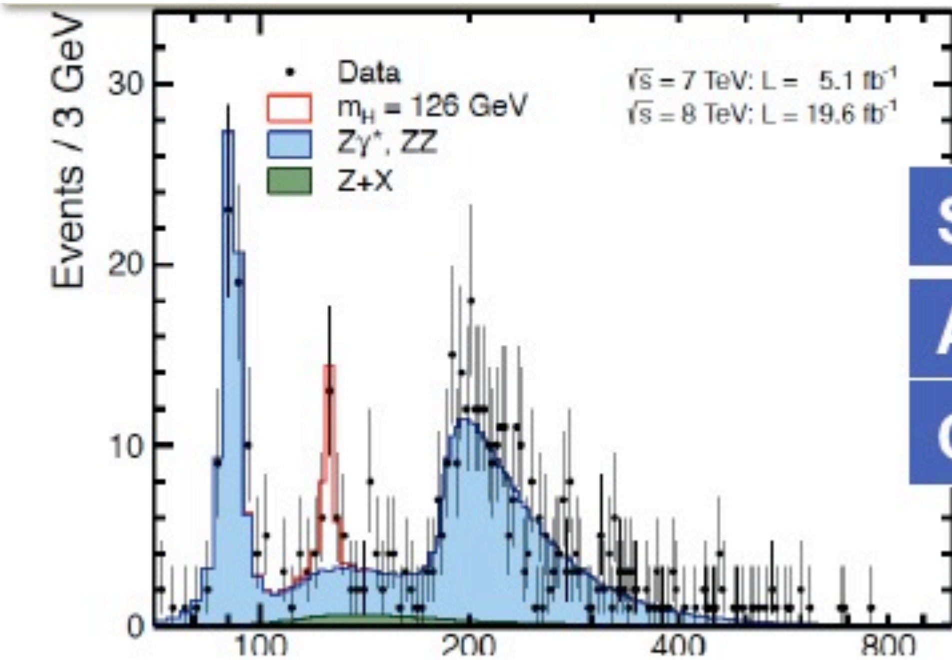




Z_1 Z_2 mass ok



Moriond March 9



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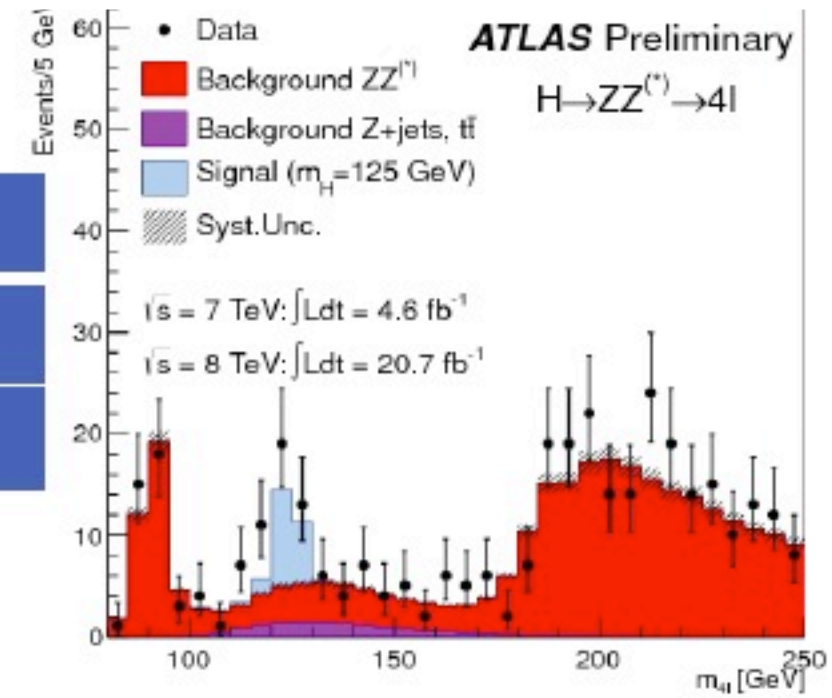

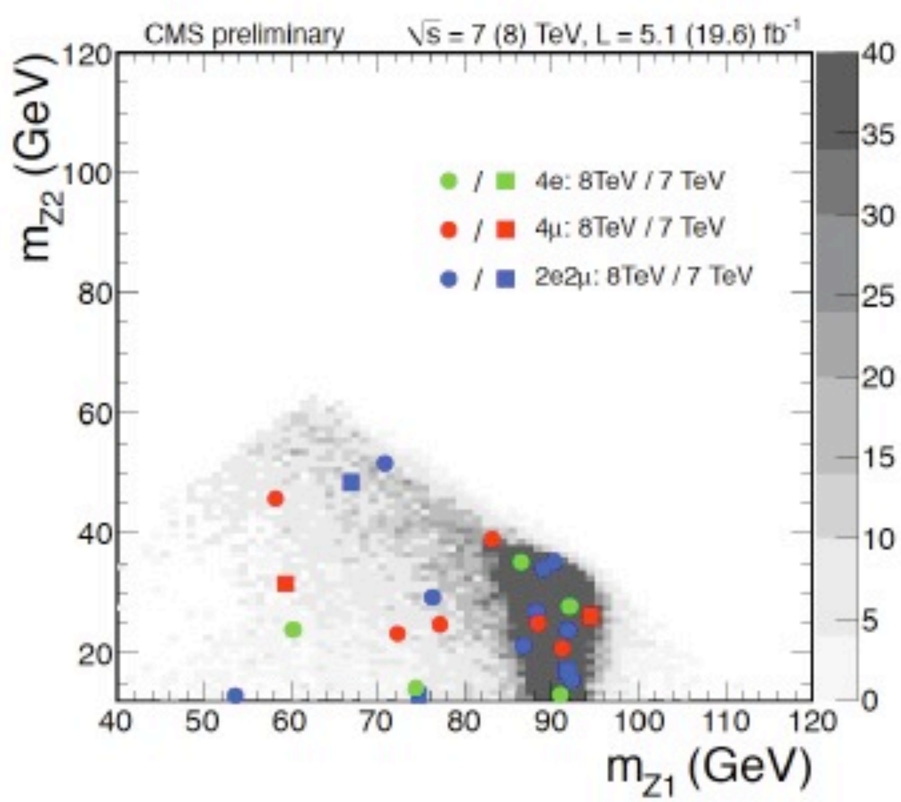

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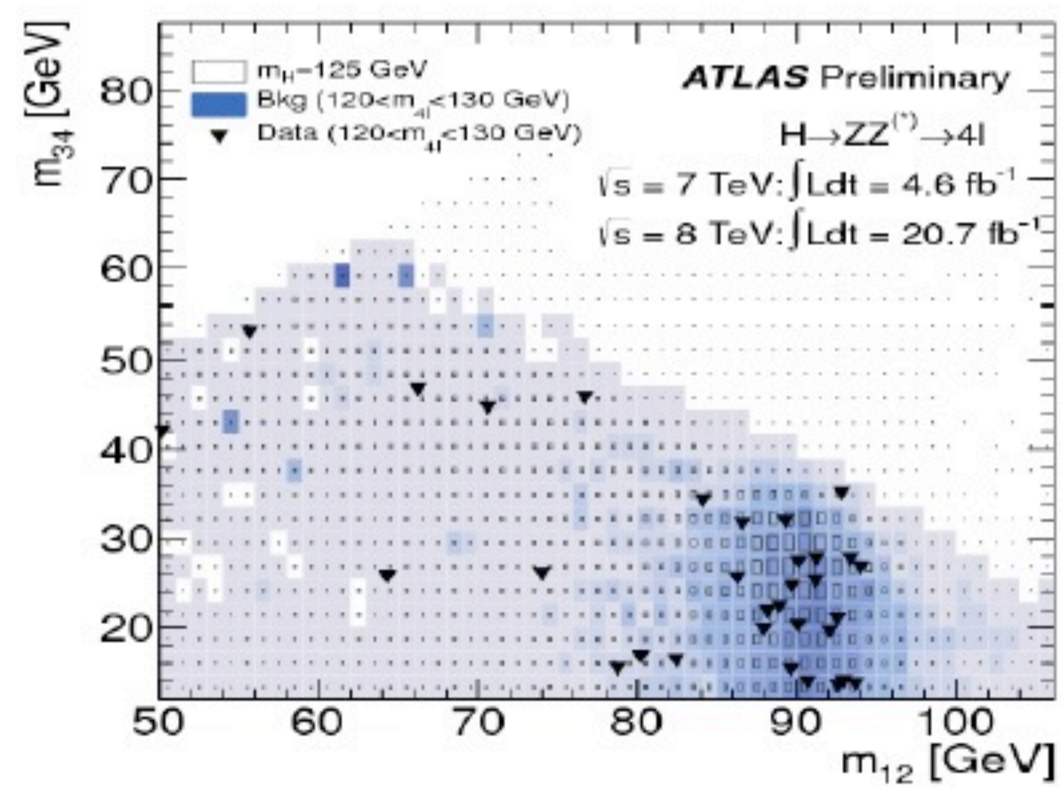
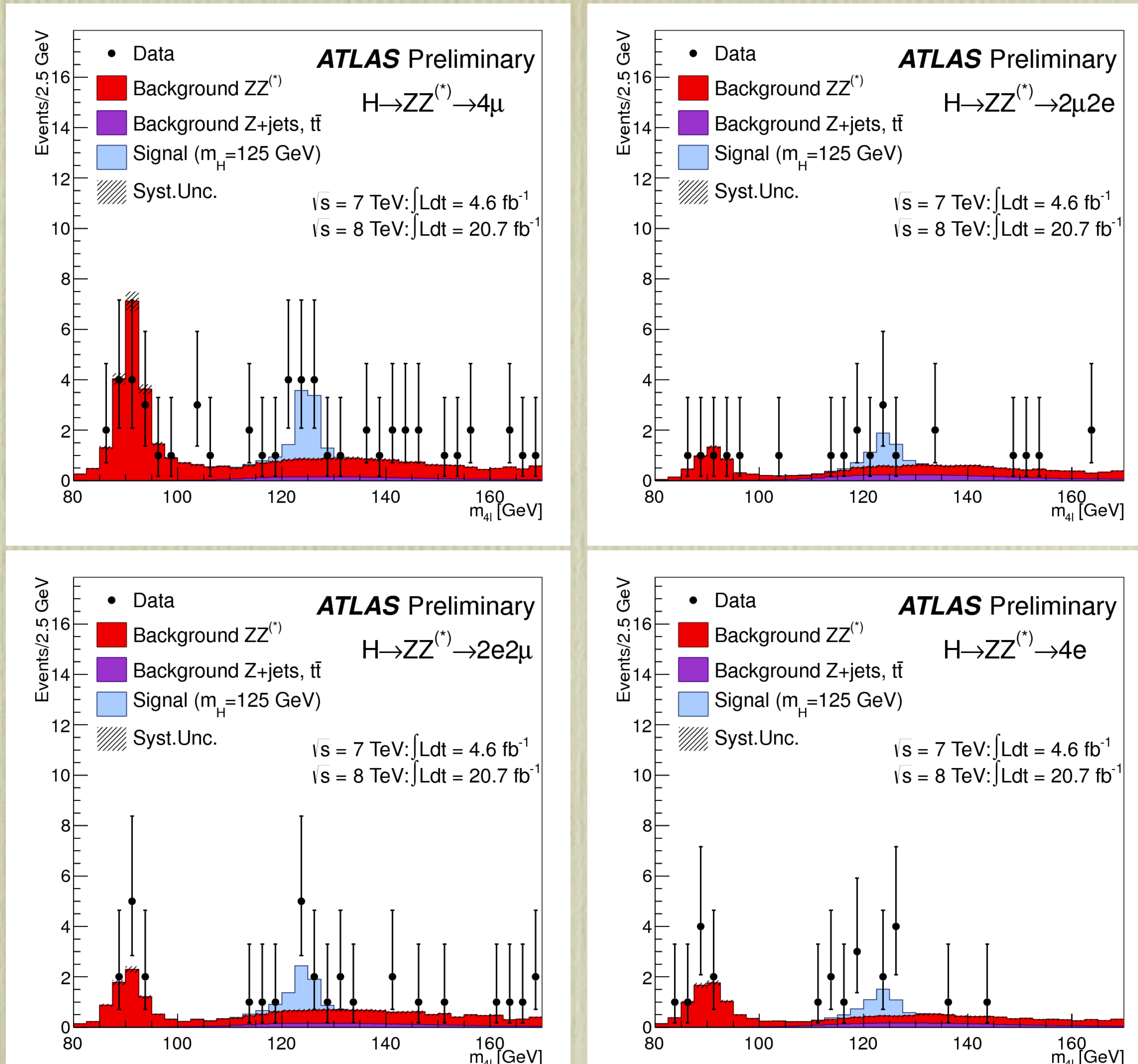
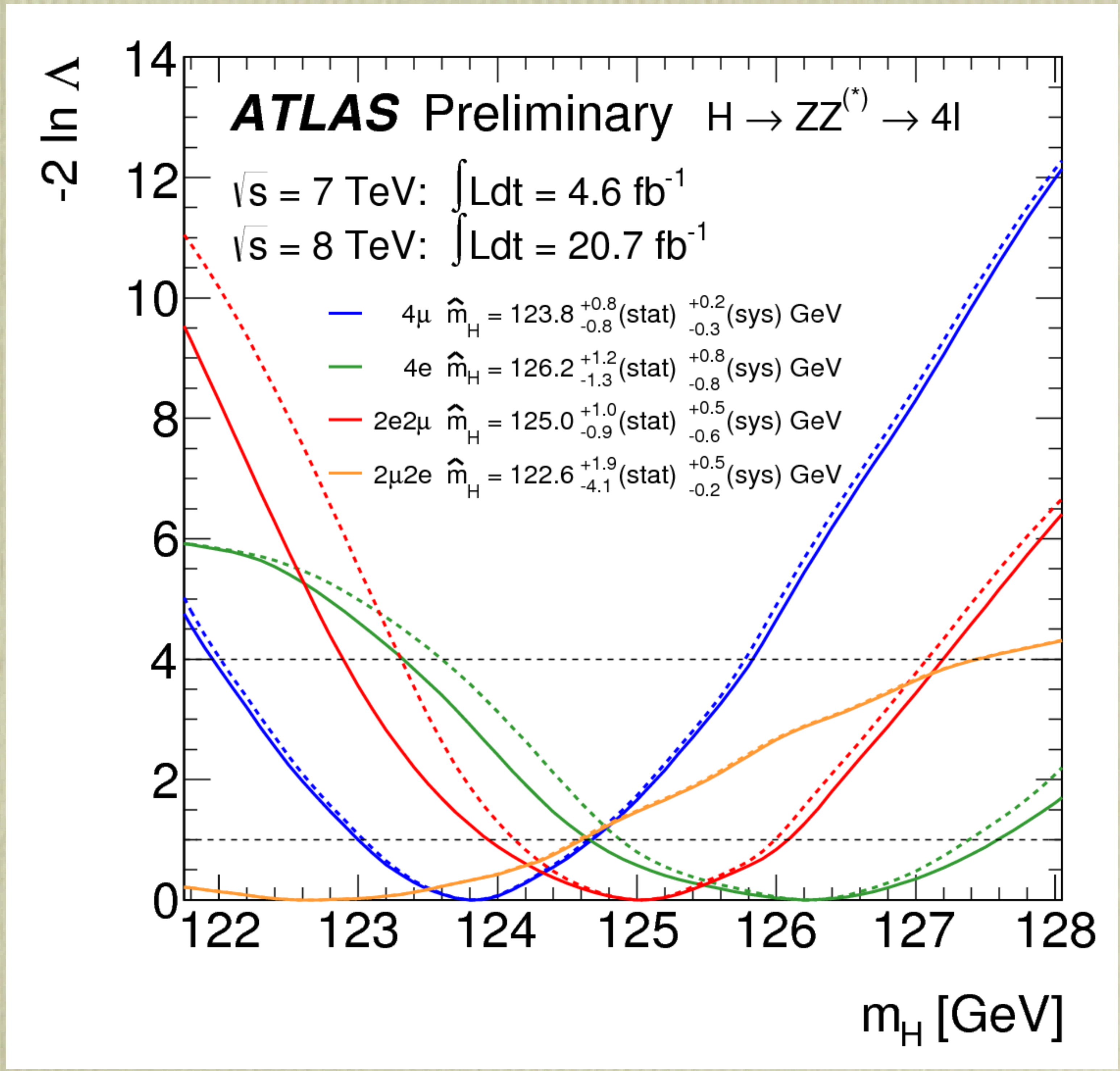


different lepton final states: mass with 2.5 GeV bins (“strange signal




ATLAS Preliminary H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
4μ m̂H = 123.8 +0.8 -0.8 (stat) +0.2 -0.3 (sys) GeV
4e m̂H = 126.2 +1.2 -1.3 (stat) +0.8 -0.8 (sys) GeV
2e2μ m̂H = 125.0 +1.0 -0.9 (stat) +0.5 -0.6 (sys) GeV
2μ2e m̂H = 122.6 +1.9 -4.1 (stat) +0.5 -0.2 (sys) GeV
-2 ln Λ
mH [GeV]

Az ATLAS és a CMS kollaborációk áltat talált 126 GeV-es tömegű rezonancia minden ésszerű kétségen felül egy Higgs-bozon

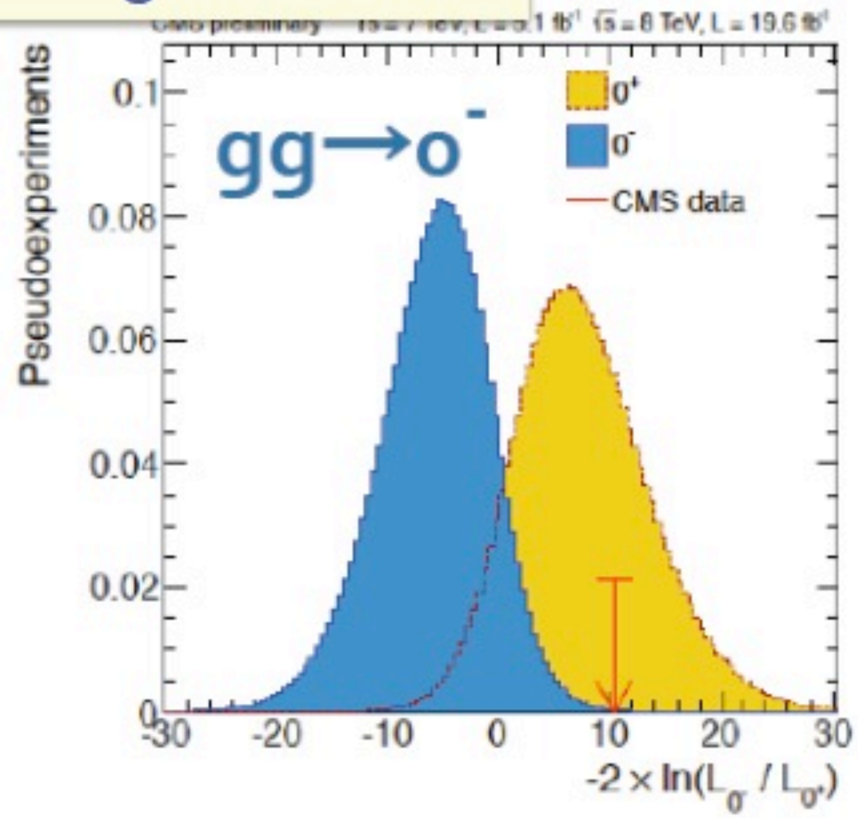
- A rezonancia spinje zérus és csatolásai pozitiv paritásúak
- Pozitiv paritást erősen favorizálja a $h \to ZZ^* \to 4l$ bomlási módusok szögeloszlásai.

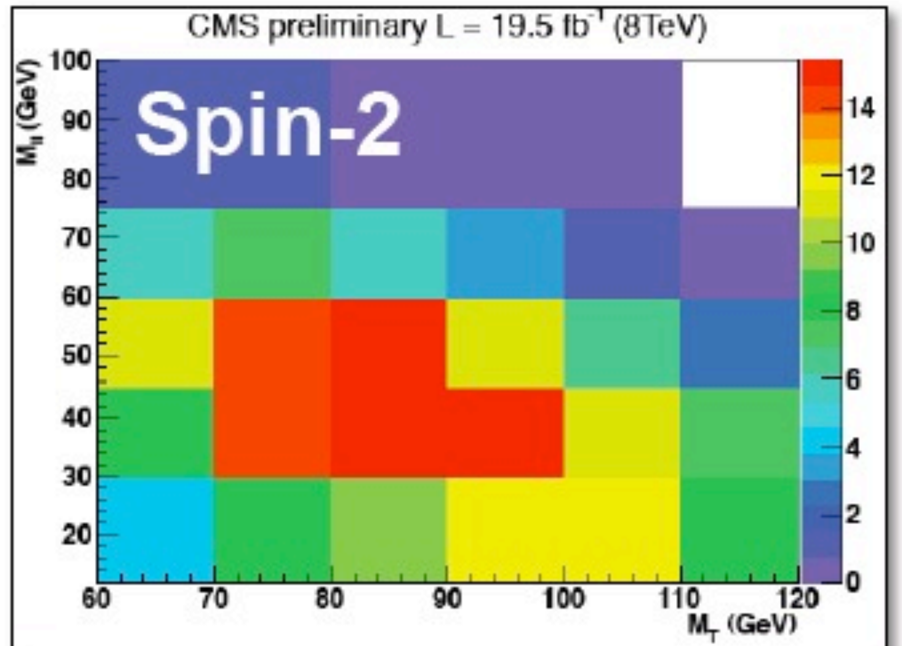
Is it the 'Higgs'?

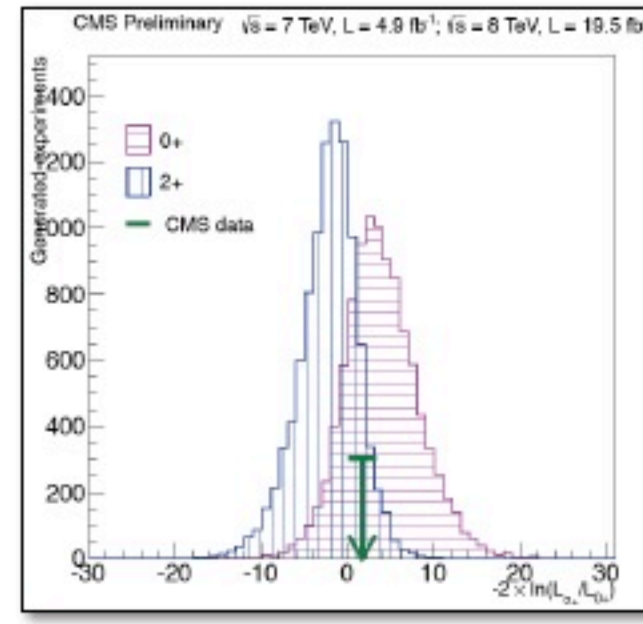
- $\mathbf{J^{PC} = 0^{++}}$
- **Its coupling to fermions and gauge bosons?**
- **Its self coupling ?**
- **What does it tell us that** $\mathbf{M_H} = \mathbf{126}\,\mathrm{GeV}$ **?**
- **Precision measurements and predictions for Higgs properties**
- **Phenomenology driven research at the LHC for 20 years**

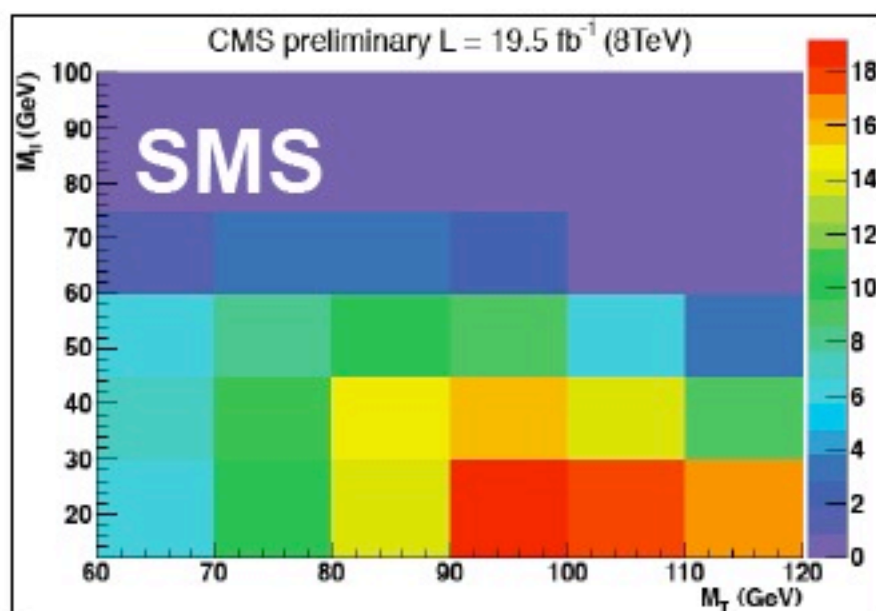
Spin-parity from ZZ* and WW*

Mingshui Chen









ZZ*:

pseudoscalar, spin-1 and spin-2 cases excluded at ≥ 95% CL

Expected separation ~ 2σ

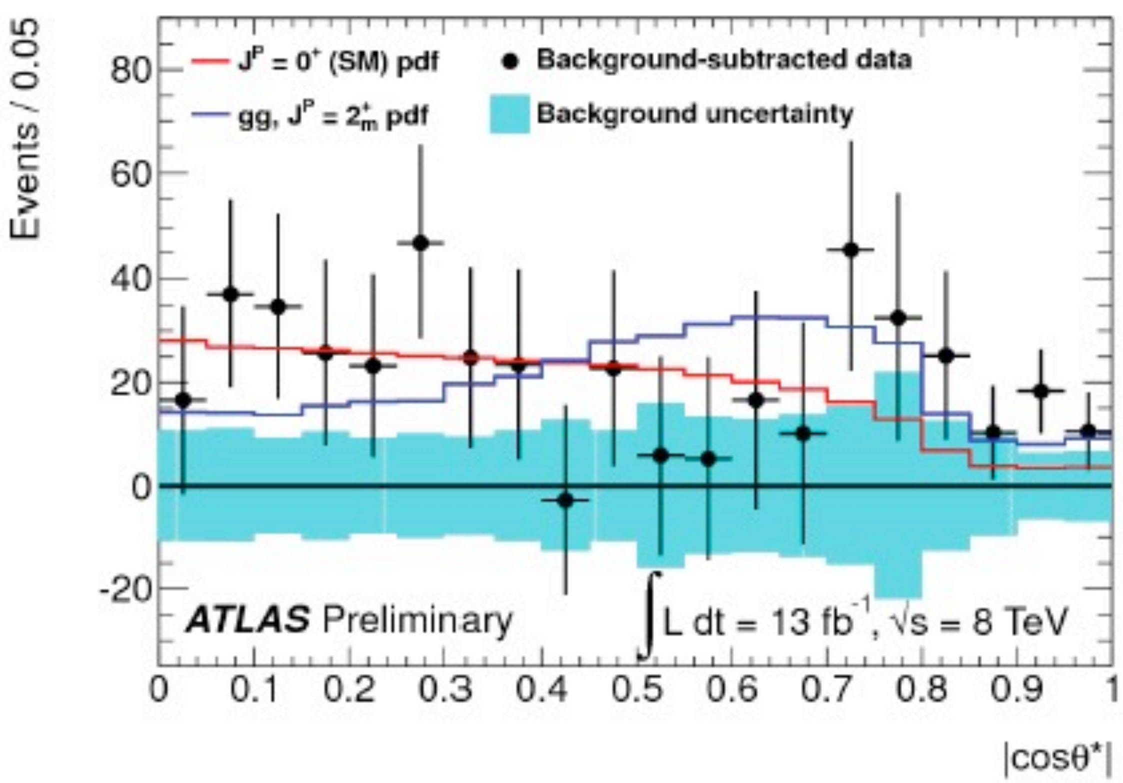
Data: consistent with both hypotheses; favors slightly 0+

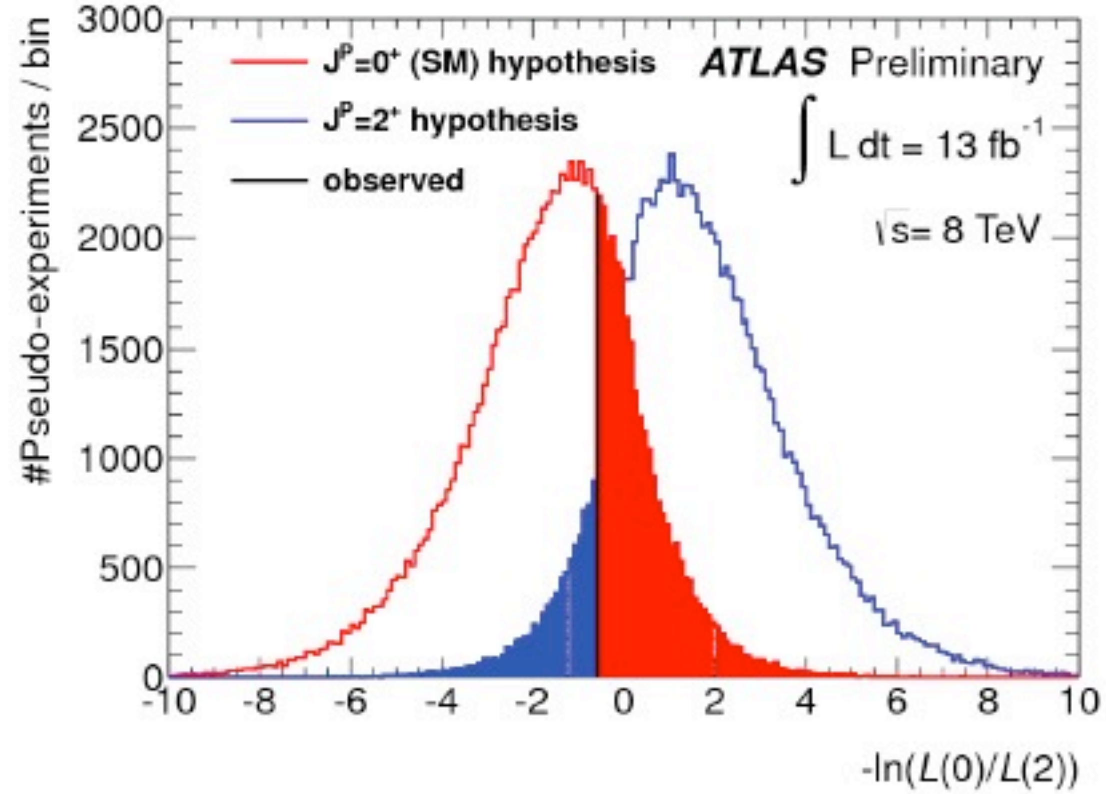
Freitag, 22. März 2013

Fabrice Hubaut

Spin-parity from γγ

- **Sensitive to spin-0 vs spin-2**





- **Spin-2^+ hypothesis expected exclusion CL_s at 93%**
- **Observation compatible with spin-0^+, slightly favored over spin-2^+ hypothesis**

Vicky Martin

ATLAS fermionic summary

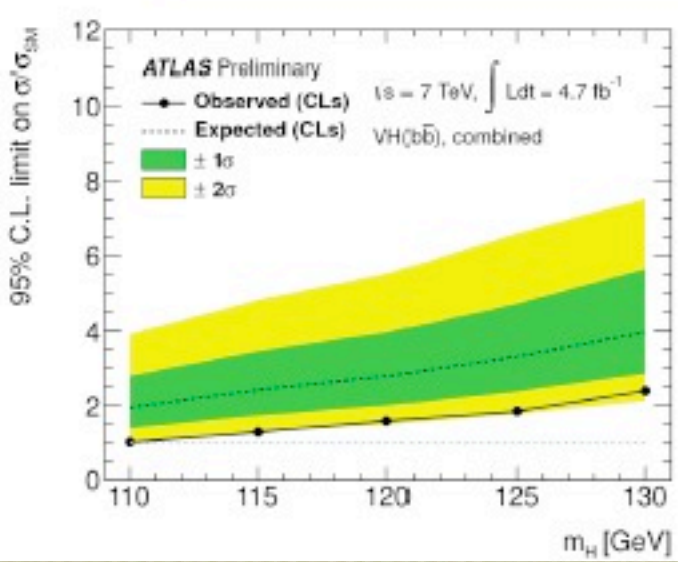
- **No observation of SM Higgs boson production, decaying into fermions or invisibly, in the range $100 < m_H/\text{GeV} < 150$.**

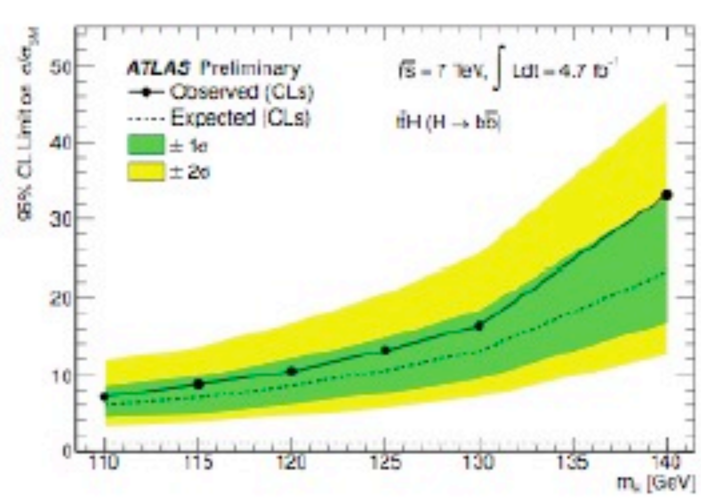
95% CL limits on SM Higgs production, for m_H=125 GeV

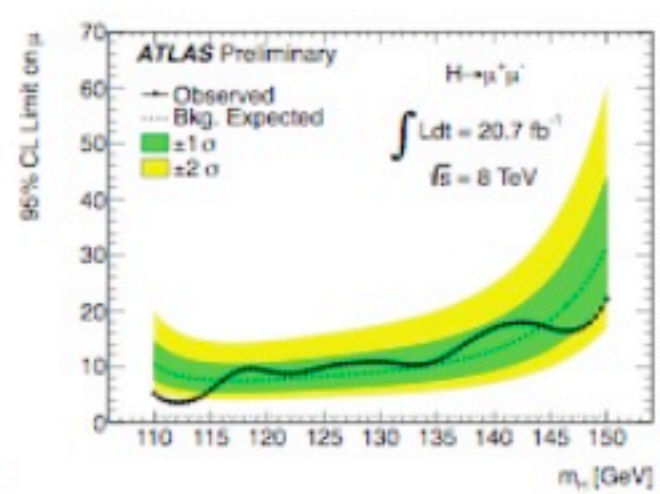
	observed	expected
$VH \to Vb\bar{b}$	1.8	1.9
$t\bar{t}H, H \to b\bar{b}$	13.1	10.5
$H \to \tau^+\tau^-$	1.9	1.2
$H \to \mu^+\mu^-$	9.8	8.2

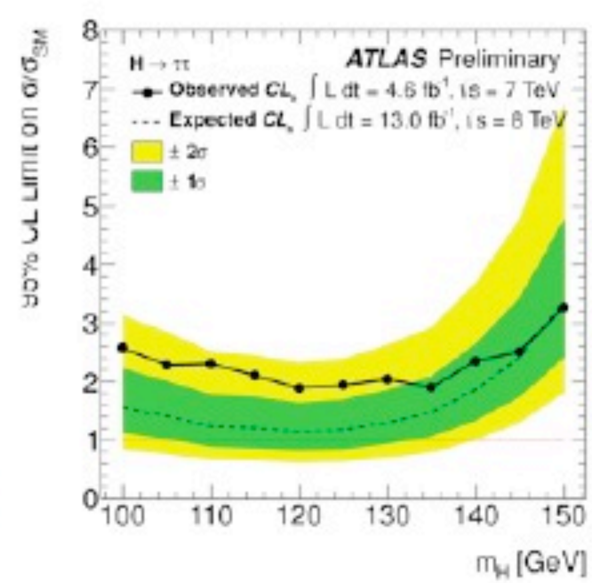
95% CL limits on SM Higgs, for m_H=125 GeV

	observed	expected
BR ($H \to$invisible)	< 65%	< 84%

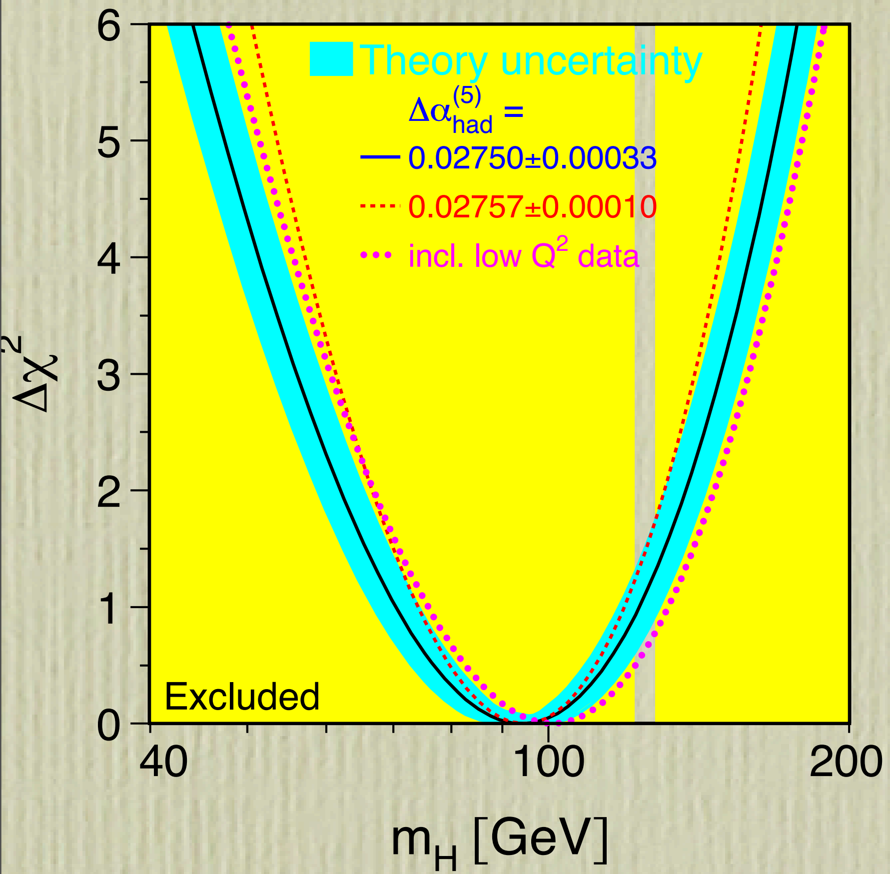


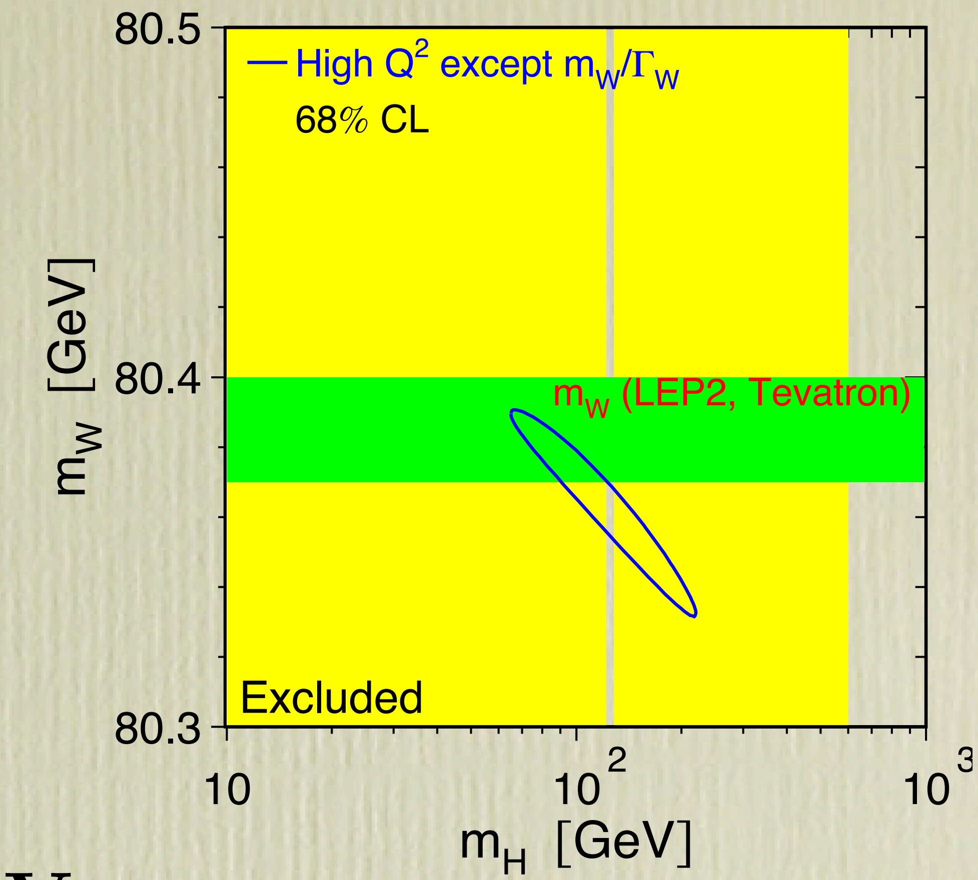




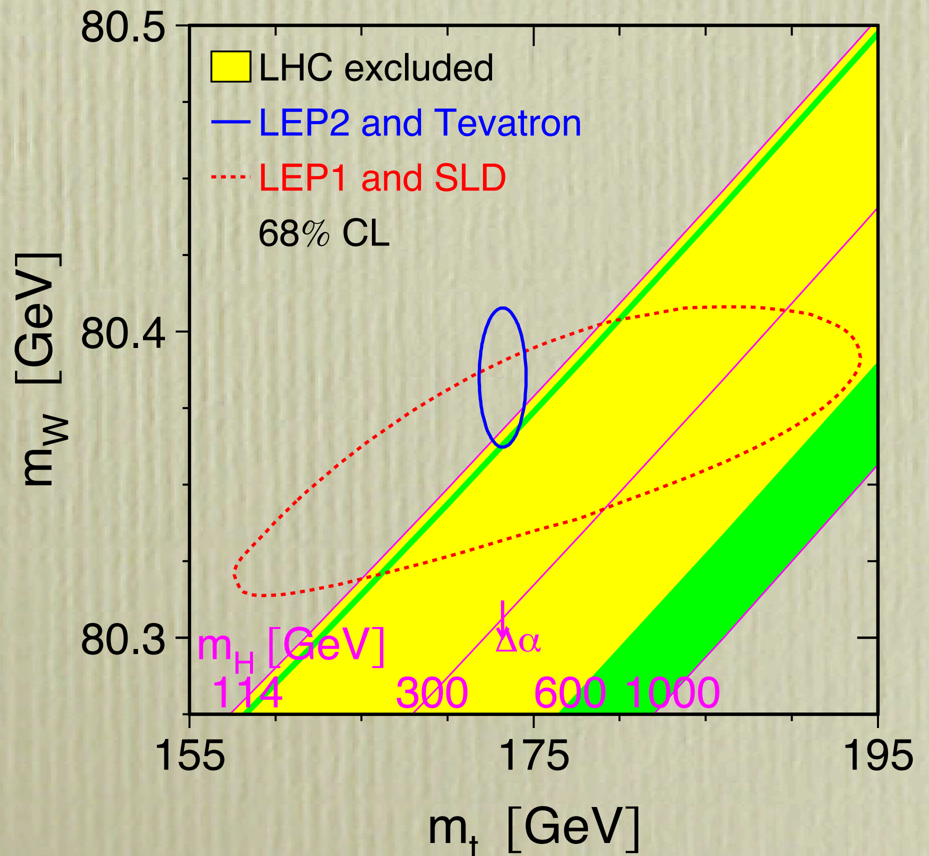


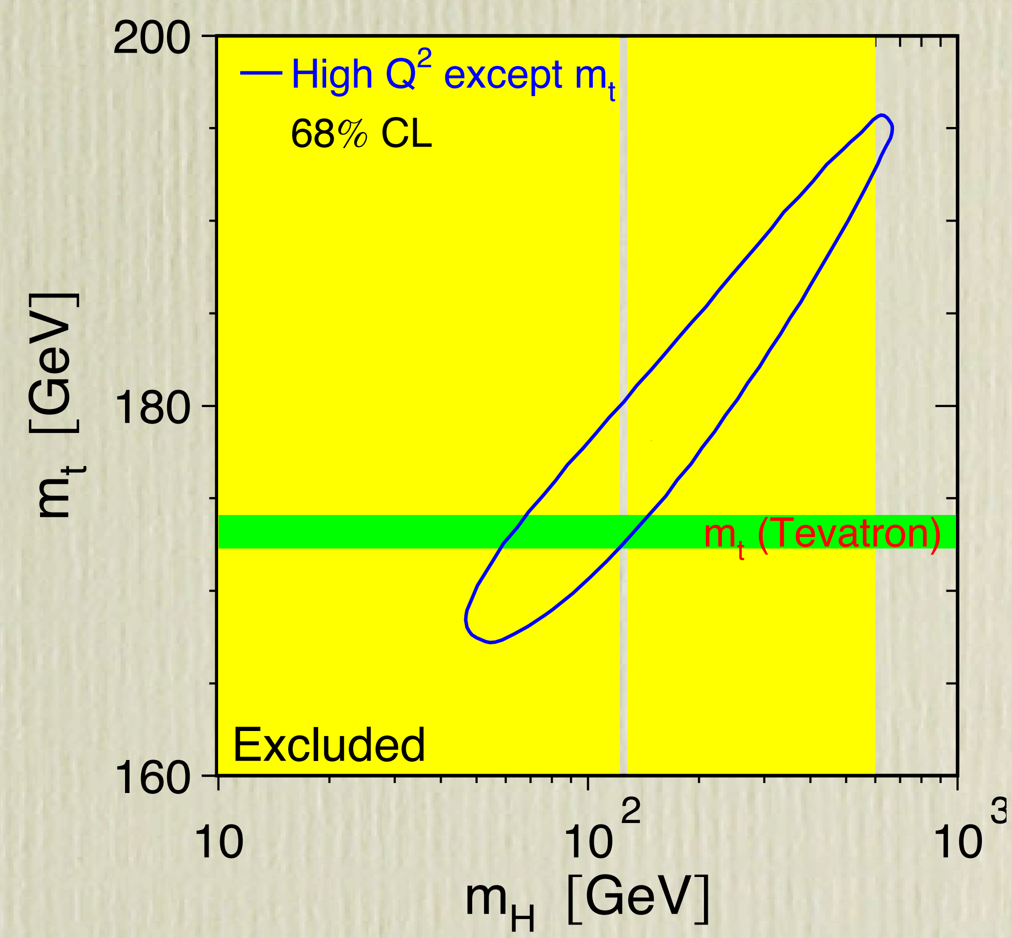
LEP-I-II, SLD constraints on the Higgs-mass





$$\mathbf{M_H < 114.4 GeV}$$
$$\mathbf{M_H = 94 \pm [29/24] GeV}$$





Triumph for he Standard Theory

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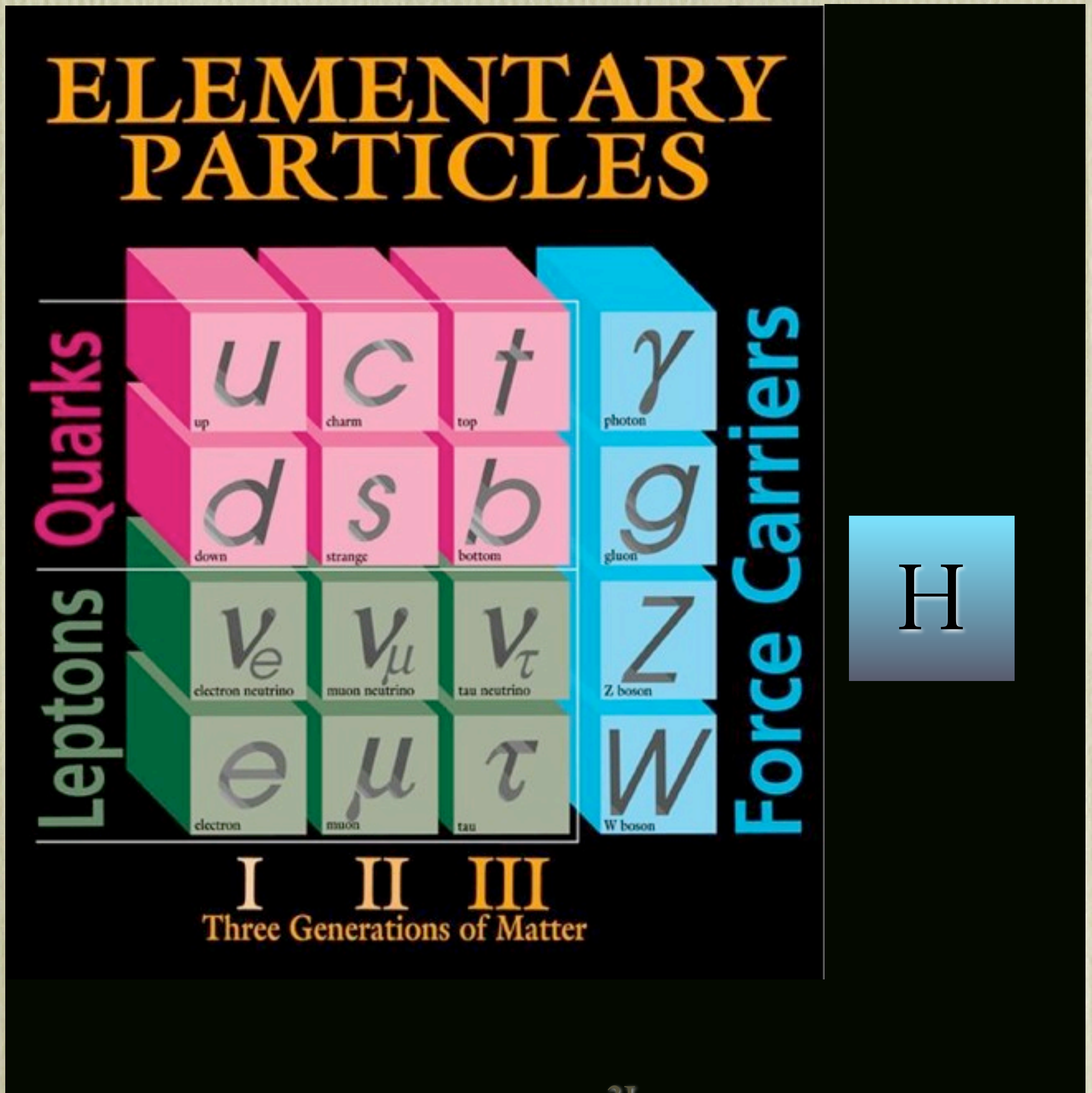
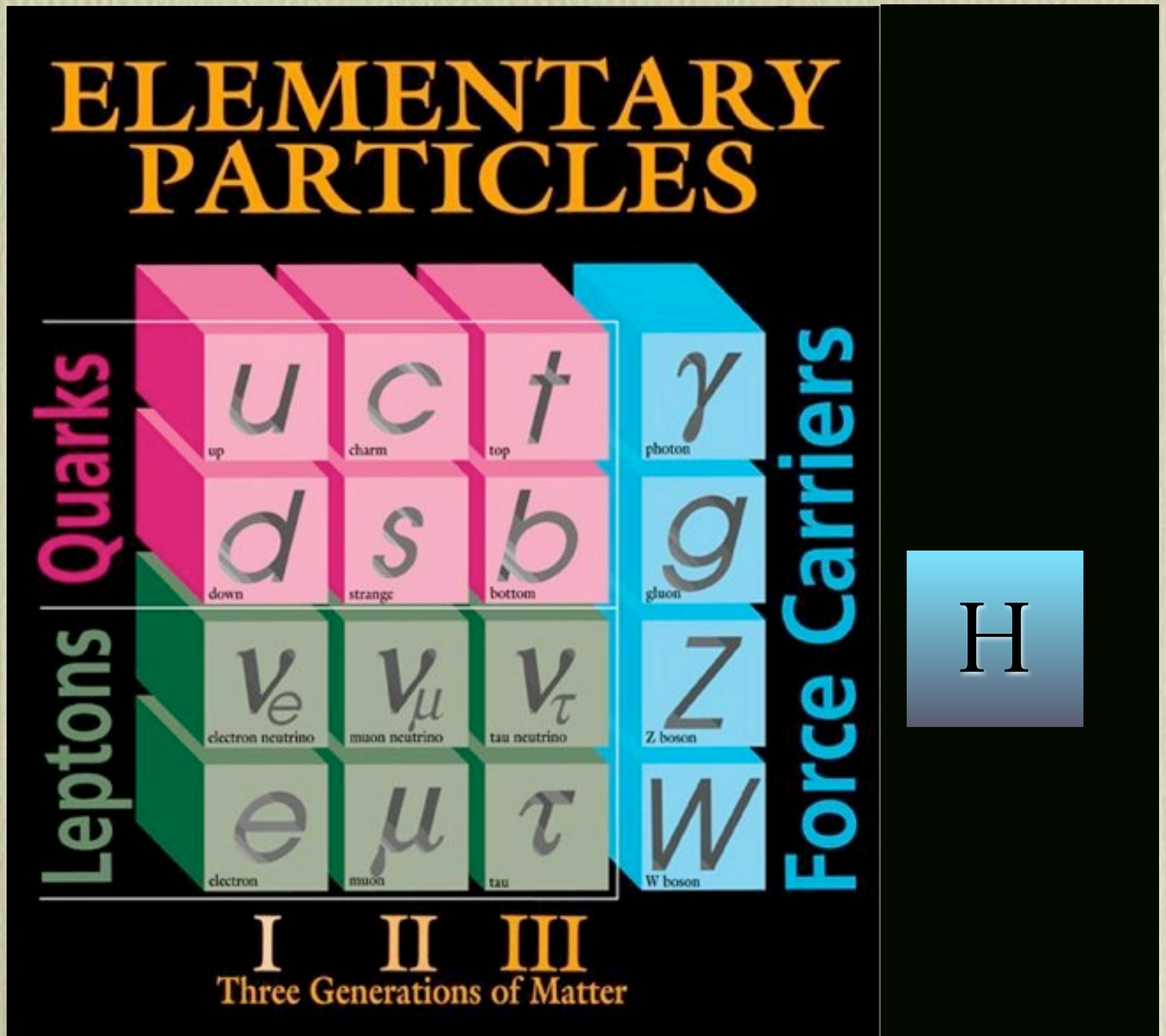


Triumph for he Standard Theory



Gauge and Higgs Interactions

The Standard Theory

The Standard Theory

$$\mathcal{L} = -\frac{\mathbf{1}}{\mathbf{4g'^2}}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} - \frac{\mathbf{1}}{\mathbf{4g^2}}\mathbf{B}^{\mathbf{I}}_{\mu\nu}\mathbf{A}^{\mu\nu\mathbf{I}} - \frac{\mathbf{1}}{\mathbf{4g_s^2}}\mathbf{G}^{\mathbf{a}}_{\mu\nu}\mathbf{G}^{\mu\nu\mathbf{a}}$$

The Standard Theory

$$\mathcal{L} = -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}B^{I}_{\mu\nu}A^{\mu\nu I} - \frac{1}{4g_s^2}G^{a}_{\mu\nu}G^{\mu\nu a}$$

$$+ \bar{Q}_i i\not{D}Q_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{L}_i i\not{D}L_i + \bar{e}_i i\not{D}e_i$$

The Standard Theory

$$\mathcal{L} = -\frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} B^{I}_{\mu\nu} A^{\mu\nu I} - \frac{1}{4g_s^2} G^{a}_{\mu\nu} G^{\mu\nu a}$$

$$+ \bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{e}_i i \not{D} e_i$$

$$+ \left(Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_L^{ij} \bar{L}_i e_j H + c.c. \right)$$

The Standard Theory

$$\mathcal{L} = -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}B^I_{\mu\nu}A^{\mu\nu I} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a}$$

$$+ \bar{Q}_i i\not{D} Q_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{L}_i i\not{D} L_i + \bar{e}_i i\not{D} e_i$$

$$+ \left(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_L^{ij}\bar{L}_i e_j H + c.c. \right)$$

$$+ (D^\mu H)^\dagger (D_\mu H) - \lambda (H^+ H)^2 + \lambda v^2 H^\dagger H + \frac{\Theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^{\rho\sigma\, a}$$

The Standard Theory

$$\mathcal{L} = -\frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} B^I_{\mu\nu} A^{\mu\nu I} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a}$$

$$+ \bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{e}_i i \not{D} e_i$$

$$+ \left(Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_L^{ij} \bar{L}_i e_j H + c.c. \right)$$

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$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

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Masses are generated by Spontaneous Symmetry Breaking

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Chiral gauge theory: no mass terms are allowed.

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(last term crossed out)

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Chiral gauge theory: no mass terms are allowed.

Masses are generated by Spontaneous Symmetry Breaking

Természetesség és a Higgs-bozon tömege

- **A Standard Elmélet a redukcionista meggyőződés látványos sikere:**
  létezik valamilyen megejtően egyszerű elmélet, amelyben minden dimenzió nélküli mennyiség meghatározható

$$\frac{1}{g^2}+\frac{1}{g'^2}=\frac{1}{e^2}$$

$$\alpha \approx \alpha_s \frac{\frac{3}{5}\cos^2\Theta_W\,(b_3-b_2)+\sin^2\Theta_W\,(b_1-b_3)}{(b_1-b_2)}$$

de a mérések szerint $\frac{m_H^2}{m_{\mathrm{Plank}}^2} \approx 2.8\times 10^{-33}$ nagyon kicsi szám

- **Lehetséges a nagyon kis tömegarányokat megmagyarázni?**

  ’t Hooft : Igen, amennyiben zérus tömegű határesetben az elmélet magasabb szimmteriára tesz szert

Miért releváns a Planck/GUT tömeg?

- **Nagy energiájú quantum fluktuációk nagy járulékot adnak a skalár részecske tömegéhez.** (Kvantum komplikáció).

Higgs propagál a fizikai vákuumban, melyben virtuális részecskék fluktuálnak

$$\mathbf{E}t \leq \hbar, \qquad E^2 - p^2 \neq m^2 \qquad \delta m_H^2 = \kappa \Lambda^2,$$

the effective strength of the of the interaction is given by the available energy

$$m_e \approx \frac{\alpha}{r} \Longrightarrow \alpha m_e \ln m_e r$$

$$\mathbf{M}_{\pi^+}^2 - M_{\pi^0}^2 = \frac{3\alpha}{4\pi}\Lambda^2, \qquad \Lambda \approx m_\rho$$

- $$\frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} = \frac{G_F^2 f_K^2}{6\pi^2} \sin^2\theta_c\, \Lambda^2, \qquad \Lambda \approx m_c$$

$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_H^2\right)\Lambda^2 \qquad \mathbf{\Lambda} \approx 1\,\mathrm{TeV}$$

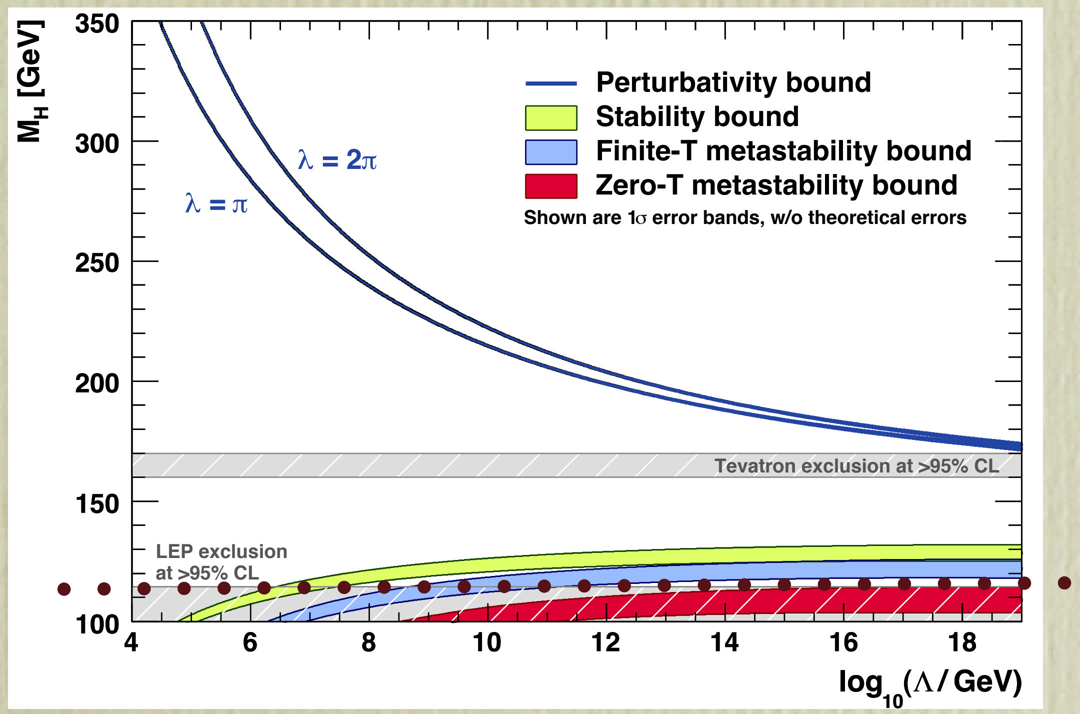
Miért releváns a Planck/GUT tömeg?

Nagy energiájú quantum fluktuációk nagy járulékot adnak a skalár részecske tömegéhez. (Kvantum komplikáció).

Higgs propagál a fizikai vákuumban, melyben virtuális részecskék fluktuálnak, a kölcsönhatás effektiv erősségét az energia adja

$\mathbf{E}t \leq \hbar, \quad E^2 - p^2 \neq m^2 \quad \delta m_H^2 = \kappa\Lambda^2, \quad \delta m_H^2 < m_H^2$

Λ **az effektiv térelmélet cut-off -ja**



Naturalness arguments work in many cases, argument for SUSY

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$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_H^2\right)\Lambda^2 \qquad \mathbf{\Lambda} \leq 0.5\mathrm{TeV}$$

Veltman

Naturalness arguments work in many cases, argument for SUSY

Fermion contribution:

$$m_h^2 \approx m_{h\,0}^2 - \frac{\lambda_f^2}{8\pi^2} N_c^f \int^{\Lambda} \frac{d^4p}{p^2} \approx m_{h\,0}^2 + \frac{\lambda_f^2}{8\pi^2} N_c^f \Lambda^2 \ ,$$

naive measure of fine tuning:

$$\kappa \equiv \frac{\delta m^2_{h\,\text{1-loop}}}{m_h^2} \qquad\qquad \kappa = 10, 100, \ldots 10^{30}$$

Softly broken supersymmetry:

$$\delta m_h^2 \approx + \frac{\lambda_f^2}{8\pi^2} N_c^f \left(m_{\tilde{f}}^2 - m_f^2 \right) \ln \left(\Lambda^2 / m_{\tilde{f}}^2 \right) \ ,$$

Upper limit on sfermion mass $m_{\tilde{f}}$

Természetesség (naturalness) $\delta m_H^2 < m_H^2$

BSM: Standard Model parameters are calculable

$$\Delta \equiv \max \left| \frac{a_i \; \partial M_Z^2(a_i)}{M_Z^2 \; \partial a_i} \right|$$

measure of naturalness

All models: tuning of delta less than 1%

Ell kell vetnünk a természetesség koncepcióját?

Light Higgs-mass value is explained by anthropic principle ?

Self organized criticality?

Can elementary scalar exist?

Spin 1 and spin 1/2 particle masses are protected due to spin

A Standard Elmélet stabilitása és a Higgs-potential

- **Nagy energiájú quantum fluktuációk nagy járulékot adnak a skalár részecske tömegéhez.**

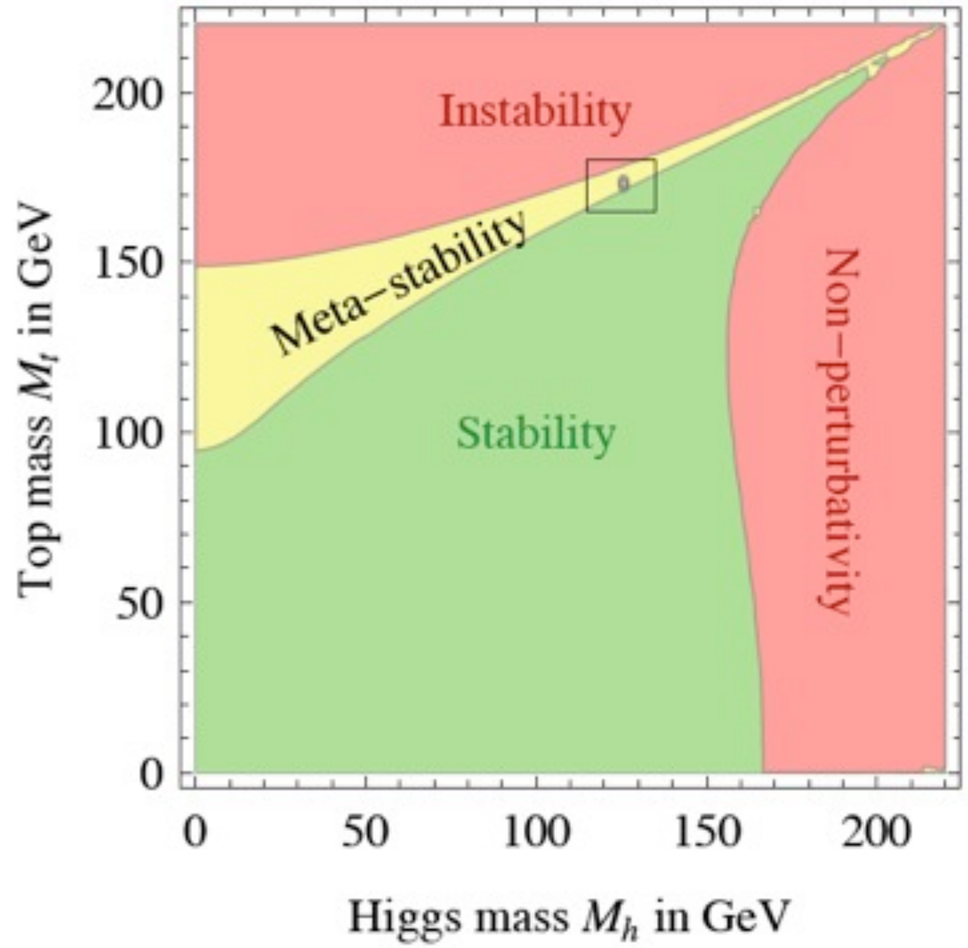
$$V(H) \approx \underbrace{-\frac{m^2(\mu \sim h)}{2}|H|^2}_{\text{negligible at } h \gg v} + \lambda(\mu \sim h)|H|^4 \qquad H = \begin{pmatrix} 0 \\ v + h/\sqrt{2} \end{pmatrix}$$

$$(4\pi)^2 \frac{d\lambda}{d\ln\mu} = -6\mathbf{y_t^4} + \frac{9}{8}g_2^4 + \frac{27}{200}g_1^4 + \frac{9}{20}g_2^2 g_1^2 + 24\lambda^2 + \text{higher order}$$

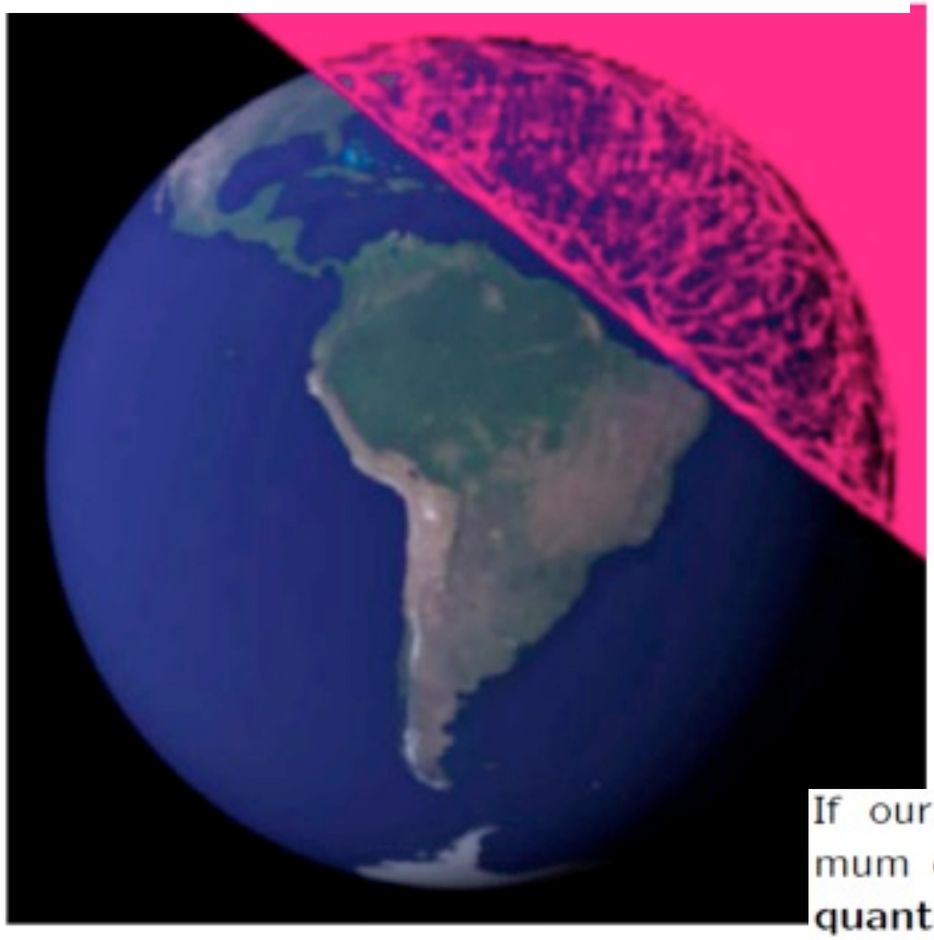
- **Túl nehéz Higgs:** $\lambda \approx m_H^2/2v^2$ **erős csatolás**

- **Túl nehéz top:** $\lambda(\mu)$ **becomes negative**

ST is valid to the Planck scale

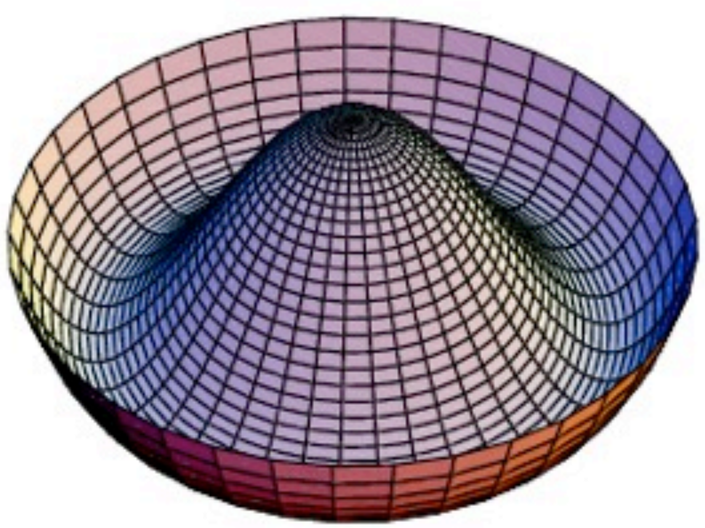


Quantum tunneling to the stable vacuum



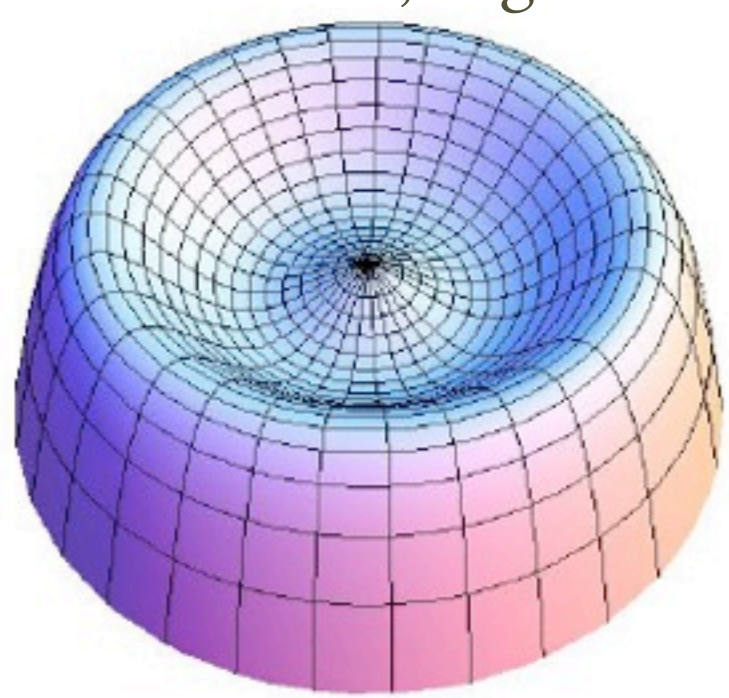
If our vacuum is only a local minimum of the potential, at some point **quantum tunnelling towards the true minimum** will happen.

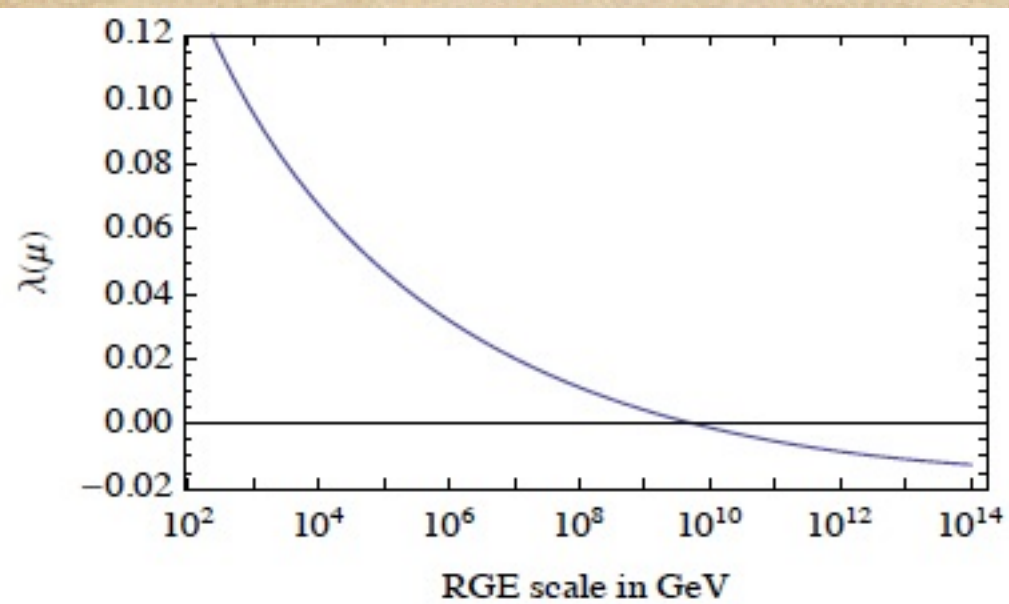
stable, Mexican hat

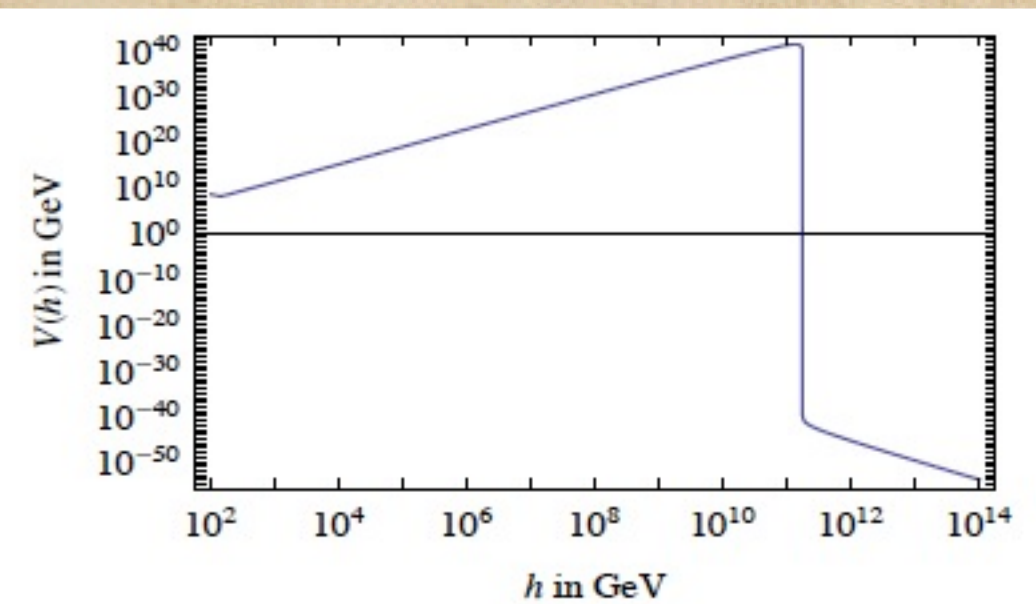


→

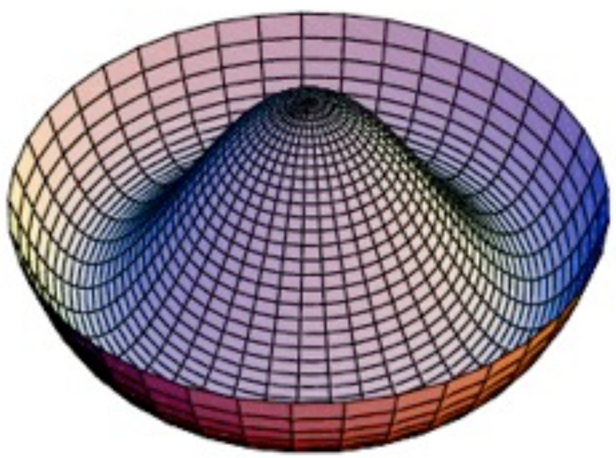
meta-stable, dog-bowl







stable, Mexican hat



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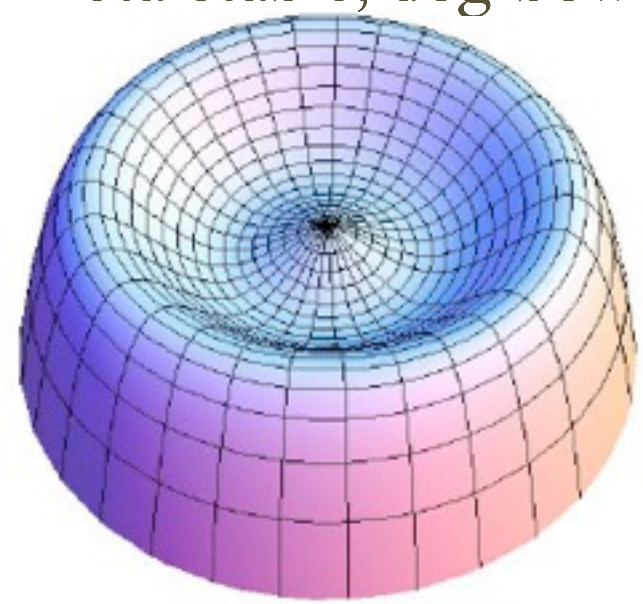
meta-stable, dog-bowl



$$\lambda(M_{Pl}) \sim 0\,, \quad \beta(\lambda(M_{Pl})) \sim 0$$

Van ennek valamilyen mély jelentése?

Self organized criticality?

More than just the SM 'Higgs'?

- SM: almost perfect effective low energy QFT but gauge hierarchy problem
- More new particles?
- Supersymmetry or compositeness
- Universal deep ideas with difficulties?
    - Supersymmetry but its breaking is not fully understood
    - Strongly coupled chiral gauge theories, non-perturbative definition
    - Conformal symmetry, quantum gravity and gauge gravity duality

Dark matter, neutrino masses, grand unification, string theory