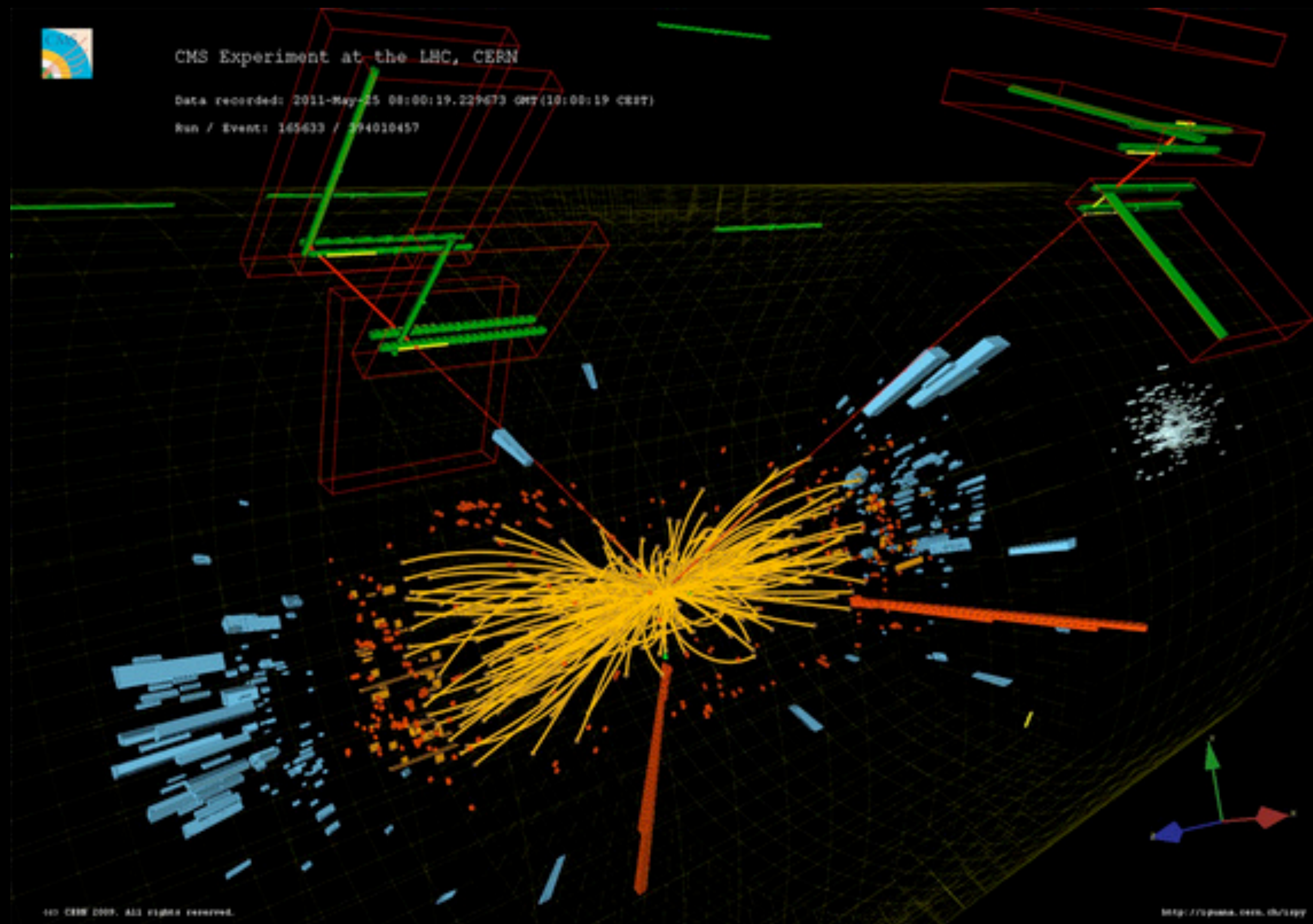
El bosón Higgs en teoría y fenomenología



Jens Erler

Seminario de Altas Energías (ICN y IF-UNAM) 25 de Abril 2012

Table of the Elementary Particles

ν_τ s=½ ~ 0	τ^- s=½ 1.9075	τ^+ s=½ 1.9075	t s=½ 176	t s=½ 176	t s=½ 176	$\bar{t}$ s=½ 176	$\bar{t}$ s=½ 176	$\bar{t}$ s=½ 176	b s=½ 4.5	b s=½ 4.5	b s=½ 4.5	$\bar{b}$ s=½ 4.5	$\bar{b}$ s=½ 4.5	$\bar{b}$ s=½ 4.5
ν_μ s=½ ~ 0	μ^- s=½ 0.11343	μ^+ s=½ 0.11343	c s=½ 1.4	c s=½ 1.4	c s=½ 1.4	$\bar{c}$ s=½ 1.4	$\bar{c}$ s=½ 1.4	$\bar{c}$ s=½ 1.4	s s=½ 0.1	s s=½ 0.1	s s=½ 0.1	$\bar{s}$ s=½ 0.1	$\bar{s}$ s=½ 0.1	$\bar{s}$ s=½ 0.1
ν_e s=½ ~ 0	e^- s=½ 0.00055	e^+ s=½ 0.00055	u s=½ 0.003	u s=½ 0.003	u s=½ 0.003	$\bar{u}$ s=½ 0.003	$\bar{u}$ s=½ 0.003	$\bar{u}$ s=½ 0.003	d s=½ 0.005	d s=½ 0.005	d s=½ 0.005	$\bar{d}$ s=½ 0.005	$\bar{d}$ s=½ 0.005	$\bar{d}$ s=½ 0.005
H s=0 134	$H^\pm$ s=0 86.3 ξ	Z s=1 97.9	W^- s=1 86.3	W^+ s=1 86.3	g s=1 0	g s=1 0	g s=1 0	g s=1 0	g s=1 0	g s=1 0	g s=1 0	g s=1 0	γ s=1 0	G s=2 0

Table of the Elementary Particles

ν_τ	τ^-	τ^+	t	t	t	$\bar{t}$	$\bar{t}$	$\bar{t}$	b	b	b	$\bar{b}$	$\bar{b}$	$\bar{b}$	
s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	
~ 0	1.9075	1.9075	176	176	176	176	176	176	4.5	4.5	4.5	4.5	4.5	4.5	
ν_μ	μ^-	μ^+	c	c	c	$\bar{c}$	$\bar{c}$	$\bar{c}$	s	s	s	$\bar{s}$	$\bar{s}$	$\bar{s}$	
s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	
~ 0	0.11343	0.11343	1.4	1.4	1.4	1.4	1.4	1.4	0.1	0.1	0.1	0.1	0.1	0.1	
ν_e	e^-	e^+	u	u	u	$\bar{u}$	$\bar{u}$	$\bar{u}$	d	d	d	$\bar{d}$	$\bar{d}$	$\bar{d}$	
s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	
~ 0	0.00055	0.00055	0.003	0.003	0.003	0.003	0.003	0.003	0.005	0.005	0.005	0.005	0.005	0.005	
H	$H^\pm$	Z	W^-	W^+	g	g	g	g	g	g	g	g	γ	G	
s=0	=0	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=2	
[illegible]	86.3 ξ	97.9	86.3	86.3	0	0	0	0	0	0	0	0	0	0	

Outline

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Outline

- the weak interaction

Outline

- the weak interaction
- spontaneous symmetry breaking

Outline

- the weak interaction
- spontaneous symmetry breaking
- theoretical constraints

3

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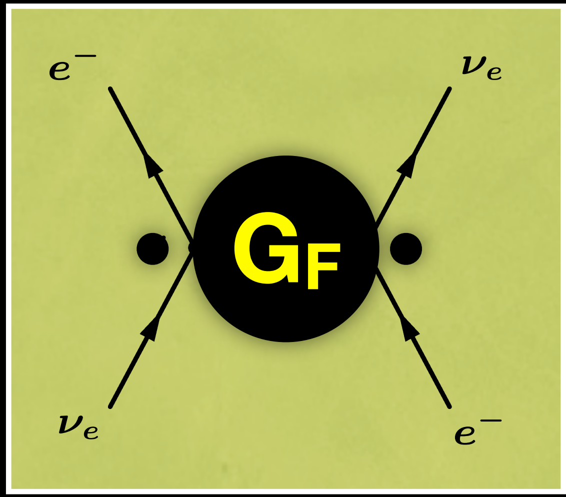
- conclusions

the weak interaction

Problems with Fermi theory



- $\sigma(\nu_e\, e^- \rightarrow e^-\, \nu_e) \rightarrow E^2/(2\pi\, v^4) \leq 16\pi/E^2 \Rightarrow$

  tree level unitarity violation for $E \gtrsim 1$ TeV

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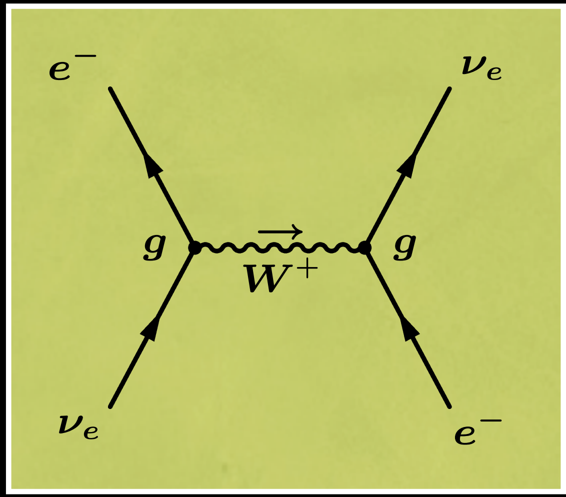

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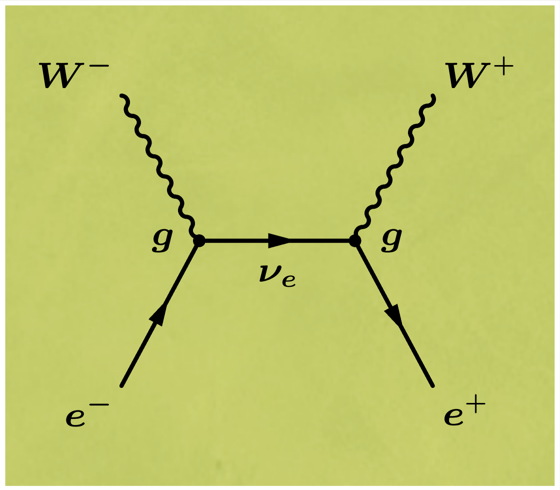
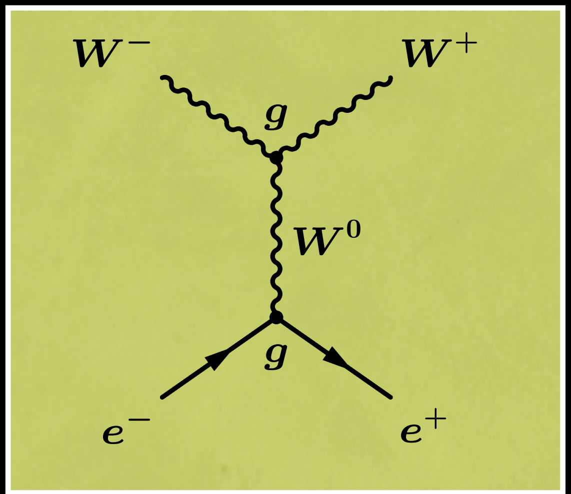
  tree level unitarity violation for $E \gtrsim 1$ TeV

➡ intermediate vector bosons ***Yukawa 1935, Schwinger 1957***

- but now trouble computing $\sigma(e^+\, e^- \to W^+\, W^-)$

Gauge invariance I





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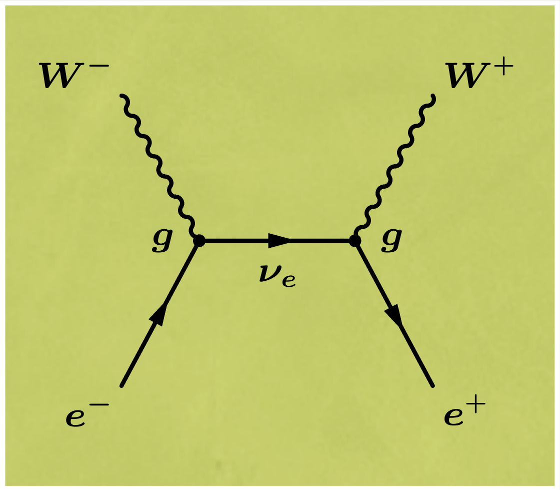
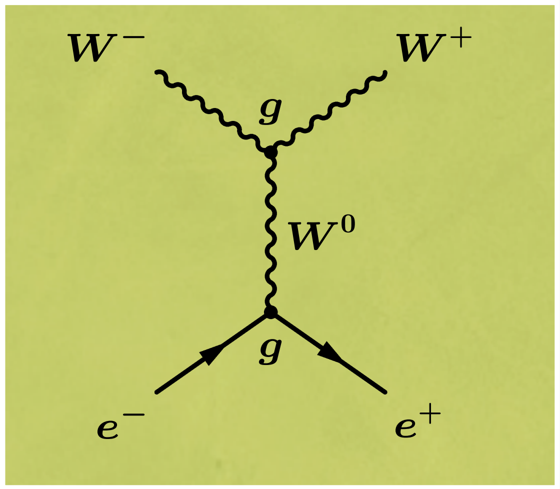
Gauge invariance I

- Bad behavior in $\sigma(e^+ e^- \to W^+ W^-)$ and $\sigma(\bar{\nu}_e e^- \to W^- W^0)$ cancels if the currents satisfy $[J, J^\dagger] \propto J^0 \Rightarrow$





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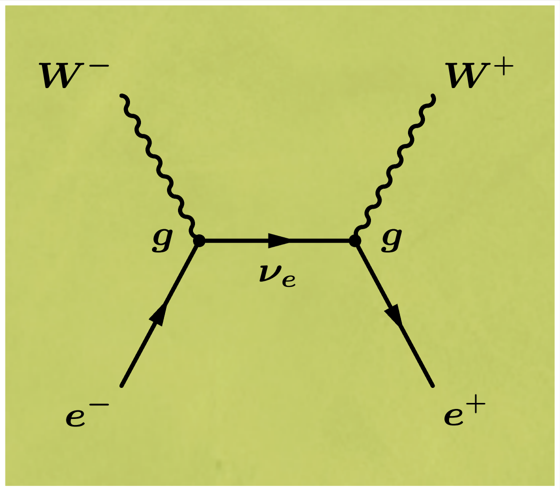
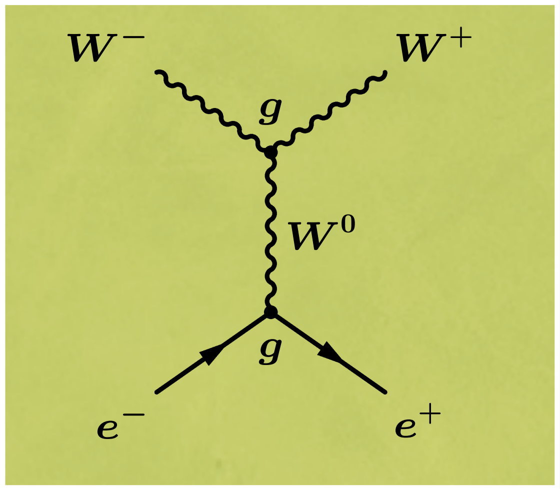
- SU(2) gauge invariance





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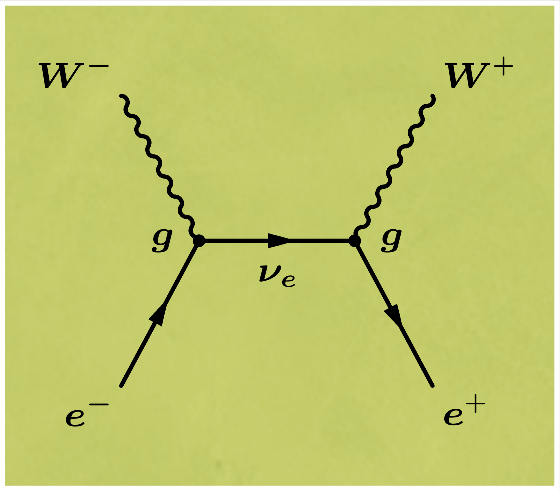

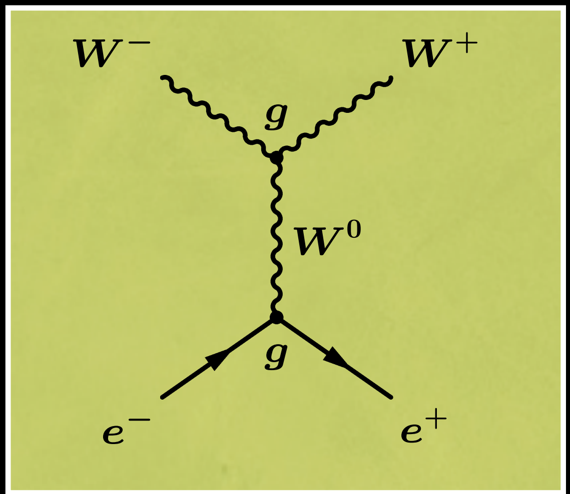

- SU(2) gauge invariance
- Need to add photons

$\Rightarrow SU(2)_L \times U(1)_Y$ ***Glashow 1961***

Gauge invariance II

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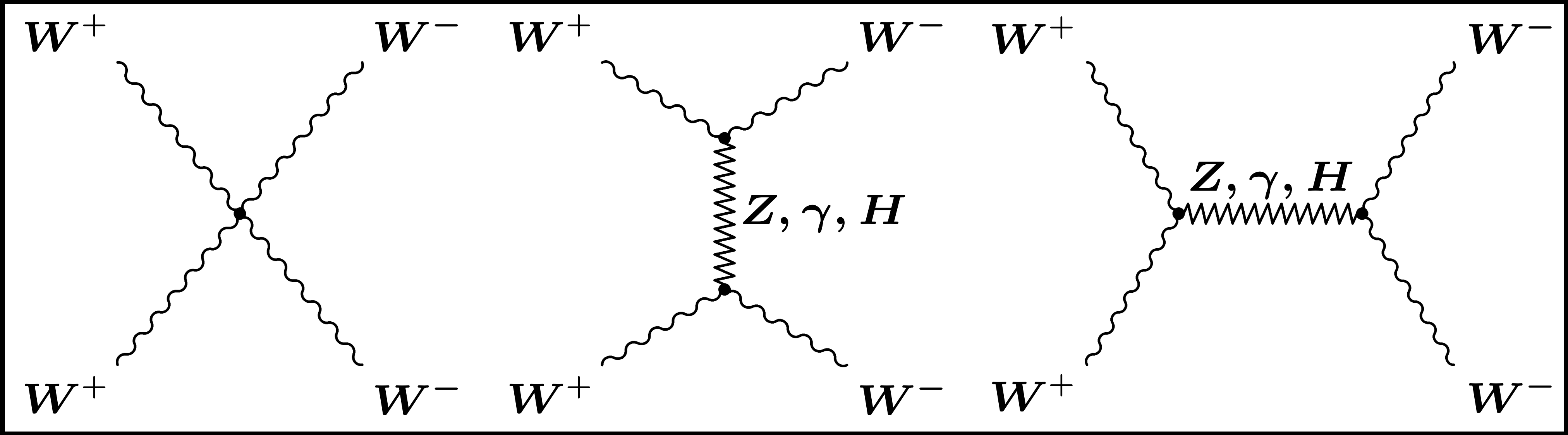
- Solution: take couplings of A_μ as $A_\mu J^\mu$ with $\partial_\mu J^\mu = 0$
- Implications:
  - breaking gauge invariance breaks Lorentz invariance
  - $m_A = 0$

Need for Higgs particles



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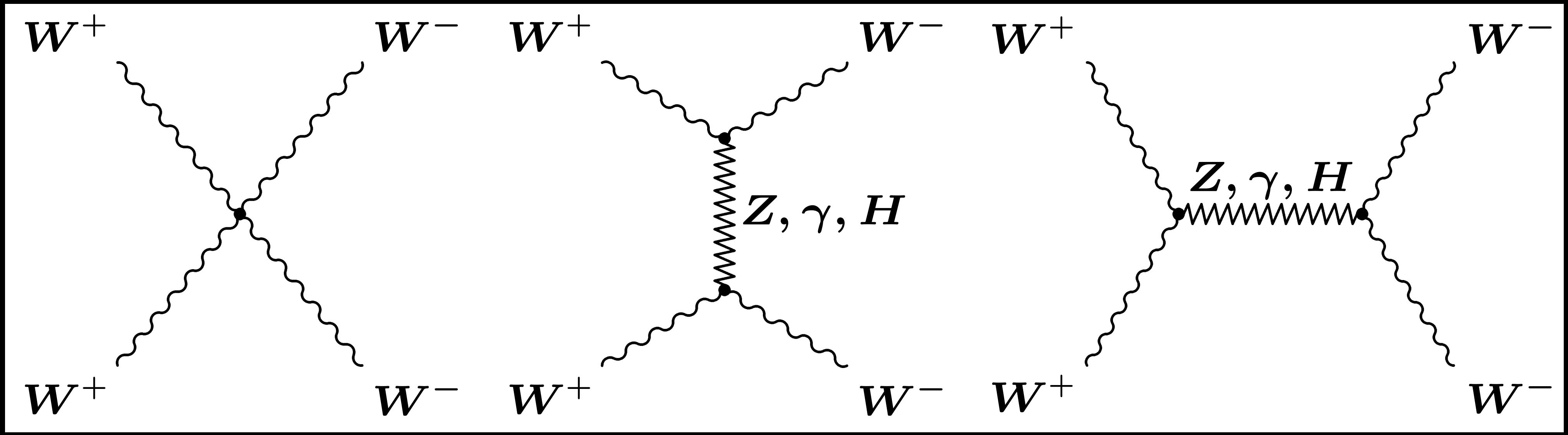

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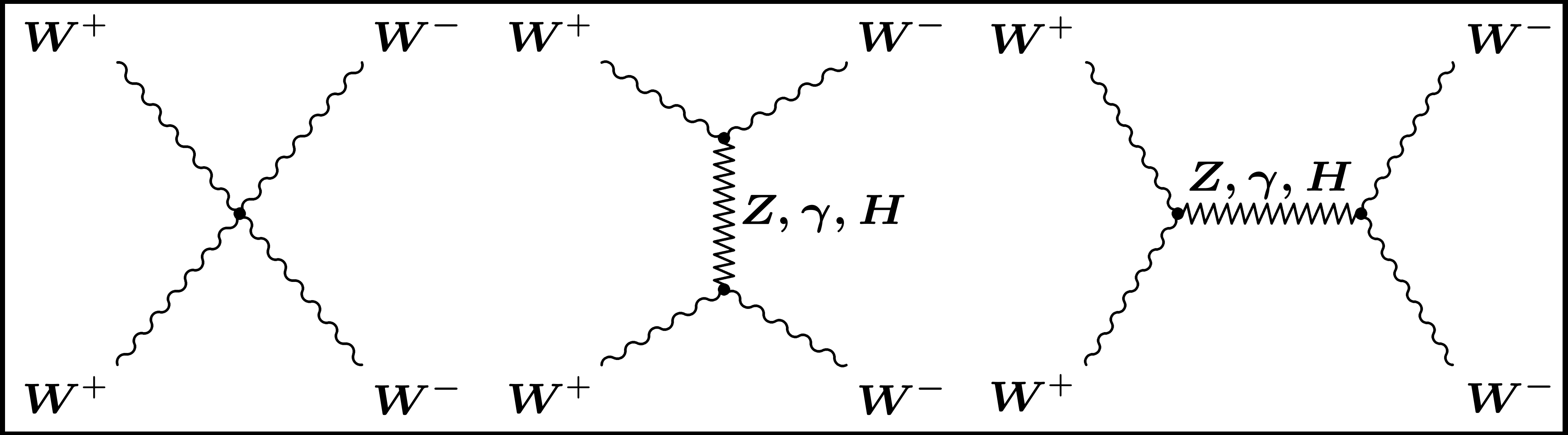

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- $M_H^2 \lesssim 16\pi / 5\ v^2 \approx (780\ \text{GeV})^2$ ***Lüscher, Weisz 1988***

spontaneous symmetry breaking

mechanisms of ***Nambu-Goldstone*** (Nobel Prize 2008) and

Brout-Englert-Higgs-Guralnik-Hagen-Kibble (Sakurai Prize 2010)

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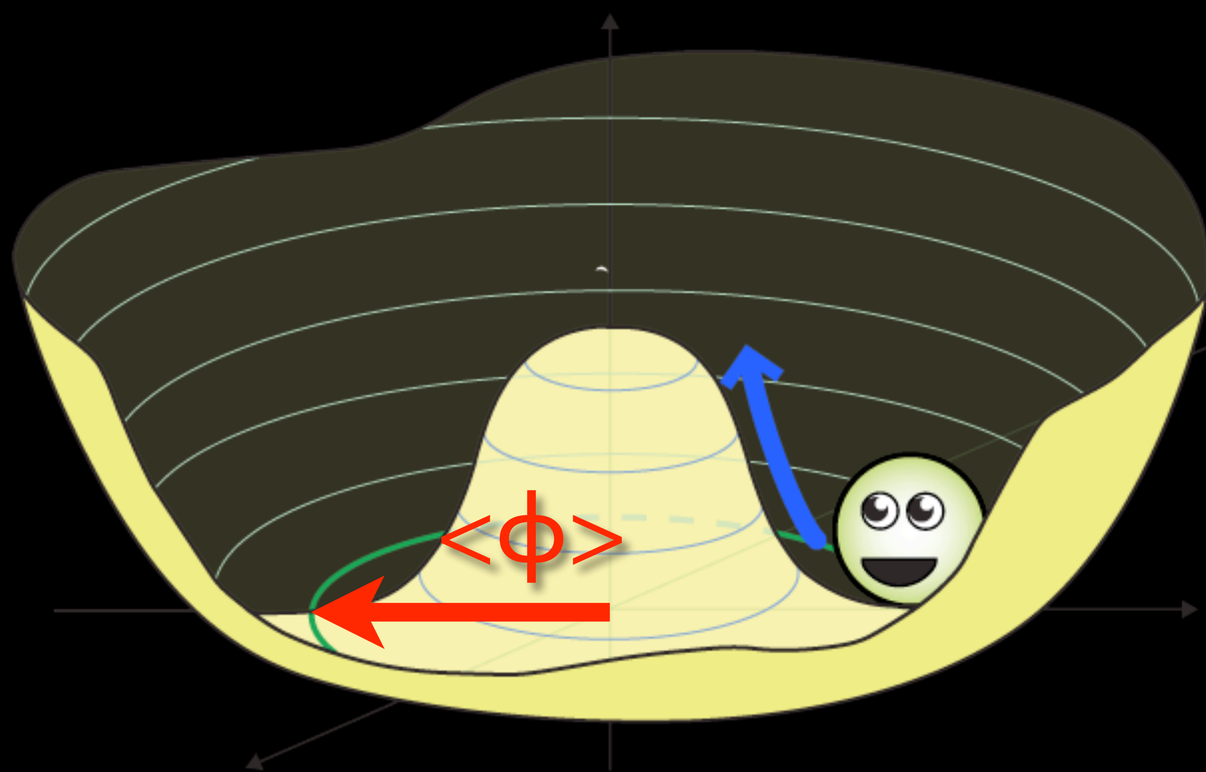
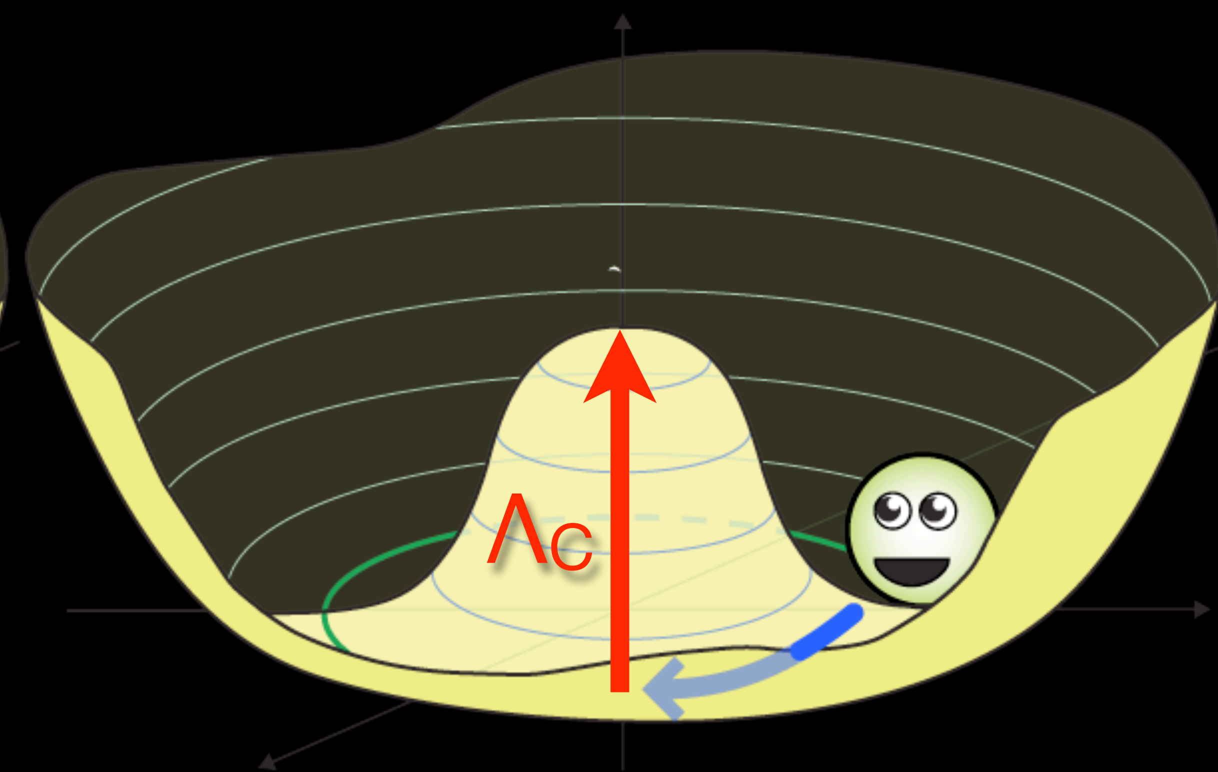
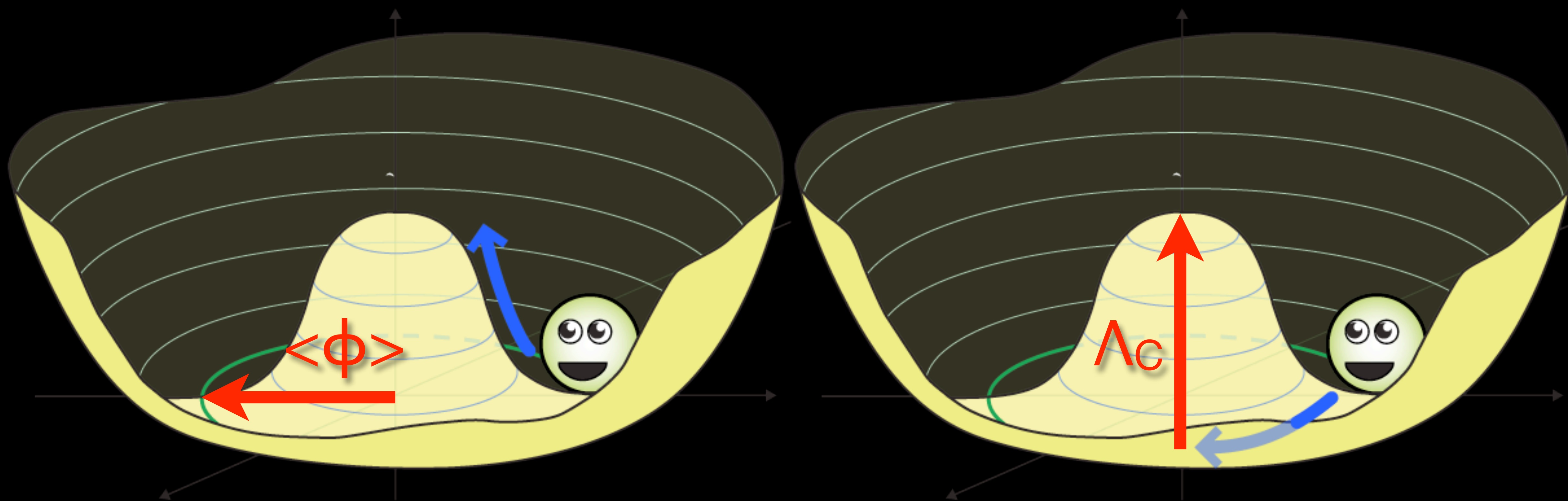




massive scalar
also for discrete symmetry
as in ***Landau-Ginzburg*** theory

massless
Nambu-Goldstone mode
(V = 0 exactly)



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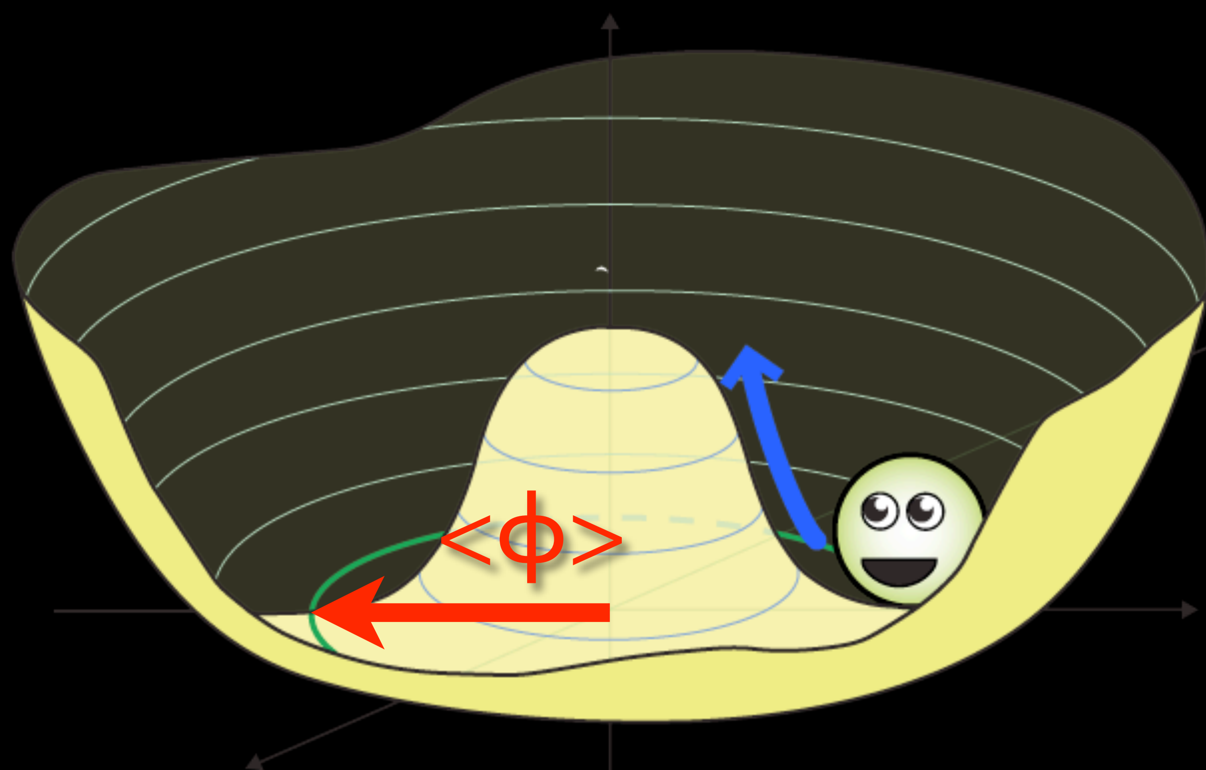

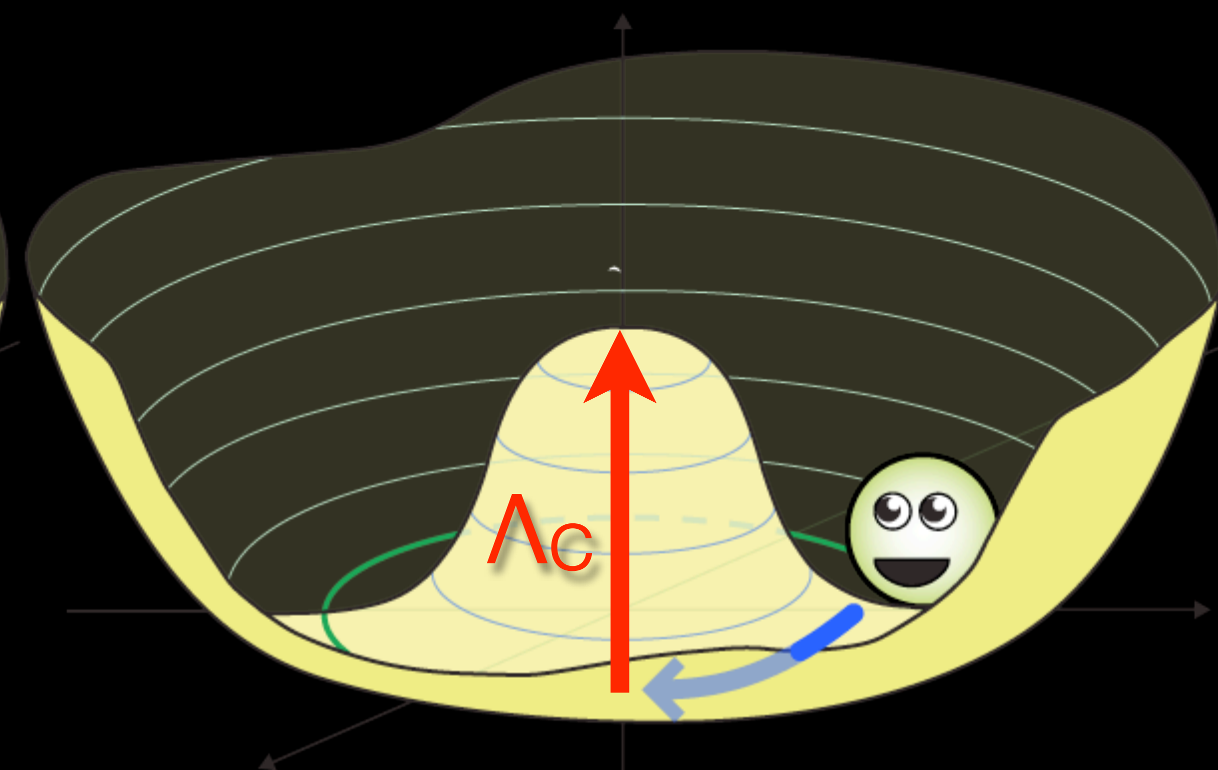

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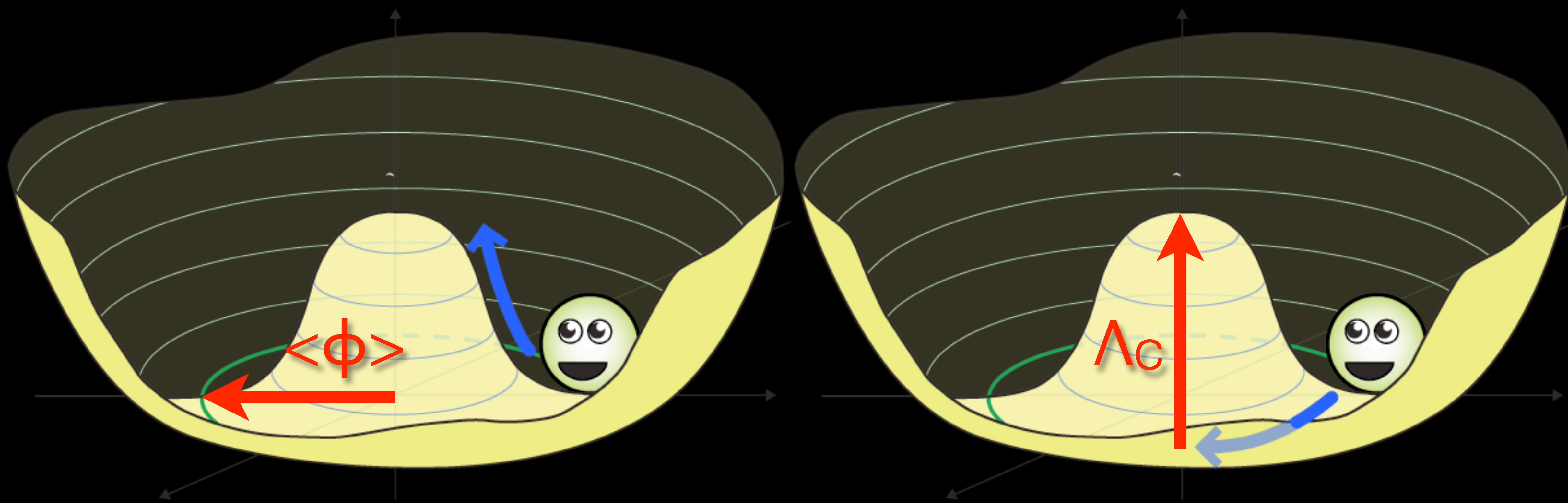
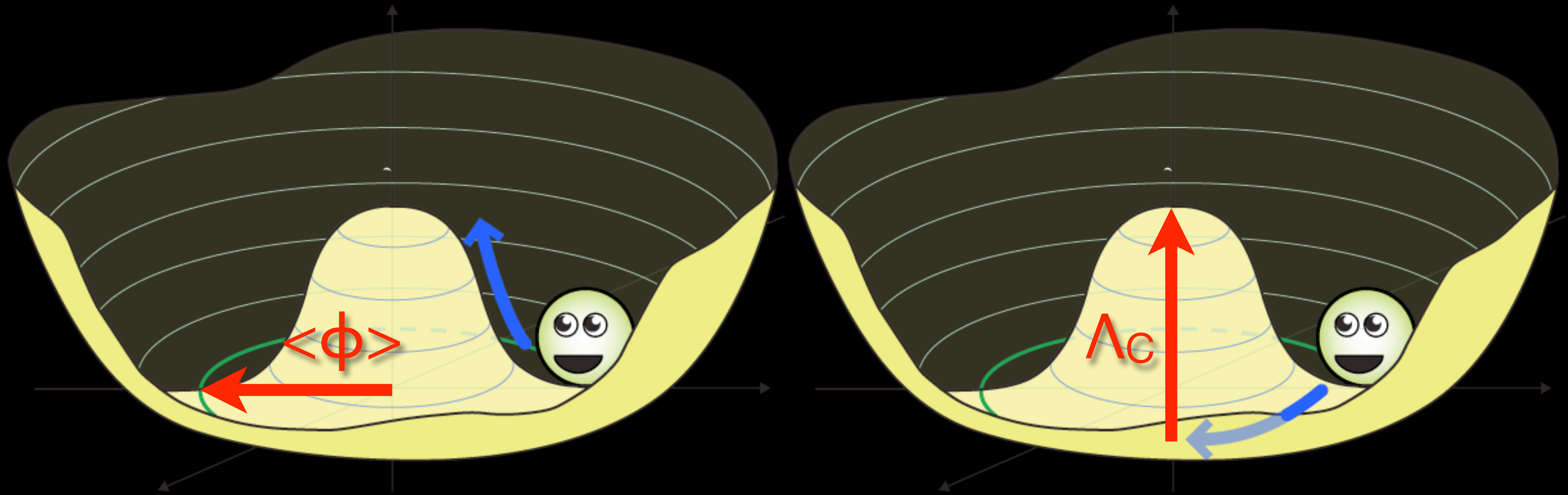
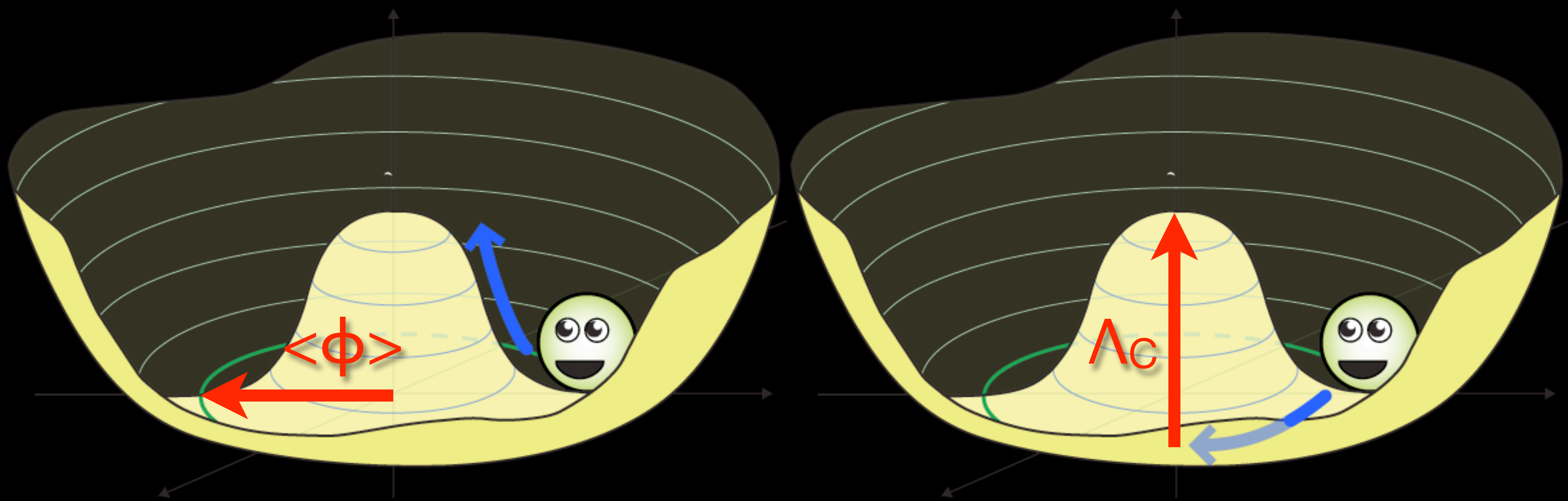
- field gets vacuum expectation value <φ> (order parameter)
- but may be elementary or composite (e.g. quark condensate breaking chiral symmetry of strong interaction, or ***Cooper*** pairs in BCS theory of superconductivity)


<ϕ>
Λc



- BCS theory: approximate model; exact properties (like zero resistance and flux quantization) follow from symmetry breaking



- BCS theory: approximate model; exact properties (like zero resistance and flux quantization) follow from symmetry breaking
- electroweak theory: need new field (the Higgs) or new strong interaction (e.g. technicolor); if elementary it must be scalar so as not to break Lorentz invariance

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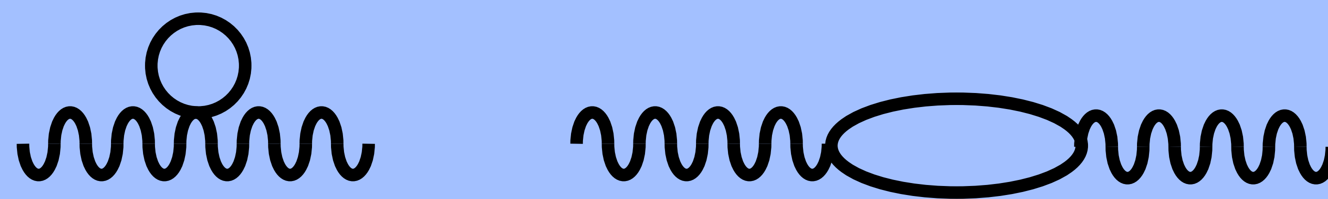
One-loop corrections to gauge boson propagator.



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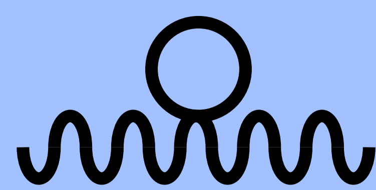
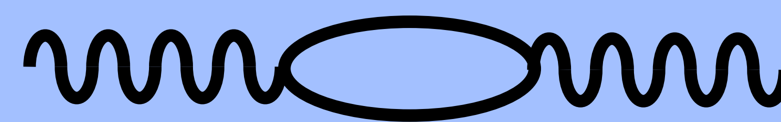
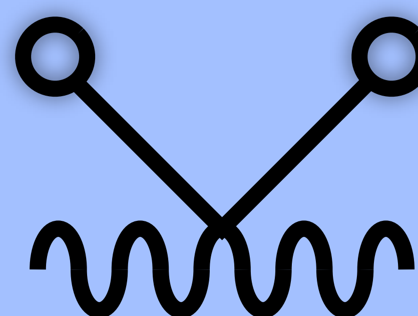
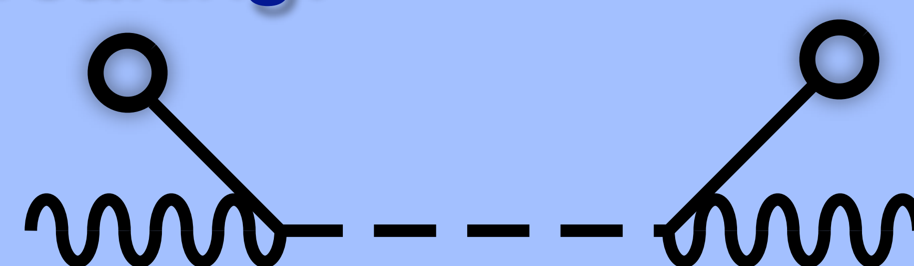




Additional tadpole graph corrections after spontaneous symmetry breaking.





effective mass term
(London's penetration depth)
renormalizability!

Nambu-Goldstone boson
provides longitudinal
degree of freedom
unitarity!

theoretical constraints

One-loop RGE

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One-loop RGE

- $d\, M_H^2 / d \ln \mu^2 = 1/(8\pi^2 v^2)$

  $[\, 3 M_H^4 + 3 M_Z^4 + 6 M_W^4 - 12 m_t^4 - M_H^2 (3 M_Z^2 + 6 M_W^2 - 6 m_t^2)\,]$

  - $\mathrm{Str} = \sum (-)^{2S} (2S + 1) N_C$
  - scalar field wave function renormalization (γ)
  - the masses in the RGE are running masses (e.g. MS-bar)
  - $v = [\sqrt{2}\, G_F]^{-1/2}$ = 246.22 GeV (slightly modified definition of G_F)

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  $[\, 3\, M_H^4 + 3\, M_Z^4 + 6\, M_W^4 - 12\, m_t^4 - M_H^2\, (3\, M_Z^2 + 6\, M_W^2 - 6\, m_t^2)\,]$

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- $M_H \gg v \Rightarrow 1/M_H^2(v) - 1/M_H^2(\Lambda) = 3/(8\,\pi^2\, v^2) \ln \Lambda^2/v^2$

  - $M_H^2 < 8\,\pi^2\, v^2/(3 \ln \Lambda^2/v^2) = [147\ (144)\ \mathrm{GeV}]^2$

    for $\Lambda = 2.4\times10^{18}\ (1.2\times10^{19})$ GeV

  - $M_H < 816$ GeV for $\Lambda = M_H$

Lower bound

Lower bound

- rewrite the RGE

  $d\, M_H^2 / d \ln \boldsymbol{\mu}^2 = 3/(8\, \pi^2\, v^2)\, (M_H^2 - M_+^2)\, (M_H^2 - M_-^2)$ with $M_\pm^2 =$

  $\frac{1}{2} M_Z^2 + M_W^2 - m_t^2 \pm [(\frac{1}{2} M_Z^2 + M_W^2 - m_t^2)^2 - M_Z^4 - 2\, M_W^4 + 4\, m_t^4]^{1/2}$

  $\approx (-1 \pm \sqrt{5})\, m_t^2 \Rightarrow M_+ \sim 200$ GeV, $M_-^2 \sim -\,(300\ \text{GeV})^2$

  $\Rightarrow$ for $M_H \gtrsim 200$ GeV, Landau pole persists (potential bounded below)

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- we have worked with constant masses, but $d\,m_t^2/d\ln\mu^2 =$

  $3\,m_t^2/(16\pi^2 v^2)\,[\,(1_L + 2_R)\,m_t^2 - (2_L + 0_R)\dim SU(2)/N_D\,M_W^2 -$
  $((1/3)^2{}_L + (4/3)^2{}_R)\,(M_Z^2 - M_W^2) - (2_L + 2_R)\dim SU(3)/N_C\,(\pi\,\alpha_s\,v^2)\,] =$

  $m_t^2/(16\pi^2 v^2)\,[\,9\,m_t^2 - 10/3\,M_W^2 - 17/3\,M_Z^2 - 32\,(\pi\,\alpha_s\,v^2)\,] < 0$

summary of bounds

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- vacuum stability: $M_H \gtrsim 130$ GeV ***Casas, Espinosa, Quiros 1995***

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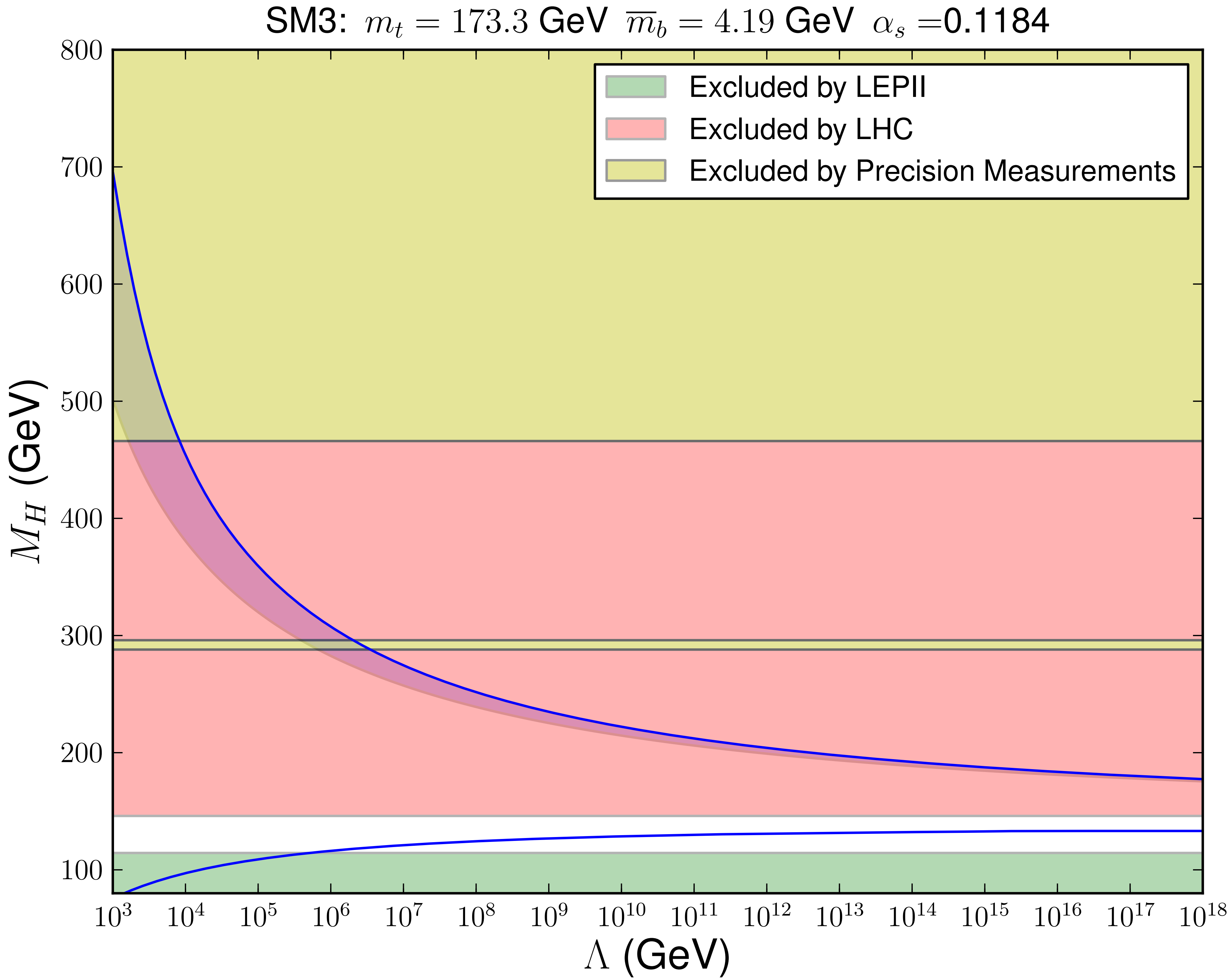
  $M_H^2/v^2 < 4\,\pi^2/3 \ln^{-1} \kappa_P/v \Rightarrow M_H < 147$ GeV

- vacuum stability: $M_H \gtrsim 130$ GeV ***Casas, Espinosa, Quiros 1995***

- vacuum meta-stability: $M_H \gtrsim 115$ GeV ***Isidori, Ridolfi, Strumia 2001***

18



originally by Hambye Riesselmann 1996

figure from Wingerter 2011

indirect constraints

M_W

M_W

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M_W

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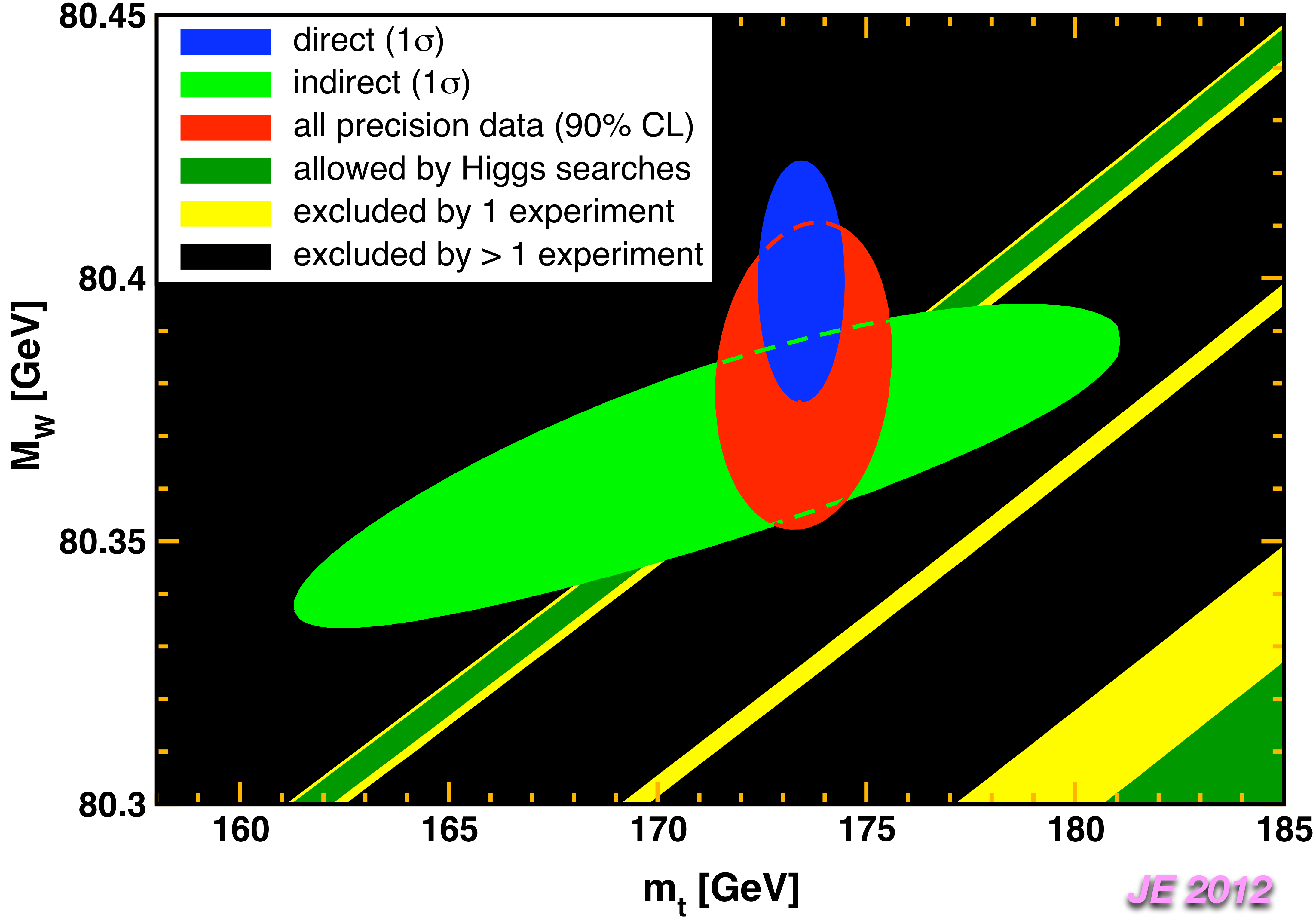
- new global electroweak fit: $M_H = 102^{+24}_{-20}$ GeV ***JE 2012***
- prospects:
  - no PDF (± 10 MeV) & QED (± 4 MeV) improvement $\Rightarrow \pm 13$ MeV ***CDF*** 10 fb^{-1}
  - ± 7 $MeV_{PDF} \Rightarrow \pm 11$ MeV ***CDF*** 10 fb^{-1}
  - ± 5 MeV_{PDF} & lepton energy scale $\pm 6 \to \pm 3$ MeV $\Rightarrow \pm 10$ MeV ***CDF*** 10 fb^{-1}
  - ILC threshold scan: ± 6 MeV


direct (1σ)
indirect (1σ)
all precision data (90% CL)
allowed by Higgs searches
excluded by 1 experiment
excluded by > 1 experiment
80.45
80.4
80.35
80.3
M_W [GeV]
160
165
170
175
180
185
m_t [GeV]
JE 2012

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m_t

23

m_t

- $m_t = 173.4 \pm 0.9_{exp} \pm 0.5_{th}$ GeV

m_t

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- Question: What is the definition of m_t?

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  We assume $m_t^{Pythia} = m_t^{pole} \pm \Lambda_{QCD}$ where

  $m_t^{pole} \equiv \overline{m}_t(\overline{m}_t)\,[1 + 4/3\ \alpha_s(\overline{m}_t)/\pi + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_s^3)]$

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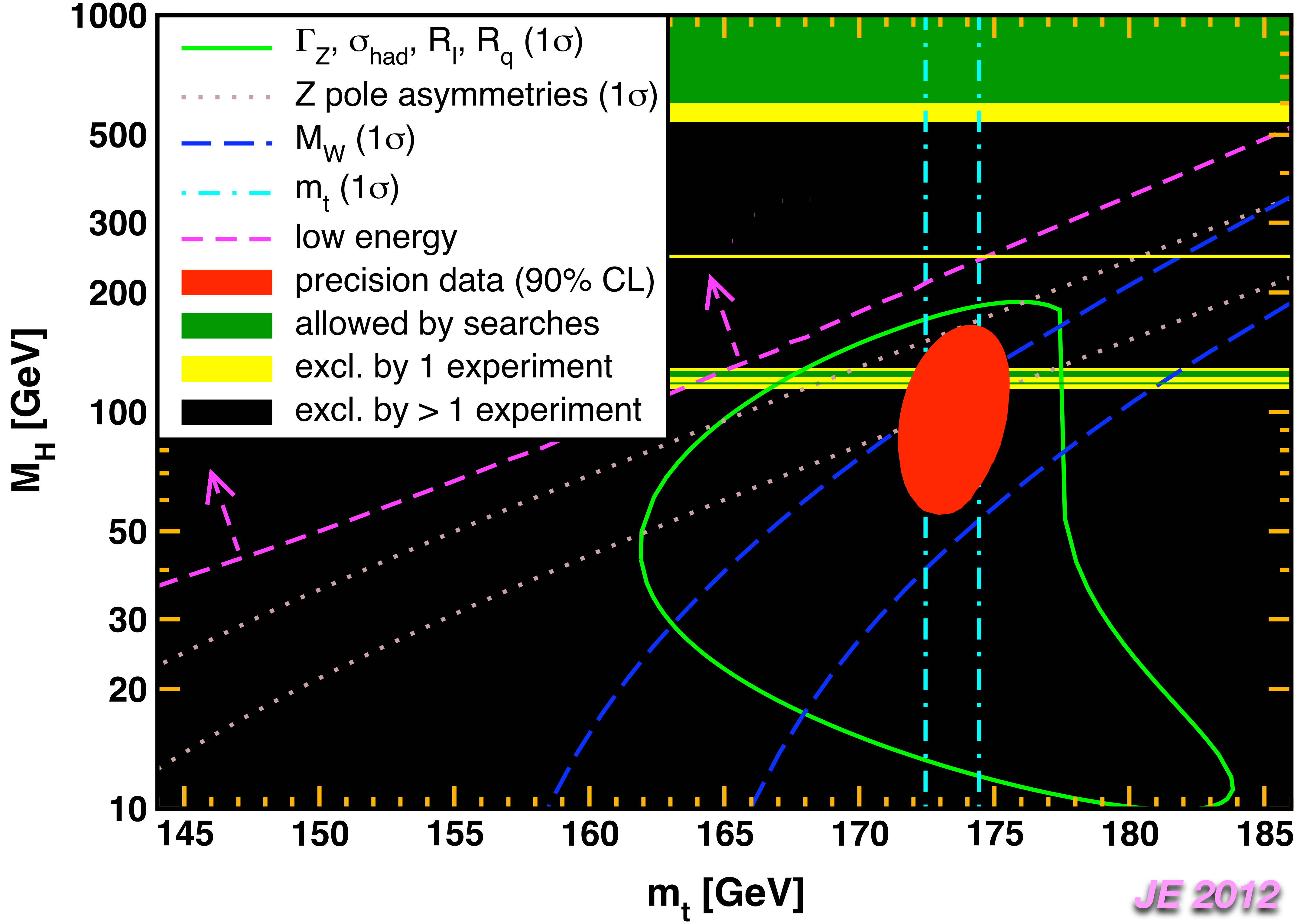
- Alternative II: get $\overline{m}_t(\overline{m}_t)$ directly from $t\,\overline{t}$ cross-section ⇒

  $\overline{m}_t(\overline{m}_t) = 160.0 \pm 3.3$ GeV ***Langenfeld, Moch, Uwer 2008***

  ⇒ $M_H = 81^{+32}_{-24}$ GeV ($m_t^{pole} = 169.6 \pm 3.5$ GeV)



1000
500
300
200
100
50
30
20
10
M_H [GeV]
145
150
155
160
165
170
175
180
185
m_t [GeV]
Γ_Z, σ_{had}, R_l, R_q (1σ)
Z pole asymmetries (1σ)
M_W (1σ)
m_t (1σ)
low energy
precision data (90% CL)
allowed by searches
excl. by 1 experiment
excl. by > 1 experiment
JE 2012

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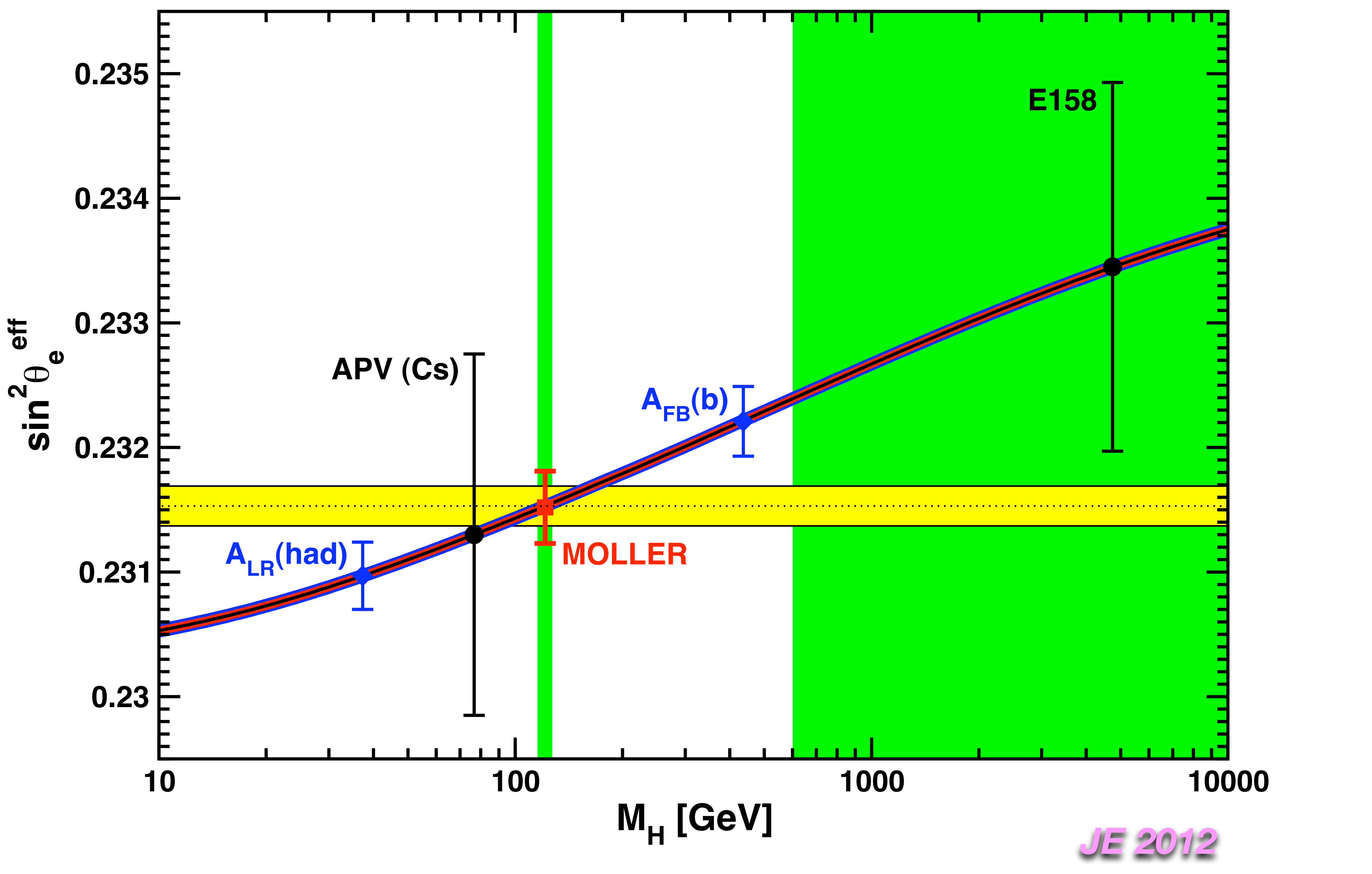
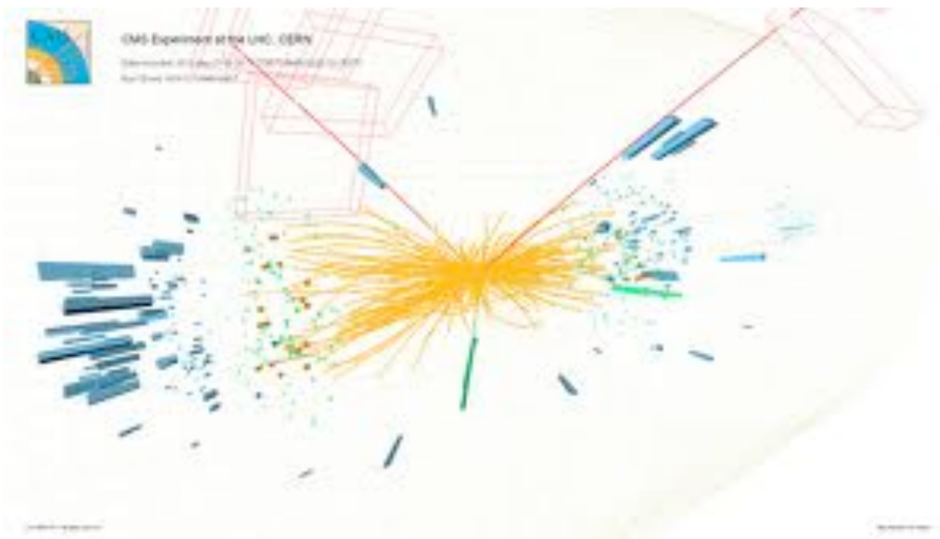
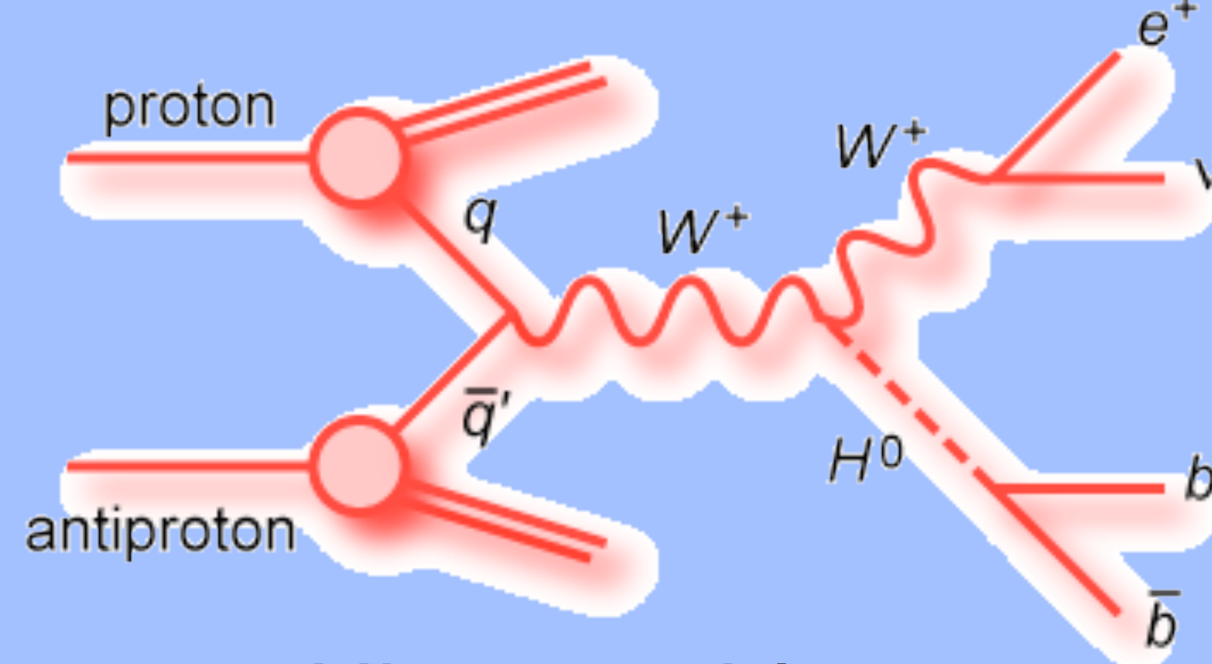


0.235
0.234
0.233
0.232
0.231
0.23
$\sin^2\theta_e^{eff}$
E158
APV (Cs)
$A_{FB}(b)$
A_{LR}(had)
MOLLER
10
100
1000
10000
M_H [GeV]
JE 2012

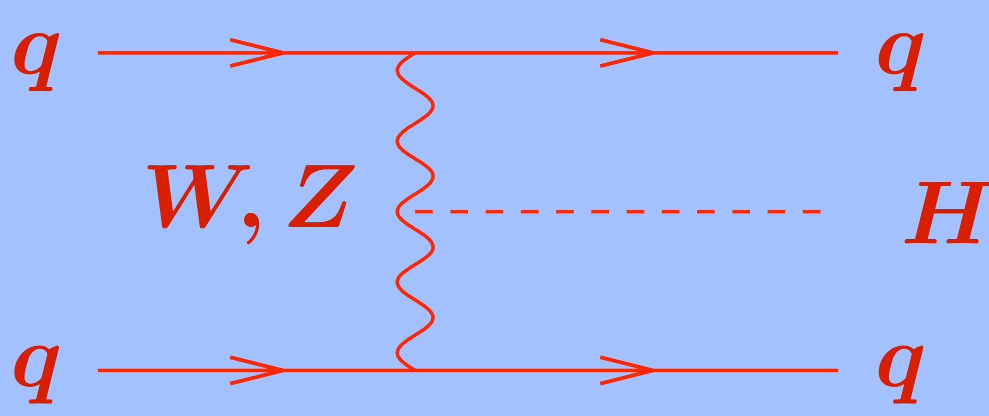
Constraints from the Higgs hunt



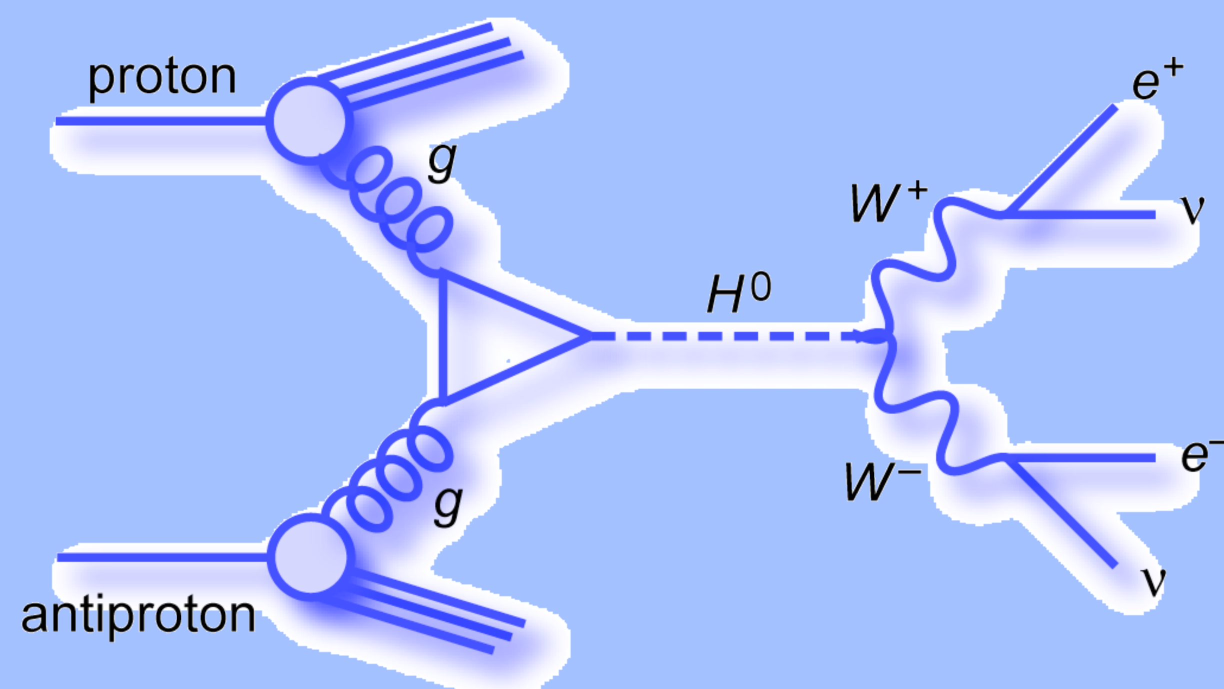
How to make a Higgs



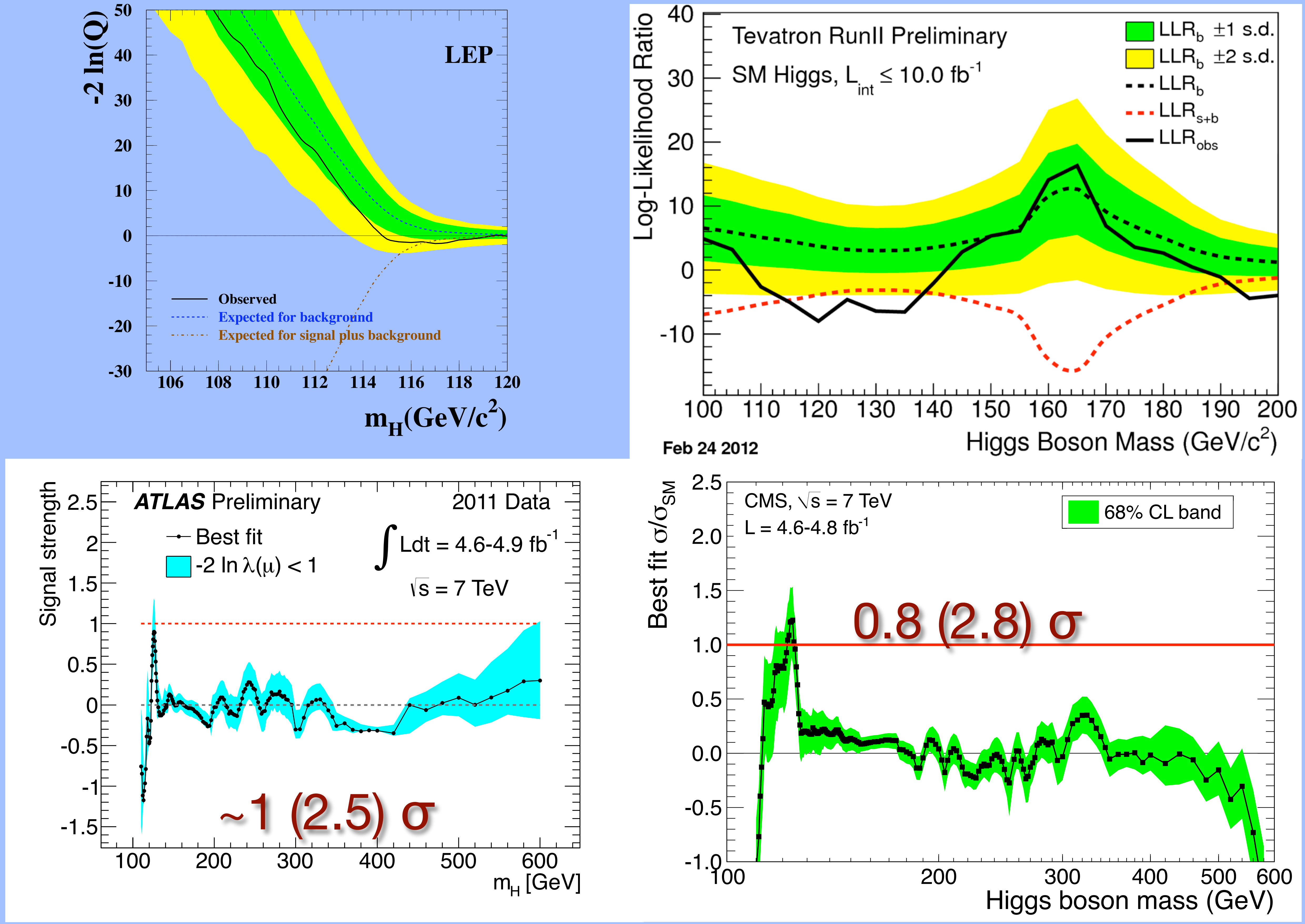
Higgsstrahlung

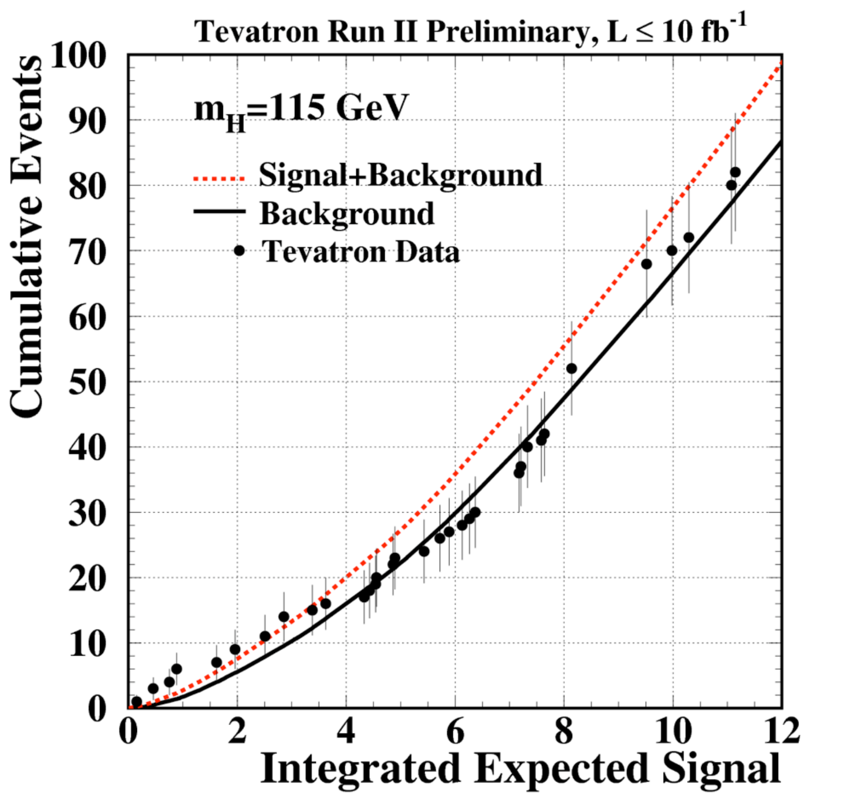


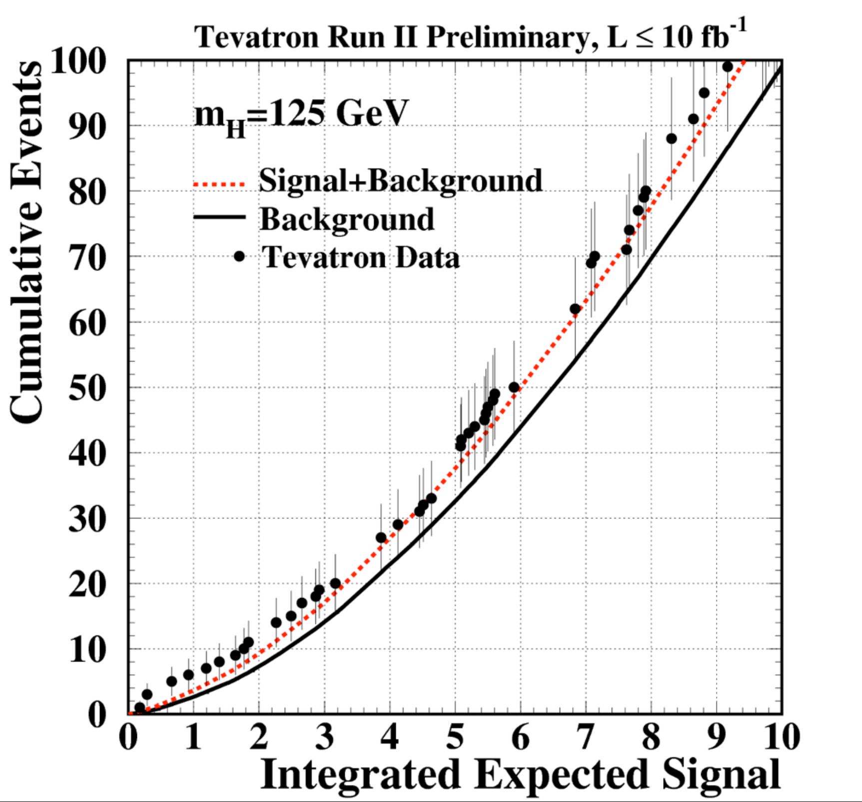
vector boson fusion

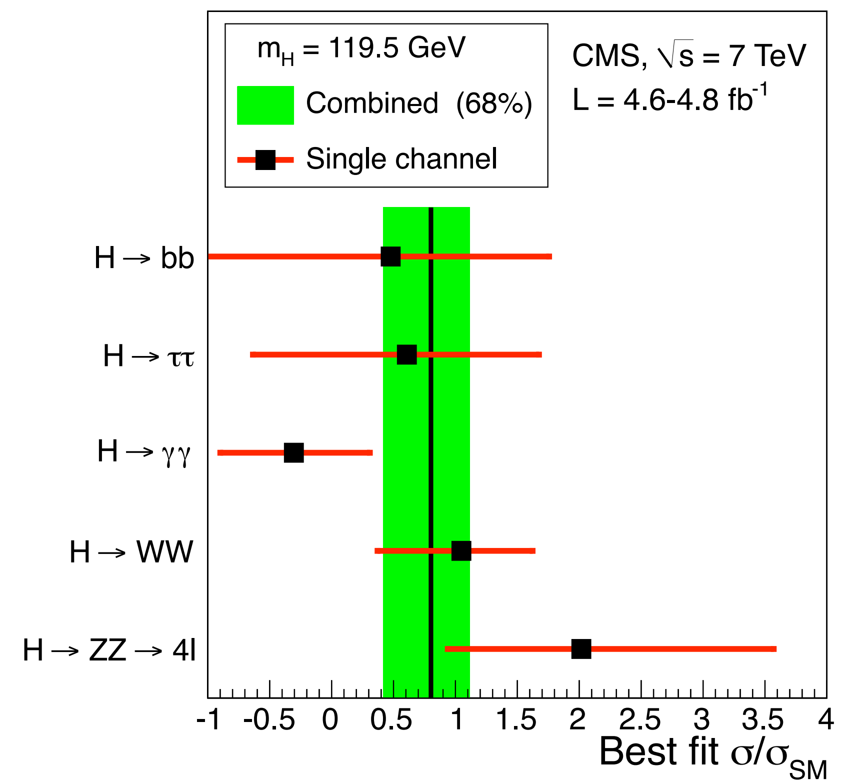


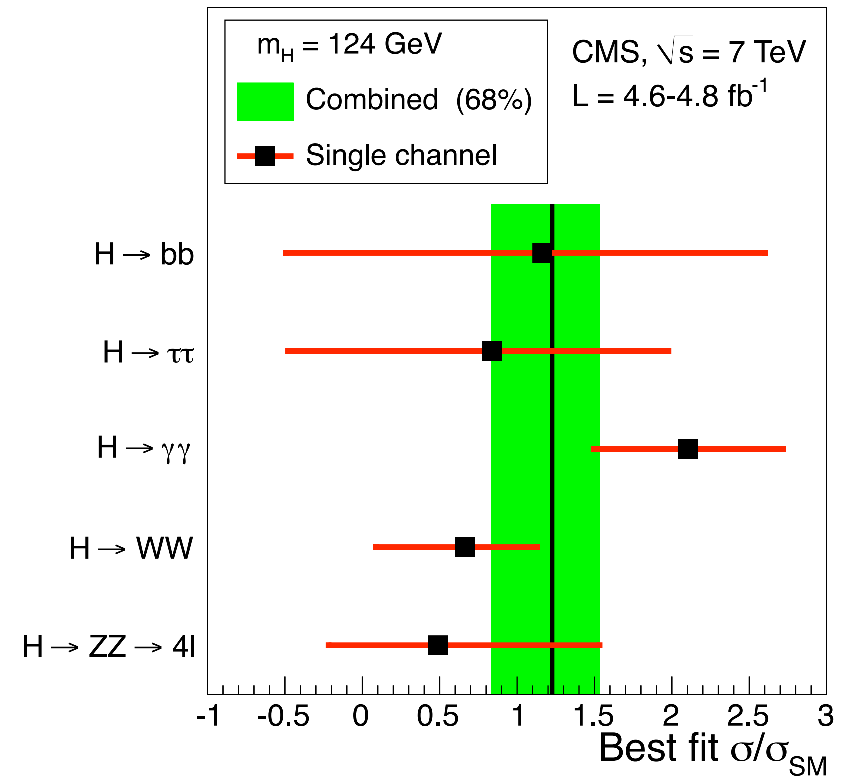
gluon fusion


-2 ln(Q)
LEP
Observed
Expected for background
Expected for signal plus background
m_H(GeV/c²)
Log-Likelihood Ratio
Tevatron RunII Preliminary
SM Higgs, L_int ≤ 10.0 fb⁻¹
LLR_b ±1 s.d.
LLR_b ±2 s.d.
LLR_b
LLR_s+b
LLR_obs
Higgs Boson Mass (GeV/c²)
Feb 24 2012
Signal strength
ATLAS Preliminary
2011 Data
Best fit
-2 ln λ(μ) < 1
∫Ldt = 4.6-4.9 fb⁻¹
√s = 7 TeV
m_H [GeV]
~1 (2.5) σ
Best fit σ/σ_SM
CMS, √s = 7 TeV
L = 4.6-4.8 fb⁻¹
68% CL band
0.8 (2.8) σ
Higgs boson mass (GeV)


Tevatron Run II Preliminary, L ≤ 10 fb-1
mH=115 GeV
Signal+Background
Background
Tevatron Data
Cumulative Events
Integrated Expected Signal


Tevatron Run II Preliminary, L ≤ 10 fb-1
mH=125 GeV
Signal+Background
Background
Tevatron Data
Cumulative Events
Integrated Expected Signal


mH = 119.5 GeV
Combined (68%)
Single channel
CMS, √s = 7 TeV
L = 4.6-4.8 fb-1
H → bb
H → ττ
H → γγ
H → WW
H → ZZ → 4l
Best fit σ/σSM


mH = 124 GeV
Combined (68%)
Single channel
CMS, √s = 7 TeV
L = 4.6-4.8 fb-1
H → bb
H → ττ
H → γγ
H → WW
H → ZZ → 4l
Best fit σ/σSM

synthesis

M_H probability density

31

M_H probability density

- $p(M_H) \equiv \exp[-\chi^2_{EW}(M_H)/2]\ Q_{LEP}\ Q_{Tevatron}\ Q_{LHC}\ M_H^{-1}$

  factorized form: neglect of correlations

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- $Q_{LHC}(M_H) = Q_{ATLAS}(M_H)\, Q_{CMS}(M_H)$ (but not available)

  instead: $2 \ln Q \equiv \chi^2_{H+B}(M_H) - \chi^2_{B}(M_H) \equiv$

  $(1 - \bar{\sigma}_{obs})^2/\Delta\bar{\sigma}_+^2 - \bar{\sigma}_{obs}^2/\Delta\bar{\sigma}_-^2$

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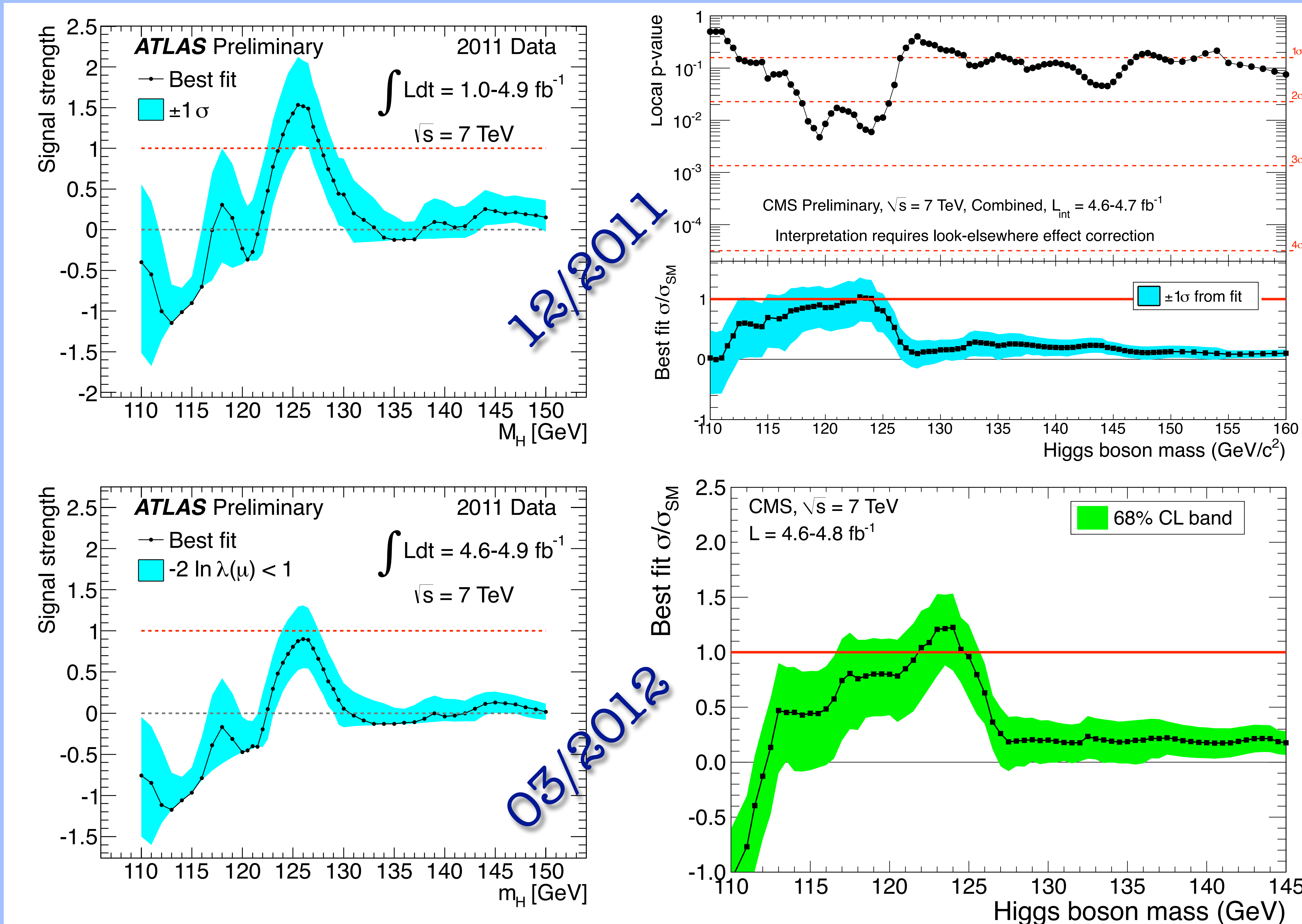
- Poisson statistics ⇒ $\Delta\bar{\sigma}_+ > \Delta\bar{\sigma}_-$ but often also $\Delta\bar{\sigma}_+ < \Delta\bar{\sigma}_-$


ATLAS Preliminary
2011 Data
Best fit
±1σ
∫Ldt = 1.0-4.9 fb-1
√s = 7 TeV
Signal strength
MH [GeV]
12/2011
CMS Preliminary, √s = 7 TeV, Combined, Lint = 4.6-4.7 fb-1
Interpretation requires look-elsewhere effect correction
Local p-value
Best fit σ/σSM
±1σ from fit
Higgs boson mass (GeV/c2)
ATLAS Preliminary
2011 Data
Best fit
-2 ln λ(μ) < 1
∫Ldt = 4.6-4.9 fb-1
√s = 7 TeV
Signal strength
mH [GeV]
03/2012
CMS, √s = 7 TeV
L = 4.6-4.8 fb-1
68% CL band
Best fit σ/σSM
Higgs boson mass (GeV)

Examples

33

Examples

- $2 \ln Q_{ATLAS}(126\ \text{GeV}) = 9.8 - 1.1 = -8.7$ ($H \to \gamma\gamma$, ZZ^*)

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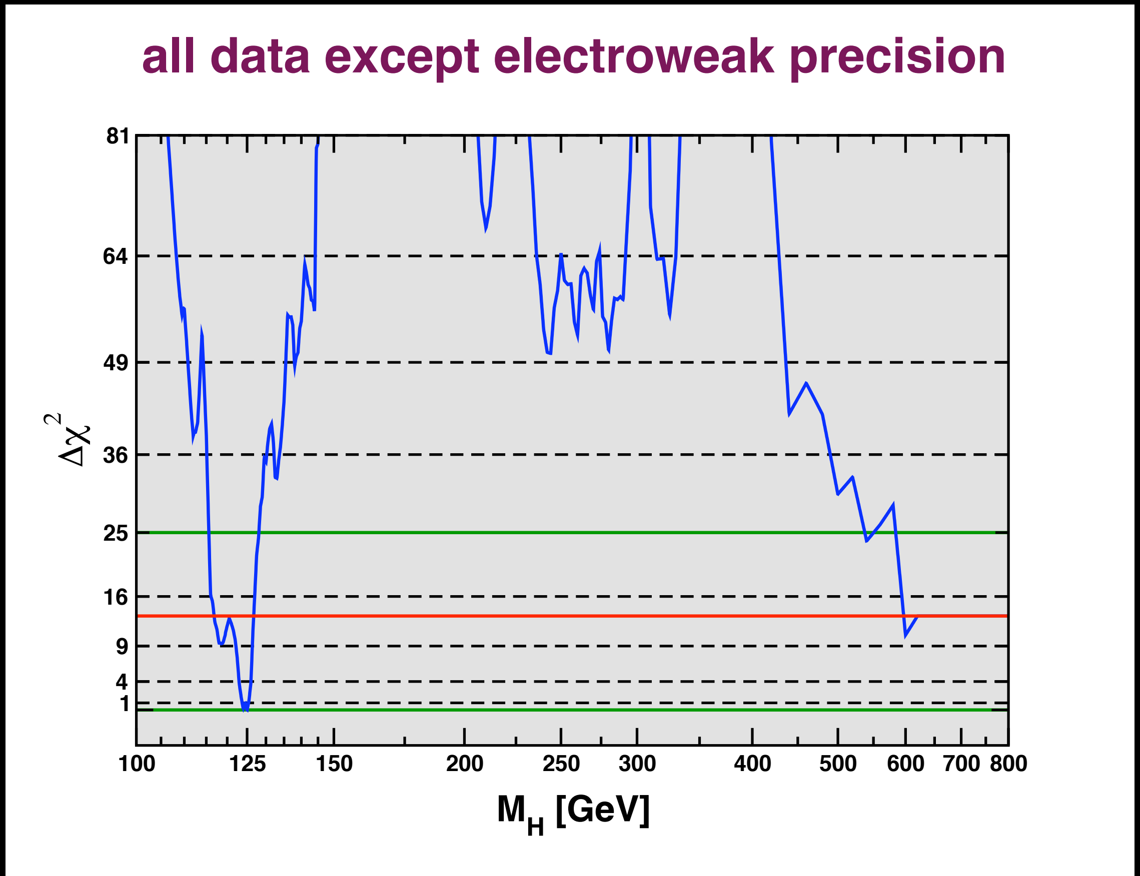
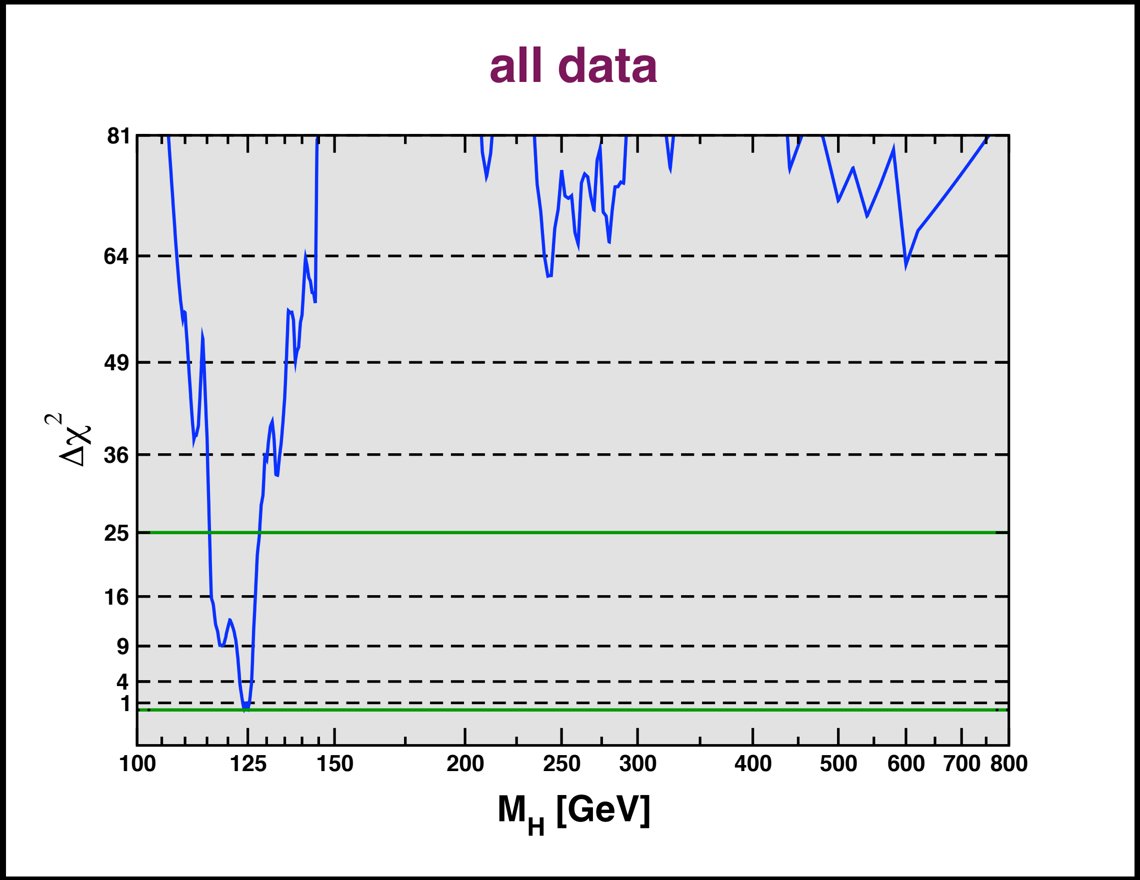
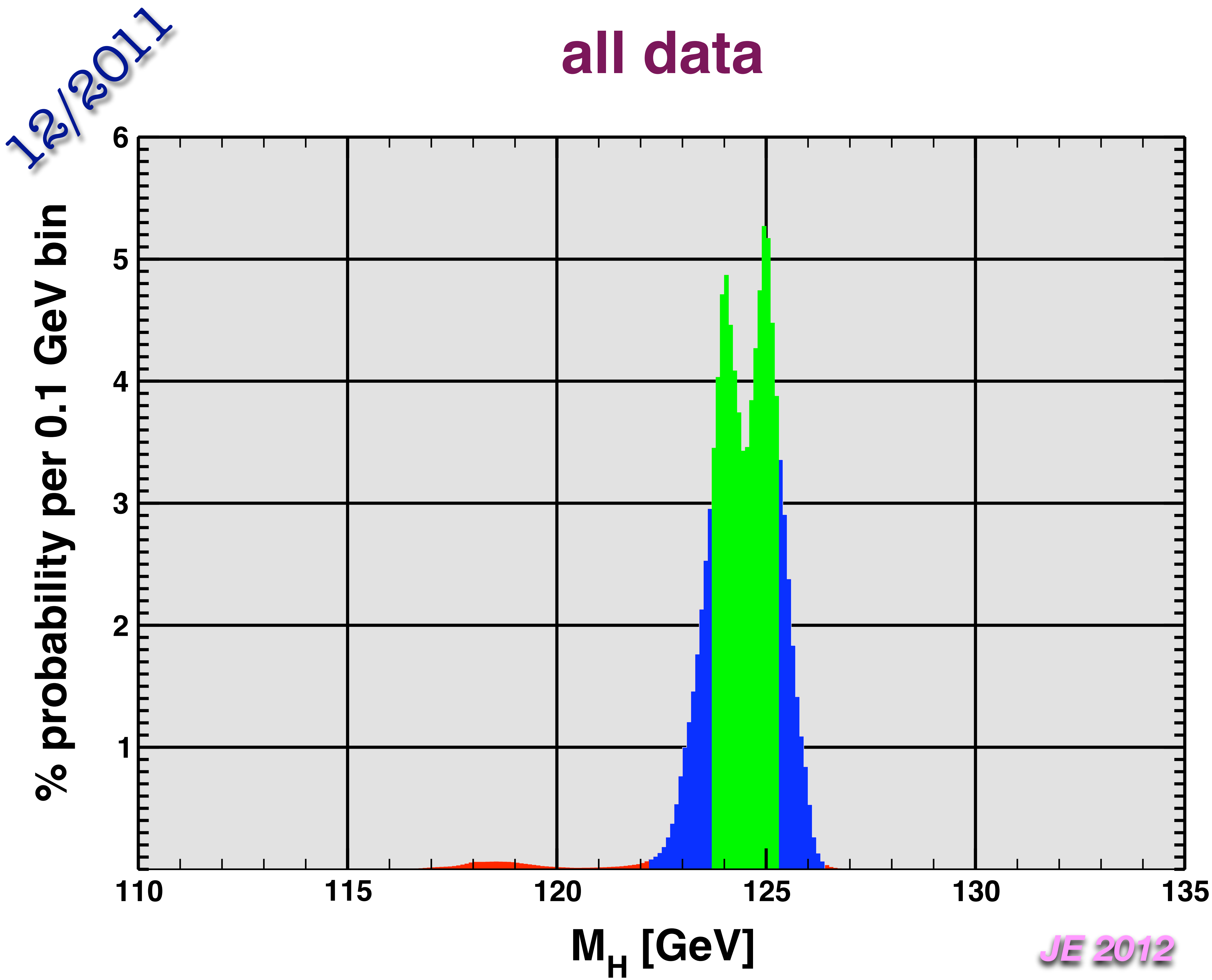
- $\chi^2_{EW}(127\ \text{GeV}) - \chi^2_{EW}(115.5\ \text{GeV}) = 0.63$
- $2 \ln p_{direct}(125\ \text{GeV}) = -13.2$

- LHC data require "look elsewhere effect correction"
- Can be avoided when combined with electroweak precision data ***JE 2012***

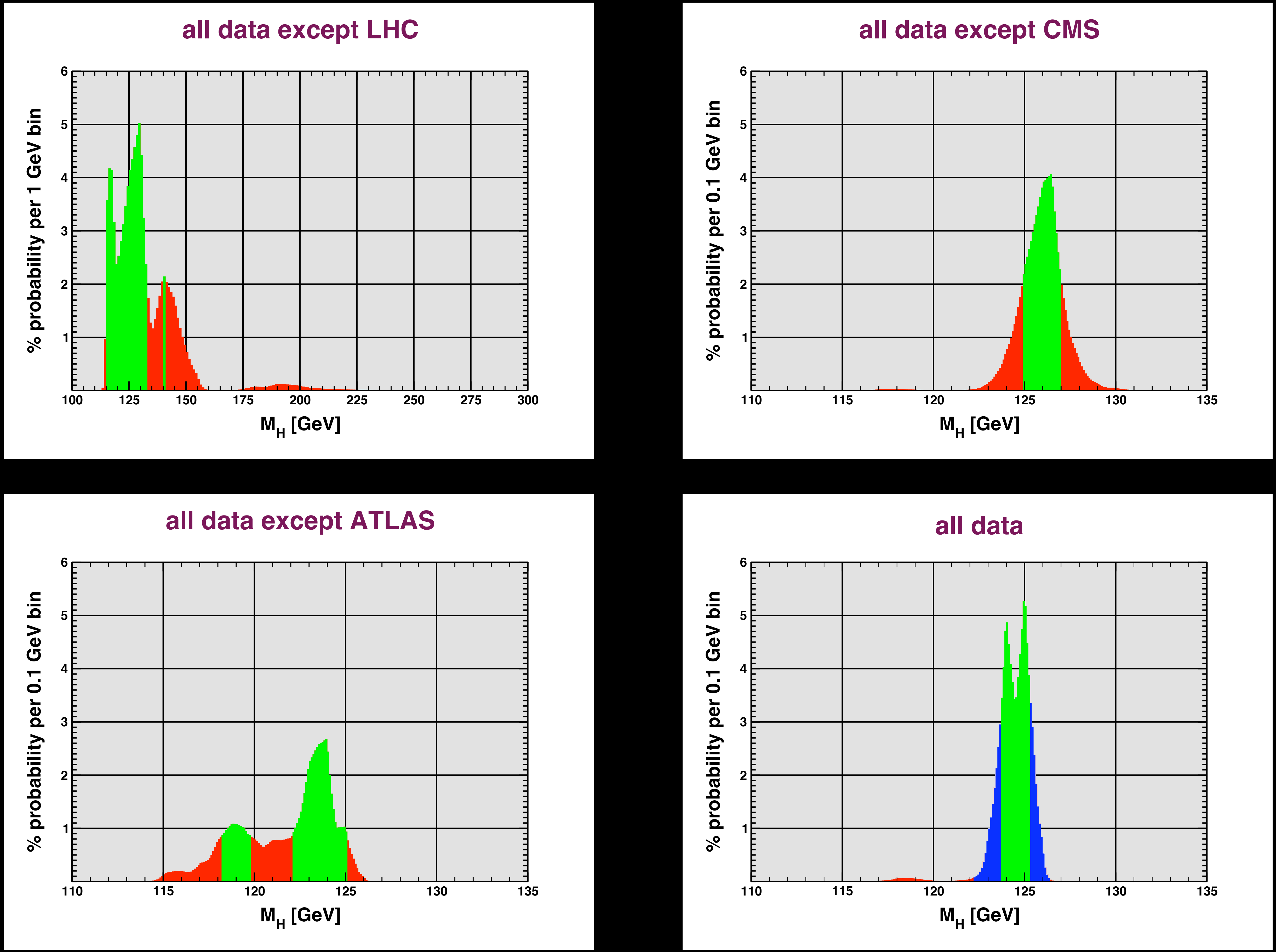




all data



12/2011
% probability per 0.1 GeV bin
6
5
4
3
2
1
110
115
120
125
130
135
M_H [GeV]
JE 2012



all data except LHC
% probability per 1 GeV bin
M_H [GeV]
100
125
150
175
200
225
250
275
300
all data except CMS
% probability per 0.1 GeV bin
M_H [GeV]
110
115
120
125
130
135
all data except ATLAS
% probability per 0.1 GeV bin
M_H [GeV]
all data
% probability per 0.1 GeV bin
M_H [GeV]

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conclusions

Summary and outlook

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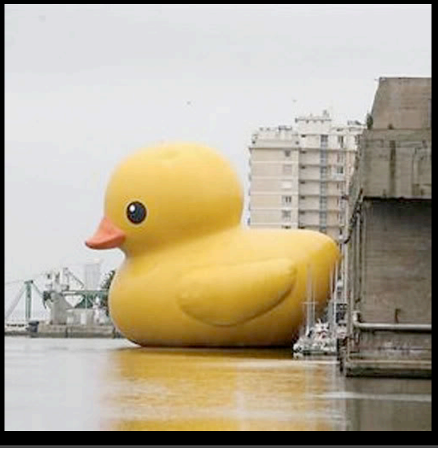

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