Precision of Standard Model Parameters and Higgs Properties

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Outline

- Precision electroweak fits
- QCD coupling
- Quark masses
- Implications for Higgs decays
- Conclusions

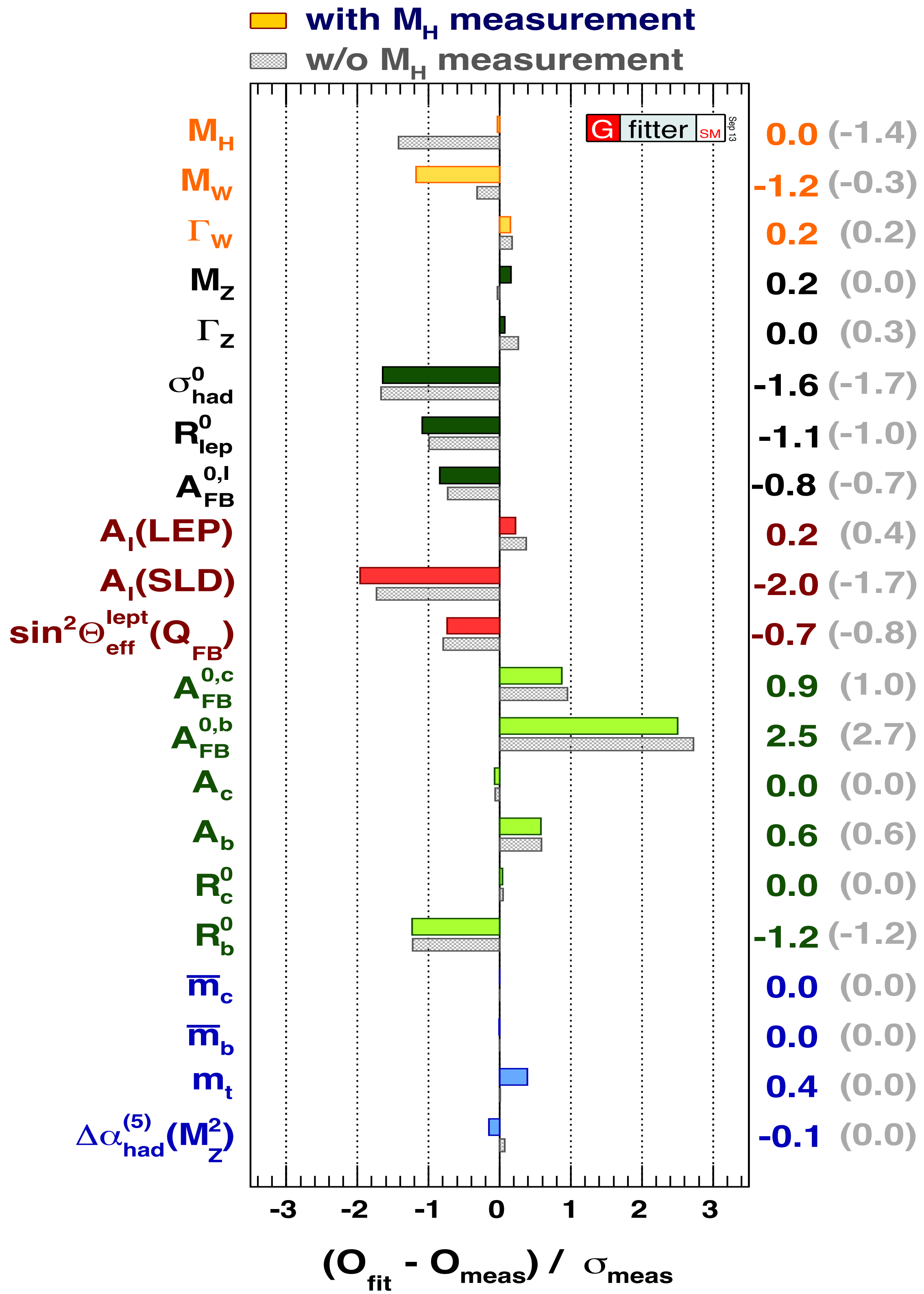
Precision Electroweak Fits

Electroweak Fit – Experimental inputs

- **Latest experimental inputs:**
  - Z-pole observables: from LEP / SLC
    [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - M_W and Γ_W from LEP/Tevatron
    [arXiv:1204.0042, arXiv:1302.3415]
  - m_{top} latest avg from Tevatron
    [arXiv:1305.3929]
  - m_c, m_b world averages (PDG)
    [PDG, J. Phys. G33,1 (2006)]
  - $\Delta\alpha_{had}^{(5)}(M_Z^2)$ including α_S dependency
    [Davier et al., EPJC 71, 1515 (2011)]
  - M_H from LHC
    [arXiv:1207.7214, arXiv:1207.7235]
- **7 (+2) free fit parameters:**
  - M_H, M_Z, $\alpha_S(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_t, m_c, m_b
  - 2 theory nuisance parameters
    - δM_W (4 MeV), $\delta\sin^2\theta^l_{eff}$ (4.7×10^{-5})

M_H [GeV]°	125.7 ± 0.4	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	Tevatron
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP / SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	SLC
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP / SLC
R^0_b	0.21629 ± 0.00066	LEP / SLC
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.20 ± 0.87	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	$(2756 \pm 10)\times10^{-5}$	

Electroweak Fit – SM Fit Results



Plot inspired by Eberhardt et al. [arXiv:1209.1101]

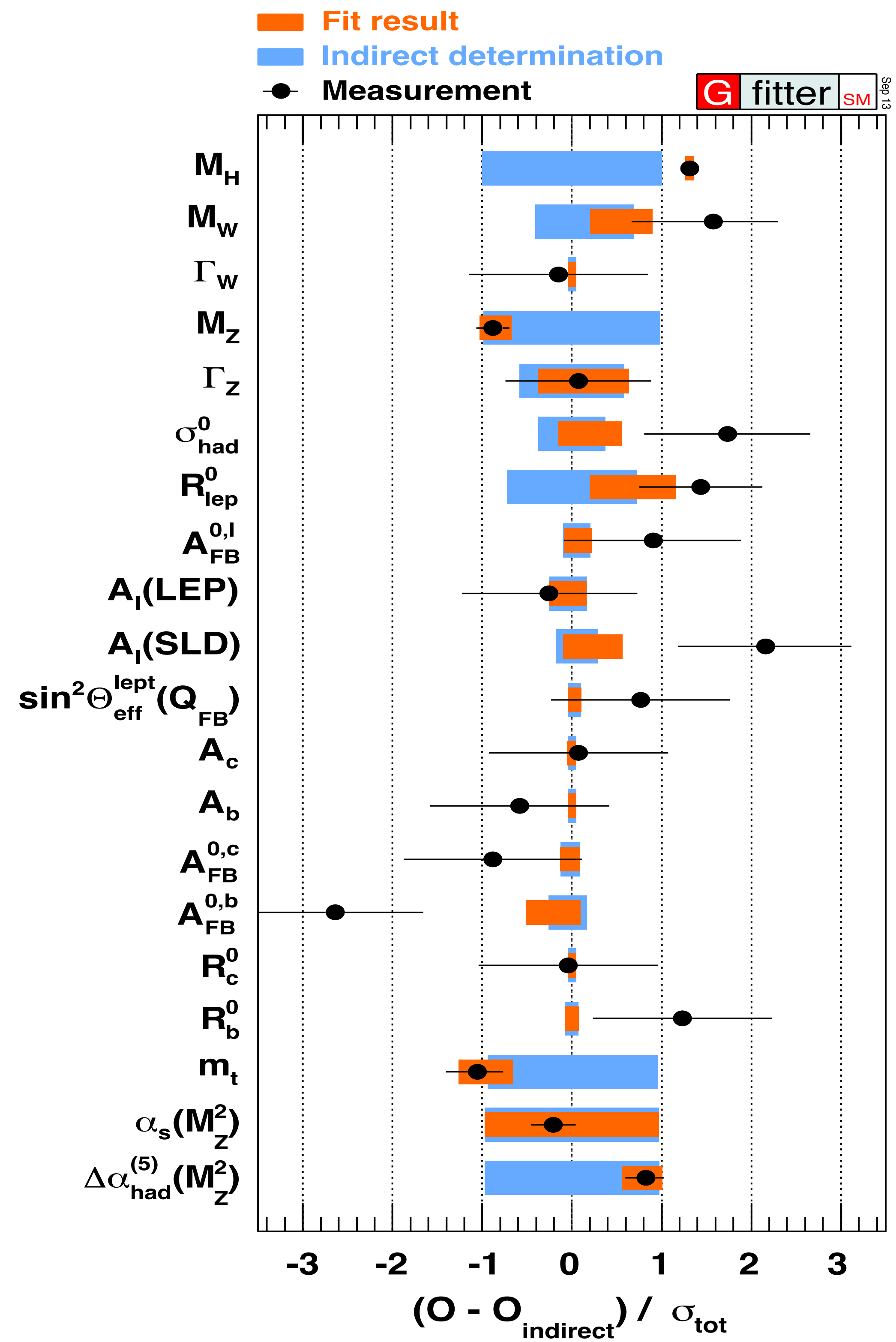
- Pull values of full fit (with M_H)
  - No individual value exceeds 3σ
  - Small pulls for M_H, M_Z, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$ indicate that input accuracies exceed fit requirements
  - Largest deviation in b-sector: $A^{0,b}_{FB}$ with 2.5σ
- Most affected when including M_H:
  - Shift in predicted M_W value of 13 MeV.
- Goodness of fit – p-value:
  - From pseudo experiments: 18^{+2} %
  - χ^2_{min}= 18.1 → Prob(χ^2_{min}, 14) = 20%
    - Large value of χ^2_{min} not due to inclusion of M_H measurement.
    - Without M_H measurement: χ^2_{min}= 16.7 → Prob(χ^2_{min}, 13) = 21%

Electroweak Fit – SM Fit Results

- Results drawn as *pull values:* → deviations to the *indirect* determinations, divided by *total error*.
- Total error: *error of direct measurement plus error from indirect determination.*

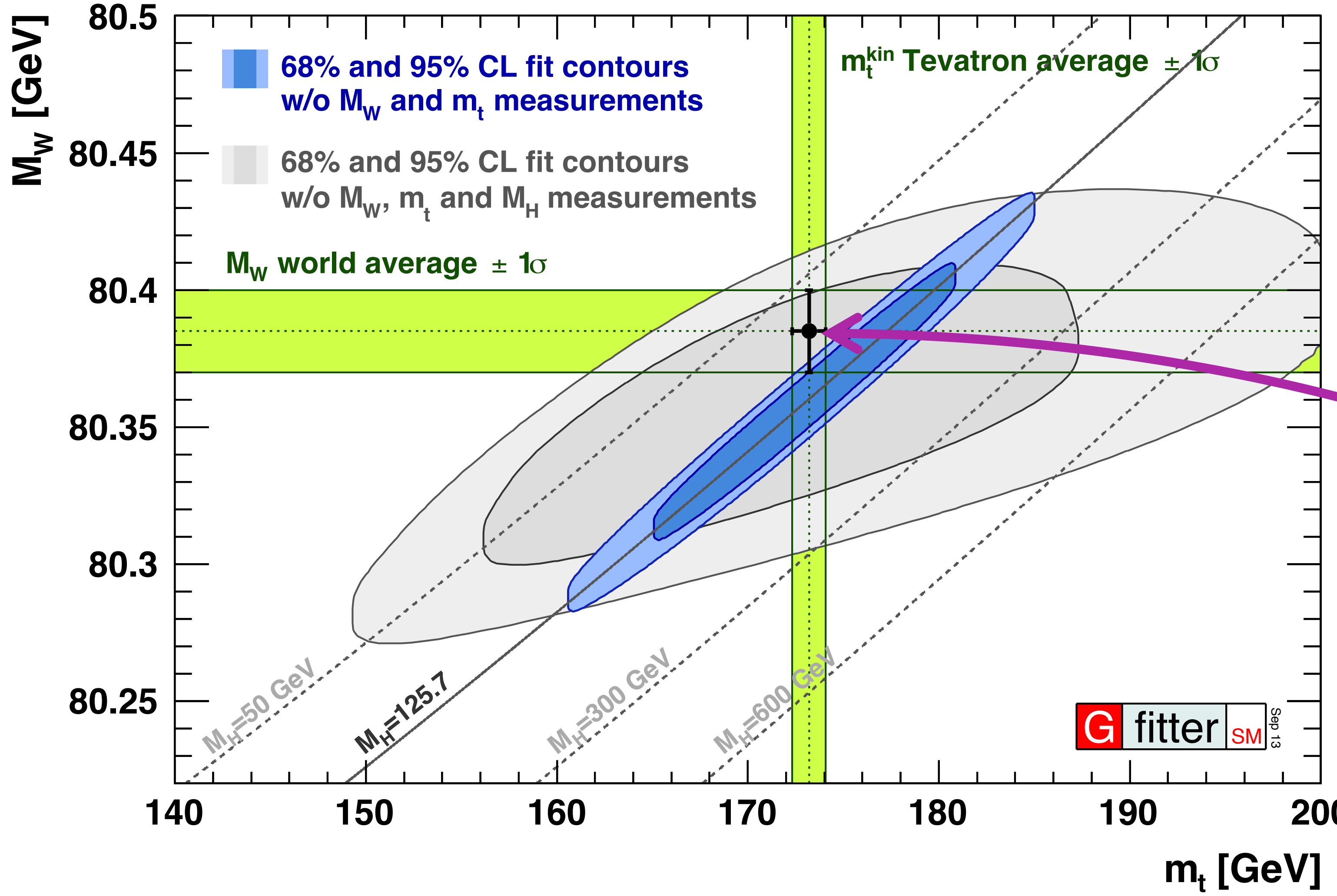
- Black: direct measurement (data)
- Orange: full fit result
- Light-blue: fit excluding input from the row

- The prediction (light blue) is often more precise than the measurement!



State of the SM: W versus top mass

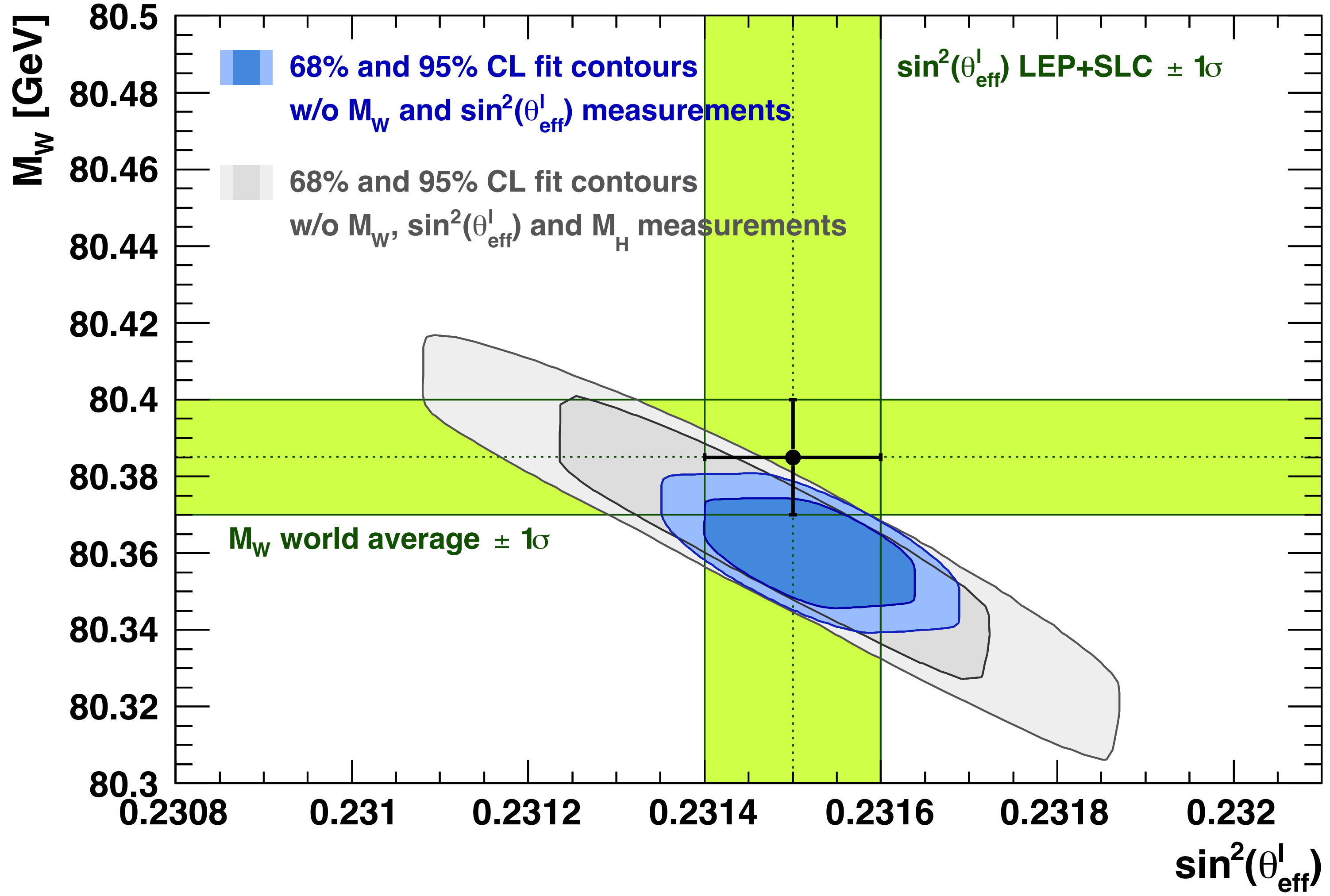
- Scan of M_W vs m_t, with the direct measurements excluded from the fit.
- Results from Higgs measurement significantly reduces allowed indirect parameter space → corners the SM!



- Observed agreement demonstrates impressive consistency of the SM!

State of the SM: W mass versus $\sin^2\theta^l_{eff}$

- Scan of M_W vs $\sin^2\theta^l_{eff}$, with direct measurements excluded from the fit.
- Again, significant reduction allowed indirect parameter space from Higgs mass measurement.



- M_W and $\sin^2\theta^l_{eff}$ have become *the* sensitive probes of new physics!
  - Reason: both are 'tree-level' SM predictions.

Muon magnetic moment

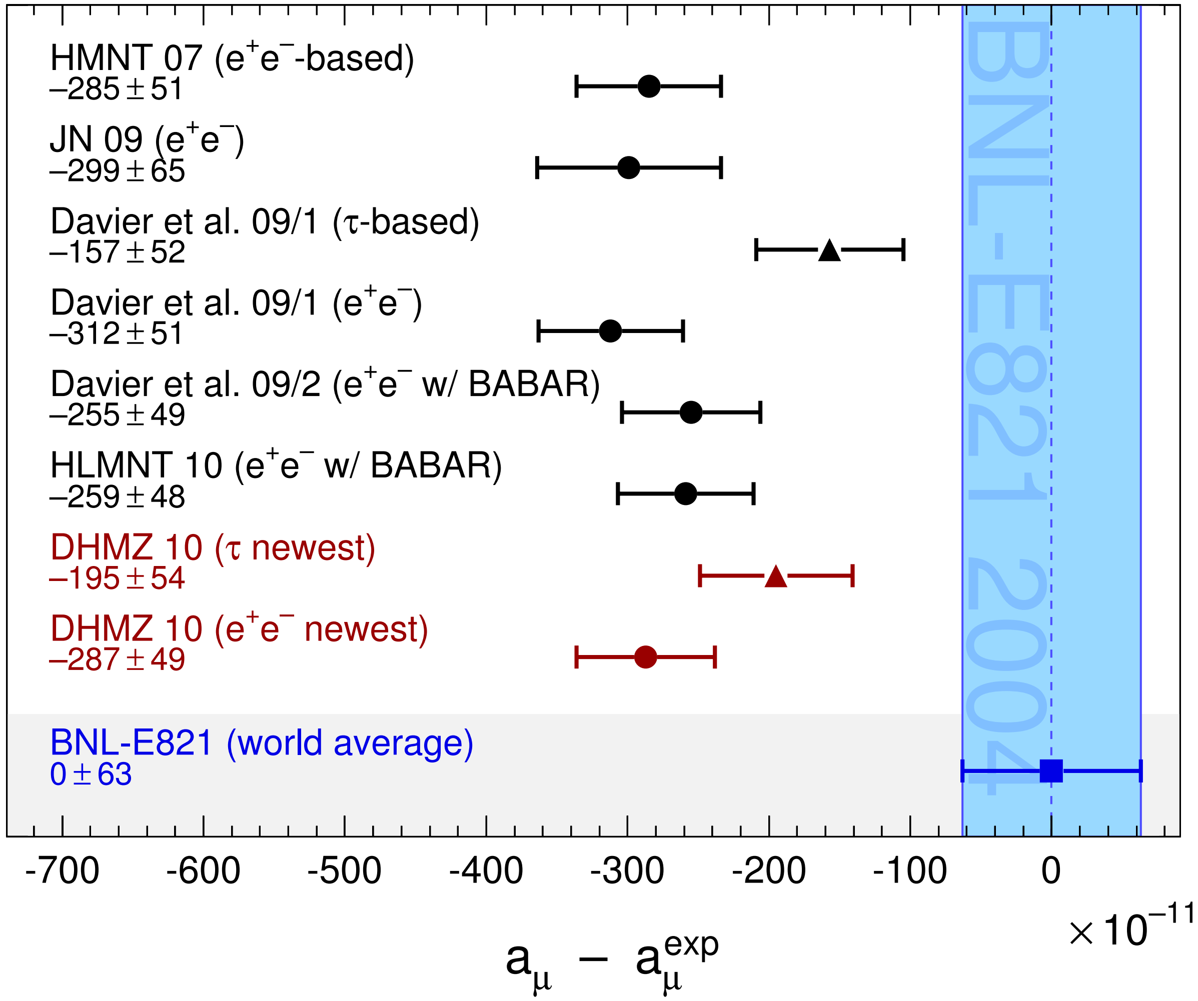
- Not included in above fits

$$a_\mu = \frac{g_\mu - 2}{2} = \frac{\alpha}{2\pi} + \ldots$$

$$a_\mu^{\rm exp} = 0.00116592089(54)(33)$$

$$a_\mu^{\rm SM} = 0.00116591802(49)$$

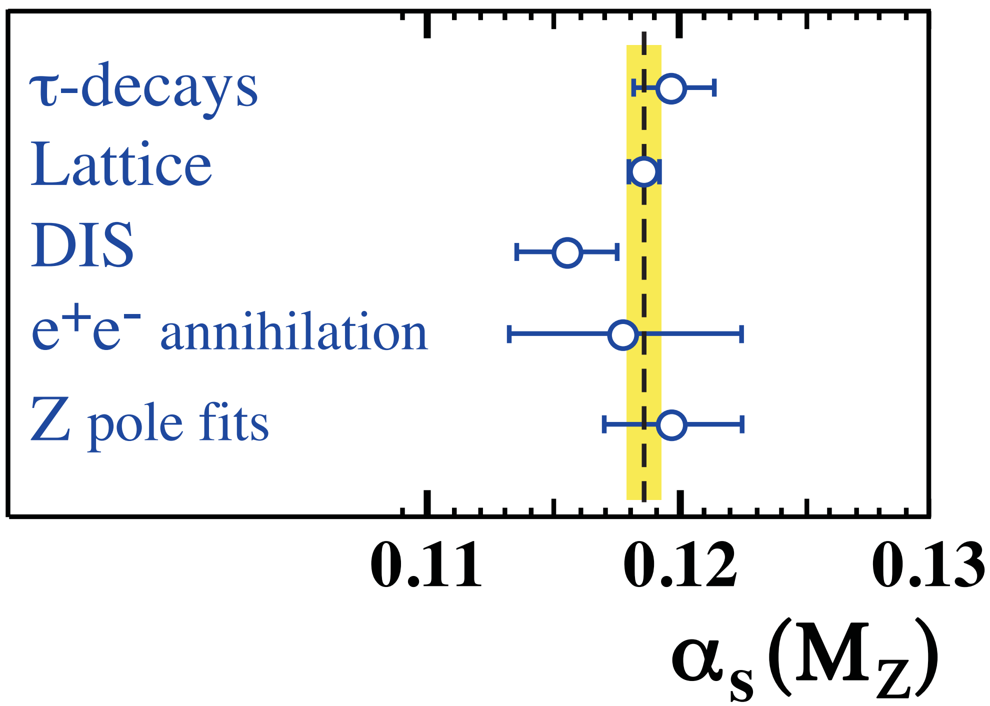
$$\Delta a_\mu^{\rm had} = (691.6 \pm 6.9) \times 10^{-10}$$

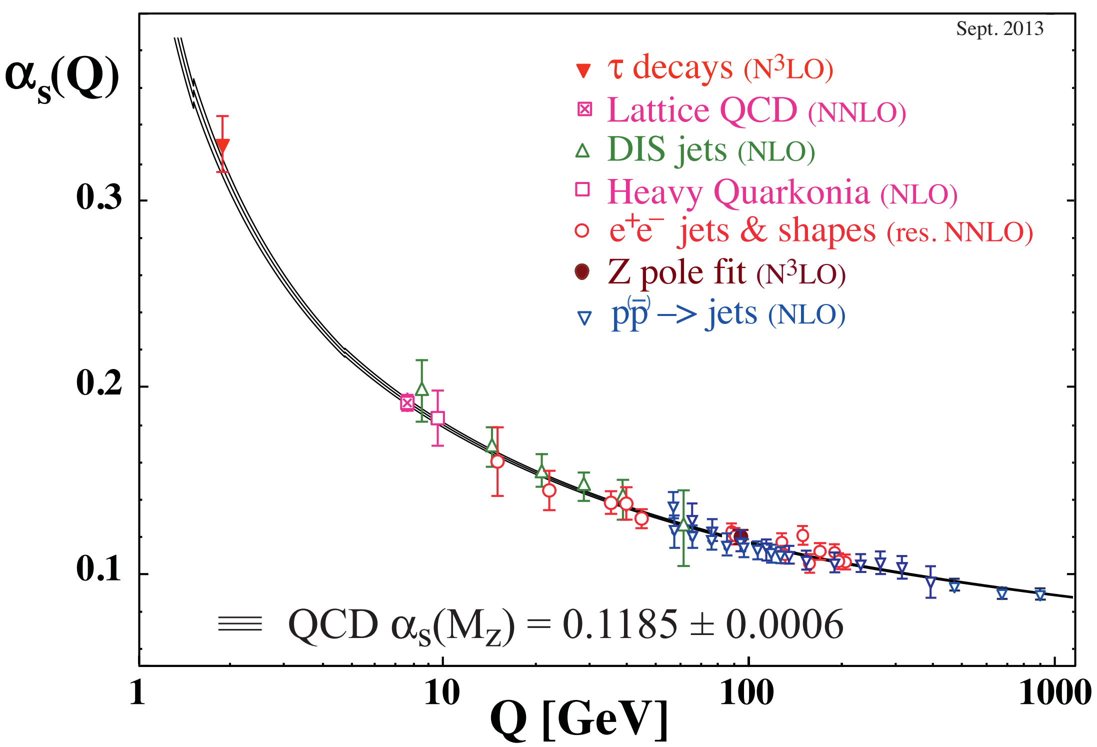


$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.7 \pm 8.0) \times 10^{-10}\ (3.6\,\sigma)$$

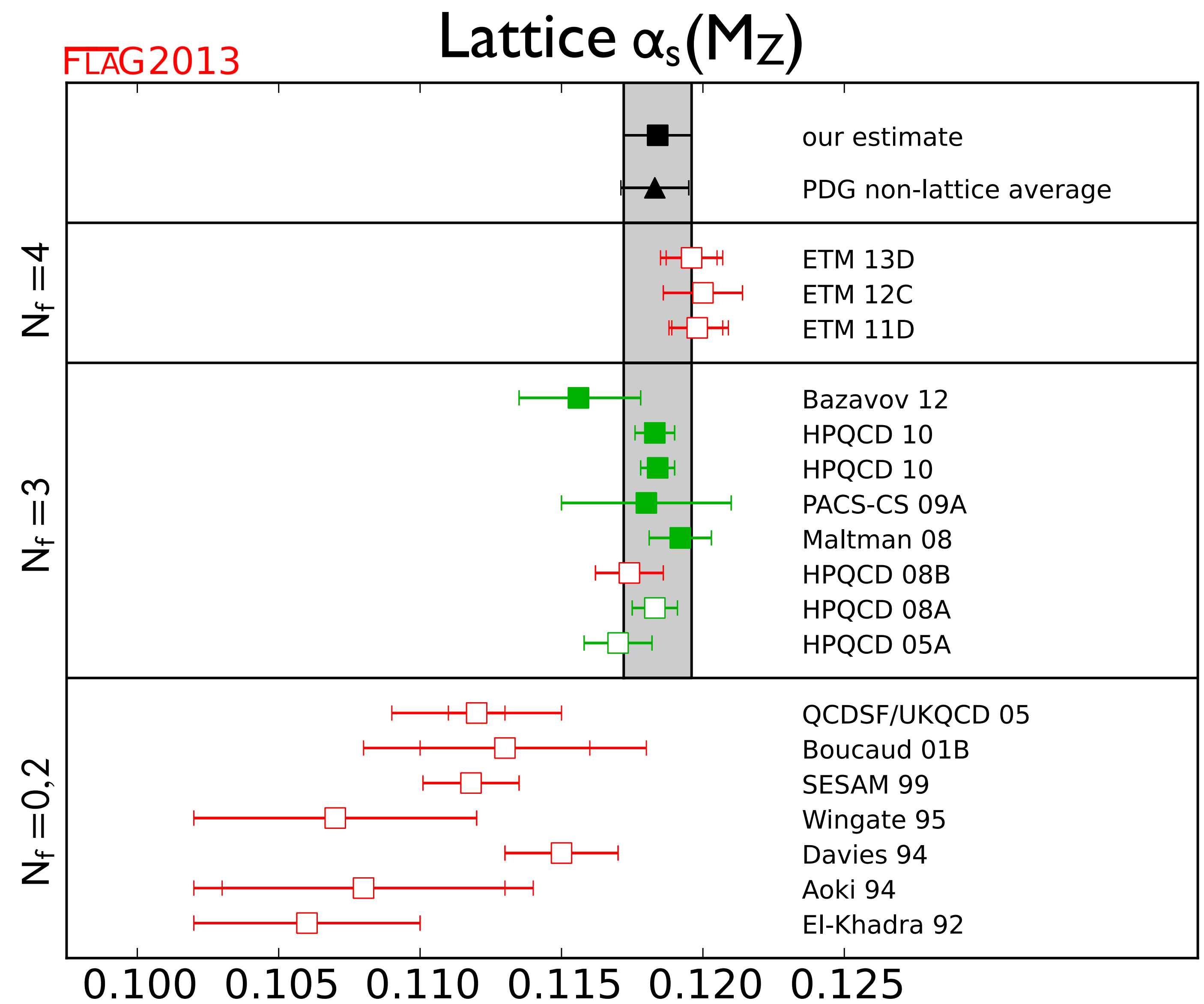
QCD Coupling

QCD Coupling





Bethke, Dissertori, Salam, RPP 2013



FLAG WG: Aoki et al., 1310.8555

$\alpha_S(M_Z)$=0.1185(5) [lattice]

$\alpha_S(M_Z)$=0.1183(12) [non-lattice]

Lattice QCD Coupling

FLAG WG: Aoki et al., 1310.8555

Collaboration	Ref.	N_f	publication status	renormalisation scale	perturbative behaviour	continuum extrapolation	$\alpha_{\overline{\rm MS}}(M_{\rm Z})$	Method	Table
ETM 13D	[544]	2+1+1	A	○	○	■	0.1196(4)(8)(16)	gluon-ghost vertex	37
ETM 12C	[545]	2+1+1	A	○	○	■	0.1200(14)	gluon-ghost vertex	37
ETM 11D	[546]	2+1+1	A	○	○	■	$0.1198(9)(5)(^{+0}_{-5})$	gluon-ghost vertex	37
Bazavov 12	[503]	2+1	A	○	○	○	$0.1156(^{+21}_{-22})$	Q-$\bar{Q}$ potential	33
HPQCD 10	[73]	2+1	A	○	○	○	0.1183(7)	current two points	36
HPQCD 10	[73]	2+1	A	○	★	★	0.1184(6)	Wilson loops	35
PACS-CS 09A	[486]	2+1	A	★	★	○	$0.118(3)^{\#}$	Schrödinger functional	32
Maltman 08	[517]	2+1	A	○	○	○	0.1192(11)	Wilson loops	35
HPQCD 08B	[85]	2+1	A	■	■	■	0.1174(12)	current two points	36
HPQCD 08A	[514]	2+1	A	○	★	★	0.1183(8)	Wilson loops	35
HPQCD 05A	[513]	2+1	A	○	○	○	0.1170(12)	Wilson loops	35
QCDSF/UKQCD 05	[518]	$0, 2 \to 3$	A	★	■	★	0.112(1)(2)	Wilson loops	35
Boucaud 01B	[539]	$2 \to 3$	A	○	○	■	0.113(3)(4)	gluon-ghost vertex	37
SESAM 99	[519]	$0, 2 \to 3$	A	★	■	■	0.1118(17)	Wilson loops	35
Wingate 95	[520]	$0, 2 \to 3$	A	★	■	■	0.107(5)	Wilson loops	35
Davies 94	[521]	$0, 2 \to 3$	A	★	■	■	0.115(2)	Wilson loops	35
Aoki 94	[522]	$2 \to 3$	A	★	■	■	0.108(5)(4)	Wilson loops	35
El-Khadra 92	[523]	$0 \to 3$	A	★	○	○	0.106(4)	Wilson loops	35

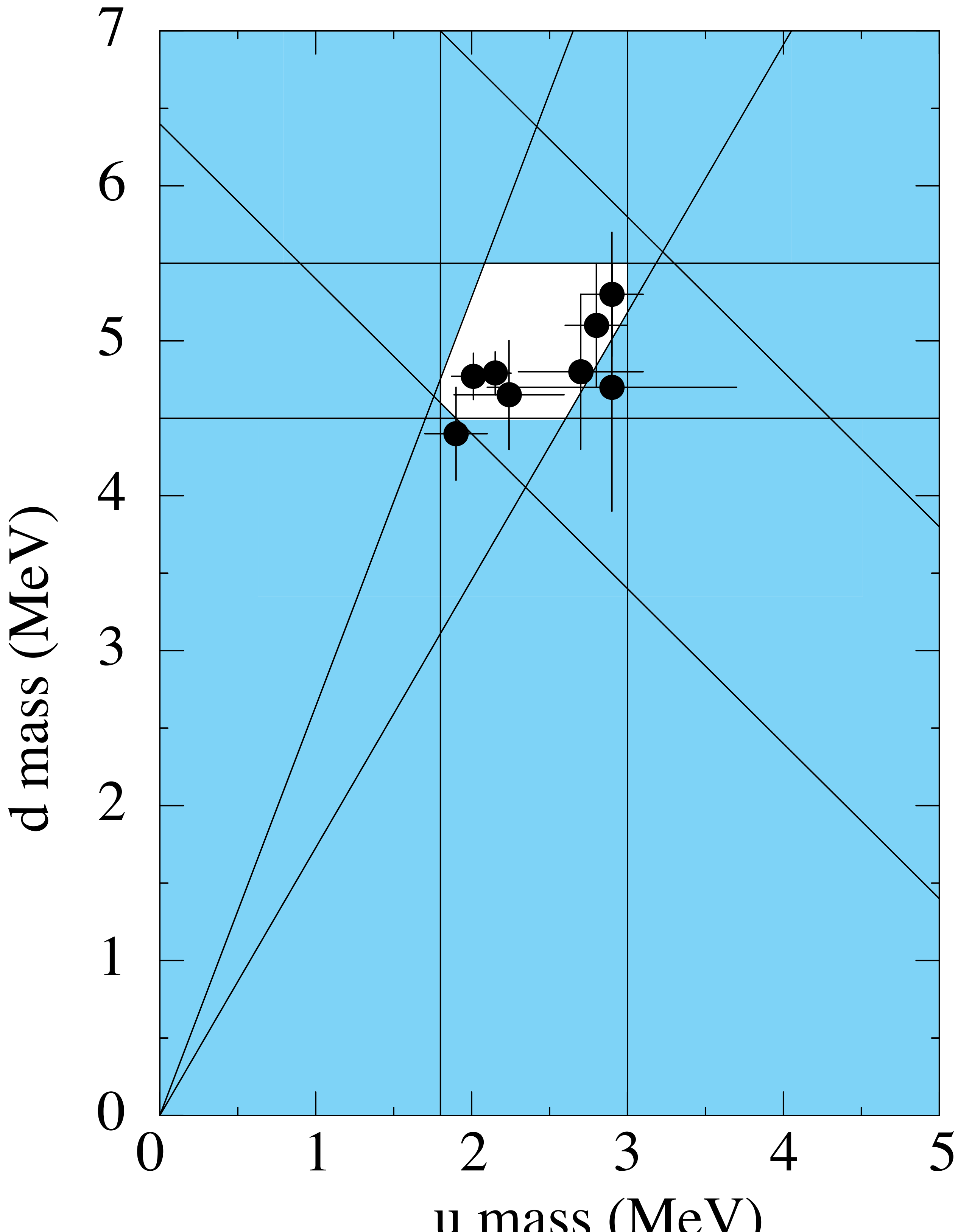
Quark Masses

Lattice light quark masses

FLAG WG: Aoki et al., 1310.8555

Collaboration	Ref.	publication status	chiral extrapolation	continuum extrapolation	finite volume	renormalization	running	m_u	m_d	m_u/m_d
PACS-CS 12*	[76]	A	★	■	■	★	a	2.57(26)(7)	3.68(29)(10)	0.698(51)
Laiho 11	[77]	C	○	★	★	○	–	1.90(8)(21)(10)	4.73(9)(27)(24)	0.401(13)(45)
HPQCD 10‡	[73]	A	○	★	★	★	–	2.01(14)	4.77(15)	
BMW 10A, 10B$^+$	[22, 23]	A	★	★	★	★	b	2.15(03)(10)	4.79(07)(12)	0.448(06)(29)
Blum 10†	[32]	A	○	■	○	★	–	2.24(10)(34)	4.65(15)(32)	0.4818(96)(860)
MILC 09A	[37]	C	○	★	★	○	–	1.96(0)(6)(10)(12)	4.53(1)(8)(23)(12)	0.432(1)(9)(0)(39)
MILC 09	[15]	A	○	★	★	○	–	1.9(0)(1)(1)(1)	4.6(0)(2)(2)(1)	0.42(0)(1)(0)(4)
MILC 04, HPQCD/ MILC/UKQCD 04	[36, 82]	A	○	○	○	■	–	1.7(0)(1)(2)(2)	3.9(0)(1)(4)(2)	0.43(0)(1)(0)(8)
RM123 13	[45]	A	○	★	○	★	c	2.40(15)(17)	4.80 (15)(17)	0.50(2)(3)
RM123 11$^\oplus$	[104]	A	○	★	○	★	c	*2.43(11)(23)*	*4.78(11)(23)*	*0.51(2)(4)*
Dürr 11*	[61]	A	○	★	○	–	–	2.18(6)(11)	4.87(14)(16)	
RBC 07†	[34]	A	■	■	★	★	–	3.02(27)(19)	5.49(20)(34)	0.550(31)

Light quark masses



Manohar, Sachrajda, RPP 2012

$\overline{\text{MS}}$ masses at 2 GeV:

$\overline{m}_u = 2.15 \pm 0.15$ MeV

$\overline{m}_d = 4.70 \pm 0.20$ MeV

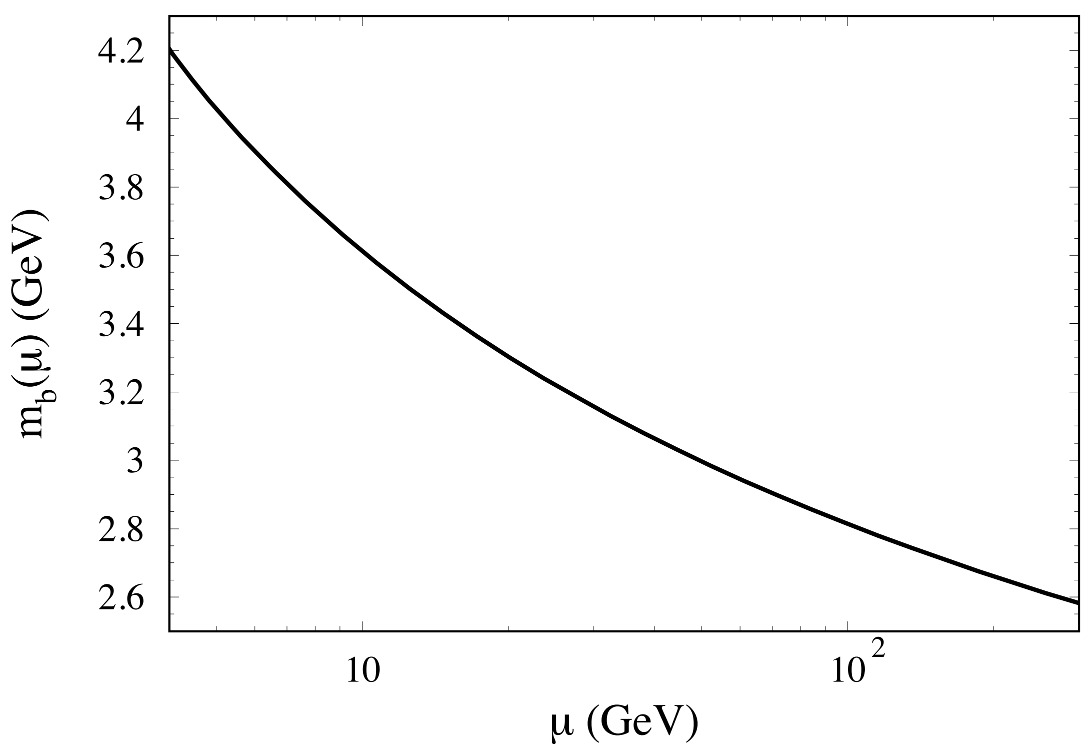
$\overline{m}_s = 93.5 \pm 2.5$ MeV

Running quark mass

- Couplings and masses (parameters in Lagrangian) must be renormalised, hence scale (and scheme) dependent

$$\mu^2 \frac{d\alpha_s}{d\mu^2} = \beta(\alpha_s)\alpha_s = -\alpha_s^2(\beta_0 + \beta_1\alpha_s + \ldots)$$

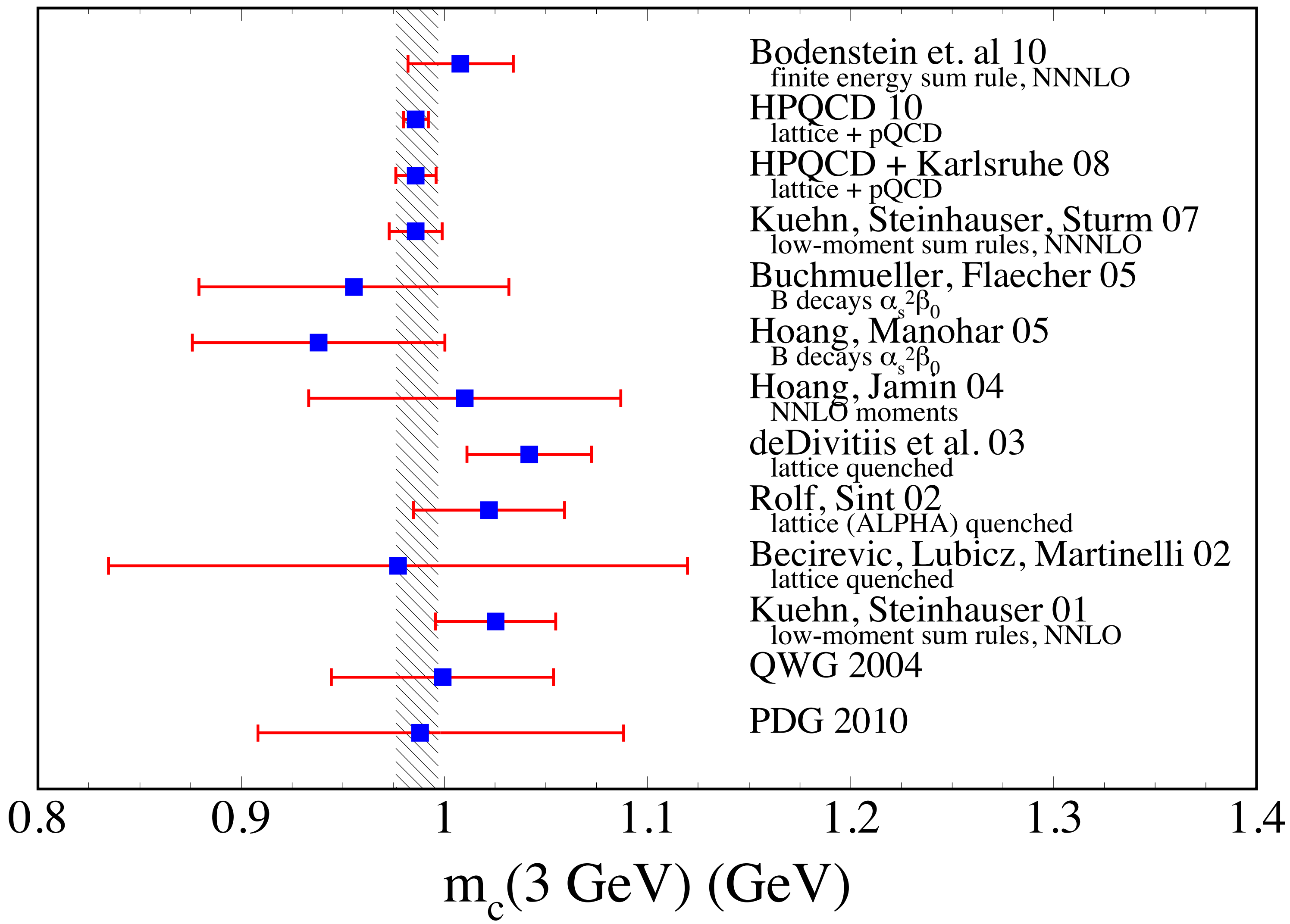
$$\mu^2 \frac{dm_q}{d\mu^2} = \gamma(\alpha_s)m_q = -\alpha_s(\gamma_0 + \gamma_1\alpha_s + \ldots)m_q \rightarrow \frac{dm_q}{m_q} = \frac{d\alpha_s}{\alpha_s}\frac{\gamma(\alpha_s)}{\beta(\alpha_s)}$$



$$m_q(\mu) = m_q(\mu_0)\left[\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right]^{\frac{\gamma_0}{\beta_0}} \left\{1 + \left(\frac{\gamma_1}{\beta_0} - \frac{\beta_1\gamma_0}{\beta_0^2}\right)[\alpha_s(\mu) - \alpha_s(\mu_0)] + \ldots\right\}$$

Charm quark mass

Kühn, 2013



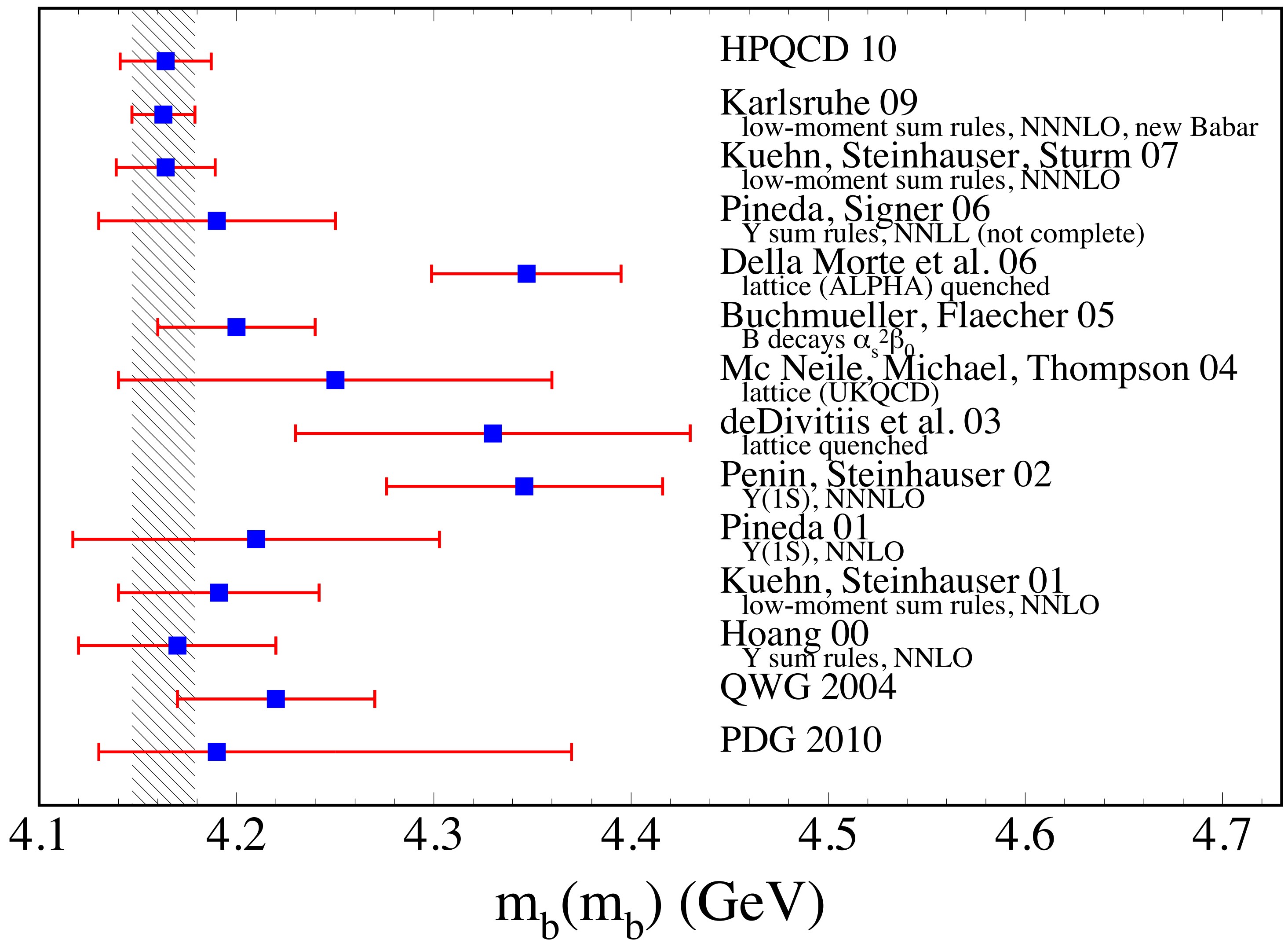
$m_c(3\ \mathrm{GeV}) = 0.986(6)\ \mathrm{GeV}$

→ $m_c(m_c) = 1.268(9)\ \mathrm{GeV}$

→ $m_c(M_H) = 0.612(5)\ \mathrm{GeV}$

Bottom quark mass

Kühn, 2013



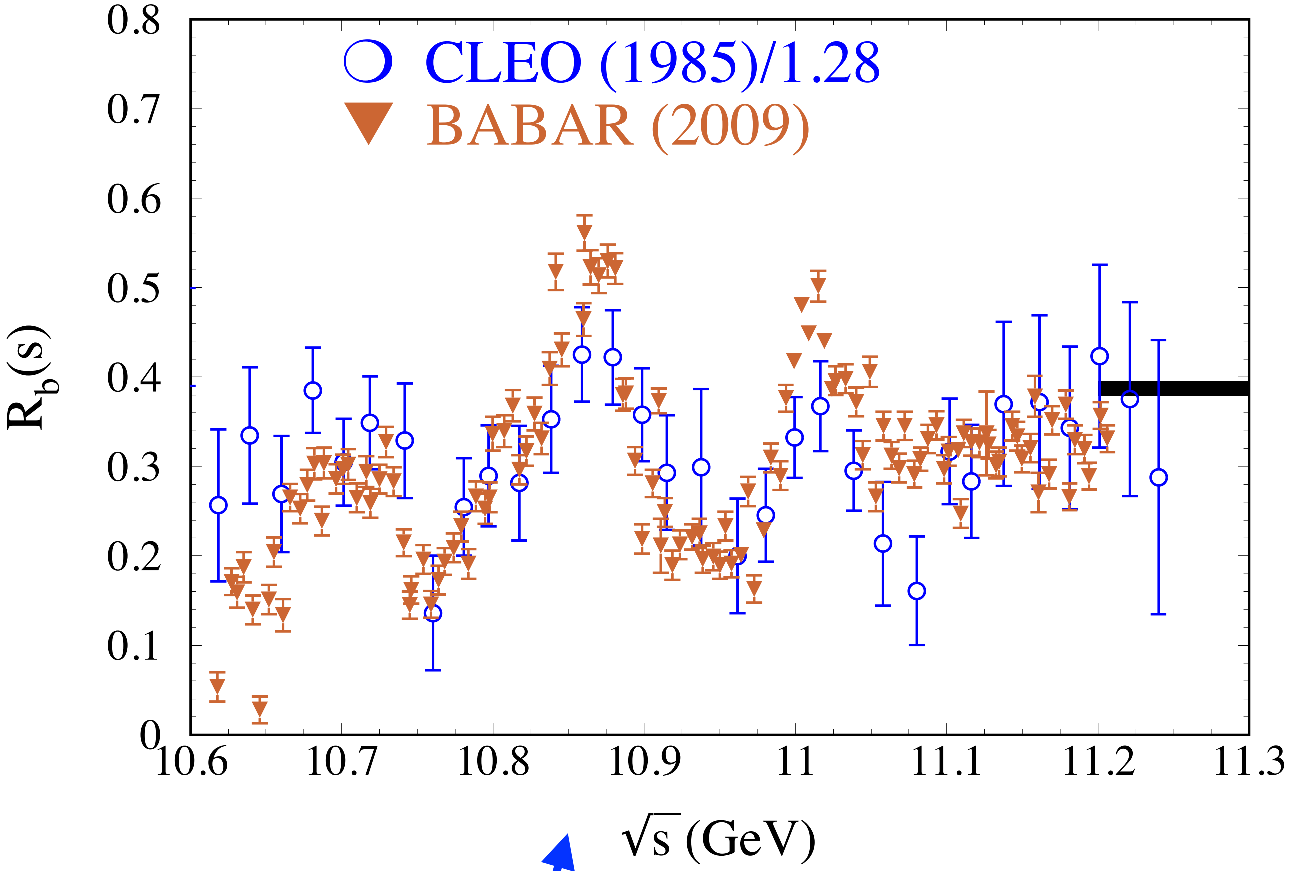
$m_b(10\ \mathrm{GeV}) = 3.617(25)\ \mathrm{GeV}$

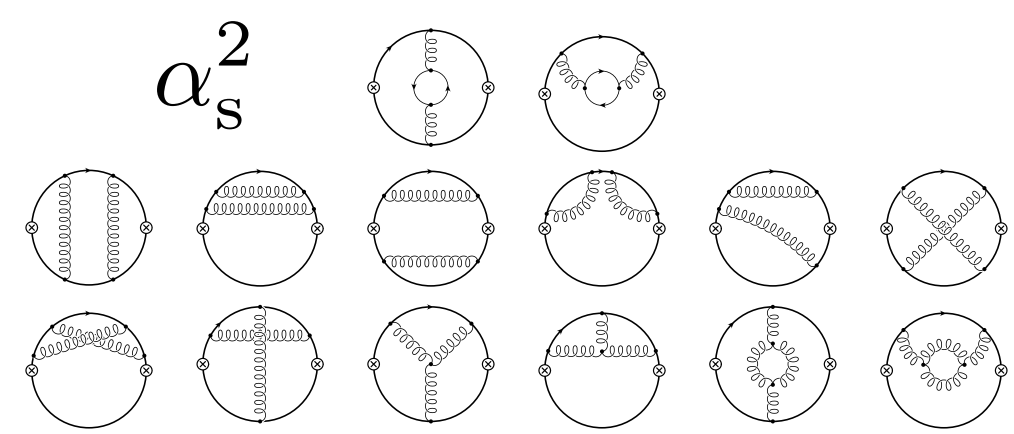
→ $m_b(m_b) = 4.164(30)\ \mathrm{GeV}$

→ $m_b(M_H) = 2.768(21)\ \mathrm{GeV}$

m_b from QCD sum rules

Chetyrkin et al., PRD80(2009)074010





$\ldots + \alpha_s^3$ (~700 diagrams)

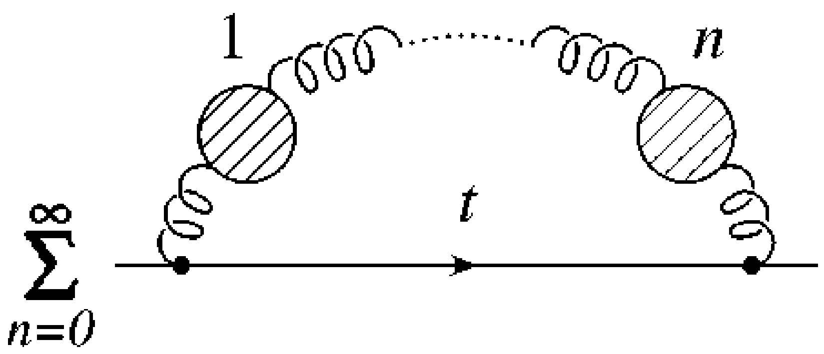
$$\mathcal{M}_n = \int \frac{ds}{s^{n+1}} R_b(s) = \frac{9}{4} e_b^2 \left(\frac{1}{4 m_b^2(\mu)} \right)^n C_n(\alpha_s, \mu) \rightarrow m_b(\mu) = \frac{1}{2} \left(\frac{9 e_b^2 C_n(\alpha_s, \mu)}{4 \mathcal{M}_n} \right)^{\frac{1}{2n}}$$

n	$m_b(10\,\text{GeV})$	exp	α_s	μ	total	$m_b(m_b)$
1	3597	14	7	2	16	4151
2	3610	10	12	3	16	4163
3	3619	8	14	6	18	4172
4	3631	6	15	20	26	4183

m_b(10 GeV) = 3.610(16) GeV

Pole quark mass

$$D(\not{p}) = \frac{i}{\not{p} - m_q - \Sigma(\not{p})}$$



$$\not{p}_{\rm pole} = m_q + \Sigma(\not{p}) = m_q + \Sigma^{(1)}(m_q) + \ldots$$

$$c_n \sim 2^n n! \sim (2n/e)^n$$

$$\Sigma^{(1)}(m_q) = \frac{16 m_q}{3\beta_0} \sum_{n=0}^{\infty} c_n\, a^{n+1}$$

$$a = \frac{\beta_0 \alpha_{\rm s}(m_q)}{4\pi} \sim \frac{1}{\log(m_q^2/\Lambda^2)}$$

Asymptotic expansion: sum to smallest term (n~L/2)

Ambiguity ~ smallest term ($c_n\, a^{n+1} \sim e^{-L/2} \sim \Lambda/m_q$)

$$m_{\rm pole} = m_q(m_q)\left\{1 + 0.4244\,\alpha_{\rm s}(m_q) + 0.835\,\alpha_{\rm s}^2(m_q) + 2.375\,\alpha_{\rm s}^3(m_q)\right] + \mathcal{O}(\Lambda)$$

Renormalon ambiguity
(There is no pole!)

Top quark mass

"Direct" (≈pole mass?) measurements:

RPP 2013

m_t (GeV/c^2)	Source	$\int \mathcal{L}dt$	Ref.	Channel
$174.94 \pm 1.14 \pm 0.96$	DØ Run II	3.6	[102]	ℓ+jets
$172.85 \pm 0.71 \pm 0.85$	CDF Run II	8.7	[101]	ℓ+jets
$173.93 \pm 1.64 \pm 0.87$	CDF Run II	8.7	[116]	Missing E_T+jets
$172.5 \pm 1.4 \pm 1.5$	CDF Run II	5.8	[122]	All jets
$172.31 \pm 0.75 \pm 1.35$	ATLAS	4.7	[99]	ℓ+jets
$173.09 \pm 0.64 \pm 1.50$	ATLAS	4.7	[108]	$\ell\ell$
$174.9 \pm 2.1 \pm 3.8$	ATLAS	2.04	[115]	All jets
$173.49 \pm 0.43 \pm 0.98$	CMS	5.0	[100]	ℓ+jets
$172.5 \pm 0.4 \pm 1.5$	CMS	5.0	[109]	$\ell\ell$
$173.49 \pm 0.69 \pm 1.21$	CMS	3.54	[114]	All jets
$173.20 \pm 0.51 \pm 0.71^*$	CDF,DØ (I+II)	$\leq$8.7	[3]	publ. or prelim. res.
$173.29 \pm 0.23 \pm 0.92^*$	ATLAS, CMS	$\leq$4.9	[121]	publ. or prelim. res.

m_t(pole) = 173.07±0.52(stat)±0.72(sys) GeV

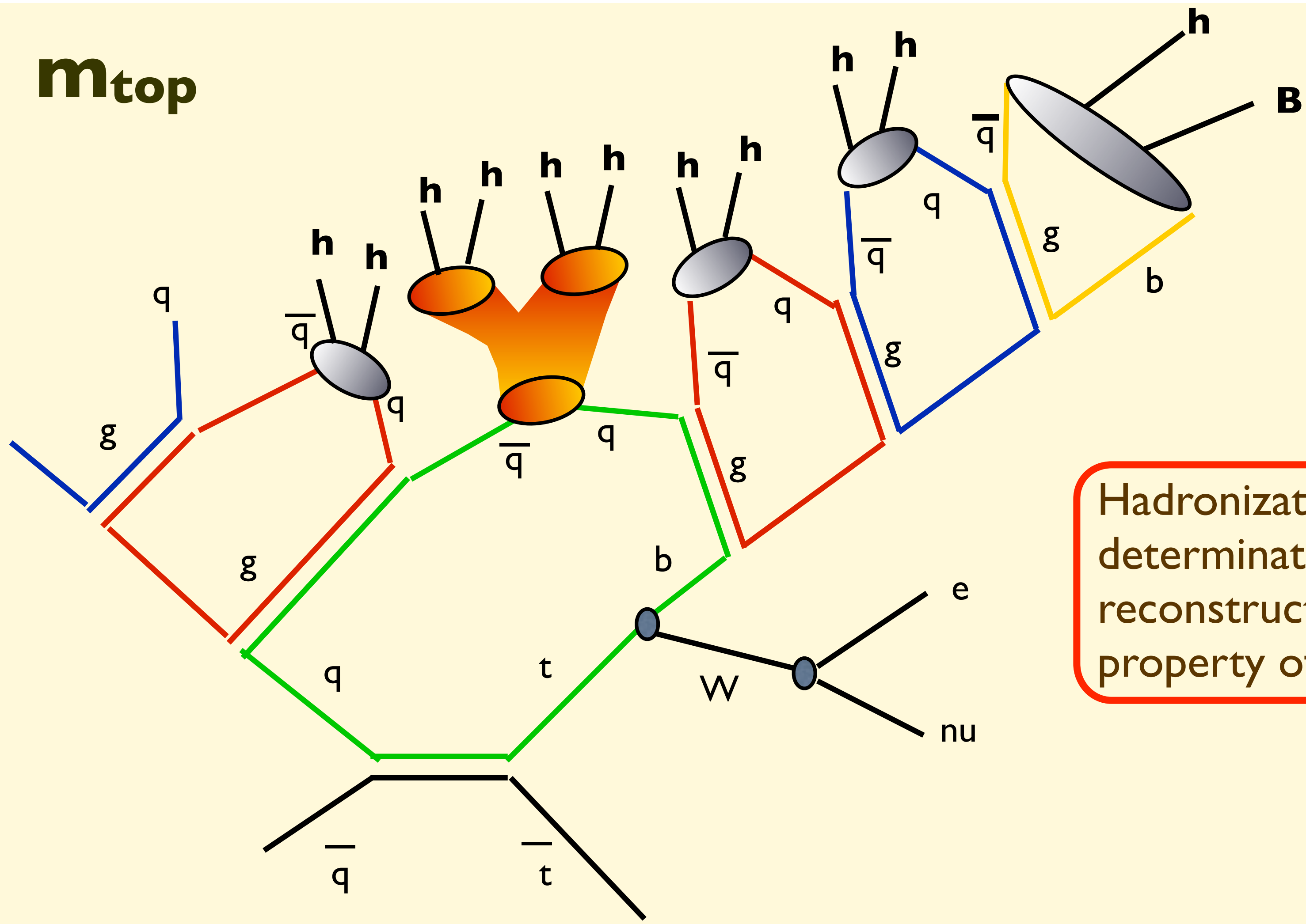
→ $m_t(m_t)$ = 163.4±0.9 GeV

$m_t(m_t)$ = 160^{+5}_{-4} GeV from cross section

Top quark mass

Mangano, Kyoto, 2012

m_{top}



Hadronization effects "pollute" the determination of mtop from the reconstruction of **any** kinematical property of top decay products.

Hadronization effects are in principle sensitive to the environment in which the top is produced. E.g.

- gg vs qqbar initial state
- pt or rapidity
- additional ISR or FSR

Monitoring this dependence and verifying MC predictions will constrian the modeling of non-perturbative effects

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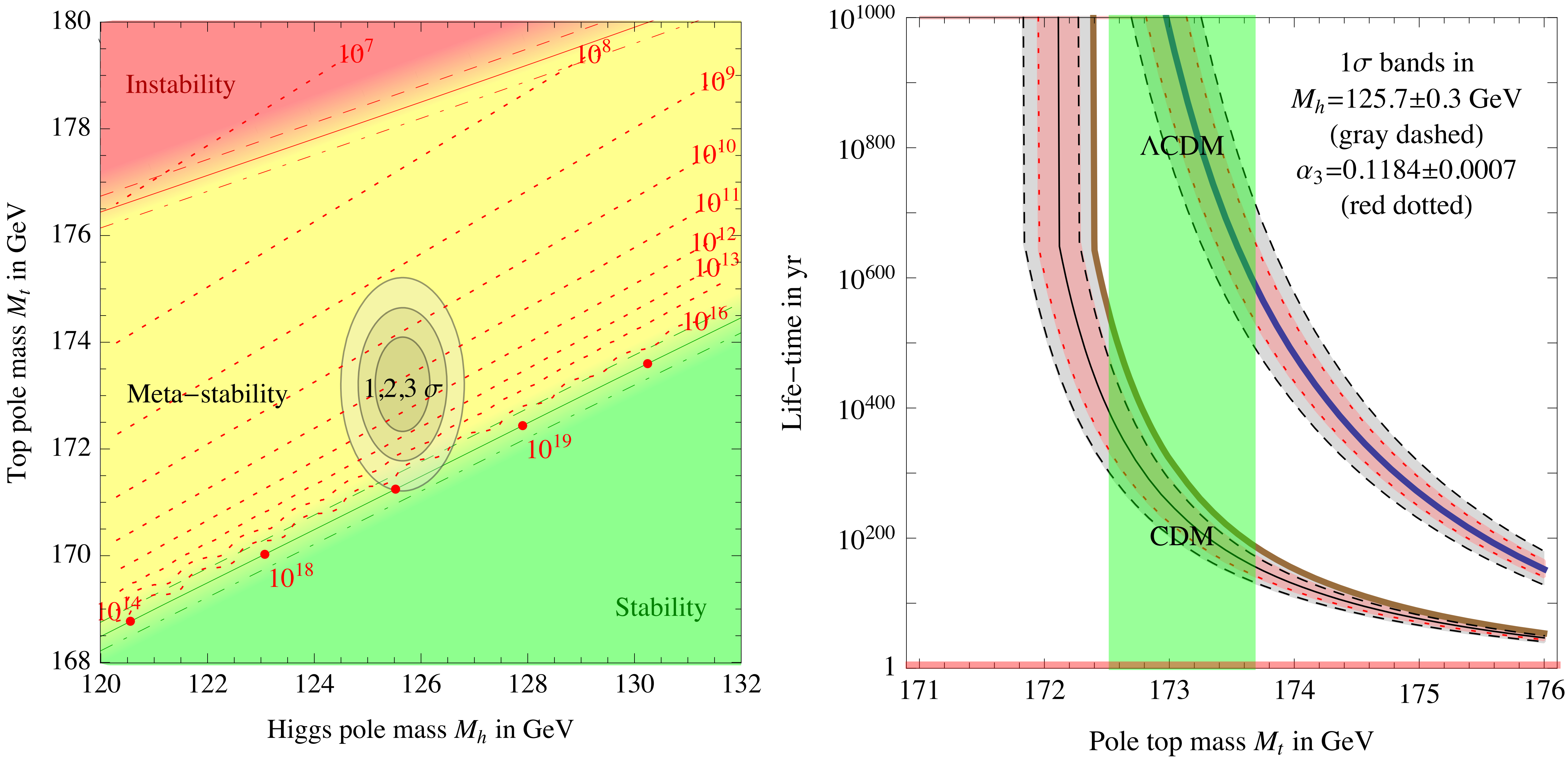
Vacuum metastability

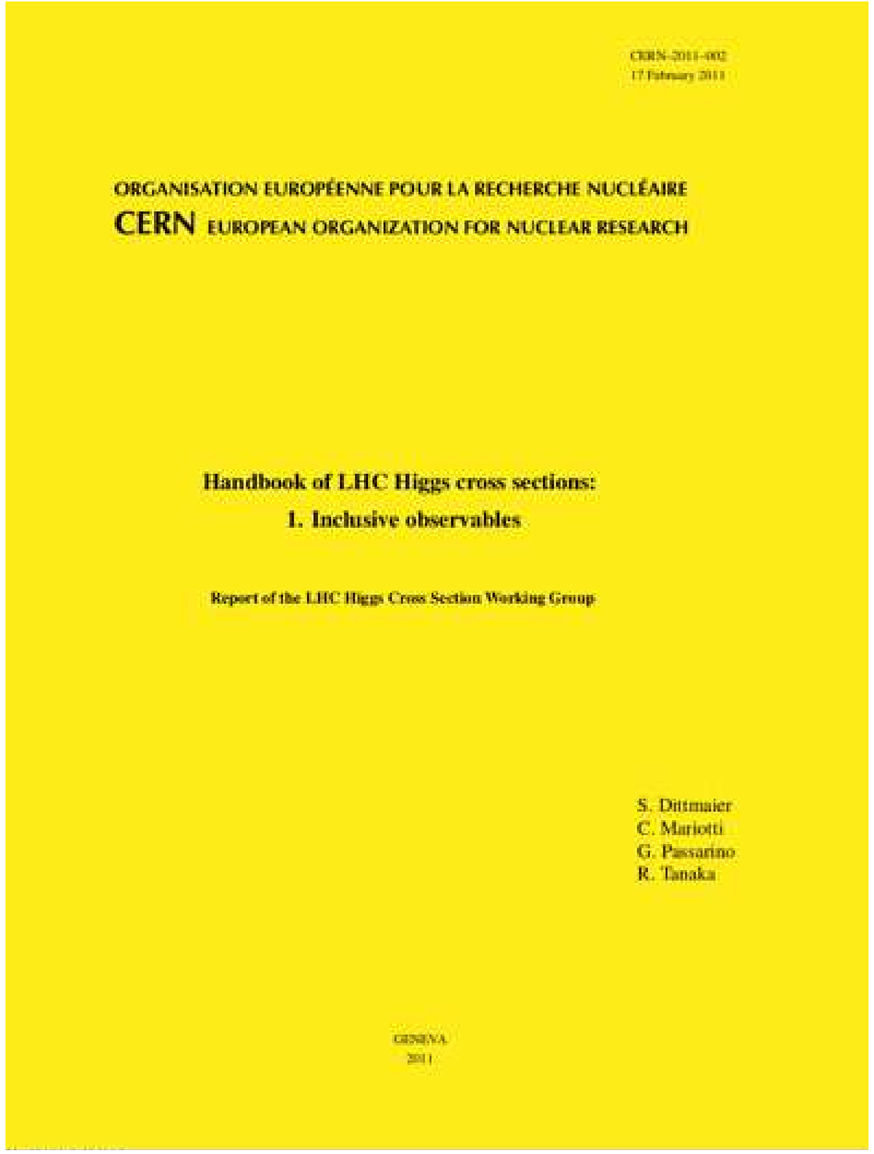
Buttazzo et al., 1307.3536



Nothing to worry about!

Implications for Higgs Decays

LHC Higgs Cross Section Working Group


CERN-2011-002
17 February 2011

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Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2011


CERN-2012-002
15 January 2012

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Handbook of LHC Higgs cross sections:
2. Differential Distributions

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
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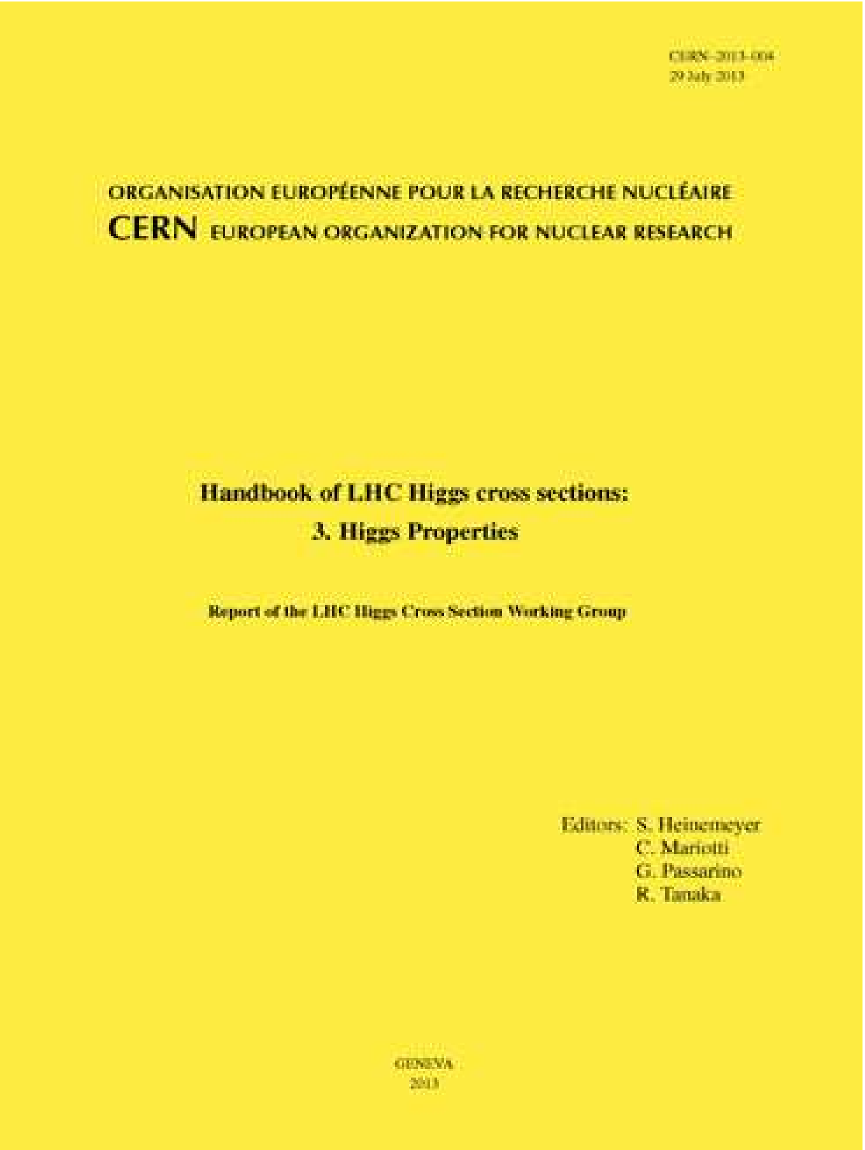
R. Tanaka

GENEVA
2012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Handbook of LHC Higgs cross sections:
3. Higgs Properties

Report of the LHC Higgs Cross Section Working Group

Editors: S. Heinemeyer
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2013

arXiv:1101.0593, 1201.3084, 1307.1347

Higgs decays

BR	Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
56.1%	$H \to bb$	122	2.30	−2.3% / +2.3%	+3.2% / −3.2%	+0.0% / −0.0%	+0.0% / −0.0%	+2.0% / −2.0%
		126	2.36	−2.3% / +2.3%	+3.3% / −3.2%	+0.0% / −0.0%	+0.0% / −0.0%	+2.0% / −2.0%
		130	2.42	−2.4% / +2.3%	+3.2% / −3.2%	+0.0% / −0.0%	+0.0% / −0.0%	+2.0% / −2.0%
6.2%	$H \to \tau^+\tau^-$	122	$2.51 \cdot 10^{-1}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.1%	+2.0% / −2.0%
		126	$2.59 \cdot 10^{-1}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.1%	+2.0% / −2.0%
		130	$2.67 \cdot 10^{-1}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.1%	+2.0% / −2.0%
0.02%	$H \to \mu^+\mu^-$	122	$8.71 \cdot 10^{-4}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.1%	+2.0% / −2.0%
		126	$8.99 \cdot 10^{-4}$	+0.0% / +0.0%	+0.0% / −0.0%	−0.1% / −0.0%	+0.0% / −0.1%	+2.0% / −2.0%
		130	$9.27 \cdot 10^{-4}$	+0.1% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.0%	+2.0% / −2.0%
2.8%	$H \to c\bar{c}$	122	$1.16 \cdot 10^{-1}$	−7.1% / +7.0%	−0.1% / −0.1%	+6.2% / −6.0%	+0.0% / −0.1%	+2.0% / −2.0%
		126	$1.19 \cdot 10^{-1}$	−7.1% / +7.0%	−0.1% / −0.1%	+6.2% / −6.1%	+0.0% / −0.1%	+2.0% / −2.0%
		130	$1.22 \cdot 10^{-1}$	−7.1% / +7.0%	−0.1% / −0.1%	+6.3% / −6.0%	+0.1% / −0.1%	+2.0% / −2.0%
8.5%	$H \to gg$	122	$3.25 \cdot 10^{-1}$	+4.2% / −4.1%	−0.1% / −0.1%	+0.0% / −0.0%	−0.2% / +0.2%	+3.0% / −3.0%
		126	$3.57 \cdot 10^{-1}$	+4.2% / −4.1%	−0.1% / −0.1%	+0.0% / −0.0%	−0.2% / +0.2%	+3.0% / −3.0%
		130	$3.91 \cdot 10^{-1}$	+4.2% / −4.1%	−0.1% / −0.2%	+0.0% / −0.0%	−0.2% / +0.2%	+3.0% / −3.0%
0.23%	$H \to \gamma\gamma$	122	$8.37 \cdot 10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+1.0% / −1.0%
		126	$9.59 \cdot 10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+1.0% / −1.0%
		130	$1.10 \cdot 10^{-2}$	+0.1% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+1.0% / −1.0%
0.16%	$H \to Z\gamma$	122	$4.74 \cdot 10^{-3}$	+0.0% / −0.1%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.1%	+5.0% / −5.0%
		126	$6.84 \cdot 10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.1%	+0.0% / −0.1%	+5.0% / −5.0%
		130	$9.55 \cdot 10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+5.0% / −5.0%
23.1%	$H \to WW$	122	$6.25 \cdot 10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
		126	$9.73 \cdot 10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
		130	1.49	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
2.9%	$H \to ZZ$	122	$7.30 \cdot 10^{-2}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
		126	$1.22 \cdot 10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
		130	$1.95 \cdot 10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%

$\Gamma_{tot}(126)$= 4.21 MeV

HXSWG v.3, 1307.1347

Theoretical uncertainty: from scale variation and missing higher orders (not uncertainty in m_H)

Parametric uncertainties from QCD coupling and quark masses

Higgs decays

HXSWG v.3, 1307.1347

BR	Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
56.1%	$H \to b\bar{b}$	122	2.30	−2.3% / +2.3%	+3.2% / −3.2%	+0.0% / −0.0%	+0.0% / −0.0%	+2.0% / −2.0%
		126	2.36	−2.3% / +2.3%	+3.3% / −3.2%	+0.0% / −0.0%	+0.0% / −0.0%	+2.0% / −2.0%
		130	2.42	−2.4% / +2.3%	+3.2% / −3.2%	+0.0% / −0.0%	+0.0% / −0.0%	+2.0% / −2.0%
6.2%	$H \to \tau^+\tau^-$	122	$2.51\cdot10^{-1}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.1%	+2.0% / −2.0%
		126	$2.59\cdot10^{-1}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.1%	+2.0% / −2.0%
		130	$2.67\cdot10^{-1}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.1%	+2.0% / −2.0%
0.02%	$H \to \mu^+\mu^-$	122	$8.71\cdot10^{-4}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.1%	+2.0% / −2.0%
		126	$8.99\cdot10^{-4}$	+0.0% / +0.0%	+0.0% / −0.0%	−0.1% / −0.0%	+0.0% / −0.1%	+2.0% / −2.0%
		130	$9.27\cdot10^{-4}$	+0.1% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.0%	+2.0% / −2.0%
2.8%	$H \to c\bar{c}$	122	$1.16\cdot10^{-1}$	−7.1% / +7.0%	−0.1% / −0.1%	+6.2% / −6.0%	+0.0% / −0.1%	+2.0% / −2.0%
		126	$1.19\cdot10^{-1}$	−7.1% / +7.0%	−0.1% / −0.1%	+6.2% / −6.1%	+0.0% / −0.1%	+2.0% / −2.0%
		130	$1.22\cdot10^{-1}$	−7.1% / +7.0%	−0.1% / −0.1%	+6.3% / −6.0%	+0.1% / −0.1%	+2.0% / −2.0%
8.5%	$H \to gg$	122	$3.25\cdot10^{-1}$	+4.2% / −4.1%	−0.1% / −0.1%	+0.0% / −0.0%	−0.2% / +0.2%	+3.0% / −3.0%
		126	$3.57\cdot10^{-1}$	+4.2% / −4.1%	−0.1% / −0.1%	+0.0% / −0.0%	−0.2% / +0.2%	+3.0% / −3.0%
		130	$3.91\cdot10^{-1}$	+4.2% / −4.1%	−0.1% / −0.2%	+0.0% / −0.0%	−0.2% / +0.2%	+3.0% / −3.0%
0.23%	$H \to \gamma\gamma$	122	$8.37\cdot10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+1.0% / −1.0%
		126	$9.59\cdot10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+1.0% / −1.0%
		130	$1.10\cdot10^{-2}$	+0.1% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+1.0% / −1.0%
0.16%	$H \to Z\gamma$	122	$4.74\cdot10^{-3}$	+0.0% / −0.1%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.1%	+5.0% / −5.0%
		126	$6.84\cdot10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.1%	+0.0% / −0.1%	+5.0% / −5.0%
		130	$9.55\cdot10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+5.0% / −5.0%
23.1%	$H \to WW$	122	$6.25\cdot10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
		126	$9.73\cdot10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
		130	1.49	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
2.9%	$H \to ZZ$	122	$7.30\cdot10^{-2}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
		126	$1.22\cdot10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
		130	$1.95\cdot10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%

Uncertainties > 2%
(mostly QCD)

Unknown EW HO

$\Gamma_{tot}(126)$= 4.21 MeV

Higgs decays

HXSWG v.3, 1307.1347

BR	Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
56.1%	$H \to bb$	122	2.30	−2.3% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
		126	2.36	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
		130	2.42	−2.4% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
6.2%	$H \to \tau^+\tau^-$	122	$2.51\cdot10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+2.0% −2.0%
		126	$2.59\cdot10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
		130	$2.67\cdot10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
0.02%	$H \to \mu^+\mu^-$	122	$8.71\cdot10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
		126	$8.99\cdot10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+2.0% −2.0%
		130	$9.27\cdot10^{-4}$	+0.1% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.0%	+2.0% −2.0%
2.8%	$H \to c\bar{c}$	122	$1.16\cdot10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.2% −6.0%	+0.0% −0.1%	+2.0% −2.0%
		126	$1.19\cdot10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.2% −6.1%	+0.0% −0.1%	+2.0% −2.0%
		130	$1.22\cdot10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.3% −6.0%	+0.1% −0.1%	+2.0% −2.0%
8.5%	$H \to gg$	122	$3.25\cdot10^{-1}$	+4.2% −4.1%	−0.1% −0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
		126	$3.57\cdot10^{-1}$	+4.2% −4.1%	−0.1% −0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
		130	$3.91\cdot10^{-1}$	+4.2% −4.1%	−0.1% −0.2%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
0.23%	$H \to \gamma\gamma$	122	$8.37\cdot10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
		126	$9.59\cdot10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
		130	$1.10\cdot10^{-2}$	+0.1% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
0.16%	$H \to Z\gamma$	122	$4.74\cdot10^{-3}$	+0.0% −0.1%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+5.0% −5.0%
		126	$6.84\cdot10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+0.0% −0.1%	+5.0% −5.0%
		130	$9.55\cdot10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+5.0% −5.0%
23.1%	$H \to WW$	122	$6.25\cdot10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
		126	$9.73\cdot10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
		130	1.49	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
2.9%	$H \to ZZ$	122	$7.30\cdot10^{-2}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
		126	$1.22\cdot10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
		130	$1.95\cdot10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%

$\Gamma_{tot}(126)$= 4.21 MeV

Uncertainties > 2% (mostly QCD)

Unknown EW HO

Strong mass dependence
δM_H=400 MeV => ~5%

Higgs → $q\bar{q}$

$$\Gamma(H \to q\bar{q}) = \frac{3\sqrt{2}}{8\pi} G_F M_H m_q^2(M_H) \left[1 - \frac{4m_q^2(M_H)}{M_H^2}\right]^{\frac{3}{2}} \left[1 + 1.803\,\alpha_s(M_H) + 2.953\,\alpha_s^2(M_H) + \ldots\right]$$

(known to 4th order)

- Running of masses is enormously important!

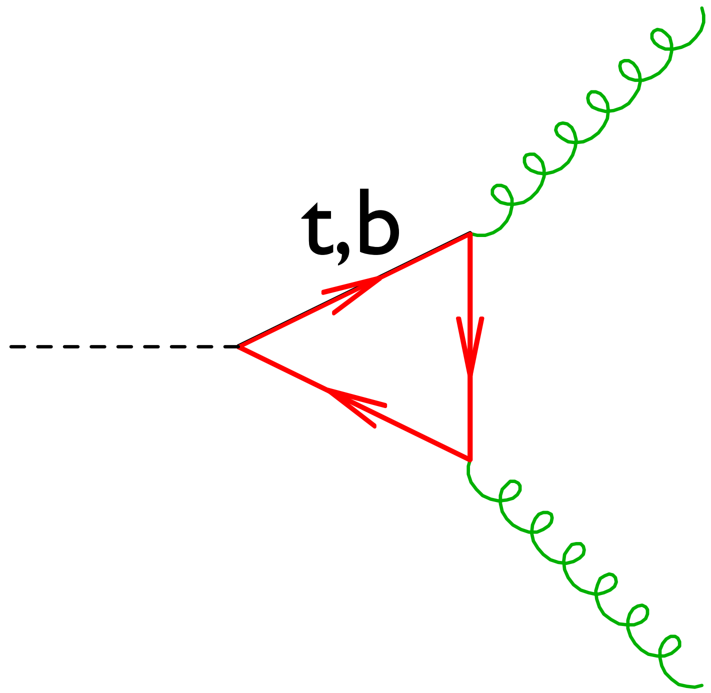
$m_b^2(M_H)/m_b^2(\text{pole}) = (2.77/4.95)^2 = 0.313$

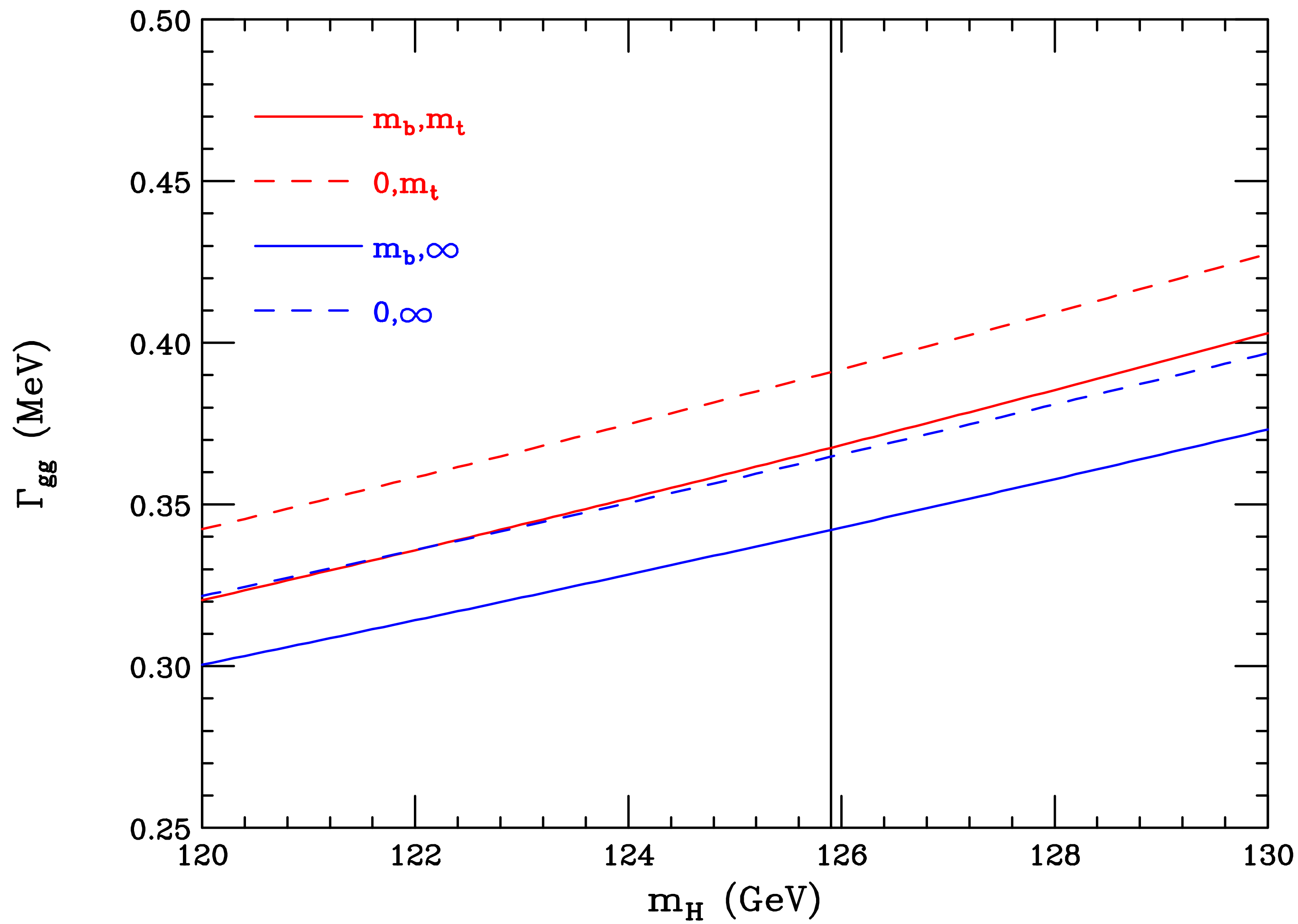
$m_c^2(M_H)/m_c^2(\text{pole}) = (0.612/1.27)^2 = 0.233$

- Γ_b affects all branching ratios!

$$\mathrm{BR(X)} = \frac{\Gamma_\mathrm{X}}{\Gamma_\mathrm{tot}} \quad \rightarrow \quad \frac{\delta\,\mathrm{BR(X)}}{\mathrm{BR(X)}} = \frac{\delta\,\Gamma_\mathrm{b}}{\Gamma_\mathrm{tot}} = 0.56\,\frac{\delta\,\Gamma_\mathrm{b}}{\Gamma_\mathrm{b}}$$

Higgs→gg

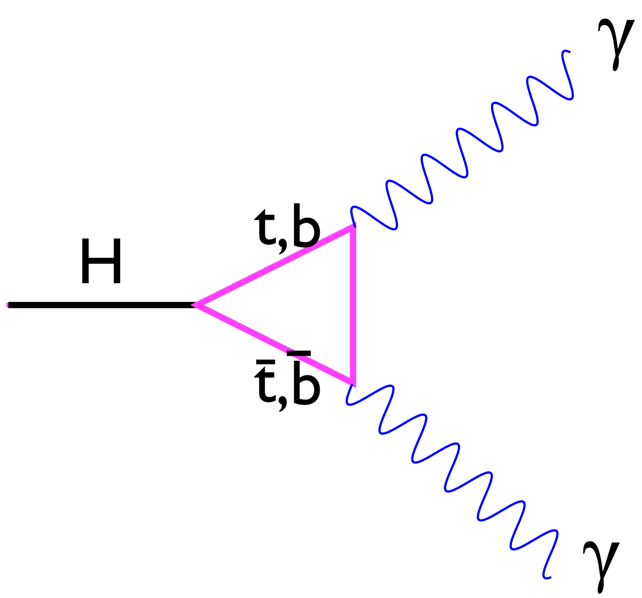


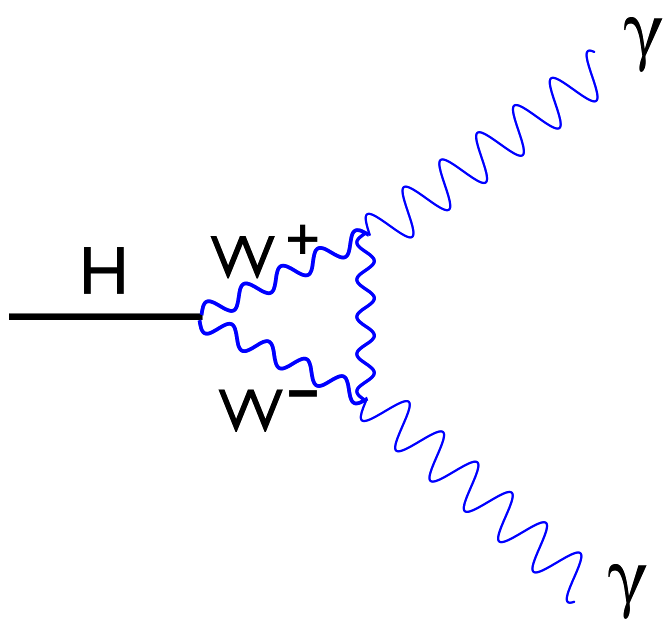


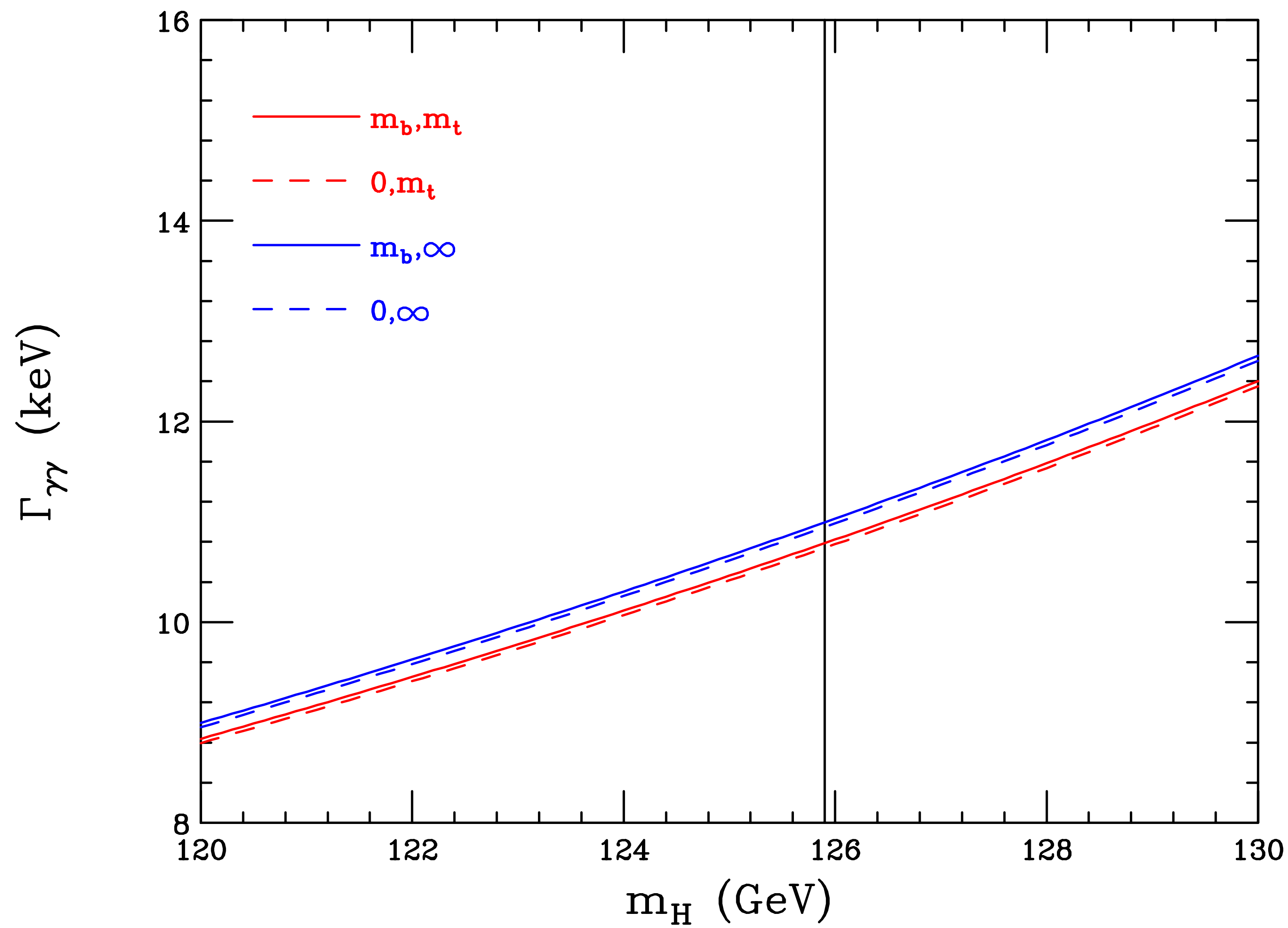
$$\Gamma_{gg} = \frac{\alpha_s^2 G_F M_H^3}{64\sqrt{2}\pi^3} \left| \sum_q I_q \left(\frac{m_q^2(M_H)}{M_H^2} \right) \right|^2 \left(1 + 6.14\,\alpha_s + 17.5\,\alpha_s^2 + 15.1\,\alpha_s^3 + \ldots\right)$$

- b contributes ~ -6%, which almost cancels top mass effect

Higgs→γγ







$$\Gamma_{\gamma\gamma} = \frac{\alpha^2 G_F M_H^3}{128\sqrt{2}\pi^3} \left| 3\sum_q e_q^2 I_q \left(\frac{m_q^2(M_H)}{M_H^2} \right) + I_W \left(\frac{M_W^2}{M_H^2} \right) \right|^2$$

- W loop dominates
- b contributes less, so top mass effect is significant (~-2%)

Higgs uncertainties: current

Almeida, Lee, Pokorski, Wells, 1311.6721v3

	Parametric uncertainties %		Scale dependence
	added linearly	in quadrature	
	$P_\Gamma^{\pm}$(par.add.)	$P_\Gamma^{\pm}$(par.quad.)	$(P_\Gamma^{+}, P_\Gamma^{-})(\mu)$
total	2.82 (1.79)	1.71 (1.07)	(0.08,0.10)
gg	2.52 (1.83)	1.74 (1.49)	(0.05,0.03)
$\gamma\gamma$	1.45 (0.42)	1.38 (0.35)	(1.31,0.60)
$b\bar{b}$	2.62 (2.43)	1.84 (1.82)	(0.29,0.01)
$c\bar{c}$	7.34 (7.15)	5.55 (5.54)	(0.45,0.35)
$\tau^+\tau^-$	0.36 (0.12)	0.32 (0.08)	(0.01,0.01)
WW^*	4.41 (1.17)	4.97 (1.25)	(0.25,0.31)
ZZ^*	4.90 (1.25)	4.42 (1.11)	(0.,0.)
$Z\gamma$	3.56 (0.92)	3.52 (0.88)	(0.56,0.23)
$\mu^+\mu^-$	0.34 (0.11)	0.32 (0.08)	(0.03,0.03)

~ THU ??

δM_H/MeV = 400(100) [ILC => 30]

Higgs uncertainties: prospects

Lepage, Mackenzie, Peskin, 1404.0319

	Parametric uncertainties %			$\delta_j = \delta\Gamma_j/2\Gamma_j$ %		
	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

$\mathrm{PT} = \mathcal{O}(\alpha_s^4)$ [current $= \mathcal{O}(\alpha_s^3)$]

LS $= 0.030$ fm [current $= 0.045$ fm]

$\mathrm{LS}^2 = 0.023$ fm [computing $\times$ 100]

ST = statistics $\times$ 100

Conclusions

Conclusions

- SM is in very good shape (within its limitations)
- Higgs partial widths currently predicted to 2%-5%
- Higgs mass uncertainty important for VV* modes (at LHC, not ILC)
- Predictions to 1%-2% look feasible, with big investments in perturbative and lattice QCD
- Is this good enough??

Thanks for listening!