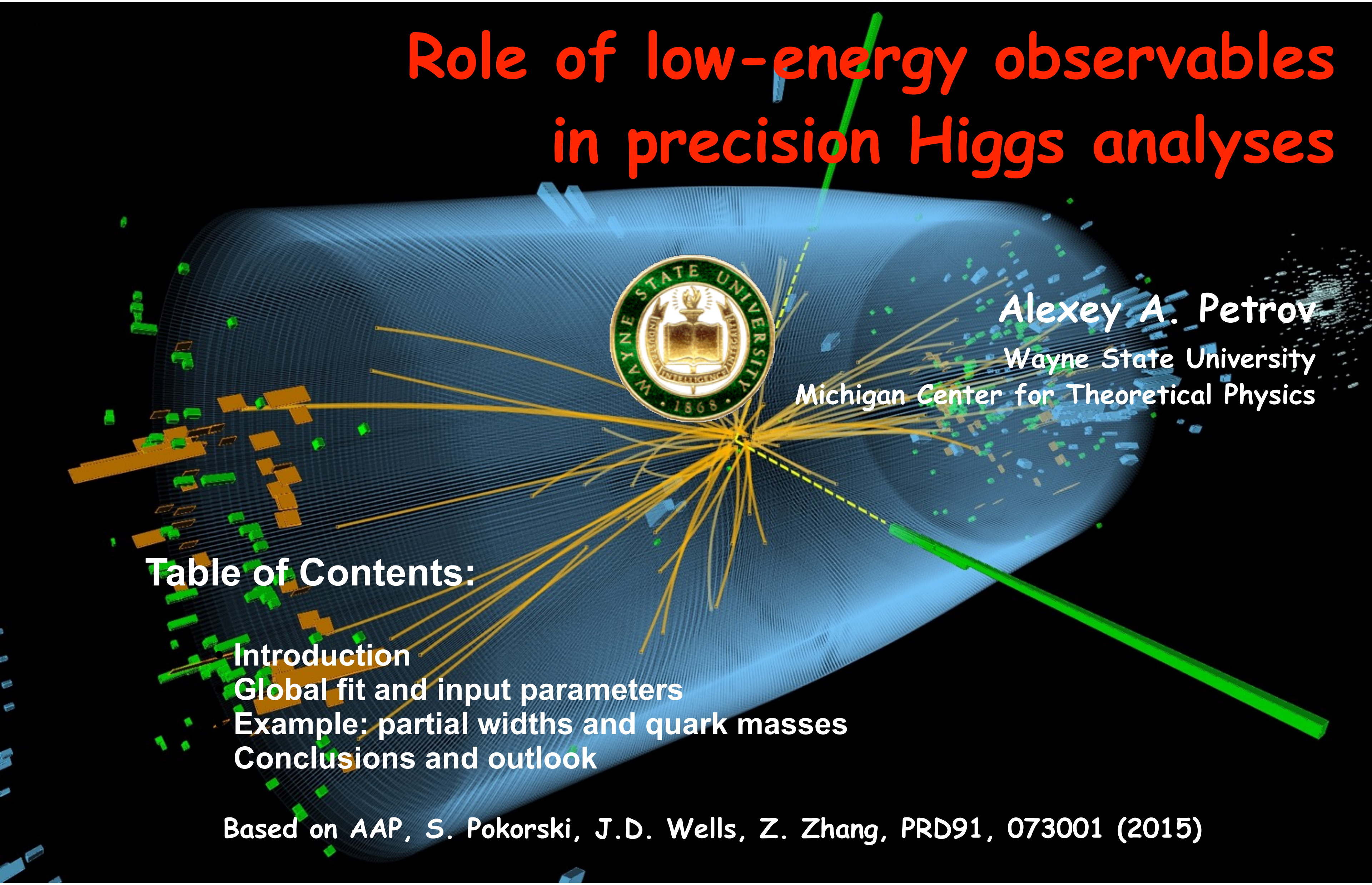

Role of low-energy observables in precision Higgs analyses

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Table of Contents:

Based on AAP, S. Pokorski, J.D. Wells, Z. Zhang, PRD91, 073001 (2015)

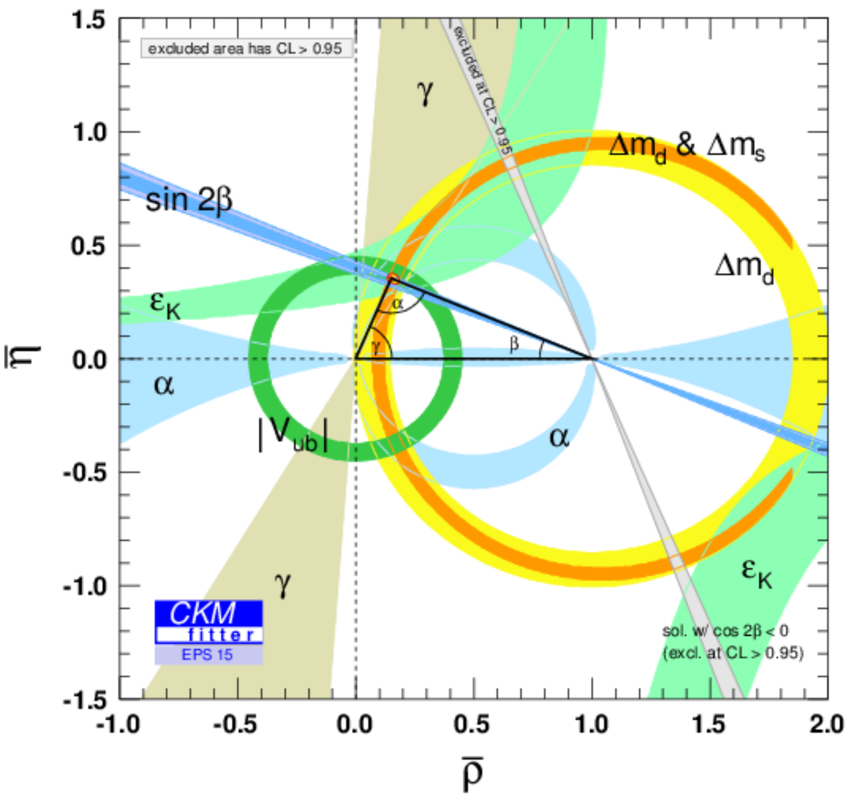
Introduction

★ Long-long time ago (31 July 2000 at ICHEP in Osaka)…

- first measurement of CP-violation in B-system: $\sin 2\beta = 0.34 \pm 0.20 \pm 0.05$

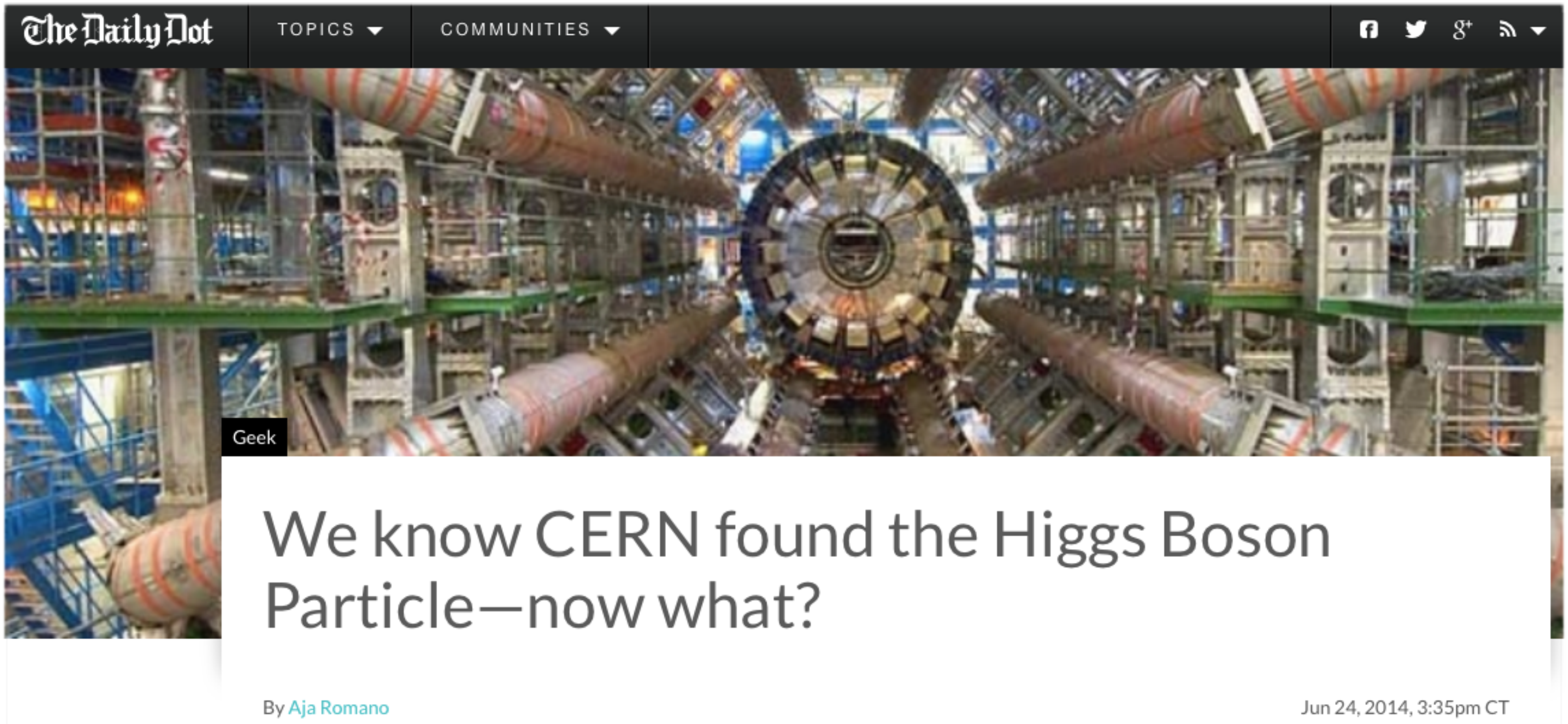
BaBar result

★ Indirect searches for New Physics via a combination of measurements



Observable	Central ± 1 σ
sin 2α	-0.036 [+0.042 -0.082]
sin 2α (meas. not in the fit)	-0.053 [+0.046 -0.146]
sin 2β	0.692 [+0.018 -0.019]
sin 2β (meas. not in the fit)	0.771 [+0.017 -0.041]

Global fit by the CKMfitter collaboration (updated January 2015)



The Daily Dot TOPICS COMMUNITIES

Geek

We know CERN found the Higgs Boson Particle—now what?

By Aja Romano

Jun 24, 2014, 3:35pm CT

Introduction: BSM Physics

★ Precision studies of the Higgs boson properties: BSM/NP discovery?

- flavor problem has NP solutions that affect Higgs partial rates

SM:

$$y_u Q_L \widetilde{H} u_R + h.c.$$

$$m_u = y_u \frac{v}{\sqrt{2}}$$ quark mass

$$\frac{y_u}{\sqrt{2}}$$ Higgs-fermion coupling

BSM:

$$\left(\frac{H^\dagger H}{\Lambda^2}\right)^n \overline{Q}_L \widetilde{H} u_R + h.c.$$

$$m_u \sim \frac{1}{\Lambda^2}\left(\frac{v}{\sqrt{2}}\right)^3$$ quark mass (top)

$$\sim \frac{3}{\Lambda^2}\left(\frac{v}{\sqrt{2}}\right)^2$$ Higgs-fermion coupling (top)

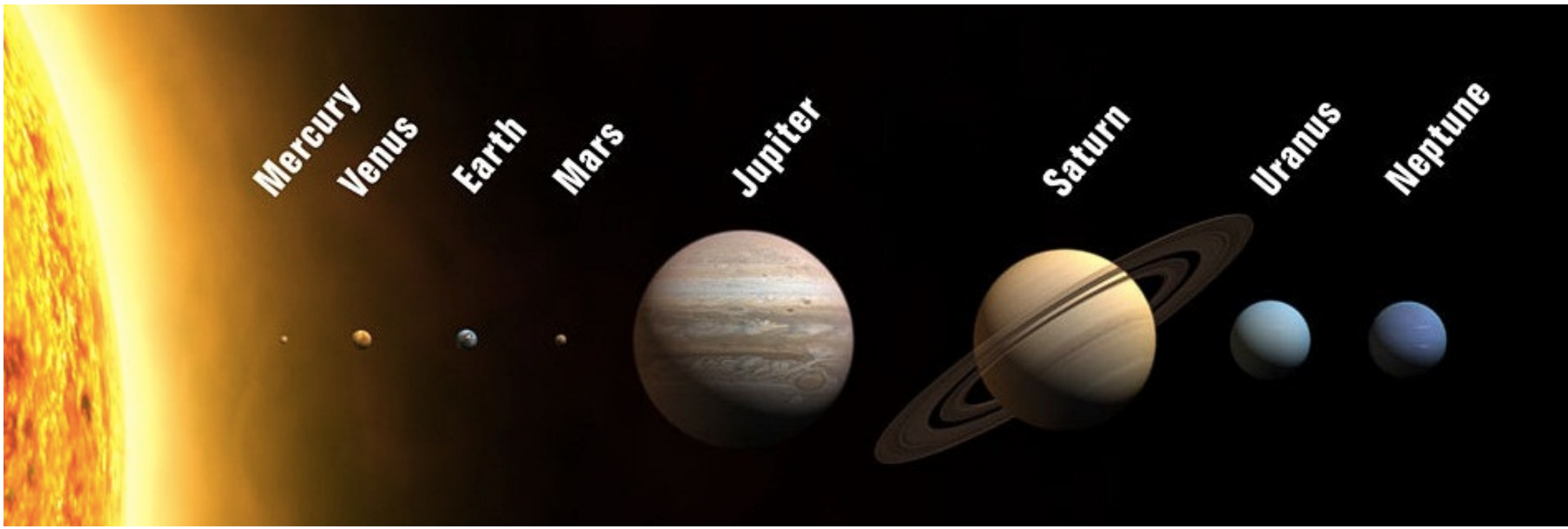
Guidice, Lebedev;
Bauer et al

BSM (2HDM):

$$\mathcal{L}_2 = -y_\psi \bar{\psi}_L \psi_R \phi_1 - y_\chi \bar{\chi}_L \chi_R \phi_2 + \text{h.c.} \longrightarrow \frac{m_\chi}{m_\psi} = \frac{y_\chi}{y_\psi}\frac{v_2}{v_1} = \frac{y_\chi}{y_\psi}\tan\beta \gg 1$$

Blechman, AAP, Yeghiyan, JHEP 1011 (2010) 075

Are there new phenomena behind flavor problem? Or not?



Why is $M_{Jupiter} \gg M_{Mercury}$?

Introduction: experiment

★ Precision studies of the Higgs boson properties: NP discovery?

- experiment: expect (sub)percent-level measurements

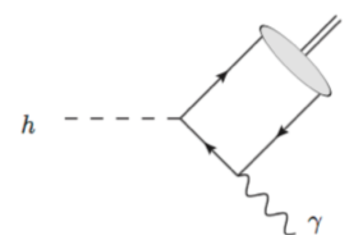
Table. 1.
List of the main observables and expected accuracy at FCC-ee and CEPC with 2 Million/1 Million Higgs boson respectively

	FCC-ee 240GeV	CEPC 250GeV
Higgs mass	-	5.4 MeV
$\sigma(ZH)$	0.4%	0.7%
$\sigma(ZH)\times Br(H\to bb)$	0.2%	0.4%
$\sigma(ZH)\times Br(H\to cc)$	1.2%	2.1%
$\sigma(ZH)\times Br(H\to gg)$	1.4%	1.8%
$\sigma(ZH)\times Br(H\to WW)$	0.9%	1.3%
$\sigma(ZH)\times Br(H\to ZZ)$	3.1%	5.1%
$\sigma(ZH)\times Br(H\to \tau\tau)$	0.7%	1.2%
$\sigma(ZH)\times Br(H\to \gamma\gamma)$	3.0%	8.0%
$\sigma(ZH)\times Br(H\to \mu\mu)$	13%	18%
$\sigma(\nu\nu H)\times Br(H\to bb)$	2.2%	3.8%

Ruan, 1411.5606

- far future: exclusive decays?

$$\mathcal{B}(h\to J/\psi\gamma) = (2.95\pm 0.17)\times 10^{-6}$$
$$\mathcal{B}(h\to \Upsilon(1S)\gamma) = (4.61^{+1.76}_{-1.23})\times 10^{-9}$$



- need to know the SM values very well

Kagan et al 1406.1722
Bodwin et al 1407.6695

Introduction

★ Precision studies of the Higgs boson properties: NP discovery?

- need to know the SM values very well ($a_s = \alpha_s(m_H)/\pi \sim 0.0336$)

$$\Gamma(H \to \bar{f} f) = \frac{G_F M_H}{4\sqrt{2}\pi} m_f^2 \tilde{R}(s = M_H^2),$$

$$\tilde{R} = 1 + 5.6668 a_s + 29.147 a_s^2 + 41.758 a_s^3 - 825.7 a_s^4$$

Baikov, Chetyrkin, Kuhn
PRL 96 012003 (2006)

★ Appreciable dependence upon input parameters, e.g. for $\Gamma_{H\to b\bar{b}}$

	LO	NLO	N^{2}LO	N^{3}LO	N^{4}LO	Total
Γ_i (KeV)	1924.28	391.74	72.38	3.73	-2.65	2389.48
$\Gamma_i/\Gamma_{\rm tot}$	80.53%	16.39%	3.03%	0.16%	-0.11%	

S.Q. Wang et al
arXiv:1308.6364 [hep-ph]

Introduction

★ Precision studies of the Higgs boson properties: NP discovery?

- need to know the SM values very well ($a_s = \alpha_s(m_H)/\pi \sim 0.0336$)

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$$\tilde{R} = 1 + 5.6668 a_s + 29.147 a_s^2 + 41.758 a_s^3 - 825.7 a_s^4$$

Baikov, Chetyrkin, Kuhn

★ SM results depend on several external input parameters

- quark masses are extracted from low energy data

$$m_c(m_c) = 1.275(25) \text{ GeV}, \quad m_b(m_b) = 4.18(3) \text{ GeV}$$

Lepage, Mackenzie, Peskin

  - lattice?
  - QCD Sum Rules? PDG?
- correlations among input parameters?
- inflation of systematic errors?

★ Maybe there is a better way to arrange the calculation?

the central value of m_c can differ by a much larger amount depending on which algorithm (all of which are formally equally good) is used to determine m_c from the data. This leads to a systematic error from perturbation theory of around 20 MeV for the c quark and 25 MeV for the b quark. Electromagnetic effects, which also are important at this precision, are often not included. For this reason, we inflate the errors on the continuum extractions of m_c and m_b. The average values of m_c and m_b from continuum determinations are (see Sec. G for the 1S scheme)

$$\overline{m}_c(\overline{m}_c) = (1.275 \pm 0.025)\,\mathrm{GeV}$$

$$\overline{m}_b(\overline{m}_b) = (4.18 \pm 0.03)\,\mathrm{GeV}\,, \quad m_b^{1\mathrm{S}} = (4.65 \pm 0.03)\,\mathrm{GeV}\,.$$

PDG (Quark Masses review)

Global fit

★ A powerful way to extract parameters is a global fit

- need to minimize the chi-square function

$$\chi^2 = \sum_{ij} \left[\hat{O}_i^{\rm th}(\{\mathcal{I}_k\}) - \hat{O}_i^{\rm expt} \right] V_{ij}^{-1} \left[\hat{O}_j^{\rm th}(\{\mathcal{I}_k\}) - \hat{O}_j^{\rm expt} \right]$$

- … which includes calculation inputs…

$$\{\mathcal{I}_k\} \equiv \{\hat{O}_k^{\rm in}\} \cup \{m_Q(m_Q)\} \cup \{p_k^{\rm other}\}$$

- … and fit observables

$$\{\hat{O}_i\} \equiv \{\hat{O}_i^{\rm in}\} \cup \{\hat{O}_i^{\rm high}\} \cup \{\hat{O}_i^{\rm low}\}$$

input observables: $\{\hat{O}_k^{\rm in}\} \equiv \{m_Z, G_F, \alpha(m_Z), m_t, \alpha_s(m_Z), m_H\}$

★ In what follows, let us concentrate on H → bb/cc partial widths

Eliminating quark masses

★ Let us understand theoretical uncertainties of input observables

- concentrate on quark masses from low-energy observables

$$\hat{O}_1^{\mathrm{low}} = \hat{O}_1^{\mathrm{low}}[\{\hat{O}_k^{\mathrm{in}}\}, \{m_Q(m_Q)\}],$$
$$\hat{O}_2^{\mathrm{low}} = \hat{O}_2^{\mathrm{low}}[\{\hat{O}_k^{\mathrm{in}}\}, \{m_Q(m_Q)\}],$$

- … which can be solved for quark masses

$$m_c(m_c) = m_c(m_c)[\{\hat{O}_k^{\mathrm{in}}\}, \hat{O}_1^{\mathrm{low}}, \hat{O}_2^{\mathrm{low}}],$$
$$m_b(m_b) = m_b(m_b)[\{\hat{O}_k^{\mathrm{in}}\}, \hat{O}_1^{\mathrm{low}}, \hat{O}_2^{\mathrm{low}}].$$

- … which can be then eliminated from the Higgs observables

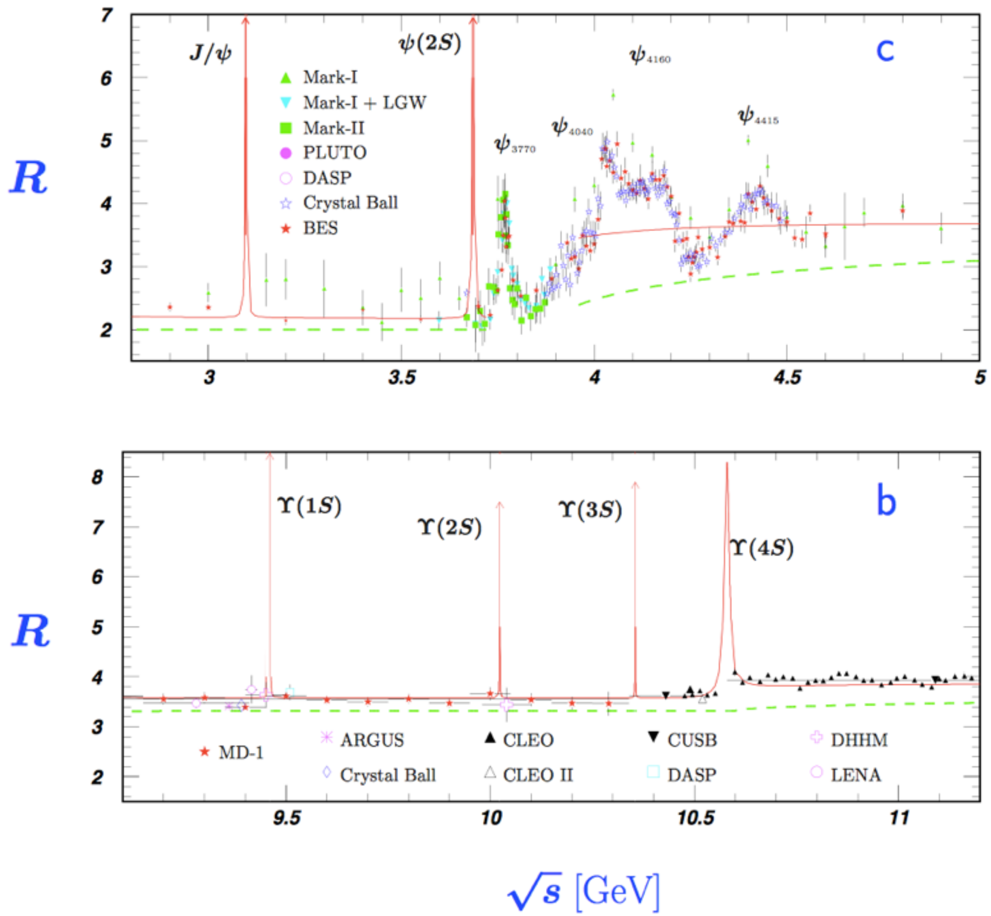
$$\hat{O}_i^{\mathrm{high}} = \hat{O}_i^{\mathrm{high}}[\{\hat{O}_k^{\mathrm{in}}\}, \{m_Q(m_Q)\}] = \hat{O}_i^{\mathrm{high}}[\{\hat{O}_k^{\mathrm{in}}\}, \hat{O}_1^{\mathrm{low}}, \hat{O}_2^{\mathrm{low}}]$$

★ We choose to deal with $\hat{O}_1^{\mathrm{low}}, \hat{O}_2^{\mathrm{low}} = \mathcal{M}_1^c, \mathcal{M}_2^b$

Eliminating quark masses

★ Find low-energy observables that are sensitive to quark masses

- (moments of) semileptonic b/c decay rates, QQ production rates, etc.



$$\mathcal{M}_n^Q \equiv \int \frac{\mathrm{d}s}{s^{n+1}} R_Q(s),$$

where

$$R_Q \equiv \frac{\sigma(e^+e^- \to Q\bar{Q}X)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

We shall use: $\mathcal{M}_1^c$ and $\mathcal{M}_2^b$

Quark masses and moments of R(s)

★ Moments of R(s) can be obtained from experimental data

$$\mathcal{M}_n^Q \equiv \int \frac{\mathrm{d}s}{s^{n+1}} R_Q(s),$$

– where, e.g. in the narrow width approximation (NWA),

$$\begin{aligned} R(t) &\equiv 4\pi \,\mathrm{Im}\, \Pi(t+i\epsilon) \\ &= \pi \frac{N}{Q_c^2\alpha^2} \sum_{J/\psi} M_\psi \Gamma_{\psi\to e^+e^-} \delta\left(t - M_\psi^2\right) \end{aligned}$$

with $$(q^2 g_{\mu\nu} - q_\mu q_\nu)\Pi_Q(q^2) = -i \int \mathrm{d}^4x e^{iq\cdot x} \langle 0|T j_\mu(x) j_\nu^\dagger(0)|0\rangle$$

★ At the moment need to use a combination of NWA, data, and pQCD results

★ What does it have to do with the quark masses?

Quark masses and moments of R(s)

★ Assuming (global) quark-hadron duality, can calculate moments in QCD

- moments are related to derivatives of the correlation function

$$\mathcal{M}_n^Q = \frac{12\pi^2}{n!}\left(\frac{\mathrm{d}}{\mathrm{d}q^2}\right)^n \Pi_Q(q^2)|_{q^2=0}$$

- use operator-product expansion of the correlation function

$$(q^2 g_{\mu\nu} - q_\mu q_\nu)\Pi_Q(q^2) = -i\int \mathrm{d}^4x e^{iq\cdot x}\langle 0|T j_\mu(x) j_\nu^\dagger(0)|0\rangle$$

- … to get the "QCD expression" for the moments

$$\mathcal{M}_n^Q = \frac{(Q_Q/(2/3))^2}{(2m_Q(\mu))^{2n}}\sum_{i,j}\bar{C}_{n,i}^{(j)}(n_f)\left(\frac{\alpha_s(\mu)}{\pi}\right)^i \ln^j\frac{m_Q(\mu)^2}{\mu^2} + \mathcal{M}_n^{Q,\mathrm{np}},$$

★ Scales at which m_Q and α_s are renormalized should be considered independently to avoid bias in the uncertainty estimate

Dehnadi, Hoang, Mateu, Zebarjad, 1102.2264

Quark masses and moments of R(s)

★ Assuming (global) quark-hadron duality, can calculate moments in QCD

- moments are related to derivatives of the correlation function

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- … to get the "QCD expression" for the moments

$$\mathcal{M}_n^Q = \frac{(Q_Q/(2/3))^2}{(2m_Q(\mu_m))^{2n}}\sum_{i,a,b} C_{n,i}^{(a,b)}(n_f)\left(\frac{\alpha_s(\mu_\alpha)}{\pi}\right)^i \times \ln^a \frac{m_Q(\mu_m)^2}{\mu_m^2}\ln^b\frac{m_Q(\mu_m)^2}{\mu_\alpha^2} + \mathcal{M}_n^{Q,\mathrm{np}}.$$

★ Calculated moments exhibit dependence on scales μ_m and μ_α

- thus, Higgs observables will be sensitive to them as well

Non-perturbative corrections

★ Sensitivity of moments to non-perturbative parameters?

- depends on what moment we are dealing with

$$\mathcal{M}_n^Q = \frac{12\pi^2}{n!}\left(\frac{\mathrm{d}}{\mathrm{d}q^2}\right)^n \Pi_Q(q^2)|_{q^2=0}$$

- … but for low-order moments dependence is not large

$$\mathcal{M}_1^{c,\mathrm{np}} = \frac{\langle\frac{\alpha_s}{\pi}G^2\rangle}{(2m_c^{\mathrm{pole}})^6}\left[-16.042 - 168.07\,\frac{\alpha_s(\mu)}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$

For $\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle = 0.006 \pm 0.012\ \mathrm{GeV}^4$

get $\mathcal{M}_1^{c,\mathrm{np}} = -0.0001^{+0.0006}_{-0.0014}\ \mathrm{GeV}^{-2}$

★ For b-quark the dependence is negligible, for c-quark it is sub-percent

Eliminating quark masses

★ Let us understand theoretical uncertainties of input observables

- concentrate on quark masses from low-energy observables

$$\mathcal{M}_1^c = \mathcal{M}_1^c[\alpha_s(m_Z), m_c(m_c), \mu_m^c, \mu_\alpha^c, \mathcal{M}_1^{c,\text{np}}]$$

$$\mathcal{M}_2^b = \mathcal{M}_2^b[\alpha_s(m_Z), m_b(m_b), \mu_m^b, \mu_\alpha^b],$$

- … which can be solved for quark masses

$$m_c(m_c) = m_c(m_c)[\alpha_s(m_Z), \mathcal{M}_1^c, \mu_m^c, \mu_\alpha^c, \mathcal{M}_1^{c,\text{np}}],$$

$$m_b(m_b) = m_b(m_b)[\alpha_s(m_Z), \mathcal{M}_2^b, \mu_m^b, \mu_\alpha^b],$$

- … which can be then eliminated from the Higgs partial widths in favor of direct observables (moments in our case)

$$\begin{aligned}\Gamma_{H\to b\bar{b}} &= \Gamma_{H\to b\bar{b}}[\{\hat{O}_k^{\text{in}}\}, m_b(m_b), \mu_H^b] \\ &= \Gamma_{H\to b\bar{b}}[\{\hat{O}_k^{\text{in}}\}, \mathcal{M}_2^b, \mu_m^b, \mu_\alpha^b, \mu_H^b],\end{aligned}$$

$$\begin{aligned}\Gamma_{H\to c\bar{c}} &= \Gamma_{H\to c\bar{c}}[\{\hat{O}_k^{\text{in}}\}, m_c(m_c), \mu_H^c] \\ &= \Gamma_{H\to c\bar{c}}[\{\hat{O}_k^{\text{in}}\}, \mathcal{M}_1^c, \mu_m^c, \mu_\alpha^c, \mu_H^c, \mathcal{M}_1^{c,\text{np}}],\end{aligned}$$

Numerics: input parameters

★ Now let us see what we can get out of this numerically

$$\mathcal{M}_1^c = 0.2121(20)(30)\ \text{GeV}^{-2}\ [17],$$

$$\mathcal{M}_2^b = 2.819(27) \times 10^{-5}\ \text{GeV}^{-4}\ [45],$$

$$\alpha_s(m_Z) = 0.1185(6)\ [14],$$

$$m_H = 125.7(4)\ \text{GeV}\ [14],$$

$$m_t = 173.21(51)(71)\ \text{GeV}\ [14],$$

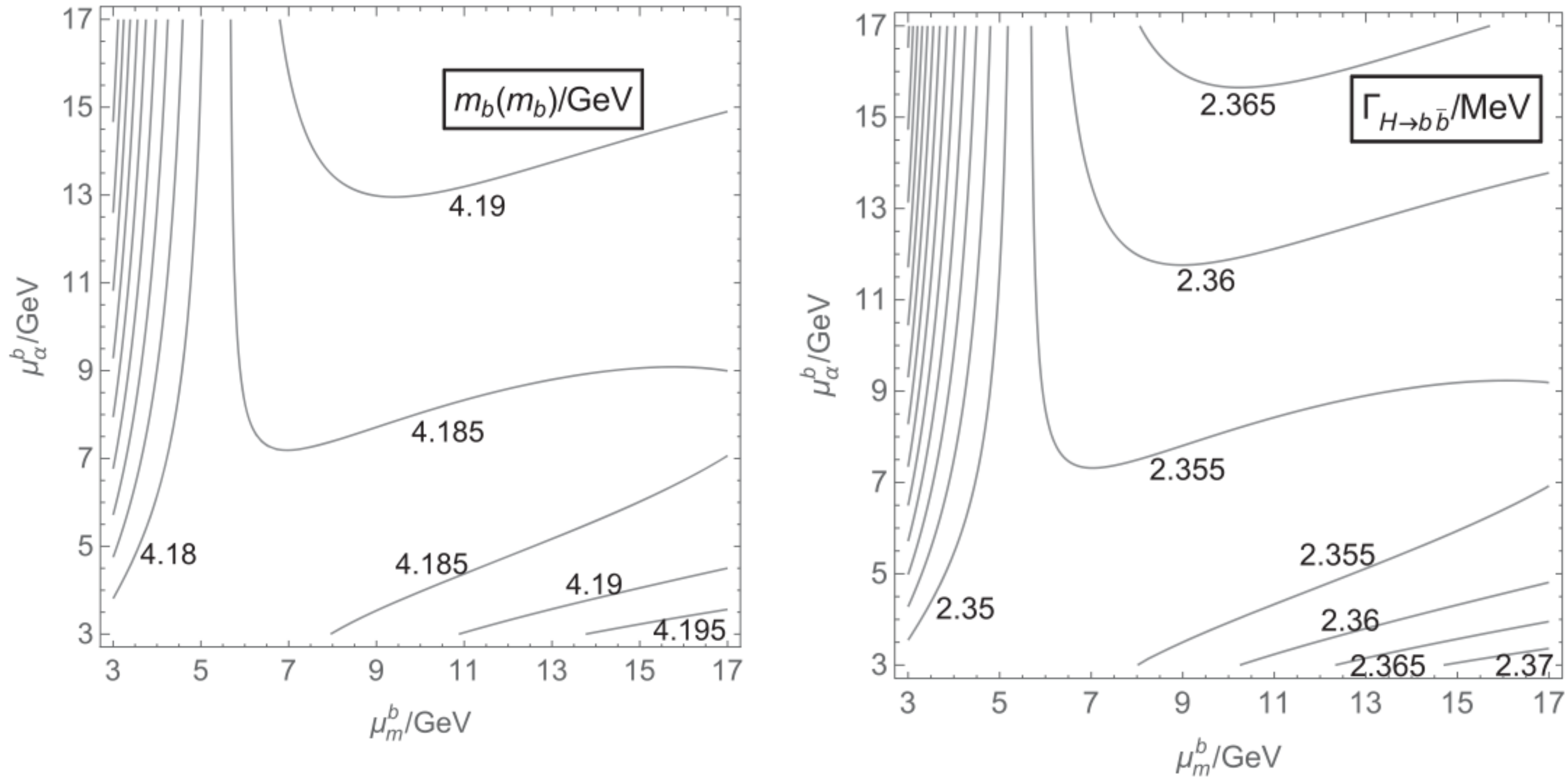
$$m_Z = 91.1876(21)\ \text{GeV}\ [14],$$

$$\alpha(m_Z) = 1/127.940(14)\ [14],$$

$$G_F = 1.1663787(6) \times 10^{-5}\ \text{GeV}^{-2}\ [14].$$

Parametric dependence

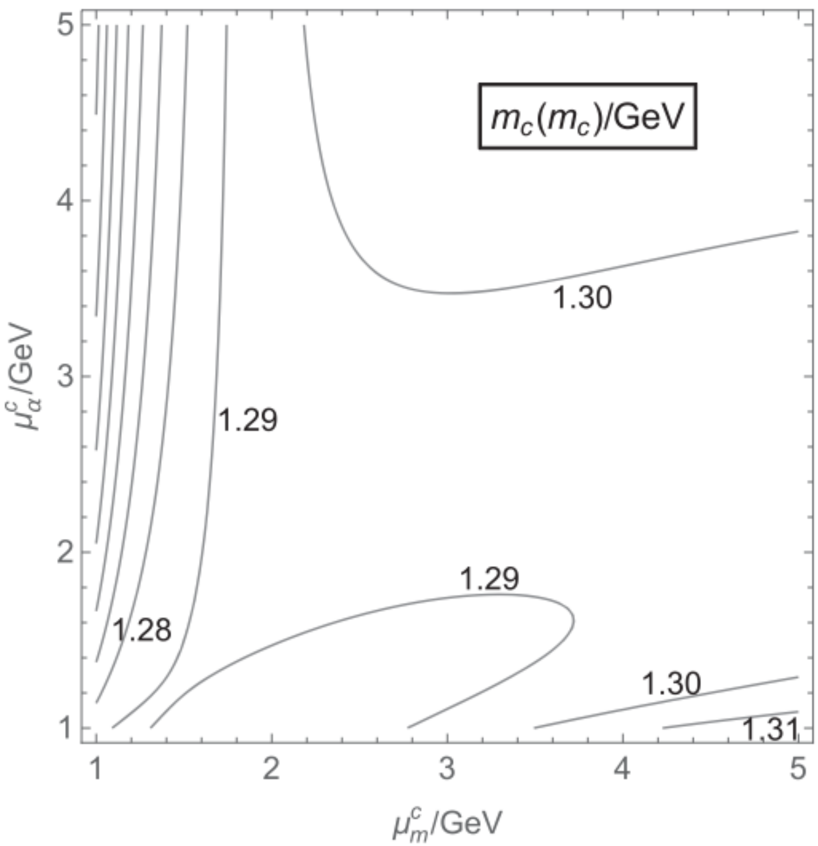
PRD91, 073001 (2015)

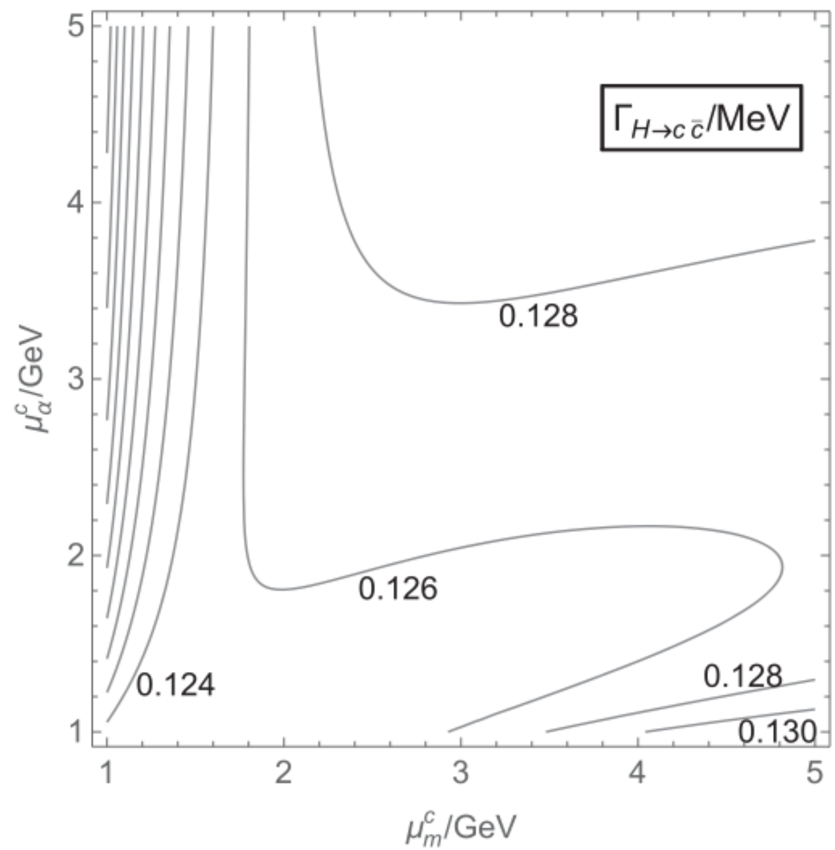


$$\Gamma_{H\to b\bar{b}} = \Gamma_{H\to b\bar{b}}[\{\hat{O}_k^{\rm in}\}, m_b(m_b), \mu_H^b]$$
$$= \Gamma_{H\to b\bar{b}}[\{\hat{O}_k^{\rm in}\}, \mathcal{M}_2^b, \mu_m^b, \mu_\alpha^b, \mu_H^b],$$

Parametric dependence

PRD91, 073001 (2015)





$$
\begin{aligned}
\Gamma_{H\to c\bar{c}} &= \Gamma_{H\to c\bar{c}}[\{\hat{O}_k^{\rm in}\}, m_c(m_c), \mu_H^c] \\
&= \Gamma_{H\to c\bar{c}}[\{\hat{O}_k^{\rm in}\}, \mathcal{M}_1^c, \mu_m^c, \mu_\alpha^c, \mu_H^c, \mathcal{M}_1^{c,\rm np}],
\end{aligned}
$$

Parametric dependence

★ How to deal with low-energy scale uncertainties?

- vary scales, BLM/principle of maximum conformality, convergence test, etc?

PRD91, 073001 (2015)

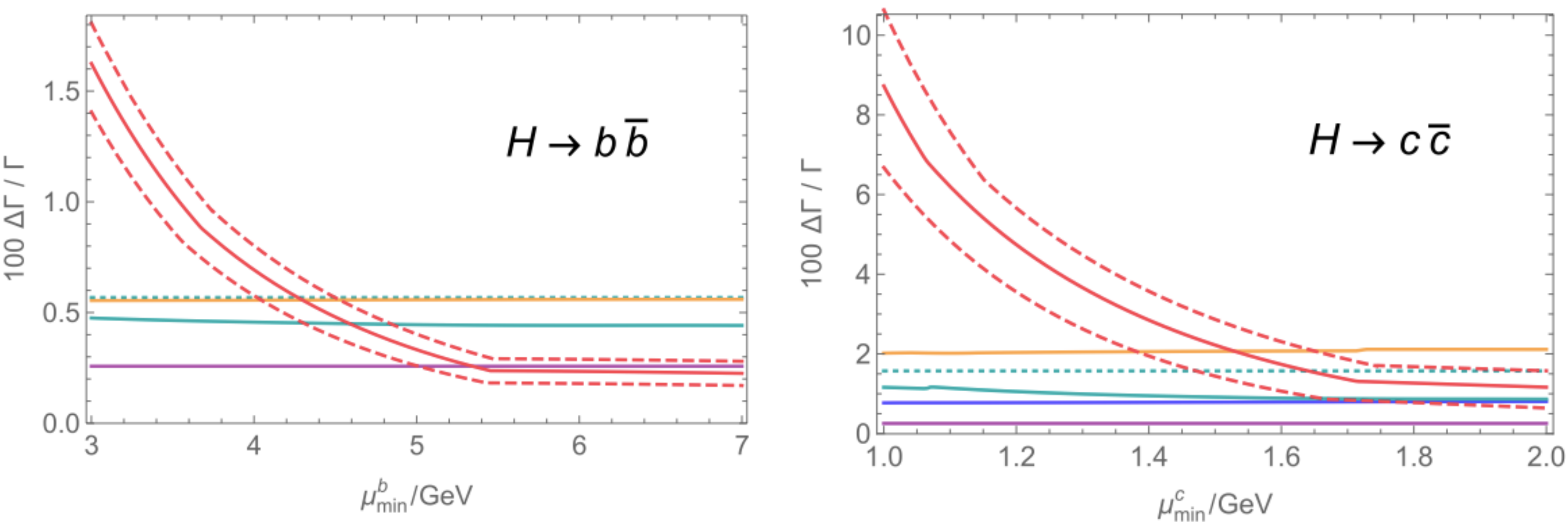


FIG. 2 (color online). Percent relative uncertainties in $\Gamma_{H\to c\bar{c}}$ (left) and $\Gamma_{H\to b\bar{b}}$ (right) as functions of $\mu_{\rm min}$ from various sources: perturbative uncertainty with $\mu^c_{\rm max} = 4$ GeV, $\mu^b_{\rm max} = 15$ GeV (red solid) or alternatively $\mu^c_{\rm max} = 3, 5$ GeV, $\mu^b_{\rm max} = 13, 17$ GeV (red dashed), parametric uncertainties from $\mathcal{M}^c_1$ or $\mathcal{M}^b_2$ (orange), $\alpha_s(m_Z)$ (cyan solid), $\mathcal{M}^{c,\rm np}_1$ (blue, for $\Gamma_{H\to c\bar{c}}$ only), and m_H (purple). The parametric uncertainty from $\alpha_s(m_Z)$ incorrectly calculated assuming no correlation with m_Q (cyan dotted) is also shown for comparison.

Conclusions

- We are entering the era of precision Higgs studies
  - Higgs as part of the Intensity Frontier?
    - observation of discrepancies in Higgs observables from New Physics
    - understanding of uncertainties of low-energy inputs
- Global fits to Higgs/LE observables to avoid using “processed numbers"
  - study Higgs partial widths with direct inputs from low energy
    - issues in proper selection of renormalization scale
    - …which result in uncertainties of partial widths

$$\frac{\Delta\Gamma_{H\to c\bar{c}}}{\Gamma_{H\to c\bar{c}}} \simeq \frac{\Delta m_c(m_c)}{10\text{ MeV}} \times 2.1\%,$$

$$\frac{\Delta\Gamma_{H\to b\bar{b}}}{\Gamma_{H\to b\bar{b}}} \simeq \frac{\Delta m_b(m_b)}{10\text{ MeV}} \times 0.56\%.$$

- New data from Belle-II on R(s) is welcome - reduce uncertainty
- More data from ATLAS/CMS then Fcc-ee/CEPC on Higgs partial widths

- Maybe Higgs will show us the first glimpses of New Physics…
- …but then again, maybe not.

Thank you for your attention!

JOURNAL OF APPLIED BEHAVIOR ANALYSIS 1974, 7, 497 NUMBER 3 (FALL 1974)

THE UNSUCCESSFUL SELF-TREATMENT OF A CASE OF "WRITER'S BLOCK"[1]

DENNIS UPPER

VETERANS ADMINISTRATION HOSPITAL, BROCKTON, MASSACHUSETTS

REFERENCES

[1]Portions of this paper were not presented at the 81st Annual American Psychological Association Convention, Montreal, Canada, August 30, 1973. Reprints may be obtained from Dennis Upper, Behavior Therapy Unit, Veterans Administration Hospital, Brockton, Massachusetts 02401.

Received 25 October 1973.
(*Published without revision.*)

Hopefully, I did better than him...

"Uncertainties from m_Q" are decomposed into concrete sources.

Uncertainty source	$\Delta\Gamma_{H\to c\bar{c}}/\Gamma_{H\to c\bar{c}}$	$\Delta\Gamma_{H\to b\bar{b}}/\Gamma_{H\to b\bar{b}}$
$\mathcal{M}_n^Q$ measurement†	2%	0.6%
$\mathcal{M}_n^Q$ calculation	see next 3 slides	
α_s (vs. no correlation)	1% (1.6%)	0.5% (0.6%)
$\mathcal{M}_n^{Q,\mathrm{np}}$	<0.8%	$\to$0
m_H	<0.3%	<0.3%