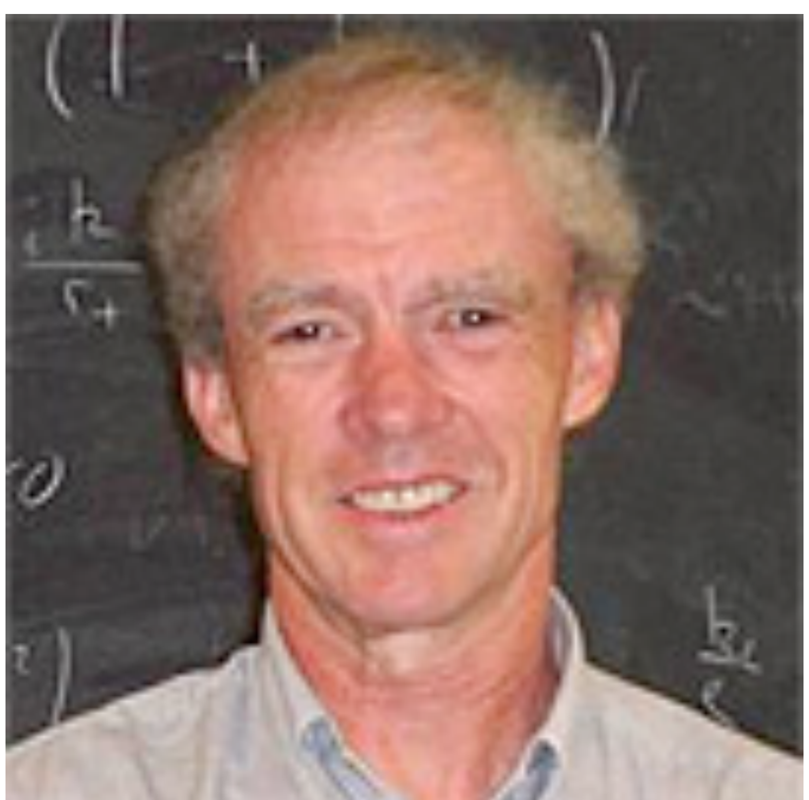
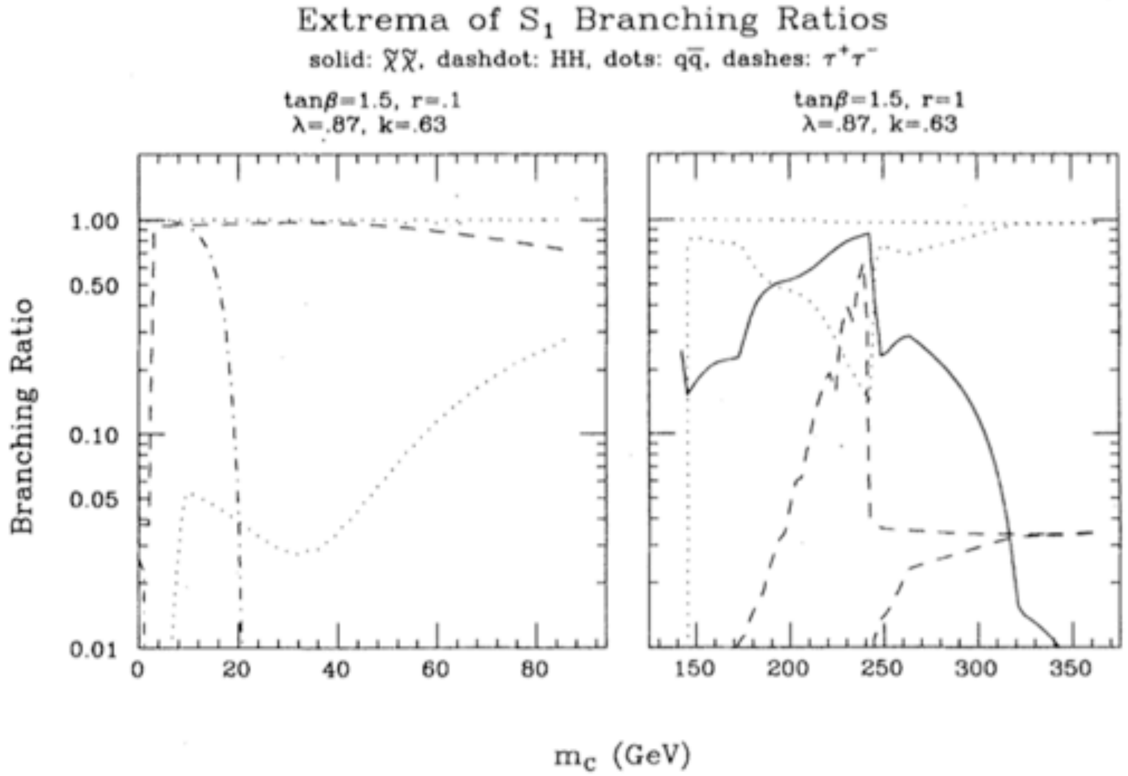
Toward a Precision Standard Model Theory of the Higgs Boson Couplings



M. E. Peskin
Gunion-fest
March 2014

describing work with
P. Lepage, P. Mackenzie



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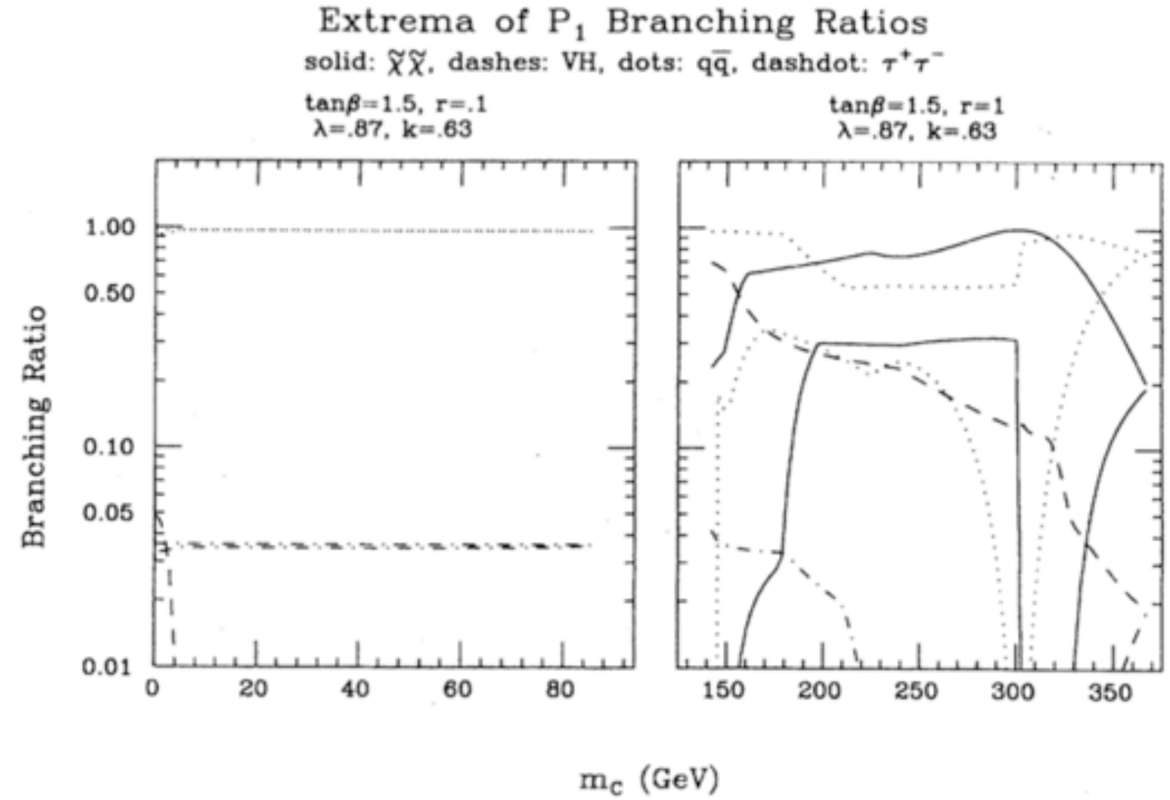

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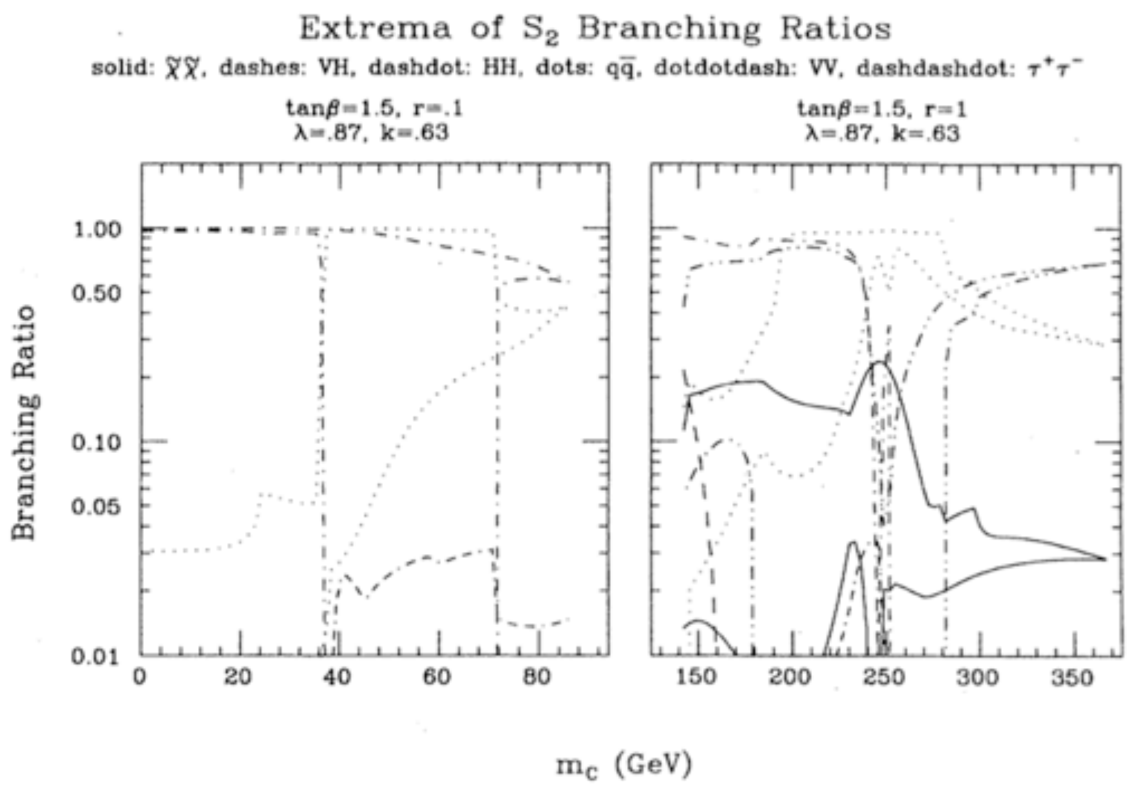

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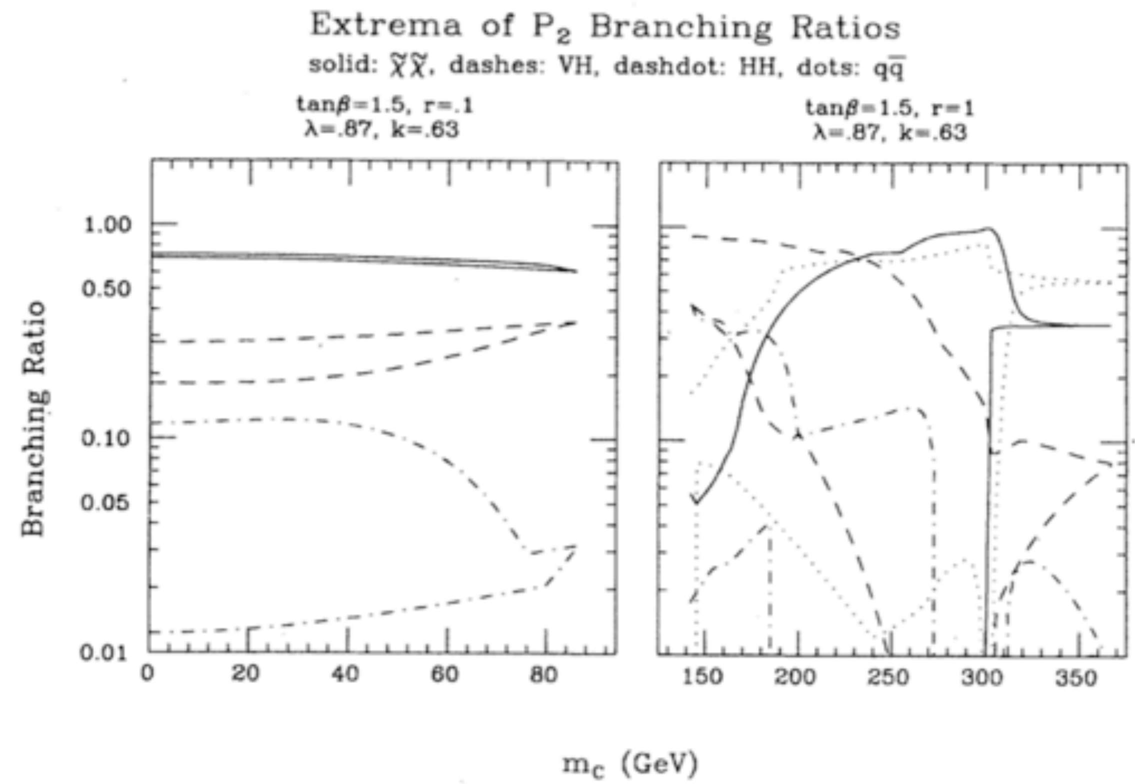
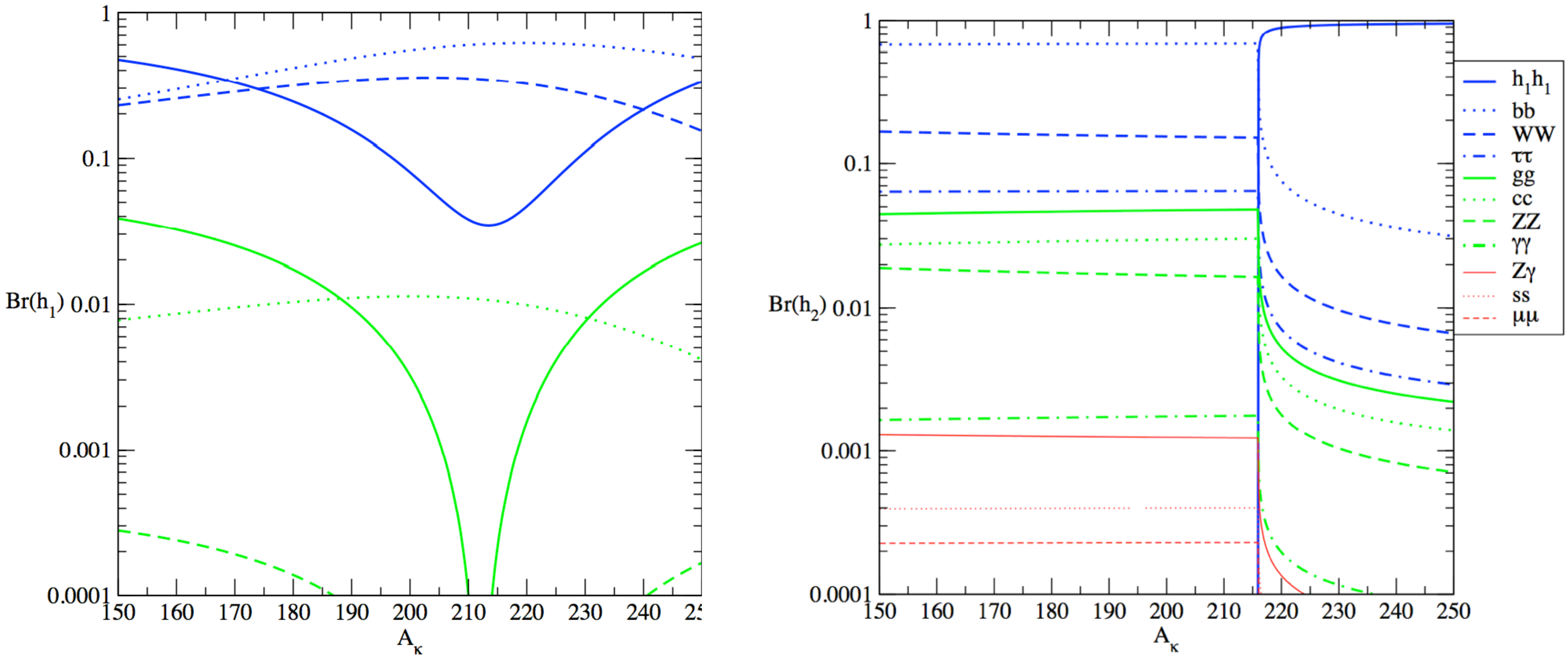


(e)

Ellis, Gunion, Haber, Roszkowski, Zwirner, PR D 39, 844 (1989)



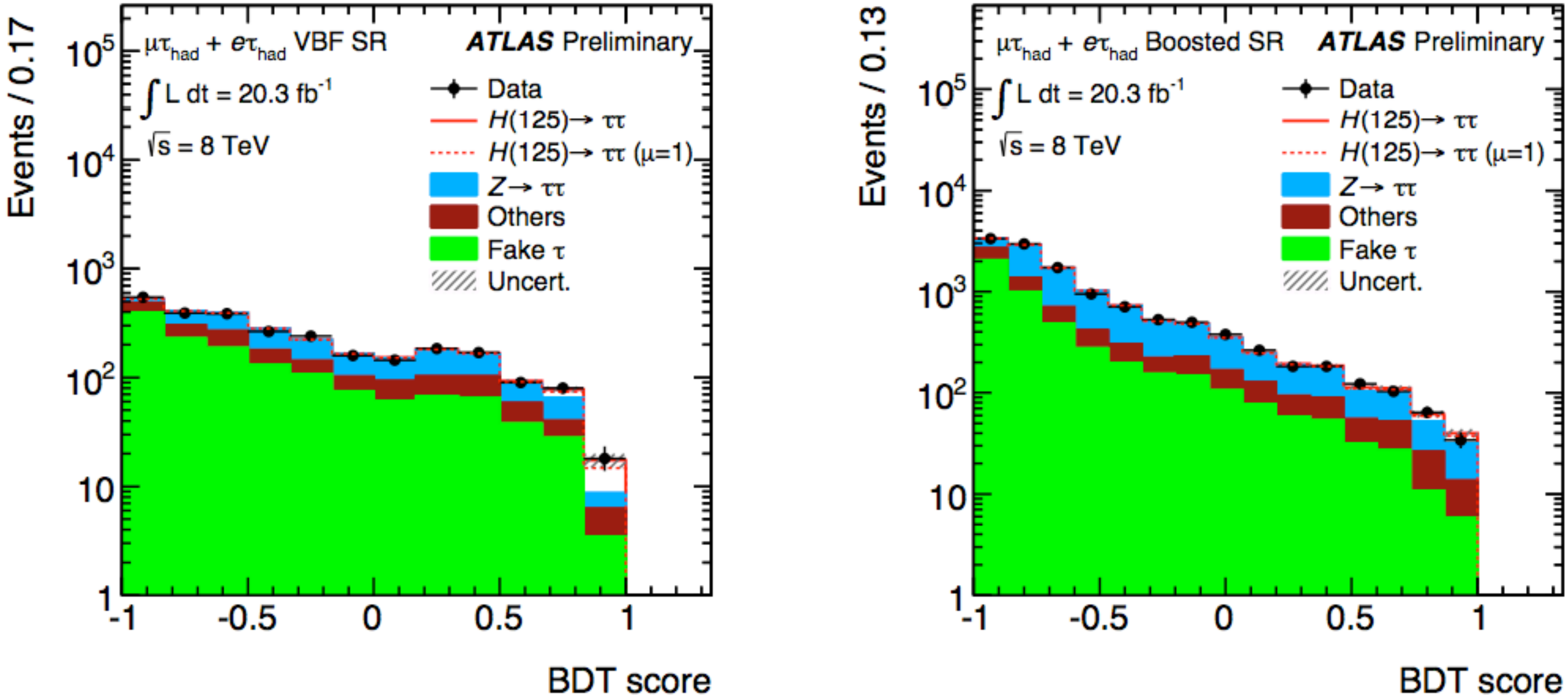
Ellwanger, Gunion, Hugonie, JHEP 0502, 066 (2005)

Challenges for Higgs coupling analysis:

The lightest Higgs is Standard Model-like, with deviations in partial width of order m_h^2/M^2 (Decoupling Theorem).

Higgs production rates are small, or (especially at LHC) backgrounds that resemble the Higgs are very large.

Different non-Standard models of Higgs predict effects in different couplings. Need high statistical and systematic confidence.



4 σ observation at the LHC

Snowmass Higgs Working Group: (M ~ 1 TeV)

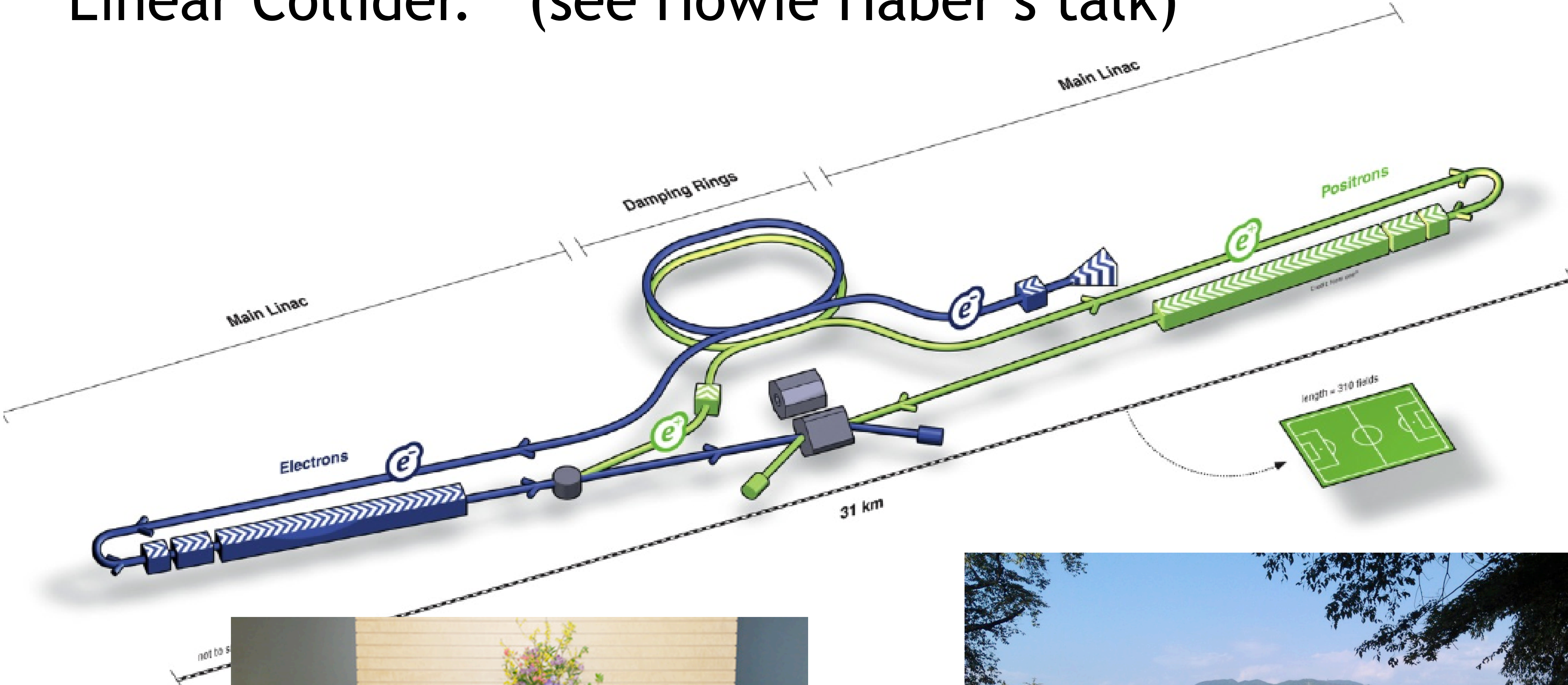
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

A goal for the future precision Higgs program should be 5 σ detection of effects of this size.

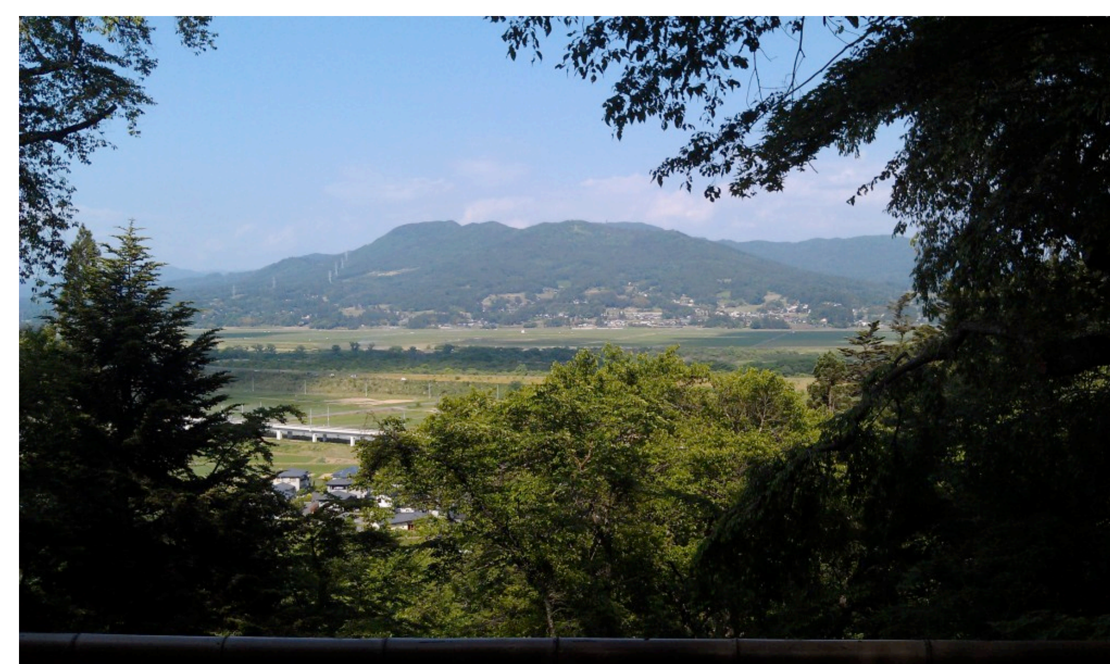
This criterion applies not only to the experimental precision but also to the precision of the Standard Model predictions to which the measurements must be compared.

"… the SM uncertainty in computing B(h➛bb) is presently 3.7% (sum of absolute values of all errors) and expected to not get better than 2.8%, with most of that coming from the uncertainty of the bottom Yukawa coupling determination … Thus, without reducing this error, any new physics contribution to the bb branching fraction that is not at least a factor of two or three larger than 2% cannot be discerned. Thus, a deviation of at least 5\% is required of detectable new physics." - Almeida, Lee, Pokorski, and Wells

On the experimental side, the requirements of a precision Higgs program are met by the International Linear Collider. (see Howie Haber's talk)

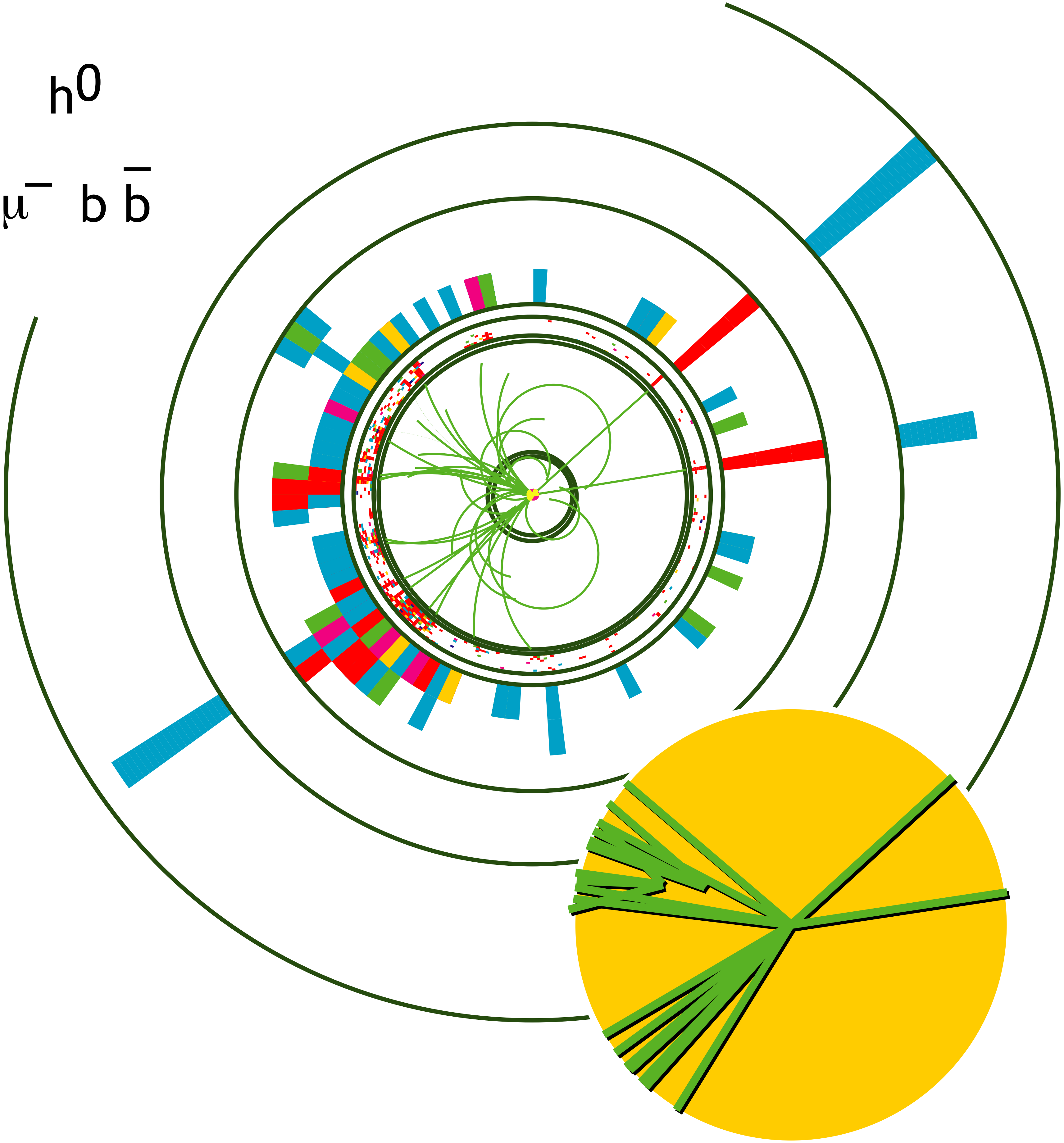


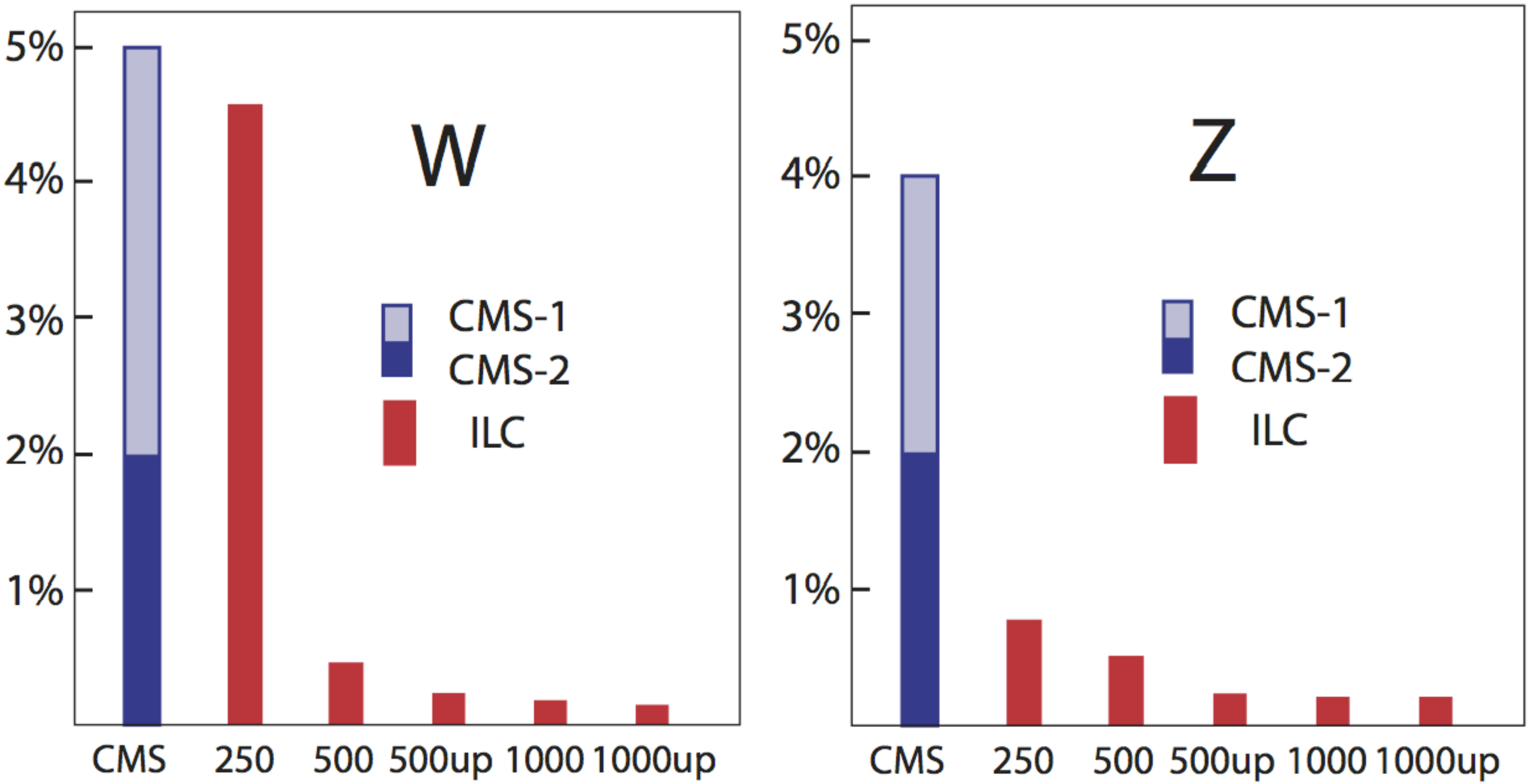
ILC Scheme | © www.form-one.de



$e^+e^- \to Z^0 \quad h^0$

$\to \mu^+\mu^- \; b\,\bar{b}$





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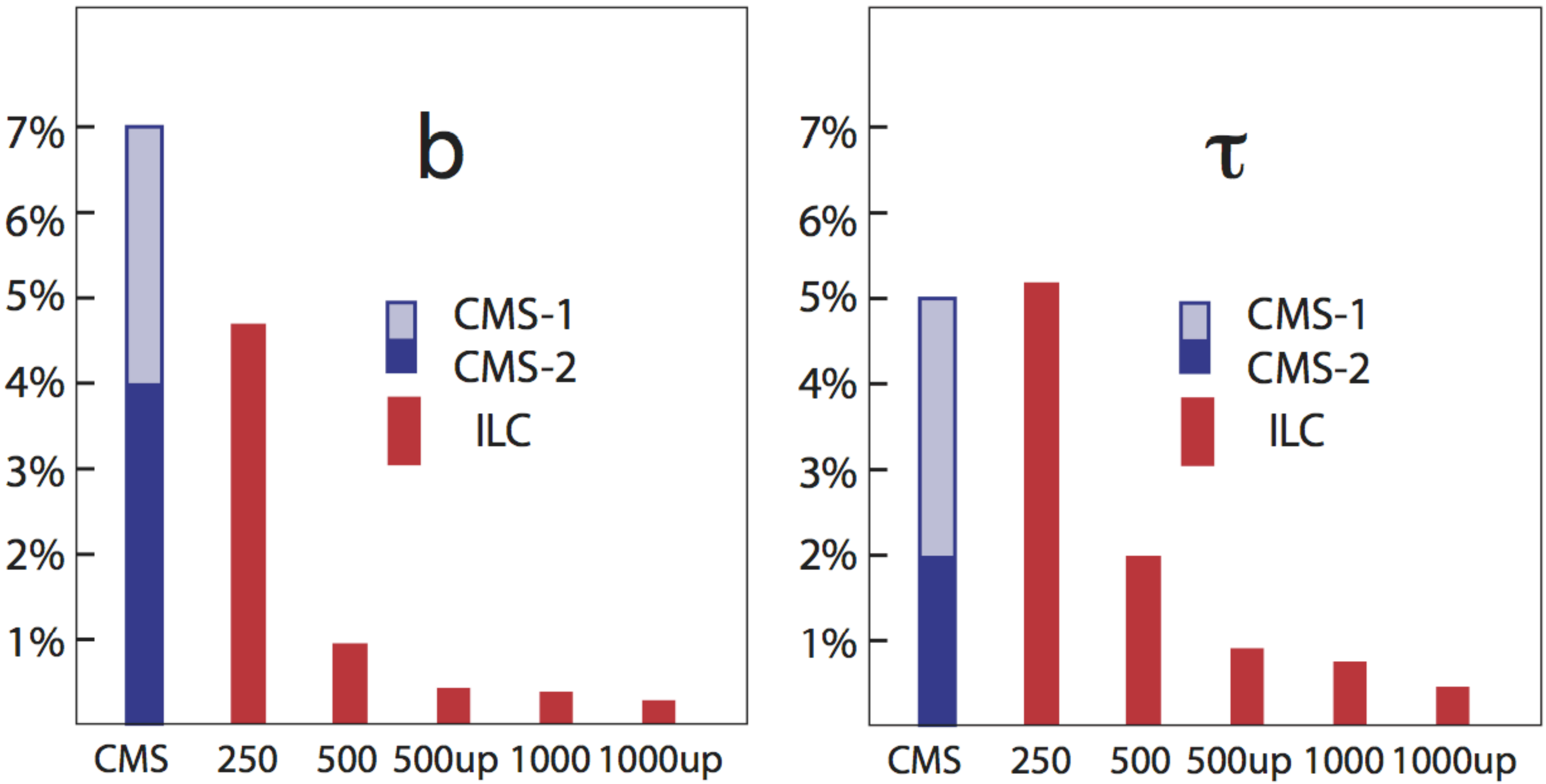
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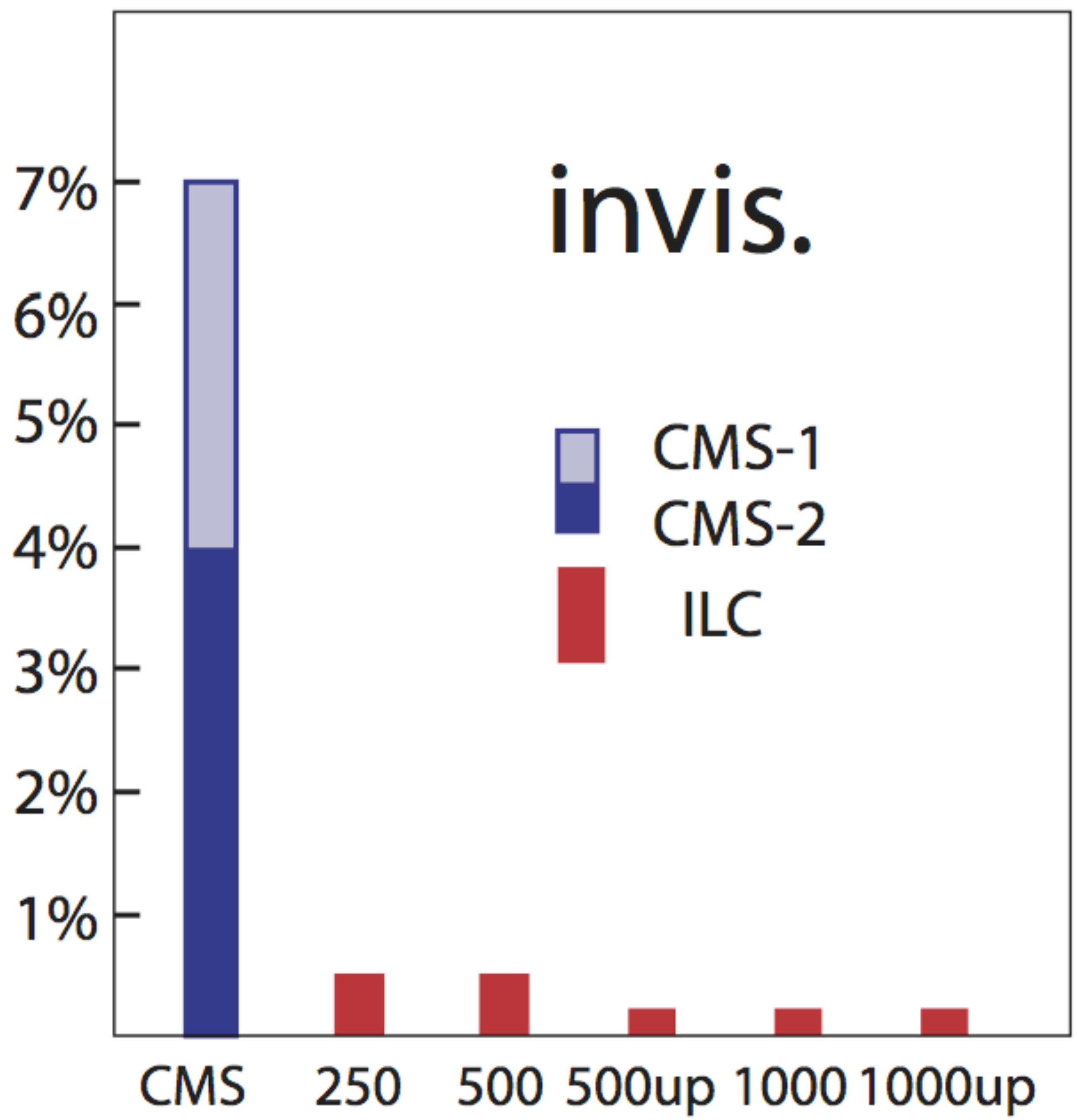
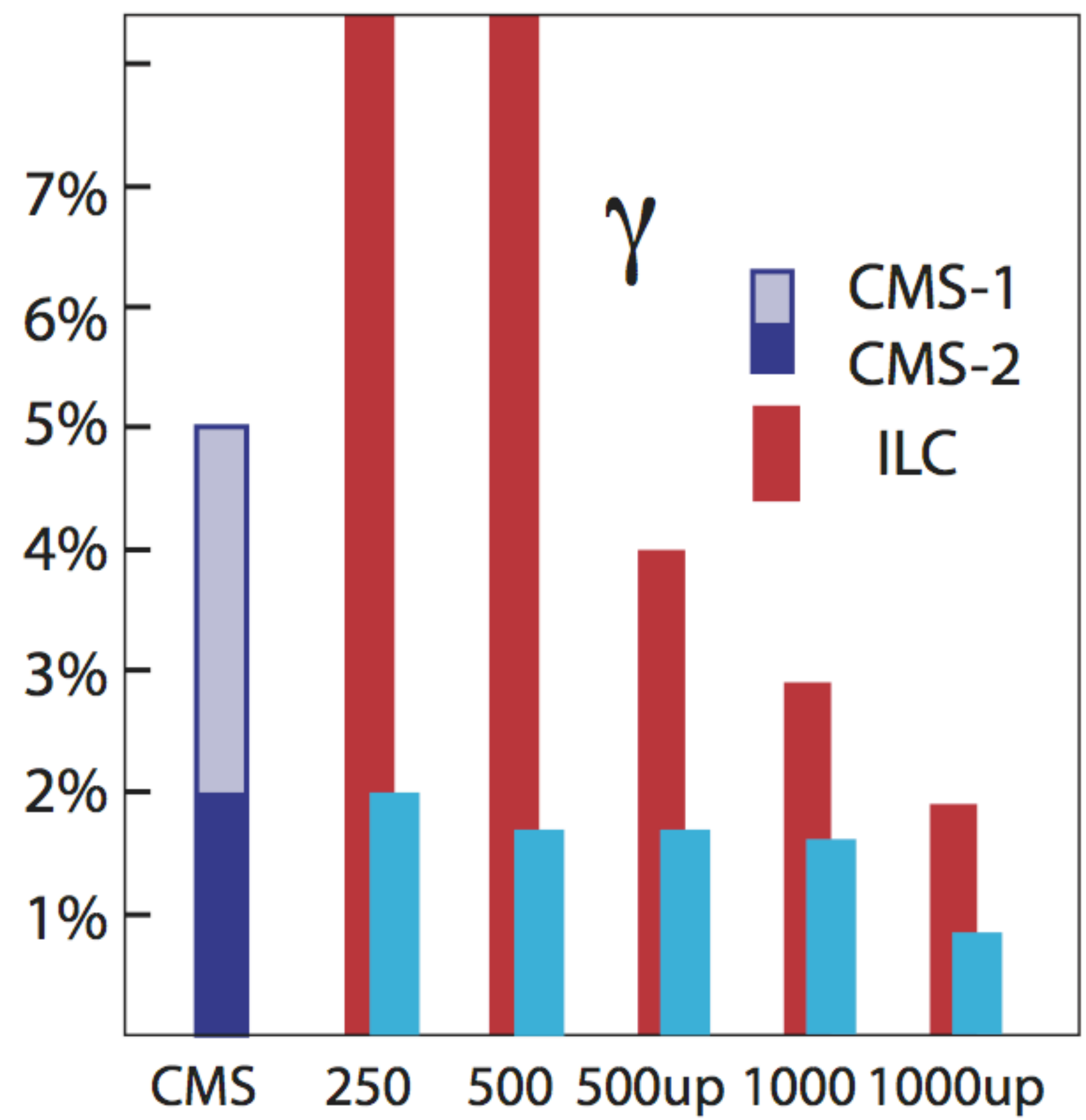




w. $\dfrac{BR(h \to \gamma\gamma)}{BR(h \to ZZ^*)}$ from LHC

We still must answer the question: Can we know the Standard Model predictions for Higgs partial widths to an accuracy comparable to that expected from the measurements ?

Two sources of uncertainty:

Perturbative: uncertainty due to truncation of perturbation theory at fixed order

Parametric: uncertainty due to uncertainty in the input parameters

We express uncertainties on Higgs couplings as

$$\delta_A = \frac{1}{2} \frac{\Delta\Gamma(h \to A\overline{A})}{\Gamma(h \to A\overline{A})}$$

and, for parameters,

$$\delta X = \frac{\Delta X}{X}$$

The prediction for a Higgs partial width has the form

$$\Gamma(H \to A\overline{A}) = \frac{G_F}{\sqrt{2}} \frac{m_h m_A^2}{4\pi} \cdot \mathcal{F}$$

important parametric dependence

compute in perturbation theory

Perturbative uncertainties: $\Gamma(h \to b\bar{b})$

QCD corrections - known to $\mathcal{O}(\alpha^4)$!

Baikov, Chetyrkin, Kuhn

$a = \alpha_s/\pi$

$$\tilde{R} = 1 + 5.667a + 29.15a^2 + 41.76a^3 - 825.7a^4$$
$$= 1 + 0.2037 + 0.0377 + 0.0019 - 0.0013 \,,$$

electroweak and mixed EW/QCD:

$$\delta\Gamma = 0.3\% - 0.02\% + 0.05\%$$

$\mathcal{O}(\alpha a m_t^2/m_h^2)$
Kwiatkowski-Steinhauser
Kniehl-Spira

$\mathcal{O}(\alpha^2 m_t^4/m_h^4)$
Butenschoen-Fugel-Kniehl

Perturbative uncertainties: $\Gamma(h \to gg)$

double perturbation theory in α_s, $m_h^2/4m_t^2$:

$$\frac{\Gamma}{\Gamma_0} = 1.0671 + 19.306a + 172.76a^2 + 467.68a^3$$
$$= 1.0671 + 0.6942 + 0.2234 + 0.0217$$

Schreck-Steinhauser, Baikov-Chetyrkin, Moch-Vogt

Perturbative uncertainties: $\Gamma(h \to WW^*)$

state of the art: complete $\mathcal{O}(\alpha)$ prophecy4f

Bredenstein, Denner, Dittmaier, Weber

1-loop corrections are 7% for leptons, 10% for quarks

difference from the Improved Born Approximation is 1%

leading 2-loop corrections known in the IBA:
Kneihl-Veretin

strong parametric dependence on Higgs mass:

$$\delta_W = 6.9 \cdot \delta m_h \ , \quad \delta_Z = 7.7 \cdot \delta m_h$$

this is a 0.2% uncertainty for $\Delta m_h = 30 \ \mathrm{MeV}$

My conclusion is that perturbative uncertainties of order 0.1% are within the state of the art.   Much work is required, but no new theoretical tools are needed.

Now turn to parametric uncertainties. The strongest dependences are those on $m_b, m_c,\ \alpha_s$.

Most of the parametric dependence comes from the prefactor. The factors of mass must be defined carefully. The perturbation theory is free of large logarithms for

$$m_A^2 \to m_A^2(\overline{MS}, \mu = m_h)$$

This must be determined by parameter values measured at lower energies. We choose as our parameters the $\overline{MS}$ values

$$m_b(10.0\ \mathrm{GeV})\ , \quad m_c(3.0\ \mathrm{GeV})\ , \quad \alpha_s(m_Z)$$

Formulae for running $\overline{MS}$ masses are known to 4 loops.

Using RunDec (Chetyrkin-Kuhn-Steinhauser) or the private code of HPQCD, we find

$$\delta m_b(m_h) = 1.0 \cdot \delta m_b(10) \oplus (-0.38) \cdot \delta\alpha_s(m_Z)$$
$$\delta m_c(m_h) = 1.0 \cdot \delta m_c(3) \oplus (-0.90) \cdot \delta\alpha_s(m_Z) \oplus (0.006) \cdot \delta m_b(10)$$

Note that the coefficients are much larger if the quark masses are evaluated at lower scales, or at scales that depend on the quark mass. For example,

$$\delta m_b(m_h) = 1.19 \cdot \delta m_b(m_b) \oplus (-0.69) \cdot \delta\alpha_s(m_Z)$$

Combining this dependence with that from the perturbation theory, we find

$$\delta_b = 1. \cdot \delta m_b(10) \oplus (-0.28) \cdot \delta \alpha_s(m_Z)$$

$$\delta_c = 1. \cdot \delta m_c(3) \oplus (-0.80) \cdot \delta \alpha_s(m_Z)$$

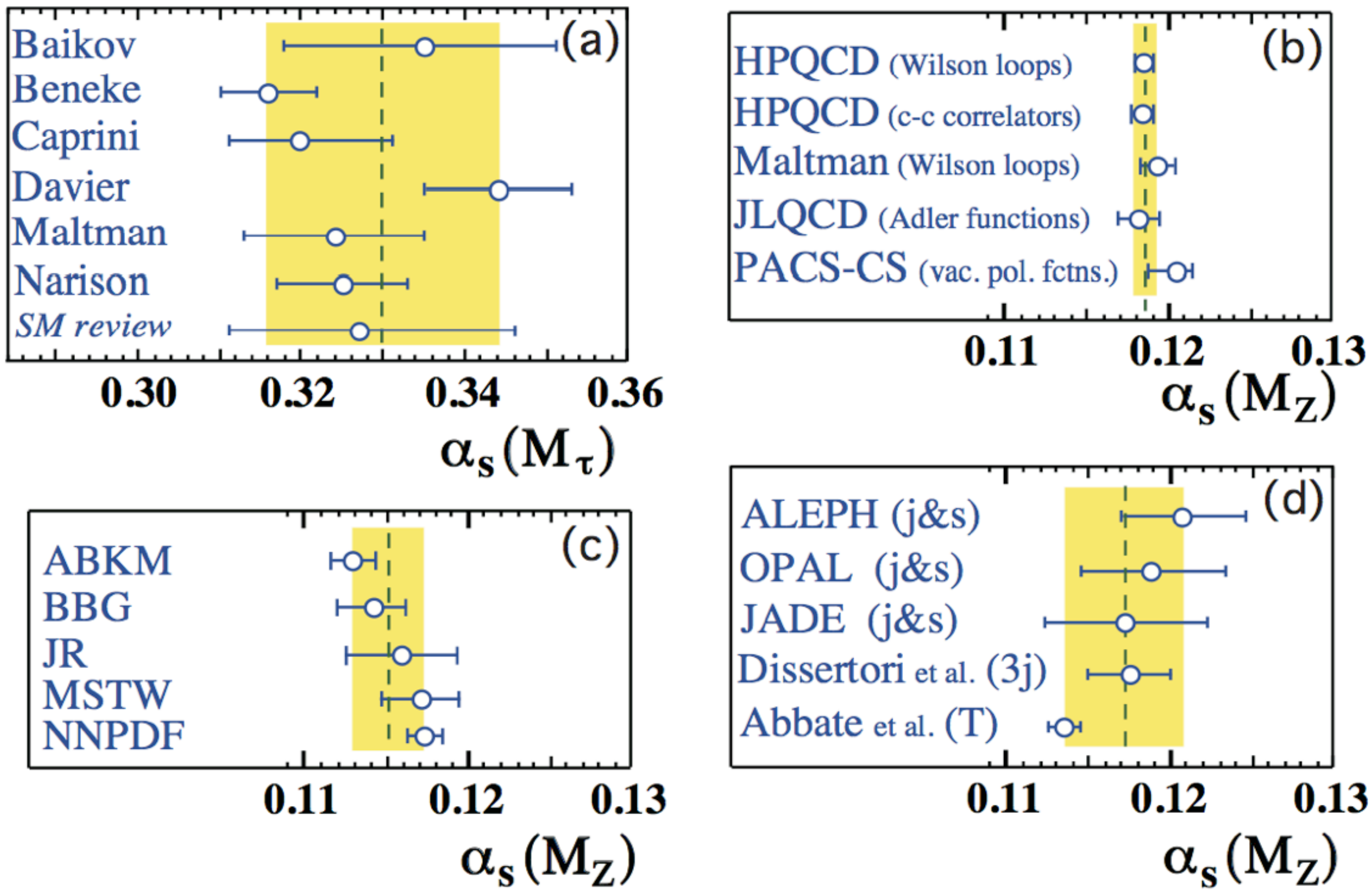
$$\delta_g = 1.2 \cdot \delta \alpha_s(m_Z)$$

The coefficients are of order 1. Thus, we still need the input parameters at the 0.1% level.

We claim that this level of precision can be achieved by lattice QCD.

Lattice QCD already gives the highest-precision measurements of α_s and measurements of precision comparable to the state of the art for heavy quark masses.

most recent PDG compilation of α_s measurements



The PDG value, dominated by lattice QCD, is

$$0.1184\ (7)\quad (0.6\%)$$

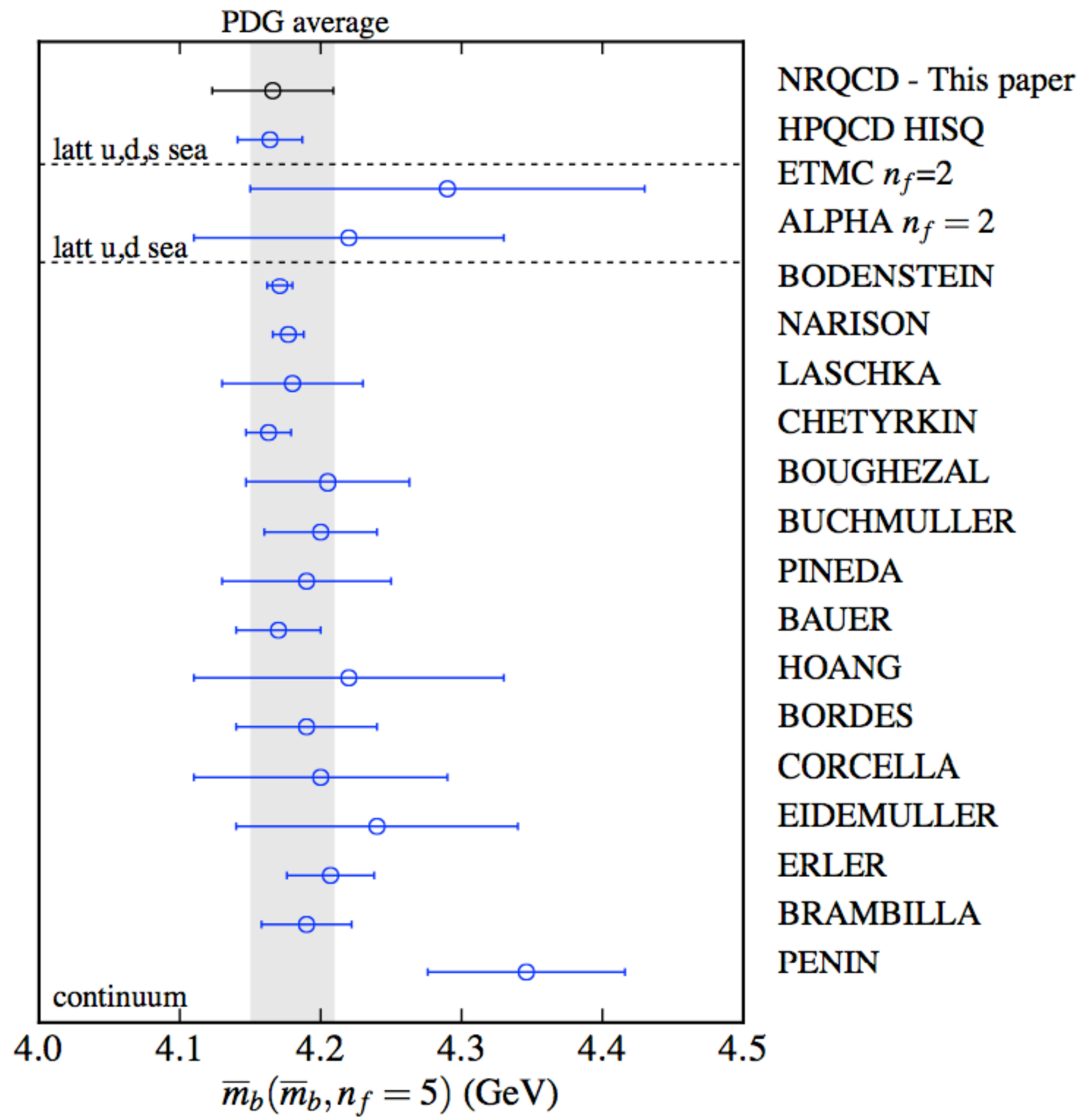
$m_b(m_b;\overline{MS})$

The current best determinations of from lattice QCD calculations of the Υ spectrum give

$$4.166\ (43)$$
$$4.164\ (23)$$

Comparable results from QCD sum rules are

$$4.171\ (9)$$
$$4.177\ (11)$$
$$4.163\ (16)$$



From the global fit to B decay distributions using HQET (HFAG): $4.194\ (43)$

I will now describe one strategy for reaching high precision using lattice QCD:

Study a 2-point correlation function

$$G(t) \equiv a^3 \sum_{\mathbf{x}} m_{0Q}^2 \langle 0 | j_{5Q}(\mathbf{x}, t)\, j_{5Q}(0,0) | 0 \rangle$$

Take moments, and extrapolate these to the continuum limit

$$G_{2n} \equiv a \sum_t t^{2n} G(t) = (-1)^n \frac{\partial^{2n}}{\partial E^{2n}} G(E=0)$$

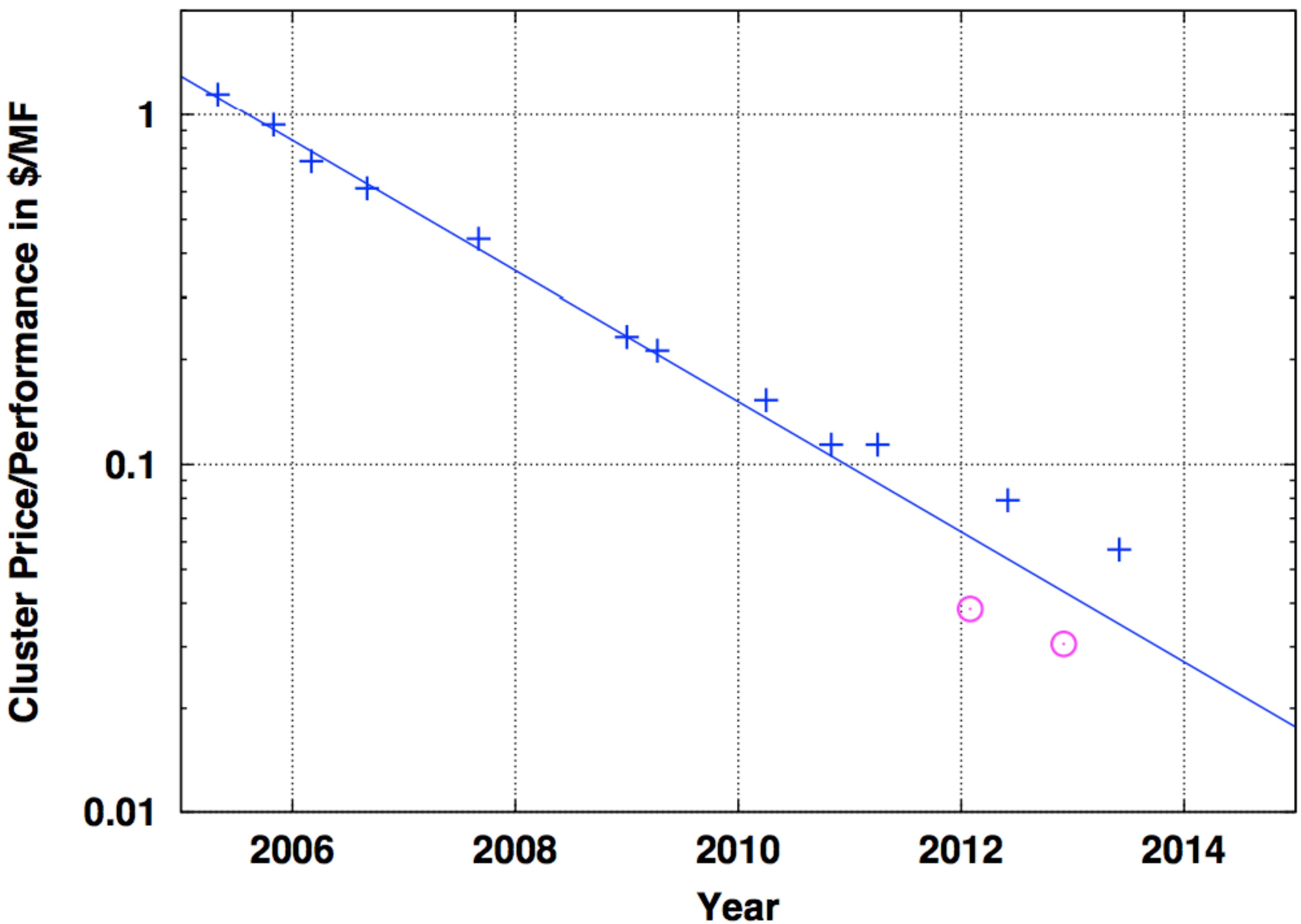
Use $f_\pi, m(\eta_c), m(\eta_b)$ to set the scale of masses for the lattice spacing. G_{2n} depends on off-shell masses at $Q \sim 2m_Q$

This gives the continuum values of QCD sum rules. Analyze these using continuum QCD formulae with $\overline{MS}$ subtraction. This evades the need for high order QCD perturbation theory.

The perturbation expansions for the moments $2n \leq 10$ are known to 3rd order in QCD perturbation theory.

Chetyrkin-Kuhn-Sturm, Boughezal-Czakon-Schutzmaier, Maier-Maierhofer-Marquand-Smirnov

The method is similar to the direct use of experimental data, except that it is systematically improvable.



Fermilab and JLab clusters

Foreseen improvements:

LS - decrease lattice spacing from 0.045 fm to 0.03 fm

LS^2 - decrease lattice spacing from 0.045 fm to 0.023 fm

PT - compute one more order in QCD perturbation theory

ST - increase statistics by a factor 100

LS^2 requires a factor 100 increase in computing power.

fractional uncertainties in %

	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	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

Lepage-Mackenzie (preliminary)

Other, independent, methods are available to measure α_s in a manner uncorrelated with heavy quark masses, and to measure those masses using different techniques.

Conclusion:

We will have a precision Standard Model theory of the HIggs boson partial width to match the precision of the ILC experiments.

Changes in the pattern of Higgs couplings expected from models of new physics will become evident with high statistical significance.

Jack would love to see this. Let’s take the opportunity present now to make the ILC accelerator available.