Precision Higgs Coupling Analysis:

one theorist's perspective

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LCWS 2013
November 2013

The purpose of this talk is to discuss some physics issues associated with the program of precision Higgs coupling measurement.

My intent is to offer some sharp opinions to make the discussion in this session more interesting.

I will discuss three topics:

1. Deconstruction of the ATLAS and CMS estimates for sensitivity to Higgs couplings in the HL-LHC era

2. Theoretical uncertainties in the calculation of SM Higgs partial widths

3. The power of the constraint $\sum_i BR_i = 1$

1. ATLAS and CMS futures analyses

For the European Strategy study and for Snowmass 2013, the ATLAS and CMS collaborations made projections of their future capability for measuring Higgs boson couplings.

ATLAS has recently explained its projections in some detail in ATL-PHYS-PUB-2013-014.

CMS has presented very strong results, but there is, to my knowledge, no public explication of these results.

Linear collider folks should understand these projections better. I will point out some important features and questions.

Both analyses separate the uncertainties into three components:

statistical, systematic (experimental), theoretical

Theoretical uncertainties can be significant. LHC experiments do not measure Higgs couplings directly. They measure

$$\sigma(A\overline{A} \to h) \cdot BR(h \to B\overline{B}) \sim \frac{\Gamma(h \to A\overline{A})\Gamma(h \to B\overline{B})}{\Gamma_T}$$

Higgs couplings are extracted from a global fit to these quantities. Higgs production cross sections have large QCD uncertainties, and these are reflected directly as uncertainties in the relation between the measured rates and their Standard Model values.

These theory uncertainties are of 3 types:

Uncertainties in the total rate of Higgs production

Uncertainties in the probability of specific event properties (e.g., 0 jets)

Uncertainties in the detailed modeling of events, both signal and background

Errors of the first type have received much attention from the LHC Higgs Cross Section Working Group. Errors of the latter two types are less well understood.

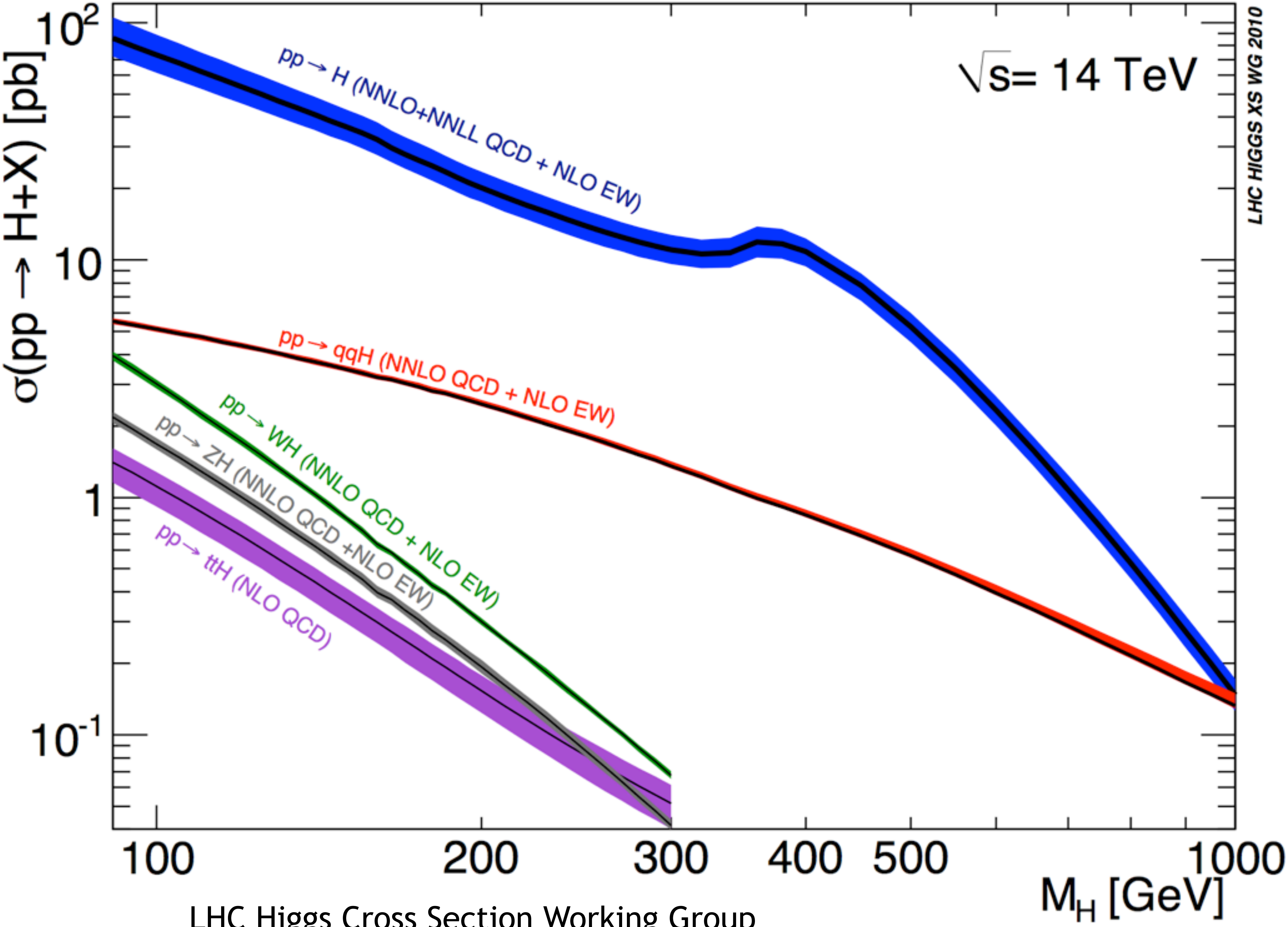
The distinction is important in evaluating the CMS strategy for Higgs coupling uncertainty estimation.

Scenario 1: use current systematics and theory errors
Scenario 2: theory errors decrease by 2,
experimental systematics by $\sqrt{N}$

From today to the end of HL-LHC,

$$\sqrt{N_{today}/N_{2030}} \sim 1/12$$

so it is important to know what is classified as a theory error and what is classified as an experimental systematic improvable with data.



LHC Higgs Cross Section Working Group

Theory uncertainties from the LHC Higgs Cross Section Working Group for 14 TeV:

	$\sigma(\mathrm{pb})$	scale error %	PDF and error %	in quadrature %
gg fusion	50.0	10.3	6.8	12.3
VB fusion	4.2	0.6	2.3	2.9
W h	1.5	0.5	3.8	3.8
Z h	0.9	2.3	3.7	4.3
$t \bar{t}$ h	0.6	7.6	8.9	11.7

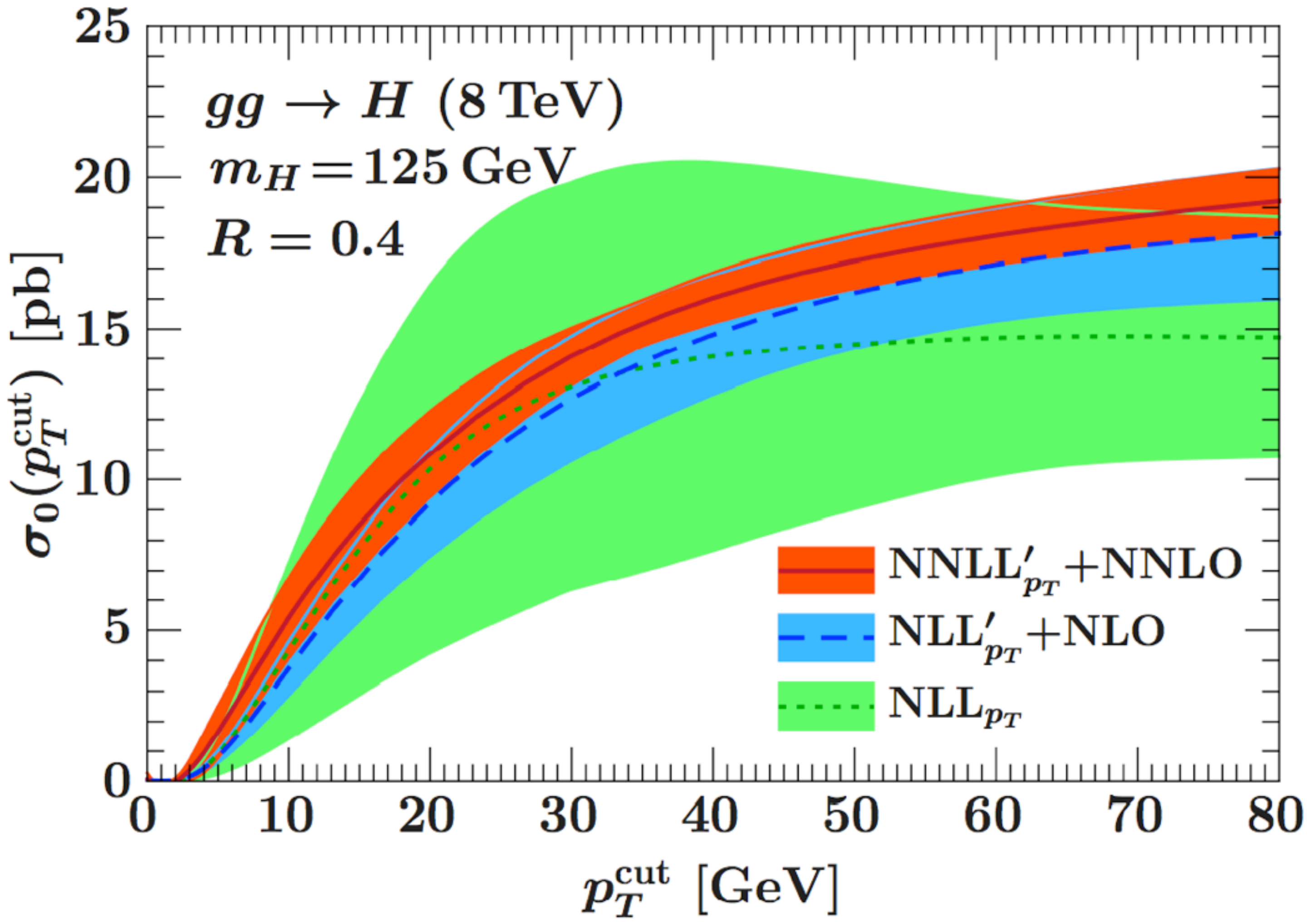
It is very likely that these uncertainties can be improved.

PDFs will improve from LHC data, especially with input of the NNLO cross section for $pp \to t\bar{t}$

The perturbative QCD community has recognized a new “NNLO frontier”. Several $2 \to 2$ processes have already been computed at NNLO.

Improvements are also likely in predictions of event characteristics such as 0, 1 - jet fraction.

Still, event modeling is an important part of all LHC Higgs analyses. What part goes theory, what part is improveable with data ?

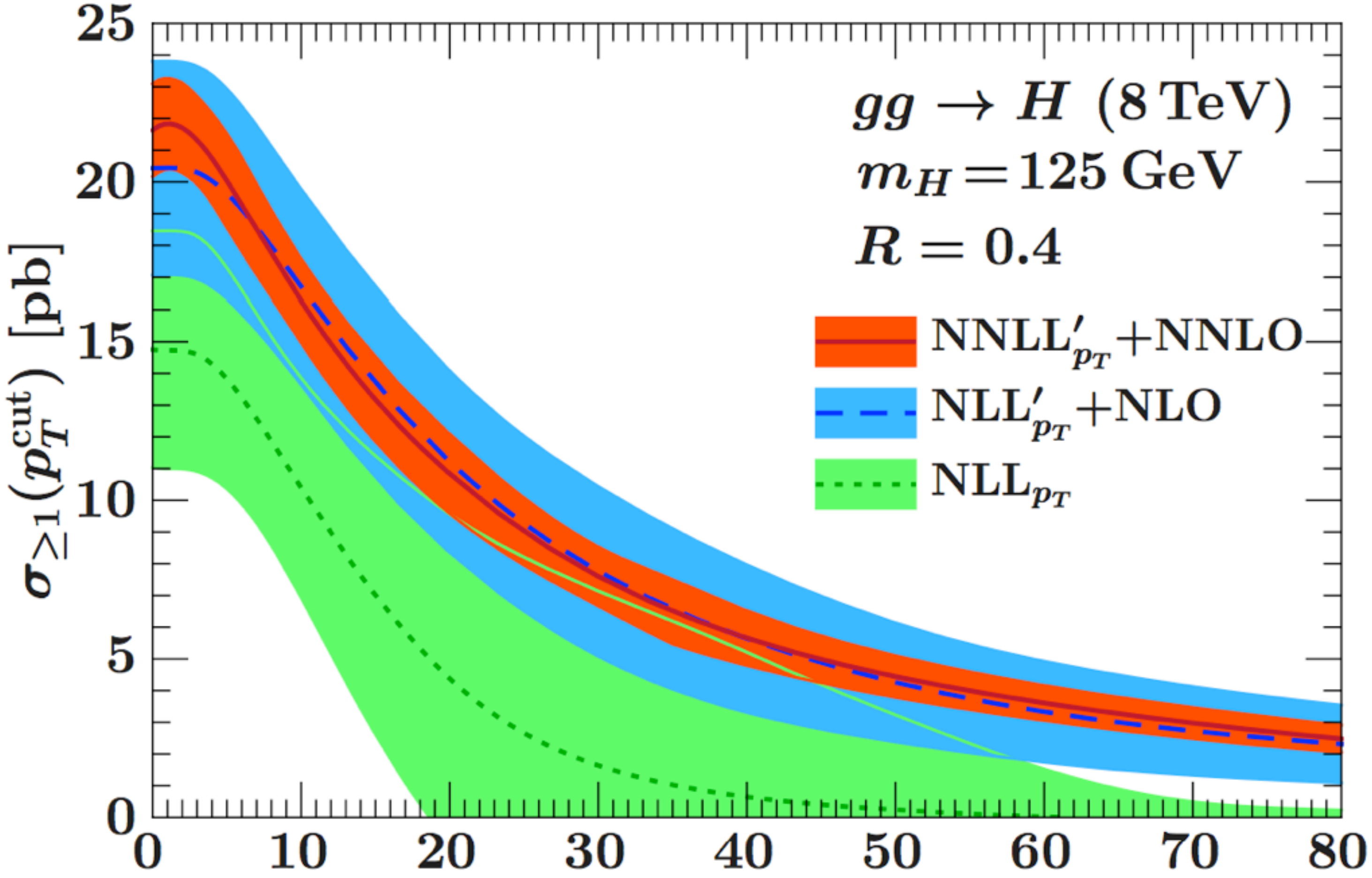


0-jet

Stewart, Tackmann, Walsh, Zuberi

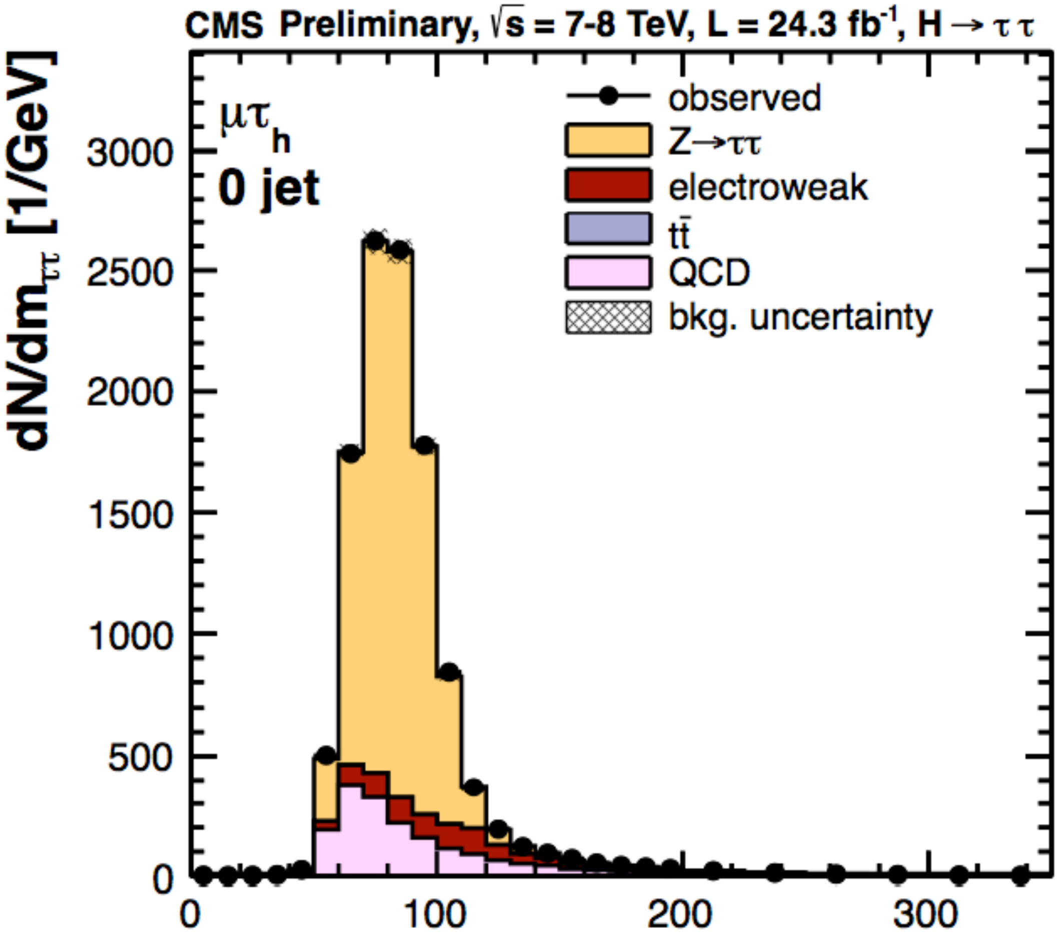
also

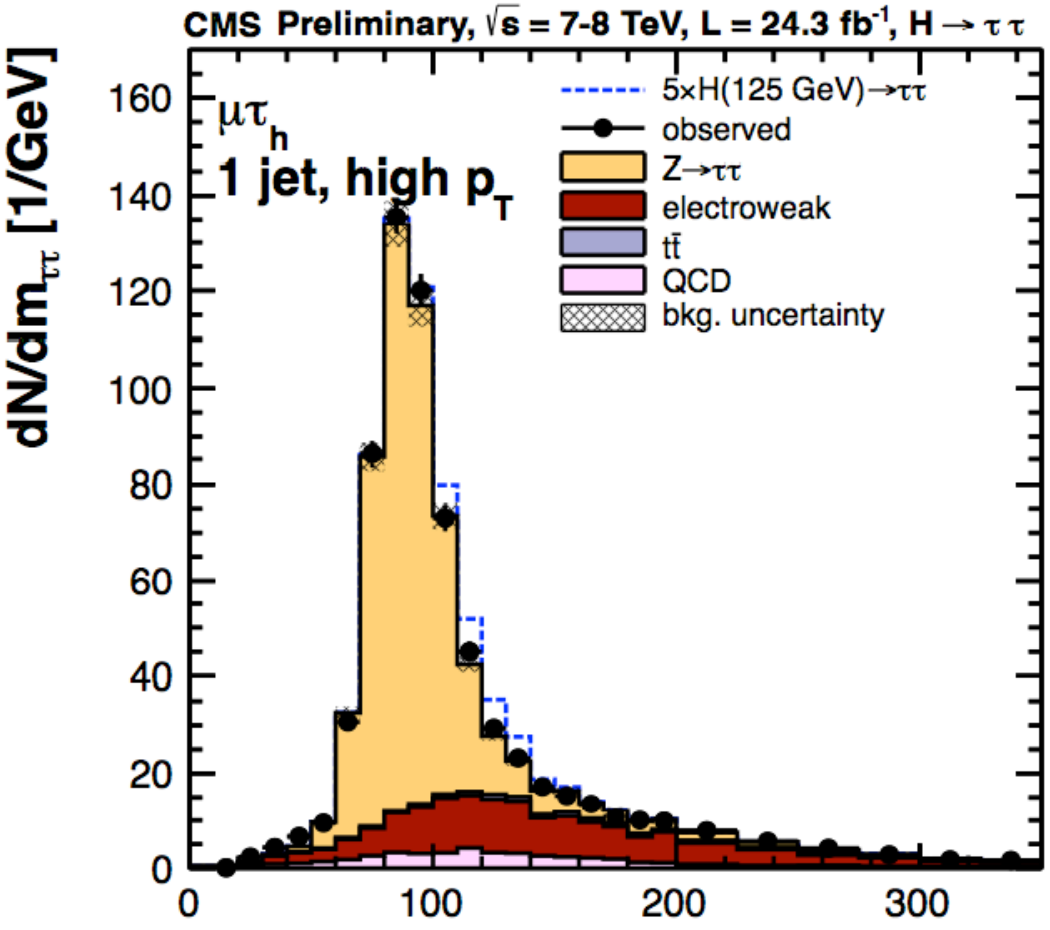
Banfi, Monni, Salam, Zanderighi
Becher, Neubert, Rothen
Shao, Li, Li

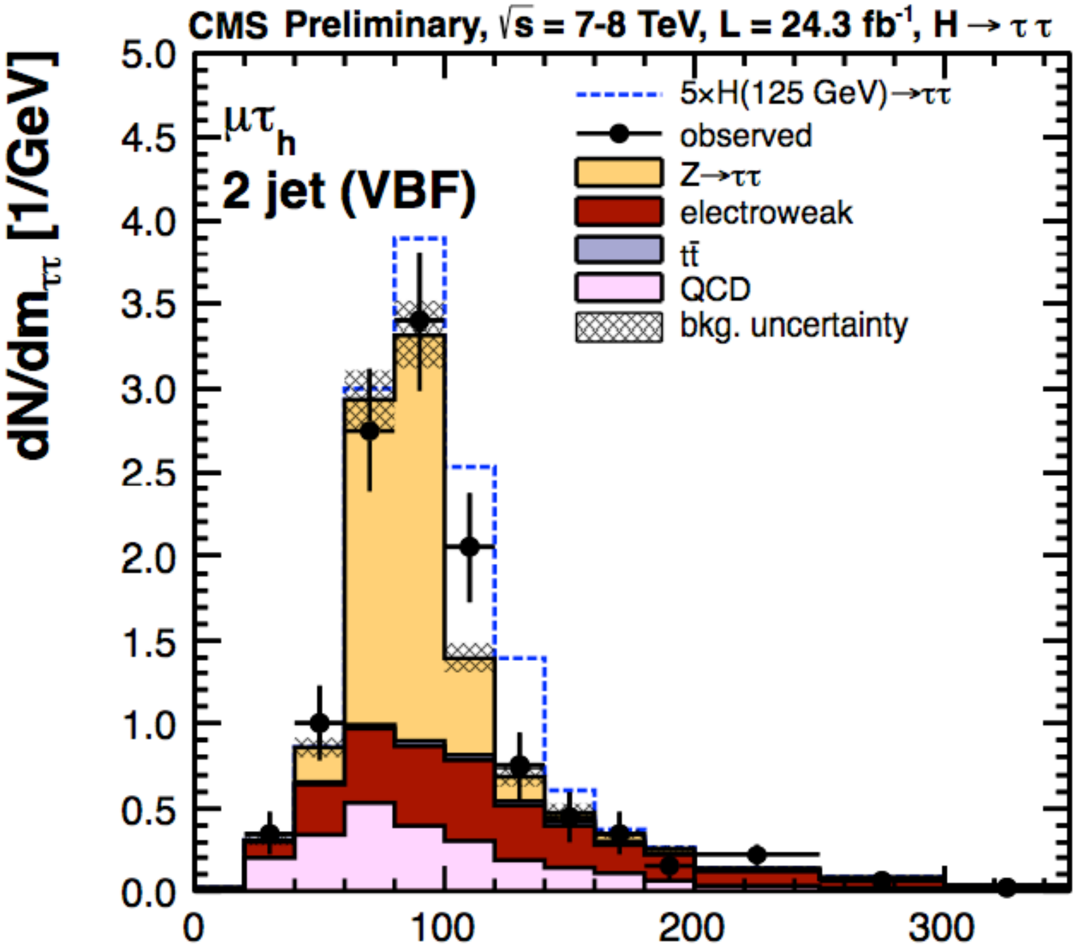


These studies claim 7% uncertainty in exclusive jet cross sections

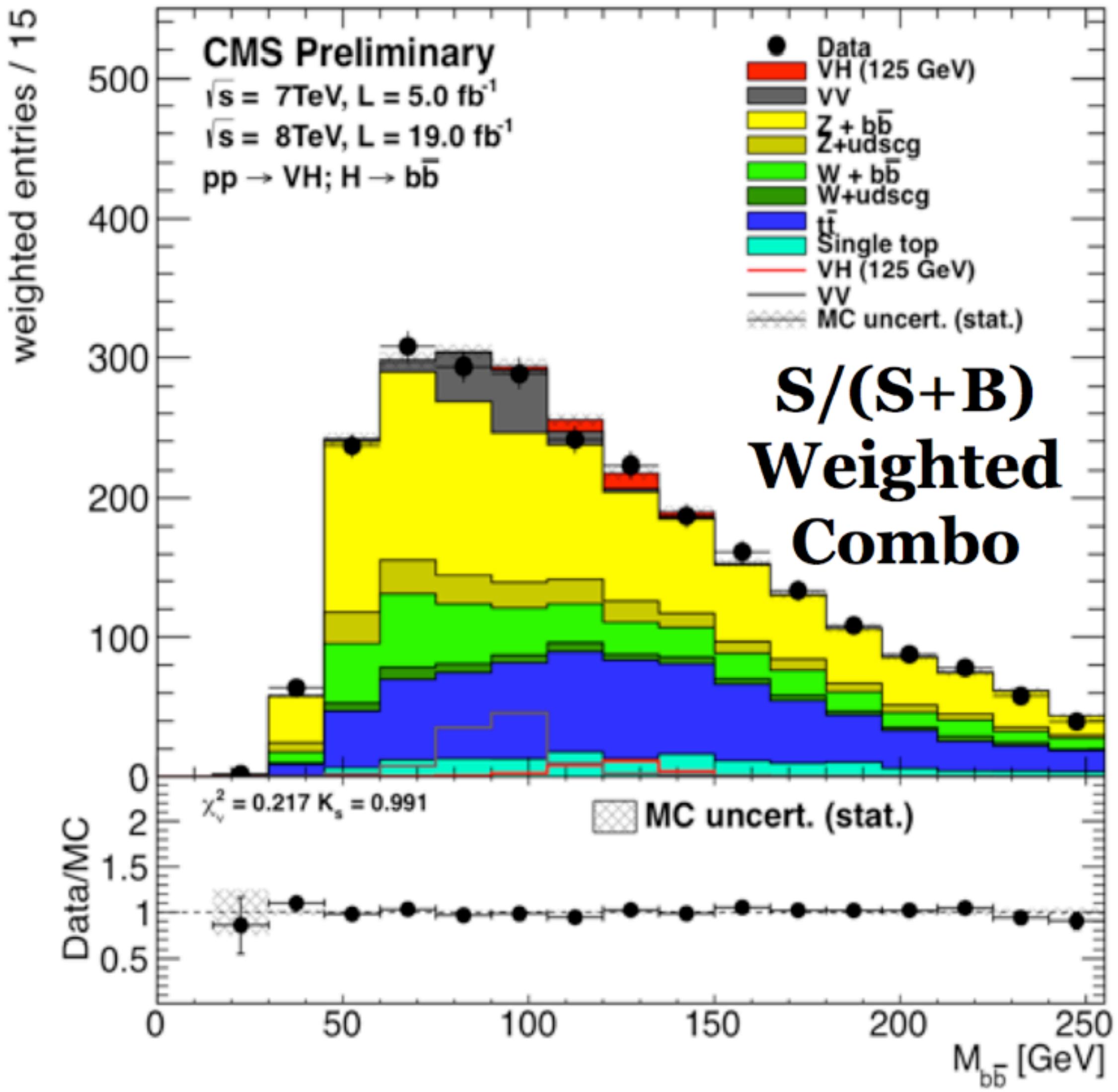
1-jet inclusive

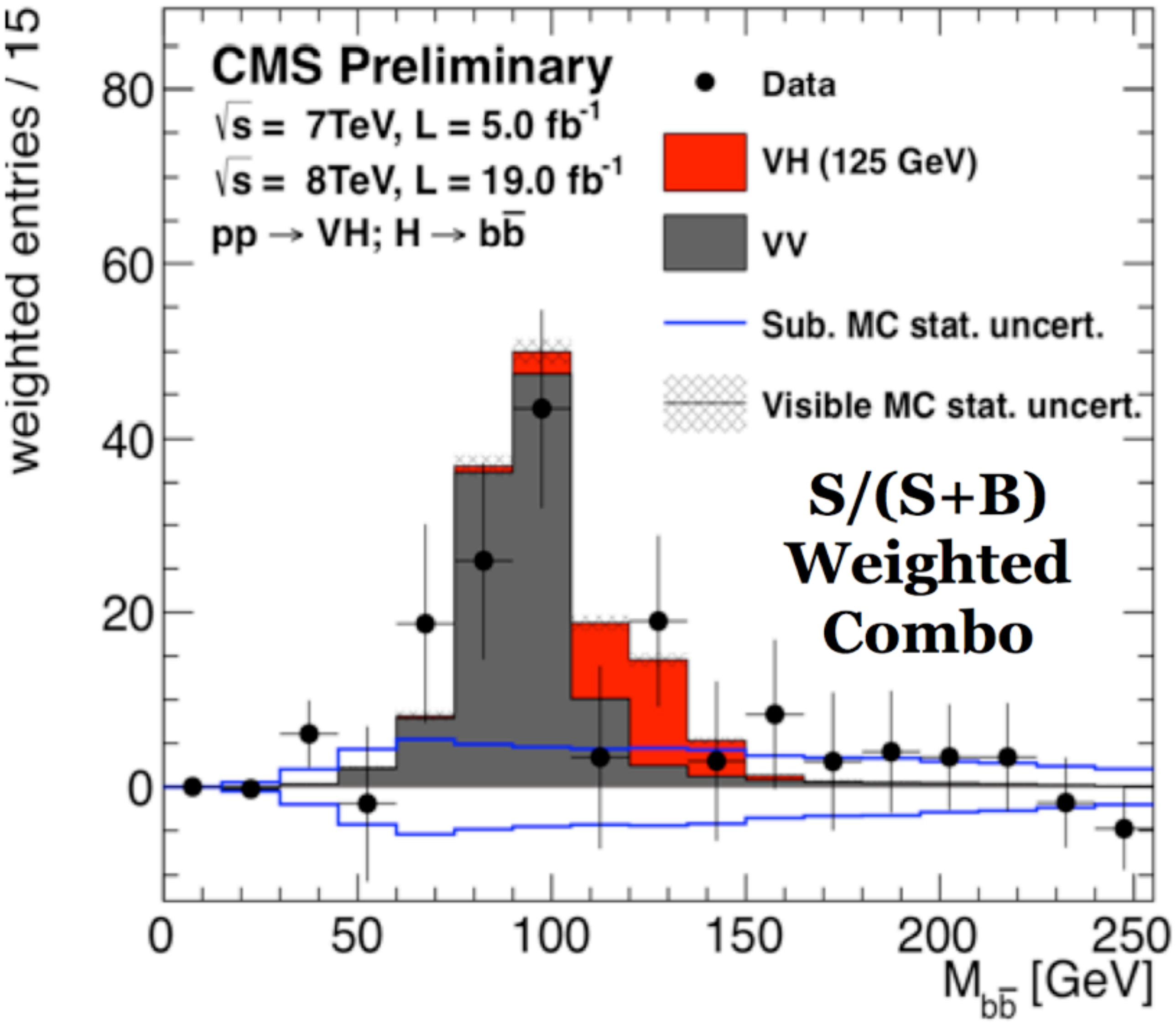

CMS Preliminary, $\sqrt{s}$ = 7-8 TeV, L = 24.3 fb^{-1}, H → τ τ
$\mu\tau_h$
0 jet
observed
Z→ττ
electroweak
$t\bar{t}$
QCD
bkg. uncertainty
dN/dm$_{\tau\tau}$ [1/GeV]
0
500
1000
1500
2000
2500
3000
0
100
200
300


CMS Preliminary, $\sqrt{s}$ = 7-8 TeV, L = 24.3 fb^{-1}, H → τ τ
$\mu\tau_h$
1 jet, high p_T
5×H(125 GeV)→ττ
observed
Z→ττ
electroweak
$t\bar{t}$
QCD
bkg. uncertainty
dN/dm$_{\tau\tau}$ [1/GeV]
0
20
40
60
80
100
120
140
160
0
100
200
300

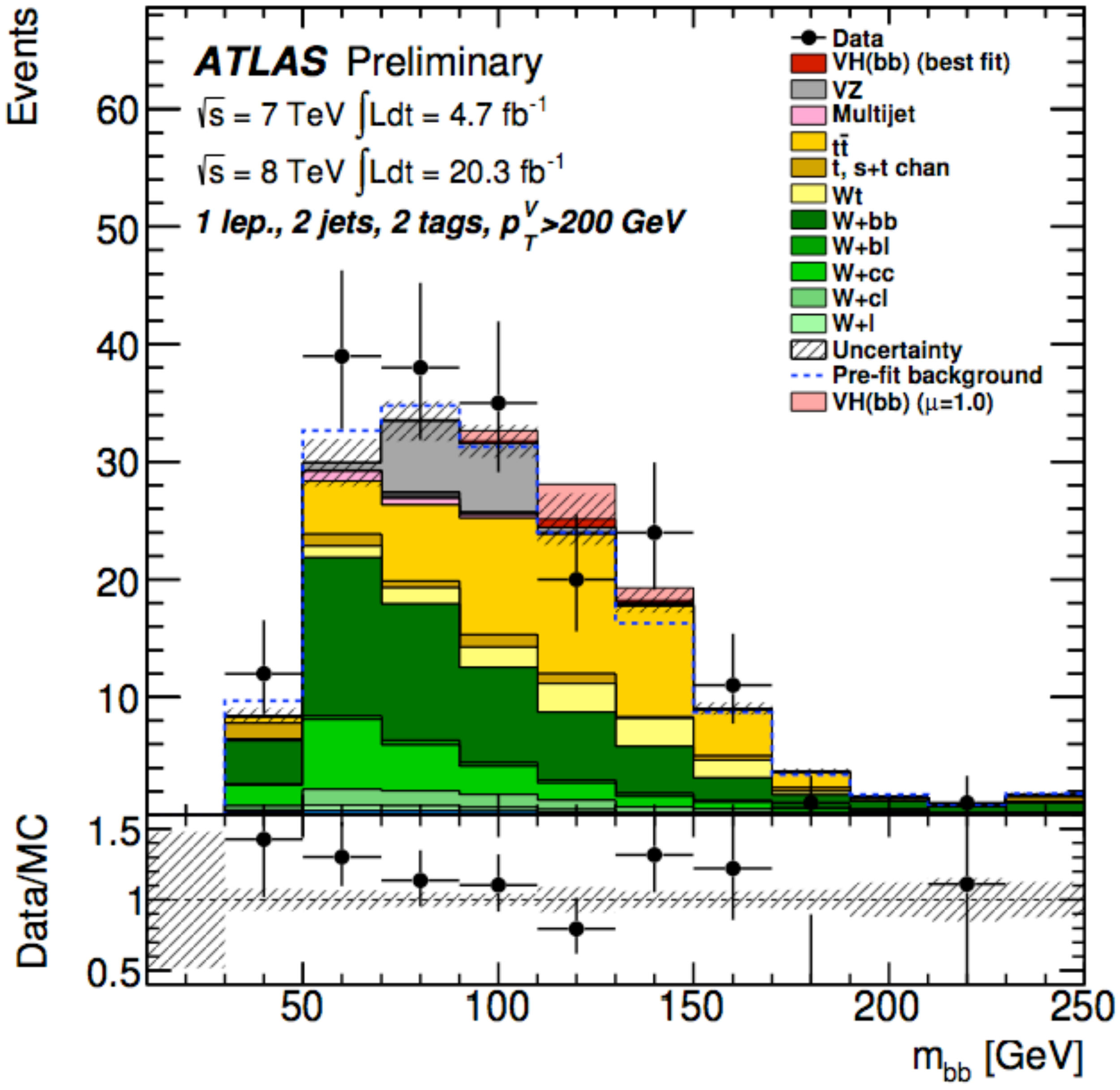

CMS Preliminary, $\sqrt{s}$ = 7-8 TeV, L = 24.3 fb^{-1}, H → τ τ
$\mu\tau_h$
2 jet (VBF)
5×H(125 GeV)→ττ
observed
Z→ττ
electroweak
$t\bar{t}$
QCD
bkg. uncertainty
dN/dm$_{\tau\tau}$ [1/GeV]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0
100
200
300

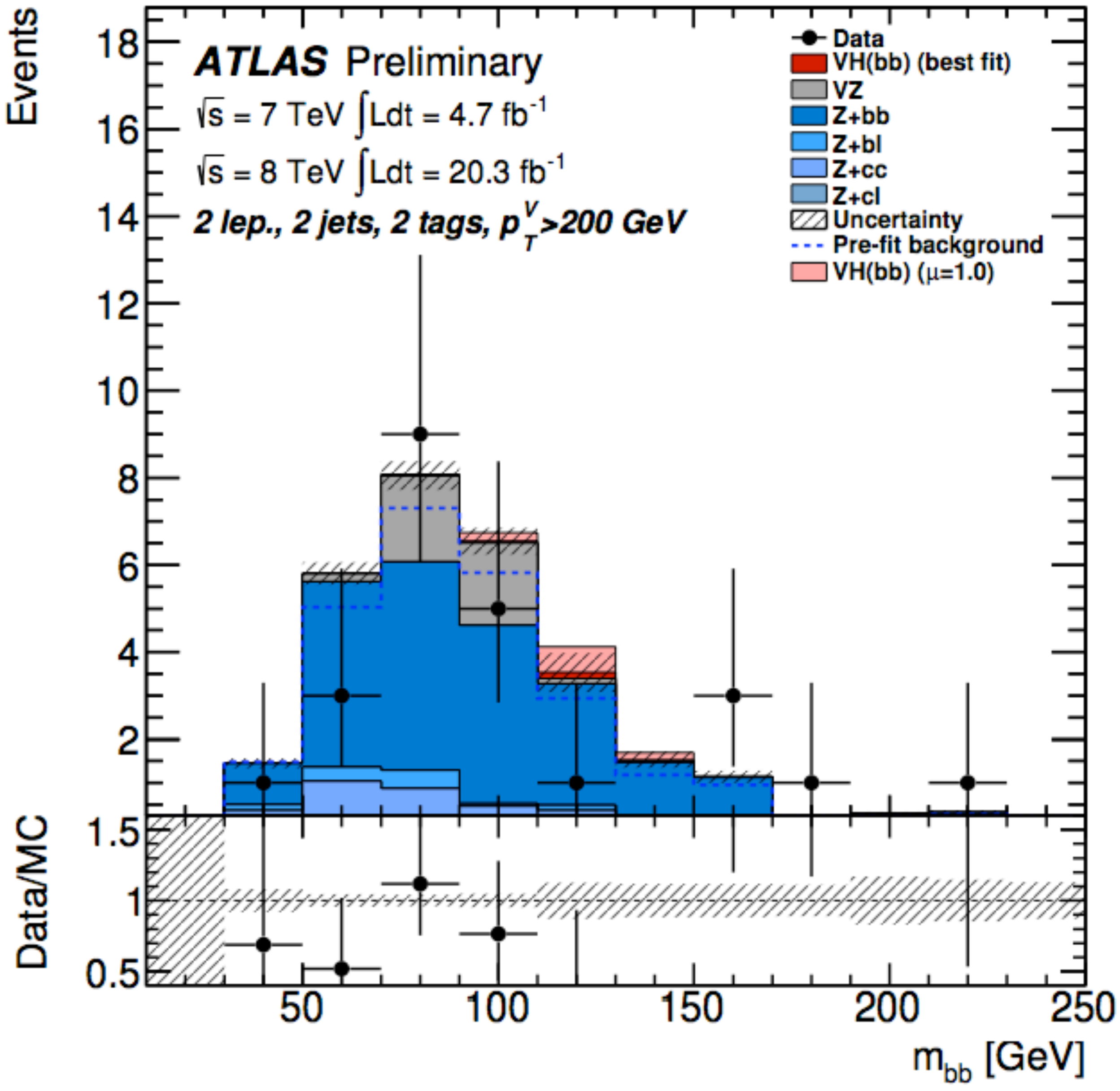
$m_{\tau\tau}$ [GeV]





M. Mooney, for CMS DPF 2013

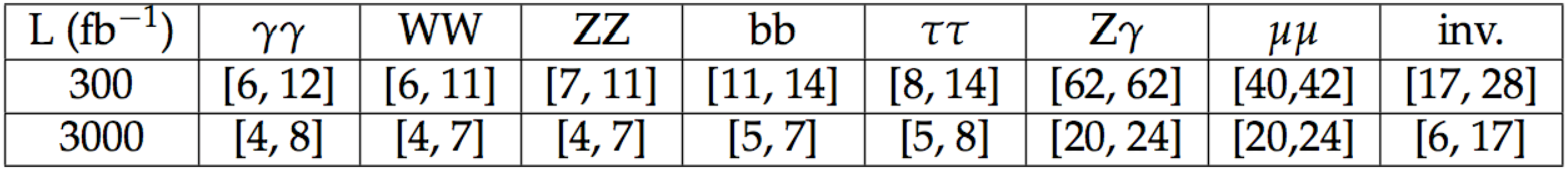




N.Morange, for ATLAS DPF 2013

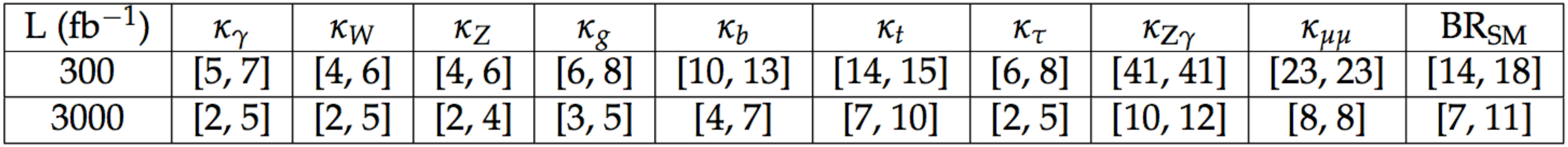
My attempt to deconstruct the CMS results from the White Paper for Snowmass, CMS-Note-13-002

% uncertainties in signal strengths



L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]

% uncertainties in Higgs boson coupling strengths from a 7-parameter fit



L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	$\mathrm{BR}_{\mathrm{SM}}$
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

[Scenario 2, Scenario 1]

$300\ \mathrm{fb}^{-1}$:

Observable	ATLAS	CMS-1	CMS-2
$\sigma(gg) \cdot BR(\gamma\gamma)$	$12 \oplus 19$	$6 \oplus 12.3$	$3 \oplus 6.2$
$\sigma(WW) \cdot BR(\gamma\gamma)$	$47 \oplus 15$	$20 \oplus 2.4$	$14 \oplus 1.2$
$\sigma(gg) \cdot BR(WW)$	$8 \oplus 18$	$6 \oplus 12.3$	$5 \oplus 6.2$
$\sigma(WW) \cdot BR(WW)$	$20 \oplus 8$	$35 \oplus 2.4$	$28 \oplus 1.2$
$\sigma(gg) \cdot BR(ZZ)$	$6 \oplus 11$	$7 \oplus 12.3$	$5 \oplus 6.2$
$\sigma(WW) \cdot BR(ZZ)$	$31 \oplus 13$	$12 \oplus 2.4$	$10 \oplus 1.2$
$\sigma(gg) \cdot BR(\tau\tau)$	—	$13 \oplus 12.3$	$6 \oplus 6.2$
$\sigma(WW) \cdot BR(\tau\tau)$	$16 \oplus 15$	$16 \oplus 2.4$	$9 \oplus 1.2$
$\sigma(Wh) \cdot BR(b\bar{b})$	—	$17 \oplus 3.8$	$14 \oplus 1.7$
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	—	$60 \oplus 11.7$	$50 \oplus 5.9$
$\sigma(t\bar{t}h) \cdot BR(\gamma\gamma)$	$54 \oplus 10$	$40 \oplus 11.7$	$38 \oplus 5.9$
$\sigma(Zh) \cdot BR(invis)$	—	$16 \oplus 4.3$	$11 \oplus 2.2$

$3000\ \mathrm{fb}^{-1}$:

Observable	ATLAS-HL	CMS-HL-1	CMS-HL-2
$\sigma(gg) \cdot BR(\gamma\gamma)$	$5 \oplus 19$	$4 \oplus 12.3$	$0.9 \oplus 6.2$
$\sigma(WW) \cdot BR(\gamma\gamma)$	$15 \oplus 15$	$10 \oplus 2.4$	$4.4 \oplus 1.2$
$\sigma(gg) \cdot BR(WW)$	$5 \oplus 18$	$6 \oplus 12.3$	$1.6 \oplus 6.2$
$\sigma(WW) \cdot BR(WW)$	$9 \oplus 8$	$24 \oplus 2.4$	$8.9 \oplus 1.2$
$\sigma(gg) \cdot BR(ZZ)$	$4 \oplus 11$	$4 \oplus 12.3$	$1.6 \oplus 6.2$
$\sigma(WW) \cdot BR(ZZ)$	$16 \oplus 13$	$7 \oplus 12.3$	$1.9 \oplus 6.2$
$\sigma(WW) \cdot BR(\tau\tau)$	$12 \oplus 15$	$8 \oplus 2.4$	$2.8 \oplus 1.2$
$\sigma(Wh) \cdot BR(b\bar{b})$	—	$8 \oplus 3.8$	$4.4 \oplus 1.7$
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	—	$35 \oplus 11.7$	$16 \oplus 5.9$
$\sigma(t\bar{t}h) \cdot BR(\gamma\gamma)$	$17 \oplus 12$	$28 \oplus 11.7$	$12 \oplus 5.9$
$\sigma(Zh) \cdot BR(invis)$	—	$10 \oplus 4.3$	$3.5 \oplus 2.2$

μ values	300 fb^{-1}		3000 fb^{-1}	
	CMS	here	CMS	here
$\gamma\gamma$	[6 , 12]	[6.2 , 11.3]	[4 , 8]	[3.7 , 8.0]
WW	[6 , 11]	[7.6 , 12.7]	[4 , 7]	[5.2 , 11.9]
ZZ	[7 , 11]	[6.2 , 12.7]	[4 , 7]	[3.0 , 7.0]
$b\bar{b}$	[11 , 14]	[13.6 , 16.7]	[5 , 7]	[4.7 , 8.6]
$\tau^+\tau^-$	[8 , 14]	[6.2 , 12.0]	[5, 8]	[2.8 , 7.2]
invis.	[11 , 17]	[11.2 , 16.6]	[4 , 11]	[4.1 , 10.9]
κ values	300 fb^{-1}		3000 fb^{-1}	
	CMS	here	CMS	here
γ	[5 , 7]	[5.7 , 9.0]	[2 , 5]	[2.9 , 6.5]
W	[4 , 6]	[4.2 , 5.4]	[2 , 5]	[1.6 , 3.3]
Z	[4 , 6]	[5.7 , 8.5]	[2 , 4]	[2.8 , 6.3]
g	[6 , 8]	[4.9 , 6.9]	[3 , 5]	[2.3 , 4.8]
b	[10 , 13]	[11.4 , 14.9]	[4 , 7]	[4.2 , 8.5]
t	[14 , 15]	[17.3 , 20.5]	[6 , 8]	[5.7 , 12.9]
τ	[6 , 8]	[5.8 , 9.5]	[2 , 5]	[2.7 , 6.5]
inv.	[8 , 11]	[6.3 , 8.0]	[4 , 7]	[2.0 , 4.0]

Most important feature revealed in this study:

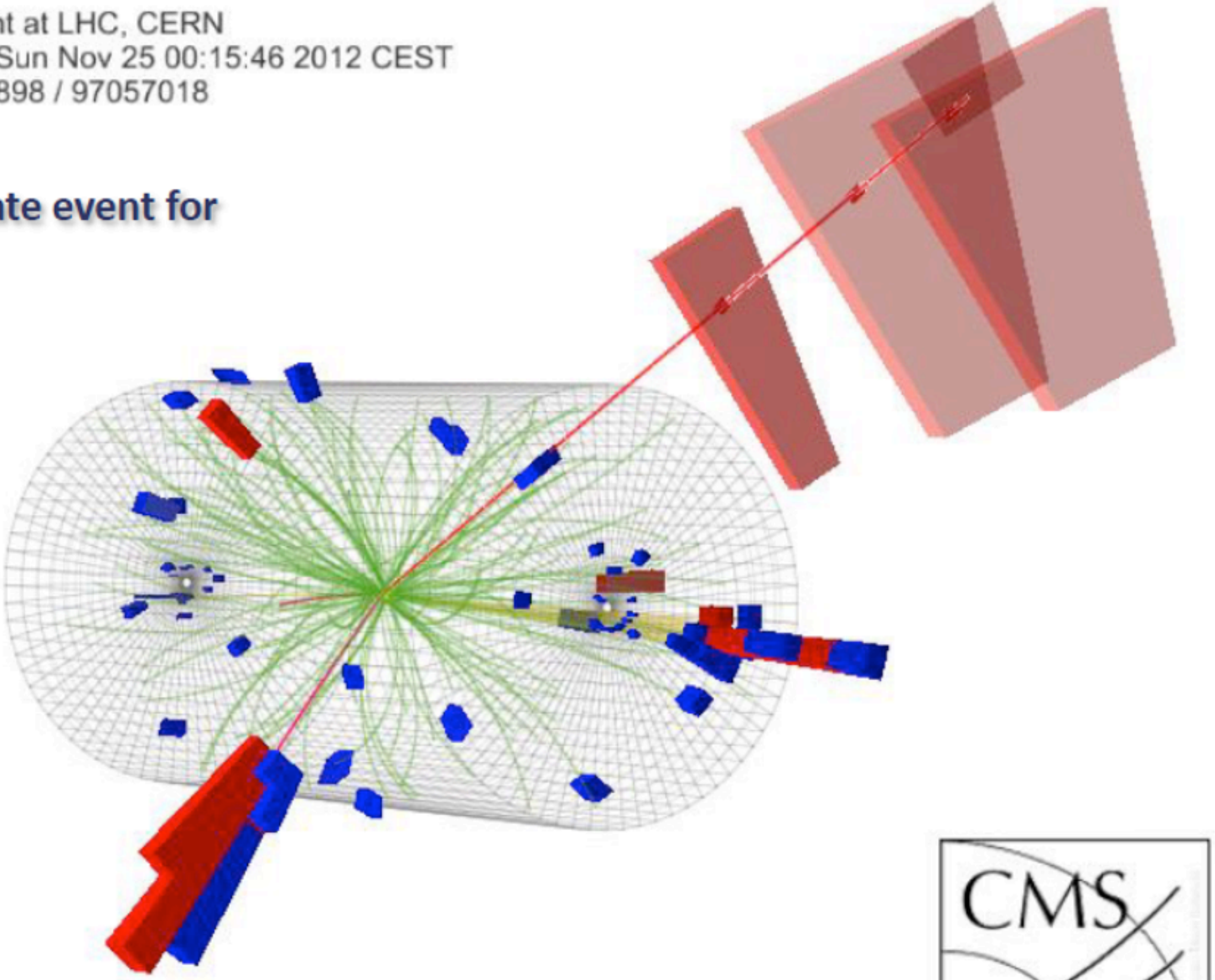
As statistics increase, the production processes dominating Higgs rate measurements shift from gg fusion to VB fusion and Wh, Zh associated production.

These latter processes have much smaller theory errors in the total rates.

There is still much uncertainty in the projections for $h \to b\bar{b}$ processes. These involve sophisticated selections against $g \to b\bar{b}$, $Z \to b\bar{b}$. In fitting for Higgs couplings, these processes have the largest effects on the estimation of Γ_T , which affects all output Higgs couplings.

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 25 00:15:46 2012 CEST
Run/Event: 207898 / 97057018

VBF candidate event for $H \rightarrow \tau\tau \rightarrow \mu\tau_h$



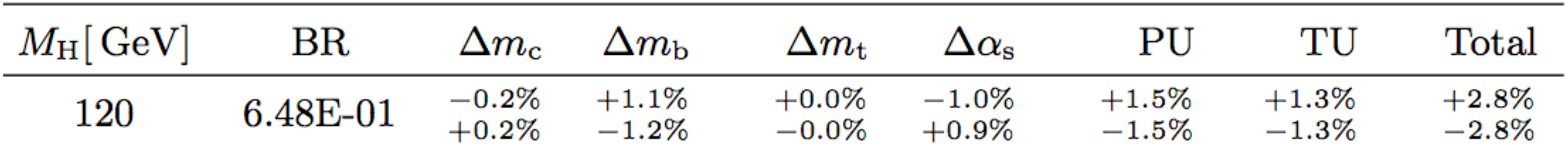
2. Theoretical uncertainties in the SM predictions for Higgs partial widths

from the 2012 paper of Gupta, Rzehak, and Wells:

“It is impossible to pin down the bottom quark Yukawa coupling to better than a few percent no matter how well the partial width is measured due to the higher order corrections. Thus, measuring the partial widths, or equivalently measuring some “observable coupling”, to significantly better than a few percent is not needed, although such precision would be welcome for future generations who might be able to calculate better than us.”

This is a totally incorrect statement.

Here is the Higgs Cross Section Working Group's assessment of current errors in $BR(h \to b\bar{b})$, from Denner, et al. arXiv:1107.5909. Errors in the partial width are roughly double these; errors in $g(hb\bar{b})$ are then roughly comparable to these.



M_{H}[GeV]	BR	Δm_{c}	Δm_{b}	Δm_{t}	$\Delta \alpha_{\mathrm{s}}$	PU	TU	Total
120	6.48E-01	−0.2% +0.2%	+1.1% −1.2%	+0.0% −0.0%	−1.0% +0.9%	+1.5% −1.5%	+1.3% −1.3%	+2.8% −2.8%

It is important to realize that these are conservative uncertainties tabulated for the purpose of current LHC experimental analyses.

It is a very different question to estimate how well we will predict Higgs partial widths in the precision era.

The uncertainties are of two types:

- Theory uncertainty, from uncalculated terms in perturbation theory

- Parametric uncertainty, from uncertainties in the input parameters

In this discussion, I will quote uncertainties in $g(hb\bar{b})$; uncertainties in the partial width are double these.

Theory uncertainties can be assessed by looking at the effect of the highest terms in perturbation theory currently computed.

$\mathcal{O}(\alpha_s^4) \;:\quad +0.15\%$ Baikov, Chetyrkin, Kuhn

$\mathcal{O}(\alpha_w) \;:\quad +0.3\%$ Dabelstein, Hollik, Kniehl

$\mathcal{O}(\alpha_s \alpha_w \frac{m_t^2}{m_W^2}) \;:\quad -0.2\%$ Kwiatkowski, Steinhauser

There is currently no complete calculation of $\Gamma(h \to b\bar{b})$ to 2-loop order. This is within the state of the art. Completing this calculation will leave QCD as the dominant theoretical uncertainty.

Next, discuss parametric uncertainties. The dominant ones are captured by the formula:

$$\Gamma(h \to b\bar{b}) \sim m_b^2(m_b)\ \left[\frac{\alpha_s(m_b)}{\alpha_s(m_h)}\right]^{24/23}\ \left(1 + 5.67\frac{\alpha_s(m_h)}{\pi} + \cdots\right)$$

This leads to

$$\frac{\Delta[g(hb\bar{b})]}{g(hb\bar{b})} = \frac{\Delta[m_b(m_b)]}{m_b(m_b)} \oplus (0.4\frac{\Delta[\alpha_s(m_Z)]}{\alpha_s(m_Z)} + 0.1\frac{\Delta[\alpha_s(m_Z)]}{\alpha_s(m_Z)})$$

Sub-percent accuracy in the theoretical prediction indeed looks very challenging.

The solution comes from appreciating the power of lattice gauge theory.

Lattice gauge theory results already bring the parametric uncertainties below 1%.

These results are systematically improvable as computers become more powerful.

Paul Mackenzie (Fermilab) will give a talk on this subject on Thursday.

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

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

$$4.166\ (43)$$

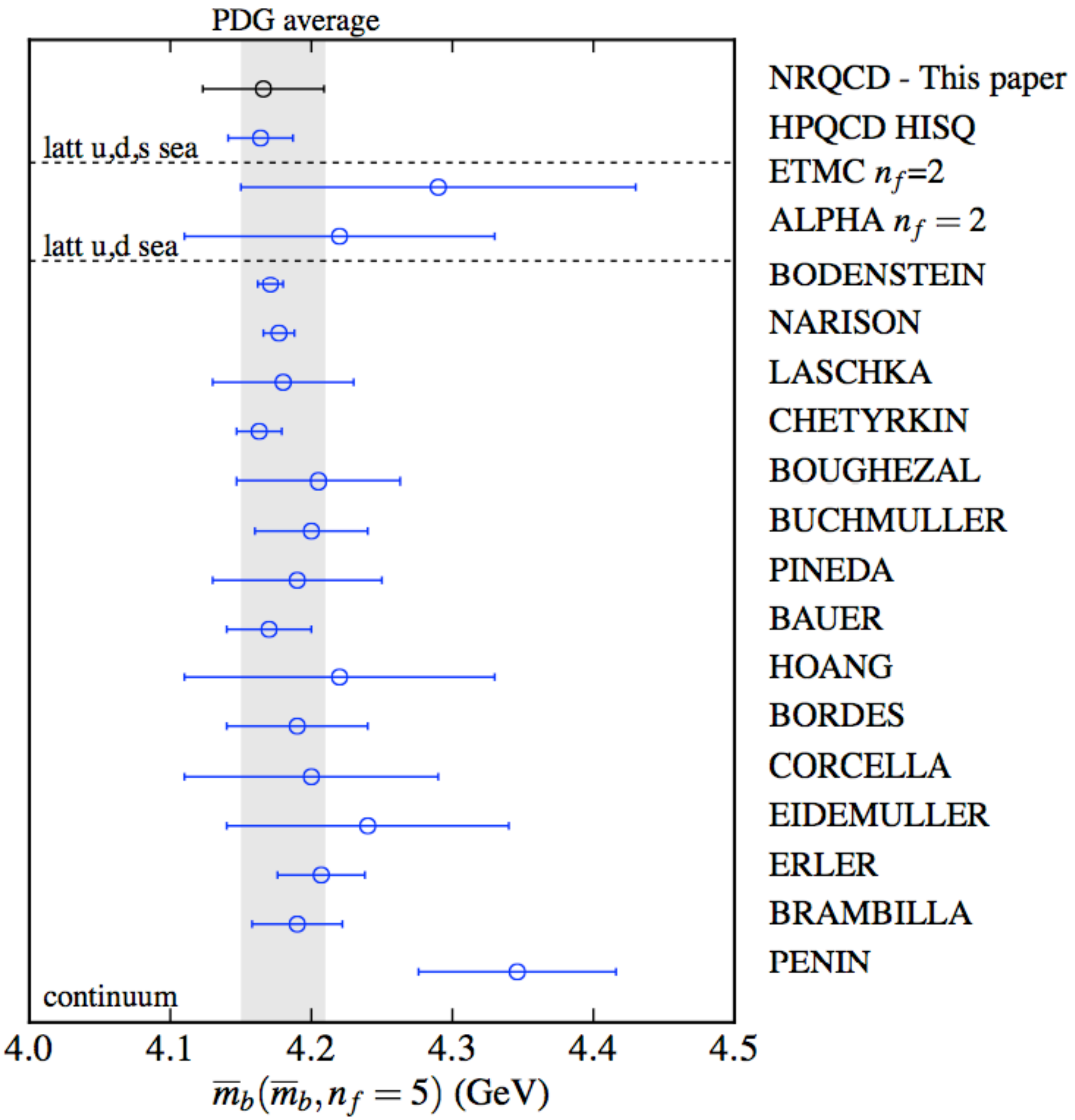
$$4.164\ (23)$$

Comparable results from QCD sum rules are

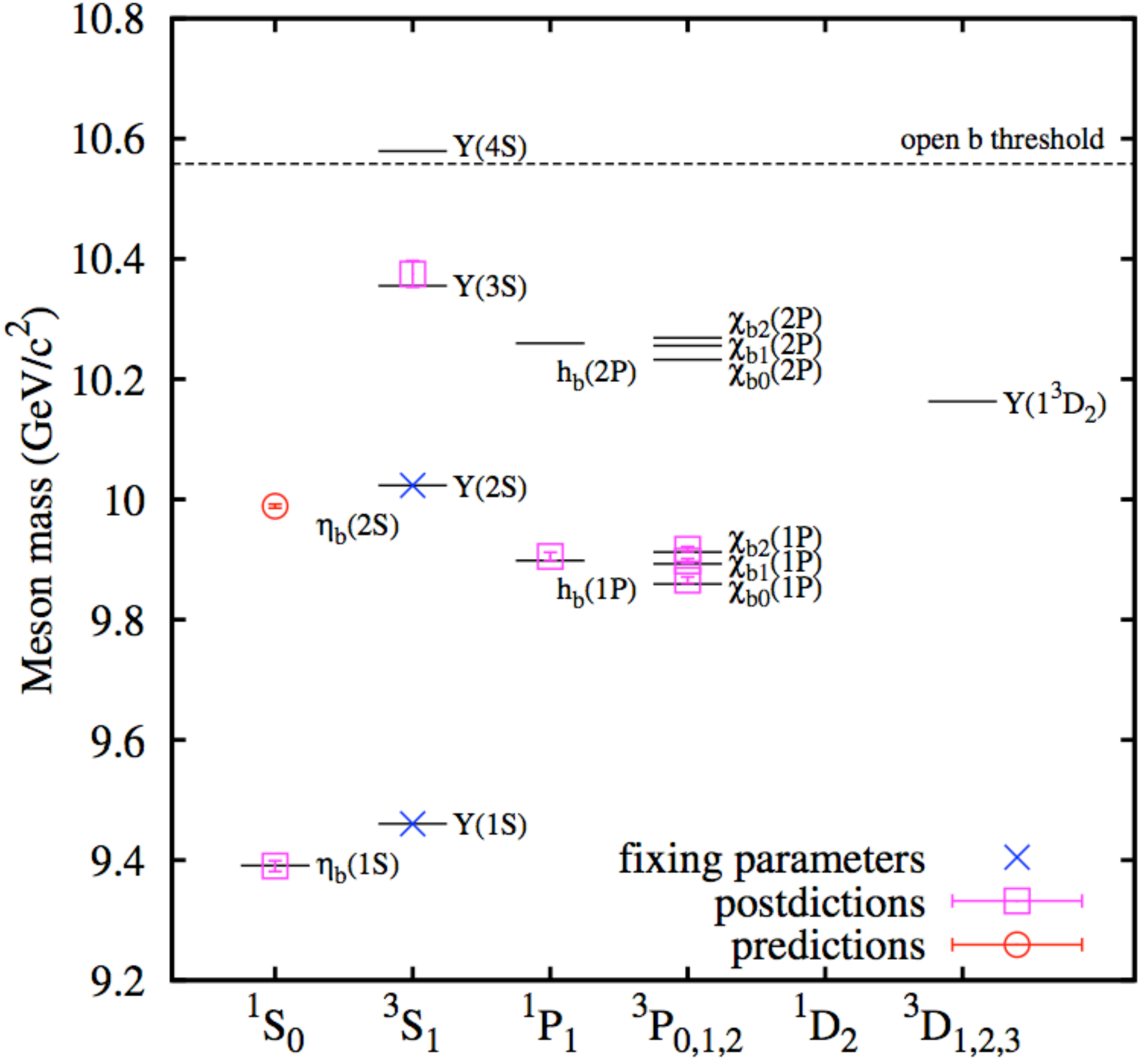
$$4.171\ (9)$$

$$4.177\ (11)$$

$$4.163\ (16)$$



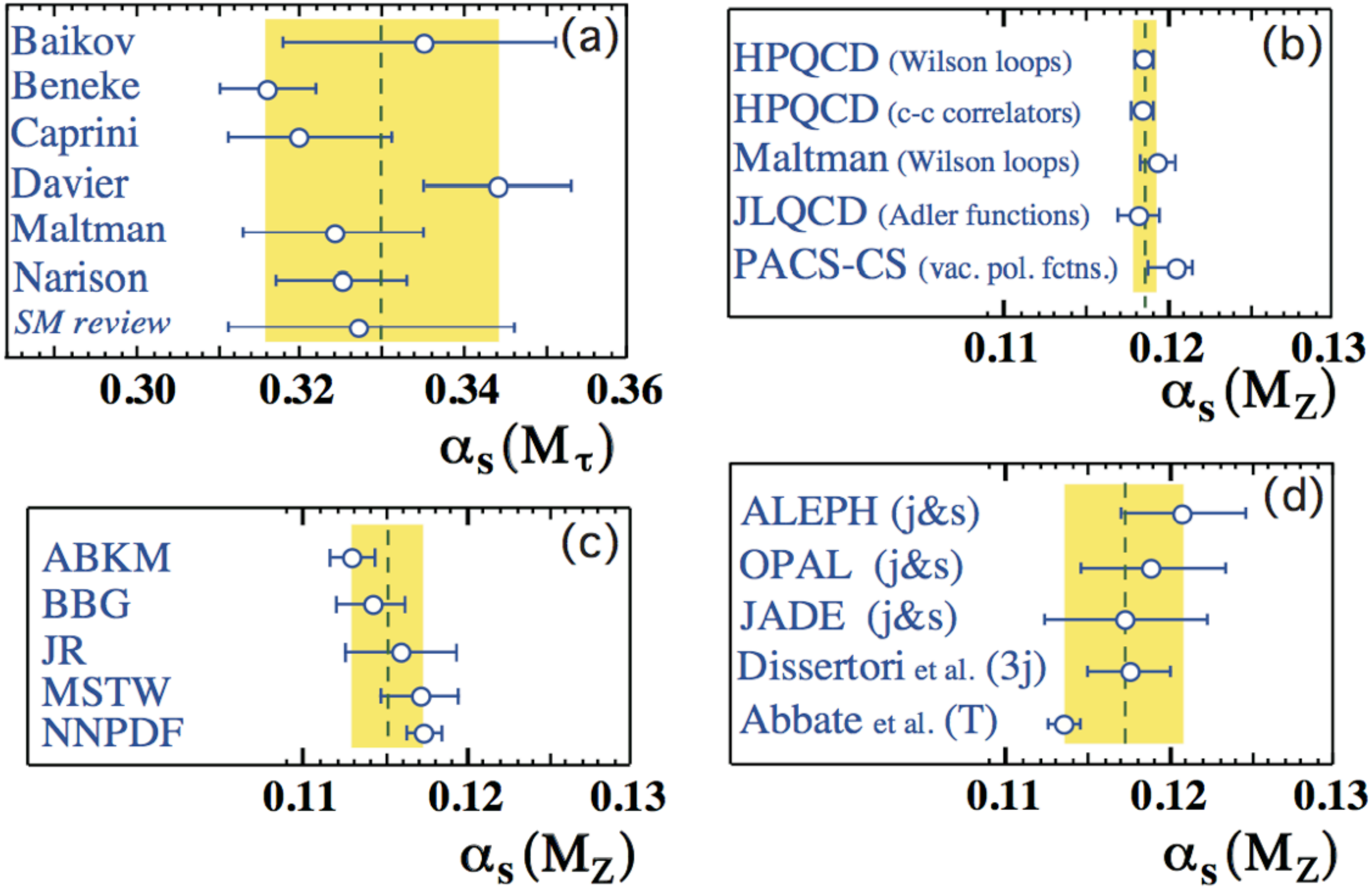
From the global fit to B decay distributions using HQET (HFAG): $4.194\ (43)$



10.8
10.6
10.4
10.2
10
9.8
9.6
9.4
9.2
Meson mass (GeV/c^2)
$^1S_0$
$^3S_1$
$^1P_1$
$^3P_{0,1,2}$
$^1D_2$
$^3D_{1,2,3}$
open b threshold
Υ(4S)
Υ(3S)
χ_{b2}(2P)
χ_{b1}(2P)
χ_{b0}(2P)
h_b(2P)
Υ(1^3D_2)
Υ(2S)
η_b(2S)
χ_{b2}(1P)
χ_{b1}(1P)
χ_{b0}(1P)
h_b(1P)
Υ(1S)
η_b(1S)
fixing parameters
postdictions
predictions

HPQCD

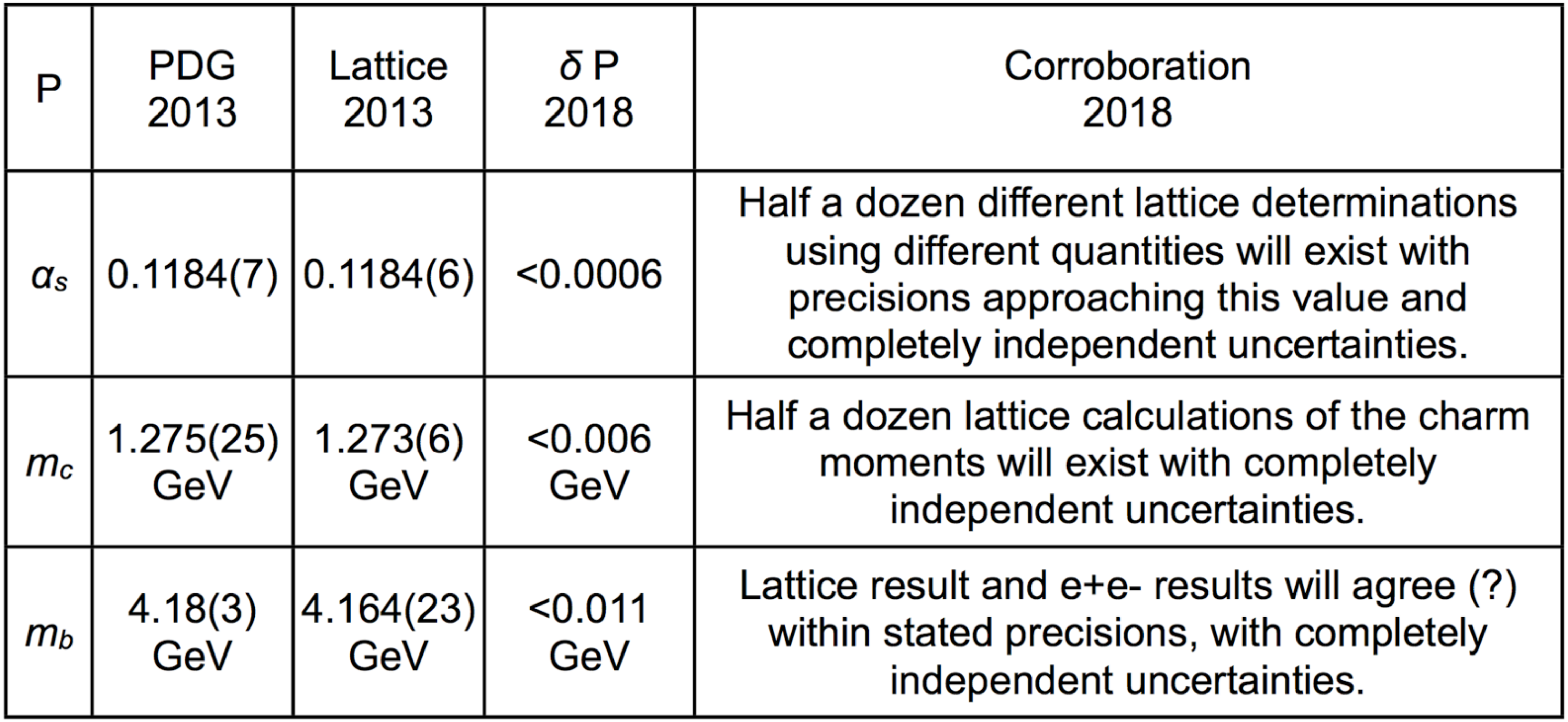
most recent PDG compilation of α_s measurements



The PDG value, dominated by lattice, is

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

from Paul Mackenzie’s talk at Snowmass:



P	PDG 2013	Lattice 2013	δ P 2018	Corroboration 2018
α_s	0.1184(7)	0.1184(6)	<0.0006	Half a dozen different lattice determinations using different quantities will exist with precisions approaching this value and completely independent uncertainties.
m_c	1.275(25) GeV	1.273(6) GeV	<0.006 GeV	Half a dozen lattice calculations of the charm moments will exist with completely independent uncertainties.
m_b	4.18(3) GeV	4.164(23) GeV	<0.011 GeV	Lattice result and e+e- results will agree (?) within stated precisions, with completely independent uncertainties.

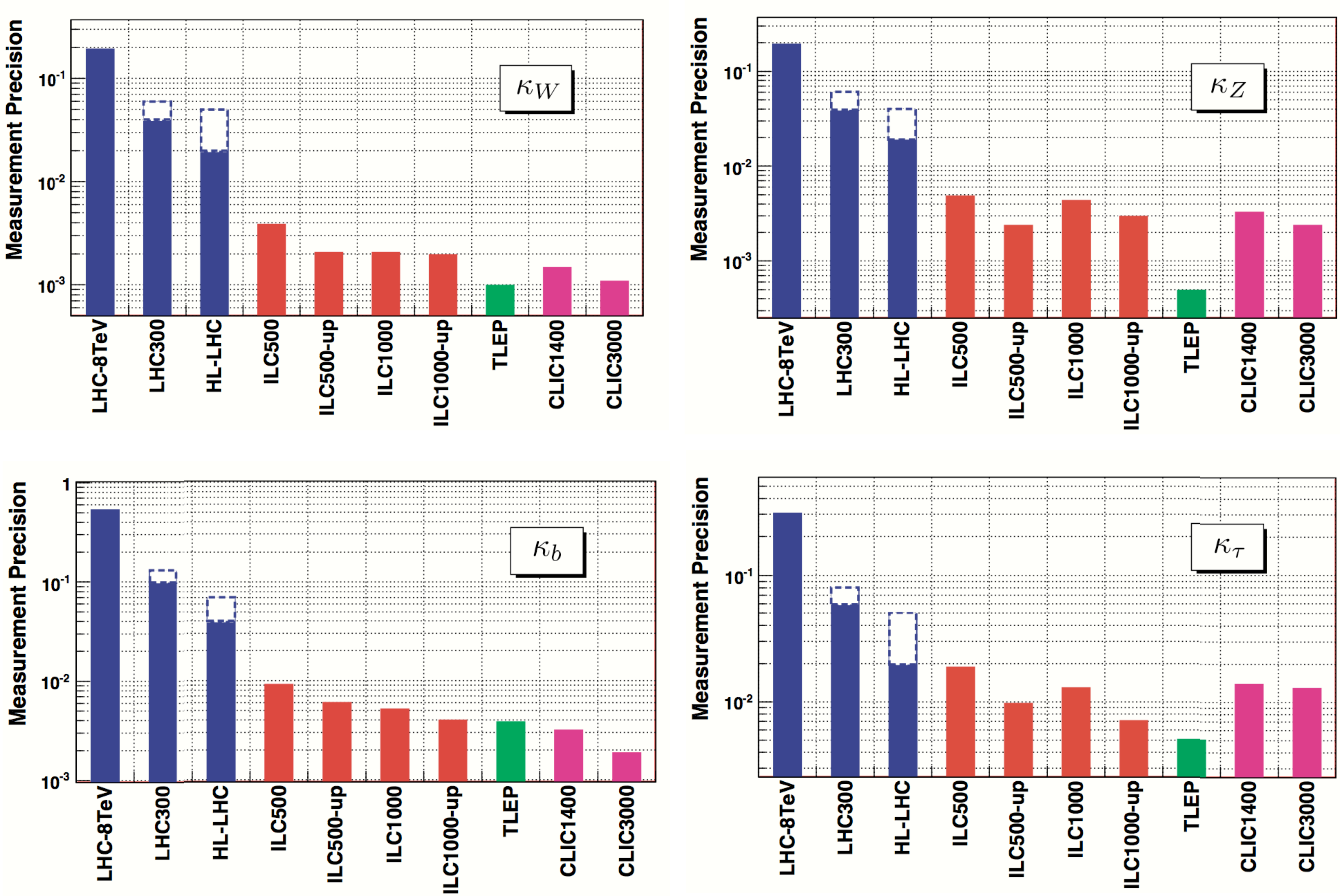
The predicted accuracies are:

0.5% in $\alpha_s(m_Z)$,
0.5% in $m_c(3\ \mathrm{GeV})$,
0.3% in $m_b(m_b)$

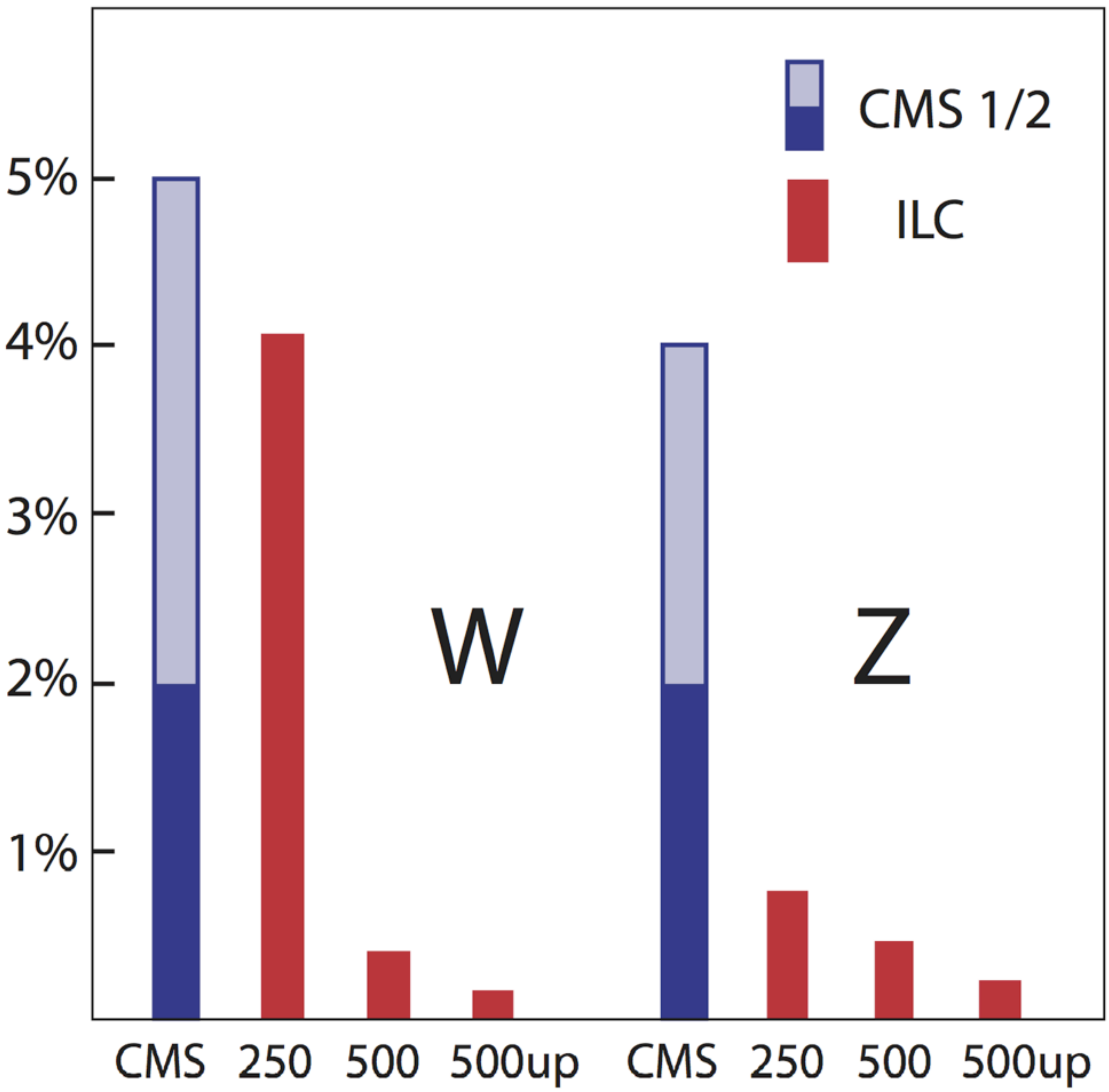
predicts
0.4% param.
uncertainty in
$g(hb\bar{b})$

3. Power of the constraint $\sum_i BR_i = 1$

Those of you with sharp eyes might have noticed that the estimates of ILC uncertainty that I made yesterday are stronger than those in the ILC Higgs White Paper or in the Snowmass Higgs report.



Snowmass Higgs report


5%
4%
3%
2%
1%
CMS 1/2
ILC
W
Z
CMS
250
500
500up
CMS
250
500
500up

The reason for this is that I used a 9-parameter fit constrained to the relation $\sum_i BR_i = 1$.

This constraint is very powerful because determinations of Higgs couplings require constraining the Higgs total width.

$$\sigma(A\overline{A} \to h) \cdot BR(h \to B\overline{B}) \sim \frac{\Gamma(h \to A\overline{A})\Gamma(h \to B\overline{B})}{\Gamma_T}$$

The constraint has a large effect here:

error in Γ_T	unconstrained	$\sum BR = 1$
ILC 500	5.0%	1.6%
ILC 500 up	2.8%	0.75%
ILC 1000	4.6%	1.2%

A. Blondel at the Seattle Snowmass meeting criticized my fit for the ILC TDR. He suggested that one should make “no assumption on the Higgs exotic decays … thus making the fit truly model-independent and truly representative of the lepton-collider potential.”

However, his fit led to a limit on Higgs exotic decays

$$BR(\text{exotic}) < 2.9\%$$

This is comparable to $BR(h \to c\bar{c})$, which is measured to 5% at ILC 500.

So, wouldn’t someone have noticed that the Higgs is decaying exotically ?

In fact, the tagged Higgs process $e^+e^- \to Zh$ gives an opportunity to recognize any type of exotic Higgs decay.

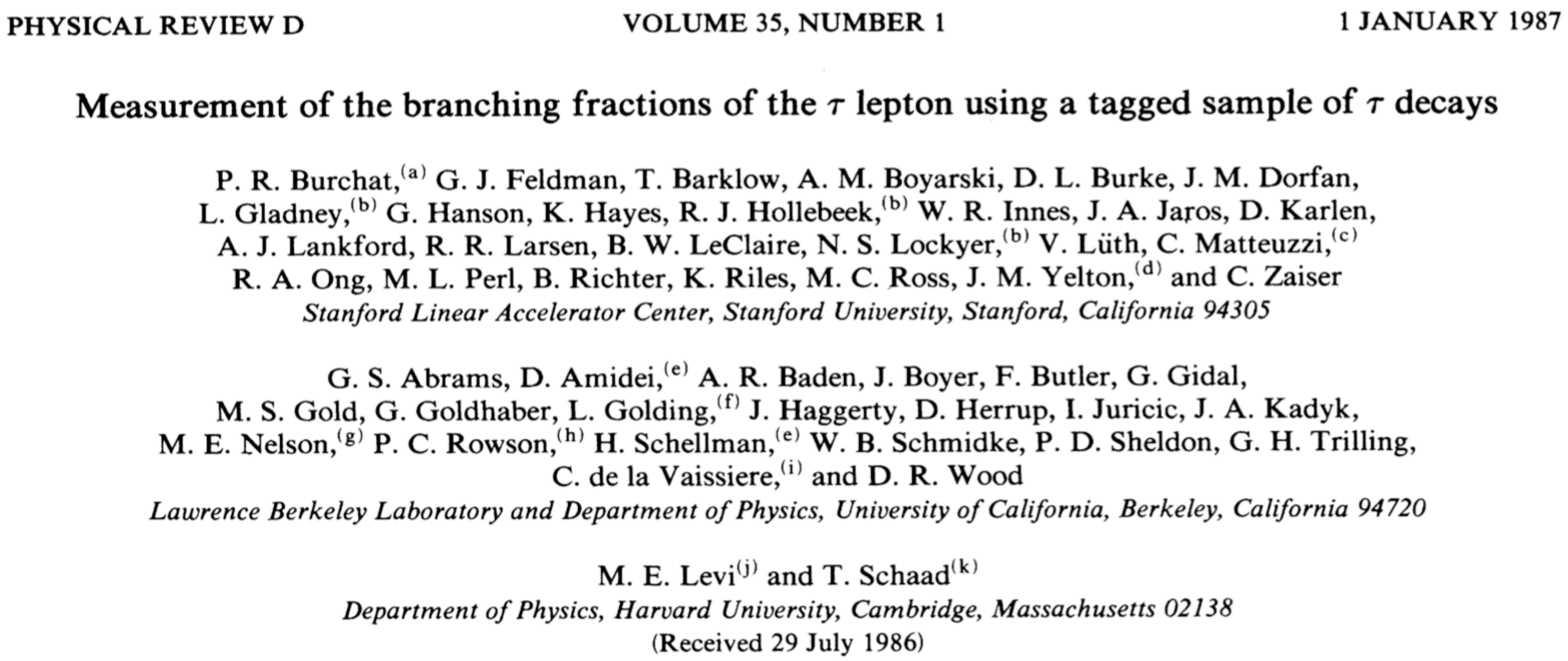
We need to formally design a Higgs coupling analysis that takes advantage of this and allows us to impose the constraint

$$\sum_i BR_i = 1$$

when we determine Higgs couplings at the ILC.

There is some relevant experience from the 1980's: "tau 1-prong problem"

Are there additional non-Standard tau decays ?



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Measurement of the branching fractions of the τ lepton using a tagged sample of τ decays

P. R. Burchat,(a) G. J. Feldman, T. Barklow, A. M. Boyarski, D. L. Burke, J. M. Dorfan,
L. Gladney,(b) G. Hanson, K. Hayes, R. J. Hollebeek,(b) W. R. Innes, J. A. Jaros, D. Karlen,
A. J. Lankford, R. R. Larsen, B. W. LeClaire, N. S. Lockyer,(b) V. Lüth, C. Matteuzzi,(c)
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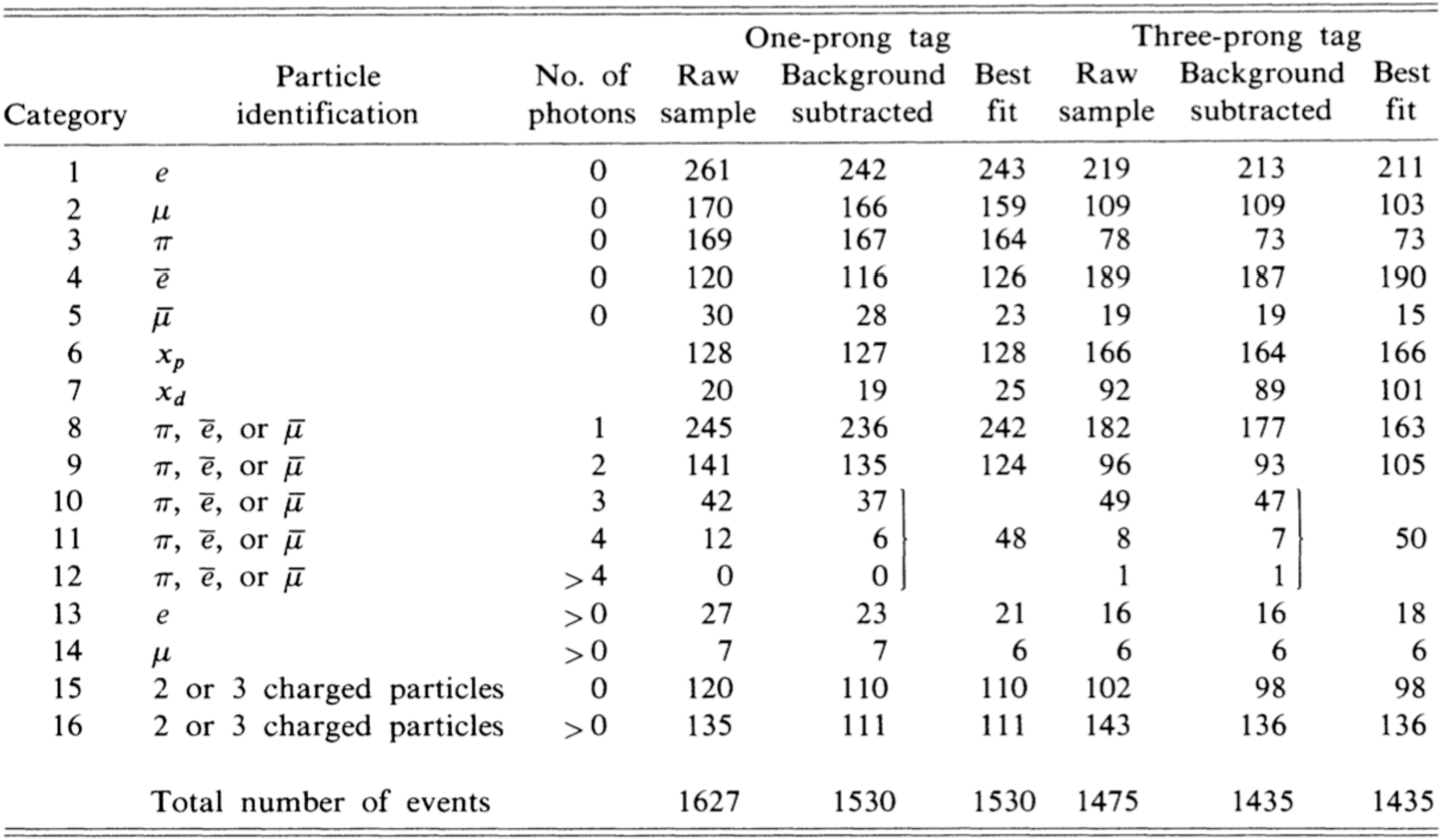
and Patricia Burchat's thesis

collect $e^+e^- \to \tau^+\tau^-$ events with one τ cleanly identified ; look at the recoiling state; classify all events



			One-prong tag			Three-prong tag		
Category	Particle identification	No. of photons	Raw sample	Background subtracted	Best fit	Raw sample	Background subtracted	Best fit
1	e	0	261	242	243	219	213	211
2	μ	0	170	166	159	109	109	103
3	π	0	169	167	164	78	73	73
4	$\bar{e}$	0	120	116	126	189	187	190
5	$\bar{\mu}$	0	30	28	23	19	19	15
6	x_p		128	127	128	166	164	166
7	x_d		20	19	25	92	89	101
8	π, $\bar{e}$, or $\bar{\mu}$	1	245	236	242	182	177	163
9	π, $\bar{e}$, or $\bar{\mu}$	2	141	135	124	96	93	105
10	π, $\bar{e}$, or $\bar{\mu}$	3	42	37	48	49	47	50
11	π, $\bar{e}$, or $\bar{\mu}$	4	12	6		8	7	
12	π, $\bar{e}$, or $\bar{\mu}$	>4	0	0		1	1	
13	e	>0	27	23	21	16	16	18
14	μ	>0	7	7	6	6	6	6
15	2 or 3 charged particles	0	120	110	110	102	98	98
16	2 or 3 charged particles	>0	135	111	111	143	136	136
	Total number of events		1627	1530	1530	1475	1435	1435

more categories than decay modes;
goodness of fit tests the SM hypothesis

This strategy sacrifices statistics for cleanliness of tau ID.

But, at ILC, Higgs statistics are also at a premium.

An optimal strategy would also include:

additional categories for background events;
compare these to precise SM expectations

BDT or other classifier applied to sort all
events potentially tagged as Higgs

We still have much to learn about how to measure the Higgs boson couplings with high precision.

I hope that this talk has offered some relevant opinions that we can debate over the next few days.