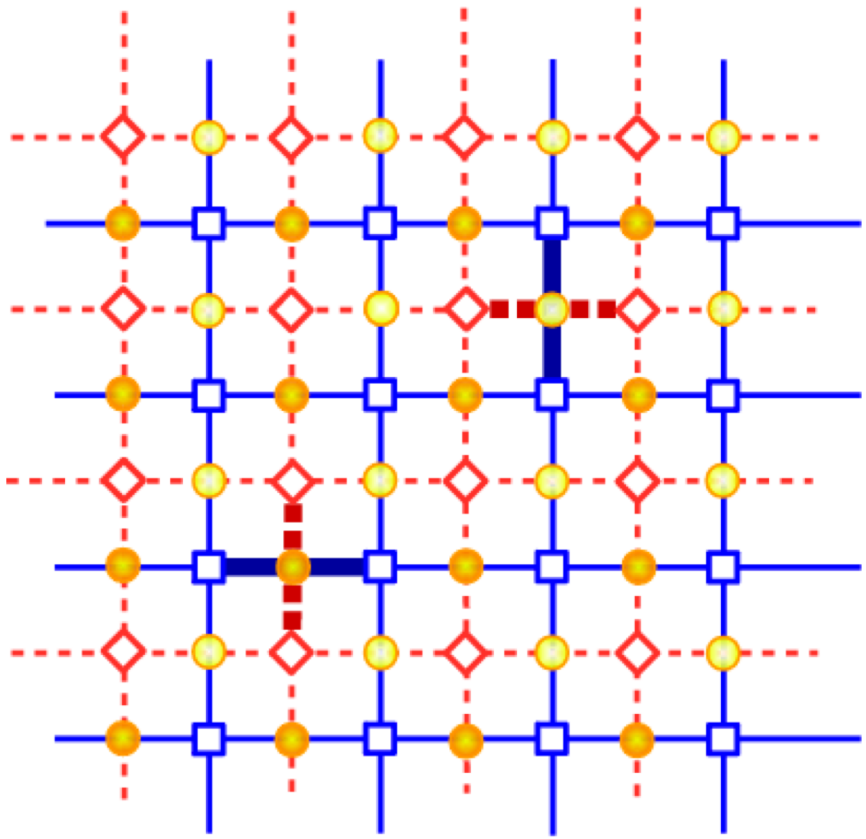
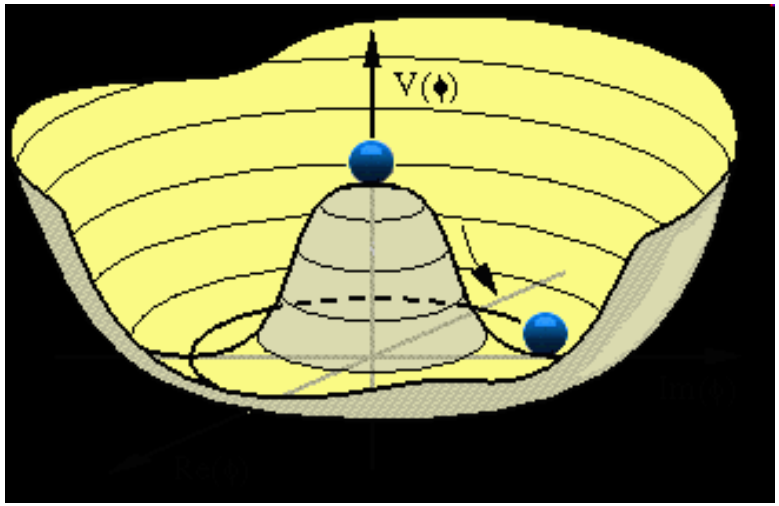
The Lattice and the Higgs Boson

Paul MacKenzie Symposium

Fermilab, Nov. 7, 2019

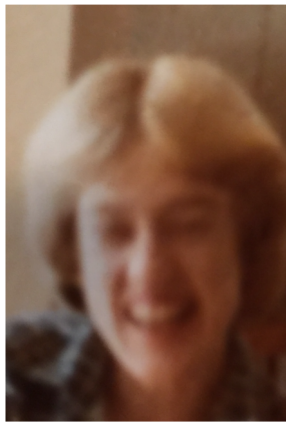
S. Dawson





Fermilab theory circa 1982

- It was a much smaller group
  - Fellow postdocs

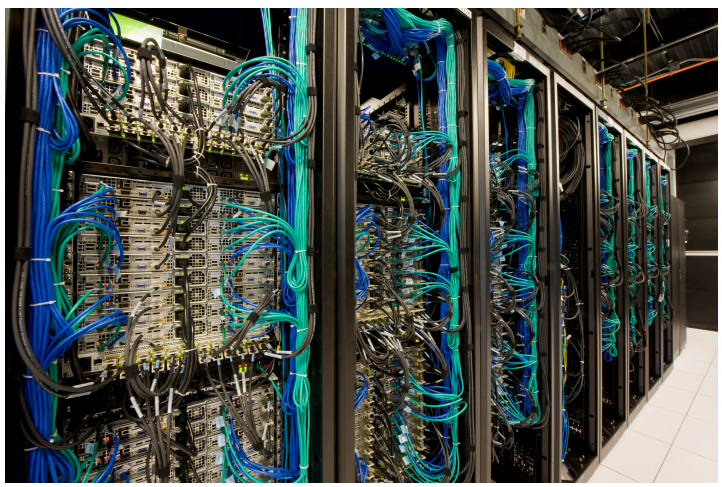


The lab was young

- 15th anniversary party, July 1982

The theory landscape was very different

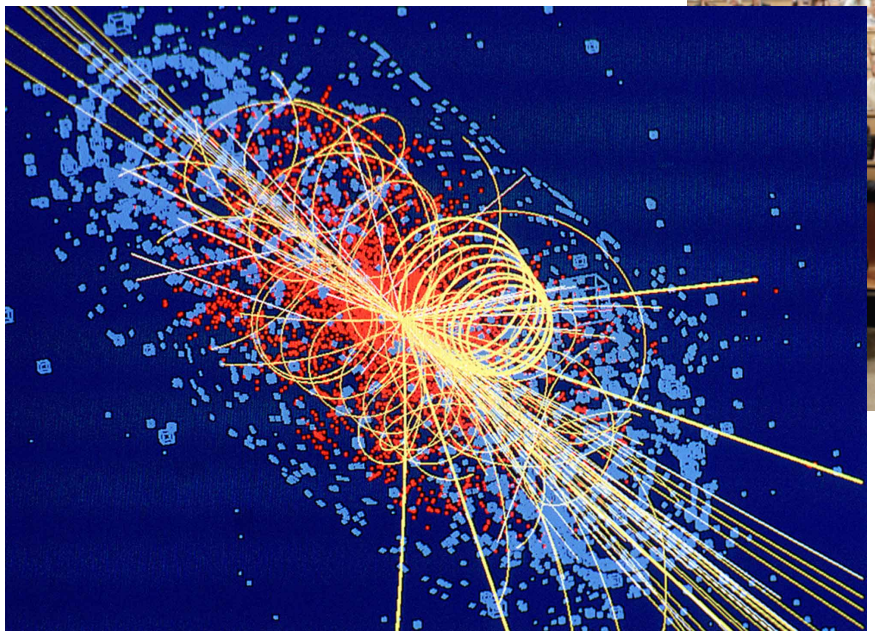
- The top quark and Higgs boson hadn't been discovered
- Theory calculations were much less sophisticated
- Lattice gauge theory was a small effort
- In Paul's career we went from



*VAX

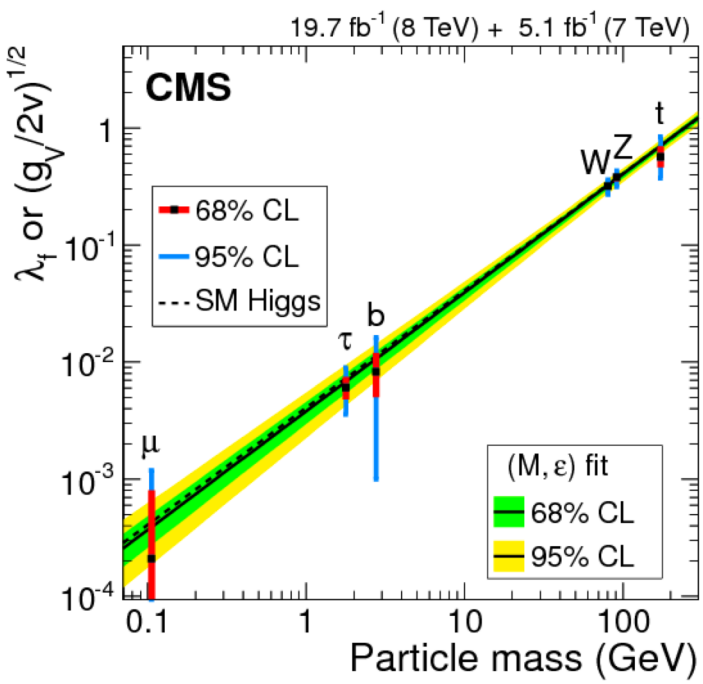
The discovery of the Higgs in 2012 changed everything….

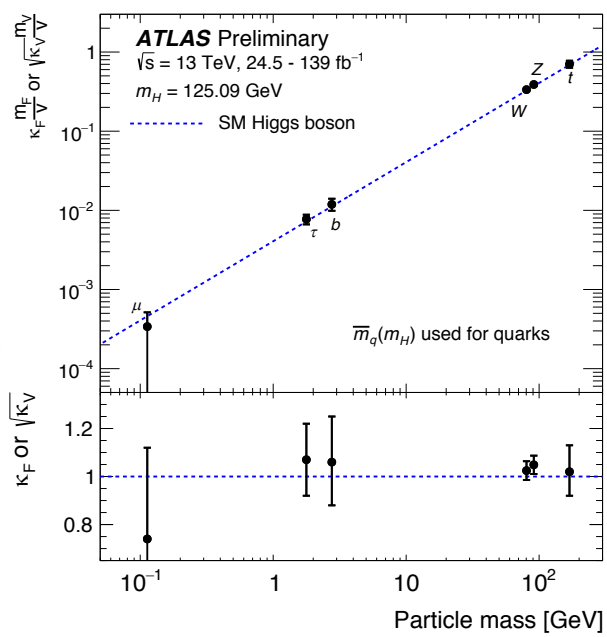
- LHC discovered a Higgs boson; it appears to have predicted properties



All Higgs Couplings predicted in SM

- Very precise predictions
  - Couplings to fermions proportional to mass
  - Couplings to gauge bosons proportional to gM_V
  - Higgs self-couplings proportional to M_H^2





If couplings didn't have this pattern, it would indicate that not all mass comes from a single Higgs boson

First step to Higgs couplings: κ approach

- κ_i=(Higgs coupling to particle i)/(SM Higgs coupling to particle i)
  - Simple rescaling; no momentum dependence
  - Gauge invariance of SM requires κ=1
- Assuming loops resolved and no BSM:

Current Limits

	CMS	ATLAS
k_Z	$.99^{+.11}_{-.12}$	$1.10^{+.08}_{-.08}$
k_W	$1.10^{+.12}_{-.17}$	$1.05^{+.08}_{-.08}$
k_t	$1.11^{+.12}_{-.10}$	$1.02^{+.11}_{-.10}$
k_b	$-1.10^{+.33}_{-.23}$	$1.06^{+.19}_{--.18}$
k_τ	$1.01^{+.16}_{-.20}$	$1.07^{+.15}_{-.15}$
k_μ	$.79^{+.58}_{-.79}$	<1.51 at 95% cl

- Couplings to gauge bosons at 8-12%
- Couplings to 3rd generation fermions at 15-20%

We are just getting to the interesting regime: Generically expect deviations

$$\kappa \sim \frac{v^2}{\Lambda^2}\left(\frac{1\ TeV}{\Lambda}\right)^2$$

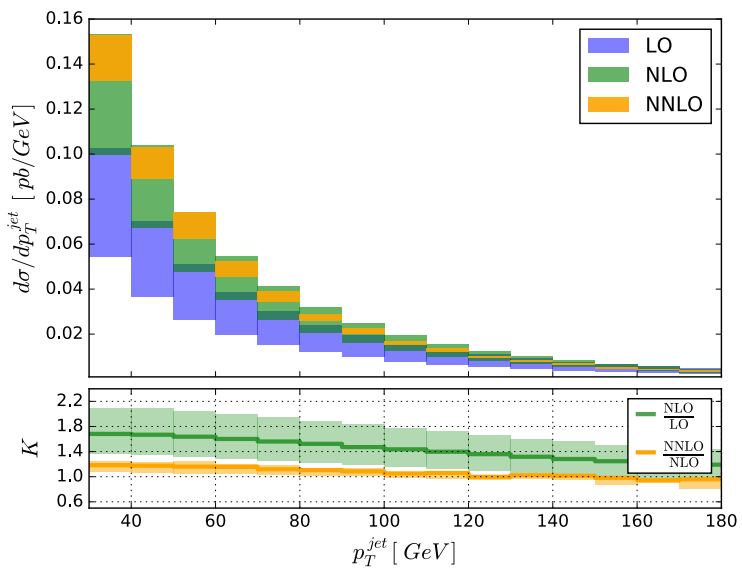
* As of July, 2019

CMS, arXiv:1809.10733
ATLAS, ATLAS-CONF-2019-005

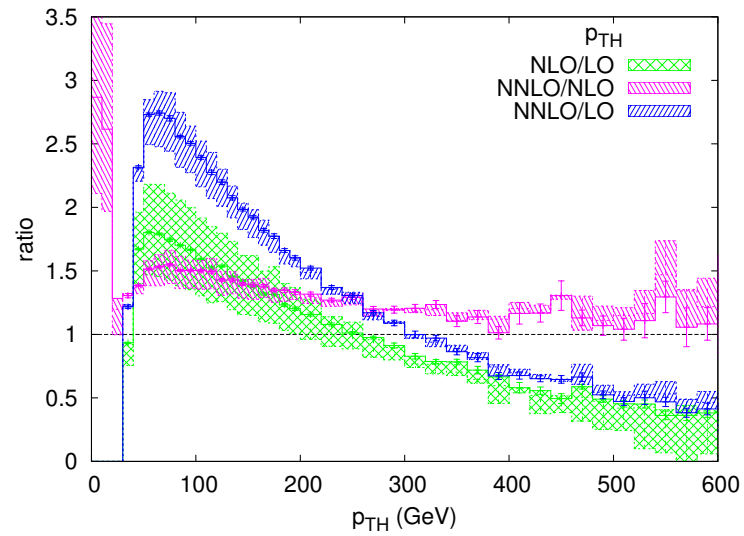
The era of precision Higgs physics

- Not just total rates
- Precision information from distributions

pp→H + jet, 8 TeV



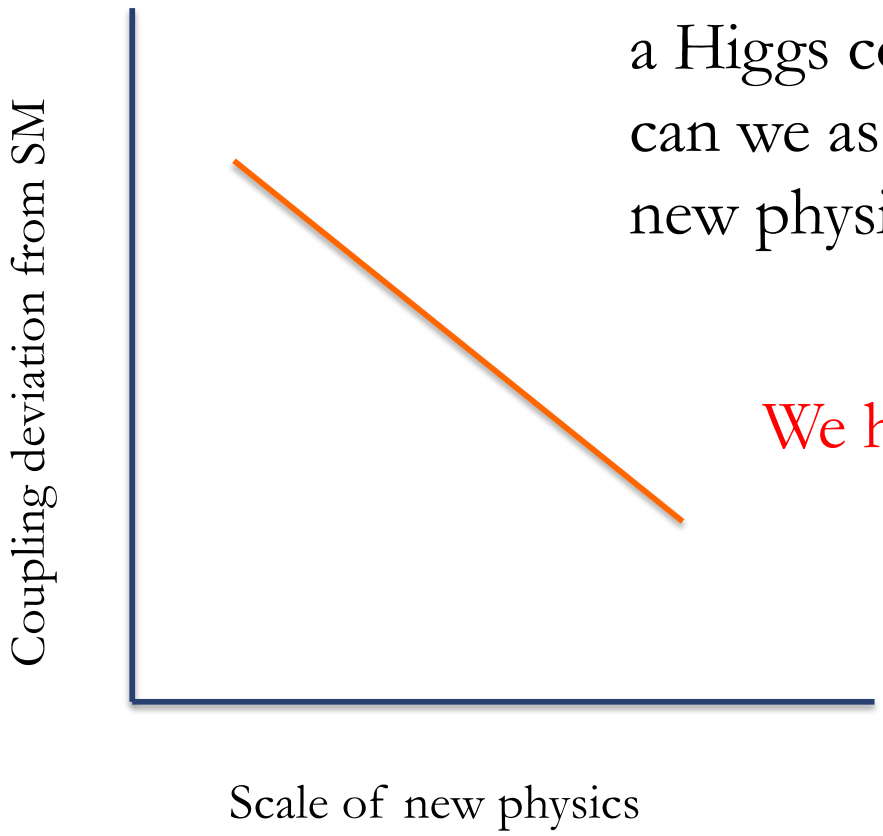
pp→H + jet, 8 TeV



New physics inferred from tails of distributions

Boughezal, Focke, Giele,Liu,Petriello, arXiv:1505.03893; Chen, Gerhrmann, Glover, Jaquier, arxiv:1408.5325

What we hope for



If we measure a large deviation of a Higgs coupling from the SM, can we associate it with a scale of new physics?

We have to understand the SM first

Many ingredients in theory predictions

Precision calculations of production and decay rates

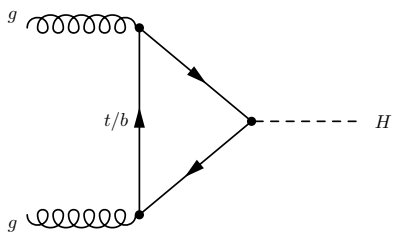
Parton distribution functions

Input parameters: α_s, m_t, m_b, ….

Lattice contributes to PDF and input parameters

Higgs Production

- Dominant production of Higgs boson is gluon fusion



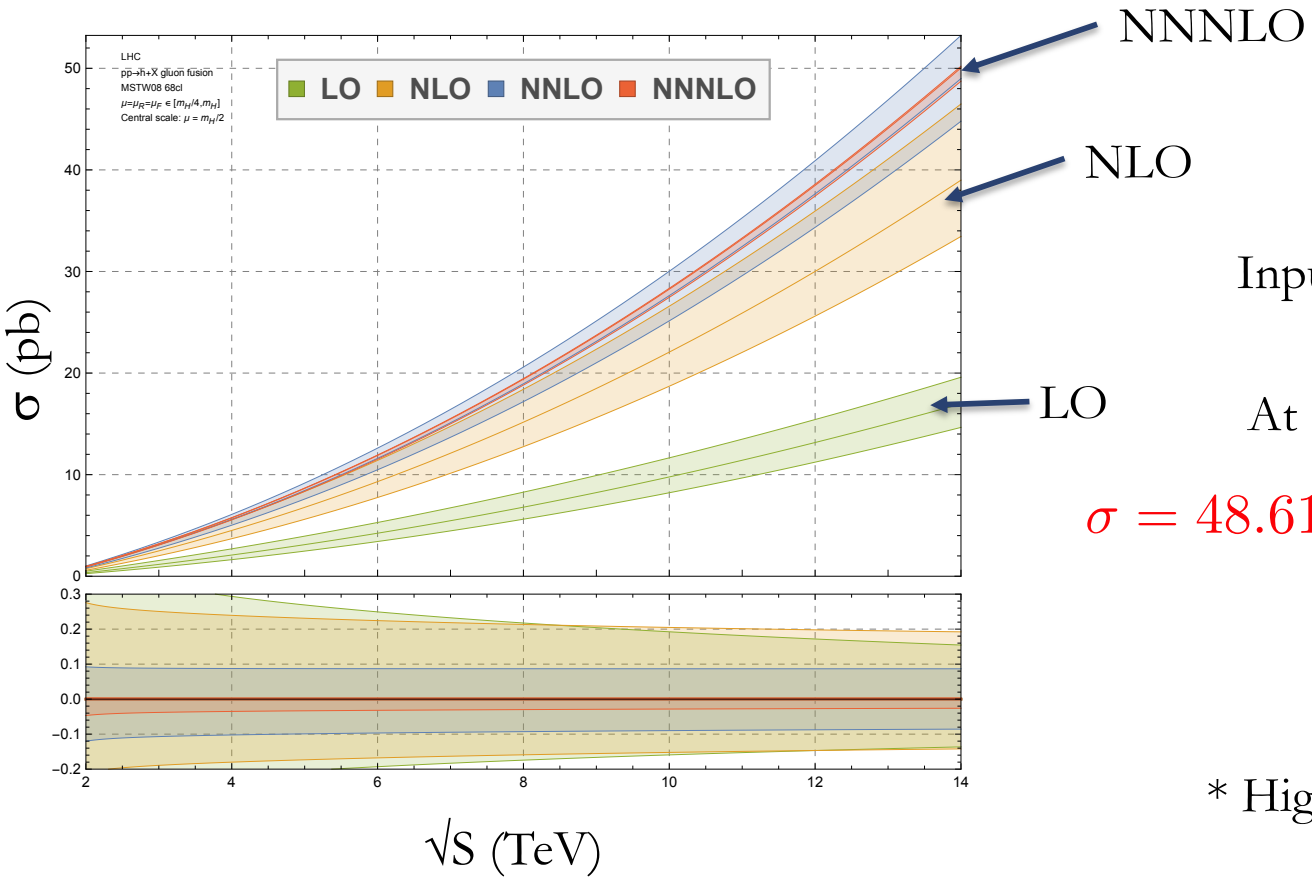
- Rate is power series in strong coupling constant, $\alpha_s \sim .118$

$$\sigma(gg \to H) = \alpha_s^2 \Big(\sigma_{LO} + \alpha_s \delta\sigma_{NLO} + \alpha_s^2 \delta\sigma_{NNLO} + \alpha_s^3 \delta\sigma_{NNNLO} + \ldots \Big)$$

1977 → 1995 → 2002 → 2015

Precision Higgs Production

- Bands are scale uncertainties



[Anastasiou,Duhr,Dulat,Herzog,Mistleberger, arXiv:1503.06056]

Input: $\alpha_s(M_Z)=0.118 \pm 0.0015$

At 13 TeV, NNNLO result:

$$\sigma = 48.61\ pb\ \underbrace{{}^{+4.27\%}_{-6.49\%}}_{\text{Theory}} \pm \underbrace{1.85\%}_{\text{PDF}} \pm \underbrace{2.6\%}_{\alpha_s}$$

* Higgs cross section working group

Theory errors dominate determination of Higgs parameters

Present status

ATLAS, Global Higgs signal strength

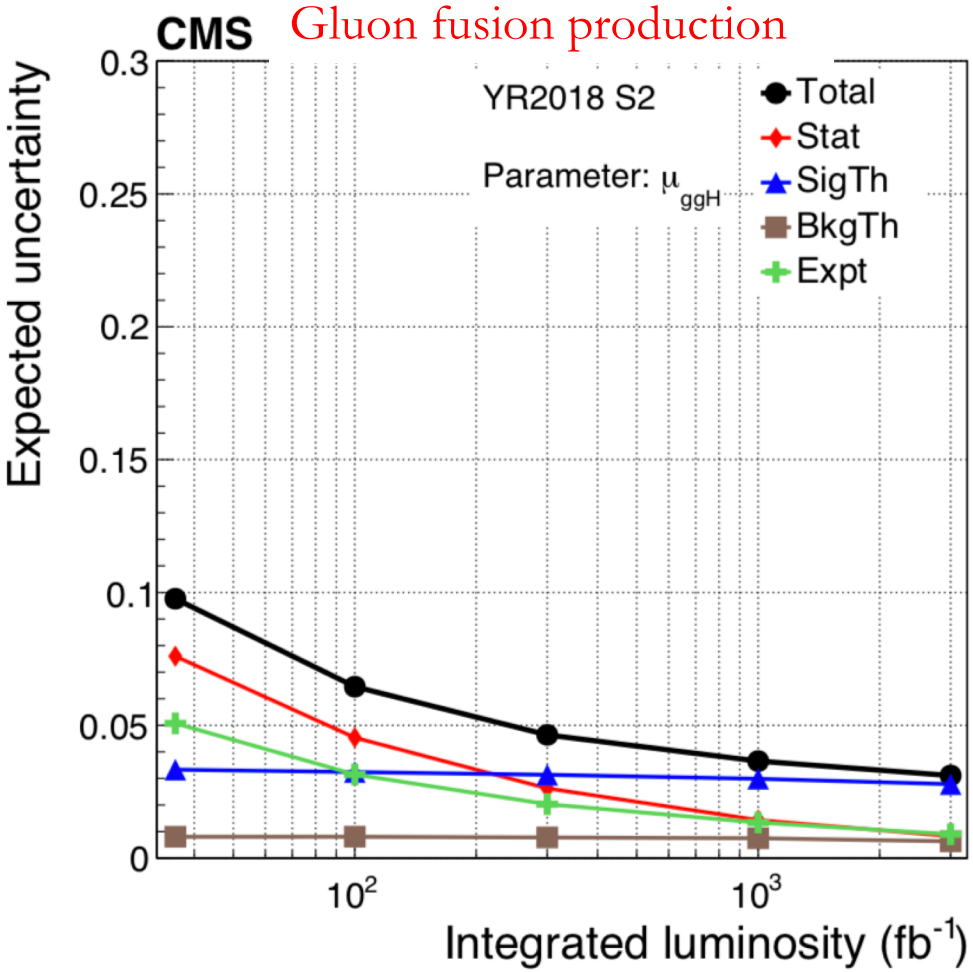
Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.4
Flavour tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

$$\mu = \frac{\sigma \cdot BR}{[\sigma \cdot BR]\,|_{SM}}$$

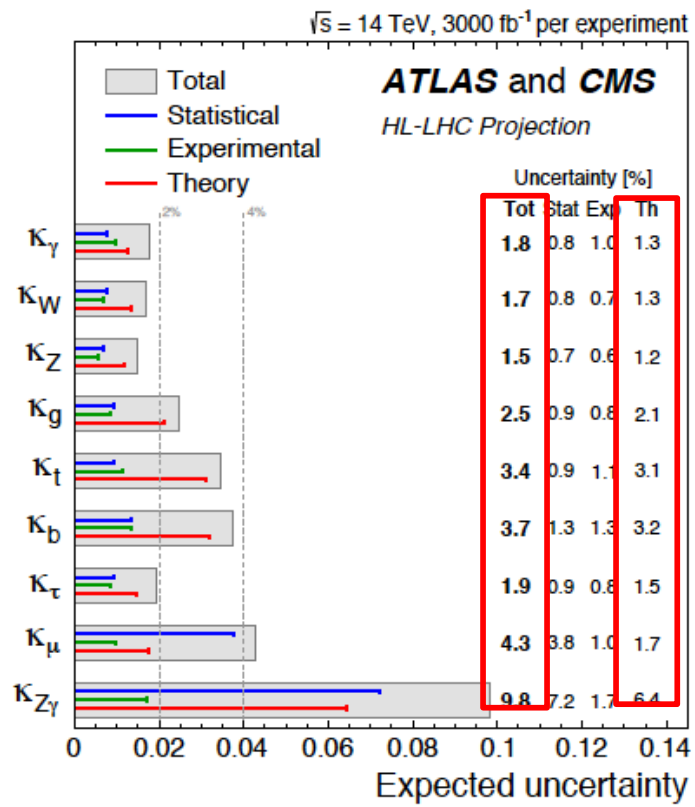
Lots of theoretical work needed!

The LHC Future (2032)

Gluon fusion production



Higgs Couplings

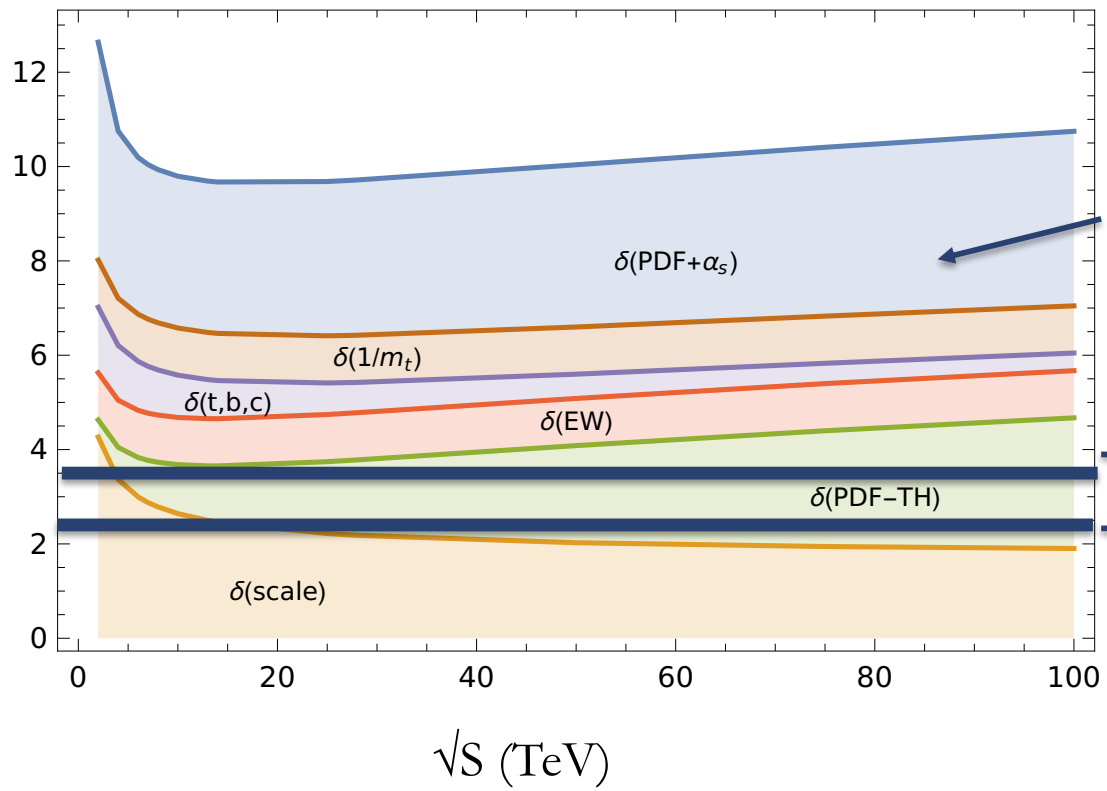


Theory errors dominate

Reducing Uncertainties on predictions

- Where do theory errors on gluon fusion rate for Higgs production come from?

Cumulative contributions to errors in %



PDF + α_s largest uncertainty

Projections assume a big improvement over the current status

[Dulat, Lazopoulos, Mistlberger, 1802.00827]

Paul has been working on α_s for a long time…..

- Paul's first mention on SPIRES: CLEO result

A Determination Of Alpha-s From The Leptonic Decay Of The Upsilon (1s) (1981)

- Followed by an early lattice result…

$$\alpha_s(M_Z) = .105 \pm 0.004$$

Fermi National Accelerator Laboratory

FERMILAB-PUB-91/354-T

A Determination of the Strong Coupling Constant from the Charmonium Spectrum

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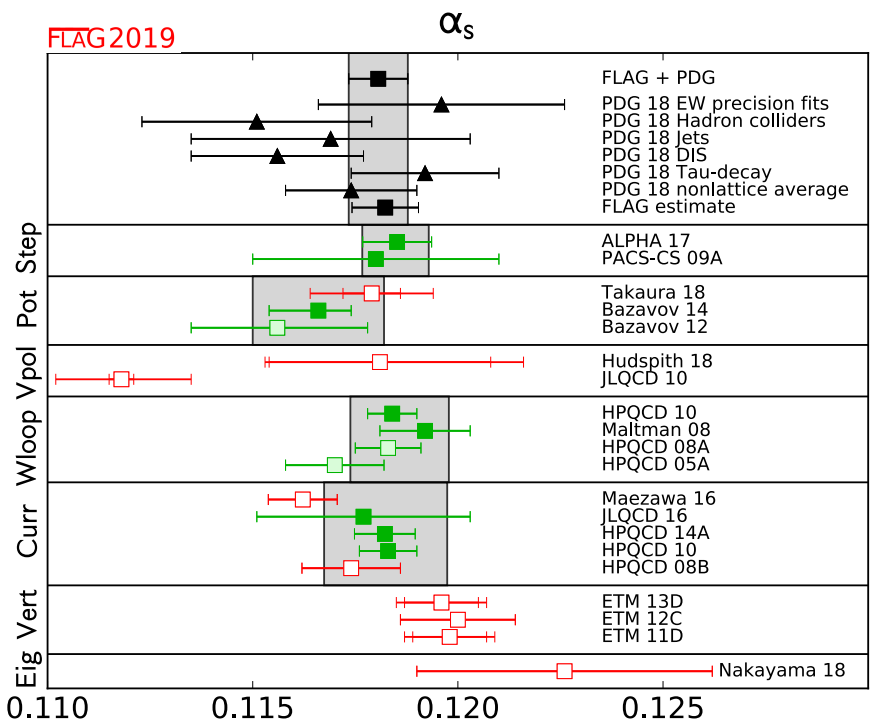
ABSTRACT

Lattice gauge theory techniques have recently achieved sufficient accuracy to permit a determination of the strong coupling constant from the 1P–1S splitting in the Charmonium system, with all systematic errors estimated quantitatively. The present result is $\alpha_{\overline{MS}}(5\text{ GeV}) = 0.174 \pm 0.012$, or equivalently, $\Lambda^{(4)}_{\overline{MS}} = 160^{+47}_{-37}$ MeV.

α_s on the lattice

Lattice (FLAG19) average: $\alpha_s(M_Z) = 0.11832 \pm .00081$

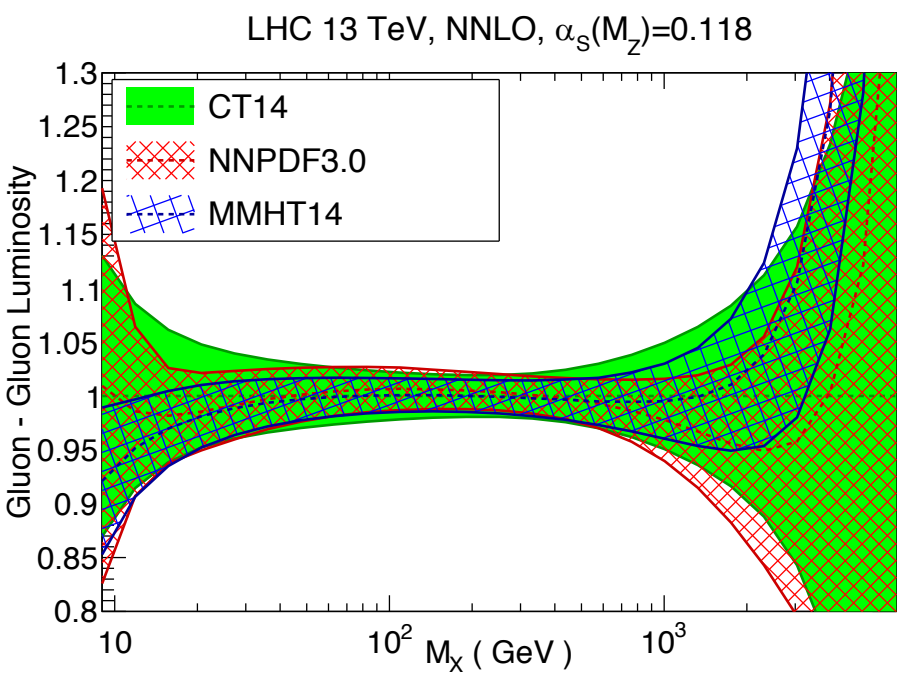
(Factor of 2 smaller error than used in Higgs studies)

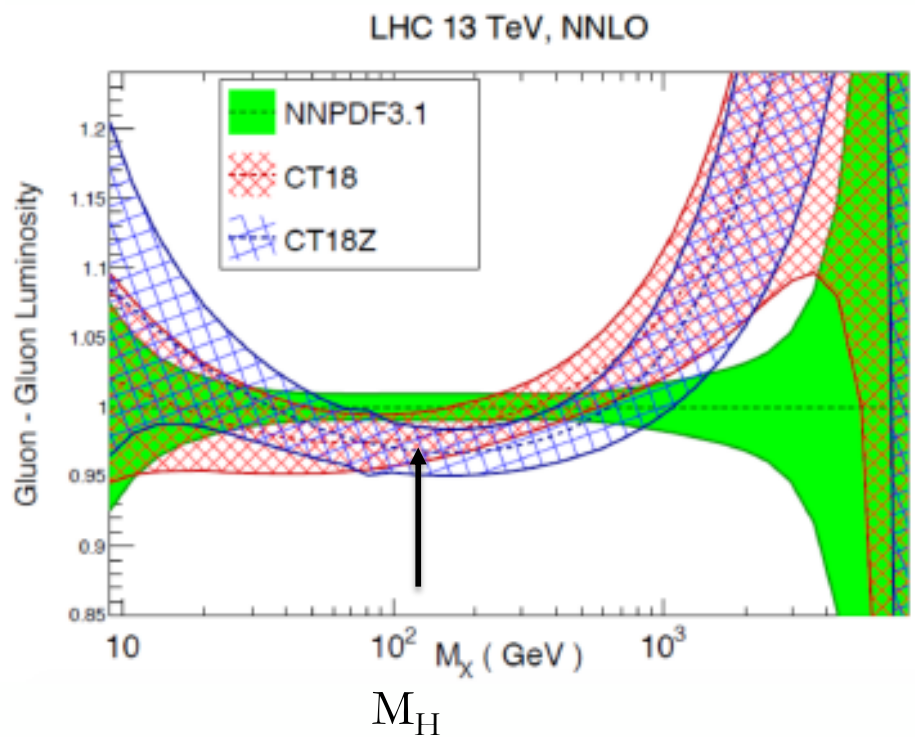


Uncertainty reduced by factor of 5 from early results

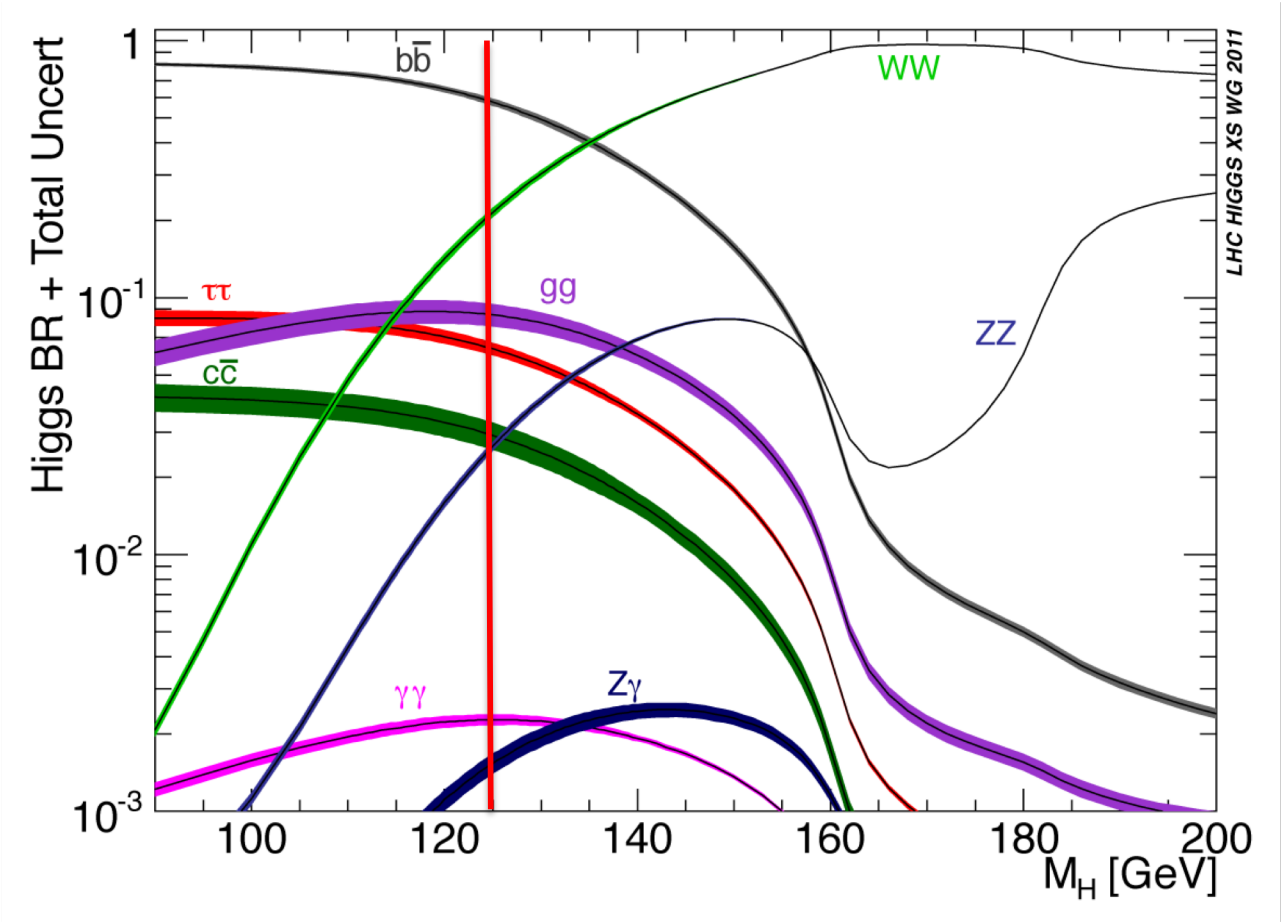
What about PDFS?

- Previous agreement among PDF sets for gluon luminosity near Higgs mass deteriorates with new CT18 PDF set
- *It would be really nice if the lattice could calculate the gluon PDF!*





Higgs Branching Ratios



Width of lines are theory uncertainties

[LHC Higgs cross section working group]

Largest Higgs BR is to b's

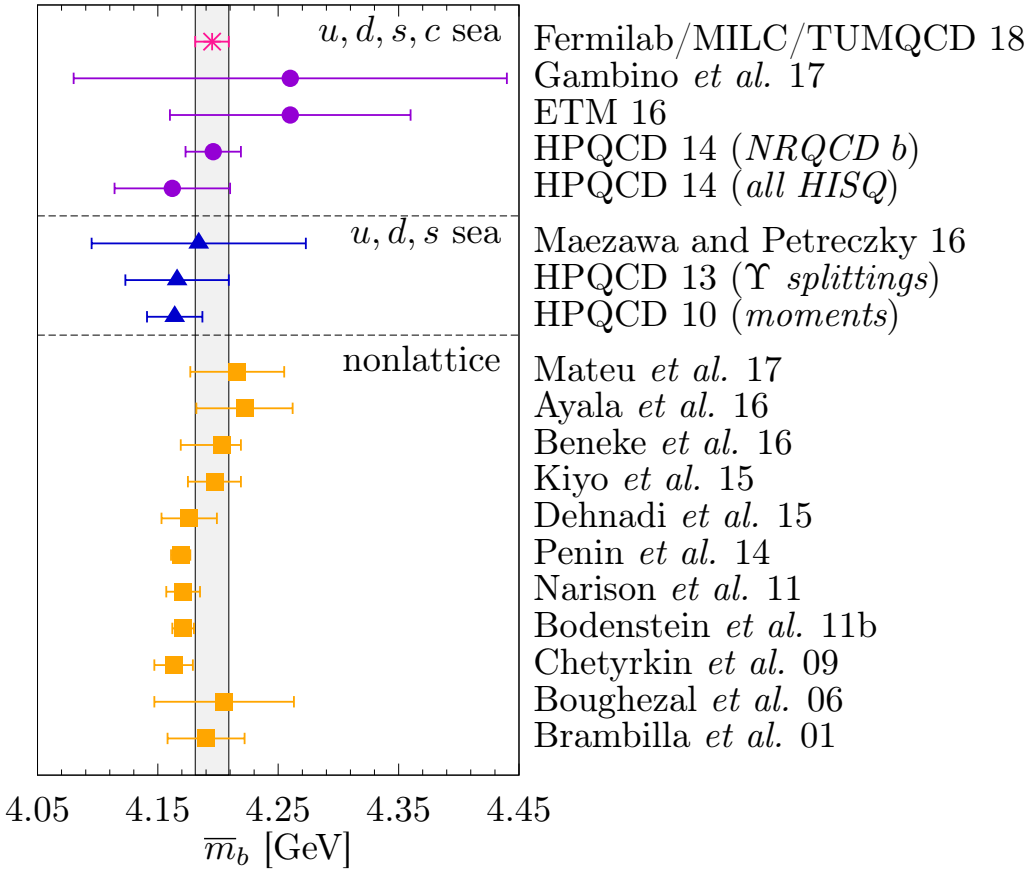
- Sensitive to m_b:

$$\Gamma(H \to b\bar{b}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H \beta^3 m_b^2$$

- QCD included to NNNLO for $H \to bb$ predictions
  - Dominant effect contained by using running $m_b(m_b)$
- Calculate parametric uncertainties by varying m_t, m_c, m_b, α_s and finding maximum deviation from central value
- Add parametric uncertainties in quadrature

Lepage, Mackenzie, and Peskin, *Expected Precision of Higgs Boson Partial Widths within the Standard Model*, arxiv: 1404.0319

Precision results for m_b from lattice



$m_b(m_b)=4.201 \pm 0.014$

Fermilab lattice, MILC, TUMQCD collaborations, 1802.04248

Parametric uncertainties

- Theory can give ~1-2 % predictions for Higgs branching ratios

$$BR(H \to b\bar{b}) = 0.5824 \pm .65\% \pm .73\% \pm .79\%$$

$$BR(H \to \gamma\gamma) = .002 \pm \underbrace{1.72\%}_{\text{Theory}} \pm \underbrace{.96\%}_{m_b} \pm \underbrace{.61\%}_{\alpha_s}$$

Since dominant Higgs decay is to b's, uncertainty on m_b contributes to total width

$$\Gamma_{tot} = 4.088\ MeV \pm .73\% \pm .99\% \pm .62\%$$

Input to these numbers: $m_b(m_b) = 4.18 \pm .03\ GeV$

- Lattice calculations of m_b and α_s allow 1% precision on Higgs branching ratios

What about Higgs decays to 2nd generation fermions?

- Does Higgs couple to 1st and 2nd generations?

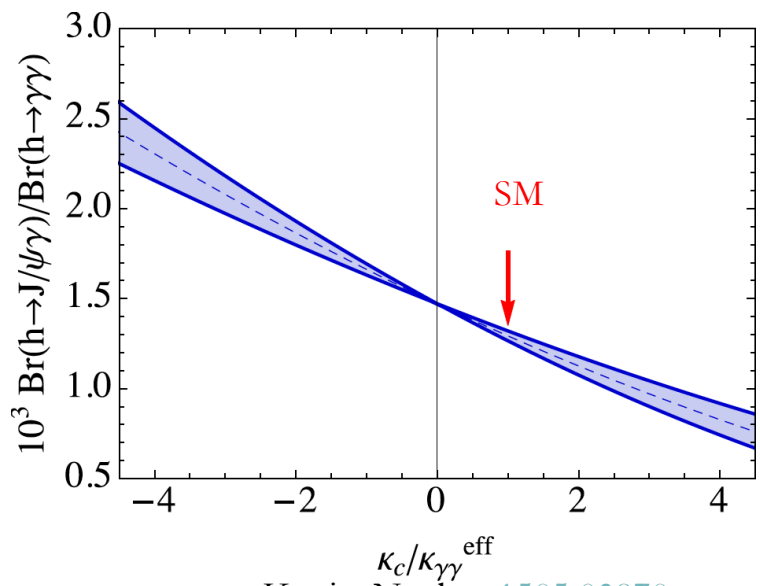
$$\sigma_H \cdot BR(H \to \mu^+\mu^-) < 2.8[SM]$$

- 3 ab^{-1} projection is 7σ for H → μμ with δμ/μ ~ ± 20%

Small rates for H→ψγ

3 ab^{-1} ATLAS projects sensitivity to 15 x SM

LHCb: ZH, H→cc
3 ab^{-1} $\sigma/\sigma_{SM} < 2$

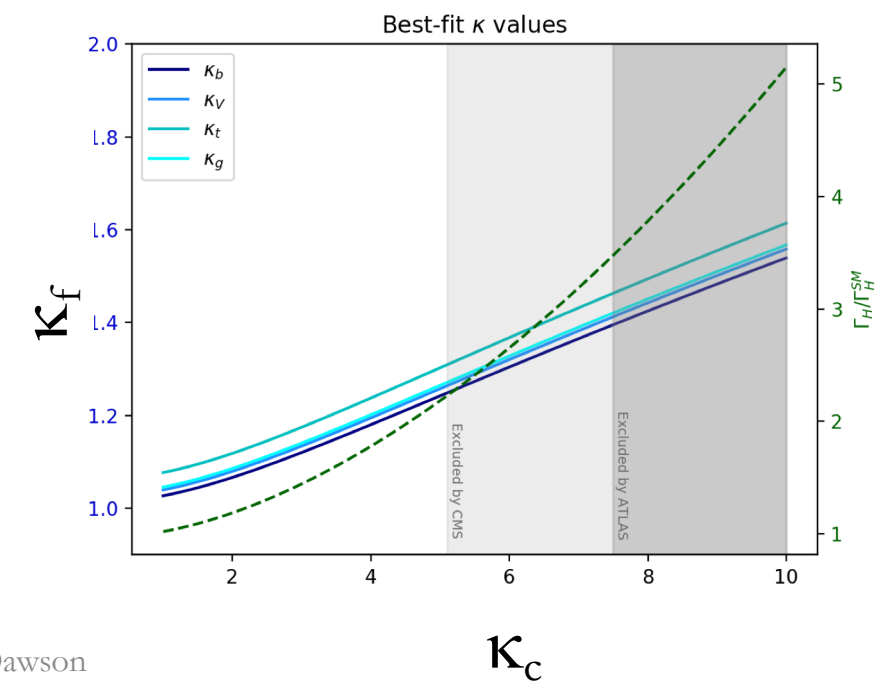


Konig, Neubert1505.03870

Can we infer the Higgs-charm coupling?

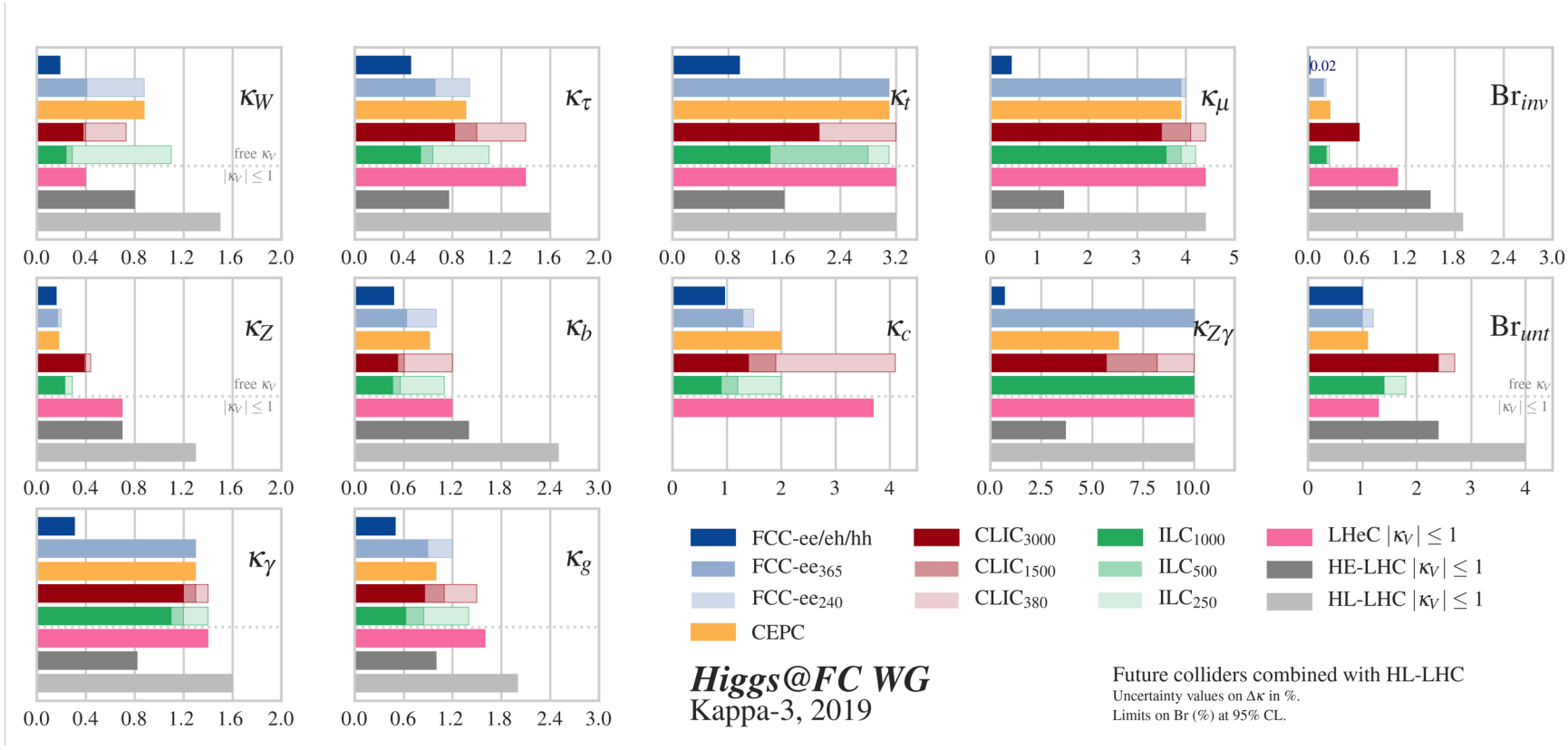
- Current measurements of the charm mass give a ~5% uncertainty on the Higgs branching ratio to charm
  - BR(H→cc)=.03
- Total Higgs width increased if coupling to charm increased
- Approximate blind direction in Higgs coupling fits, no real limit on Higgs charm coupling, k_c

Need another input; could use experimental limit on total Higgs width



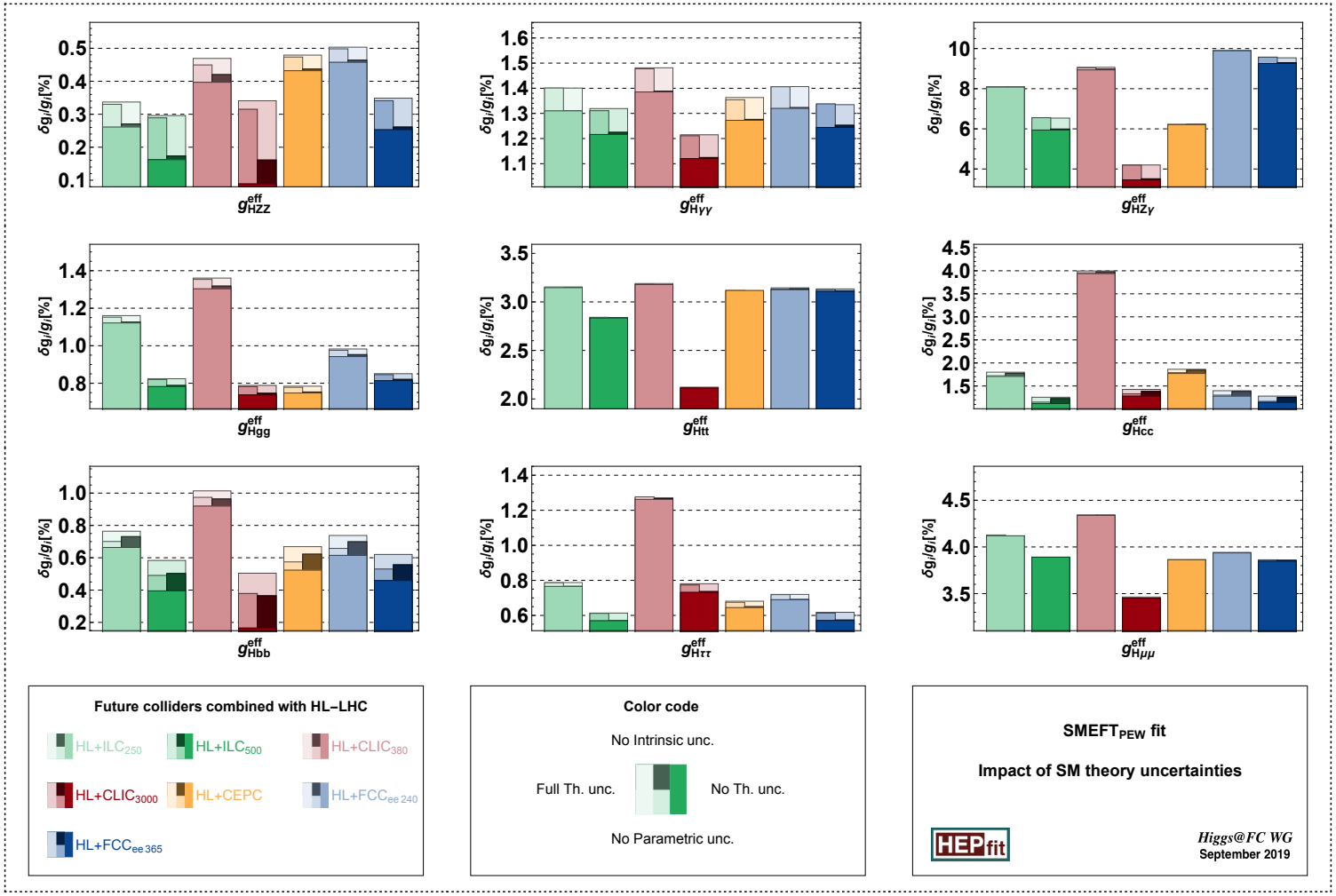
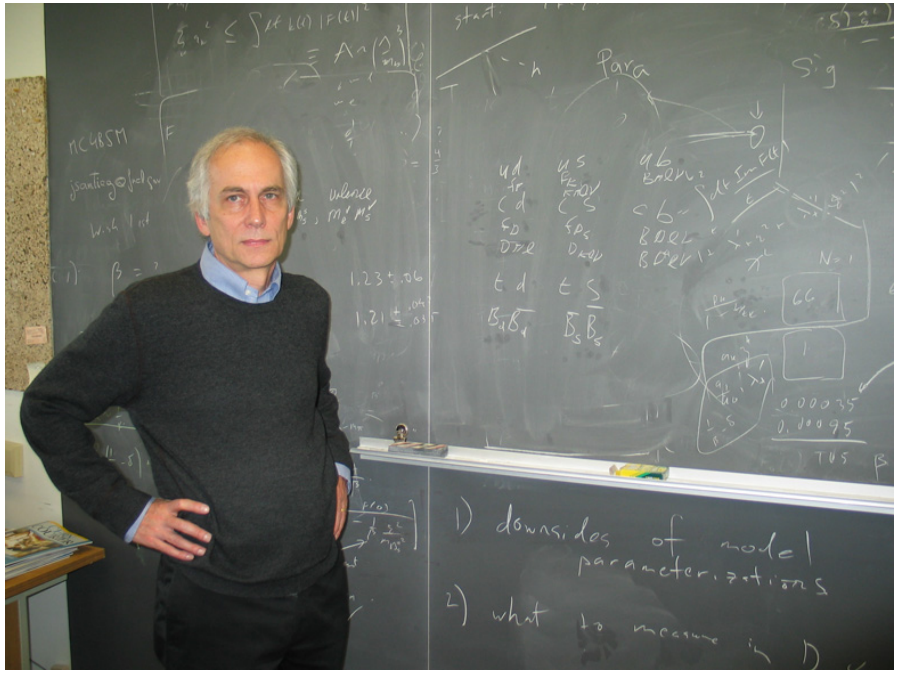
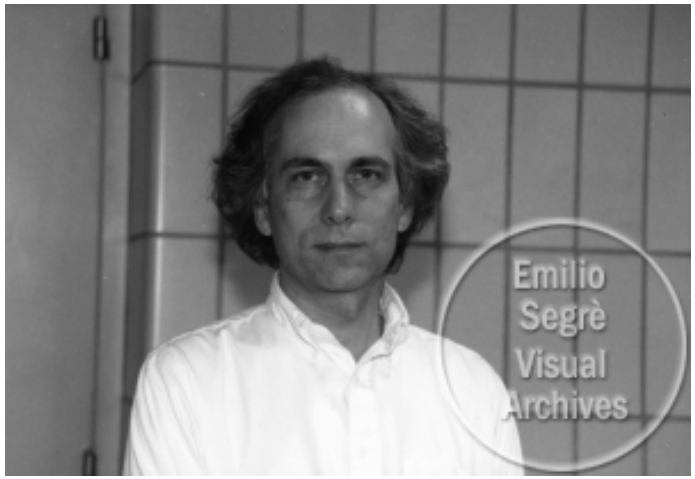
Coyle, Wagner, Wei, arxiv:1905.09360

1% measurements of Higgs couplings at future e^+e^- machines



deBlas et al, arxiv:1905.03764

Effects of parametric improvements



- Best of luck in your retirement, Paul