Highlights of the Higgs WG Activities and Future Outlook

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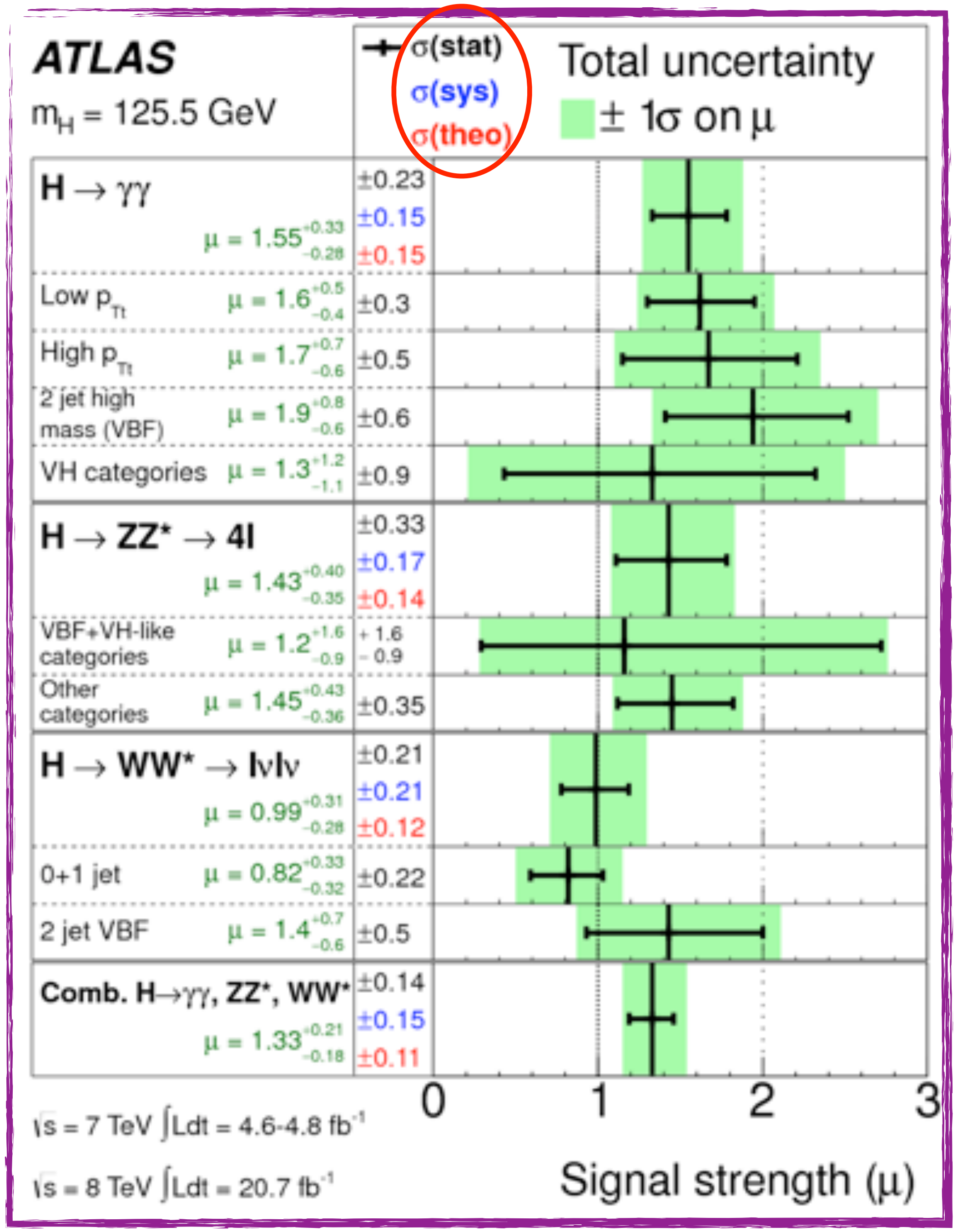
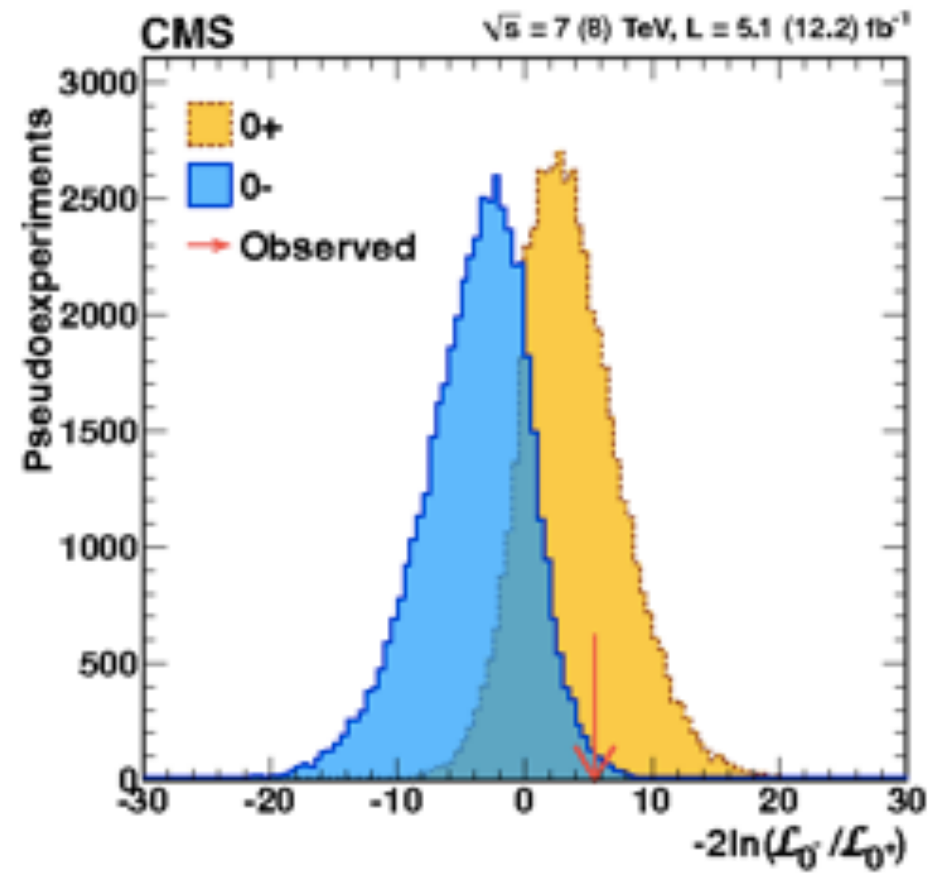
Argonne NATIONAL LABORATORY

The LHC circa 2014

- Remarkable in both breadth and depth of coverage



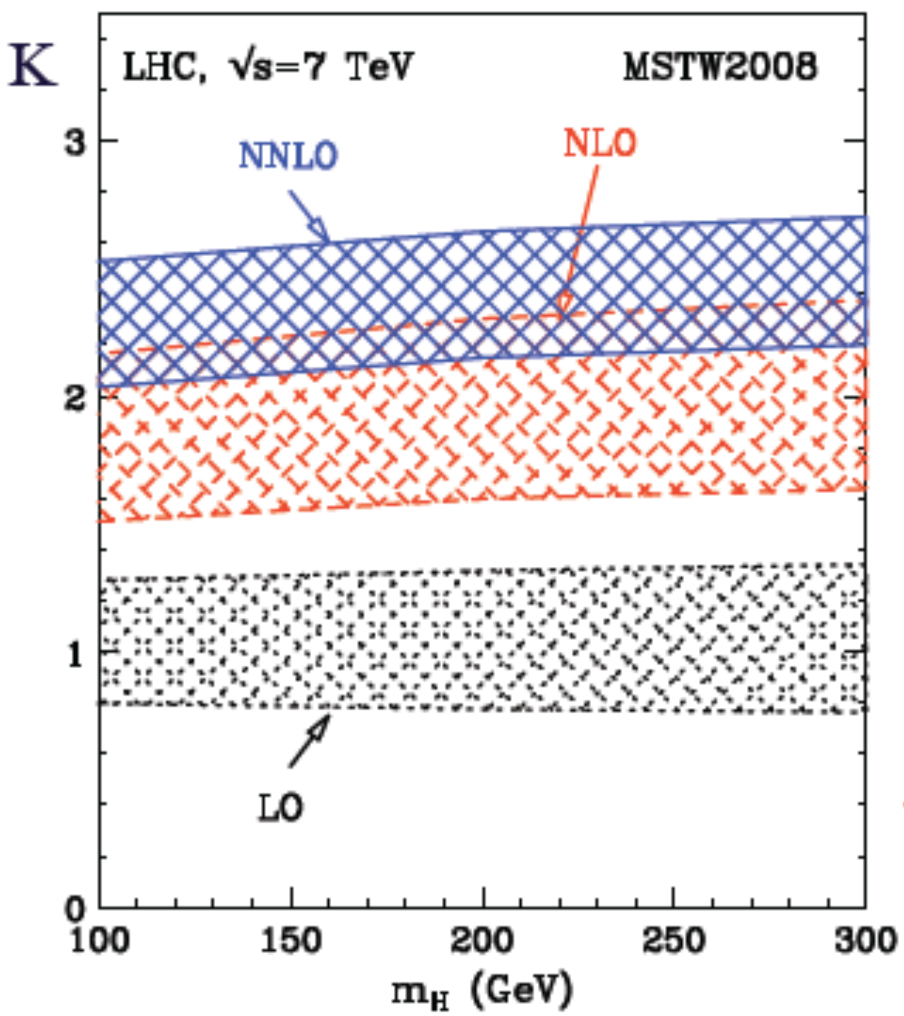


- Higgs mass: a new precision parameter of SM
- Spin-0 is favored, and it is a CP-even state

Underlying identity of the Higgs is slowly revealed

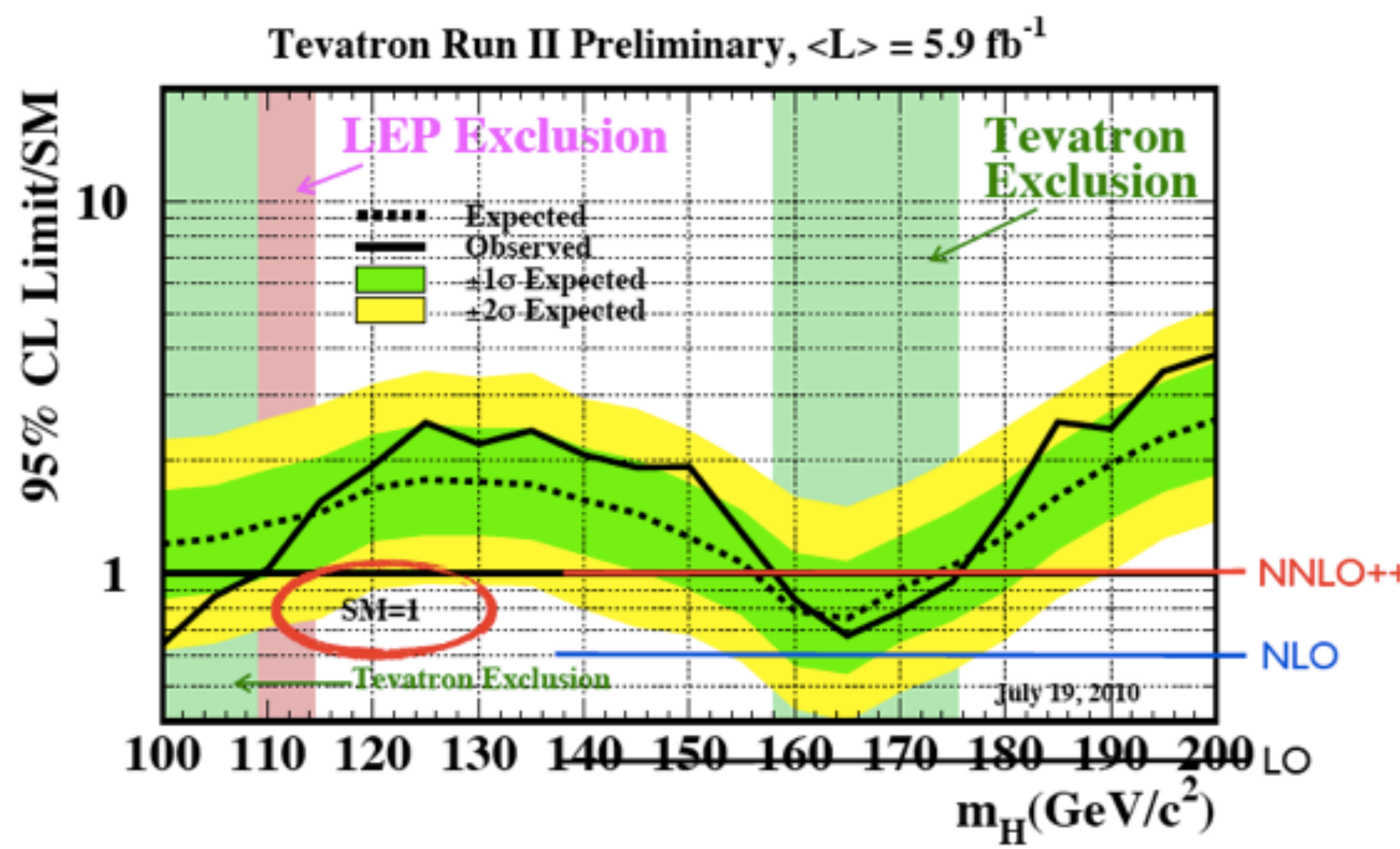
Role of theory

- Precision SM theory played a crucial role in the hunt for the Higgs boson



Higgs predictions receive famously large perturbative corrections

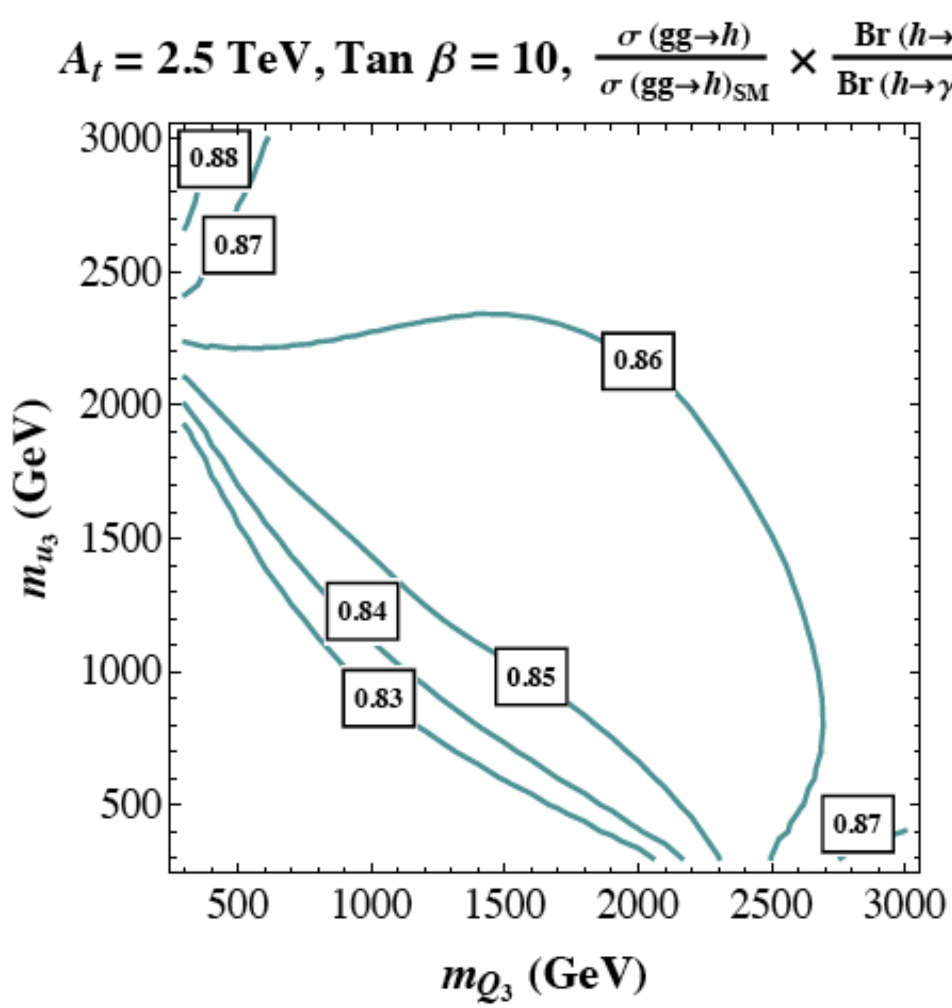
Harlander, Kilgore; Anastasiou, Melnikov;
Ravindran, Smith, van Neerven 2002-2003



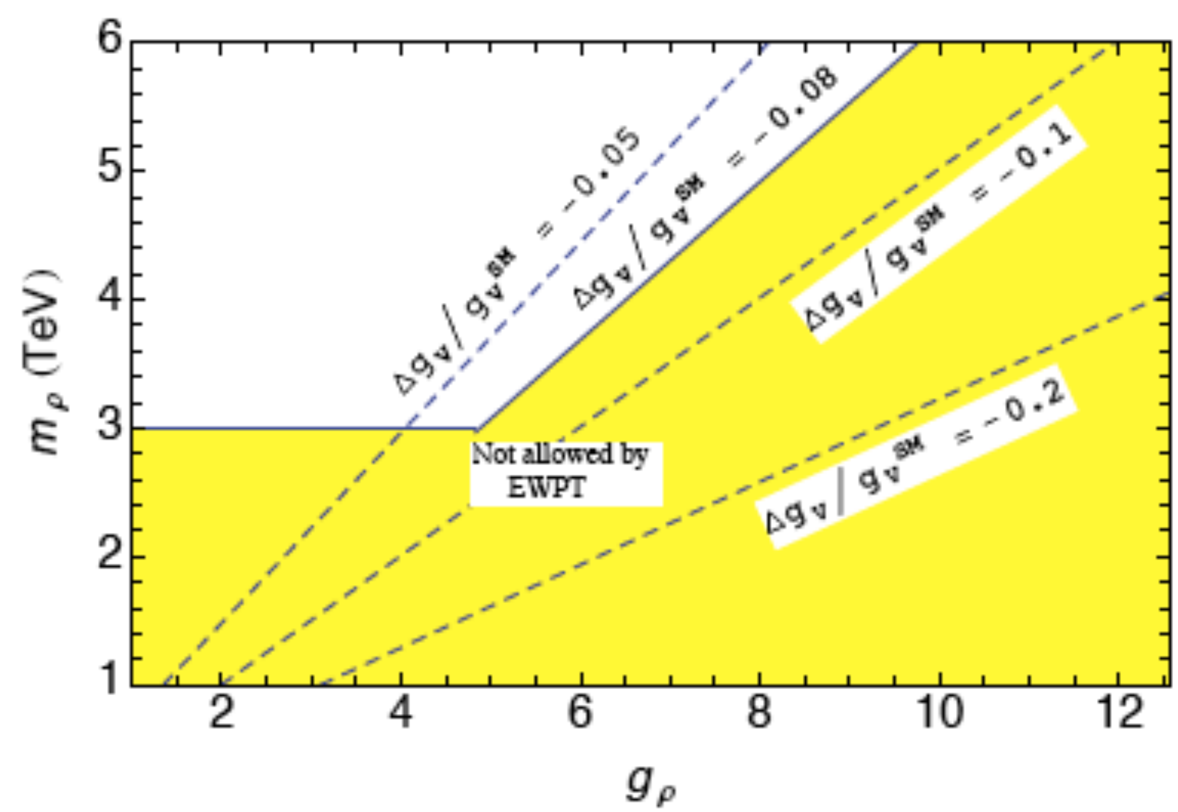
Without NNLO predictions, wouldn't have even realized we were probing the SM Higgs at the Tevatron!

Harlander
First three years of the LHC, Mainz, 2013

More precision needed for LHC Run II



Carena et al



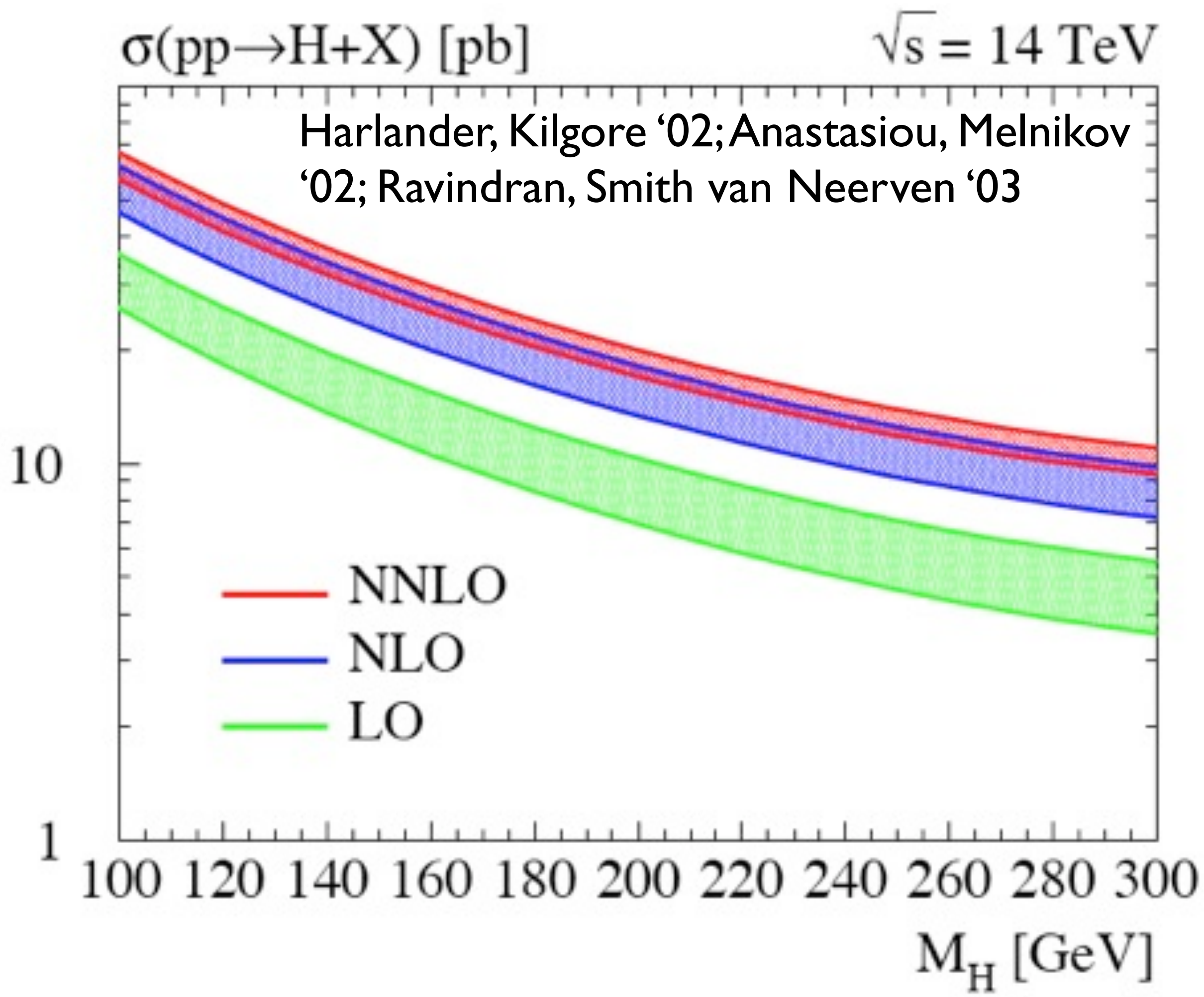
Gupta et al

Small deviations from SM predictions may be a crucial window into physics beyond the SM

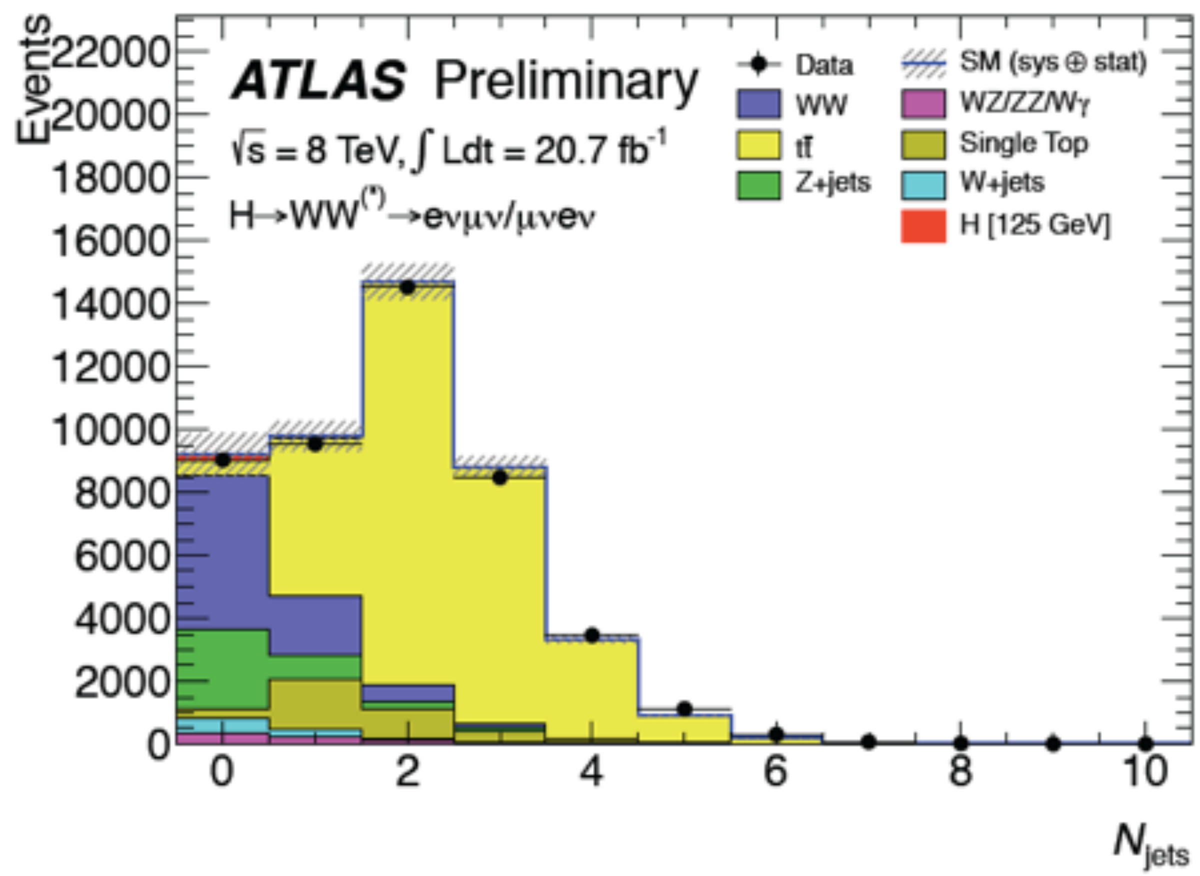
Want to control the SM predictions at least at the 5-10%. Still a chance for BSM effects to appear

Theory Uncertainties

- Two reasons for the dominance of theory uncertainties in Higgs analyses



Large fixed-order QCD corrections to Higgs production processes

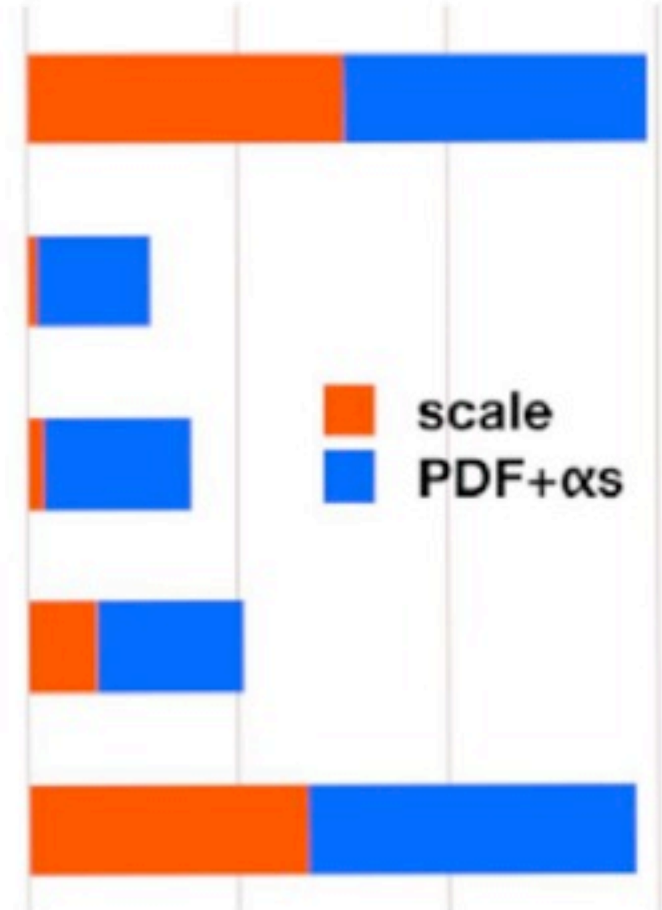


Division into exclusive jet bins introduces large logarithms that must be resummed

- Progress on both fronts needed to improve Higgs-signal modeling for Run II of the LHC, as well as controlling PDFs and parametric uncertainties.

THE IMPACT OF PDF+α_s UNCERTAINTIES

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



(J. Campbell, HCP2012)

- PDF UNCERTAINTY ALWAYS DOMINANT
- IN GLUON FUSION, COMPARABLE TO SCALE BUT VERY LARGE

What we have covered in the Higgs WG

- 12 presentations, 6 theory talks, and 6 experimental ones

Tuesday:

Stefano Forte: "Review of recent deveopements in SM Higgs physics"
Pamela Ferrari: "Measurement of Higgs decay in Bosonic final states at LHC"
Anna kropivnitskaya: "Measurement of Higgs decay in Fermionic final states at LHC"
Sven Heinemeyer: "Review of recent developements in SM Higgs physics"

Wednesday:

Giampiero Passarino: "Measuring Higgs width at the LHC via interference effects"
Kentarou Mawatari: "Effective theory approach in coupling determination"
Mykhailo Dalchenko: "Measurement of the Higgs Boson mass, width and Spin-CP quantum numbers at LHC and Tevatron"
Frank Tackmann: "Combining resummed Higgs predictions across jet bins"

Thursday:

Sara Valentinetti: "Test of the Higgs Boson couplings with LHC and Tevatron data"
Franz Herzog: "Higgs production in gluon fusion at N^3LO"
Hugh Skottowe: "Measurement of SM Higgs differential cross-sections at LHC"
Stefano Casasso: "Search for rare and BSM Higgs decays"

Can only show some highlights in this 15min talk

N^3LO results for the inclusive cross section: approximate results

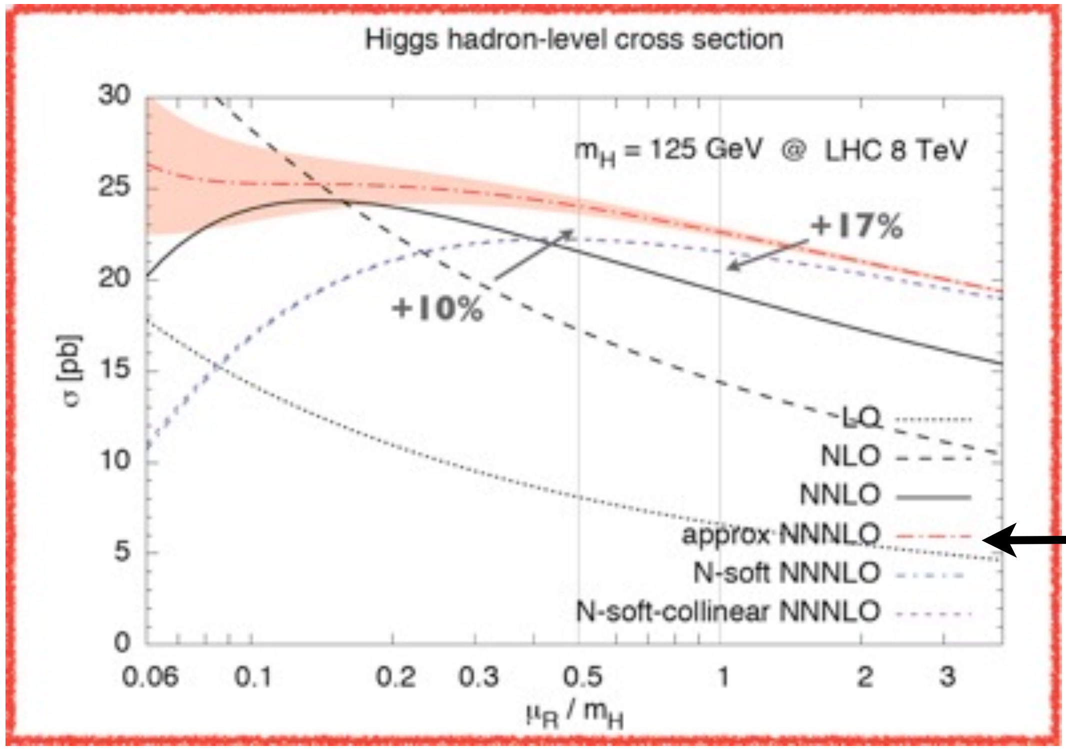
NLO in EFT:

$$\Delta\sigma = \sigma_0 \frac{\alpha_s}{\pi} \left\{ \left(\frac{11}{2} + \pi^2\right)\delta(1-z) + 12\left[\frac{\ln(1-z)}{1-z}\right]_+ - 12z(-z+z^2+2)\ln(1-z) \right.$$
$$\left. -6\frac{(z^2+1-z)^2}{1-z}\ln(z) - \frac{11}{2}(1-z)^3 \right\}$$

$z = m_H^2/(x_1 x_2\, s)$

eikonal emission of soft gluons

collinear emission of gluons



- Up to now we only had an approximate N^3LO result. It did strongly motivate an exact calculation of this contribution

Ball et al, 2013

10% corrections for mu = $m_H/2$

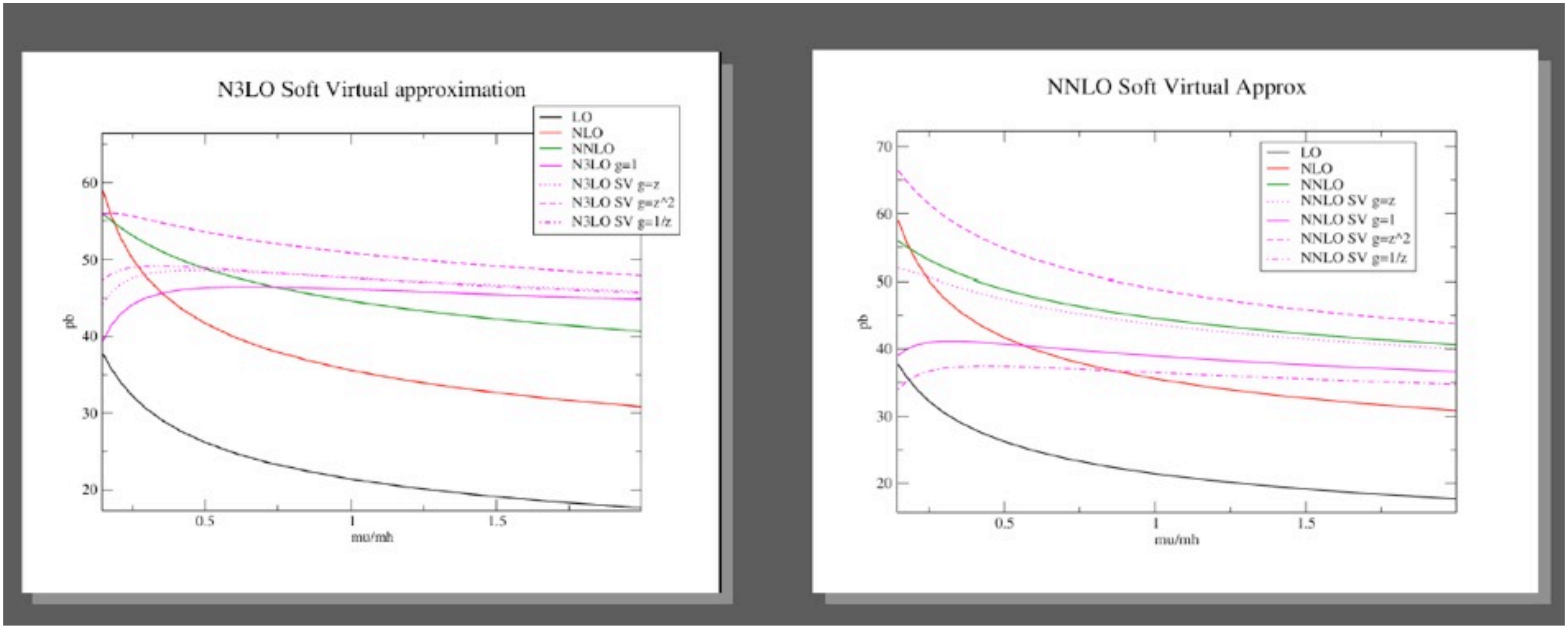
Soft+Virtual exact N^{3}LO results for the inclusive cross section

Higss Production at Threshold at N3LO

$$
\begin{aligned}
\hat{\eta}^{(3)}(z) = \delta(1-z)\Bigg\{ & C_A^3\left(-\frac{2003}{48}\zeta_6+\frac{413}{6}\zeta_3^2-\frac{7579}{144}\zeta_5+\frac{979}{24}\zeta_2\zeta_3-\frac{15257}{864}\zeta_4-\frac{819}{16}\zeta_3+\frac{16151}{1296}\zeta_2+\frac{215131}{5184}\right) \quad (1\\
&+N_F\Bigg[C_A^2\left(\frac{869}{72}\zeta_5-\frac{125}{12}\zeta_3\zeta_2+\frac{2629}{432}\zeta_4+\frac{1231}{216}\zeta_3-\frac{70}{81}\zeta_2-\frac{98059}{5184}\right)\\
&\quad +C_A C_F\left(\frac{5}{2}\zeta_5+3\zeta_3\zeta_2+\frac{11}{72}\zeta_4+\frac{13}{2}\zeta_3-\frac{71}{36}\zeta_2-\frac{63991}{5184}\right)+C_F^2\left(-5\zeta_5+\frac{37}{12}\zeta_3+\frac{19}{18}\right)\Bigg]\\
&+N_F^2\left[C_A\left(-\frac{19}{36}\zeta_4+\frac{43}{108}\zeta_3-\frac{133}{324}\zeta_2+\frac{2515}{1728}\right)+C_F\left(-\frac{1}{36}\zeta_4-\frac{7}{6}\zeta_3-\frac{23}{72}\zeta_2+\frac{4481}{2592}\right)\right]\Bigg\}\\
+\left[\frac{1}{1-z}\right]_+\Bigg\{ & C_A^3\left(186\zeta_5-\frac{725}{6}\zeta_3\zeta_2+\frac{253}{24}\zeta_4+\frac{8941}{108}\zeta_3+\frac{8563}{324}\zeta_2-\frac{297029}{23328}\right)+N_F^2 C_A\left(\frac{5}{27}\zeta_3+\frac{10}{27}\zeta_2-\frac{58}{729}\right)\\
&+N_F\left[C_A^2\left(-\frac{17}{12}\zeta_4-\frac{475}{36}\zeta_3-\frac{2173}{324}\zeta_2+\frac{31313}{11664}\right)+C_A C_F\left(-\frac{1}{2}\zeta_4-\frac{19}{18}\zeta_3-\frac{1}{2}\zeta_2+\frac{1711}{864}\right)\right]\Bigg\}\\
+\left[\frac{\log(1-z)}{1-z}\right]_+\Bigg\{ & C_A^3\left(-77\zeta_4-\frac{352}{3}\zeta_3-\frac{152}{3}\zeta_2+\frac{30569}{648}\right)+N_F^2 C_A\left(-\frac{4}{9}\zeta_2+\frac{25}{81}\right)\\
&+N_F\left[C_A^2\left(\frac{46}{3}\zeta_3+\frac{94}{9}\zeta_2-\frac{4211}{324}\right)+C_A C_F\left(6\zeta_3-\frac{63}{8}\right)\right]\Bigg\}\\
+\left[\frac{\log^2(1-z)}{1-z}\right]_+ \Bigg\{ & C_A^3\left(181\zeta_3+\frac{187}{3}\zeta_2-\frac{1051}{27}\right)+N_F\left[C_A^2\left(-\frac{34}{3}\zeta_2+\frac{457}{54}\right)+\frac{1}{2}C_A C_F\right]-\frac{10}{27}N_F^2 C_A\Bigg\}\\
+\left[\frac{\log^3(1-z)}{1-z}\right]_+ \Bigg\{ & C_A^3\left(-56\zeta_2+\frac{925}{27}\right)-\frac{164}{27}N_F C_A^2+\frac{4}{27}N_F^2 C_A\Bigg\}\\
+\left[\frac{\log^4(1-z)}{1-z}\right]_+ & \left(\frac{20}{9}N_F C_A^2-\frac{110}{9}C_A^3\right)+\left[\frac{\log^5(1-z)}{1-z}\right]_+ 8C_A^3 .
\end{aligned}
$$

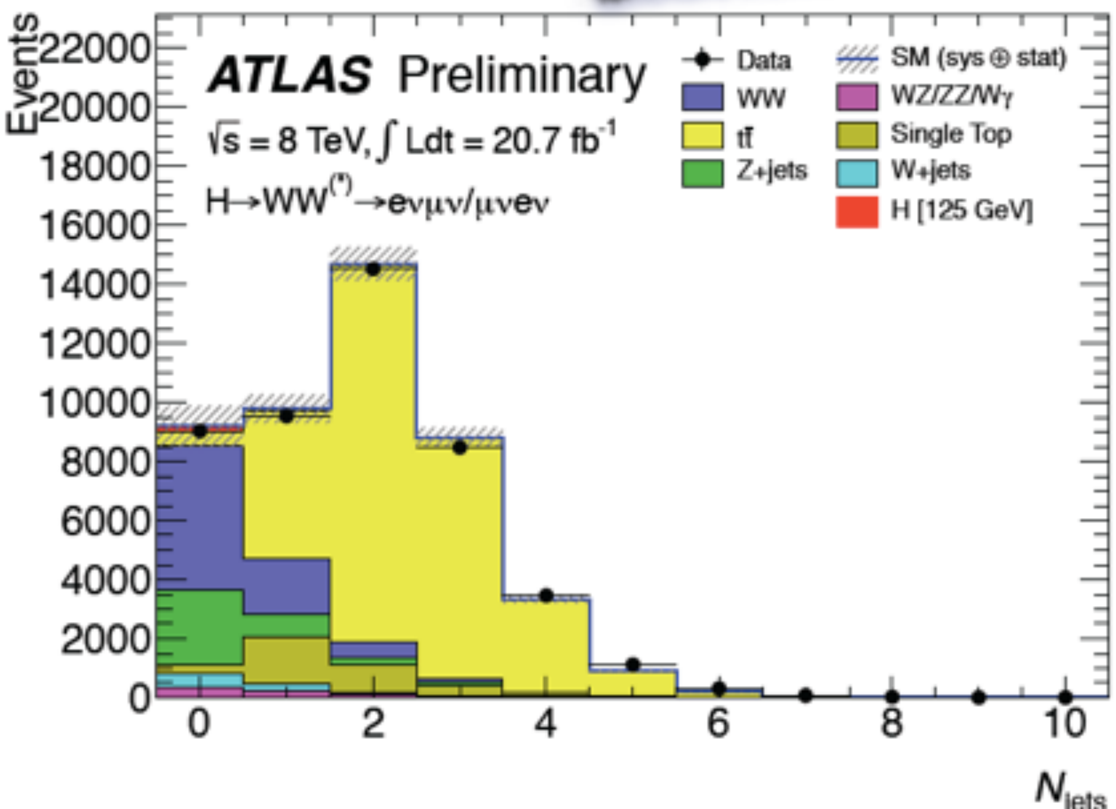
Franz Herzog

Soft+Virtual exact N³LO results for the inclusive cross section



- Further coefficients of soft expansion of the N3LO are in close reach. The full result seems feasible.

The jet veto in the WW channel



- Required in WW channel due to background composition
- 25-30 GeV jet cut used; restriction of radiation leads to large logs

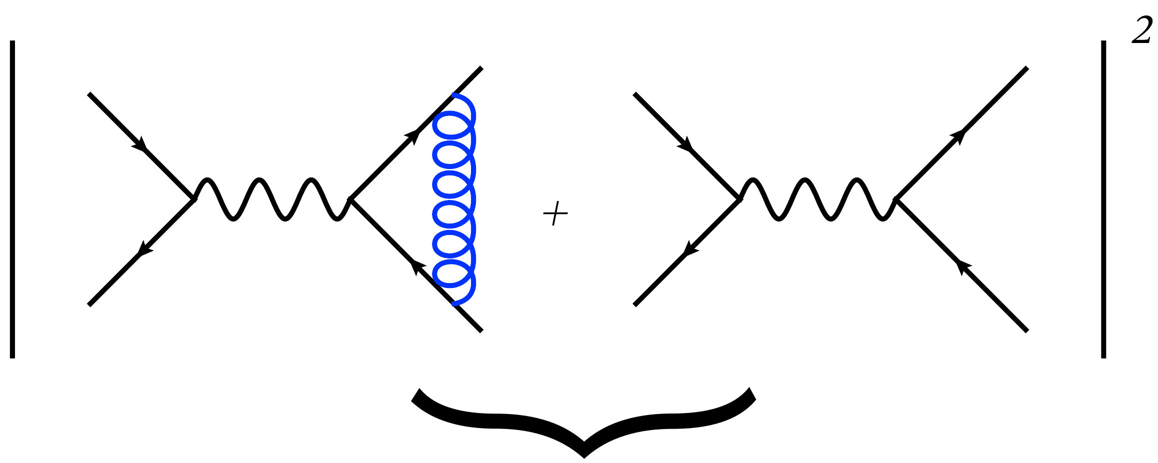
Source	Signal processes (%) $N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$	Background processes (%) $N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$
Theoretical uncertainties						
QCD scale for ggF signal for $N_{jet}\geq 0$	13	-	-	-	-	-
QCD scale for ggF signal for $N_{jet}\geq 1$	10	27	-	-	-	-
QCD scale for ggF signal for $N_{jet}\geq 2$	-	15	4	-	-	-
QCD scale for ggF signal for $N_{jet}\geq 3$	-	-	4	-	-	-
Parton shower and UE model (signal only)	3	10	5	-	-	-
PDF model	8	7	3	1	1	1
$H\to WW$ branching ratio	4	4	4	-	-	-
QCD scale (acceptance)	4	4	3	-	-	-
WW normalisation	-	-	-	1	2	4
Experimental uncertainties						
Jet energy scale and resolution	5	2	6	2	3	7
b-tagging efficiency	-	-	-	-	7	2
f_{recoil} efficiency	1	1	-	4	2	-

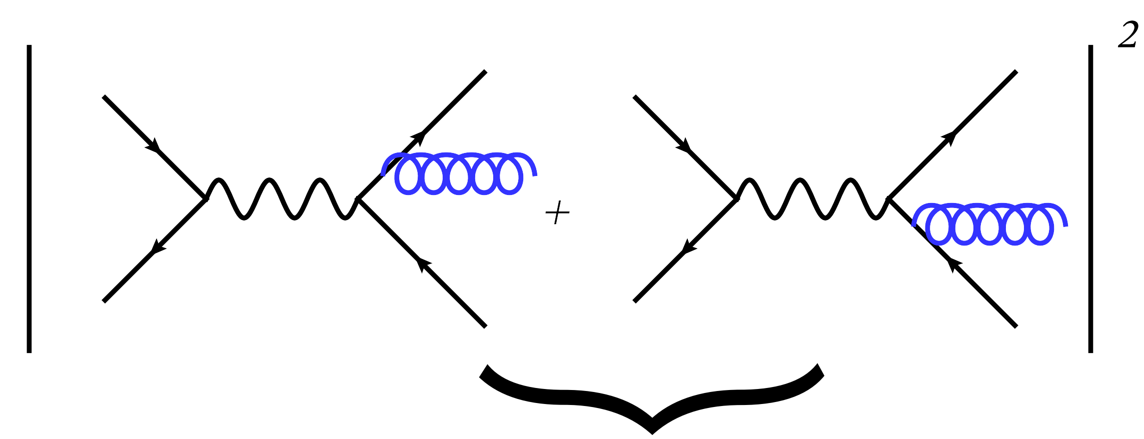
ATLAS

- Theory uncertainty becoming a limiting systematic in the 0-jet and 1-jet bins

Why are jet vetoes dangerous?

- Illustrate with simple example of $e^+e^-\rightarrow$jets
- Infrared safety: must sum both virtual and real corrections





Virtual corrections: $-1/\varepsilon_{IR}^2$

Real corrections: $1/\varepsilon_{IR}^2 - a\times\ln^2(Q/p_{T,cut})$

- Incomplete cancellation of IR divergences in presence of final state restrictions gives large logarithms of restricted kinematic variable

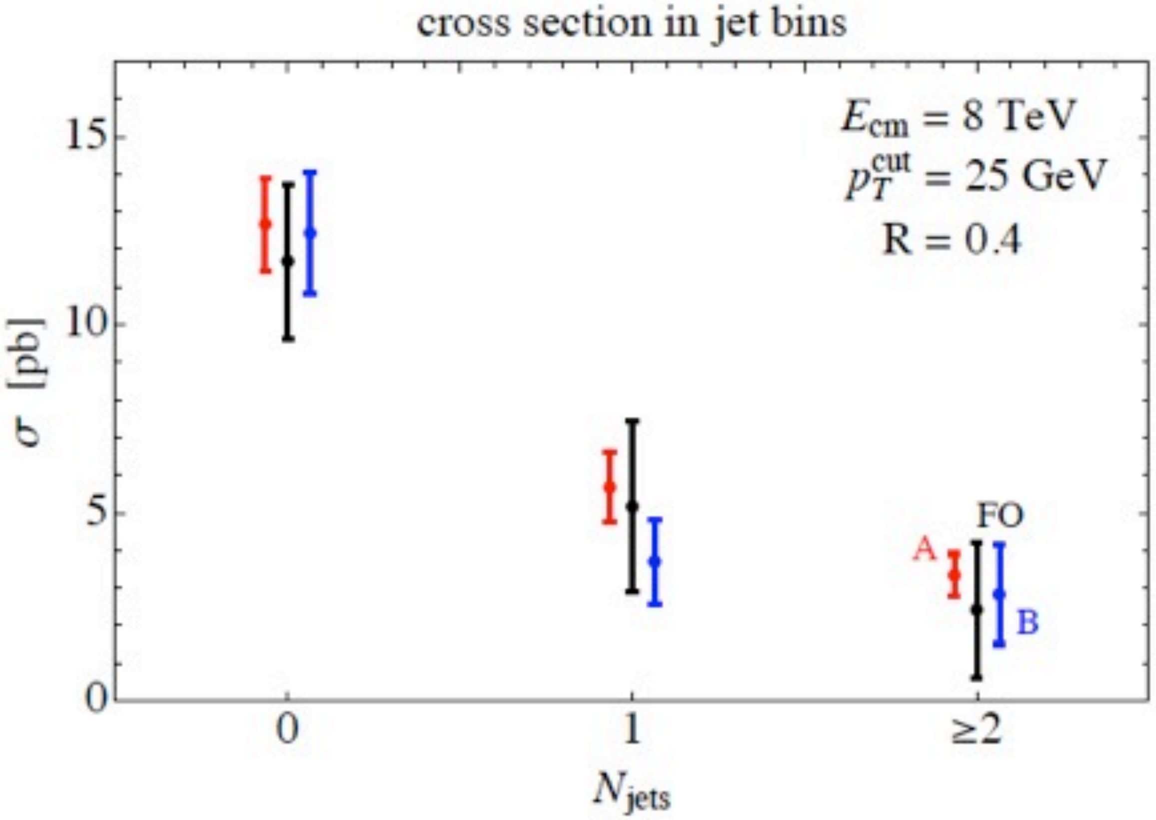
- Relevant log term for gluon-fusion Higgs searches: $6(\alpha_S/\pi)\ln^2(M_H/p_{T,veto})\sim 1/2$

$\Rightarrow$ potentially a large correction

Frank Tackmann

Combining Resummed Higgs Predictions Across Jet Bins

Final results for 0, 1, $\geq$ 2-jet Bins



red: default scheme (A)

blue: scheme B

black: fixed-order to α_s^2

- Reduces theory uncertainties on signal yield in $H \to WW$ by about factor of 2
- Framework allows us to estimate full 3x3 theory correlation matrix
  - General parametrization in terms of yield, 0-1 migration, and 1-2 migration

Higher-order resummation for p_T^{jet}

- $H+$0-jet cross section known to NNLL′+NNLO
- $H+$1-jet cross section known to NLL′+NLO

$\Rightarrow$ Framework to combine both including uncertainties and correlations (ready to be used ...)

Measurement of Higgs decays in fermionic final states at LHC and Tevatron

Anna Kropivintskaya

ttH Combination Results

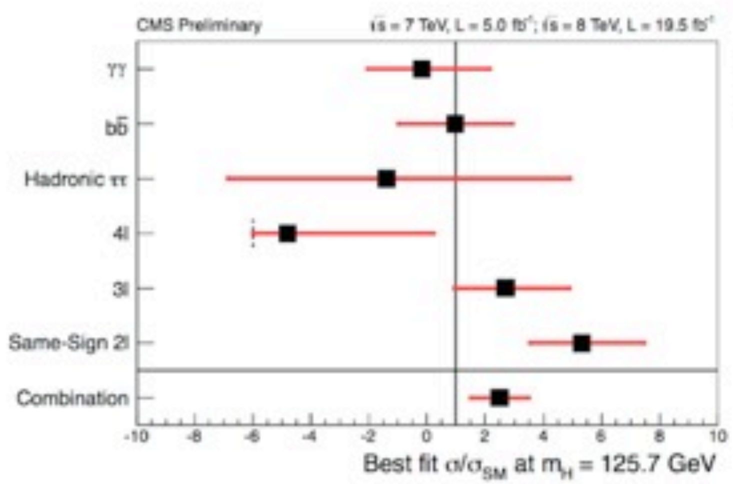
Combines the results:

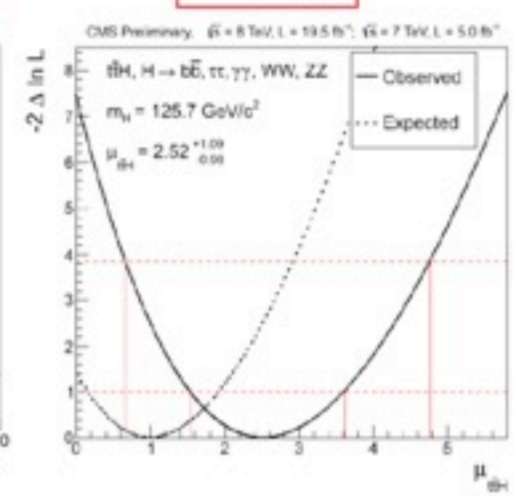
ttH, H→multi-leptons (ZZ, WW, $\tau_h\tau_h$) (Full 8 TeV dataset)	CMS-HIG-13-020
ttH, H→bb or ττ (Full 8 TeV dataset)	CMS-HIG-13-019
ttH, H→γγ (Full 8 TeV dataset)	CMS-HIG-13-015
ttH, H→bb (Full 7 TeV dataset)	CMS-HIG-12-025

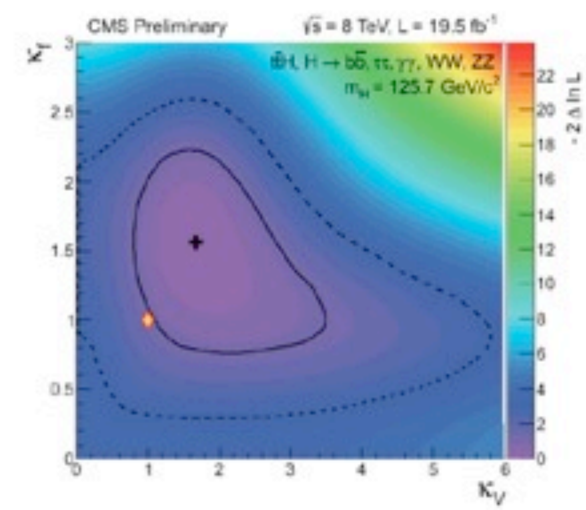
Combined

$\boxed{\mu = 2.5^{+1.1}_{-1.0}}$

Couplings consistent with SM:







Observed (expected) limit at 125 GeV is 4.3 (1.8)×SM

→ Direct hints of Higgs coupling to top quarks

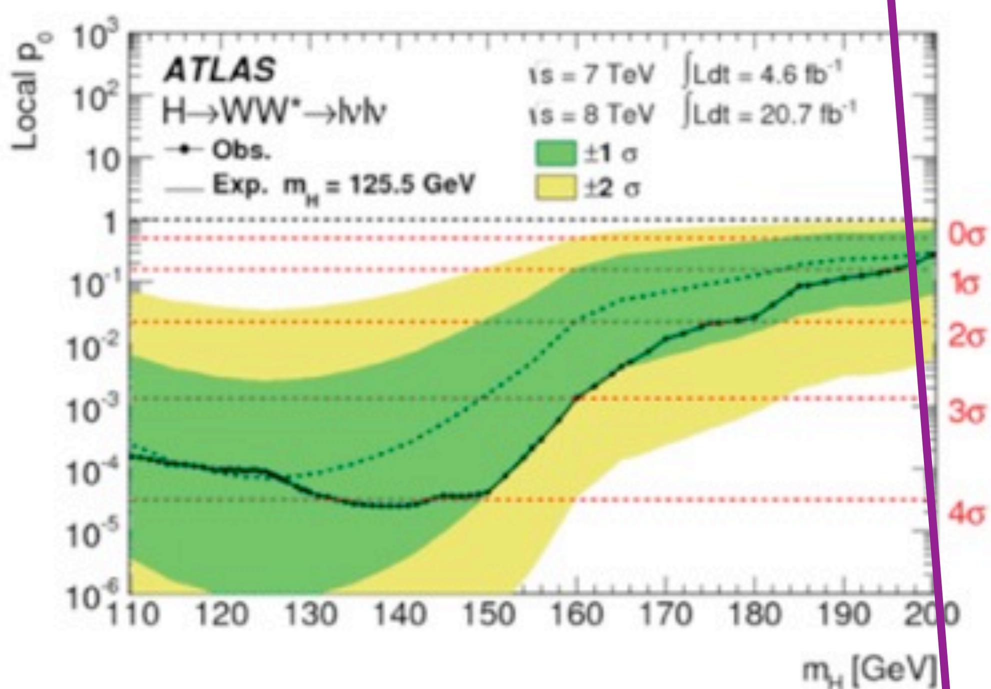
8 April SM@LHC 2014 A. Kropivnitskaya "Higgs decays in fermionic final states" 20

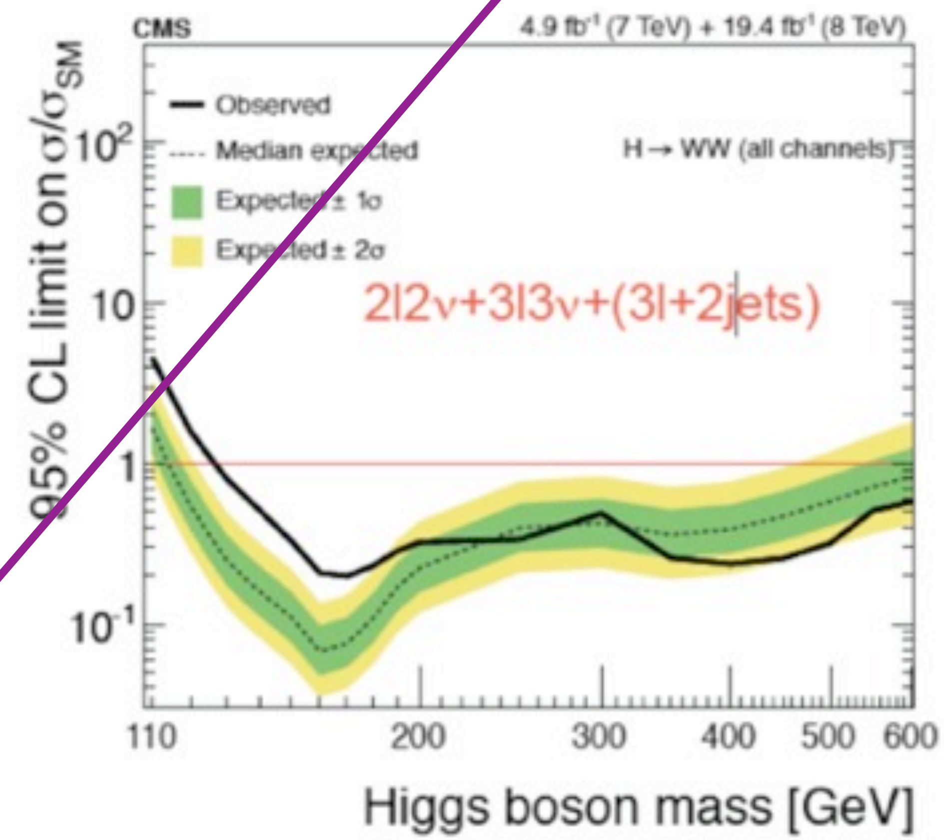
We now have evidence of direct Higgs couplings to tau, bottom and top. Will be an area to watch in LHC run II to check if the couplings are SM-like

Pamela Ferrari

H→WW results

	ATLAS m_H=125 GeV		CMS m_H=125.6 GeV	
μ	1.01 ± 0.21 (stat)± 0.12 (syst)± 0.19 (th) ± 0.04 (Lumi)		0.72 ± 0.12 (stat)± 0.10 (syst)$^{+0.12}_{-0.10}$(th)	
local p0	3.7σ exp	3.8σ obs	5.8σ exp	4.3σ obs





Theory uncertainty is becoming a limiting factor for this analysis

→ Need to improve the theory prediction.

Mykhailo Dalchenko

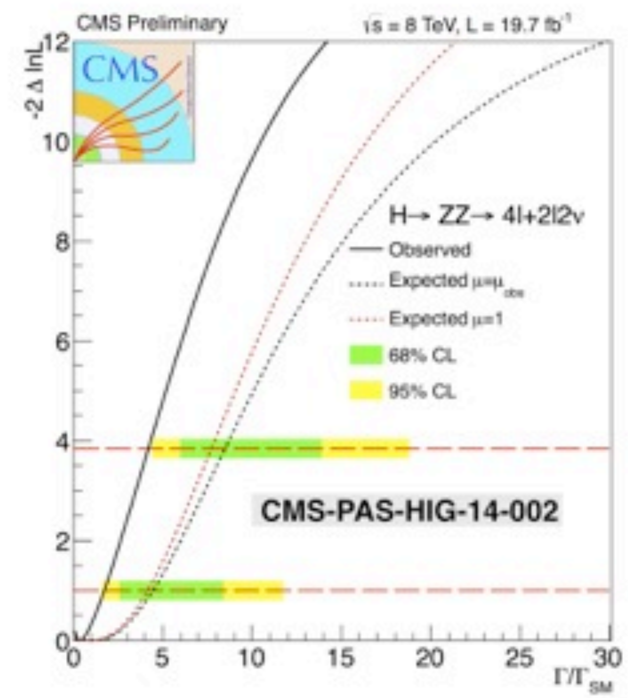
See also Passarino's talk for a detailed theory discussion of this topic

Width constraints from off-shell Higgs

Results

NEW ANALYSIS

- Unbinned likelihood fit constraining the peak yield to the observed value
- $m_H = 125.6\ GeV$, $\Gamma_H^{SM} = 4.15\ MeV$
- We expect to exclude $\Gamma_H < 35.3\ MeV$ @ 95% CL
- We observed exclusion $\Gamma_H < 17.4\ MeV$ @ 95% CL



	4ℓ	$2\ell 2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H(MeV)	27.4	26.6	17.4
Observed best fit, r	$0.5^{+2.3}_{-0.5}$	$0.2^{+2.2}_{-0.2}$	$0.3^{+1.5}_{-0.3}$
Observed best fit, Γ_H(MeV)	$2.0^{+9.6}_{-2.0}$	$0.8^{+9.1}_{-0.8}$	$1.4^{+6.1}_{-1.4}$

$^*r = \Gamma/\Gamma_{SM}$

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- **NEW ANALYSIS** from CMS: put extremely tight constraint on the Higgs boson width from the off-shell production, $\Gamma_H < 17.4\ MeV$ @95%CL.

Invisible Higgs decays

Stefano Casasso

- Motivated in dark matter models
- Invisible decays are being probed in various final states:

Reference	obs. (exp.) 95% C.L. limit on BR(h→inv.)
ATLAS arXiv:1402.3244 Z(ll)H	75 (62) %
ATLAS CONF 2014-010 (dir.+indir.)	37 (39) %
CMS PAS HIG-13-013 VBF	69 (53) %
CMS PAS HIG-13-018 Z(ll)H	75 (91) %
CMS PAS HIG-13-030 (ZH, VBF comb.)	58 (44) %
CMS PAS HIG-13-028 Z(bb)H	182 (199) %
CMS PAS HIG-13-005 (indir.)	52 (56) %

- The discovery of the Higgs gives a place to focus attention during LHC Run II

- Two ways to proceed:

  - study the obvious things extremely carefully (WW, ZZ, $\gamma\gamma$),

- The discovery of the Higgs gives a place to focus attention during Run II
- Two ways to proceed:

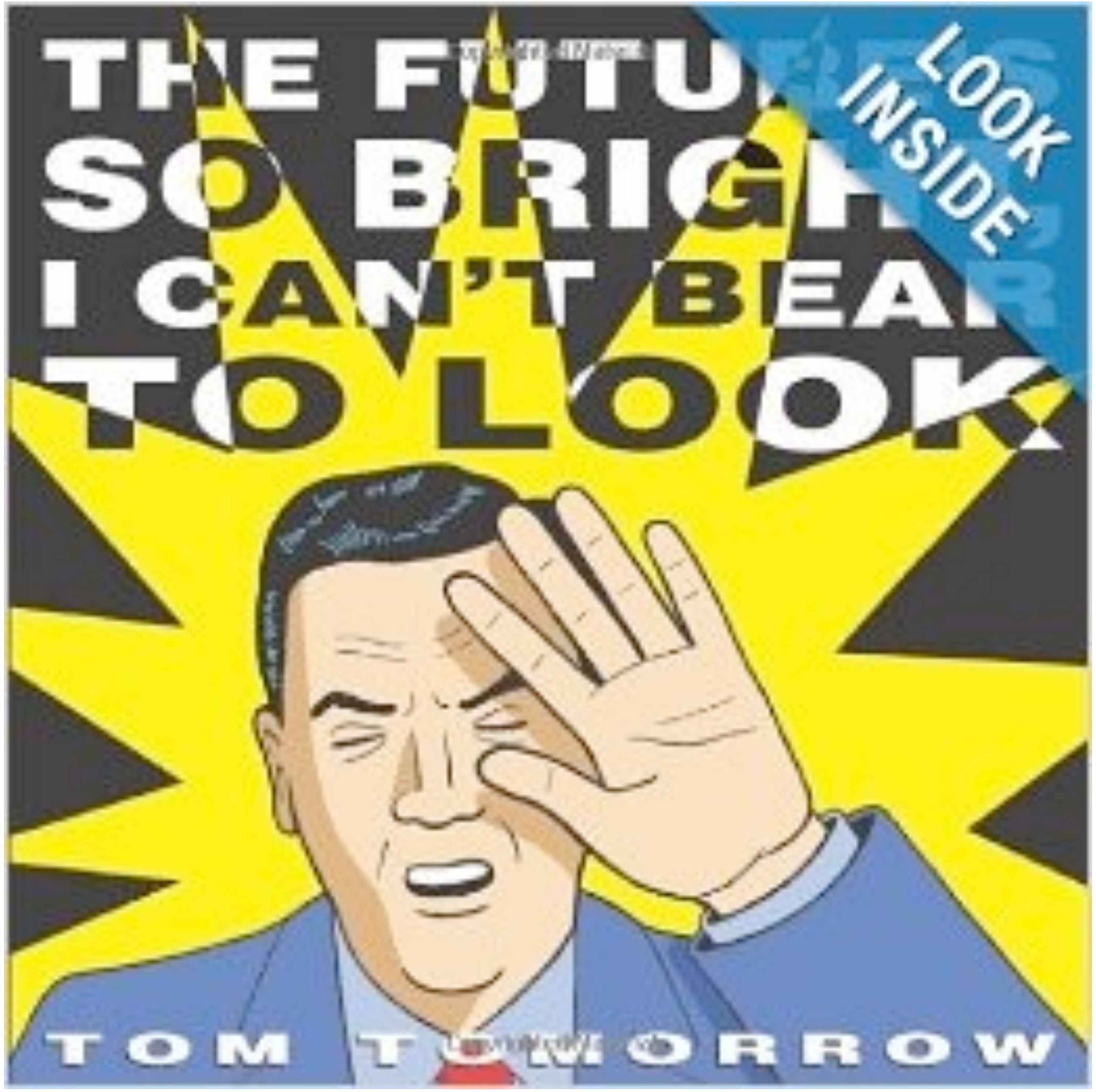
  - study the obvious things extremely carefully (WW, ZZ, $\gamma\gamma$),

  - or look for non-obvious (and probably rare) production/decay processes.

    They can offer clean measurements of the Higgs couplings, and can

    be very sensitive to new physics (see Forte's talk for some examples)

Still have questions about the future...?



A big thank you to all the organizers for this great conference!