Higgs Sessions Summary SM@LHC 2016 Pittsburgh

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Pamela Ferrari (Nikhef)
Marco Pieri (Univ. of California San Diego)

ATLAS CMS coupling combination runI

C. BECOT

	ggF	VBF	VH	$t\bar{t}H$
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to ZZ^* \to 4l$	✓	✓	✓	✓
$H \to WW^* \to 2l2\nu$	✓	✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
$H \to b\bar{b}$	✗	✗	✓	✓
$H \to \mu\mu$	✓	✓	✗	✗

Observation of
- -VBF production
- -H → ττ decay

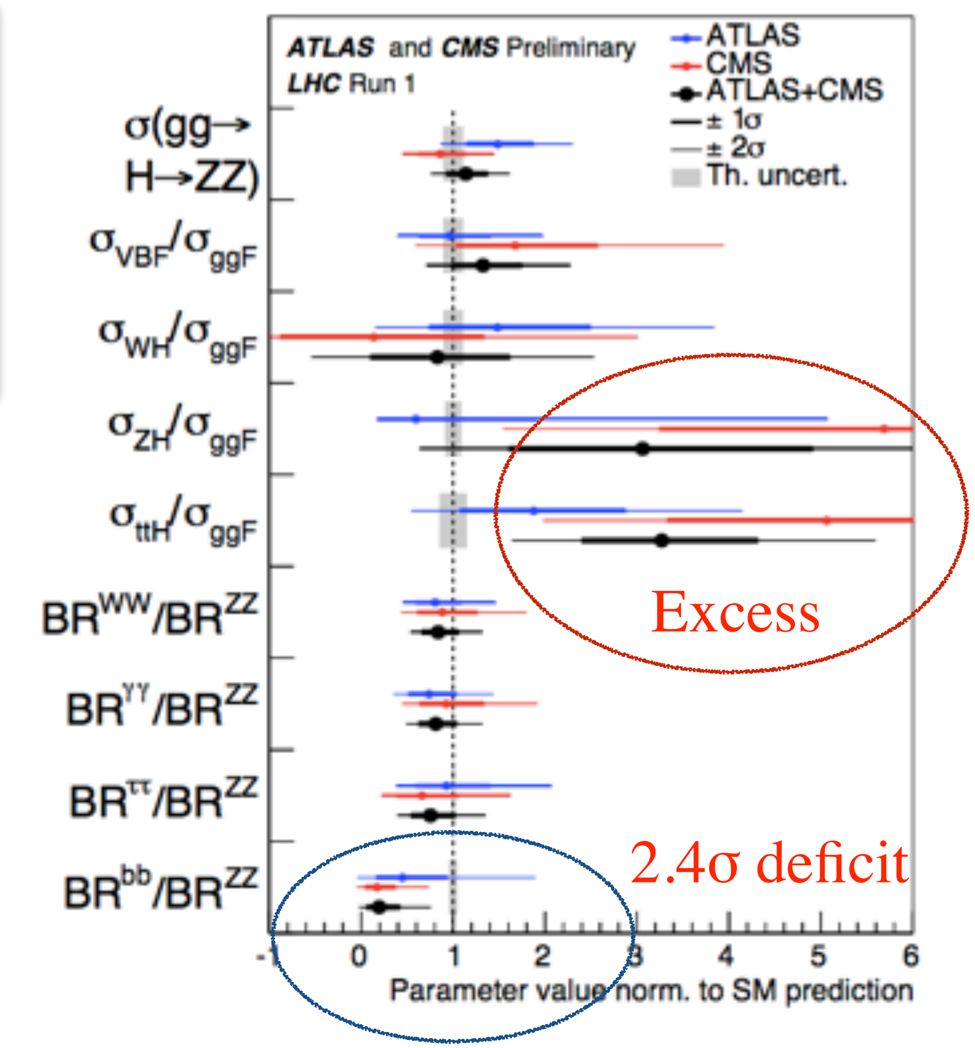
Evidence for
- -VH production
- -ttH production

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

ATLAS_CMS combinations runI

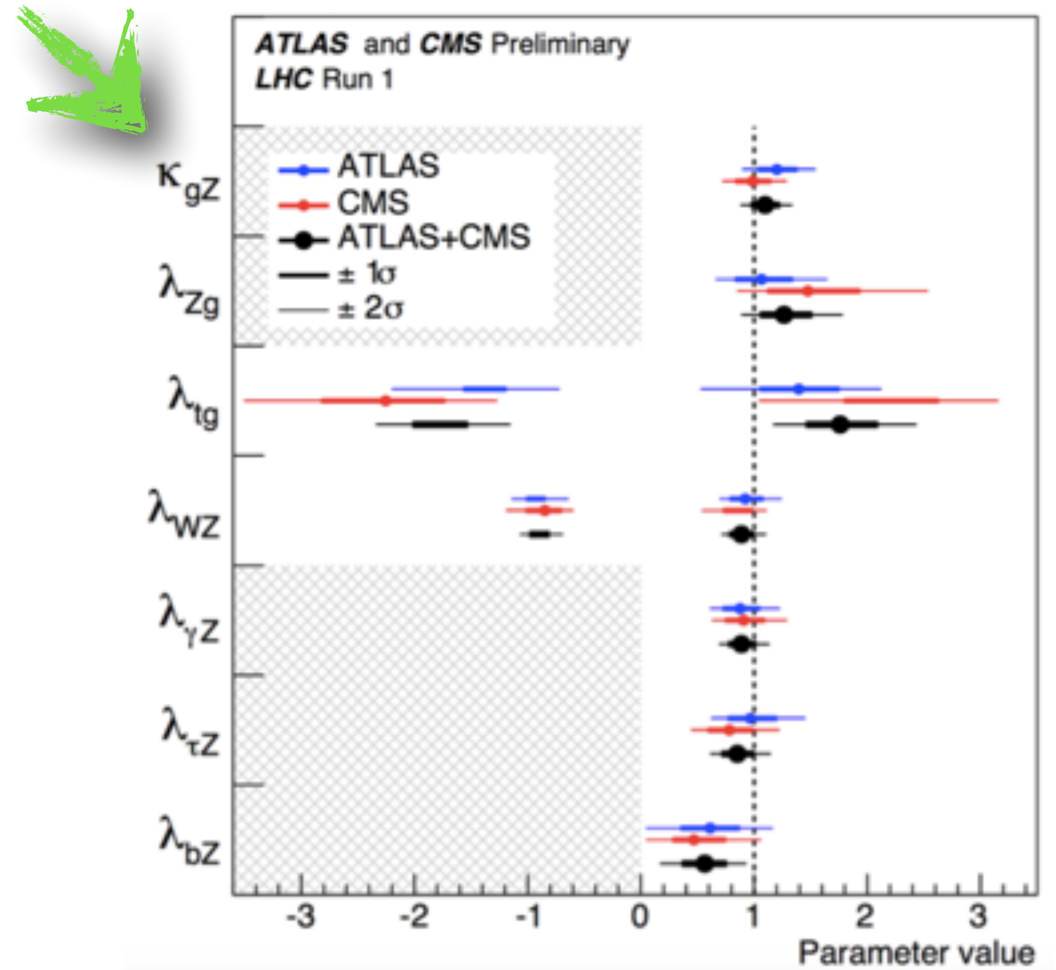
BR/x-section ratio



In addition interpretation within k-framework

Each coupling scaled by κ,

gives : κ2=σi/σSM ;κ2=BRf/BRSM



Various parametrizations have been tried and were all found in agreement with SM (worst p-value of 11%)

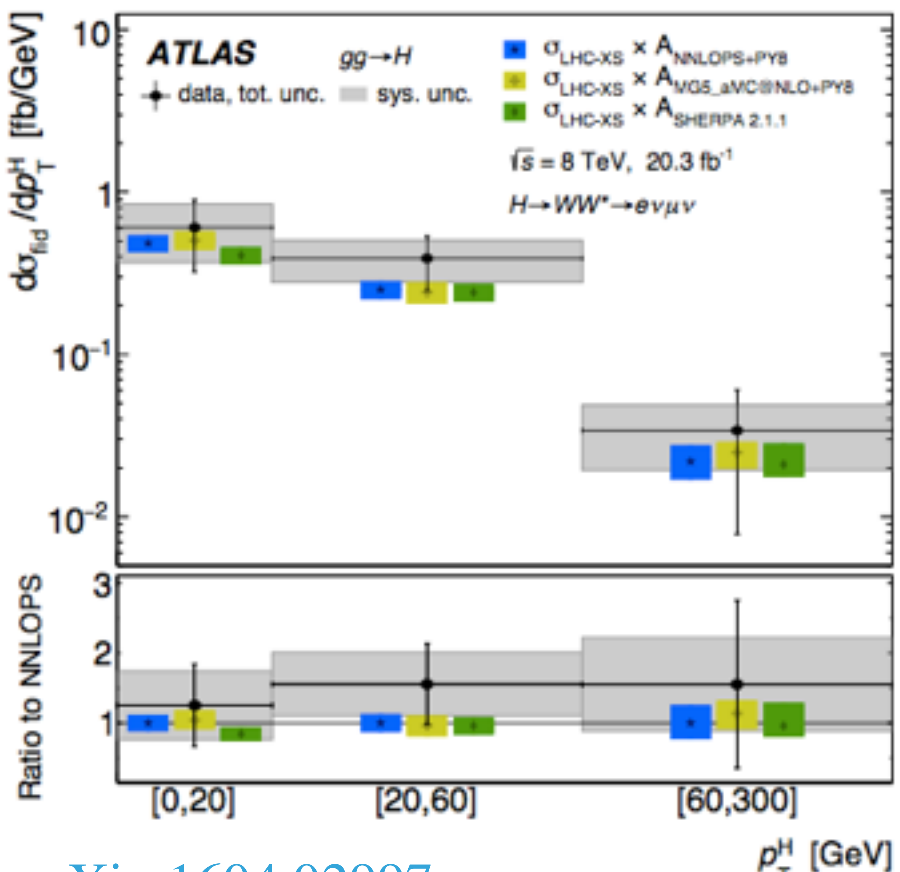
In the future perform EFT fit, template x-sections and Pseudo Observables ->

1) will imply an increase in number of parameters (will be done gradually depending on available luminosity)
2) advantage of providing more general results, easily interpretable in several models (LO EFT, NLO EFT, non linear EFT)

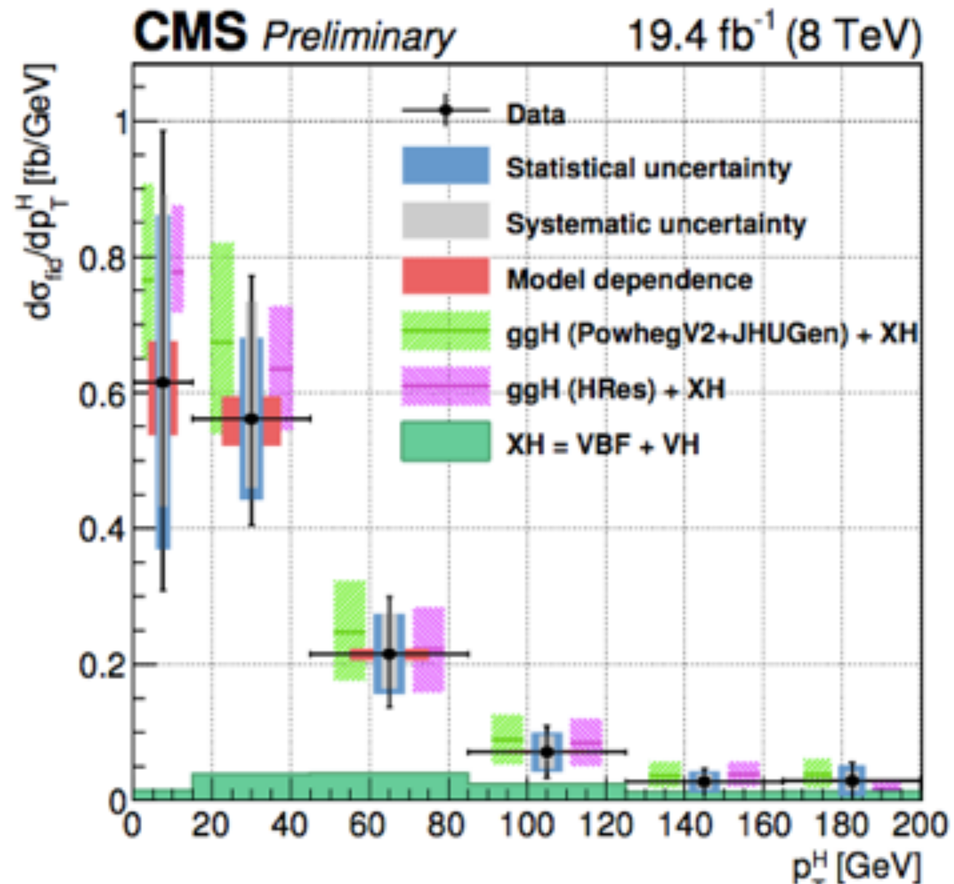
Differential measurements

Kate Whalen

H→ZZ*→4l, H→γγ, **New:** H→WW*→lνlν



arXiv:1604.02997



CMS-PAS-HIG-15-010

1) Differential distributions show good agreement with SM.

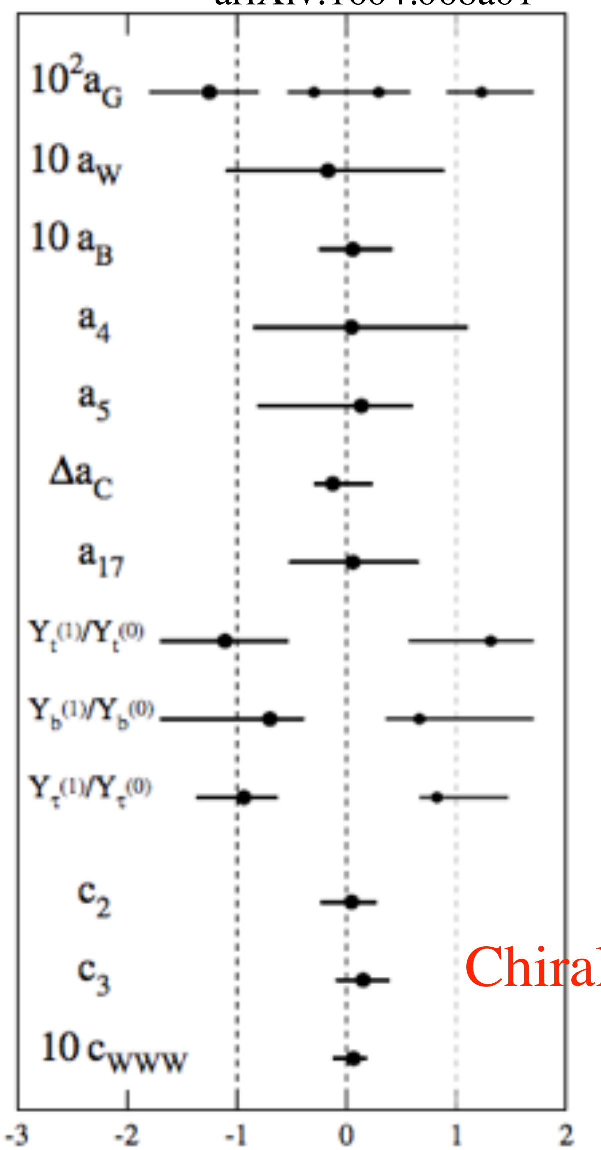
2) Several assumptions made that are acceptable given the present statistics, like the VBF subtraction in the H->WW ggF measurement performed by ATLAS.

Leading to more general interpretation of results (template x-section approach)

EFTs

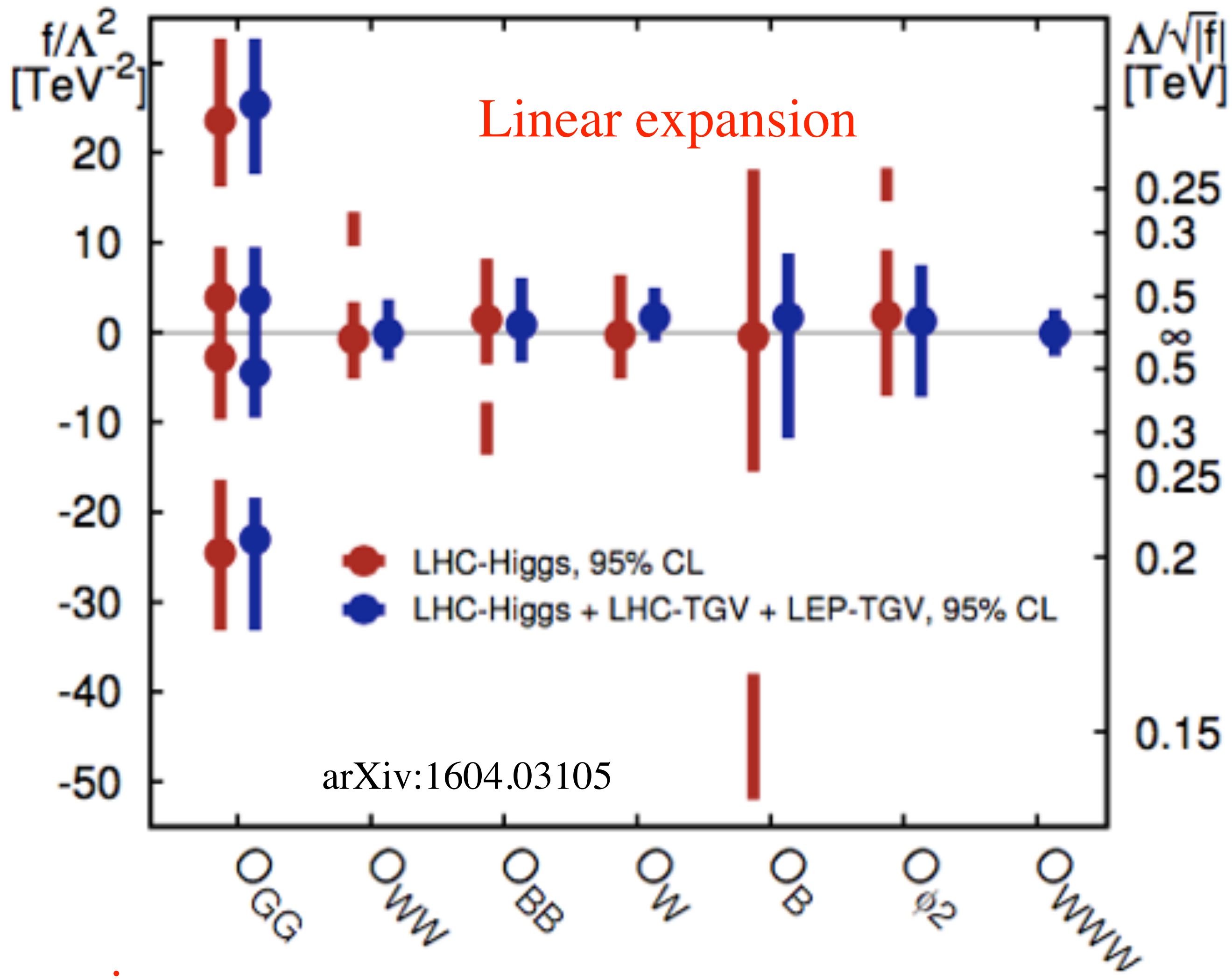
Tyler Corbett

ariXiv:1604.068a01

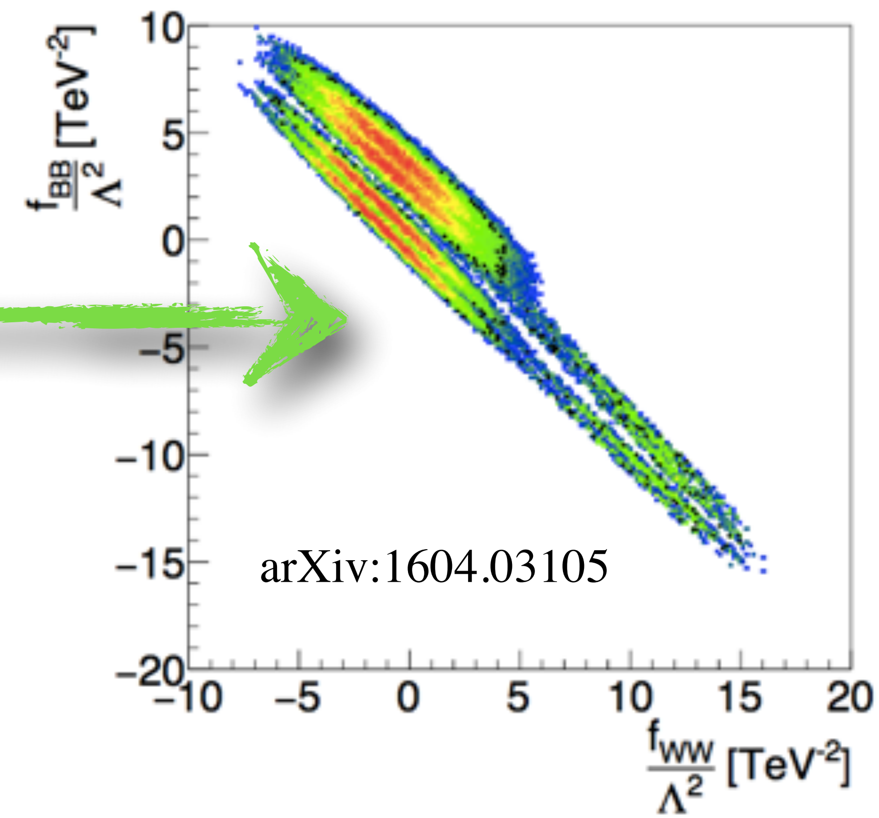


Chiral expansion

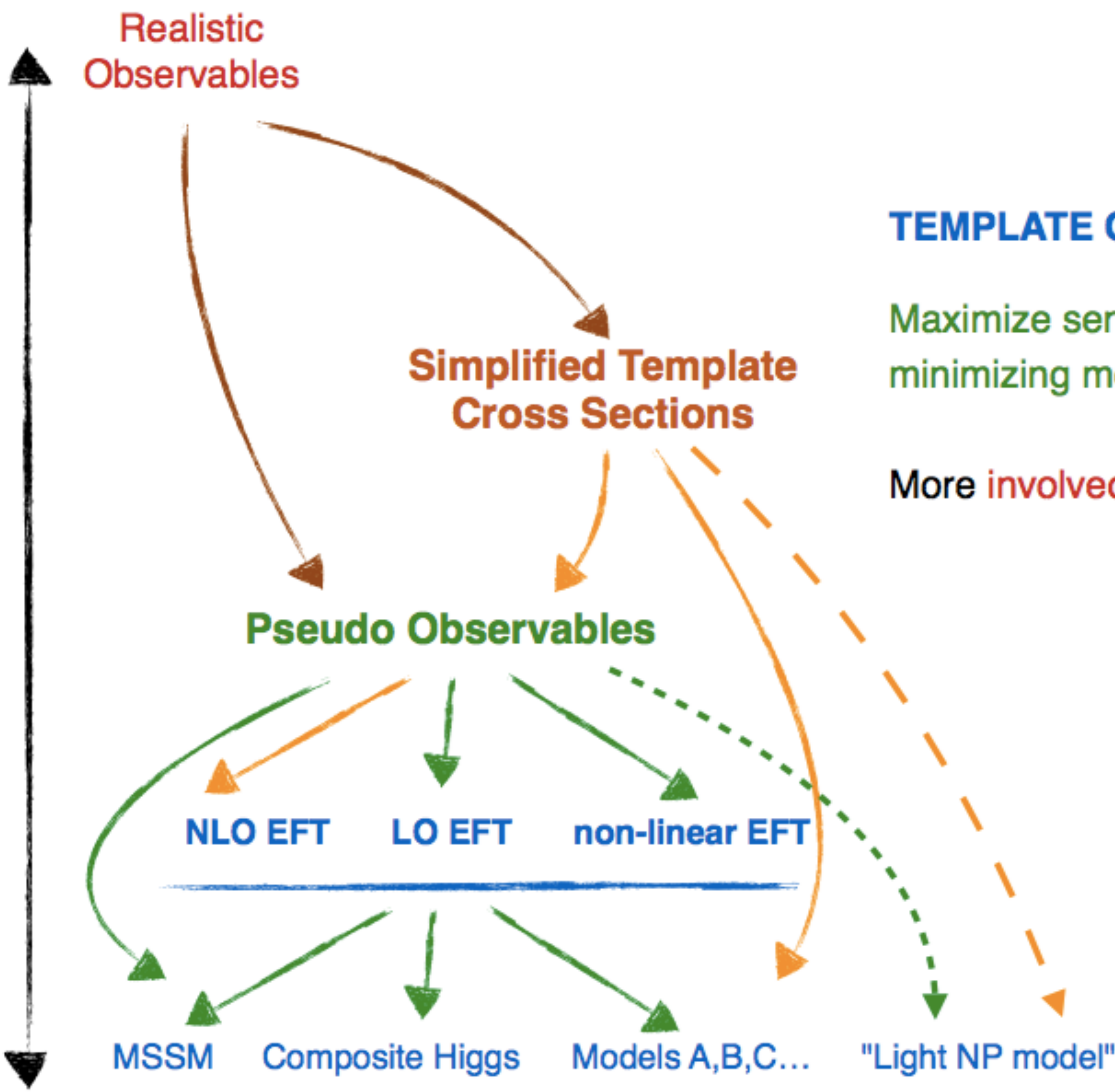
95% CL limits on operators using data from Higgs LHC and TeVatron data



- Correlations between Higgs measurements and TGCs in linear fits.
- No correlations in fits to non-linear EFTs.
- TGC may help in constraining blind directions (degeneracy) in the coefficients
-



Pseudo-Observables/Template Method



TEMPLATE CROSS SECTIONS:

Maximize sensitivity while minimizing model-dependence.

More involved model matching.

$_1^2, q_2^2)$

Pseudo-Observables/Template Method

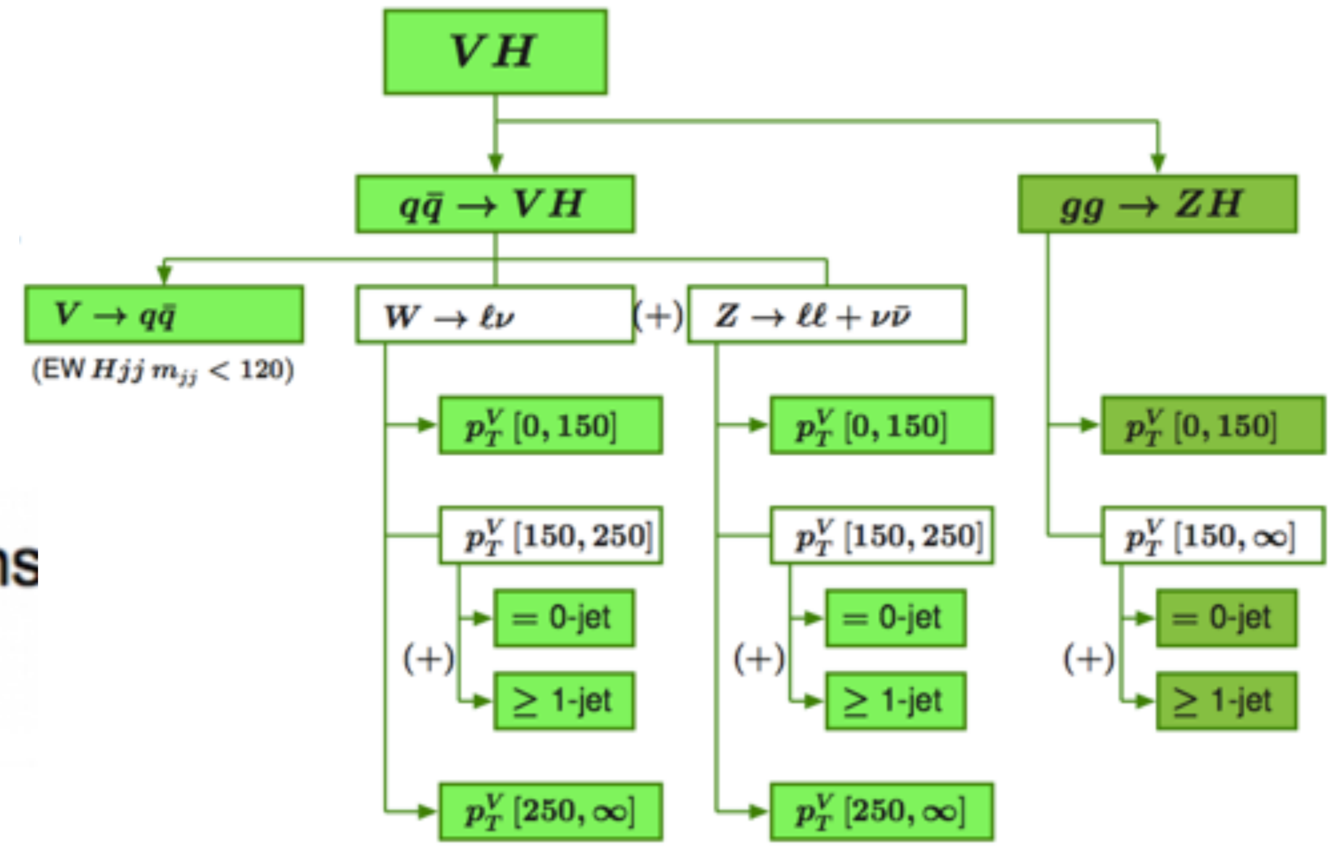
D. Marzocca

$$\sigma_1^{\text{meas}} = A_{1a}^{ggH} \times \sigma_{ggH}^{a} + A_{1b}^{ggH} \times \sigma_{ggH}^{b} + A_{1c}^{\text{VBF}} \sigma_{\text{VBF}}^{c} + \cdots$$

$$\sigma_2^{\text{meas}} = A_{2a}^{ggH} \times \sigma_{ggH}^{a} + A_{2b}^{ggH} \times \sigma_{ggH}^{b} + A_{2c}^{\text{VBF}} \sigma_{\text{VBF}}^{c} + \cdots$$

$$\sigma_3^{\text{meas}} = \cdots$$

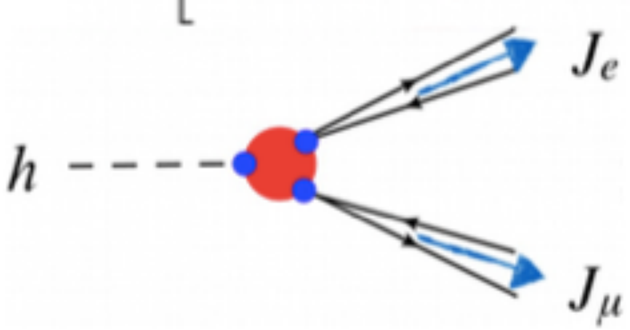
Separately fit bin cross sections σ_{ggH}^{a}, σ_{ggH}^{b}, σ_{VBF}^{c}, ...



- Template cross sections: Fit cross sections in different bins inclusive of Higgs decays.
  - Calculate in favorite model and compare.

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$

$$\left[F_L^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_T^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\, g^{\alpha\beta} - q_2{}^{\alpha} q_1{}^{\beta}}{m_Z^2} + F_{\text{CP}}^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$



$$F_X(q_1^2,q_2^2) = \sum_V \frac{(\text{const})_{2V}}{(q_1^2 - m_V^2)(q_2^2 - m_V^2)} + \frac{(\text{const})_{1V}}{(q_{1,2}^2 - m_V^2)} + (\text{const}) + f_{\text{reg}}(q_1^2,q_2^2)$$

2 poles *1 pole* *no poles*

- Pseudo-Observables: Systematic way to encode experimental information for on-shell Higgs decays.
  - Pseudo-Observables are the residues of physical poles in the decay amplitude.
  - Can systematically include more information as statistics increase.

Precision Calculations

E. Furlan

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\text{PDF}+\alpha_s)$$

at present NNLO+
NNLL QCD NLO EW

+7.4%
-7.9%

δ(PDF)	$\delta(\alpha_s)$	δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(tbc)$	$\delta(1/m_t)$	
± 0.90	$^{+1.27}_{-1.25}$	$^{+0.10}_{-1.15}$	± 0.18	± 0.56	± 0.49	± 0.40	± 0.49	pb
± 1.86	$^{+2.61}_{-2.58}$	$^{+0.21}_{-2.37}$	± 0.37	± 1.16	± 1	± 0.83	± 1	%

can be improved/eliminated

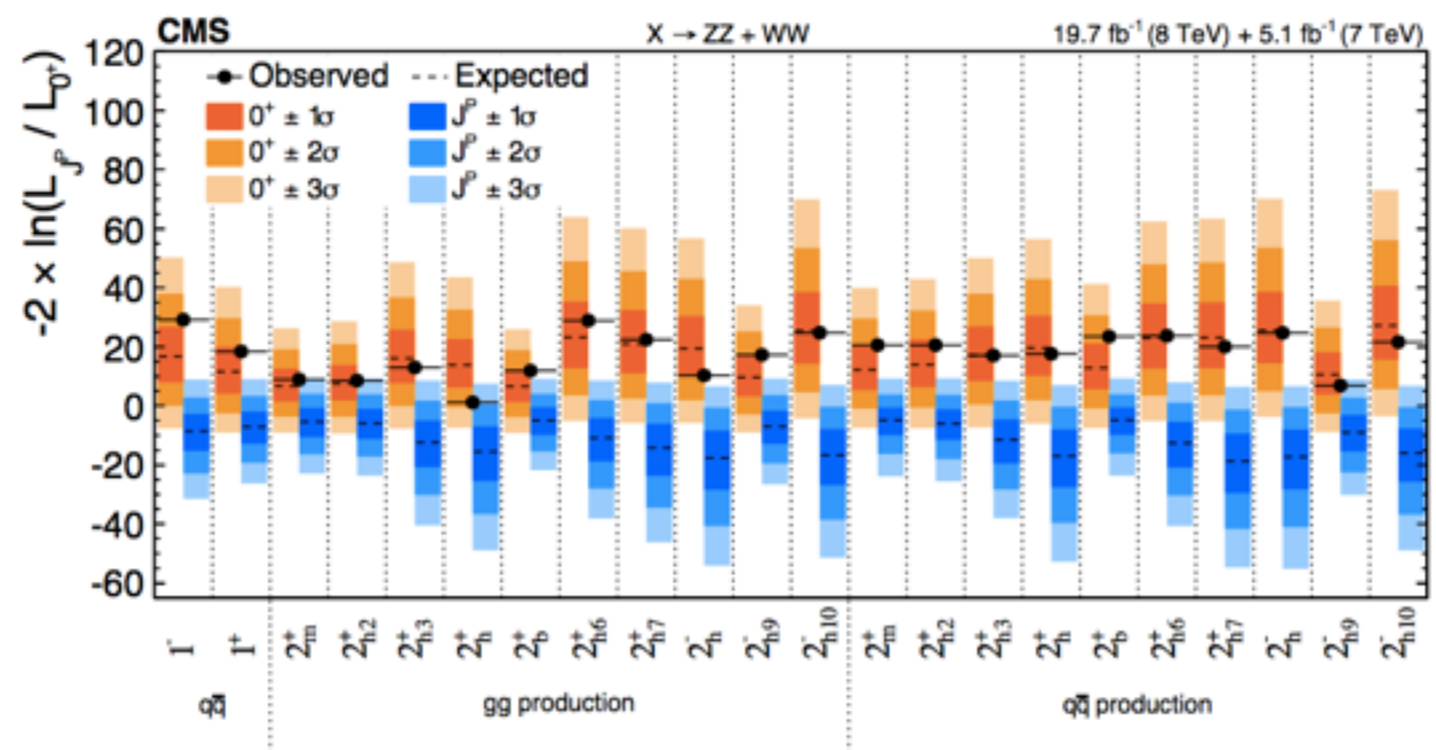
Decay channel	BR	Theory uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	+1.73% -1.72%
$H \to ZZ$	2.62×10^{-2}	+0.99% -0.99%
$H \to WW$	2.14×10^{-1}	+0.99% -0.99%
$H \to \tau\tau$	6.27×10^{-2}	+1.17% -1.16%
$H \to b\bar{b}$	5.82×10^{-1}	+0.65% -0.65%
$H \to Z\gamma$	1.53×10^{-3}	+5.71% -5.71%
$H \to \mu\mu$	2.18×10^{-4}	+1.23% -1.23%

- Branching ratio uncertainties mostly under control.
- N^{3}LO gluon fusion calculation done. Still largest source of uncertainty on rates.
- Can be improved with inclusion of mass effects.
- What are the most important calculation needed to be done?

Spin/CP run I

Anne-Marie Magnan

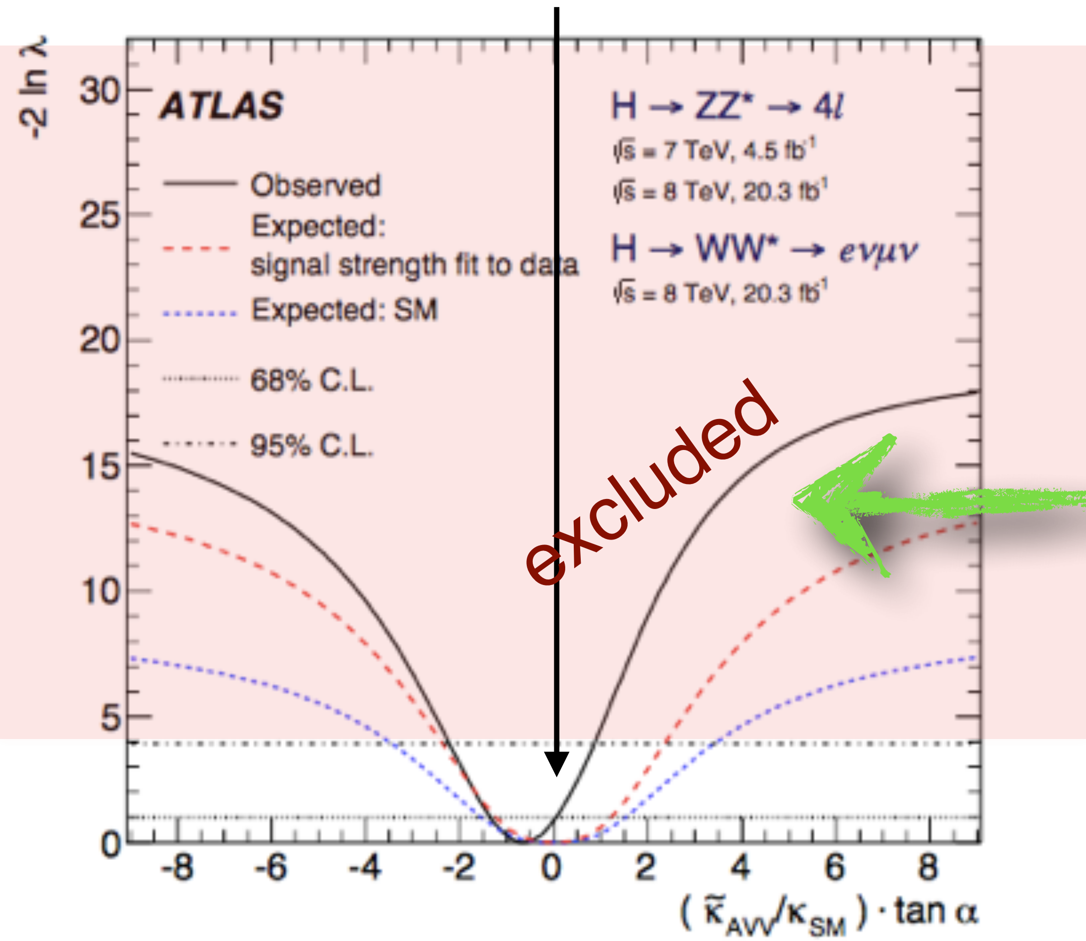
Phys. Rev. D 92 (2015) 012004



Spin 1 and 2 excluded at more than 99% CL by both collaborations

Pure CP higher order CP even and CP odd excluded at > 99.9% CL by both collaborations.

SM case



CP odd increasing

CP mixing also investigated,
large fractions of CP mixing are still allowed <30%

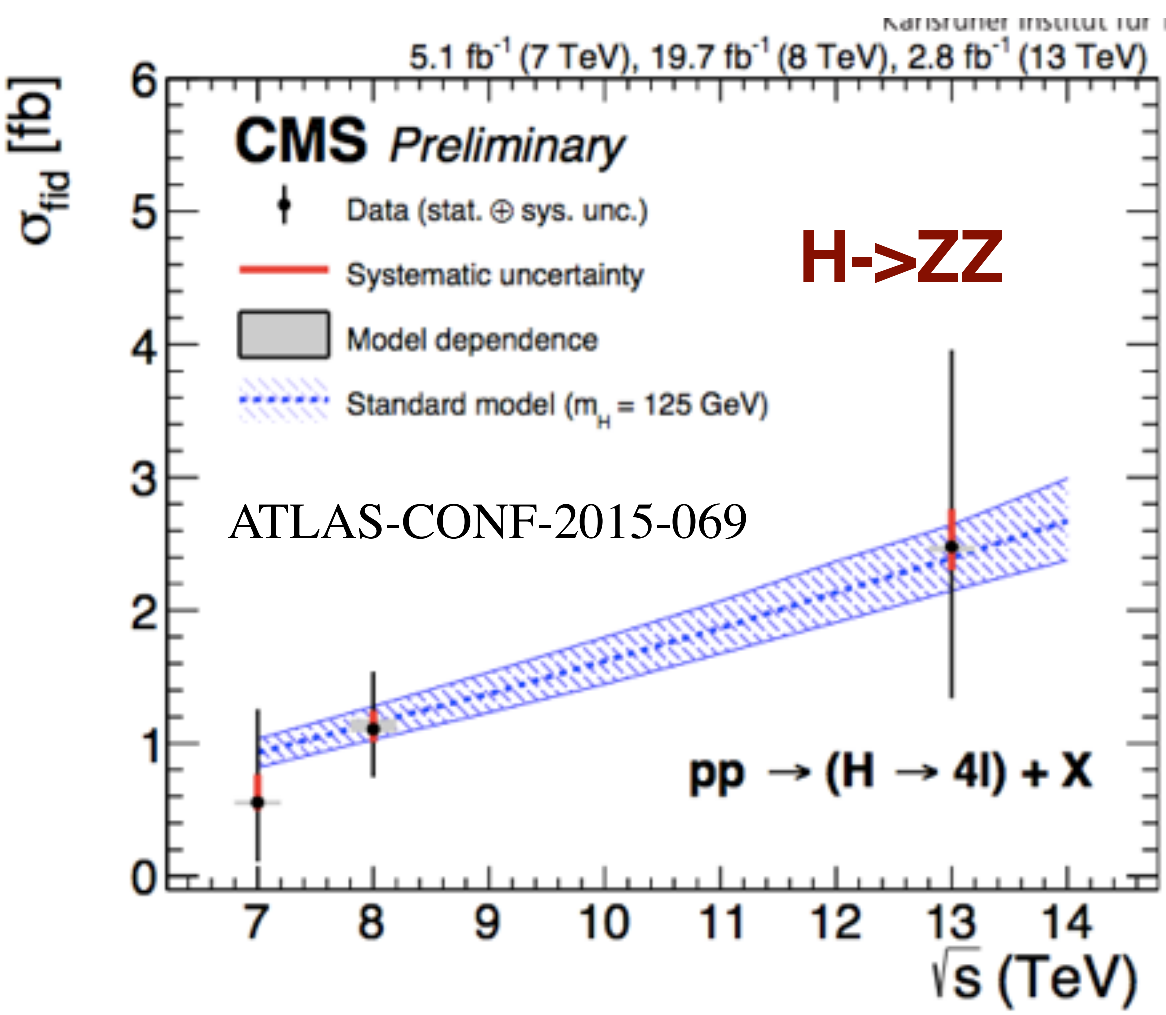
EFT interpretation should still be a priority:

- **combine couplings and CP studies!**
- increase of generality PO, K-framework limited to rates!

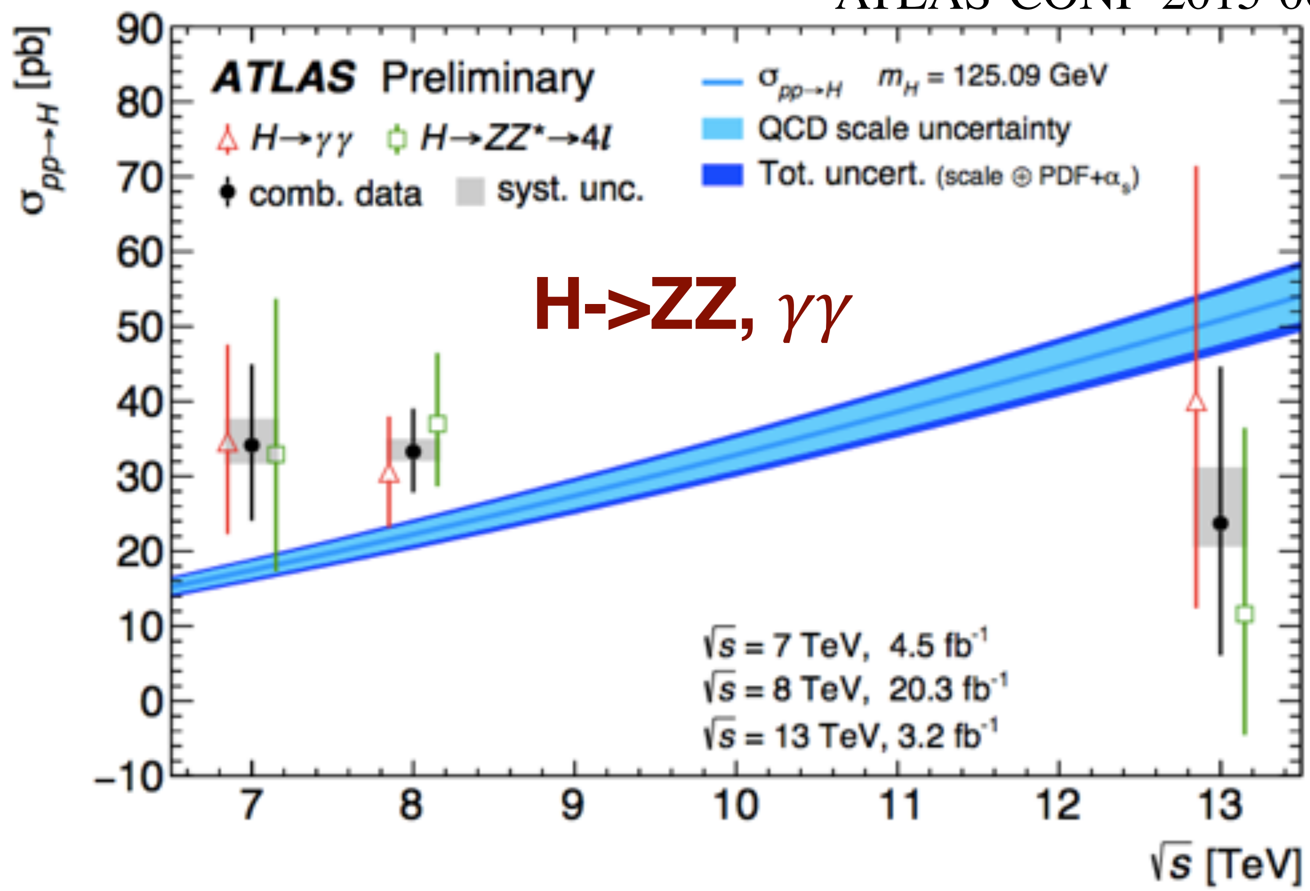
Eur. Phys. J. C75 (2015) 476

SM Higgs run II

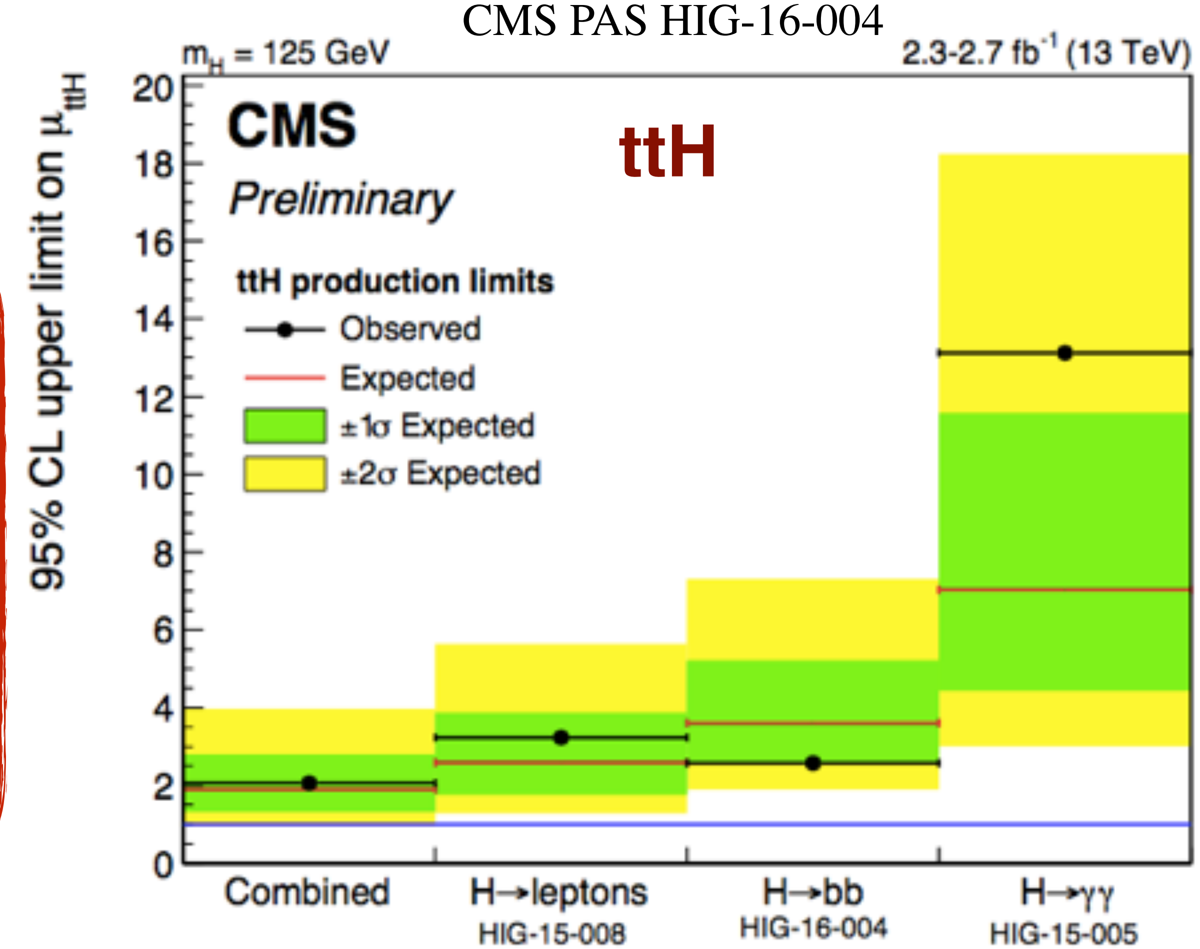
Hannes Mildner



ATLAS-CONF-2015-069

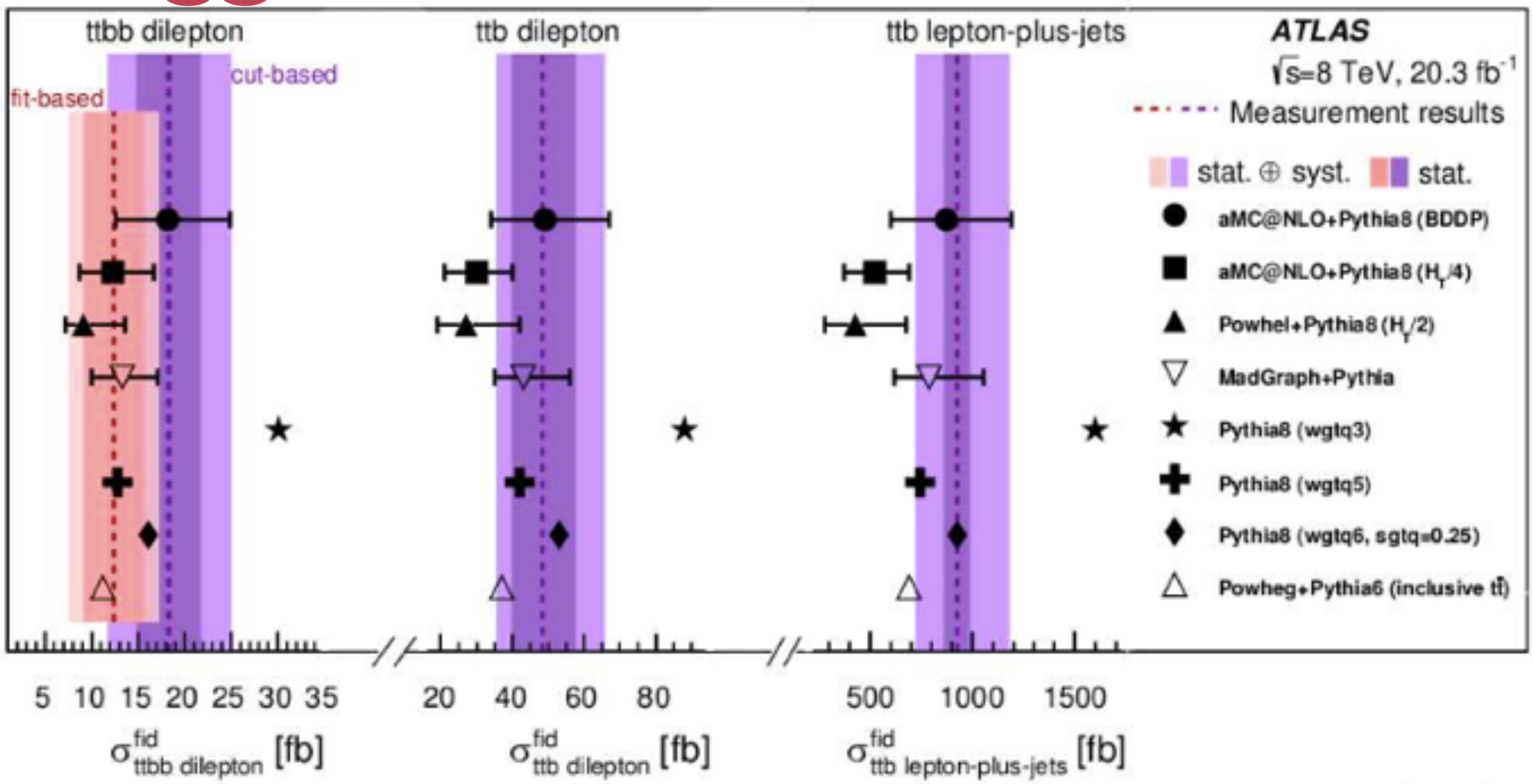


CMS PAS HIG-16-004



For ttH one of the limiting factors is the understanding the tt+HF and gluon splitting to bb.
Large uncertainties used now 50% and uncertainty on kinematics is affecting Multivariate techniques!

SM Higgs run II



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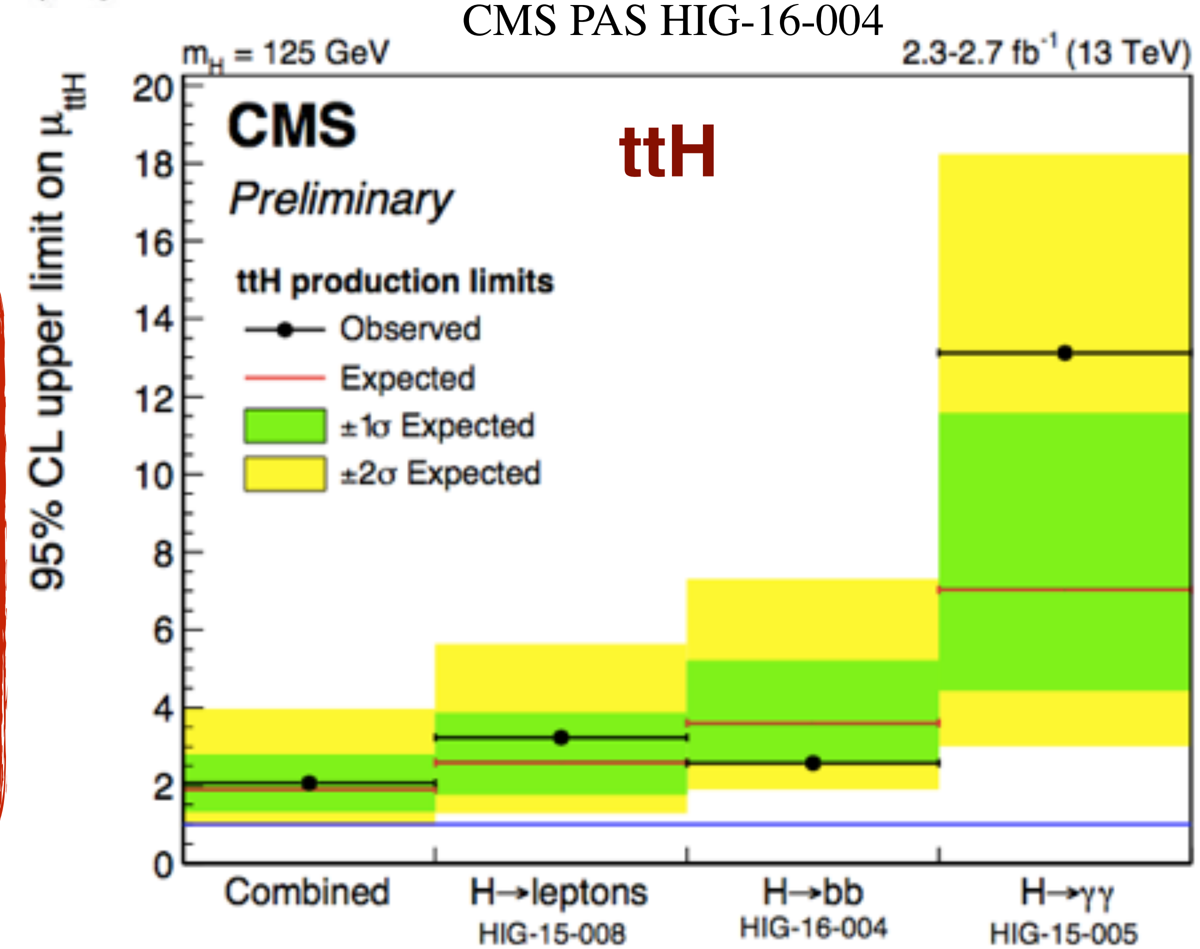


H.Abouzeid

HBSM

Charged Higgs

$H^+ \to tb$
$H^+ \to \tau\nu$

Higgs to Higgs

$H \to hh \to bb\gamma\gamma$
$H \to hh \to bb\tau\tau$
$H \to hh \to l\nu l\nu + bb$
$H \to hh \to bbbb$

Neutral Higgs

$A \to Zh \to ll/\nu\nu\ bb$
$H \to ZA \to llbb$
$H/A \to \tau\tau$

Diboson + Boosted VV

$H \to 4l$
$H \to ll\nu\nu$
$H \to llqq$
$H \to Z\gamma$

$H \to llqq$
$H \to \nu\nu qq$
$H \to l\nu qq$
$H \to qqqq$

Invisible

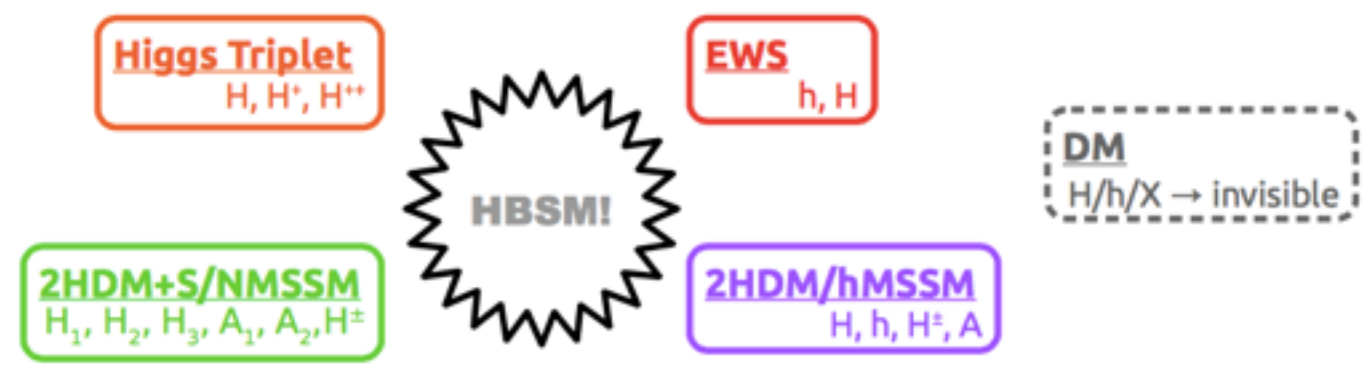
$ZH \to ll$ + *invisible*
VBF $H \to$ *invisible*

<u>Outlook, we shall use 125 GeV Higgs properties to constrain new physics:</u>

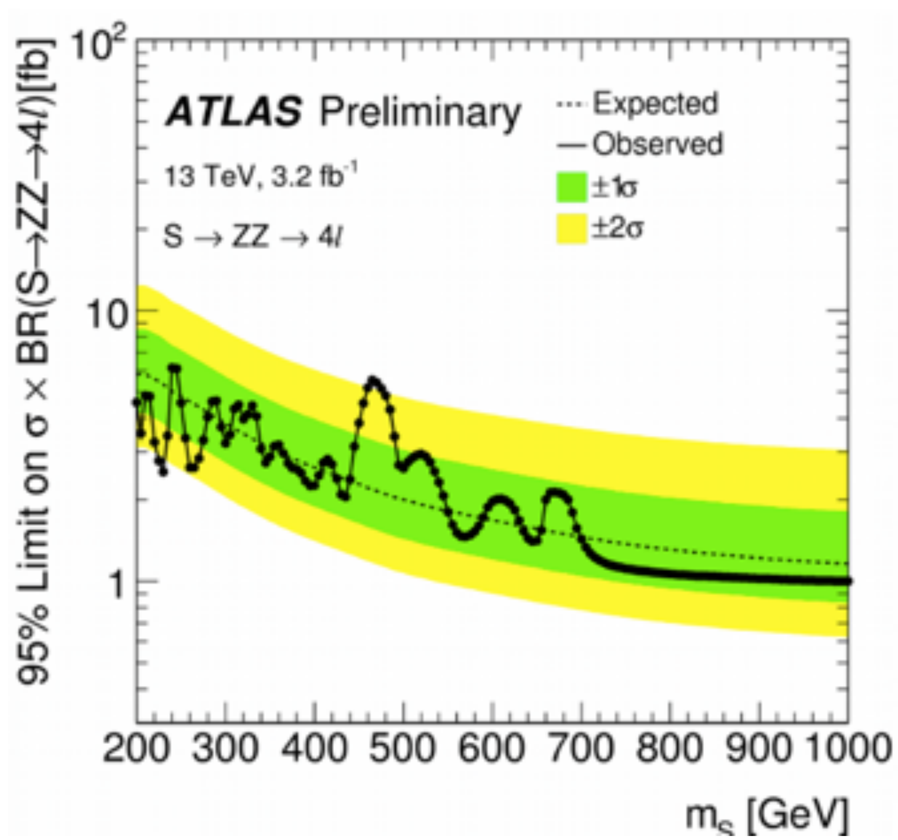
Use 125 GeV couplings and mass measurements to constrain:

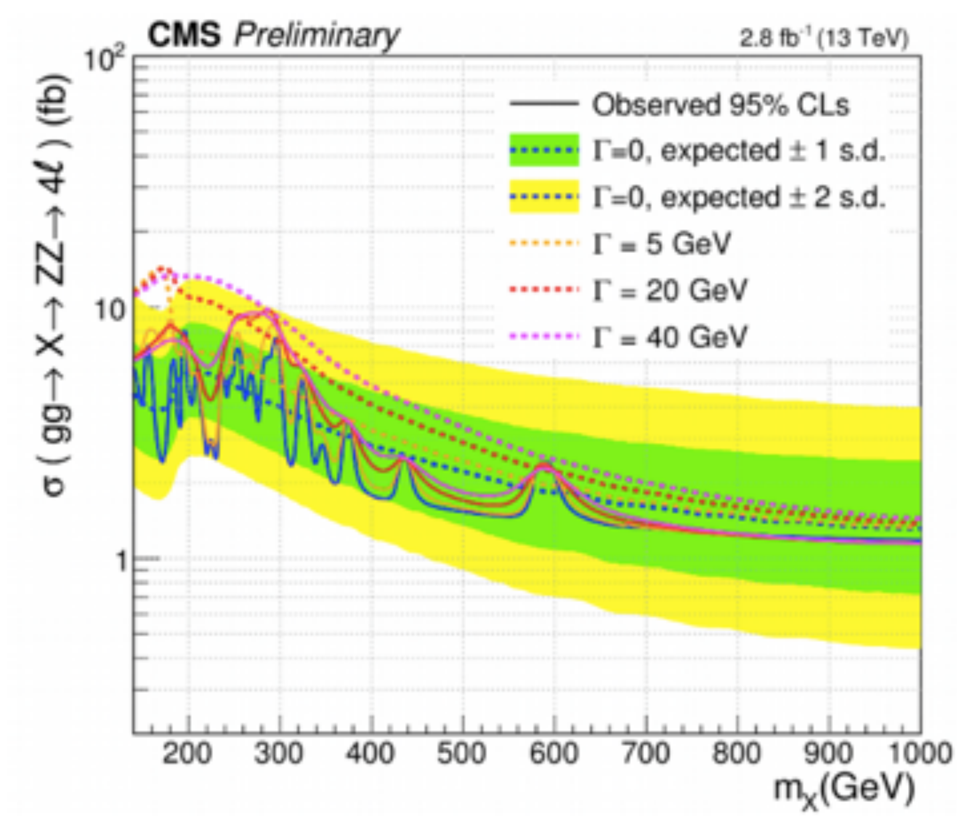
- -composite Higgs models,
- -electroweak singlet
- -2HDM, etc..
- (arXiv:1509.00672)

Wide variety of theoretical benchmarks



ATLAS-CONF-2015-059 CMS-PAS-HIG-15-004





H.Abouzeid

HBSM

Charged Higgs
$H^+ \to tb$
$H^+ \to \tau\nu$

Higgs to Higgs
$H \to hh \to bb\gamma\gamma$
$H \to hh \to bb\tau\tau$
$H \to hh \to l\nu l\nu + bb$
$H \to hh \to bbbb$

Neutral Higgs
$A \to Zh \to ll/\nu\nu\ bb$
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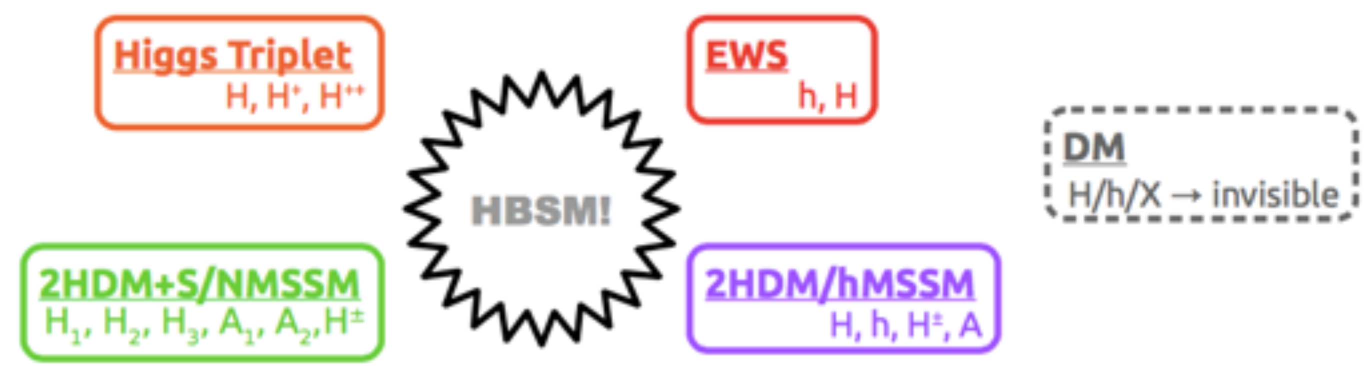
Diboson + Boosted VV
$H \to 4l$
$H \to ll\nu\nu$
$H \to llqq$
$H \to Z\gamma$

$H \to llqq$
$H \to \nu\nu qq$
$H \to l\nu qq$
$H \to qqqq$

Invisible
$ZH \to ll +$ *invisible*
VBF $H \to$ *invisible*

Wide variety of theoretical benchmarks



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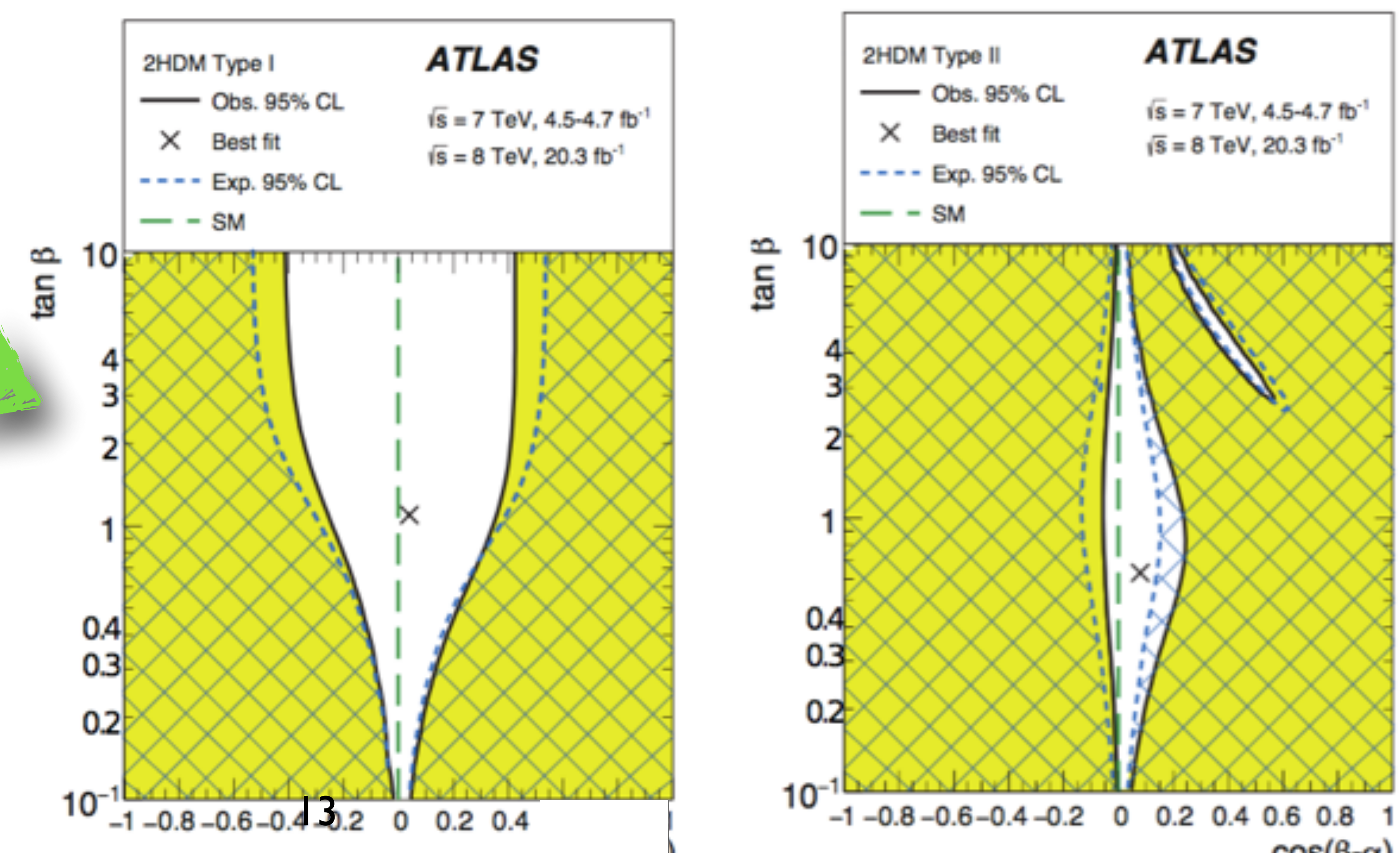
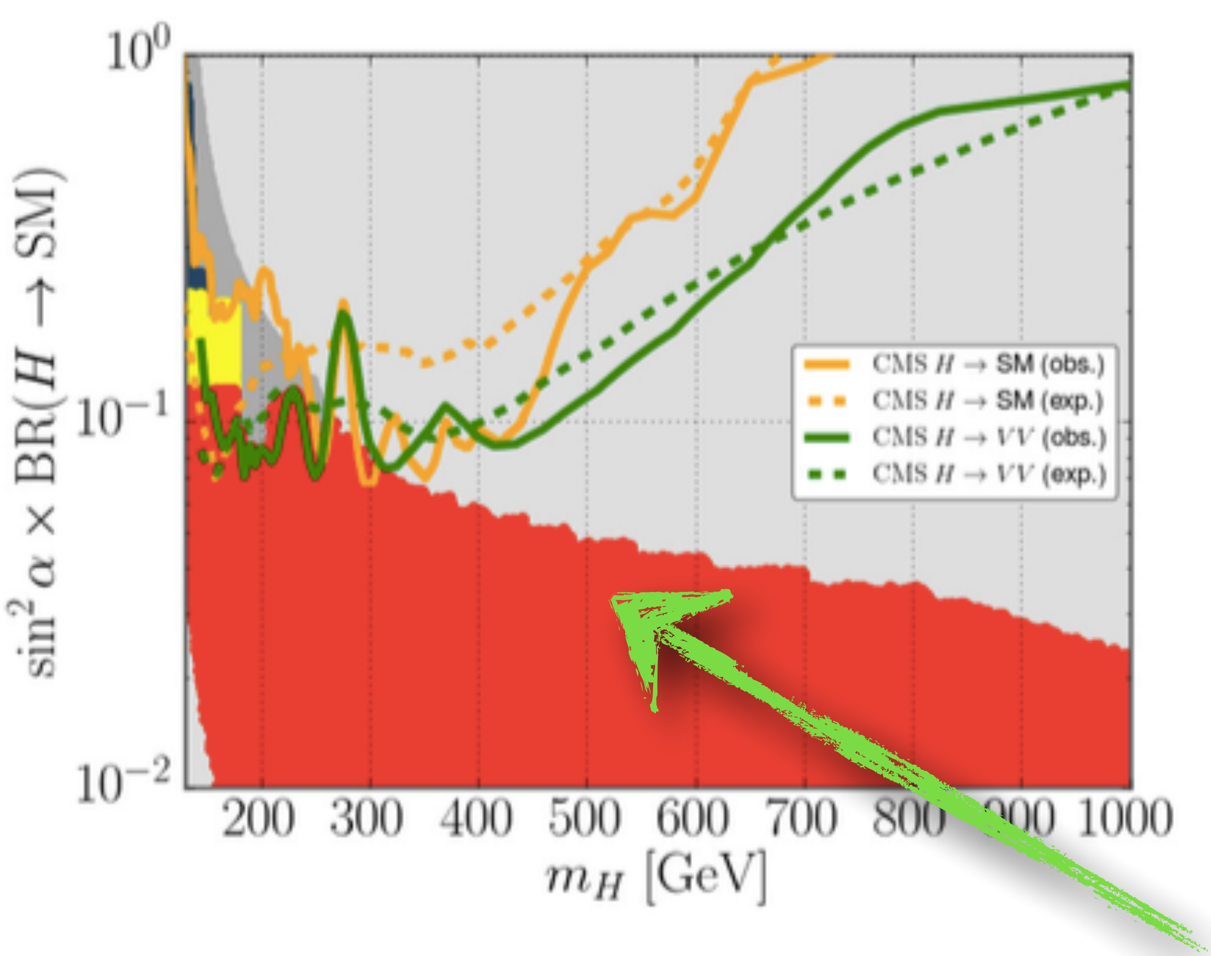
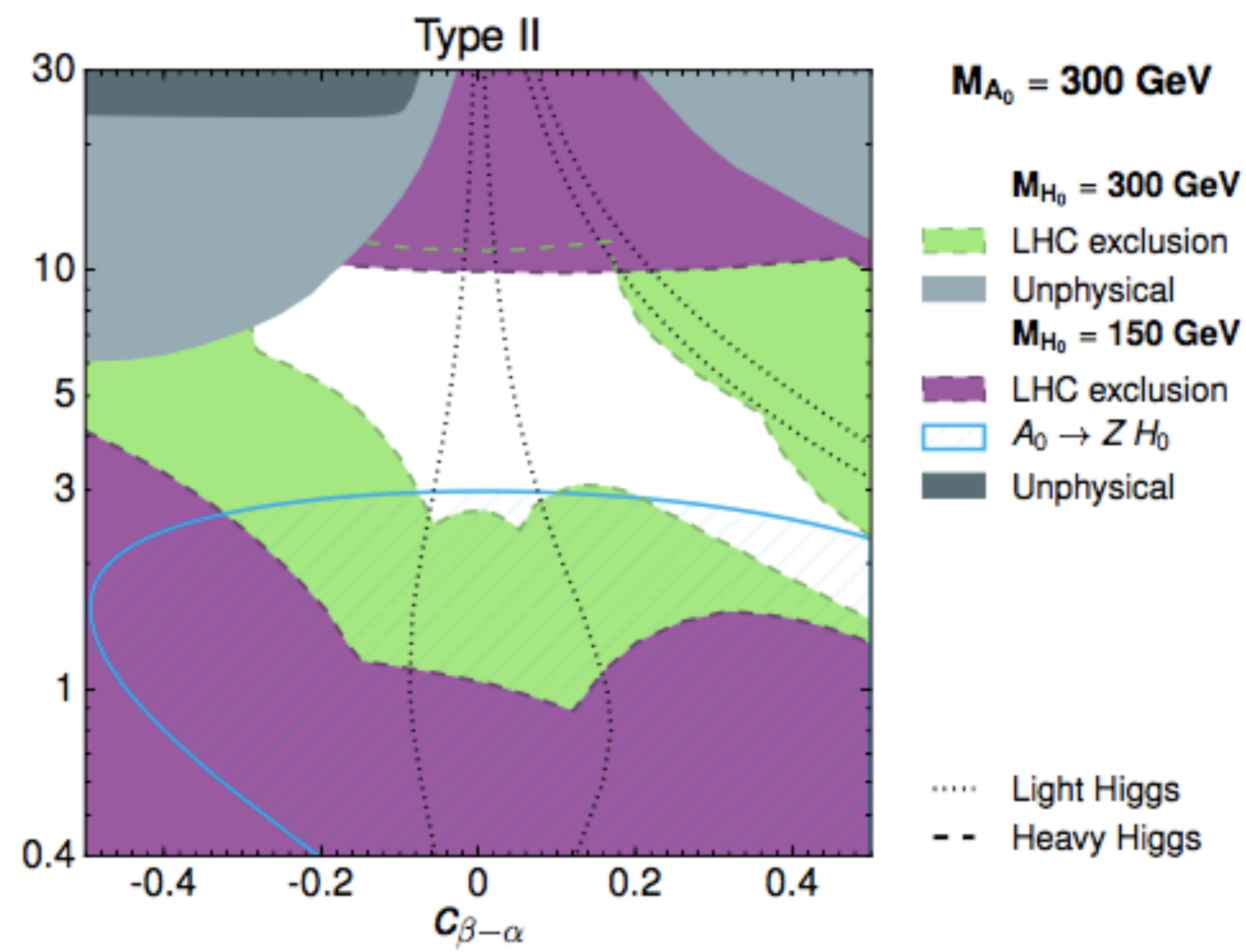


HBSM models?

Tim Stefaniak

- Many BSM models (2HDM, MSSM, NMSSM, . . .) feature an "alignment without decoupling" limit, where a SM-like Higgs is obtained while the remaining Higgs spectrum is light and accessible.





red/yellow points: $1\sigma/2\sigma$ allowed by Higgs rate measurements (HiggsSignals)

750 GeV experiment

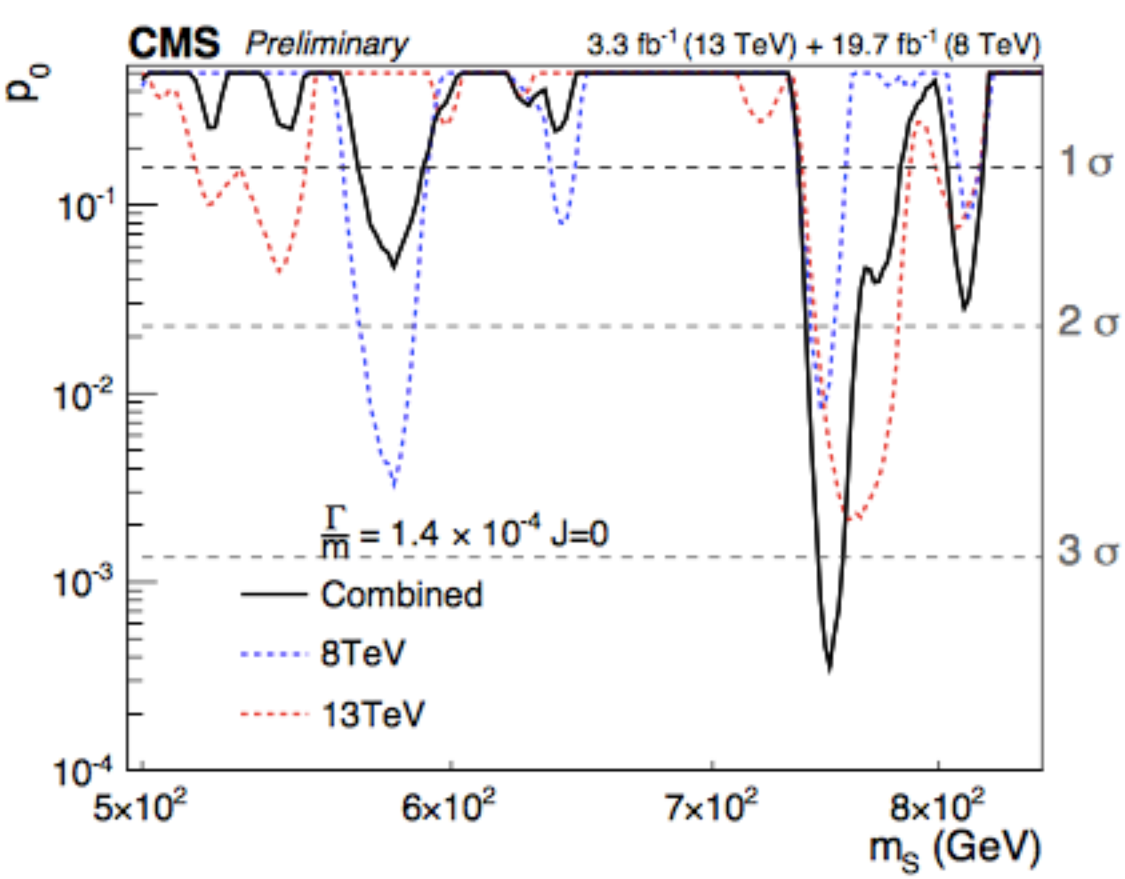
ATLAS-CONF-2016-018
CMS-PAS-2016-018

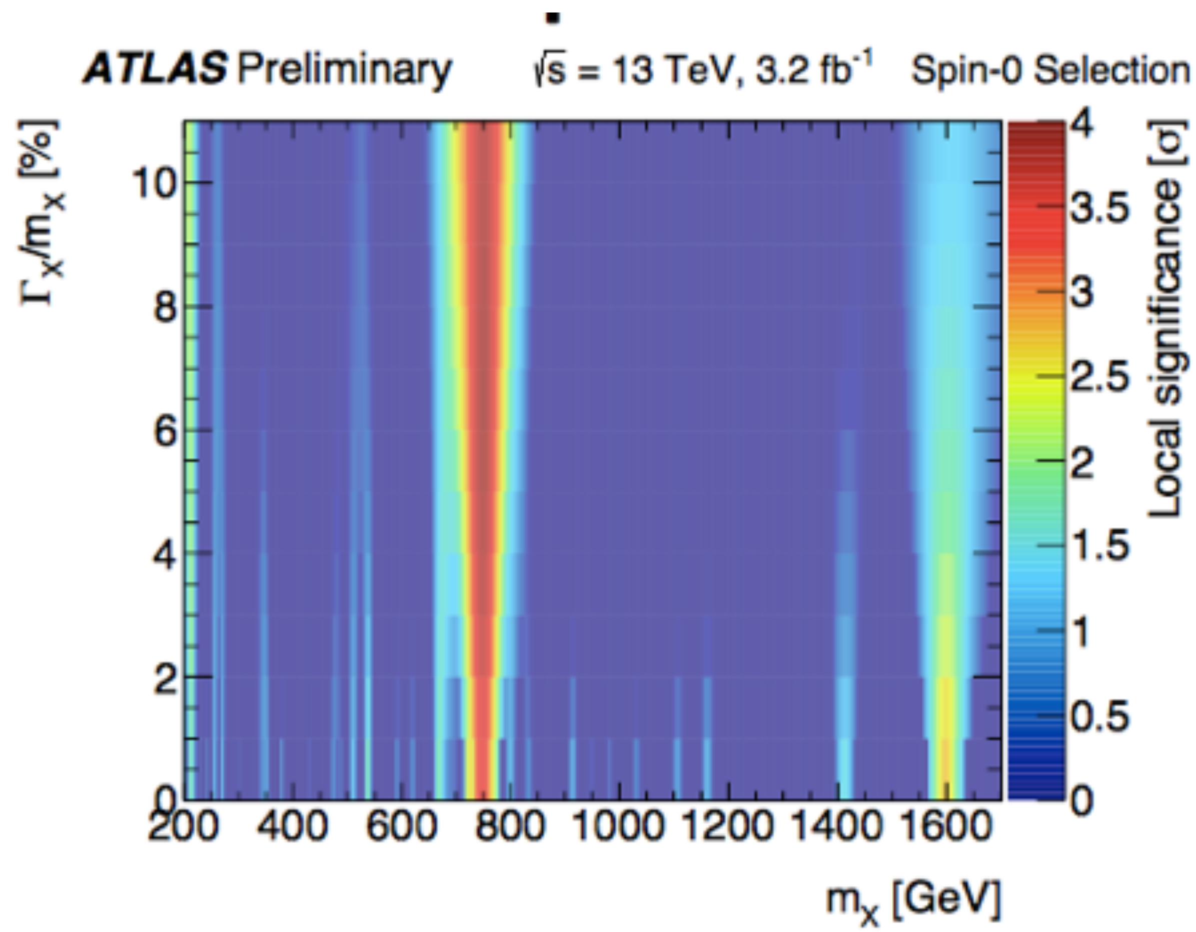
Simone Pigazzini

CMS combined run I& II
Local significance: 3.4σ (1.6σ global) NWA

ATLAS give compatibility with run I
(1.2σ Γ/m = 6% assuming gg production)
Local significance: 3.9σ (2.0σ global)

Spin-0





We have just to wait and see…

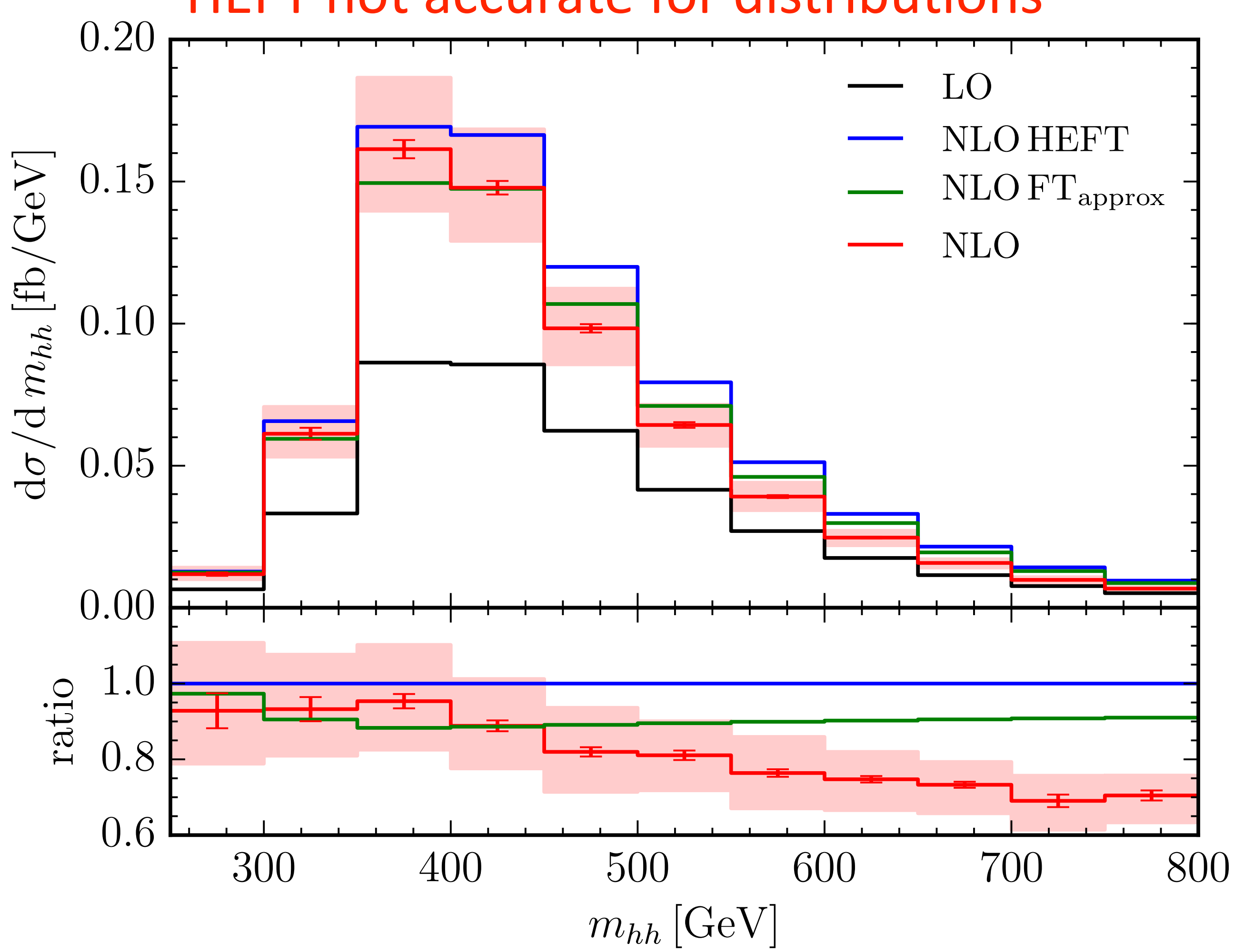
di-Higgs perpsectives

S. Dawson

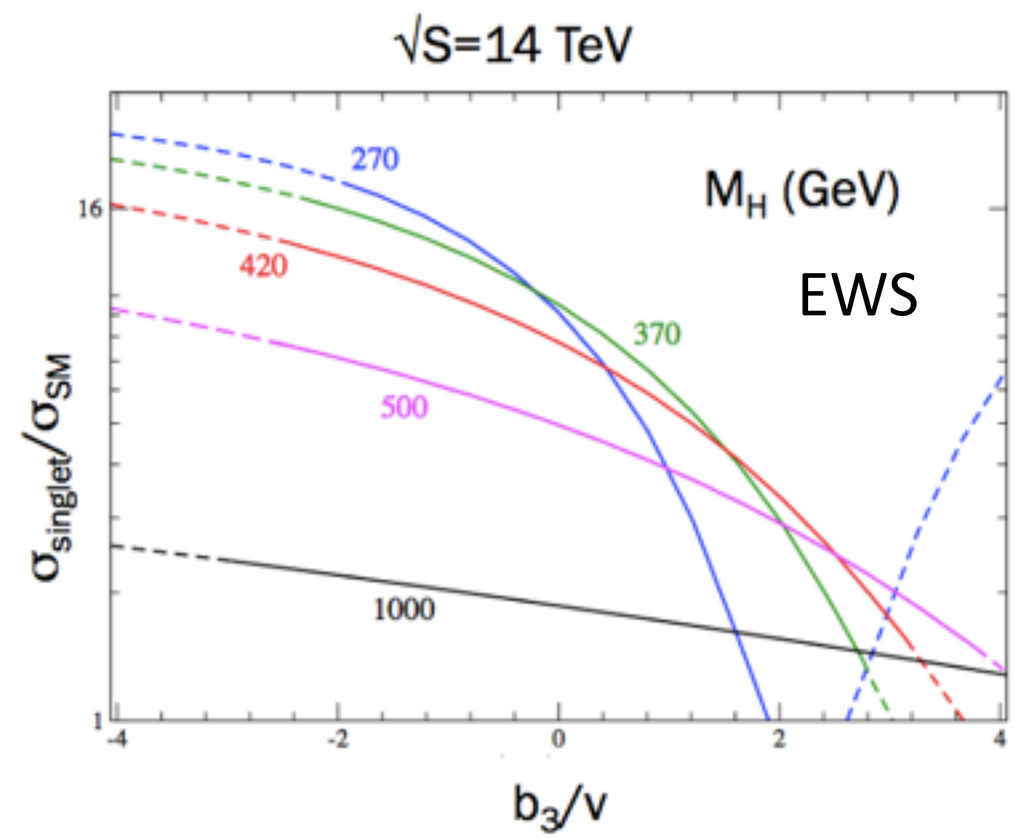
NEW arXiV: 1604.06447

New Exact top mass dependence: 2-Loop virtual with exact mass dependence now known for gg->hh. Result is 14% below HEFT result and does not fall in estimated error bands.
Result with full mass dependence 20-30% below HEFT for m_{hh} above 450 GeV

HEFT not accurate for distributions



presence of an additional high mass Higgs increases di-higgs production by a factor 20.



Higgs prospects for Run II and HL-LHC

Summary & Outlook

- **30 fb^{-1}** of LHC data at $\sqrt{s}$=8 (and 7) TeV allowed for discovery of a Higgs boson
- **300 fb^{-1}** of LHC data at $\sqrt{s}$=13/14 TeV will allow for many precision measurements in the Higgs sector (and SM, more generally) and extend searches for new phenomena
- **3000 fb^{-1}** of LHC data will enhance the LHC physics program:
  - Precision Higgs coupling measurements to elementary bosons and fermions
  - Search for rare Higgs boson decays and portal to DM
  - Higgs coupling structure
  - Di-higgs boson production

ONLY around 1.3-1.6σ per experiment!

- Achieving the physics goals requires ambitious upgrades in the ATLAS and CMS detectors and analysis techniques
- Experience suggests we can exceed our expectations over time!

Hints for discussion

- Couplings and spin fits:
  we have to gradually move from mu k-framework differential towards, EFT, PO, template x-sections.

- What are the future needs in terms of precision theory calculations for signal
  - ggF ,…
  and backgrounds:
  - ttbb
  - WW,ZZ
  - V+jets

- HBSM: combine fits of direct searches and couplings.

- Benchmark models; model independence, 2HDM, EWS, composite Higgs, NMSSM

- What will be the ultimate sensitivity of HL-LHC on di-HIggs (what channels can be added)

- 750 GeV: Which distributions would theorists like to see. What does it mean that we didn't see it in WW, ZZ? It is model dependent. What other channels should be search?