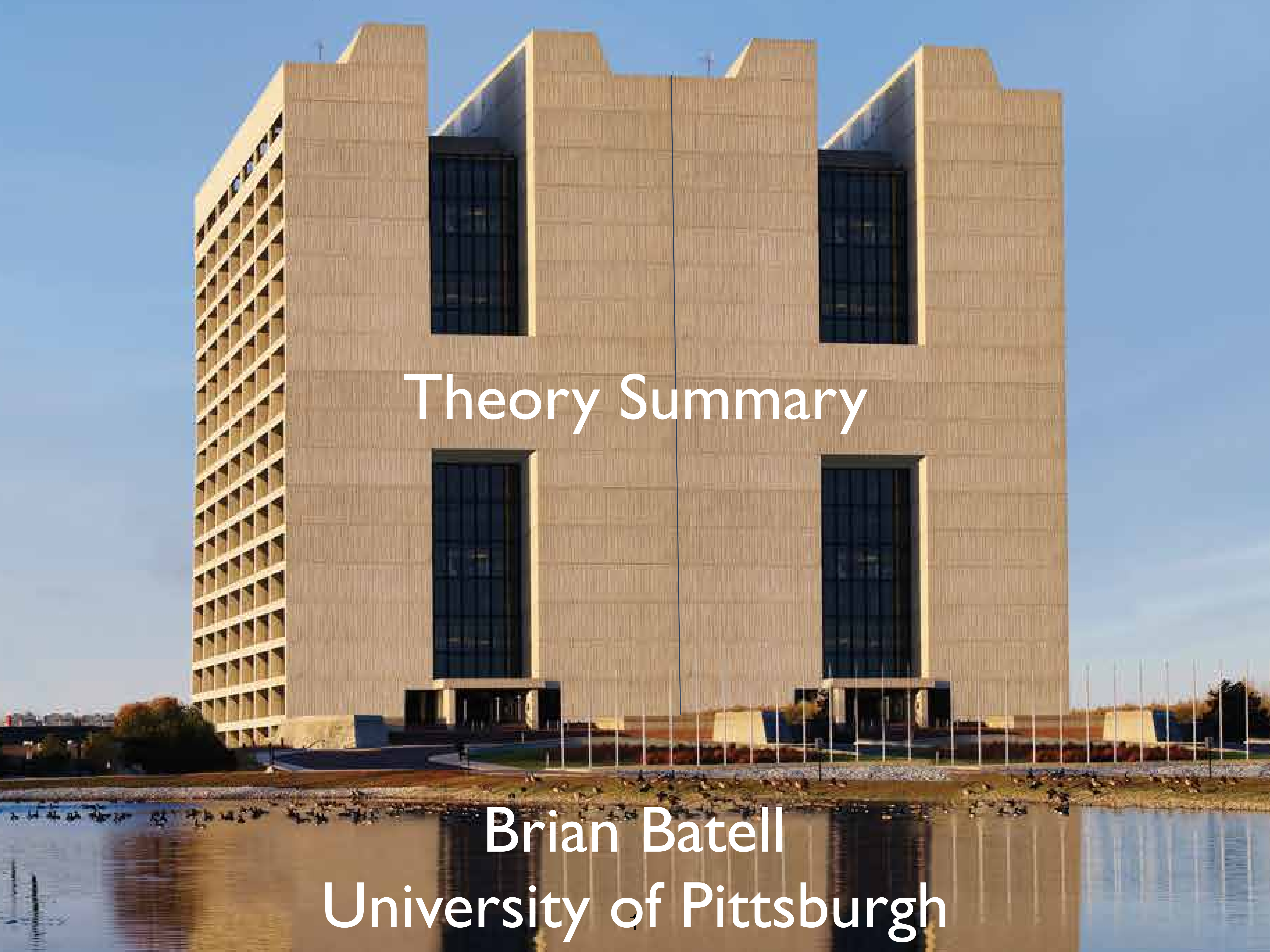
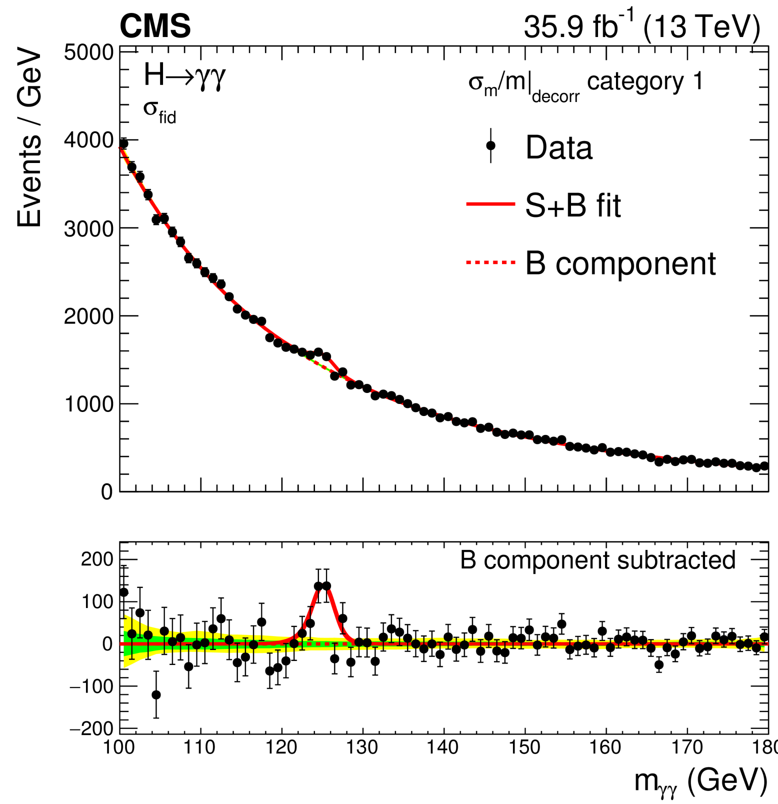
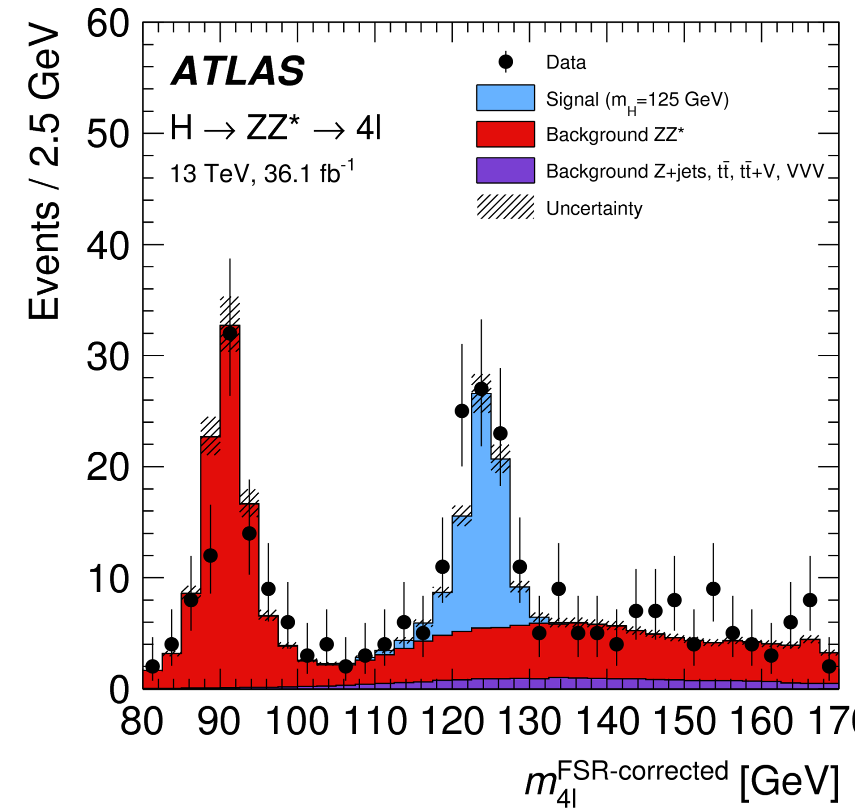


Theory Summary

Brian Batell
University of Pittsburgh

Taking Stock

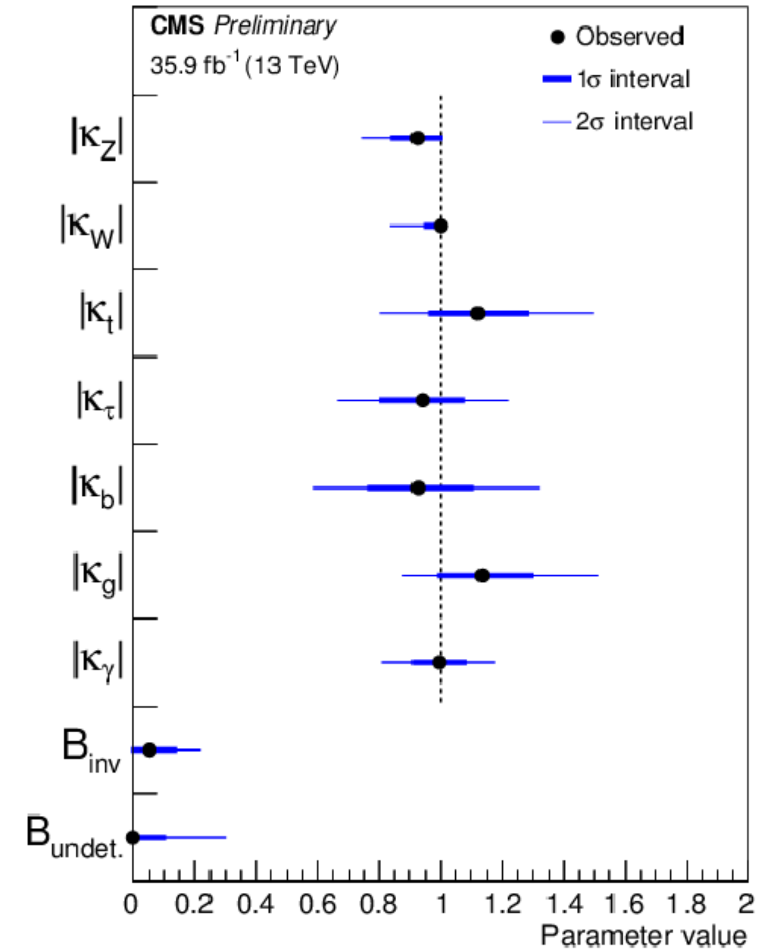


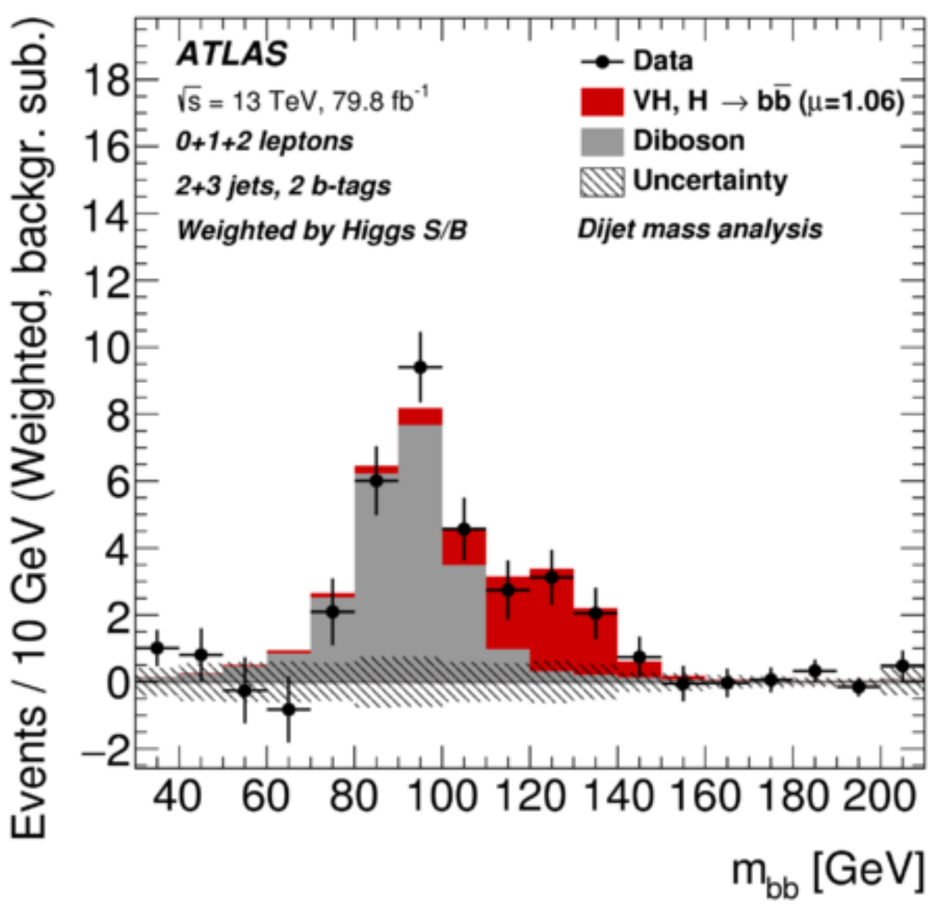


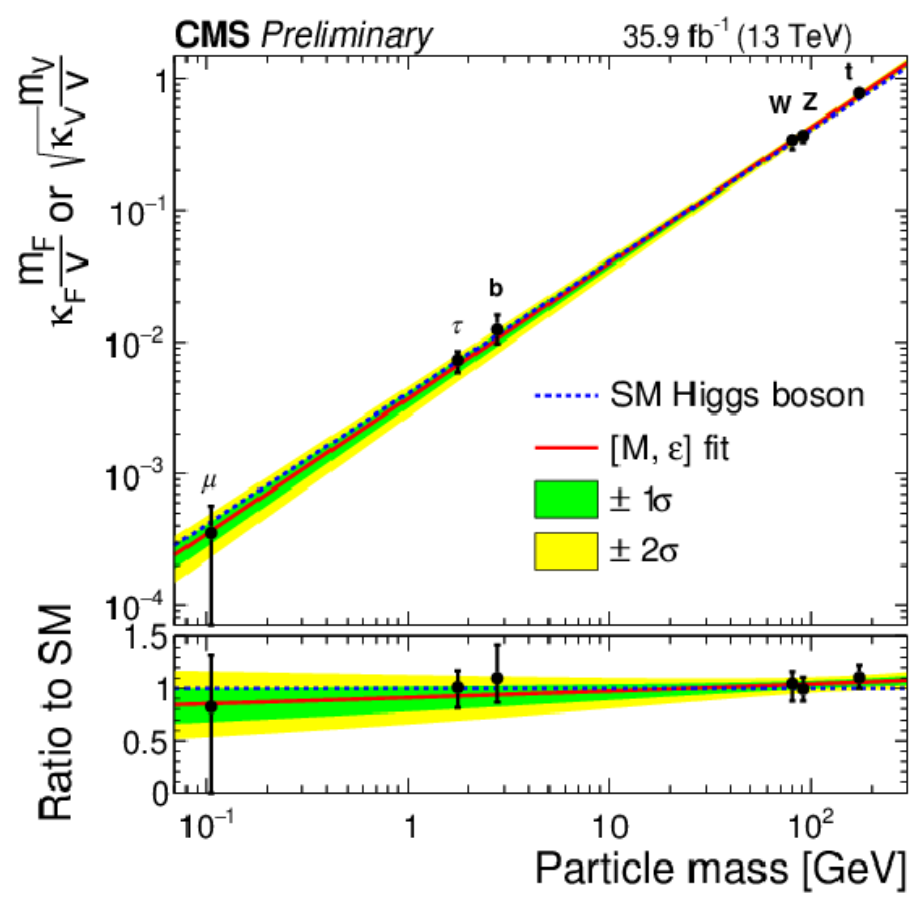
- Higgs!
- Triumph of the Standard Model
- LHC Run I + Run II - strong limits on New Physics
- Still, many good reasons to believe there is new physics
  - Theoretical: Naturalness (Higgs, CC), Flavor, Strong CP, Unification, Gravity ...
  - Empirical: Dark Matter, Neutrino Oscillations, Baryon Asymmetry
  - Higgs definitely plays a role in many, if not all, of these puzzles
- We've only collected about 5% of the total LHC dataset - still room for new physics!

What do we know about the Higgs?

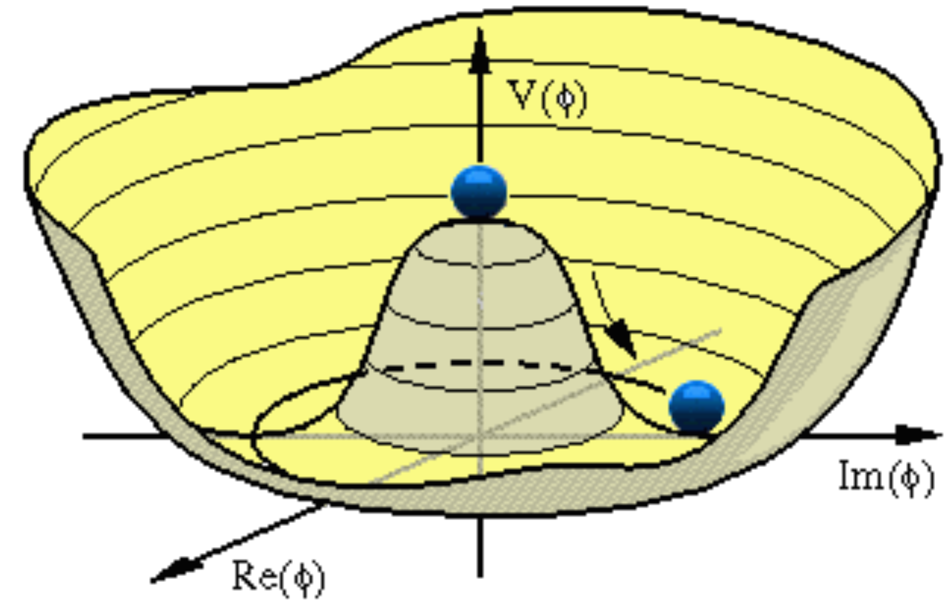
- Consistent with $J^{CP} = 0^{++}$
- Couplings to top, gauge bosons at 10-20% level
- Couplings to bottom, tau observed
- No evidence for coupling to 1st, 2nd generations
- Higgs-self coupling?







Higgs pair production (Di-Higgs)



Scalar potential

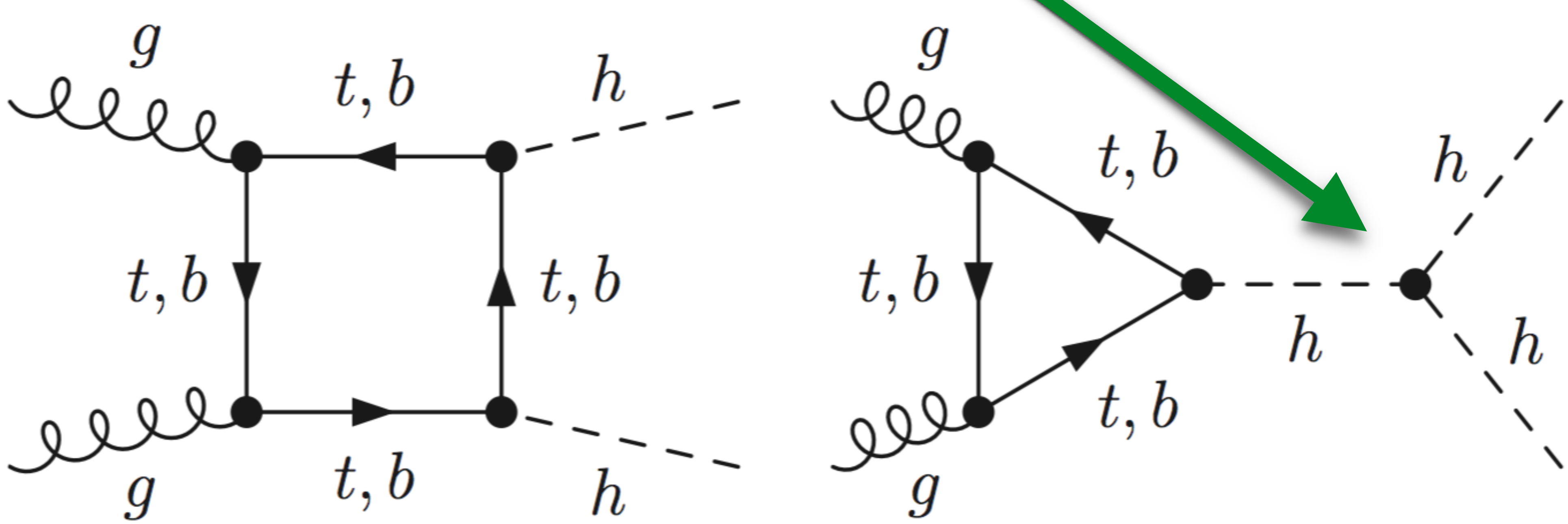
$$V = -\mu^2|H|^2 + \lambda|H|^4$$

$$= \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$

$$v = \sqrt{-\frac{\mu^2}{\lambda}} \qquad m_h^2 = 2\lambda v^2$$

Higgs pair production:

Triple coupling



First studies more than 30 years ago!

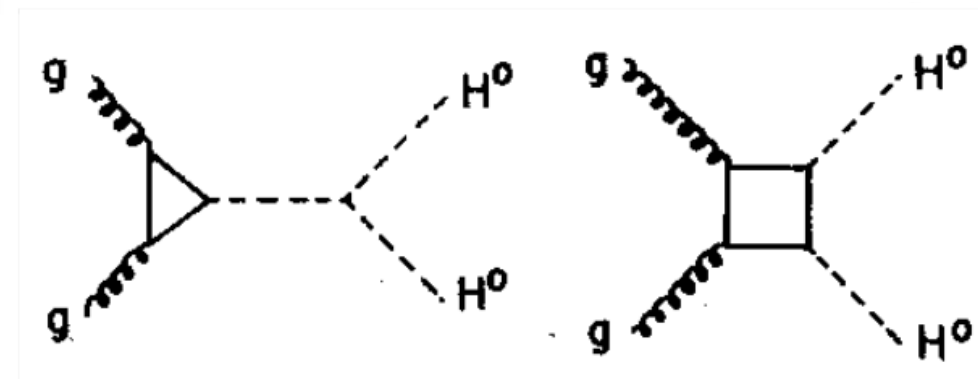
TWIN HIGGS-BOSON PRODUCTION ☆

O.J.P. ÉBOLI [1]
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

G.C. MARQUES, S.F. NOVAES
Instituto de Física, Universidade de São Paulo, CP 20516, 01498 São Paulo, S

and

A.A. NATALE
Instituto de Física Teórica, CP 5956, 01405 São Paulo, SP, Brazil

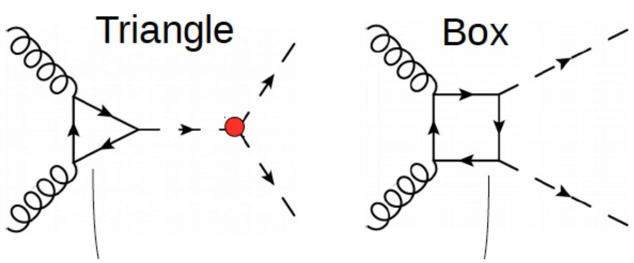


Received 31 July 1987

We investigate the production of a standard Higgs boson pair in proton–proton collisions at the SSC energy. This process allows us to study the trilinear Higgs coupling.

The long march to higher orders in ggF HH production!

- **Leading Order: loop-induced**
  Eboli, Marques, Novaes, Natale 87; Glover, Van Der Bij 88, Dicus, Kao, Willenbrock 88; Plehn, Spira, Zerwas 96



- **Full NLO corrections** **-15% w.r.t. B-i NLO**
  Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 16; Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke 16
  - Two-loop corrections computed numerically using sector decomposition
  - Grid+interpolation for fast numerical evaluation

New independent calculation, see Julien Baglio's talk

- **Next-to-Leading Order approximations**
  - NLO in the Born-improved heavy m_t limit (HTL) **+90%**
    Dawson, Dittmaier, Spira 98
  - FTapprox: full m_t dependence in real radiation **-10%**
    Maltoni, Vryonidou, Zaro 14
  - $1/m_t$ expansion in virtual corrections **±10%**
    Grigo, Hoff, Melnikov, Steinhauser 13; Grigo, Hoff, Steinhauser 15

- **More results including full NLO m_t dependence**
  - NLO matched to parton shower using MC@NLO and POWHEG frameworks
    Dedicated talk by Eleni Vryonidou
    → Sherpa (Jones, Kuttimalai 17)
    → Pythia (Heinrich, Jones, Kerner, Luisoni, Vryonidou 17)
  - NLL transverse momentum resummation → reasonable agreement with NLO+PS
    Ferrera, Pires 16
  - **NEW!** Full NLO including BSM dimension 6 operators
    Buchalla, Capozi, Celis, Heinrich, Scyboz 18
  - **NEW!** NLL threshold resummation with full m_t dependence **+4% w.r.t. NLO**
    de Florian, JM 18

- **Beyond NLO**
  - Born improved HTL at NNLO **+20% w.r.t. NLO**
    de Florian, JM 13; Grigo, Melnikov, Steinhauser 14
  - NNLL threshold resummation in the HTL
    Shao, Li, Li, Wang 13; de Florian, JM 15
  - NNLO including finite m_t effects (FTapprox) **+12% w.r.t. NLO** ← Current HXSWG recommendation for total XS (8% smaller than YR4)
    Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, JM 18
  - **NEW!** NNLL+NNLO threshold resummation in the FTapprox
    de Florian, JM 18

26 in

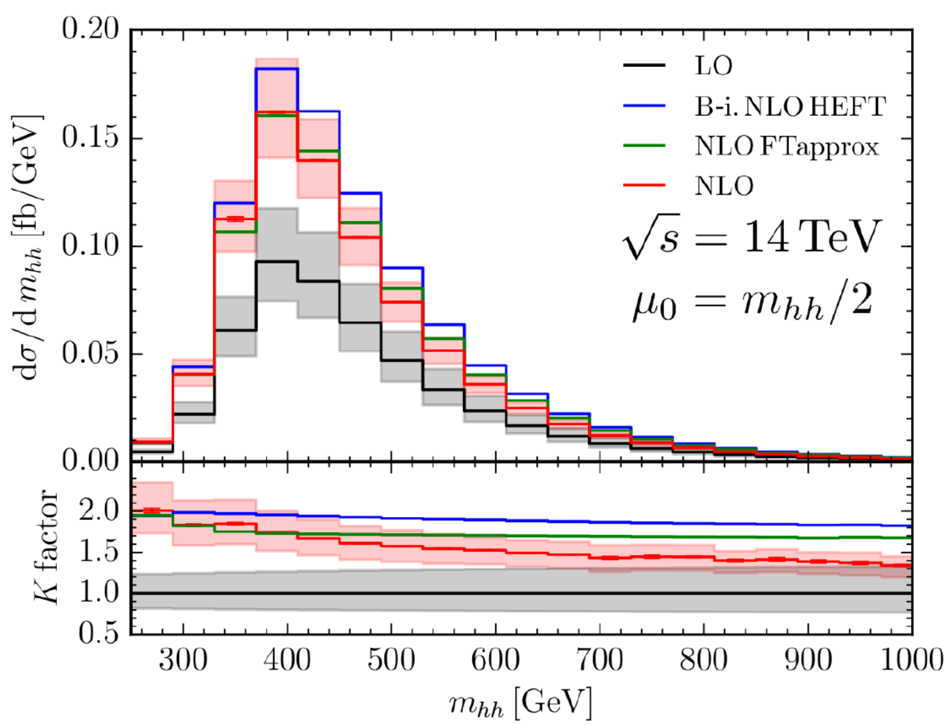
Talk by Javier Mazzitelli

Talk by
Julien Baglio

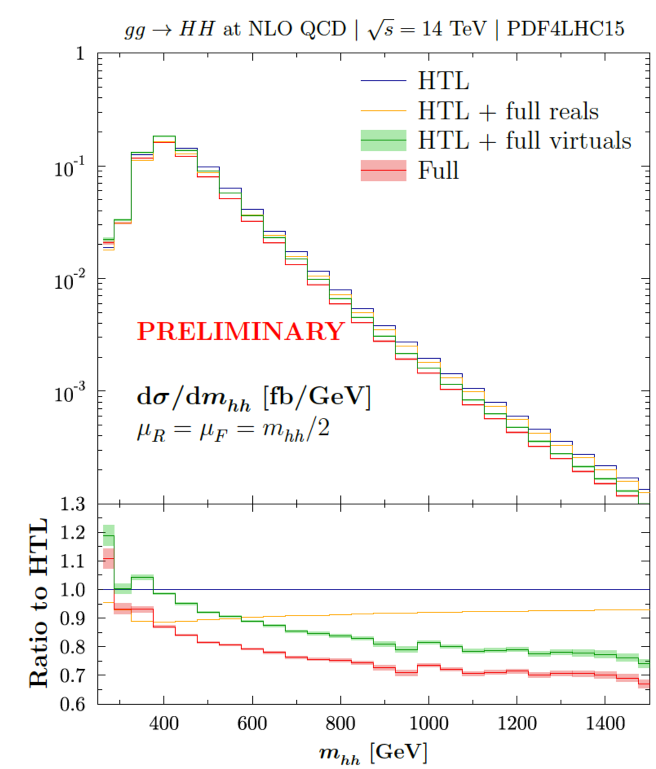
$gg \to HH$ @ NLO in 2018: Two independent calculations finally exist on the market!

- **First independent cross-check since 2016 for the full 2-loop NLO QCD corrections in gluon fusion!**
  $\to$ Complete different method compared to the 2016 calculation [IBP, Richardson extrapolation, etc]
  $\to$ Code flexible: ***m_t, M_H* not fixed a priori, can be changed at will**
  $\to$ results compatible with 2016 study

$$\sigma^{\rm NLO}_{\rm PDF4LHC} = 32.92(10)\ \text{fb vs}\ \sigma^{\rm literature} = 32.91(11)\ \text{fb}$$



[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke ’16]

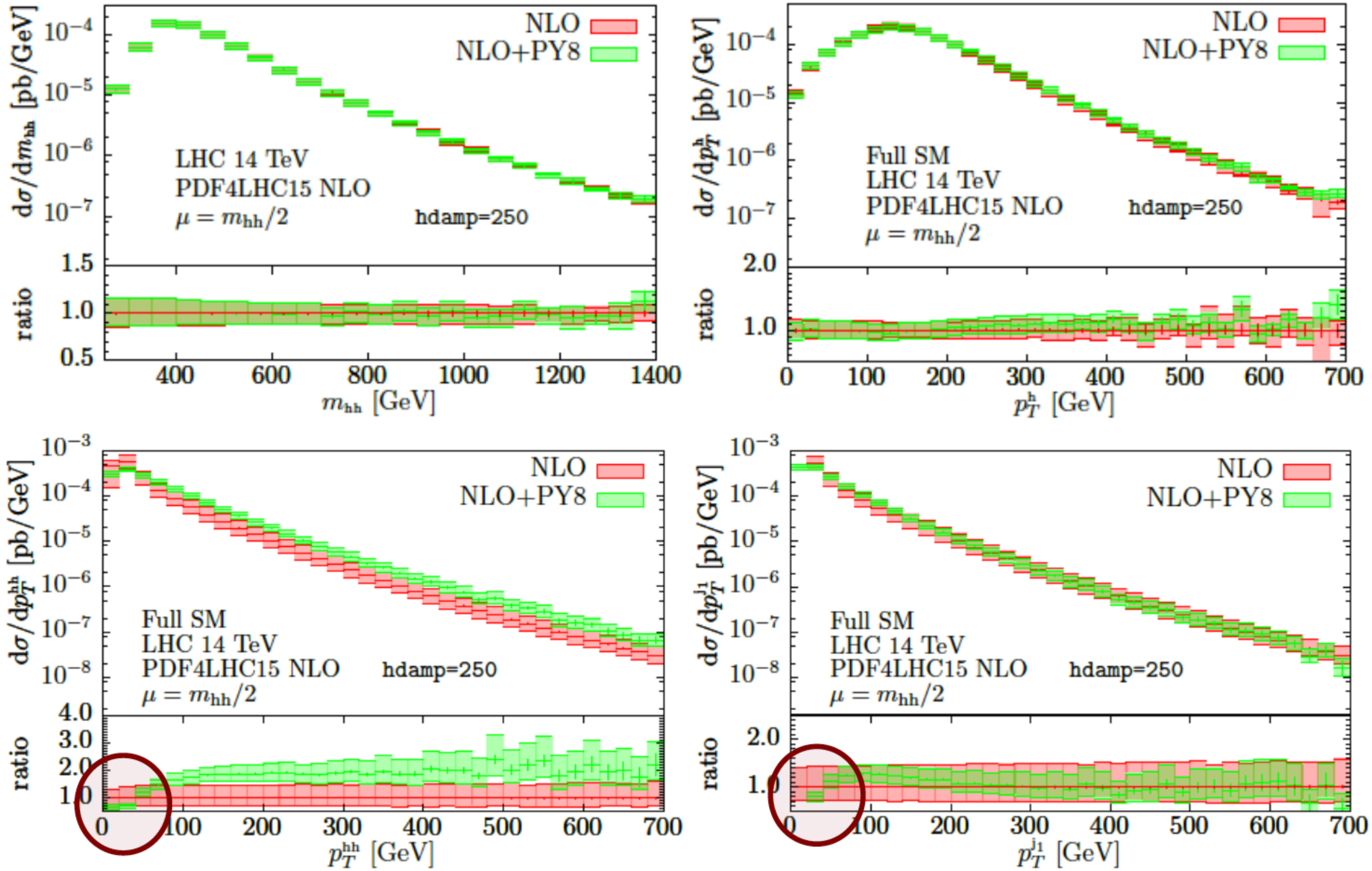


[Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher, to appear]

Talk by
Eleni Vryonidou

HH@NLO +
Parton Shower

(full mt effects)



- Reliable predictions at low HH and jet pT,
- Parton shower impacts tails of certain distributions (e.g., HH pT)
- Implemented in POWHEG and MG5_aMC@NLO

Talk by
Javier Mazzitelli

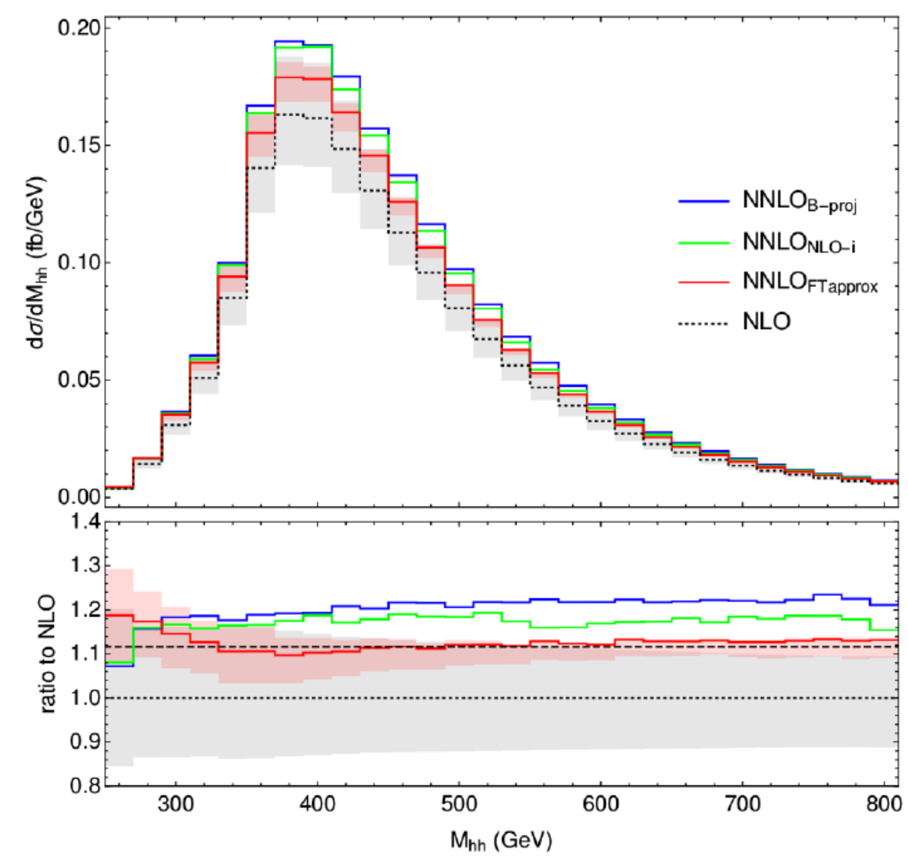
Full-theory approximation - $\mathrm{NNLO}_{\mathrm{FTapprox}}$

Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, JM 18

- Combination of **full NLO** with **heavy-m_t NNLO**, NNLO piece improved to account for **finite-m_t effects**

NNLO total cross sections

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\mathrm{NLO}_{\mathrm{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\mathrm{NNLO}_{\mathrm{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\mathrm{NNLO}_{\mathrm{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\mathrm{NNLO}_{\mathrm{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$	$\pm 2.6\%$	$\pm 2.7\%$	$\pm 3.4\%$	$\pm 4.6\%$
$\mathrm{NNLO}_{\mathrm{FTapprox}}/\mathrm{NLO}$	1.118	1.116	1.096	1.067



- **Increase** w.r.t. previous order of about **12% for LHC** (~20% for $\mu = m_{hh}$), size decreasing with the energy
- Smaller cross sections compared to previous approximations (larger difference for higher energies)
- Strong **reduction** of the **scale uncertainties**
- Size of **missing m_t effects** estimated at the **few percent level**
  Based on performance at previous order and on comparison between different approximations
- PDF+α_S uncertainties: ±3.0% at the LHC

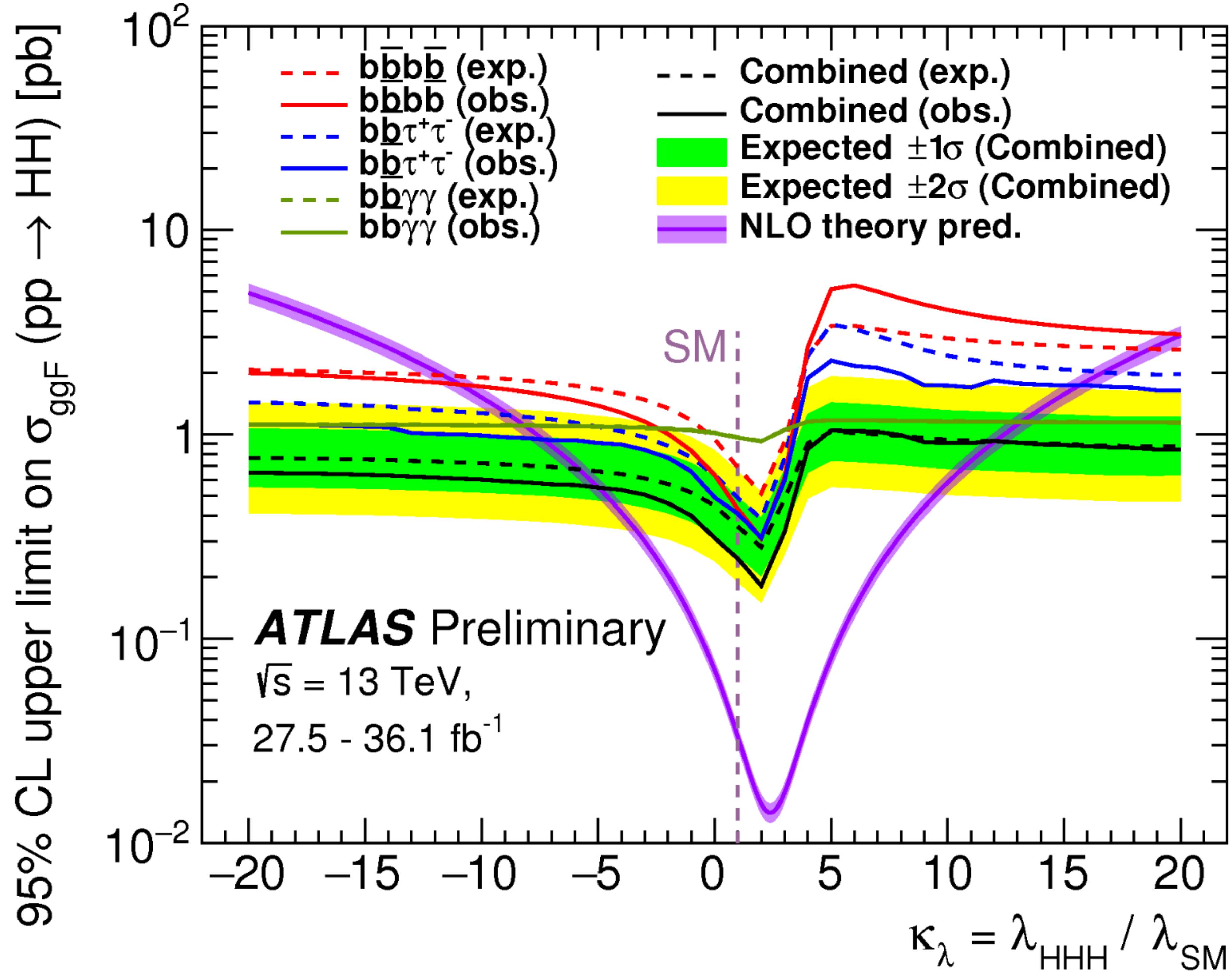
Standard Model HH theory is in good shape!

What level of precision is ultimately needed in HH calculations? Can it be achieved? Are we already there?

- Ability to discover/observe HH?
- Ability to extract the self coupling?
- To place meaningful constraints on new physics, and/or robustly state that we have detected new physics in HH?

Uncertainties in backgrounds systematics are potentially/likely a limiting factor in probing HH

- What advances from theory are needed to help mitigate background systematics?



Talks by L. Cadamuro and P. Bokan

How well do we need to measure the self-coupling?

- Answer 1: As precisely as we can!
- Answer 2: If no new state associated with EWSB is found a the LHC, then one can potentially still expect deviations on the order of 20%

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$
LHC 3 ab^{-1} [36]	$[-20\,\%, +30\,\%]$

[Gupta, Rzehak, Wells]

How large can the self-coupling be?

- Constraints from partial wave unitarity & perturbativity

$$|\lambda_{hhh}/\lambda_{hhh}^{SM}| \lesssim 6.5\,(6.0)$$

[Di Luzio, Grober, Spannowsky]

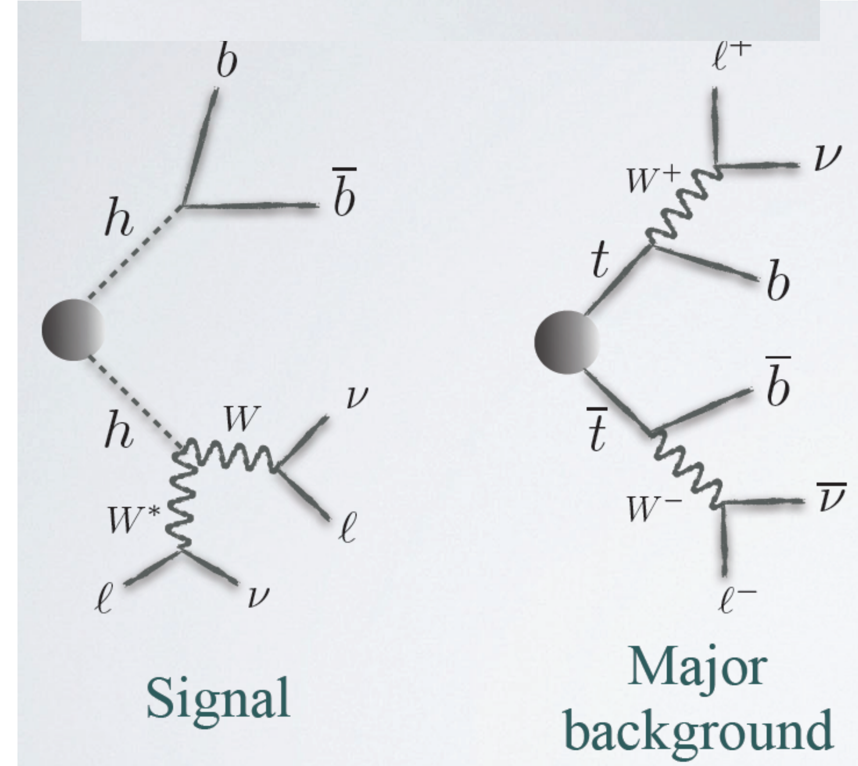
- Existing constraints combined with unitarity & perturbativity typically give smaller deviations from the SM value

See also talk by Stefano Di Vita

Talk by
Jeong Han Kim

Use new kinematic variables to discriminate dileptonic Higgs vs. tt

$hh \to bbWW^*$

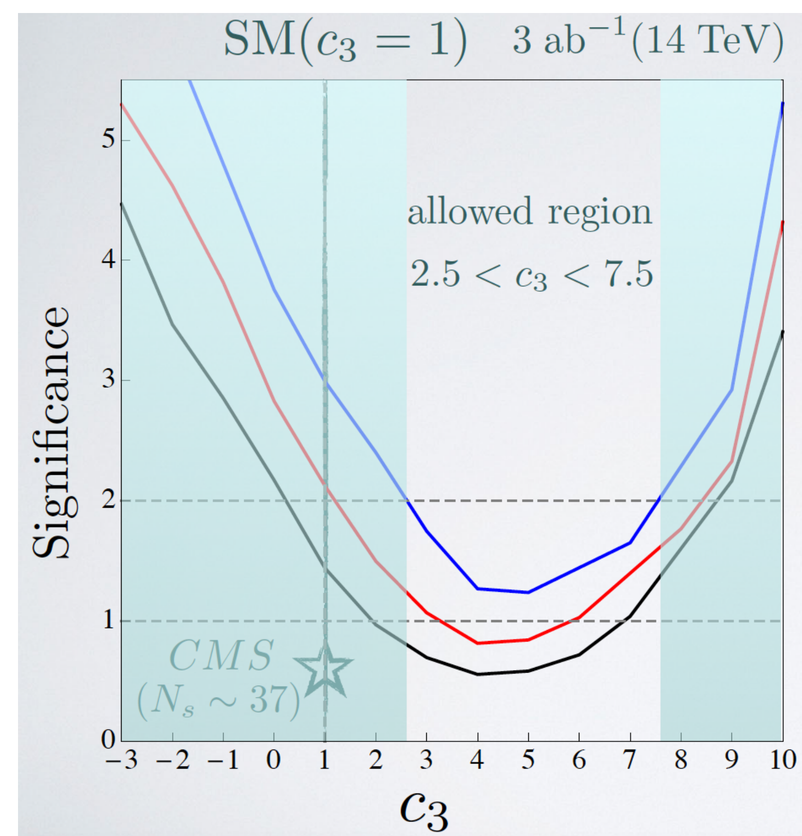


Higgsness (H)

$$H \equiv \min_{\vec{p}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{\ell^+\ell^-\nu\bar{\nu}} - m_h^2\right)^2}{\sigma^4_{h_\ell}} + \frac{\left(m^2_{\nu\bar{\nu}} - m^2_{\nu\bar{\nu},peak}\right)^2}{\sigma^4_{\nu}} + min\left(\frac{\left(m^2_{\ell^+\nu} - m_W^2\right)^2}{\sigma^4_W} + \frac{\left(m^2_{\ell^-\bar{\nu}} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}}, \frac{\left(m^2_{\ell^-\bar{\nu}} - m_W^2\right)^2}{\sigma^4_W} + \frac{\left(m^2_{\ell^+\nu} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}} \right) \right],$$

two possible ways of paring ν and ℓ

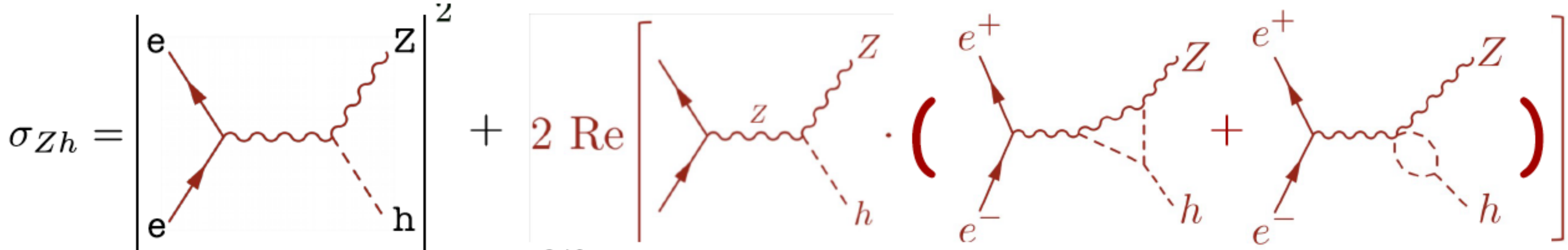
$\sim m_h - m_W$ off-shell



Triple coupling from Single Higgs Processes

Talk by
Stefano Di Vita

McCullough '13

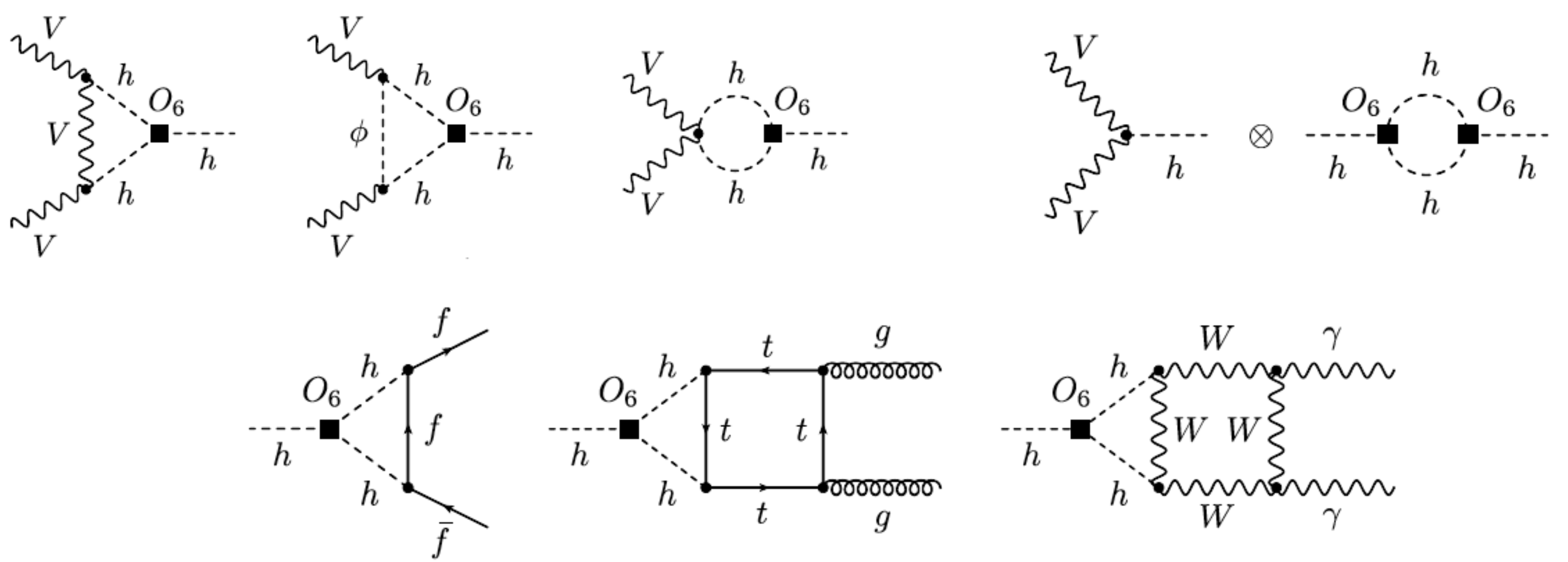


$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

Gorbahn, Haisch '16

Degrassi, Giardino, Maltoni, Pagani '16

Bizon, Gorbahn, Haisch, Zanderighi '16

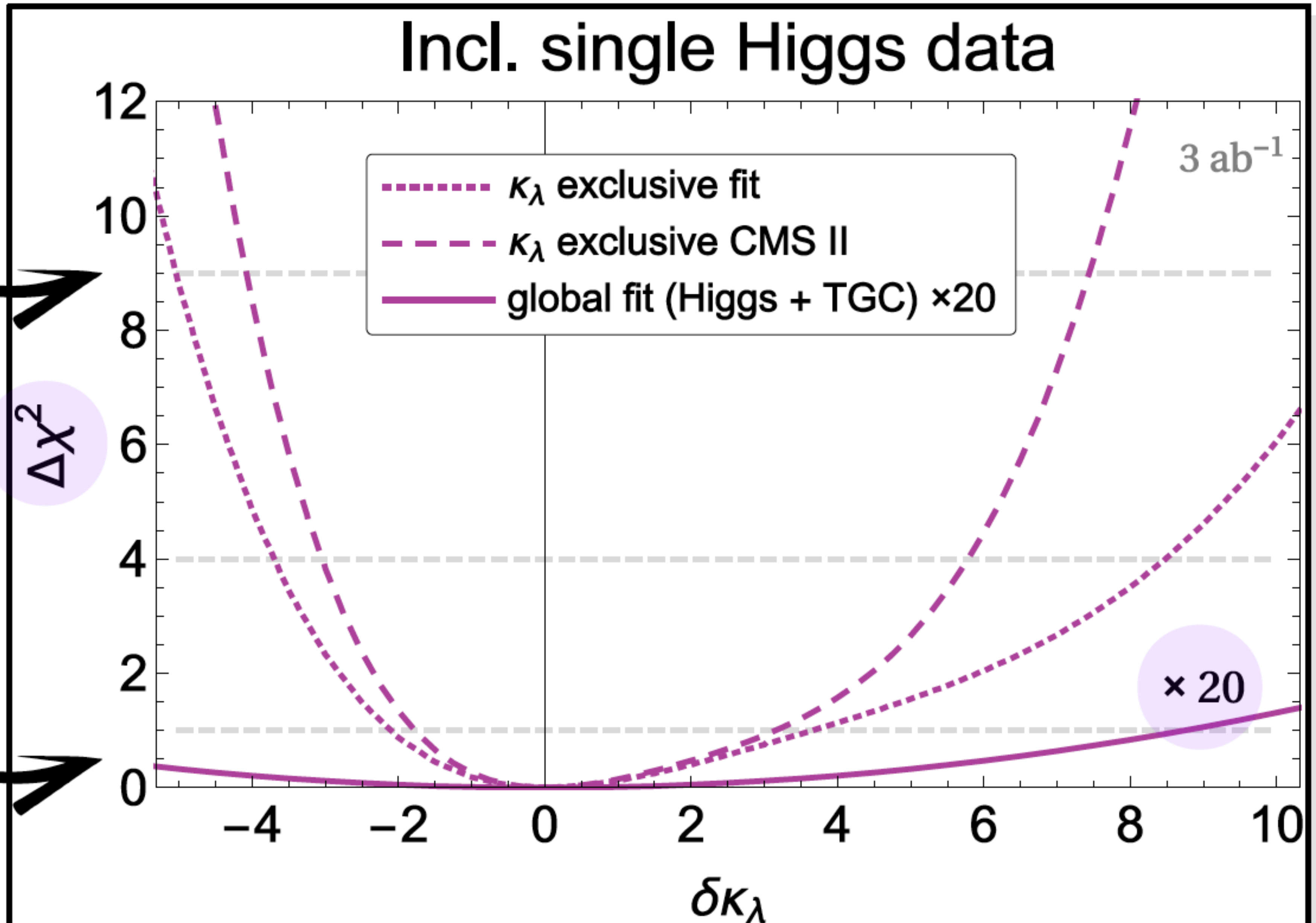


Talk by Stefano Di Vita

Bound on $\delta\kappa_\lambda$ from inclusive rates

allow only $\delta\kappa_\lambda$

$\delta\kappa_\lambda$ & 7 single-Higgs deformations

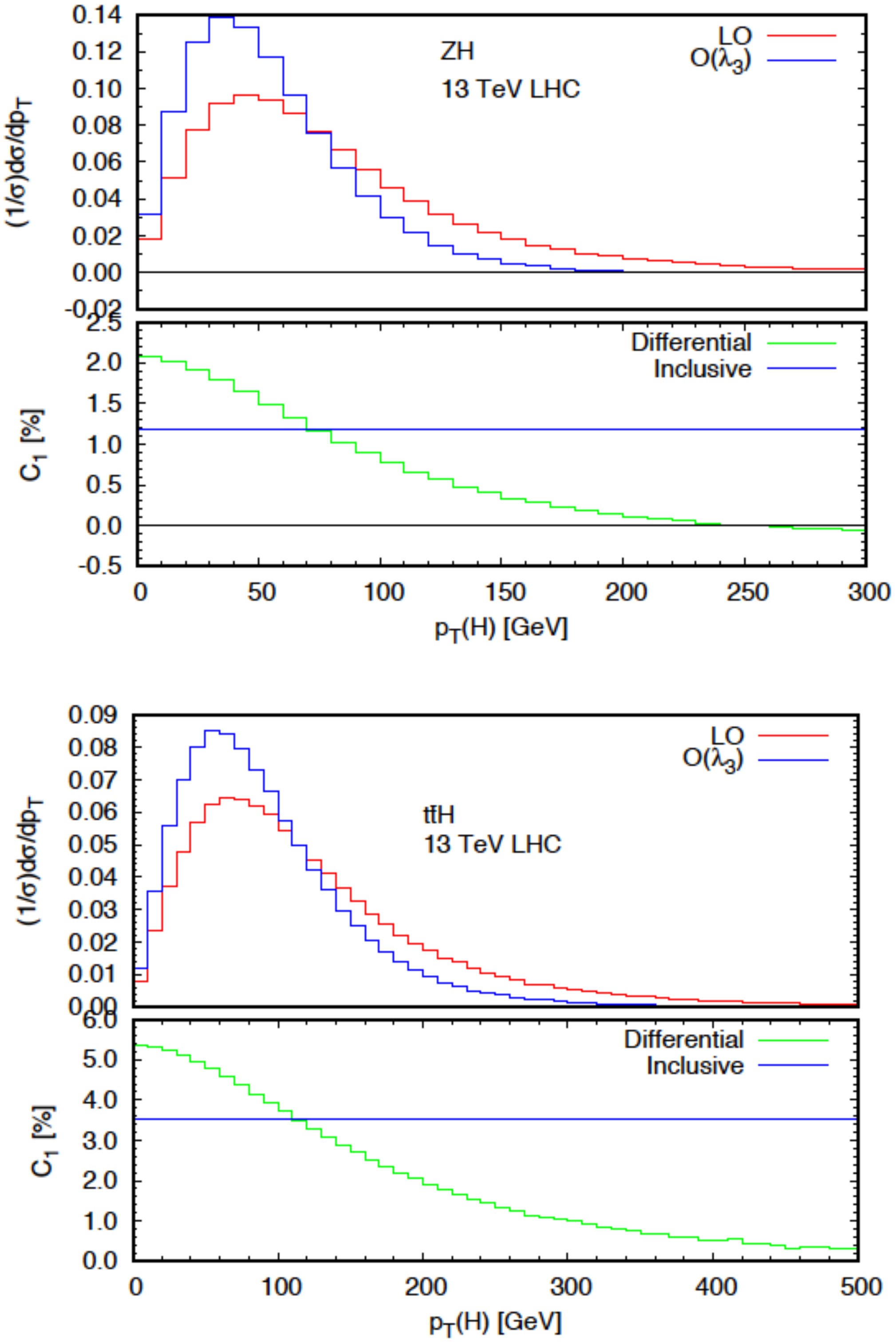


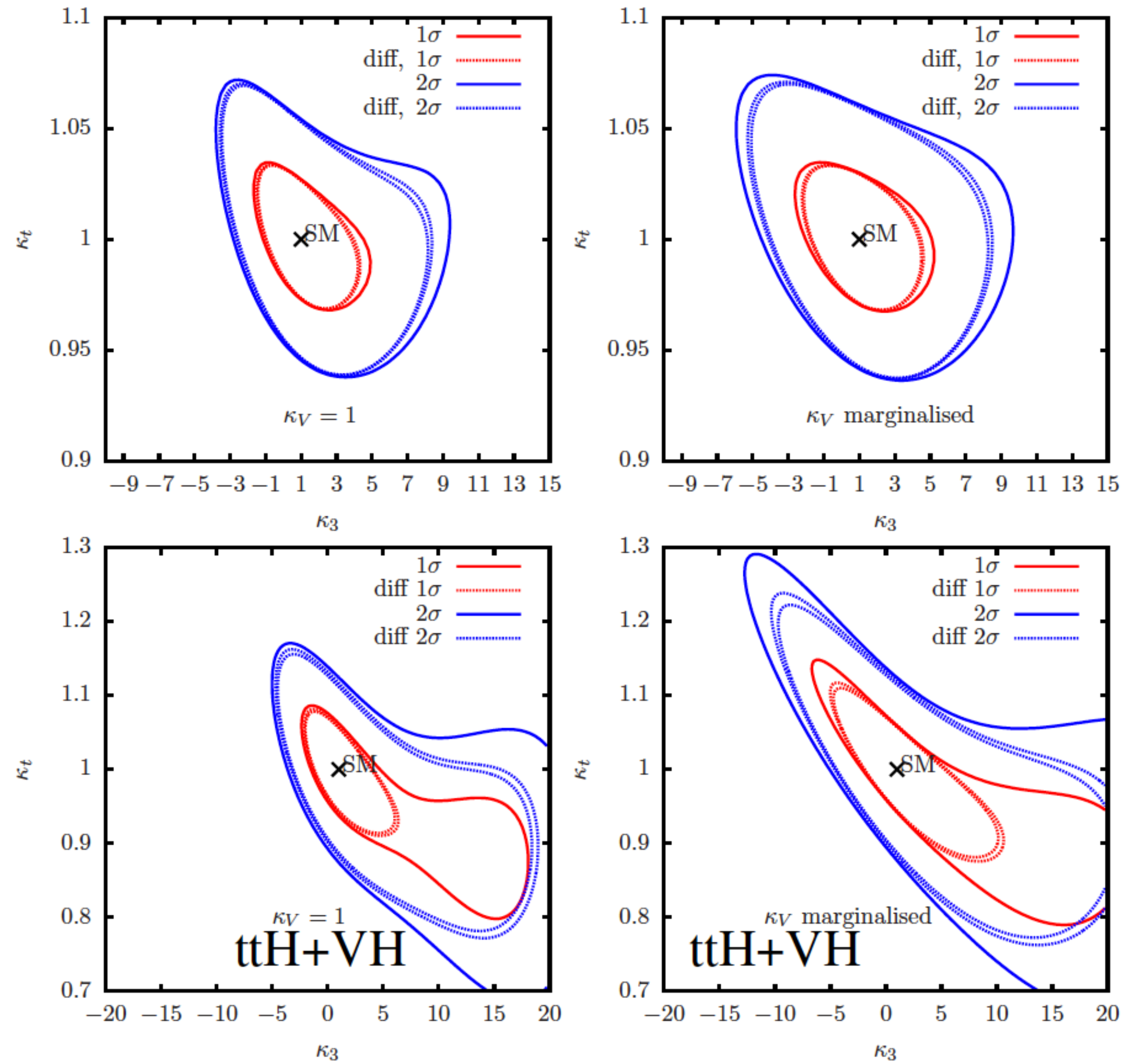
FLAT!

[Grojean, Panico, Riembau, Vantalon, Di Vita '17]

Impact of differential single Higgs measurements

Talk by Ambresh Shivaji





Single Higgs fits to $\delta\kappa_\lambda$ can complement HH measurements

- Are there motivated models that predict only deviations in $\delta\kappa_\lambda$ (or a restricted set of coupling deviations)?

- Are there other ways to pin down deviations in other SM couplings (i.e., remove flat direction)? LHC? Future Colliders?

Differential measurements will provide additional handles - still early days

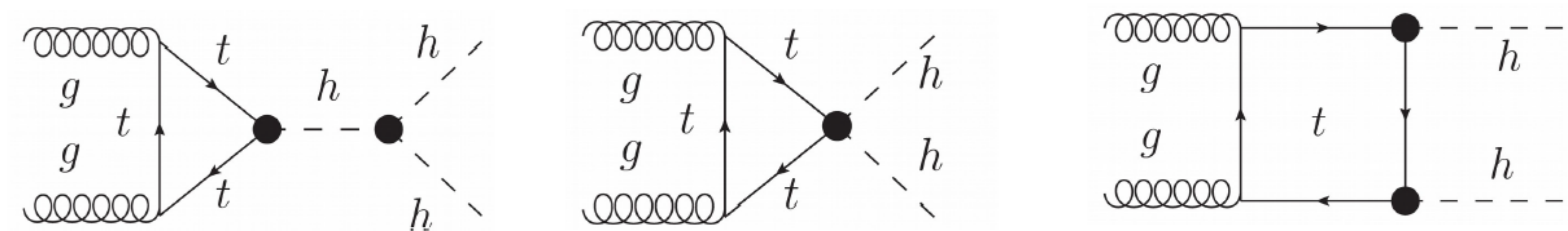
- No data available yet, impact of experimental systematics remains to be seen

- So far, differential rate studies carried out for HH, VBF, VH, ttH channels. It will also be interesting to extend to ggF

Enhancing Double Higgs Production with BSM

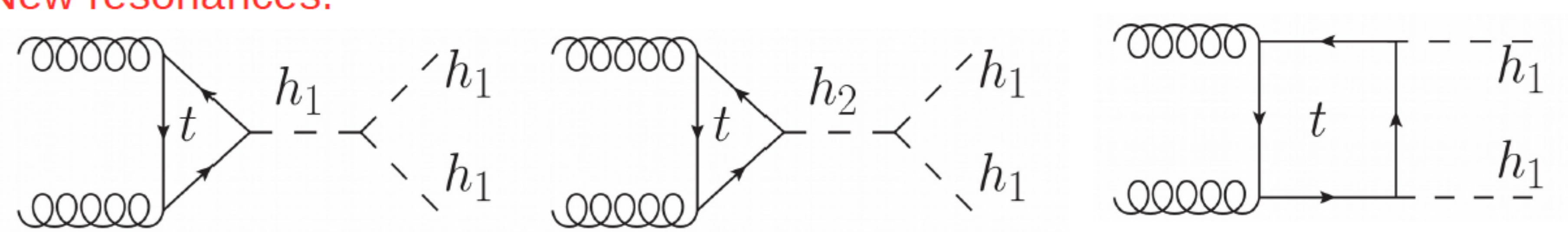
Talk by
Ian Lewis

- Couplings different from the SM+EFT

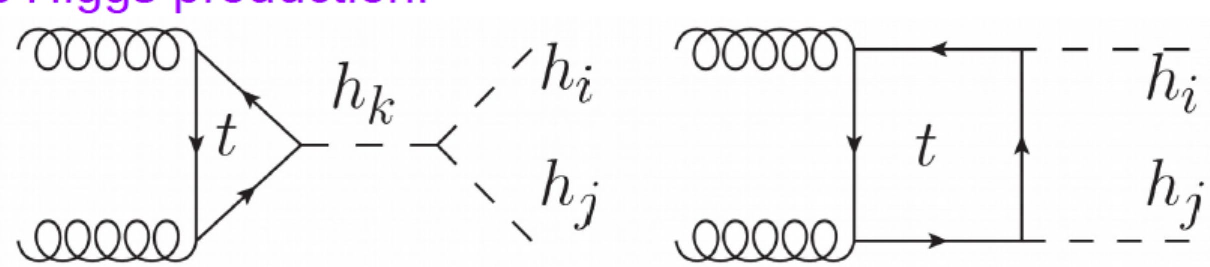


- New physics in the loop.

- New resonances.



- Double exotic Higgs production.

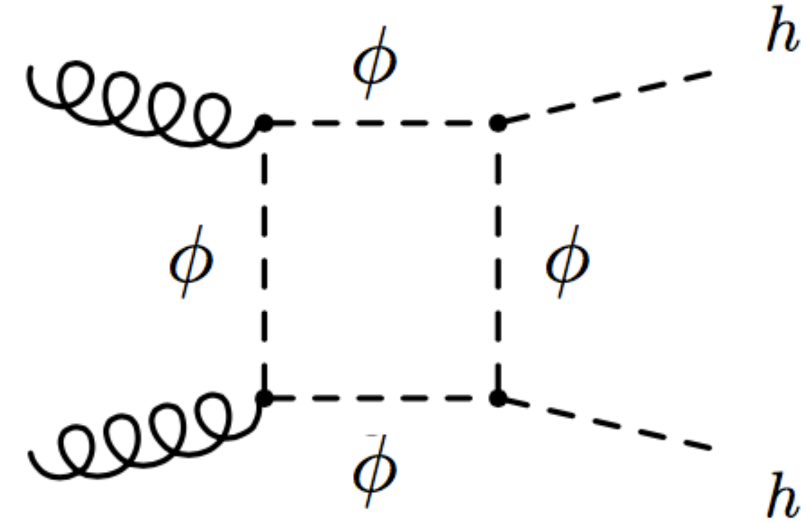


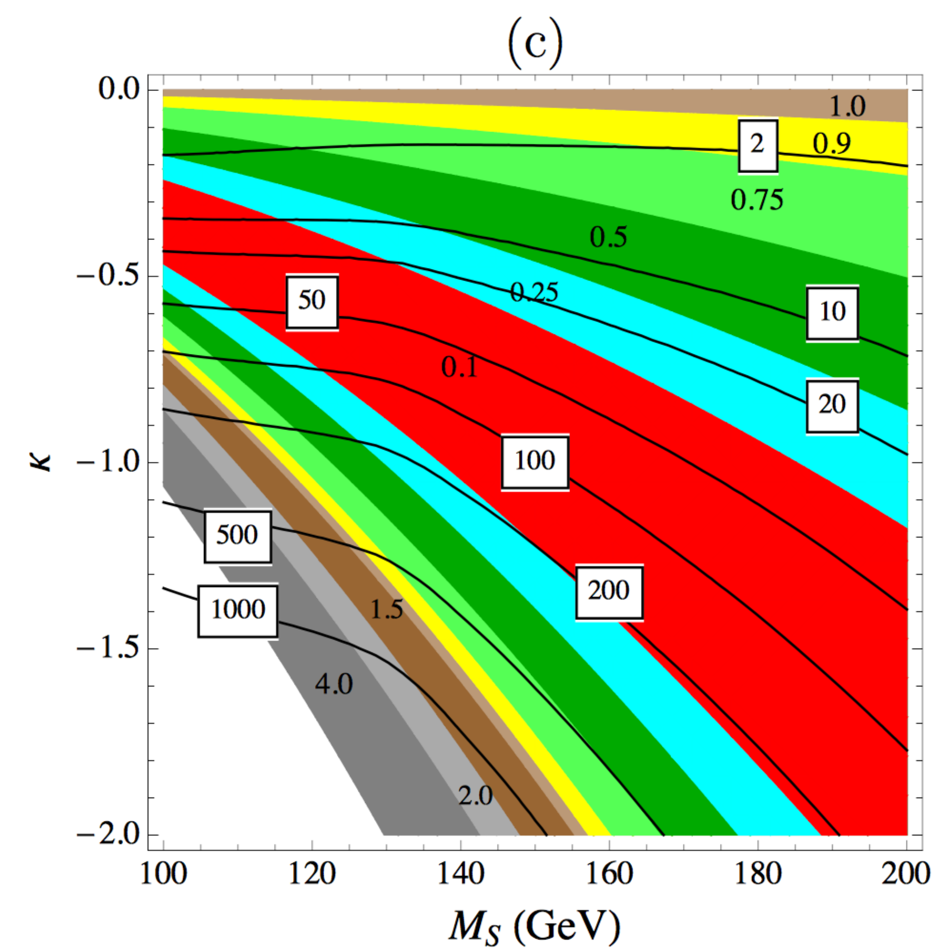
Sept. 6, 2018 3/24

New colored states in Higgs pair production

- New colored scalars can in principle dramatically enhance Higgs pair production

- However, it is difficult to get a large di-Higgs enhancement and still be consistent with the observed single Higgs production rate



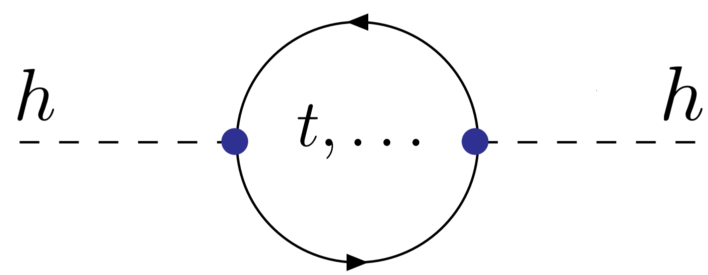


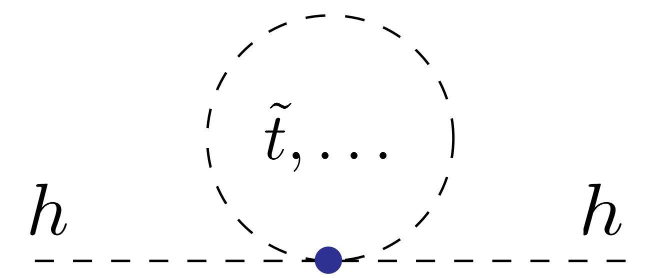
[Kribs, Martin '12]

Naturalness and top partners

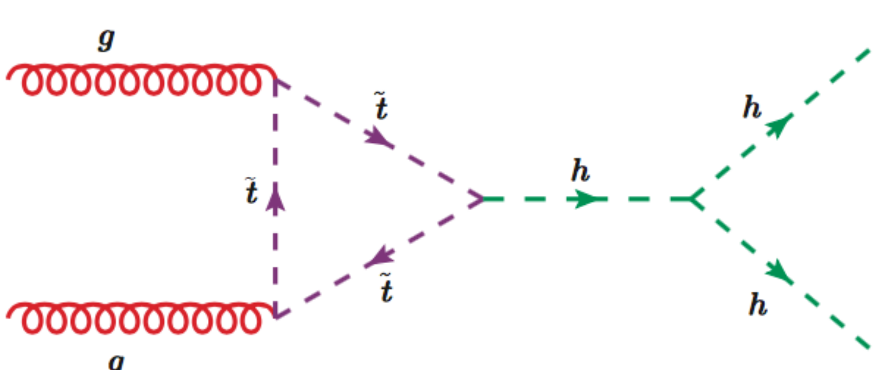
Talk by
Carlos Wagner

e.g., stops in SUSY
stabilize Higgs mass





Stops are colored, couple strongly to Higgs, and thus can provide an important contribution to Higgs pair production



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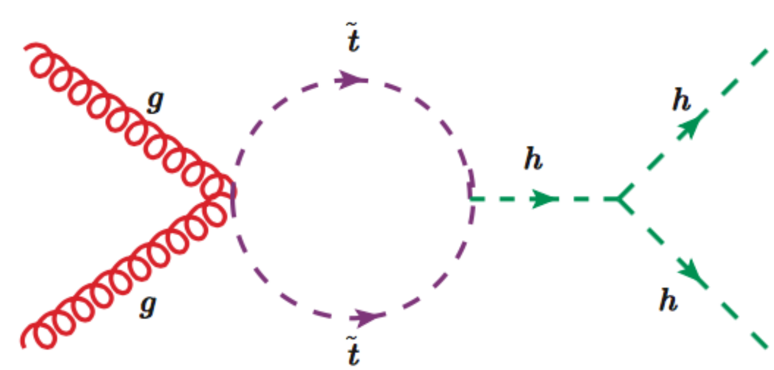

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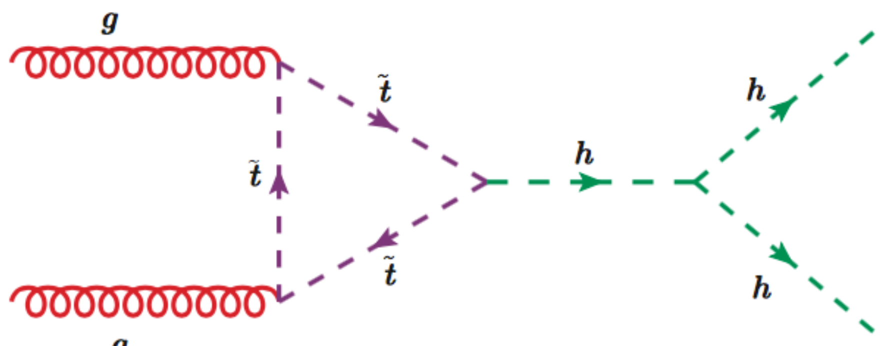
Di-Higgs modifications from stops



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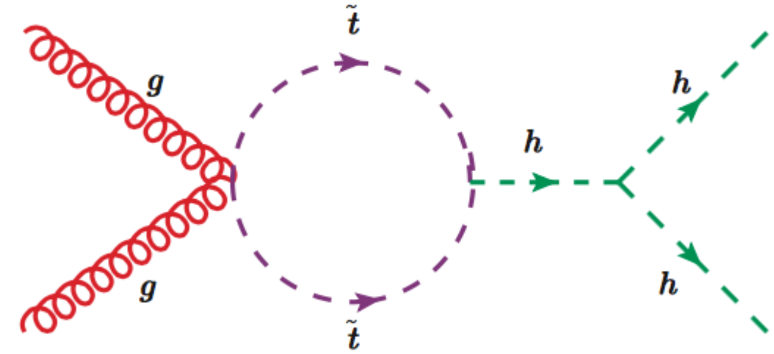

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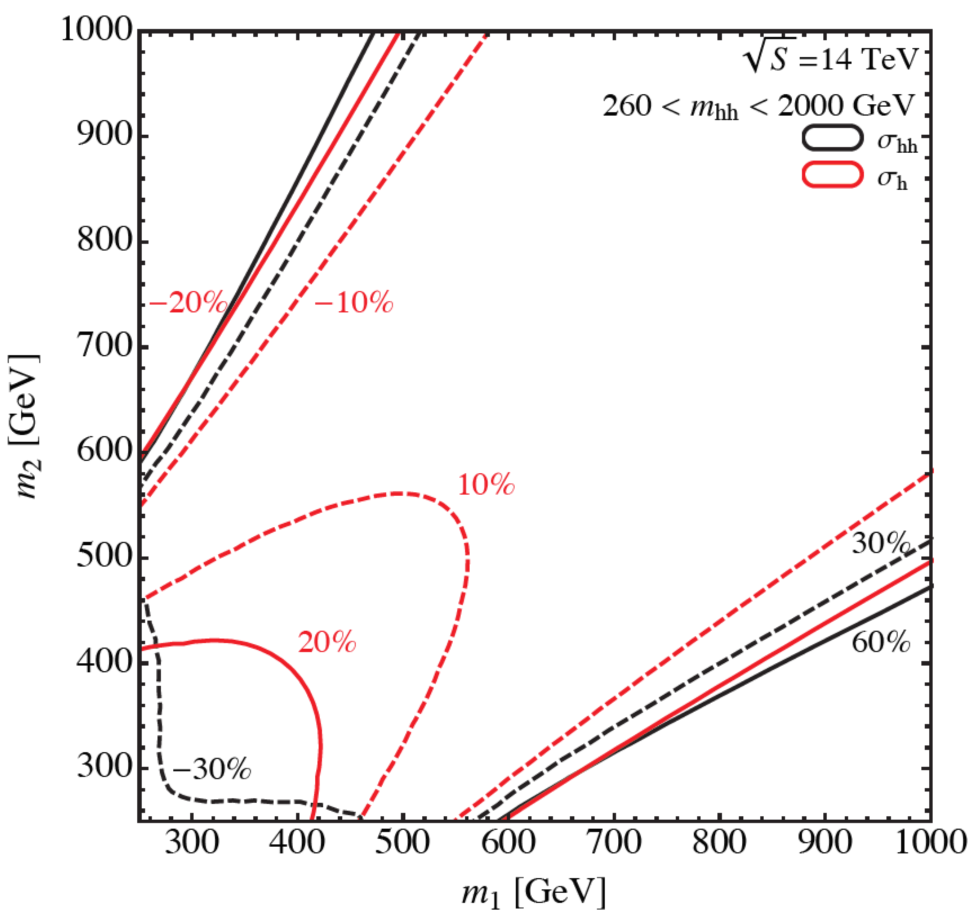
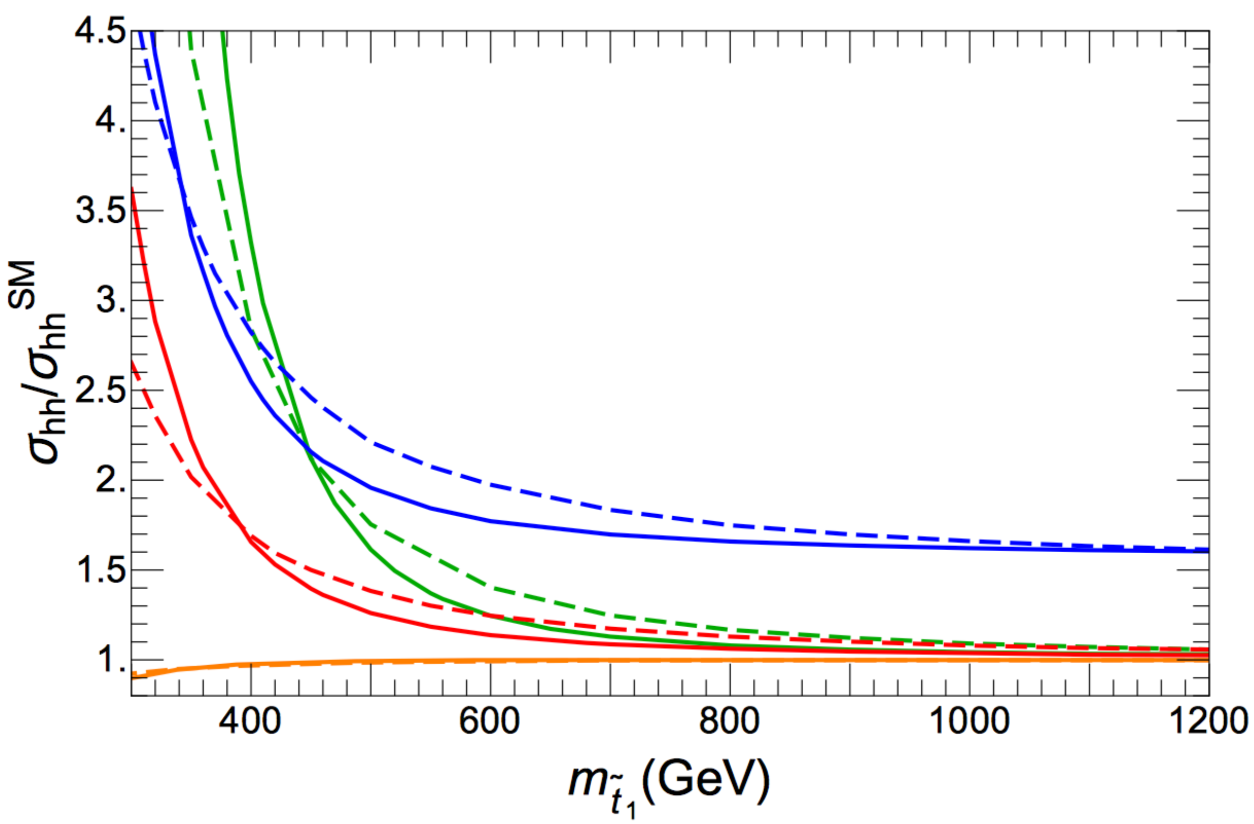


[BB, McCullough, Stolarski, Verhaaren]



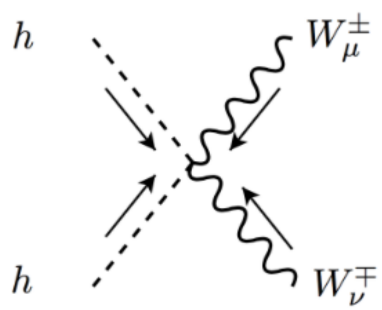
[Huang, Joglekar, Li, Wagner]

Factor of few enhancement in HH rate possible, particularly if top Yukawa is enhanced

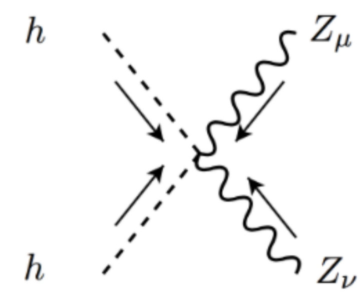
Talk by Ian Low

In my view, one class of couplings that has not received enough attention is the HHVV coupling:

$$D_\mu H^\dagger D^\mu H \supset g^2 h^2 V_\mu V^\mu$$

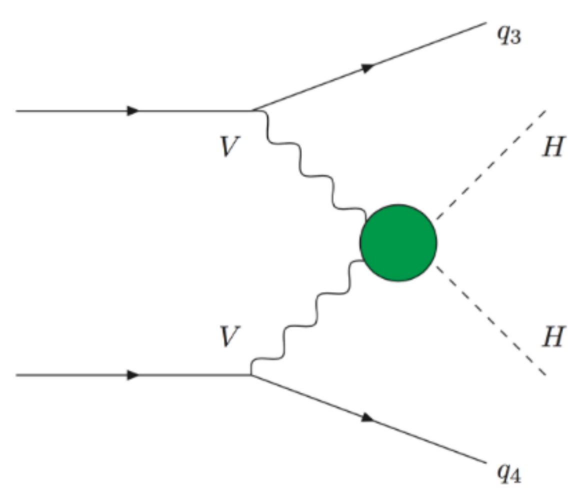


$$\frac{i}{2} g^2 g_{\mu\nu}$$



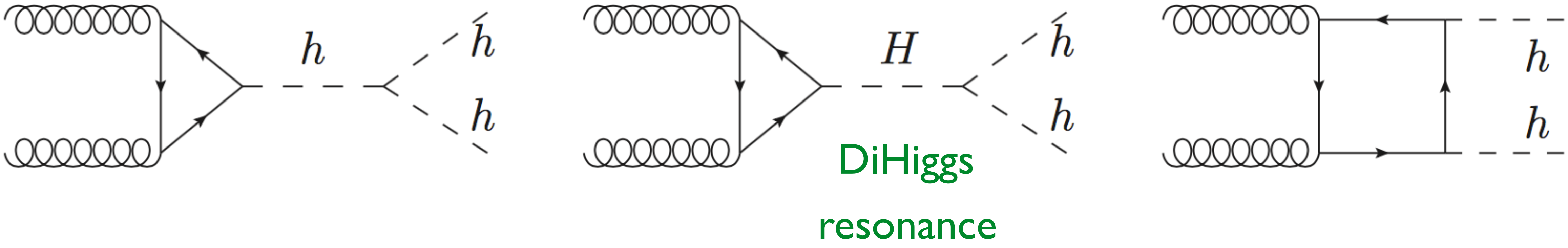
$$\frac{i}{2} \frac{g^2}{\cos^2\theta_W} g_{\mu\nu}$$

This coupling can be probed by double Higgs production in the VBF channel!



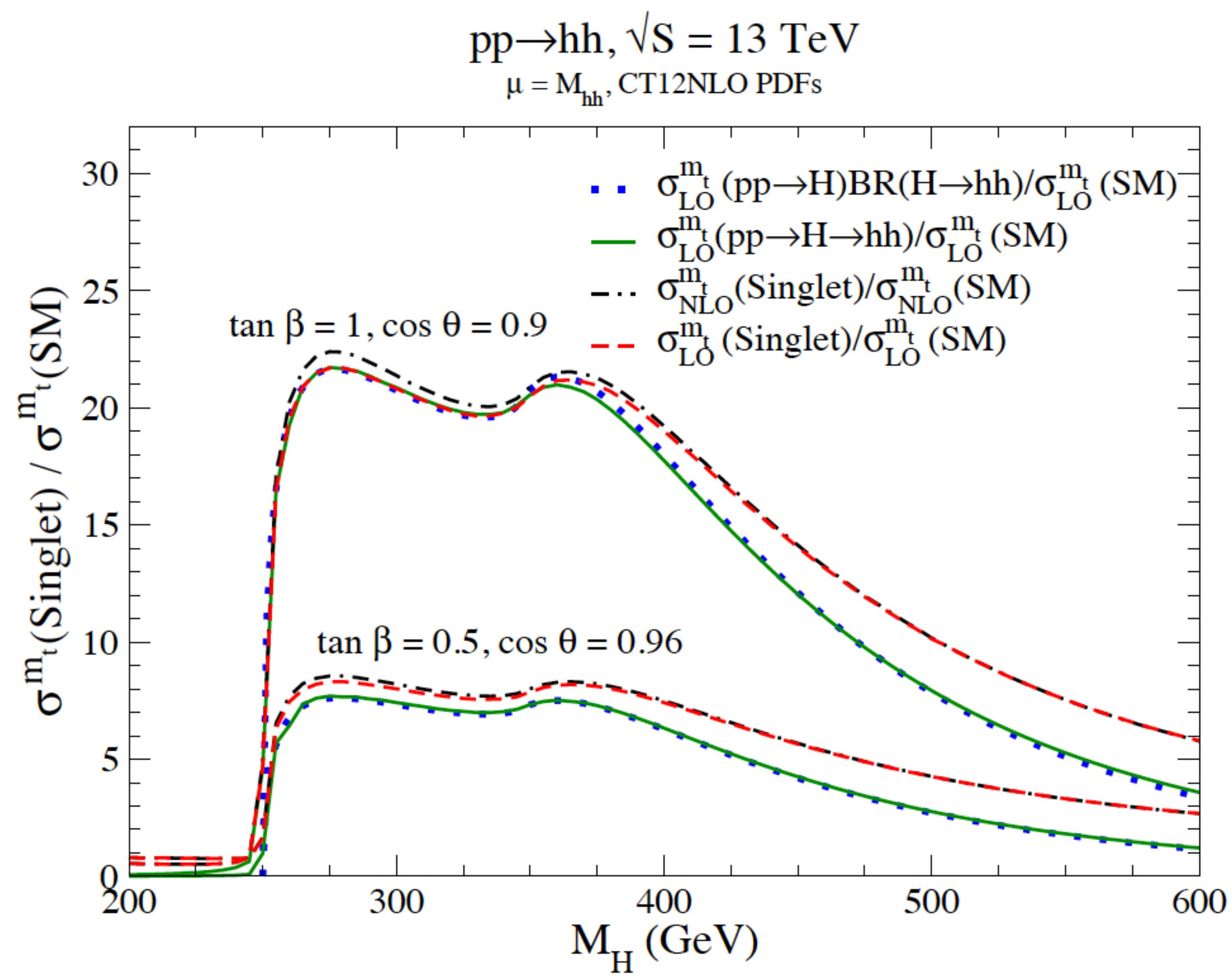
- Simultaneous measurements of HVV, HHVV and TGCs provide a unique window into the pNGB nature of the 125 GeV Higgs.

Di-Higgs resonance

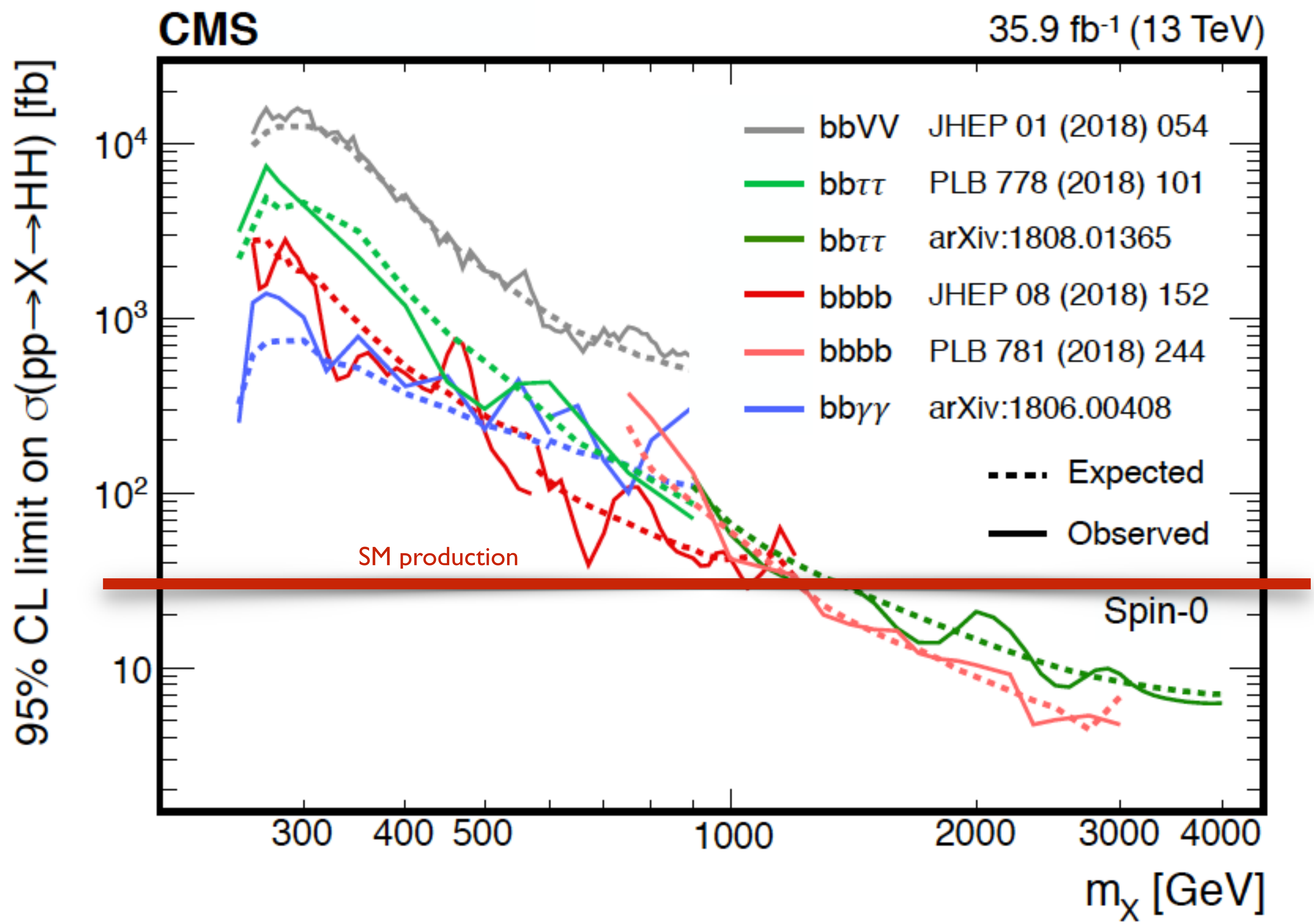


- Appears in many motivated models
- Connection to naturalness, dark matter, electroweak baryogenesis,…

- Resonance can enhance di-Higgs rate (single production) and also alter kinematics of final state Higgses



[Dawson, Lewis '15]



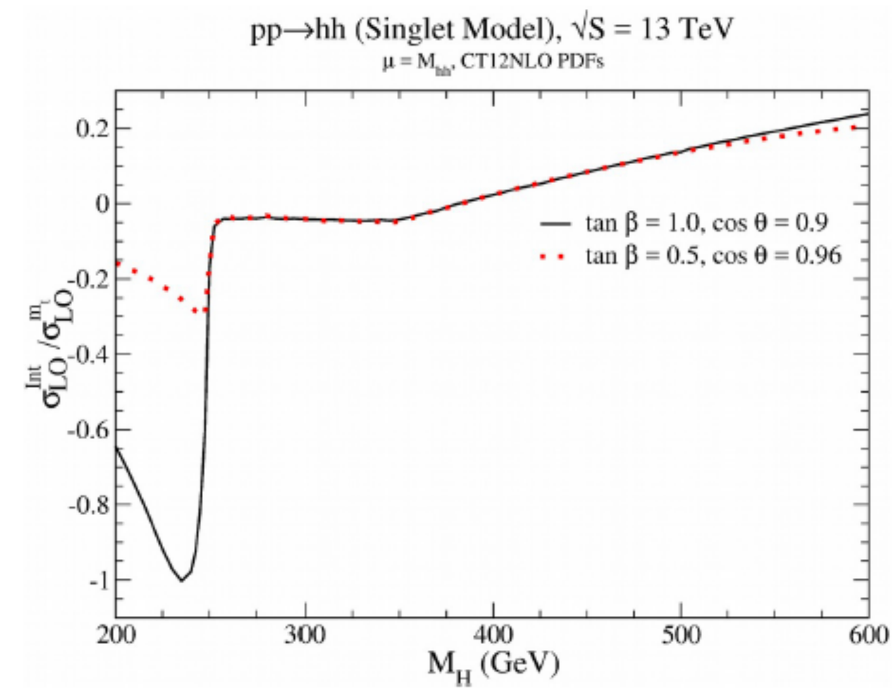
Talks by L. Cadamuro and P. Bokan

Interference effects in di-Higgs resonances

Talks by
Ian Lewis, Marcela Carena

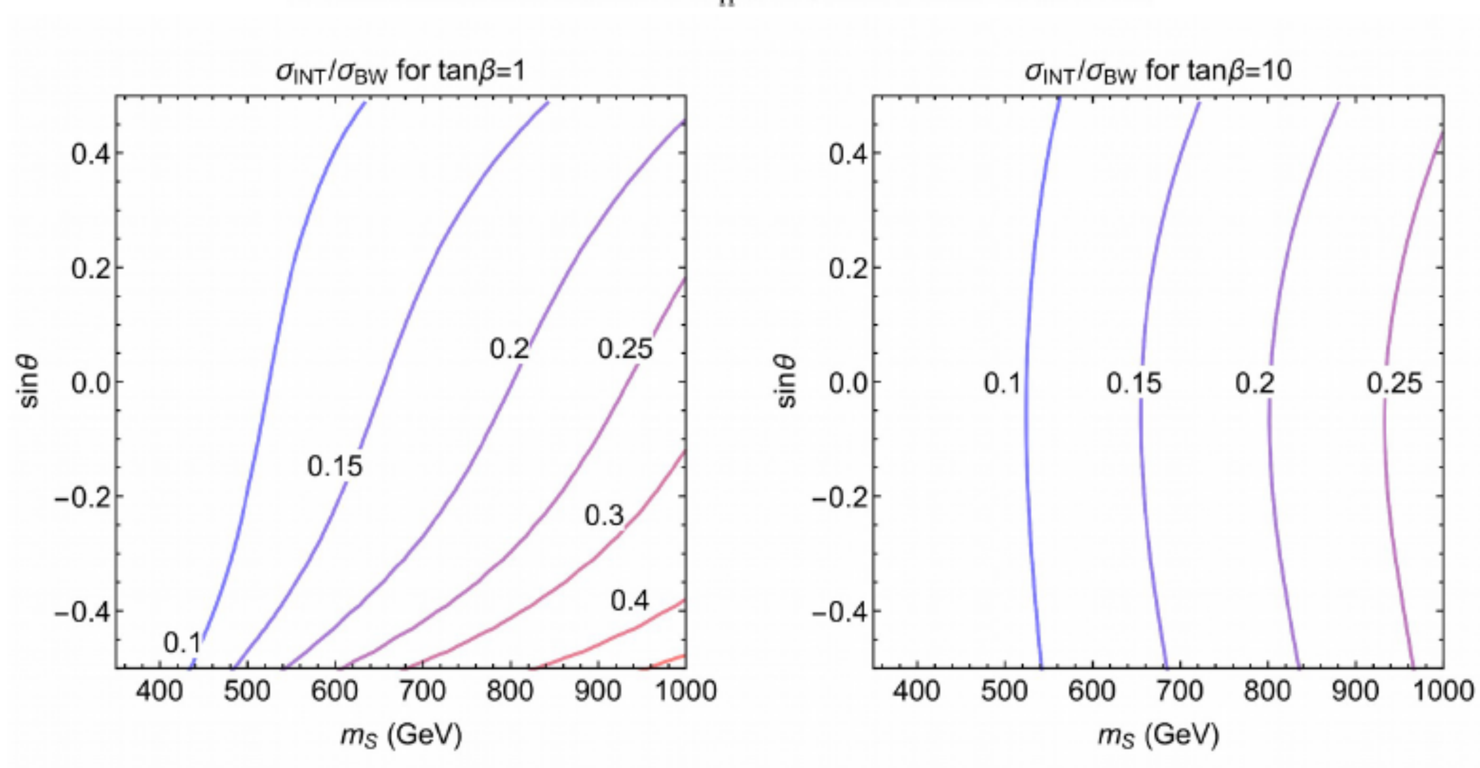
- Off-shell interference:
  - Higher mass resonance, more important

  Dawson, **IL** PRD92 (2015) 094023



- On-shell interference:
  - Need phase between loops and imaginary part of propagator.

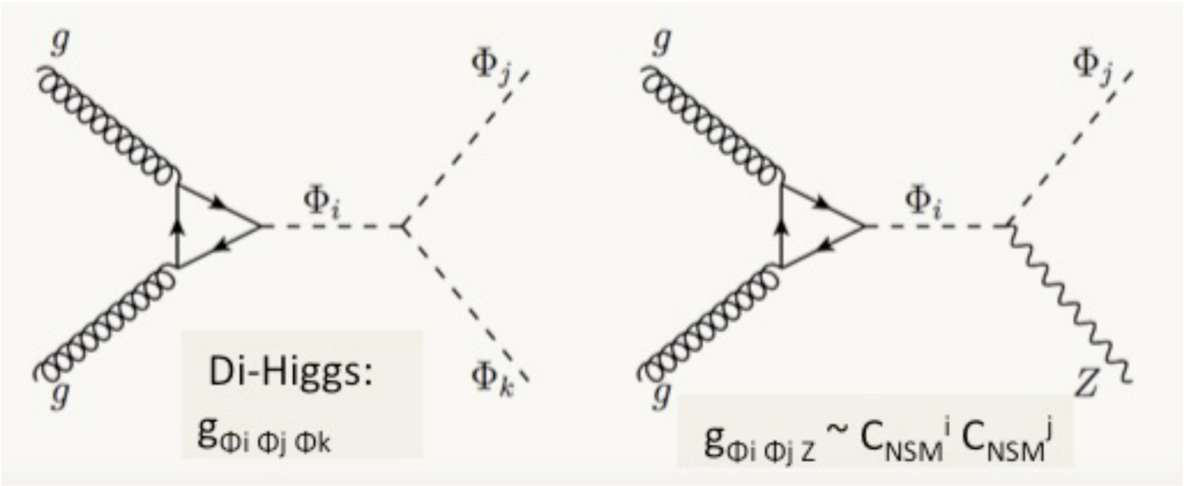
  Carena, Liu, Riembau
  PRD 97 (2018) 095032

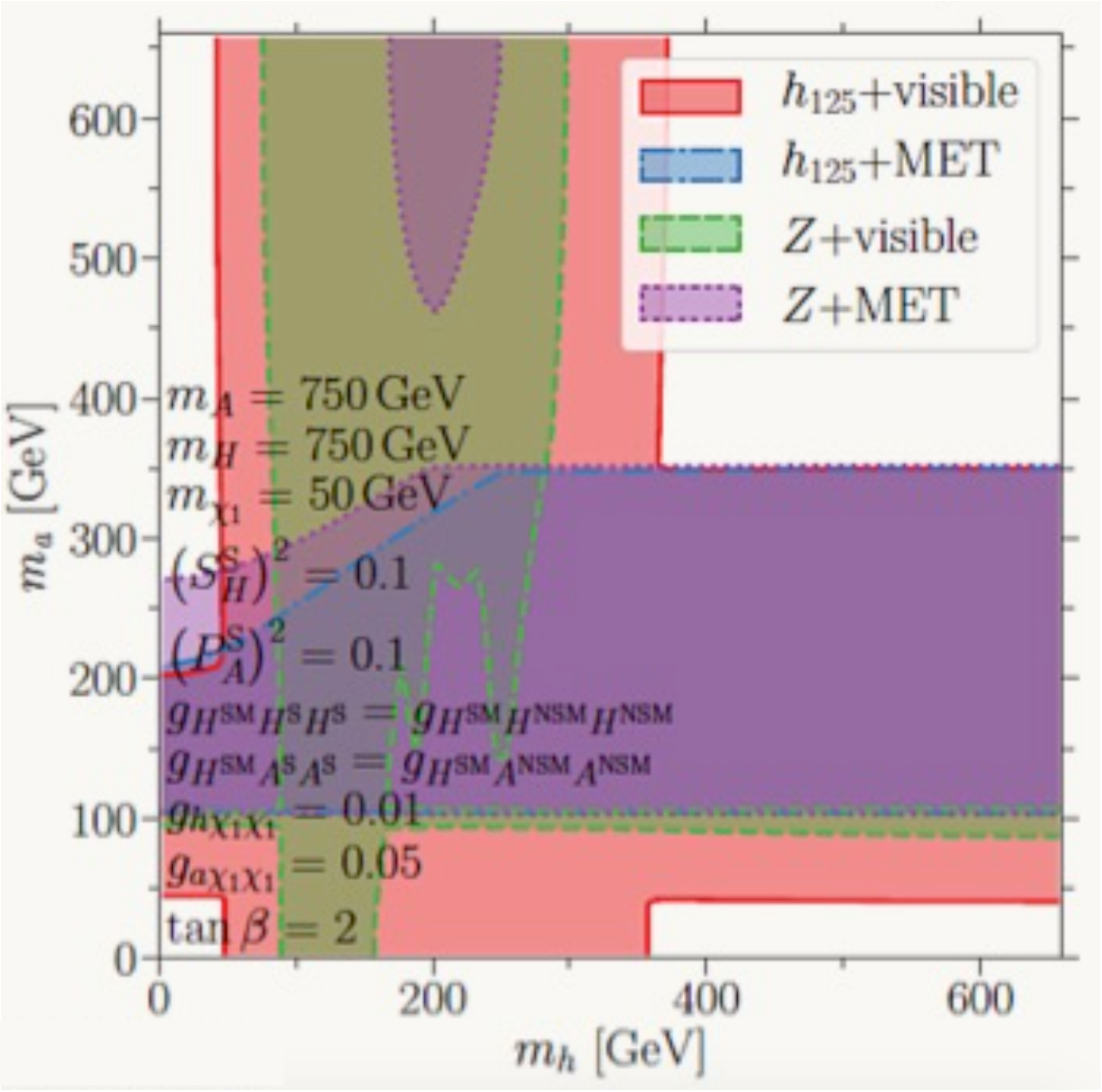


"Exotic" double Higgs production

Talks by
Nausheen Shah

Type II 2HDM + Singlet Model





- Categorize final states as
  - h_{125} + visibles
  - mono-h_{125}
  - Z + visibles
  - mono-Z

Have we constructed and explored all motivated BSM scenarios with modifications to double Higgs production?

- Can we find new connections with the open questions (naturalness, dark matter, neutrinos, baryogenesis, etc.)

- Can we find interesting connections with other experimental or observational probes (astrophysics/cosmology, intensity, precision frontiers)

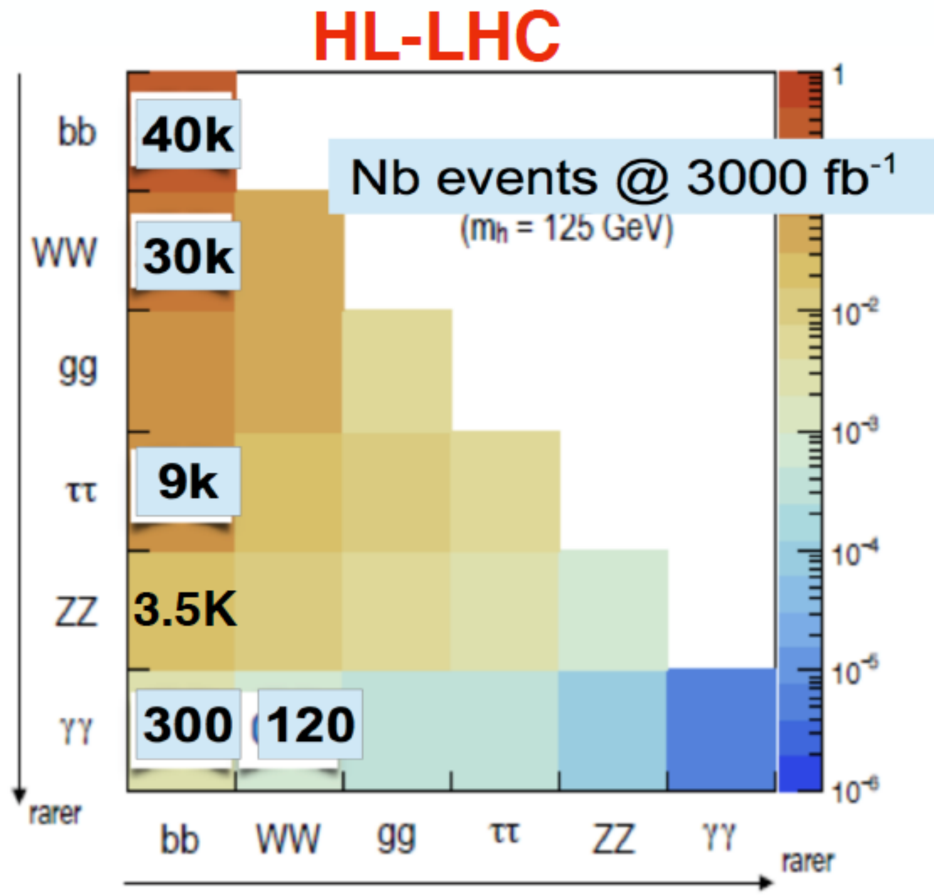
Does the experimental community require a prioritized categorization of BSM benchmarks for HH?

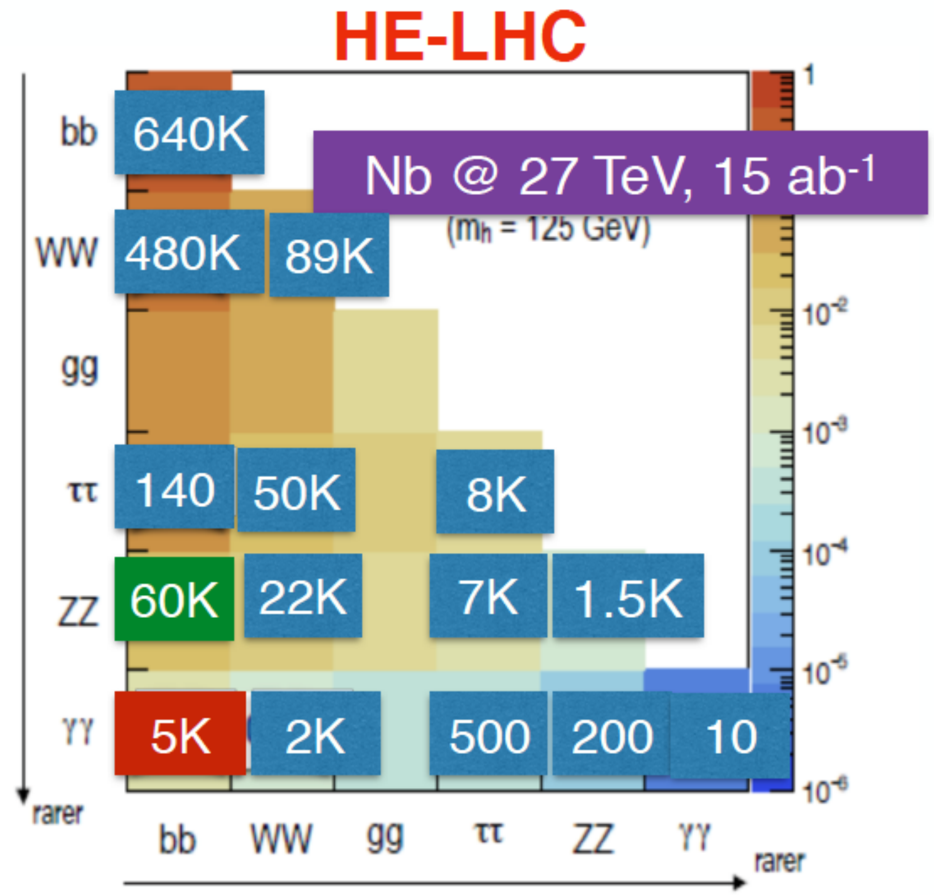
- EFT, non-resonant models (particles in the loop), resonances, exotic Higgses, …

HE-LHC opportunities for HH

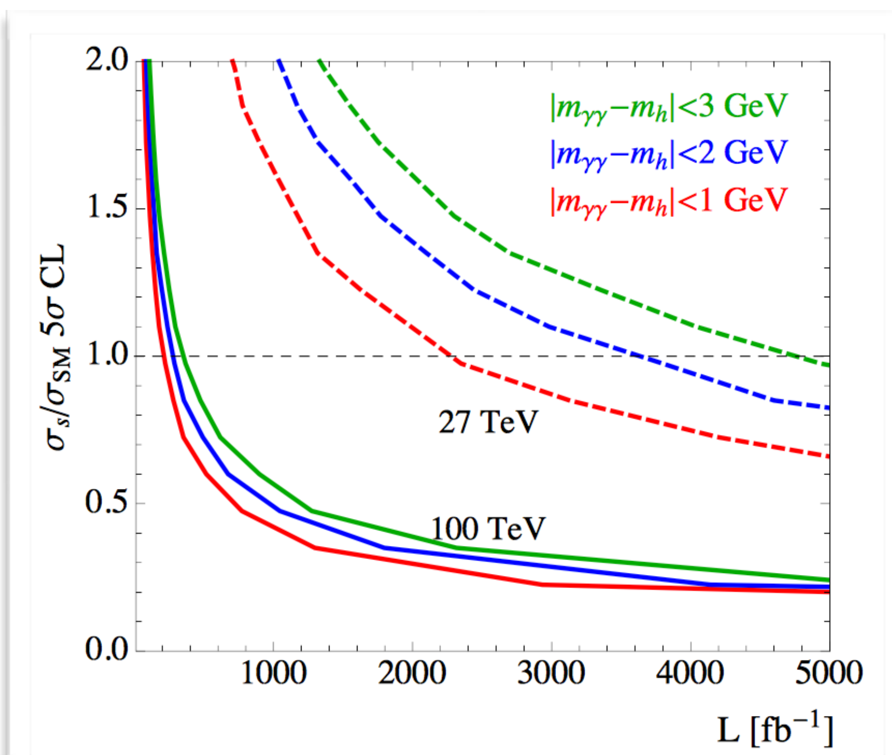
Talk by Stefania Gori

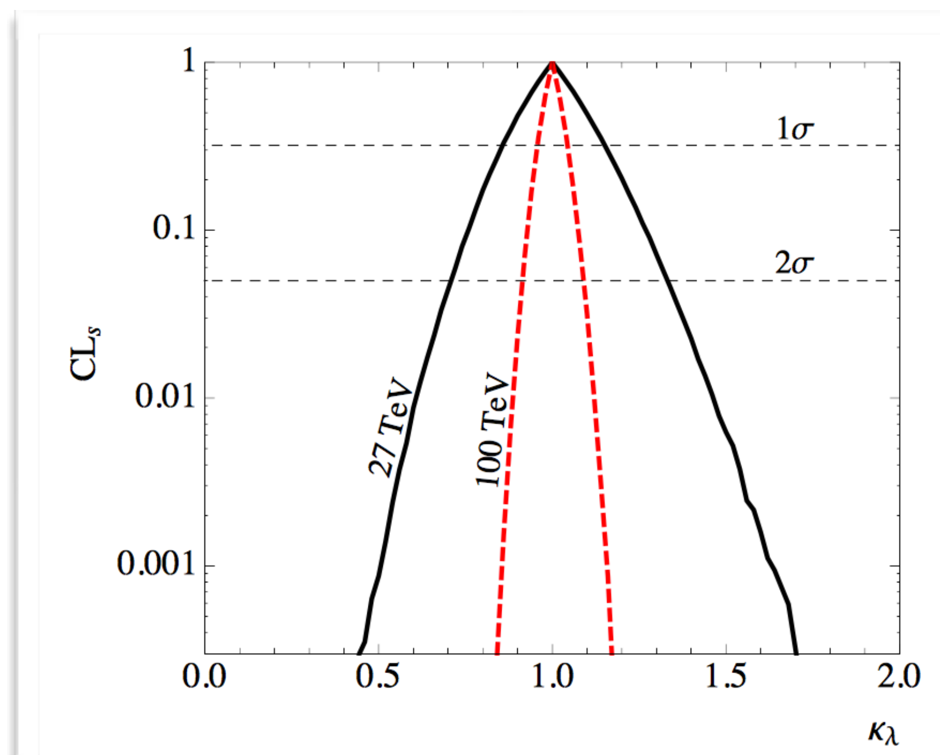
Rare channels potentially become important at HE-LHC



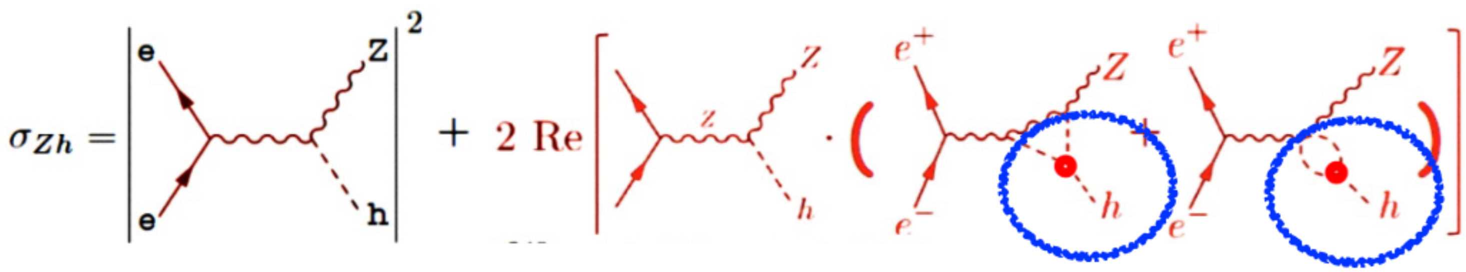


[Goncalves, Han, Kling, Plehn, Takeuchi '17]

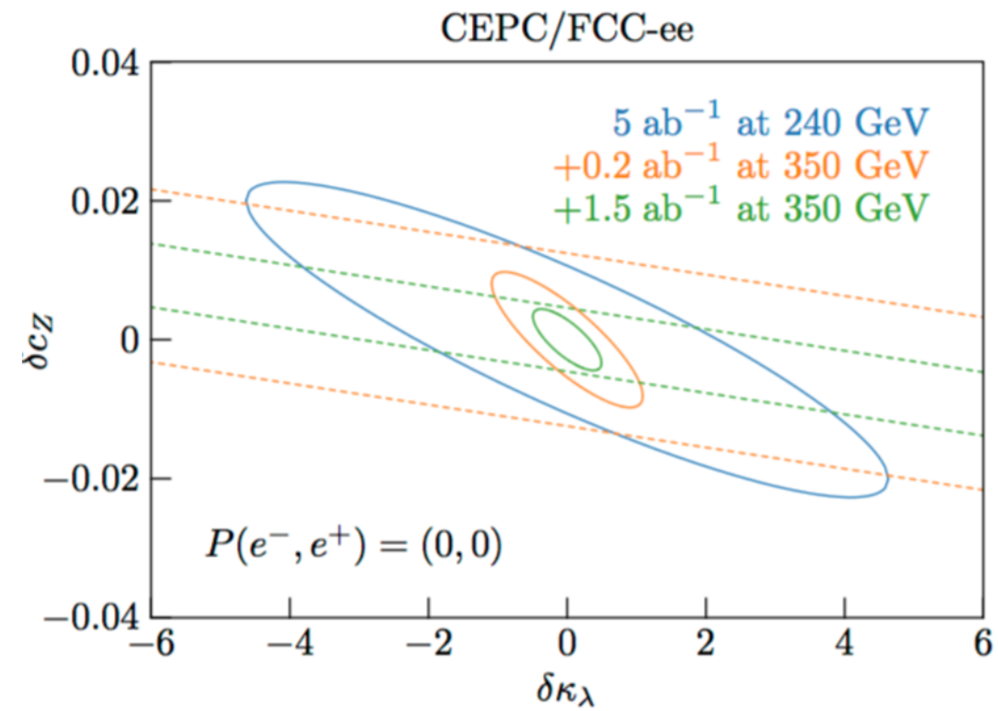




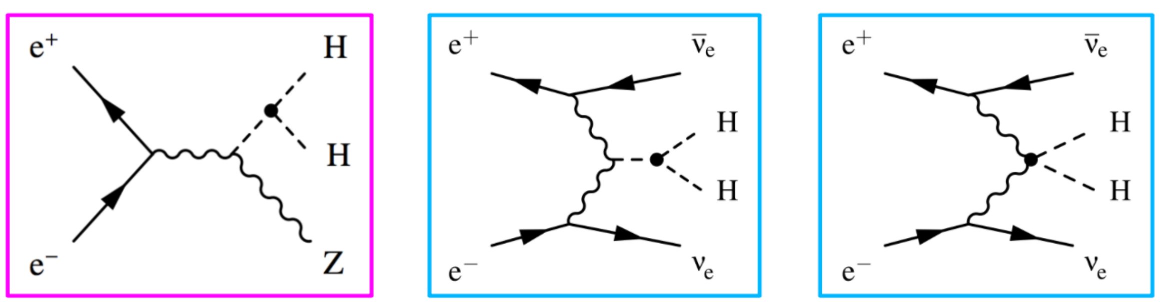
Higgs self coupling at CEPC/FCC-ee

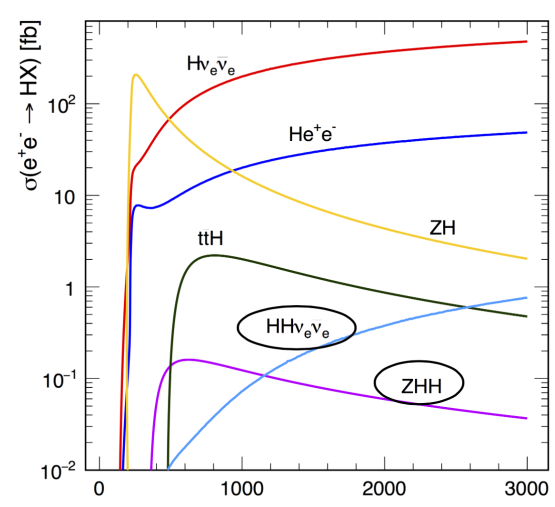


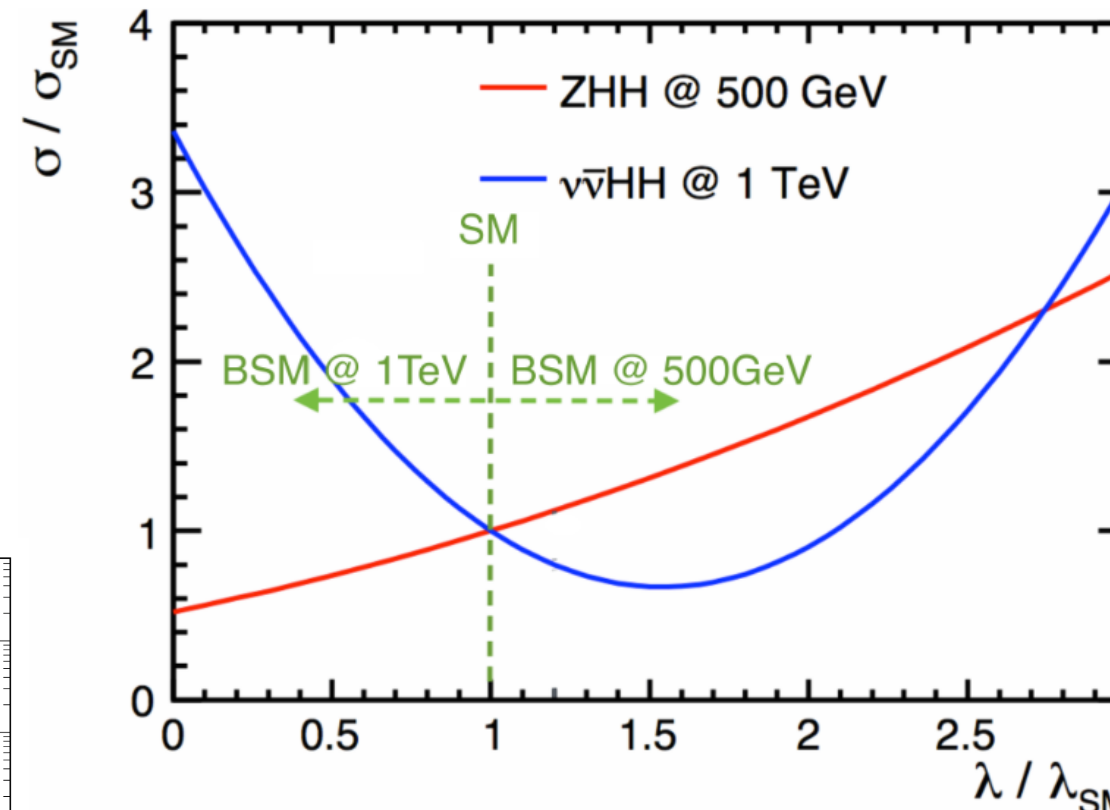
Talk by Anadi Canepa



HH production at ILC







Talk by Philipp Roloff

- **ILC**, $\sqrt{s}$ = 500 GeV, L = 4 ab^{-1}:
$\Delta\lambda/\lambda$ = 27%

DESY-THESIS-2016-027

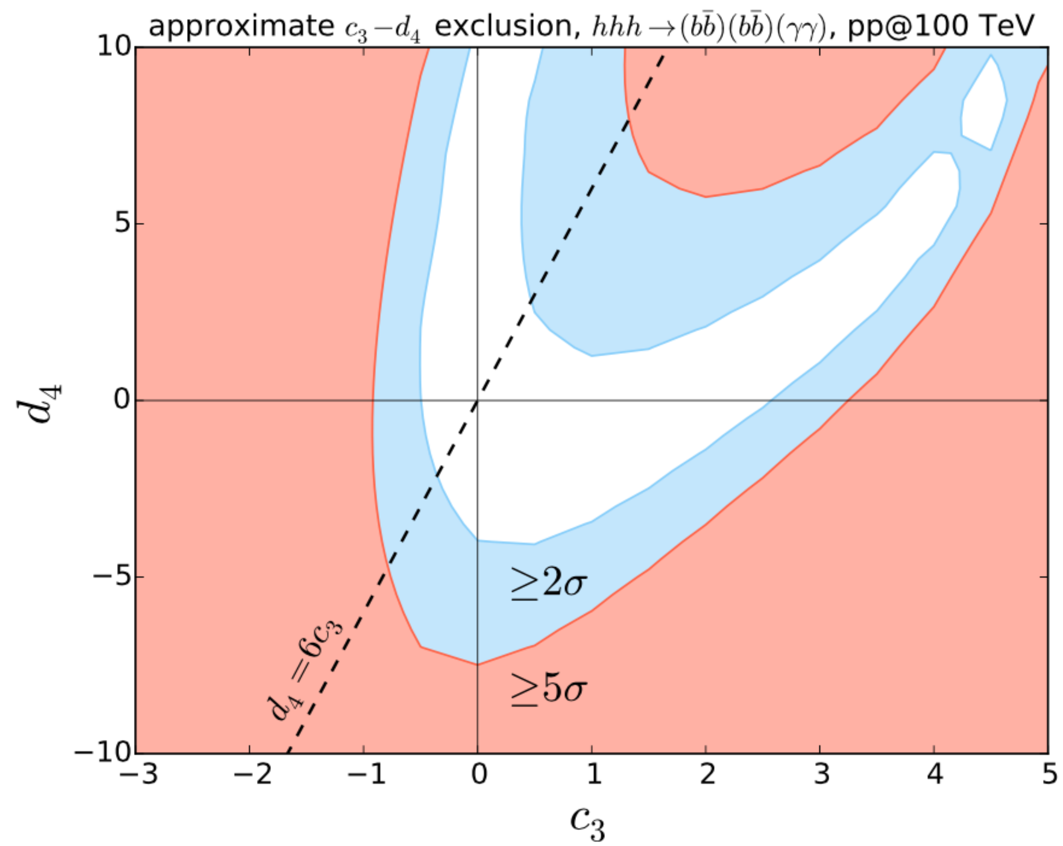
Triple Higgs Production?

Hopeless at LHC [Plehn, Rauch]

Maybe at 100 TeV pp collider (FCC-hh)?

[Papaefstathiou, Sakurai]

$$\mathcal{V}_{\rm self} = \frac{m_h^2}{2v}\left(1+c_3\right)h^3 + \frac{m_h^2}{8v^2}\left(1+d_4\right)h^4 \, ,$$



process	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}\times{\rm BR}\times\mathcal{P}_{\rm tag}$ (ab)	$\epsilon_{\rm analysis}$	$N^{\rm cuts}_{30\ {\rm ab}^{-1}}$
$hhh\to(b\bar{b})(b\bar{b})(\gamma\gamma)$, SM	2.89	5.4	0.06	9.7
$hhh\to(b\bar{b})(b\bar{b})(\gamma\gamma)$, $c_6=1.0$	0.46	0.9	0.04	1.1
$hhh\to(b\bar{b})(b\bar{b})(\gamma\gamma)$, $c_6=-1.0$	7.94	15.0	0.05	22.5
$b\bar{b}b\bar{b}\gamma\gamma$	1.28	1050	2.6×10^{-4}	8.2
hZZ, (NLO) $(ZZ\to(b\bar{b})(b\bar{b}))$	0.817	0.8	0.002	$\ll 1$
hhZ, (NLO)$(Z\to(b\bar{b}))$	0.754	0.8	0.007	$\ll 1$
hZ, (NLO) $(Z\to(b\bar{b}))$	8.019×10^{3}	1129	$\mathcal{O}(10^{-5})$	$\ll 1$
$b\bar{b}b\bar{b}\gamma$ + jets	2.948×10^{3}	2420	$\mathcal{O}(10^{-5})$	$\mathcal{O}(1)$
$b\bar{b}b\bar{b}$ + jets	5.449×10^{3}	4460	$\mathcal{O}(10^{-6})$	$\ll 1$
$b\bar{b}\gamma\gamma$ + jets	98.7	4.0	$\mathcal{O}(10^{-5})$	$\ll 1$
hh + jets, SM	275.0	592.7	7×10^{-4}	12.4
hh + jets , $c_6=1.0$	153.8	331.5	0.001	9.9
hh + jets , $c_6=-1.0$	518.2	1116.9	4×10^{-4}	13.4

Outlook

- Studies of double Higgs production are clearly important!
  - Provides the only direct probe of the self coupling
  - May provide clues to some of the open questions related to naturalness, baryongenesis, and others
- HH theory calculations are in good shape; what more can/should we do?
- Numerous examples on BSM in HH, already interesting constraints from Run-II data; keep exploring new ideas, connections to open puzzles, and novel signatures.
- Observing double Higgs remains challenging at HL-LHC. I expect there will continue to be breakthroughs in analysis methods/strategies. How can the theory/phenomenology best help with this effort?
- A rich experimental program to determine the Higgs properties, and study HH production, is underway and has a bright future ahead!

Many thanks to the organizers!!!