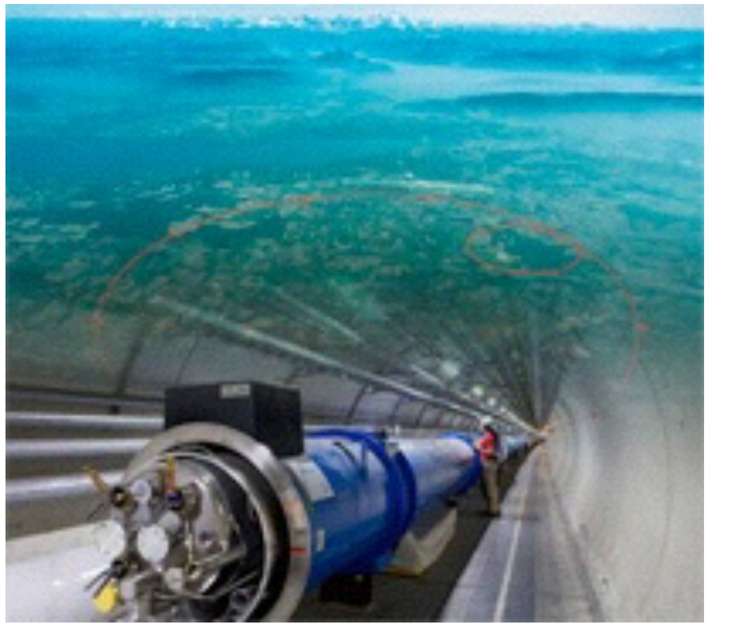
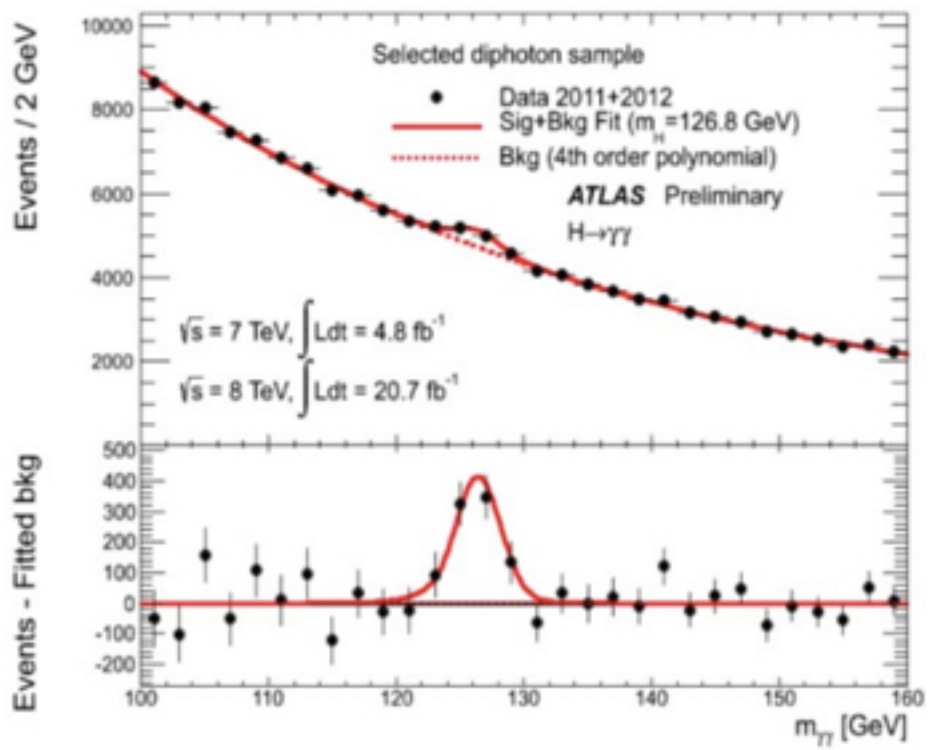


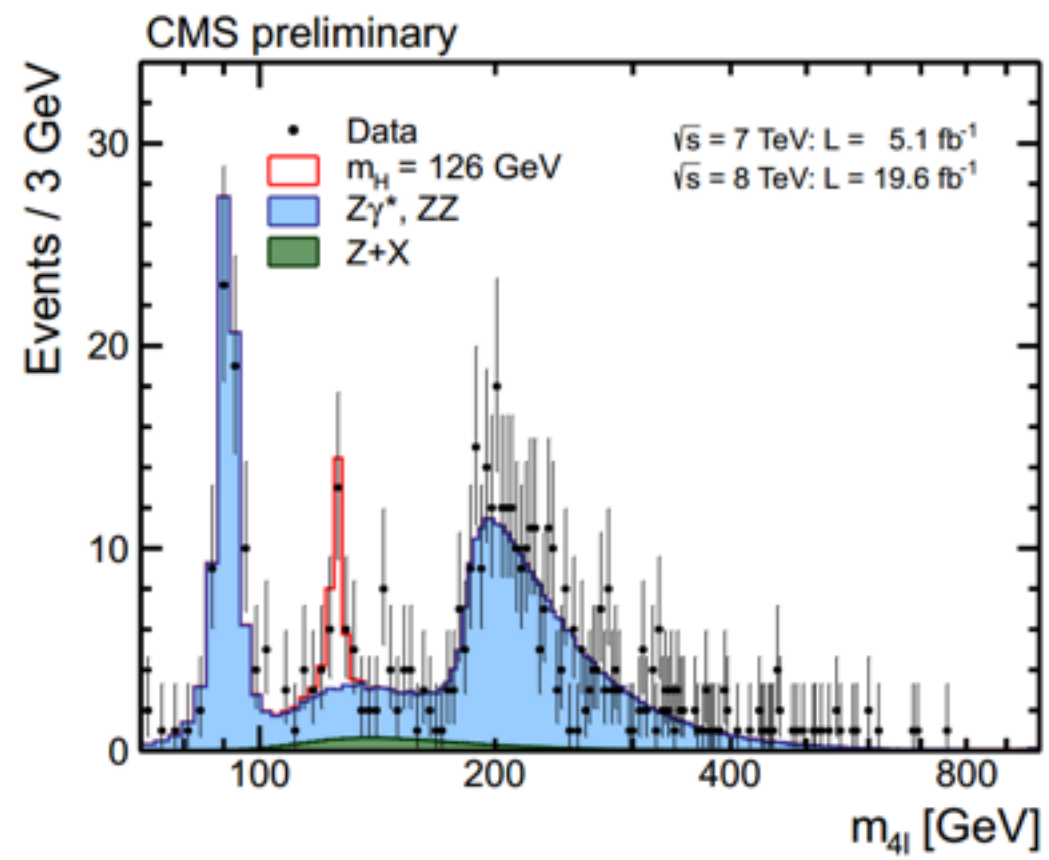
Higgs and Dark Matter Phenomenology at Colliders

Michael Spannowsky

IPPP, Durham University

Combined results for each experiment





- Huge international and intergenerational success!
- First observed in clean final states: photons, ZZ, WW
- Now more channels, e.g. taus
- In absence of other resonances Higgs is window to new physics

Results from Run 1: 'The End of the Beginning'

Mass:

ATLAS	CMS (new ZZ(4l) not used)
125.5 +-0.2 (stat) $^{+0.5}_{-0.6}$(syst) GeV	125.7 +- 0.3(stat) +- 0.3(syst) GeV

Spin

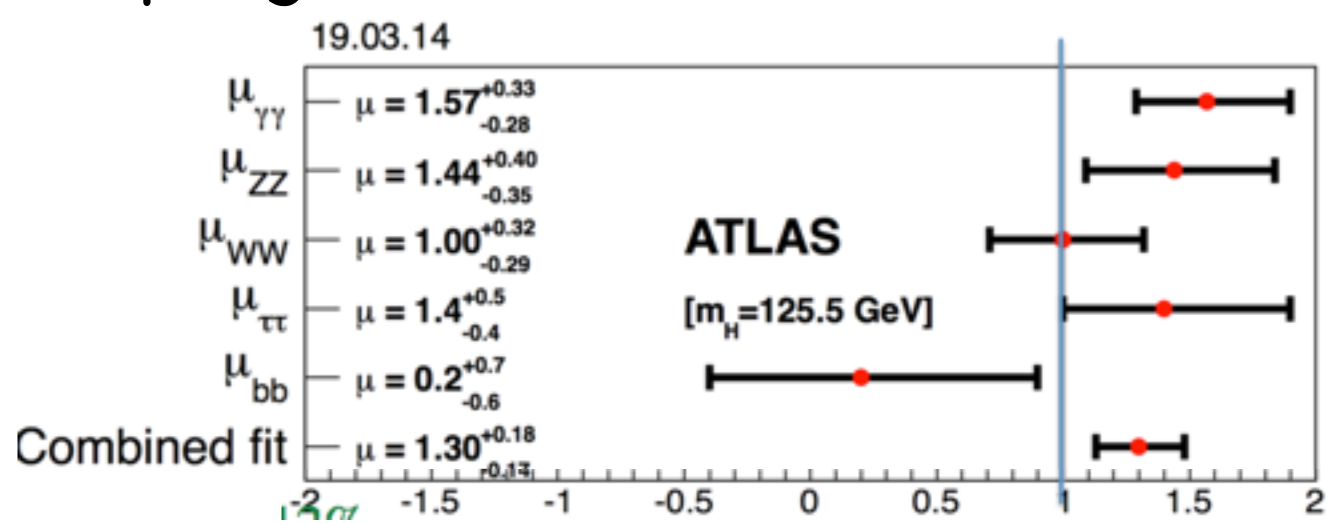
CP

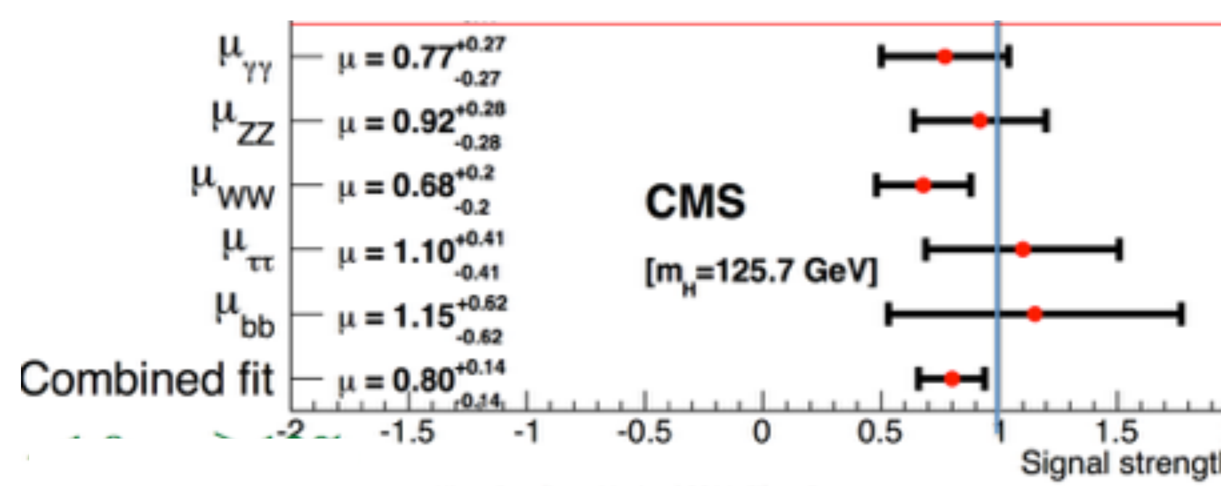
- Tested spin-1 and 0^- excluded with 1-CLs>0.99%
- Tested Spin-2 models excluded with 1-CLs>0.95%

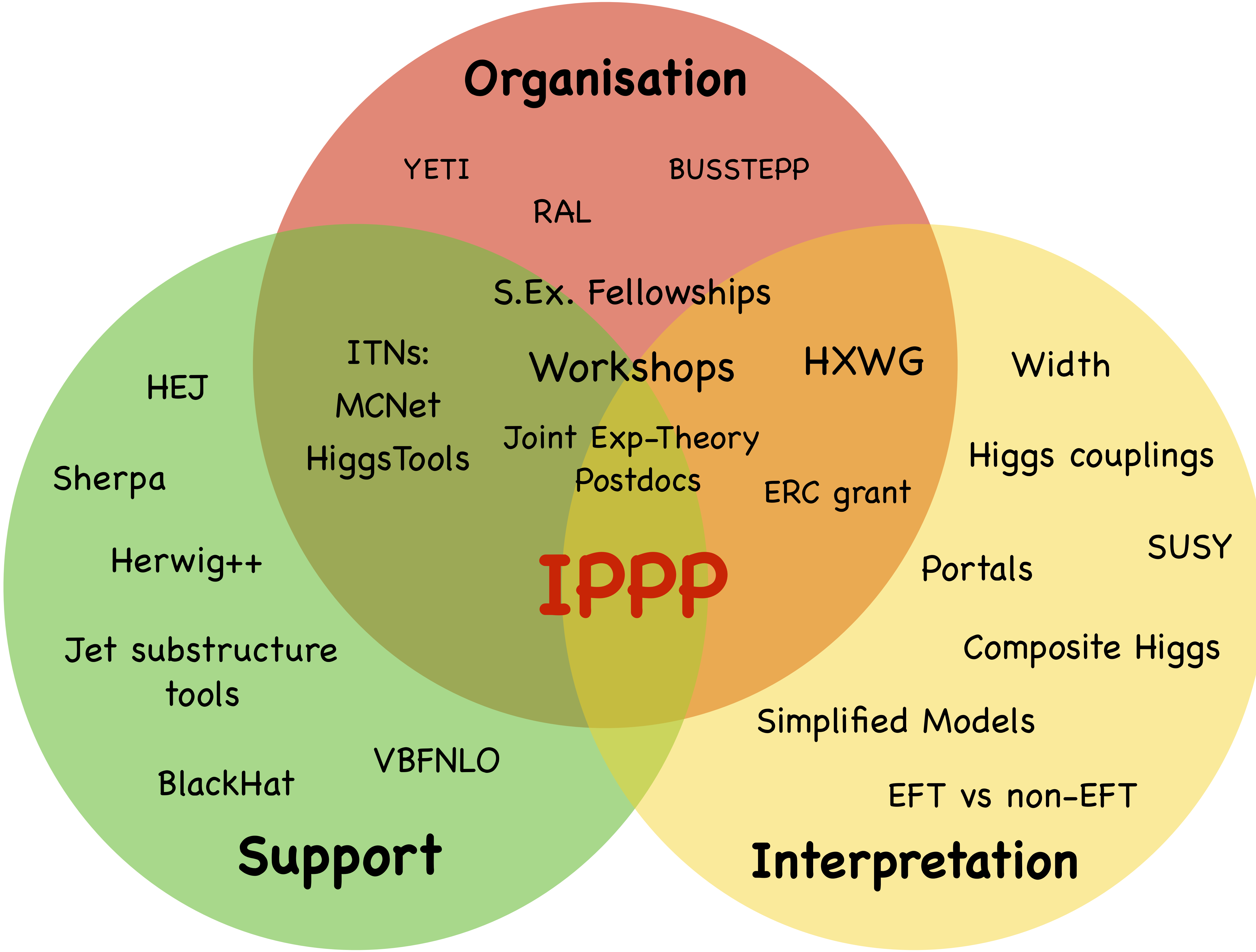
width

- Combine 4l and 2l2n decay channels.
- **Observed (expected)** 95%CL limits: Γ **< 8.5(4.2) x** Γ_{SM}

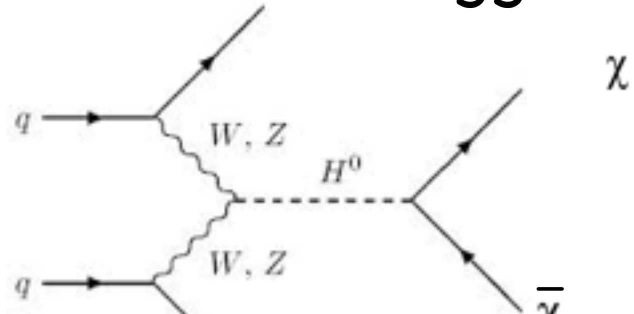
Couplings





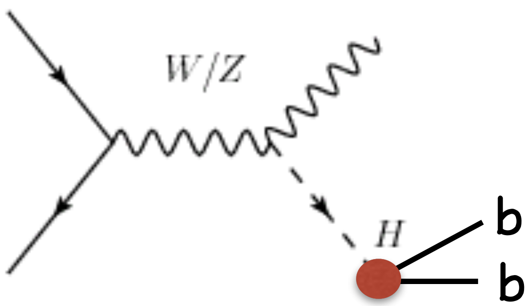

Organisation
YETI
BUSSTEPP
RAL
S.Ex. Fellowships
ITNs:
MCNet
HiggsTools
Workshops
HXWG
Joint Exp-Theory
Postdocs
ERC grant
HEJ
Sherpa
Herwig++
Jet substructure
tools
BlackHat
VBFNLO
Support
Width
Higgs couplings
SUSY
Portals
Composite Higgs
Simplified Models
EFT vs non-EFT
Interpretation
IPPP

Invisible Higgs



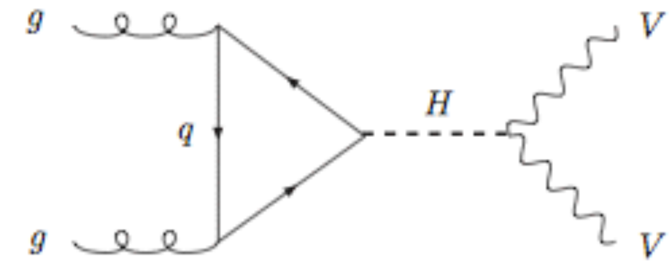
[Englert, Jaeckel, MS, Re '11]
[Englert, MS, Wymant '13]
[Bernacek, Plehn, Schichtel, Tattersall '14]

Higgs-bottom coupling



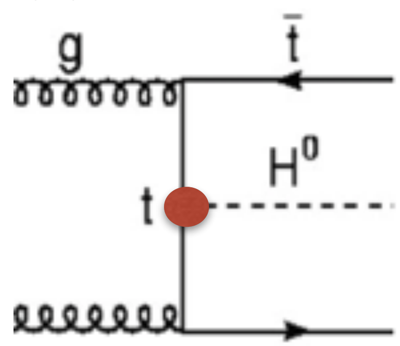
[Soper, MS '10]
[Soper, MS '11]

Off-shell Higgs (Width)



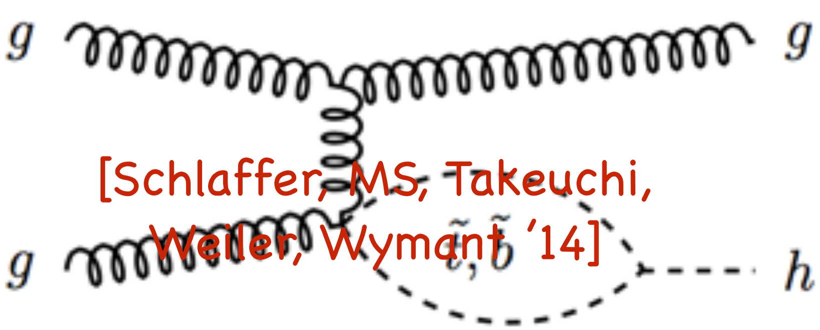
[Englert, McCullough, MS '15]
[Englert, MS '14]
[Englert, Soreq, MS '14]

Higgs-top coupling



[Plehn, Salam, MS '09]
[Artoisenet, de Aquino, Maltoni, Mattelaer '09]

ct vs cg in H+jet

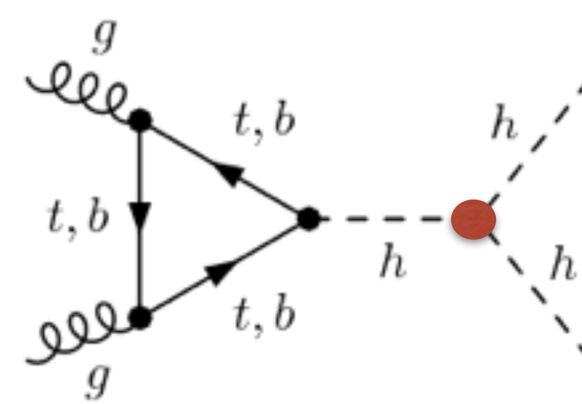


[Schlaffer, MS, Takeuchi, Weiler, Wymant '14]

[Buschmann, Englert, Goncalves, Plehn, MS '14]

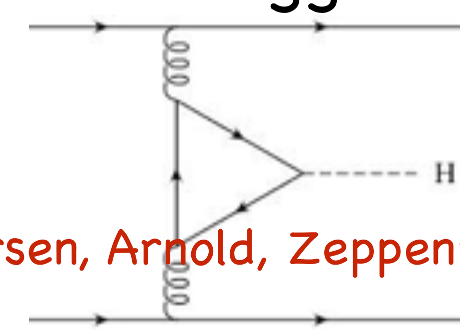
[Buschmann, Goncalves, Kutimalai, Krauss, Plehn, '14]

Higgs selfcoupling



[Dolan, Englert, MS '13 '14]
[Barr, Dolan, Englert, MS '14]
[Ferreira, Papaefstathiu, MS '14]
[Dolan, Englert, Greiner, MS '14]
[Englert, Krauss, MS, Thompson '14]

CP Higgs



[Andersen, Arnold, Zeppenfeld '10]

[Dolan, Harris, Jankowiak, MS '14]

Constraining the Higgs width at the LHC?

- alternative method using interference effects directly see [Dixon, Li '13]

Constraining the Higgs boson width with ZZ production at the LHC

Fabrizio Caola[1,*] and Kirill Melnikov[1,†]

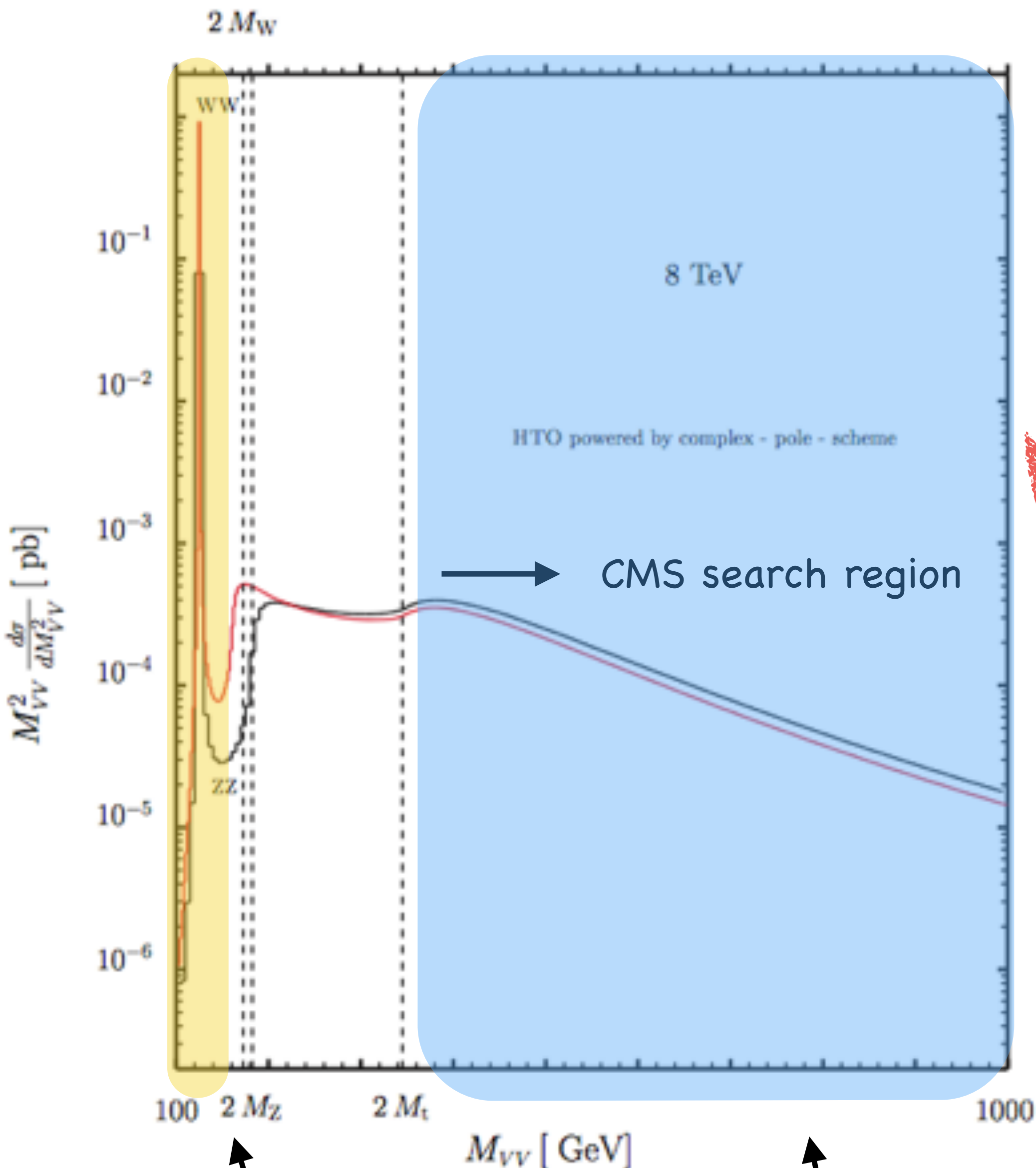
[1] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, USA*

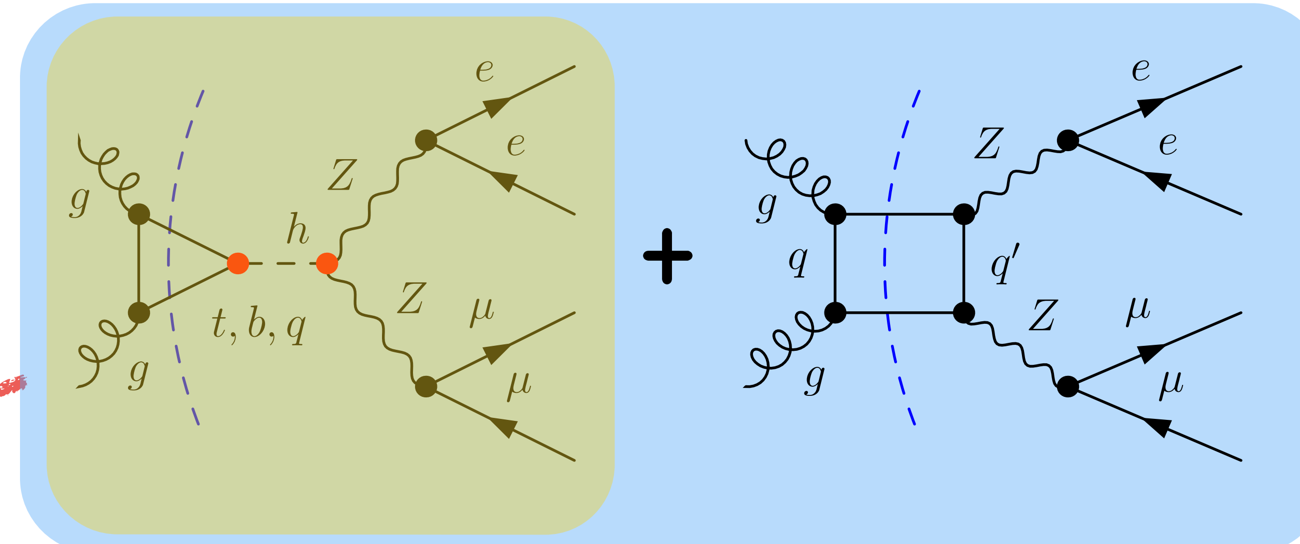
We point out that existing measurements of $pp \to ZZ$ cross-section at the LHC in a broad range of ZZ invariant masses allow one to derive a model-independent upper bound on the Higgs boson width, thanks to strongly enhanced off-shell Higgs contribution. Using CMS data and considering events in the interval of ZZ invariant masses from 100 to 800 GeV, we find $\Gamma_H \leq 38.8\ \Gamma_H^{\rm SM} \approx 163$ MeV, at the 95% confidence level. Restricting ZZ invariant masses to $M_{ZZ} \geq 300$ GeV range, we estimate that this bound can be improved to $\Gamma_H \leq 21\ \Gamma_H^{\rm SM} \approx 88$ MeV.

[Caola, Melnikov PRD 88]

Measurement done in CMS-PAS-HIG-14-002 and presented at Moriond '14
By now ATLAS has performed same measurement

CMS Measurement





I. Count events in on-shell region

→ fix signal strength $\mu_{i,j} = \sigma_{H,i} \times BR_j \sim \frac{g_{ggH} g_{HZZ}}{\Gamma_H}$

II. measure $g^2_{ggH} g^2_{HZZ}$ in off-shell region

using angular correlations of 4l decay products

III. insert off-shell coupling measurement in

on-shell signal strength to bound width

$$\sigma^{\text{on-peak}}_{gg \to H \to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$$

$$\sigma^{\text{off-peak}}_{gg \to H \to ZZ} \sim g^2_{ggH} g^2_{HZZ}$$

[Kauer, Passarino 2011]

Obs.(exp.) @95% C.L:

Γ_H< 4.2(8.5) Γ_H^{SM}

Γ_H< 17.4 (35.3) MeV

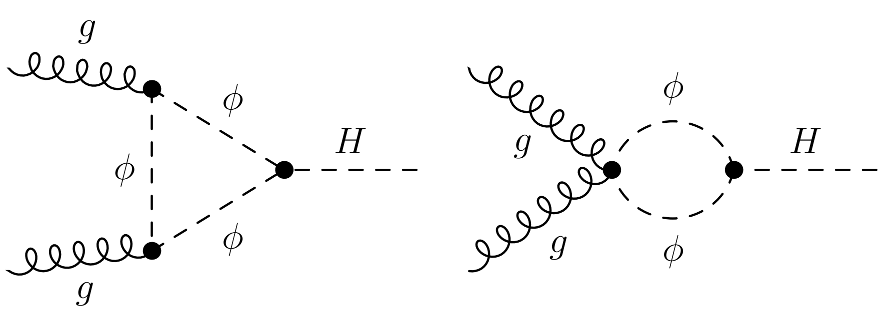
Unfortunately, method has loop-holes:

[Englert, MS '14]
[Logan, '15]

- In SM couplings in on-shell and off-shell region intimately related

- Direct correlation of on-shell $g^2_{ggh}\, g^2_{hZZ}$ and off-shell $g^2_{ggh}(\sqrt{s})\, g^2_{hZZ}(\sqrt{s})$ necessary ingredient for width measurement -> can be broken by BSM effects

Example: Higgs-portal (toy) model $\mathcal{L}_\phi = |D_\mu \phi|^2 - \tilde{m}^2_\phi |\phi|^2 - \lambda |\phi|^2 |H|^2 + \ldots\, .$



scalar only charged under $\mathrm{SU}(3)_C$

$m^2_\phi = \tilde{m}^2_\phi + \lambda v^2$ free parameter

off-shell CS

m_ϕ	μ (h peak)	$\Gamma_h/\Gamma_h^{\mathrm{SM}}$	$\overline{\sigma}/\overline{\sigma}^{\mathrm{SM}}$ [$m(4\ell) \geq 330$ GeV][a]
70 GeV	$\simeq 1.0$	$\simeq 5$	-2%
170 GeV	$\simeq 1.0$	$\simeq 4.7$	$+80\%$
170 GeV	$\simeq 1.0$	$\simeq 1.7$	$+6\%$

[a]We impose the cut set used by CMS [17] without the MELA cut [34].

$g_{ggh}(m_h) > g_{ggh,\mathrm{SM}} \longrightarrow \Gamma > \Gamma_{\mathrm{SM}}$ for $\mu \sim 1$

Despite increased on-shell coupling (and Higgs width) negligible contribution in off-shell region

- Here only simplest toy model - thus question: WHEN IS WIDTH INTERPRETATION VALID

- Width interpretation ONLY interesting if model-independent

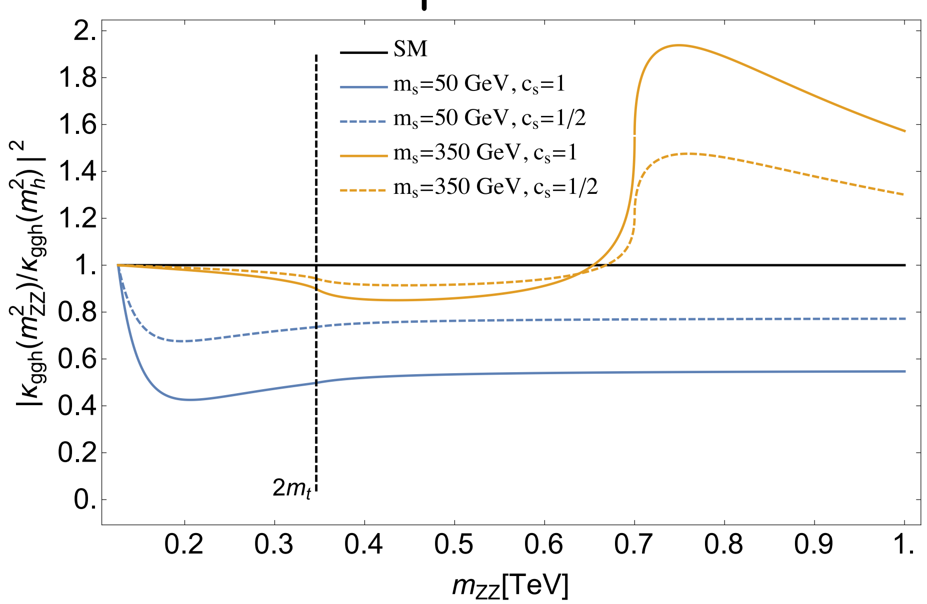
  Within a model width is fixed (not free parameter of theory), result of QFT

  Width measurement is result of global coupling fit.

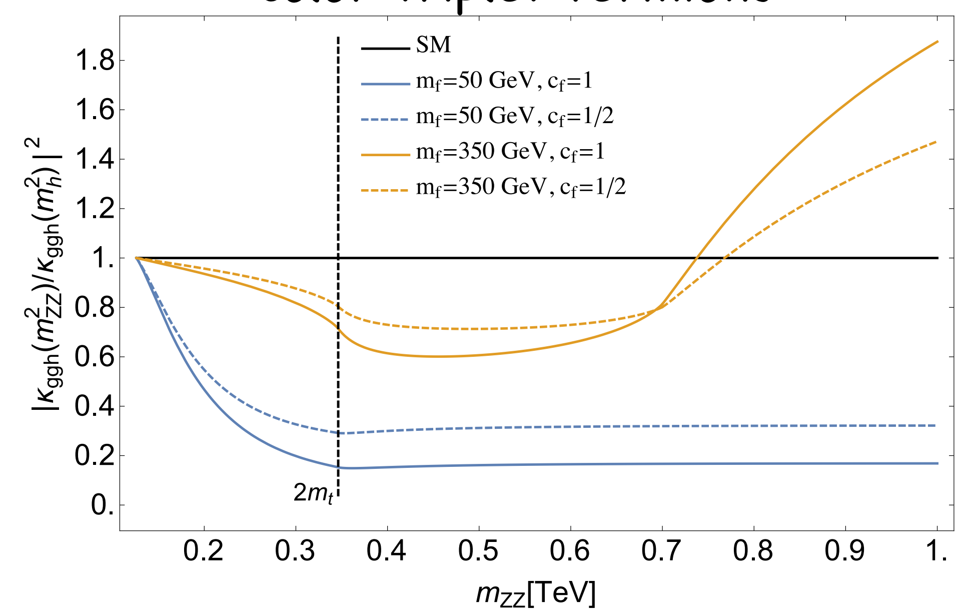
- But for classes of models a width interpretation is valid: [Englert, Soreq, MS '14]

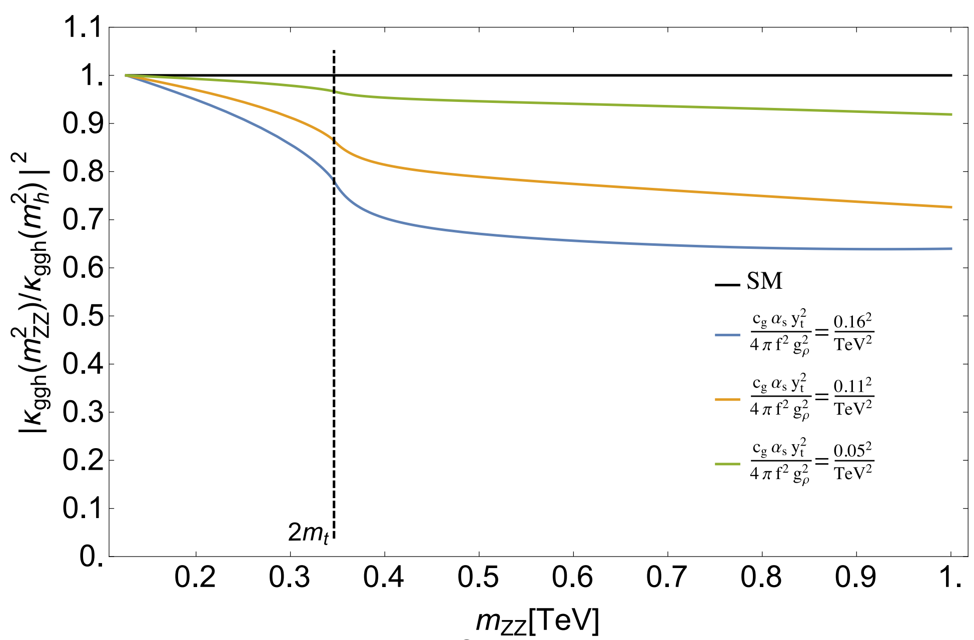
  Necessary condition: $R(m_{ZZ}^2) = \frac{ggH(m_{ZZ}^2)/ggH_{SM}(m_{ZZ}^2)}{ggH(m_H^2)/ggH_{SM}(m_H^2)} \simeq 1$ complex valued double ratio

color triplet scalar



color triplet fermions





effective GGHH coupling

9

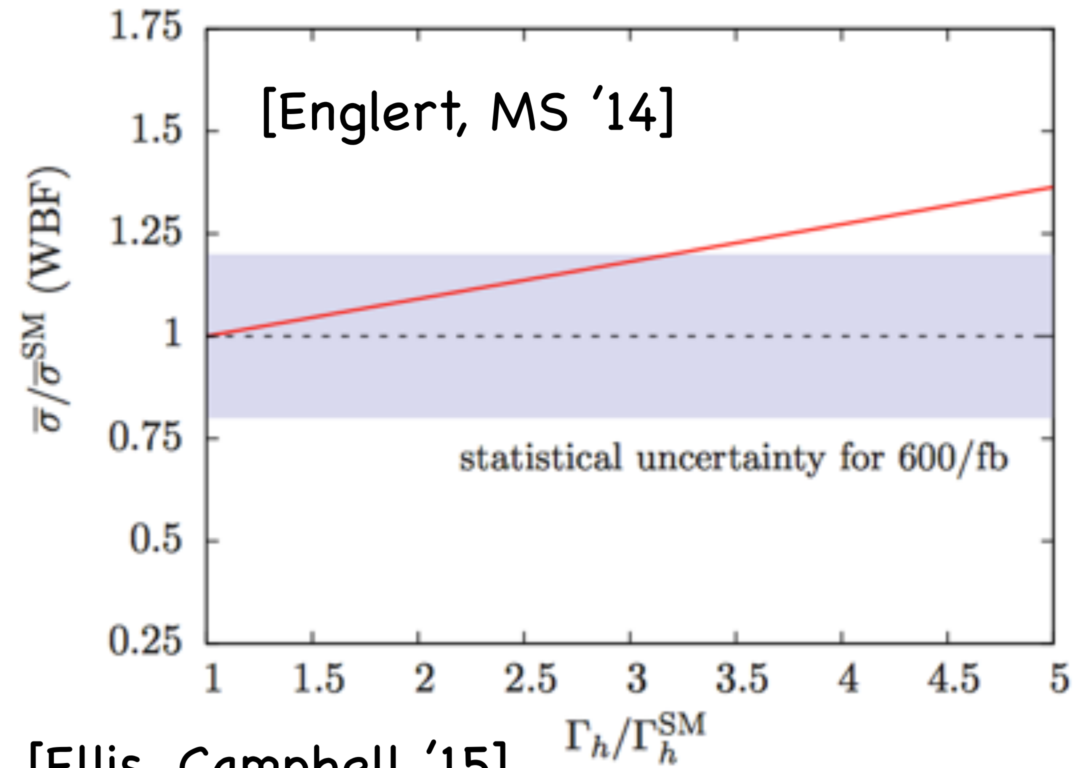
- **Way to close loophole of Caola-Melnikov method by using WBF process:**

Same tree-level coupling in production and decay

T parameter links WWH and ZZH

$$\mathcal{L}_{HD} = F_{HD}\ \mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H} - \frac{v^2}{4}\right]\cdot \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})\right]$$

assumed
$$hW^+_\mu W^-_\nu : \quad igM_W g_{\mu\nu}\frac{v^2F_{HD}}{2}$$
$$hZ_\mu Z_\nu : \quad ig\frac{M_W}{\cos^2\theta_W}g_{\mu\nu}\frac{v^2F_{HD}}{2}$$



[Ellis, Campbell '15]

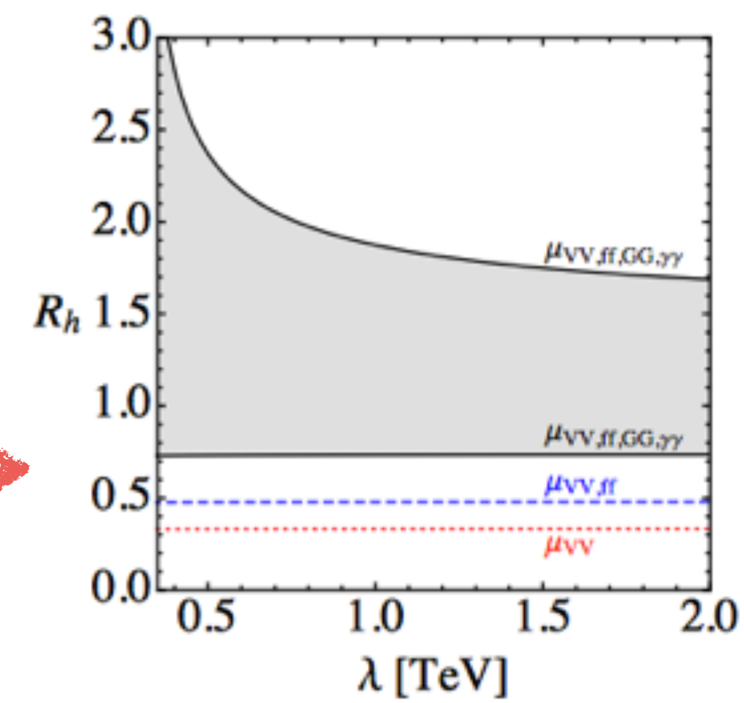
- **Use LEP as off-shell Higgs factory:**

Why off-shell LHC coupling measurement?

LEP has already performed precise Higgs coupling measurements!

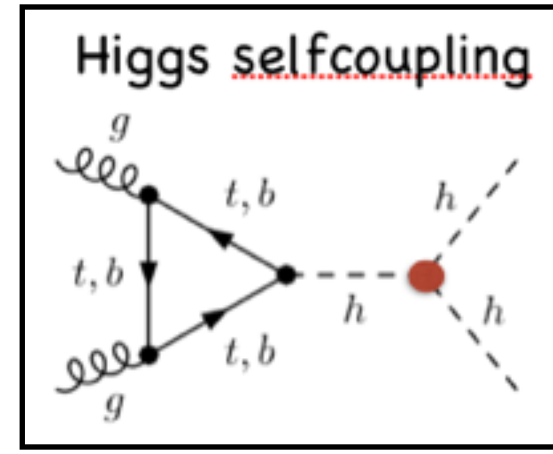
Use LEP coupling measurements and plug into LHC signal strength measurement

[Englert, McCullough, MS '15]



10

Higgs self-coupling measurements



$$= \lambda_{SM} = g^2 m_h^2 / m_W^2$$

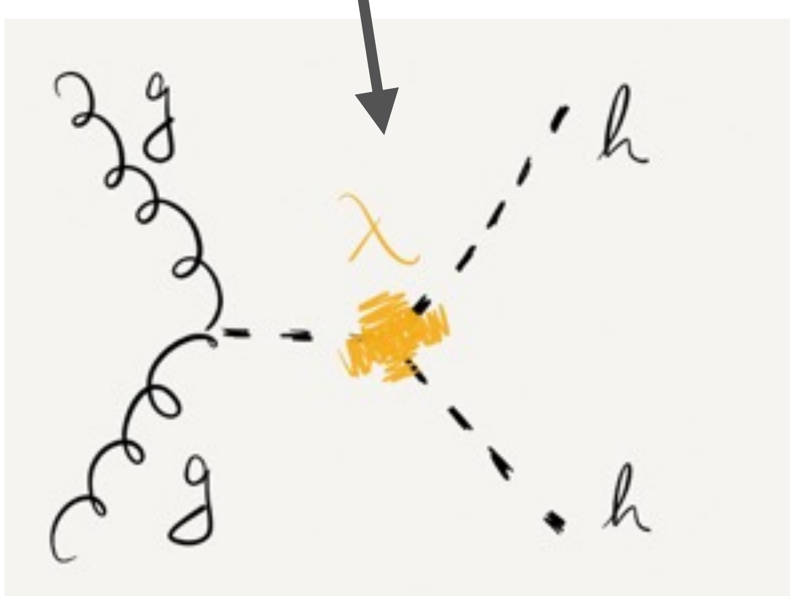
$$-\mathcal{L} \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}}\, m_h h^3 + \frac{\eta}{4} h^4$$

→ Potential needs at least dihiggs production!

$$- g m_V V^2 h - \frac{m_f}{v} \bar{f} f h$$

$$- \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

$$= -\frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h + \frac{\alpha_s}{24\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2 + \dots$$



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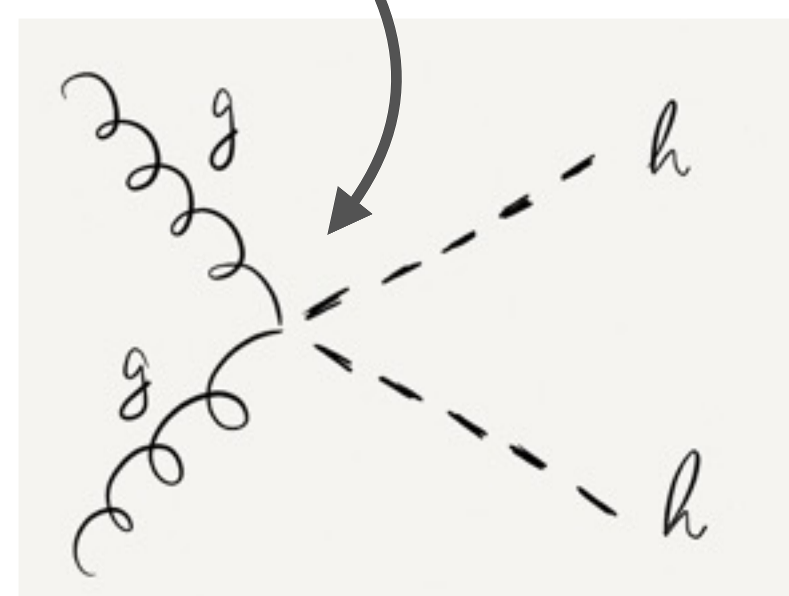
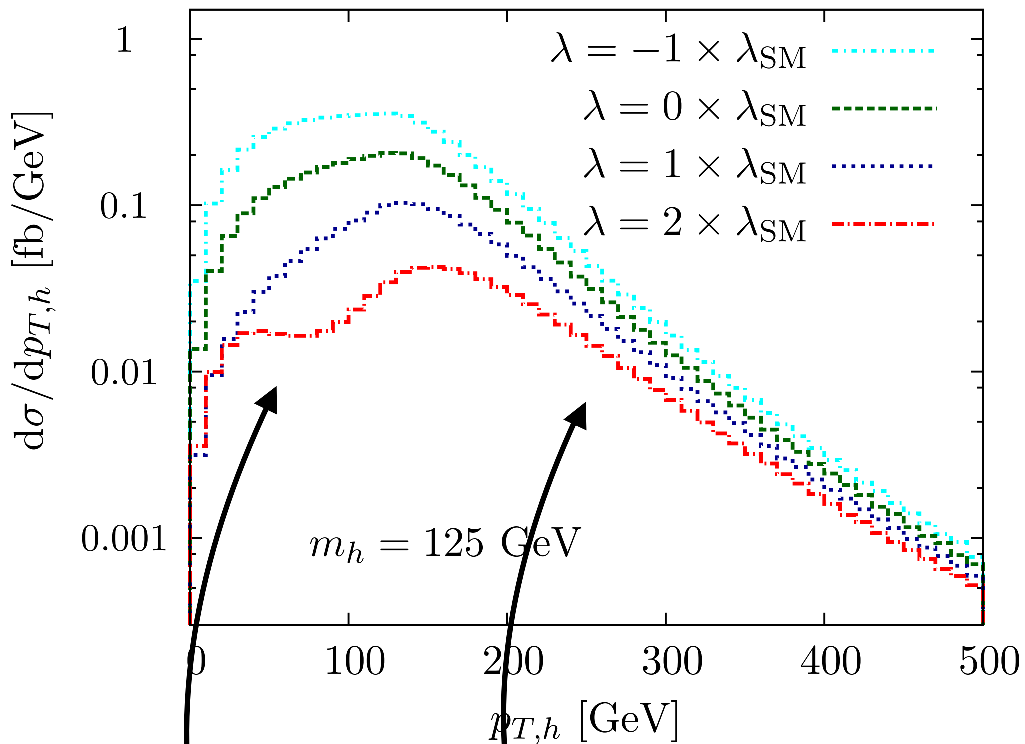
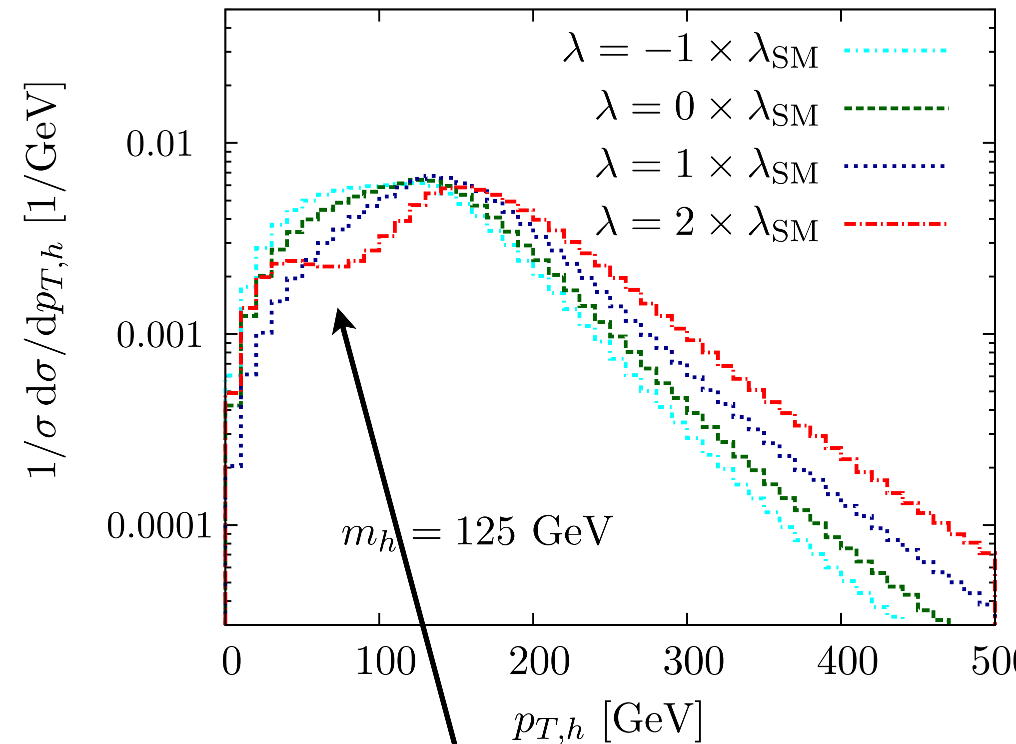
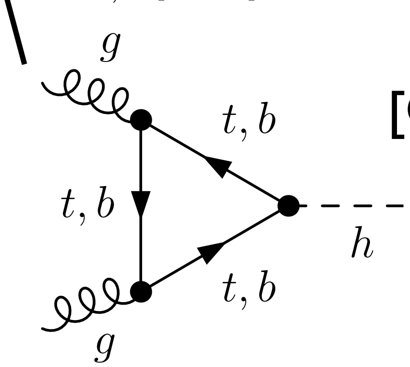


Higgs selfcoupling in HH+X



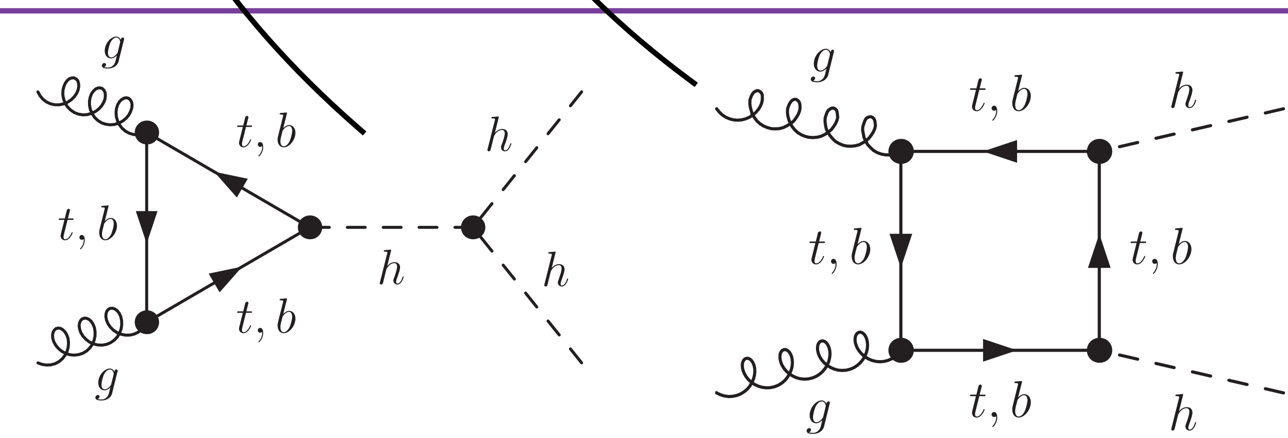




[Georgi et al. \`78]

has maximum contribution for

$$s = (p_{h,1} + p_{h,2})^2 = 4m_t^2$$



Total cross section: [HXSWG]

$pp \to HH(\lambda = 1) = 33.86$ fb

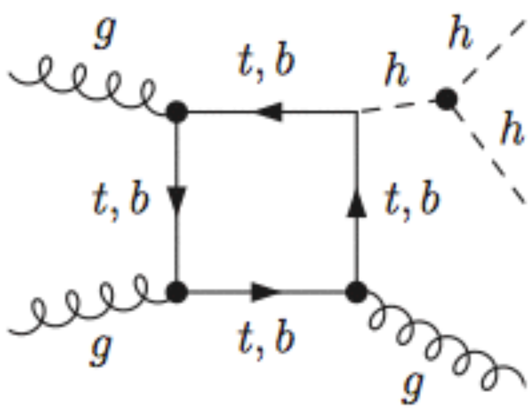
$pp \to HH(\lambda = 0) = 71.01$ fb

$pp \to HH(\lambda = 2) = 15.85$ fb

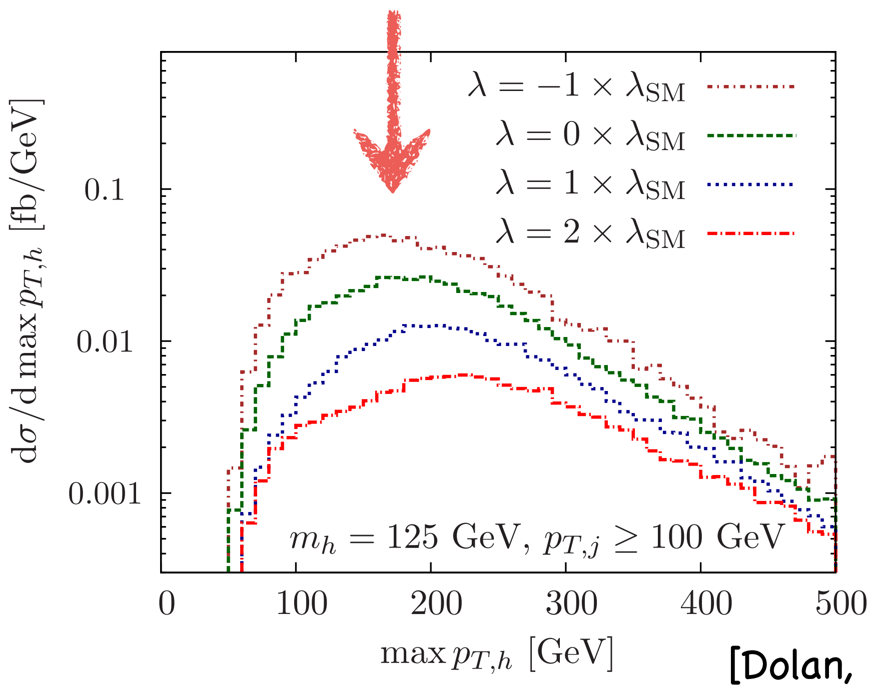
Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304] [Azatov et al. JHEP '15]
$b\bar{b}\tau^+\tau^-$	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \leq 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
others	• Many taus/W not clear if 2 Higgs • Zs, photons no rate		

More jets more fun:

First to calculate HH+jet and HH+2jets beyond effective theory



keep mHH small -> retain sensitivity for high-pT Higgs



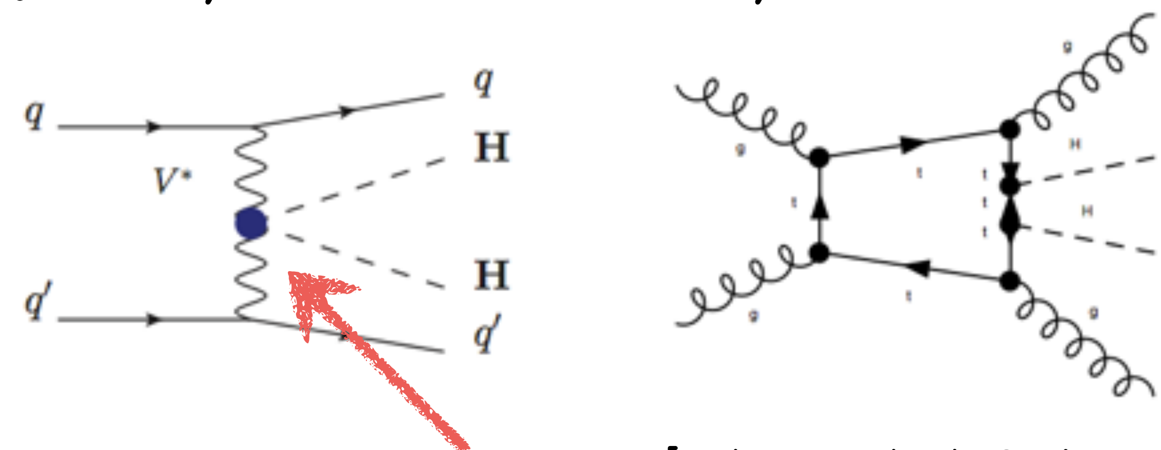
[Dolan, Englert, MS]

Additional jet can help to suppress backgrounds:

$$hhj \to b\bar{b}\tau^+\tau^- j \quad \text{S/B} \sim 3/2$$

$$hh \to b\bar{b}\tau^+\tau^- \quad \text{S/B} \sim 1/2$$

Unfortunately rate small



[Dolan, Englert, Greiner, MS]

- Want to study VVHH
  Directly related to long. gauge boson scattering
  Though strongly modified in comp. Higgs models

- In SM fixed: $g_{WWhh} = e^2/(2s_w^2)$

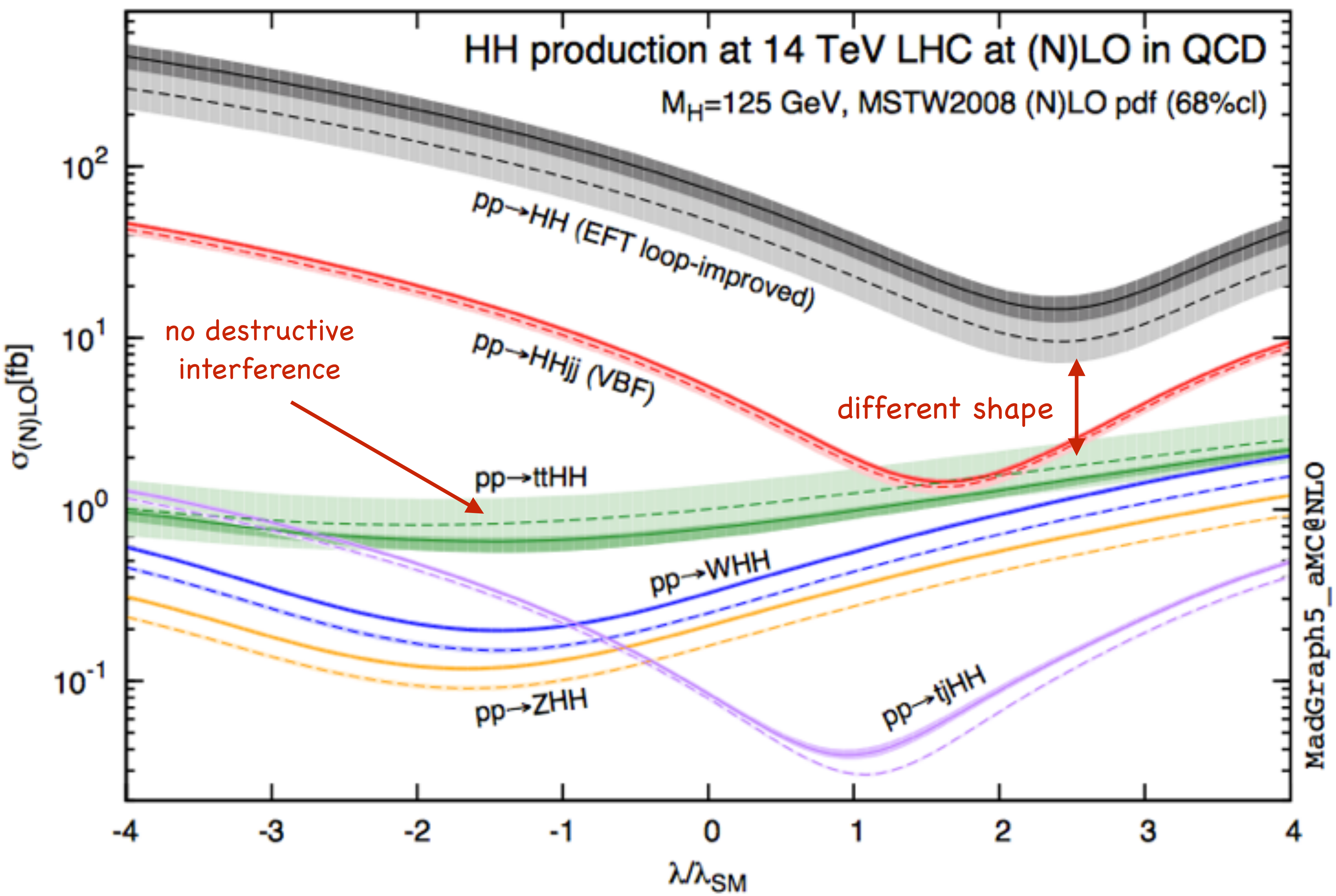
  $$g_{ZZhh} = e^2/(2c_w^2 s_w^2)$$

- Unfortunately gluon fusion dominating over WBF
  Usual WBF cuts, e.g. central jet vetos not applicable.

- WBF only measurable for large enhancement of SM coupling value

Higgs selfcoupling in ttHH

[Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torielli, Vryonidou, Zaro ‘14]



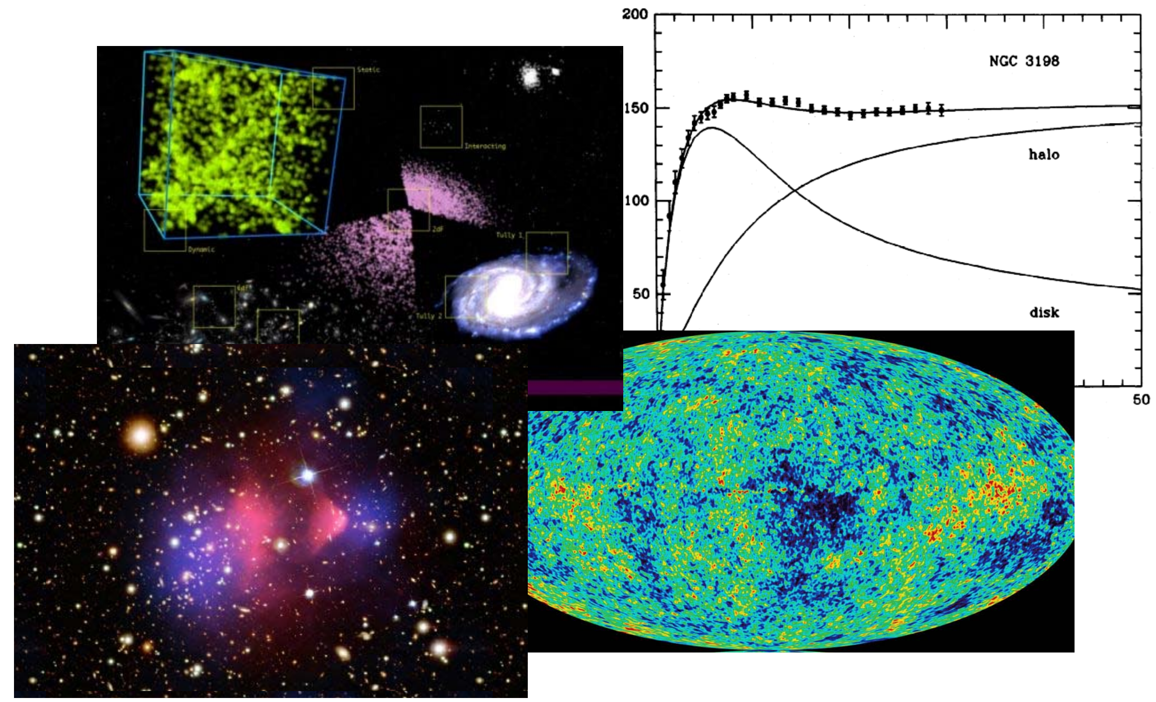
Enhanced selfcoupling can be measured in tthh

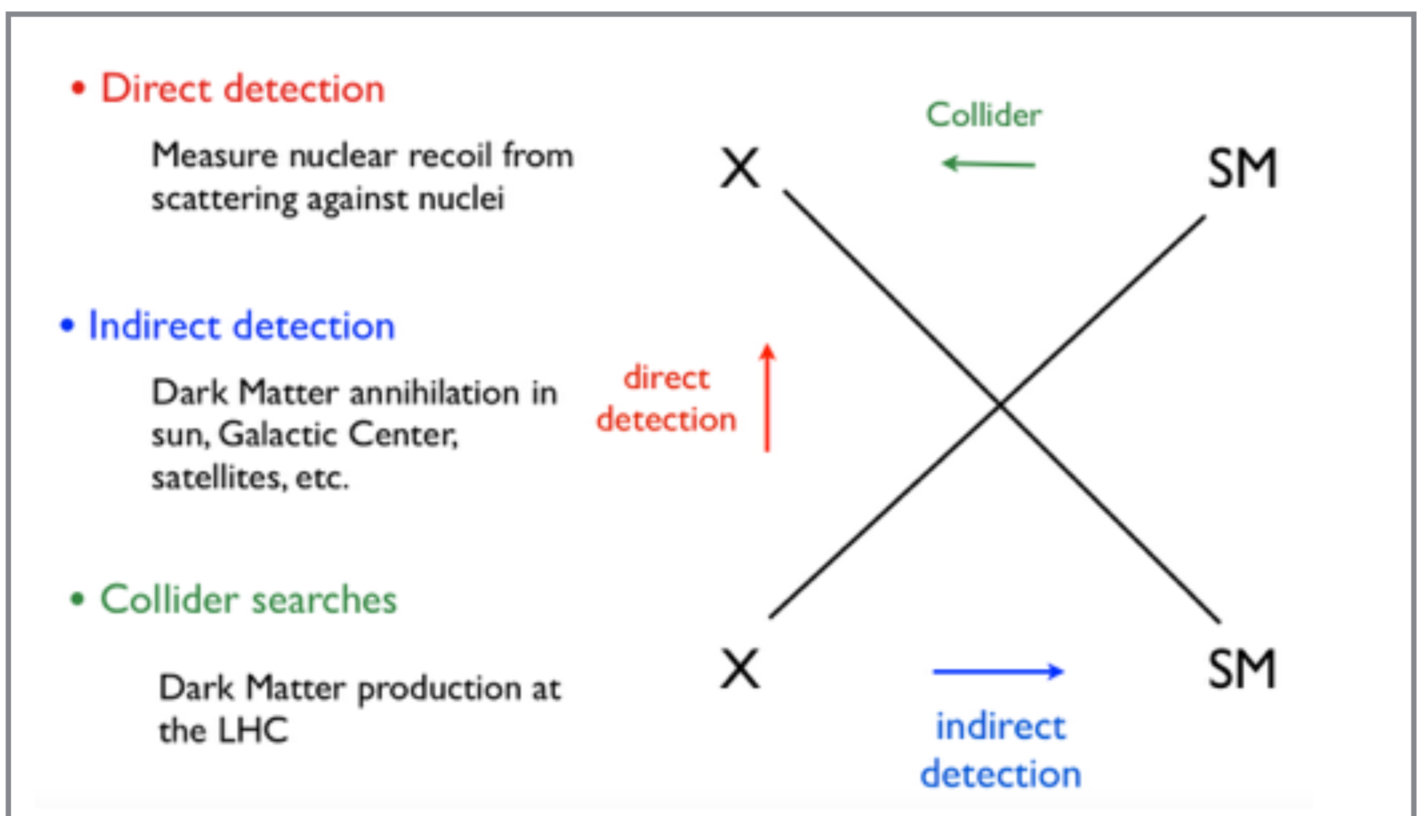
[Englert, Krauss, MS, Thompson ’14]

Higgs/Scalars and their Dark Matter relation

Evidence for Dark Matter overwhelming:

- Spiral Galaxy rotation curves
- Gravitational lensing
- Acoustic peaks



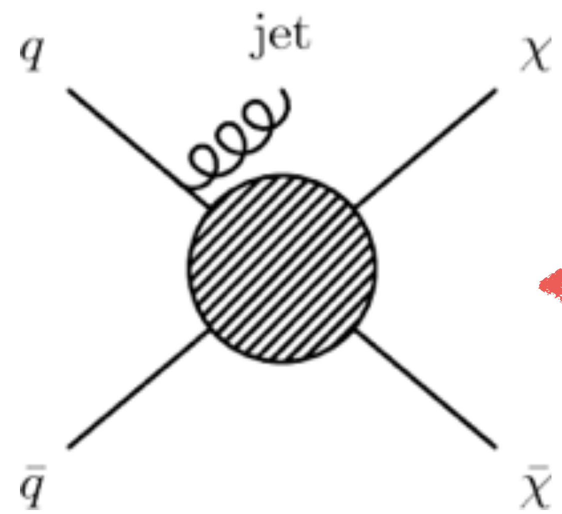


Several ways to look for Dark Matter

Which way more sensitive depends mostly on nature of mediator

Effective theory approach:

- Parametrise interactions in terms of eff. operator



Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

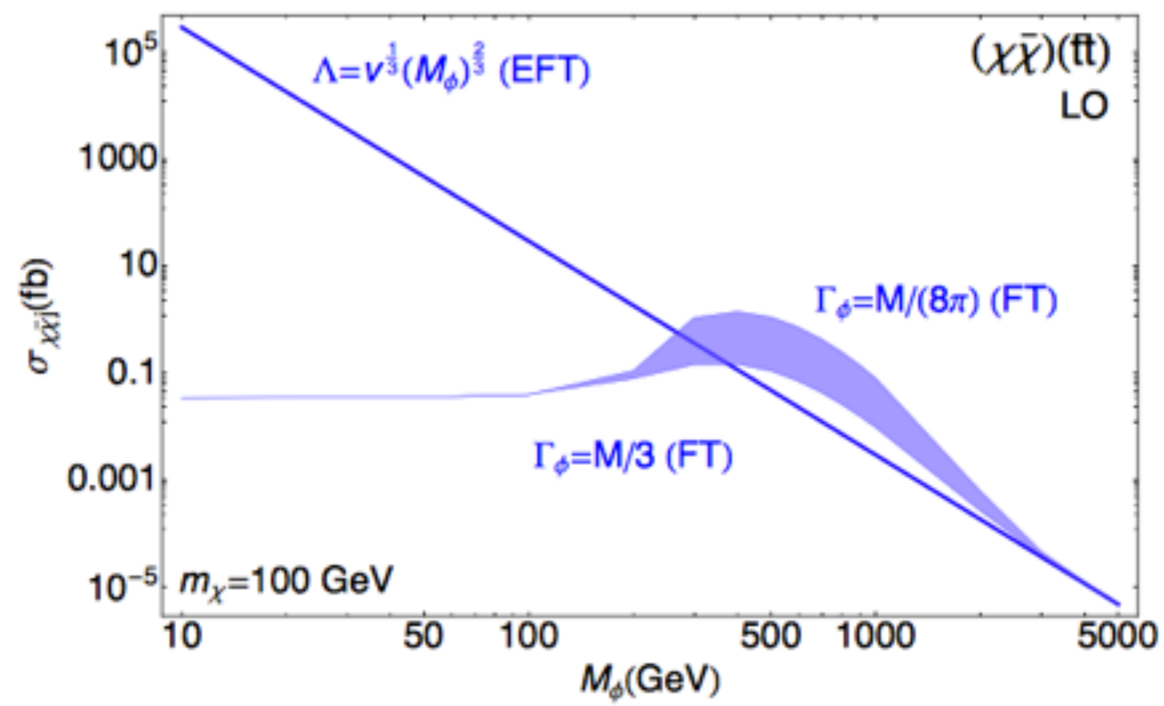
- Simplest way of capturing interactions

→ Used to be preferred choice of experiments to present results

- However, only valid if interaction not resolved

Going beyond:

- At colliders momentum transfer too large for EFT approach



→ Need simplified models

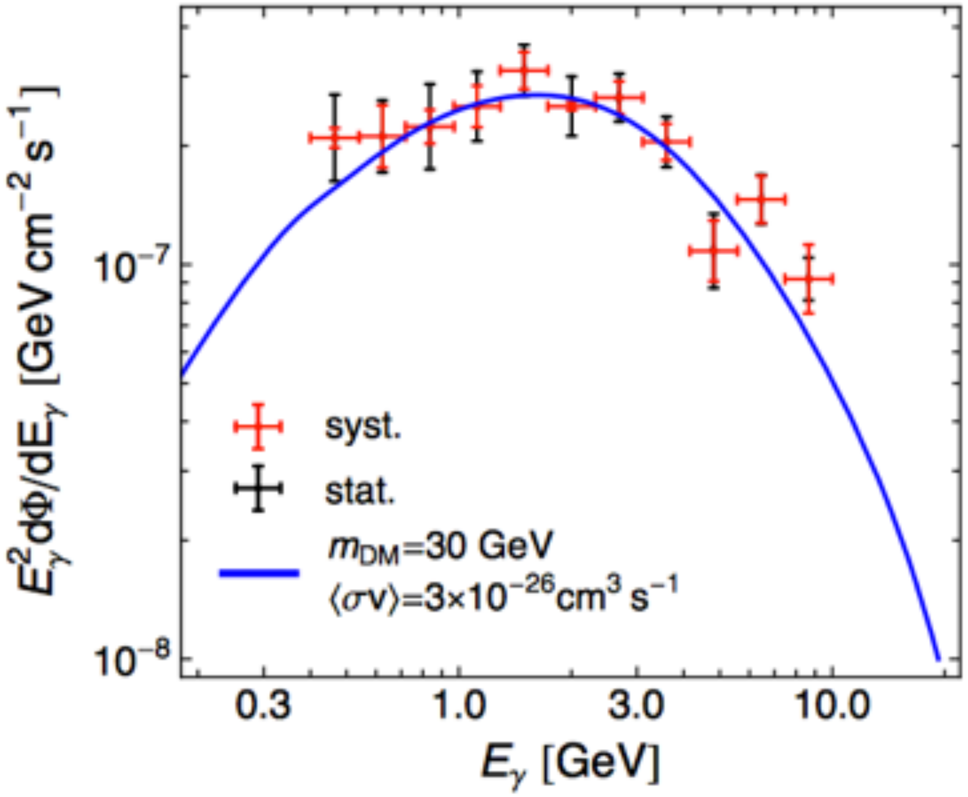
[Fox, Williams '12] [Buchmueller, Dolan, McCabe '13]

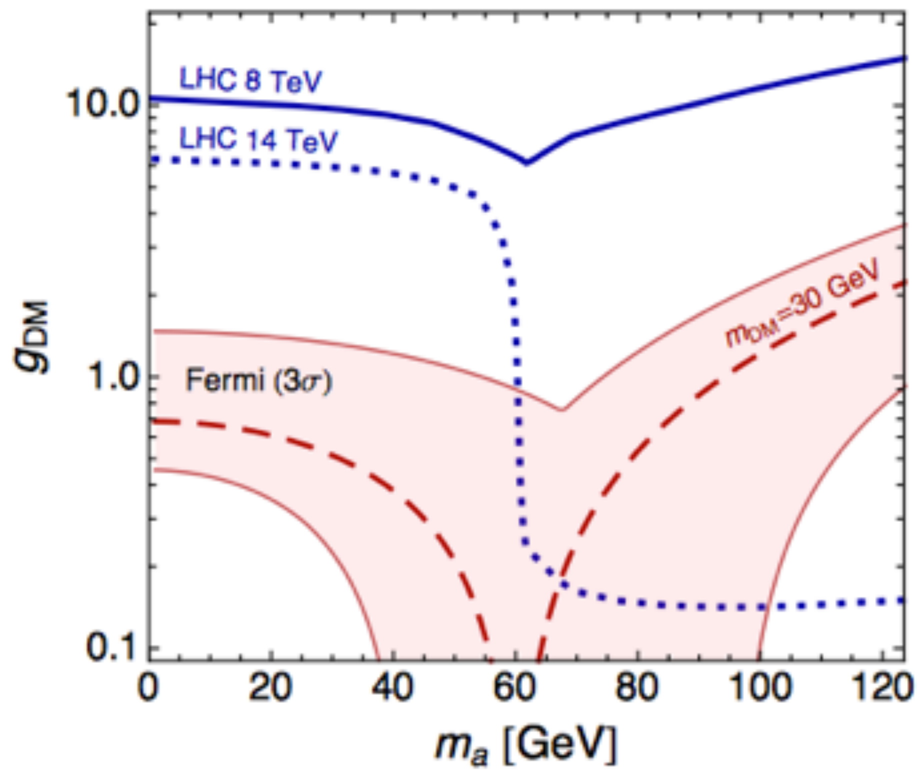
LHC-DM Forum

Dark matter could interact with SM via scalar mediator

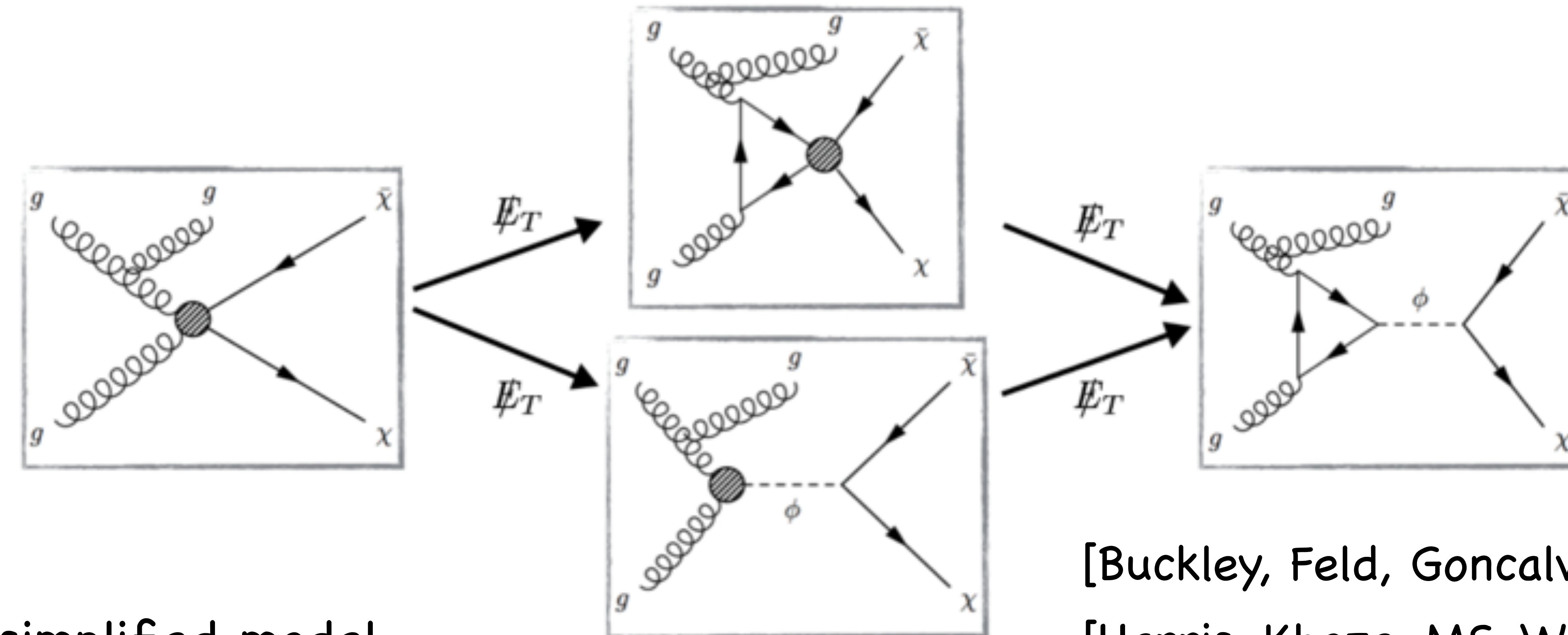
- CP-even scalar, e.g. Higgs portal, or CP-odd scalar
- Dark Matter interacting via CP-odd scalar difficult to find
  - ➡ Direct detection interaction velocity suppressed
  - ➡ Difficult to produce at colliders, e.g. LEP
  - ➡ But might give visible signal in indirect detection "Coy Dark Matter" and can fit GC excess

[Boehm, Dolan, McCabe, MS, Wallace '14]





Searching scalar DM-mediators in mono-jets



simplified model

[Buckley, Feld, Goncalves '14]
[Harris, Khoze, MS, Williams '14]

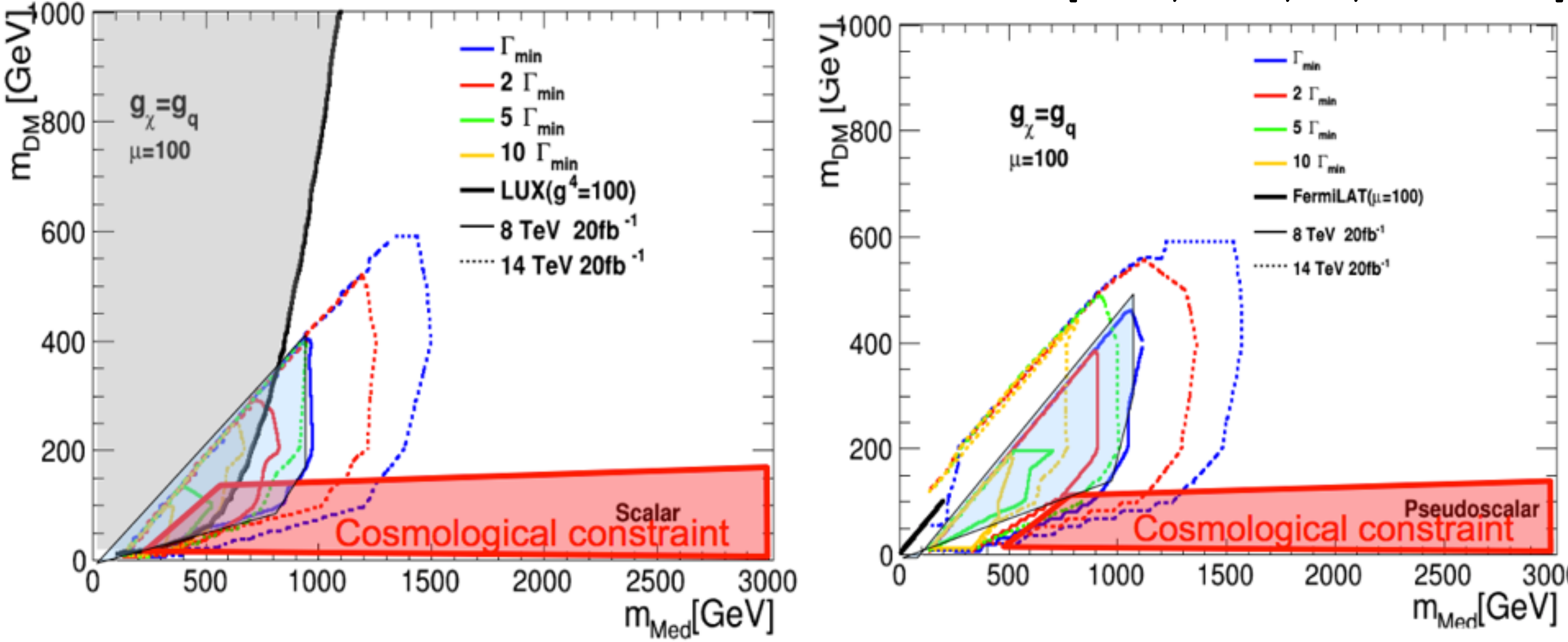
$$\mathcal{L}_{\text{pseudo-scalar}} \supset -\frac{1}{2}m_{\text{MED}}^2 P^2 - g_{\text{DM}} P\,\bar{\chi}\gamma^5\chi - g_{SM}^t P\,\bar{t}\gamma^5 t - g_{SM}^b P\,\bar{b}\gamma^5 b$$

$$\mathcal{L}_{\text{scalar}} \supset -\frac{1}{2}m_{\text{MED}}^2 S^2 - g_{\text{DM}} S\,\bar{\chi}\chi - g_{SM}^t S\,\bar{t}t - g_{SM}^b S\,\bar{b}b$$

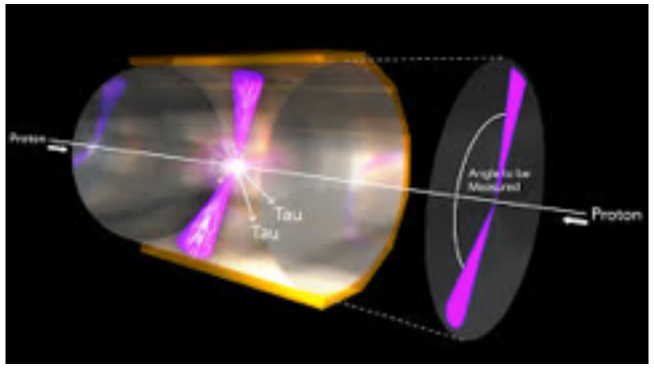
4 relevant parameters for phenomenology

1. mediator mass m_{MED}
2. mediator width Γ_{MED}
3. dark matter mass m_{DM}
4. effective coupling parameter $g_q \cdot g_\chi$

[Harris, Khoze, MS, Williams '14]



- For light Dark Matter and heavy mediators the LHC can provide complementary information to DD and ID experiments
- A joint effort of all possible ways to look for (coy) Dark Matter is needed to maximize our chances to find it



Summary

- Scalar sector most interesting for coming years, i.e. strong crosstalk between different experiments

- Higgs and Dark Matter Phenomenology hot topics for upcoming runs

- IPPP has many staff members involved in this line of research

- For a successful program close collaboration between experimentalists and theorists essential