Top Mass Effects in the Higgs–Gluon Coupling: Boosted vs Off-Shell Production

arXiv: 1405.7651 M. Buschman, C. Englert, DG, T. Plehn, M. Spannowsky
In conclusion: M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn

SHEP Seminar
October 17th 2014 Southampton

Dorival Gonçalves

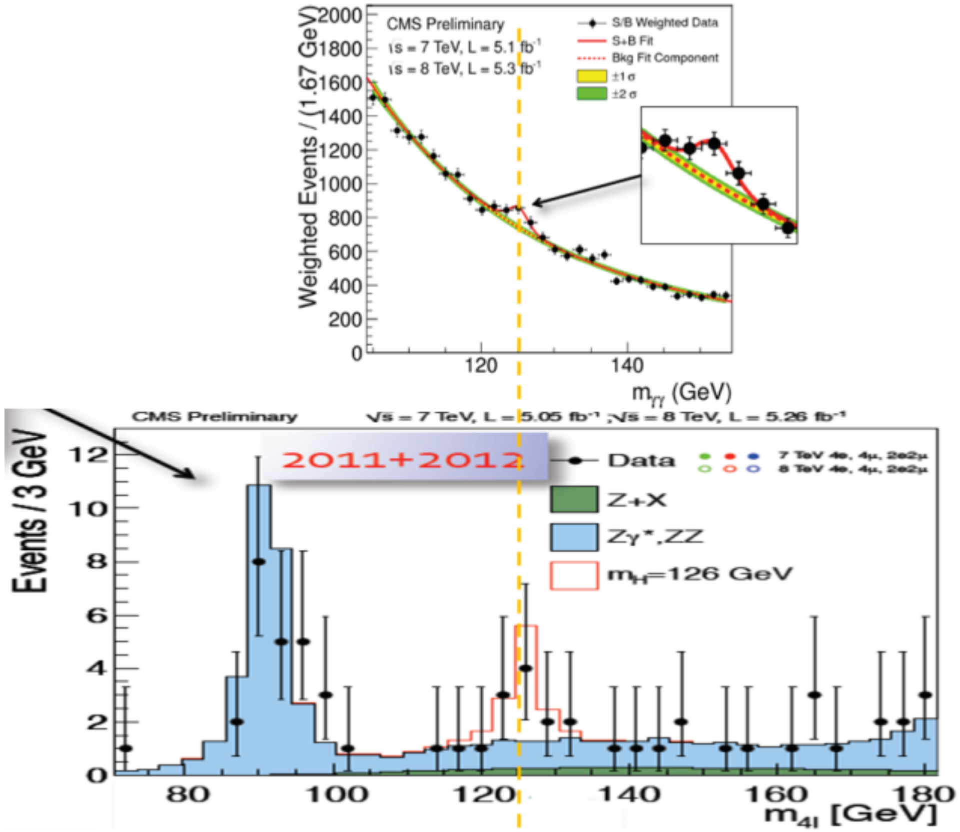
Outline

Hunting the heavy quark mass effects in Higgs production:

- Boosted Higgs
  - Hj and Hjj
  - Higgs + jets MEPS merging @LO & @NLO
  - Reweighting function $W(p_{TH})$ top mass effects
- Off-shell Higgs
  - Hj and Hjj
  - $H \to ZZ$ off-shell mass effects
  - Higgs width measurement

Motivation

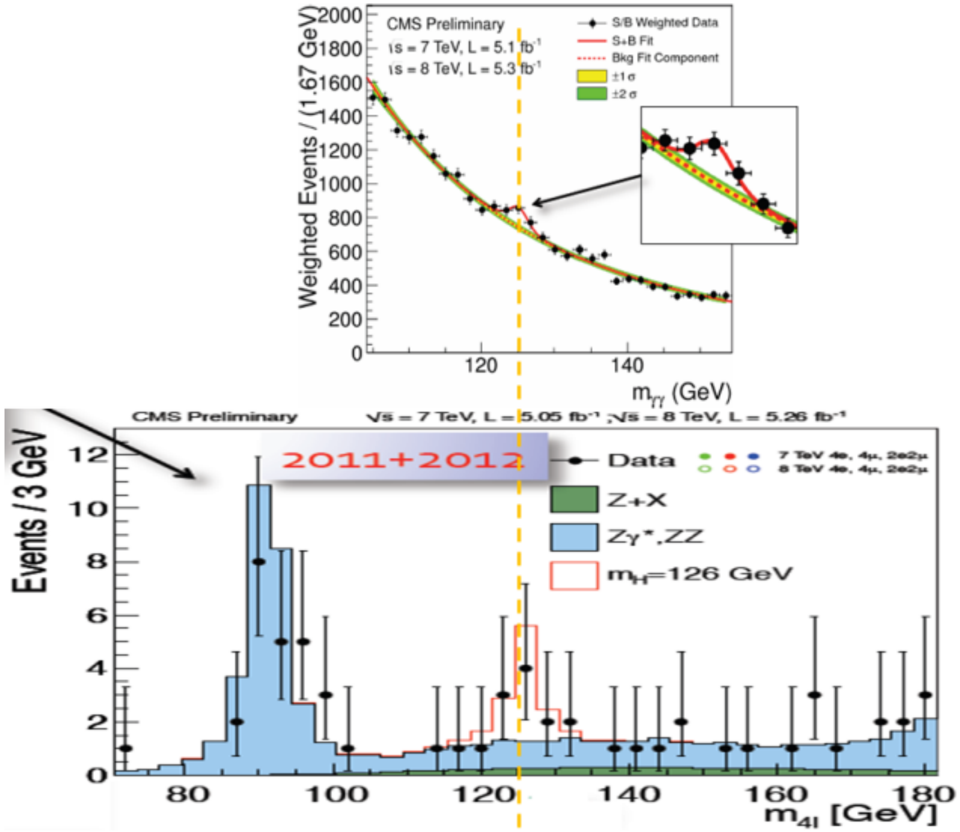
A discovery has been made



The nobel prize has been awarded

Motivation

A discovery has been made



The nobel prize has been awarded

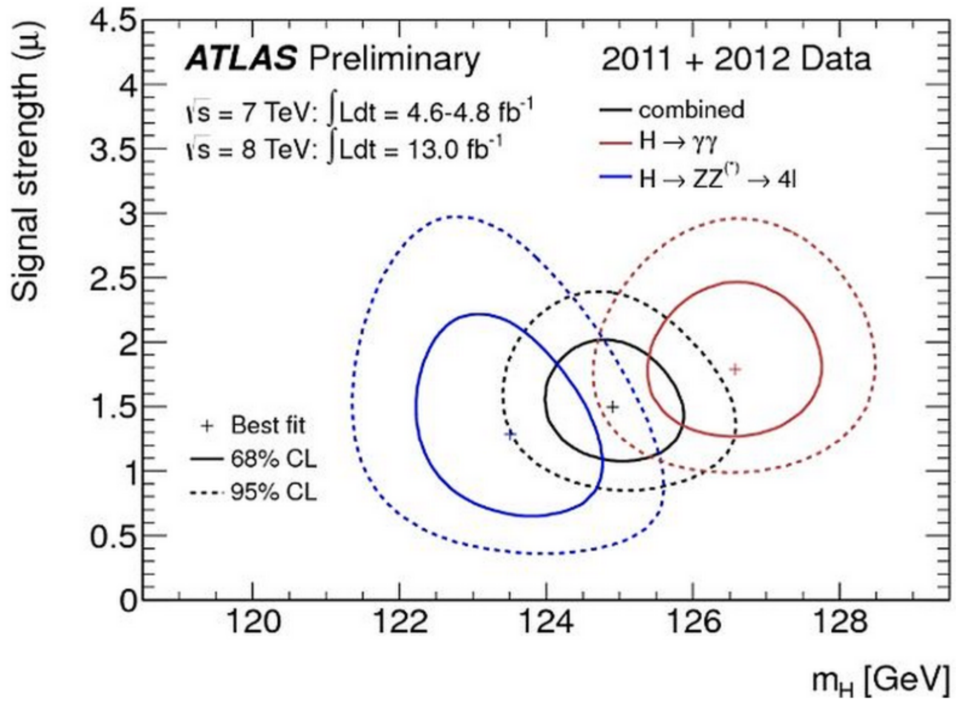
But is it really the SM Higgs boson?

Strategy of Higgs analysis

- How do we know that it is really the SM Higgs boson?

Unique resonance? → **Spin/CP?** → **Lagrangian?** → **Coupling strength?**

- Twin peaks?



Strategy of Higgs analysis

- How do we know that it is really the SM Higgs boson?

Unique resonance?

↓

Spin/CP?

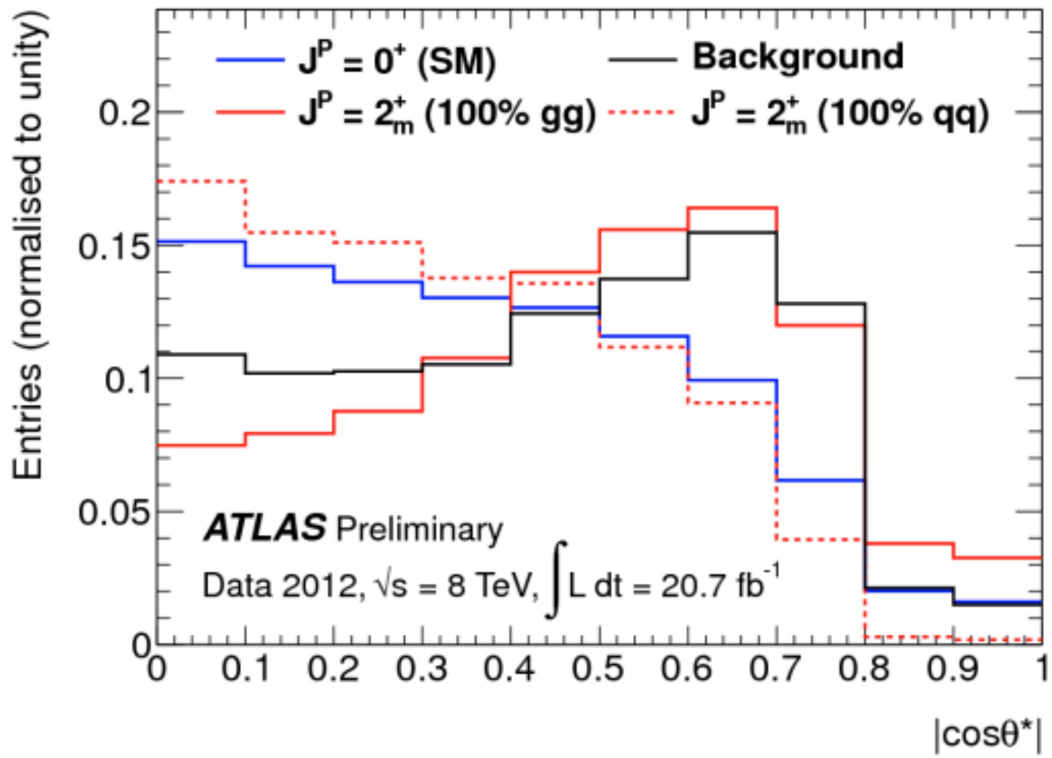
↓

Lagrangian?

↓

Coupling strength?

- $H \to \gamma\gamma$



→ Decay angle $cos\theta^*$ in the Collins-Sopper frame: sensitive to J

Strategy of Higgs analysis

- How do we know that it is really the SM Higgs boson?

Unique resonance?

↓

Spin/CP?

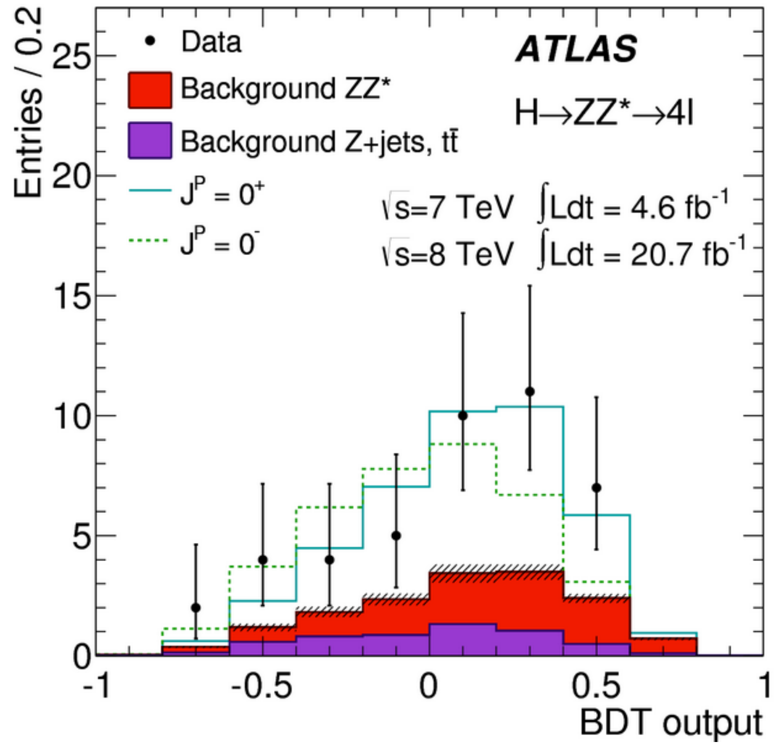
↓

Lagrangian?

↓

Coupling strength?

- $H \rightarrow ZZ$



→ Full final state reconstruction sensitive to J^P:
- 2 masses (M_{Z1}, M_{Z2}) and 5 angles
- Combined with Boosted Decision Tree (BDT) or Matrix Element based discriminant (D_{J^P})

Strategy of Higgs analysis

- How do we know that it is really the SM Higgs boson?

Unique resonance?

↓

Spin/CP?

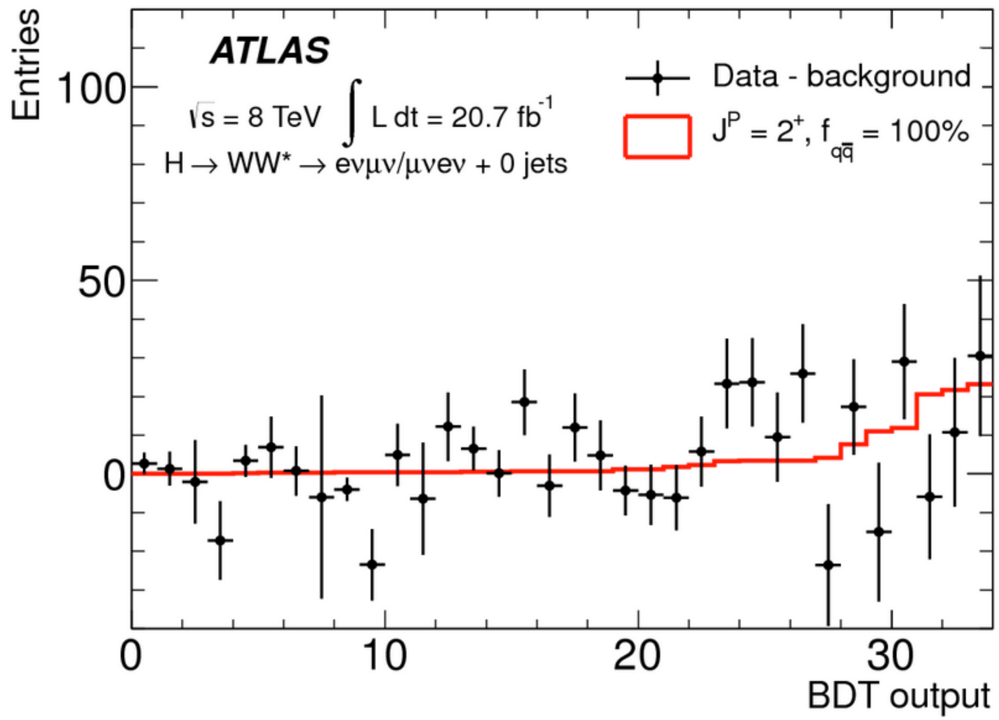
↓

Lagrangian?

↓

Coupling strength?

- $H \to WW$



→ Several variables sensitive to J^P:

- $\Delta\phi_{ll}$, M_{ll}, ...
- Combined with BDT

Strategy of Higgs analysis

- How do we know that it is really the SM Higgs boson?

Unique resonance?

↓

Spin/CP?

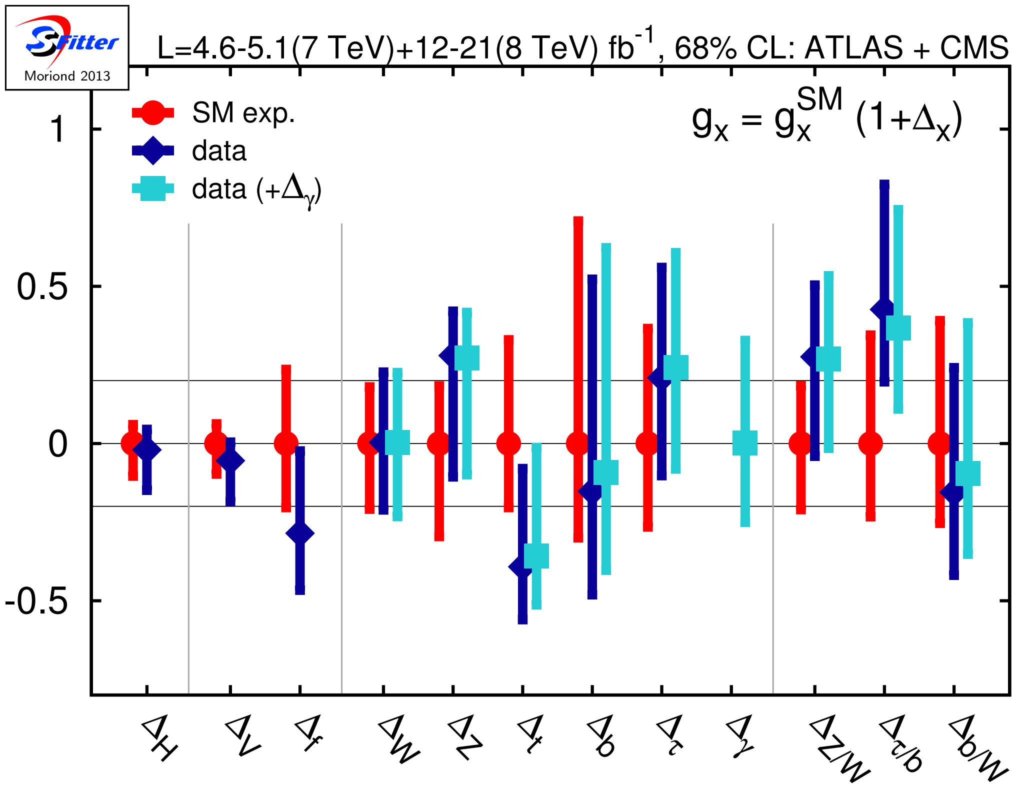
↓

Lagrangian?

↓

Coupling strength?

- All couplings in agreement with the SM



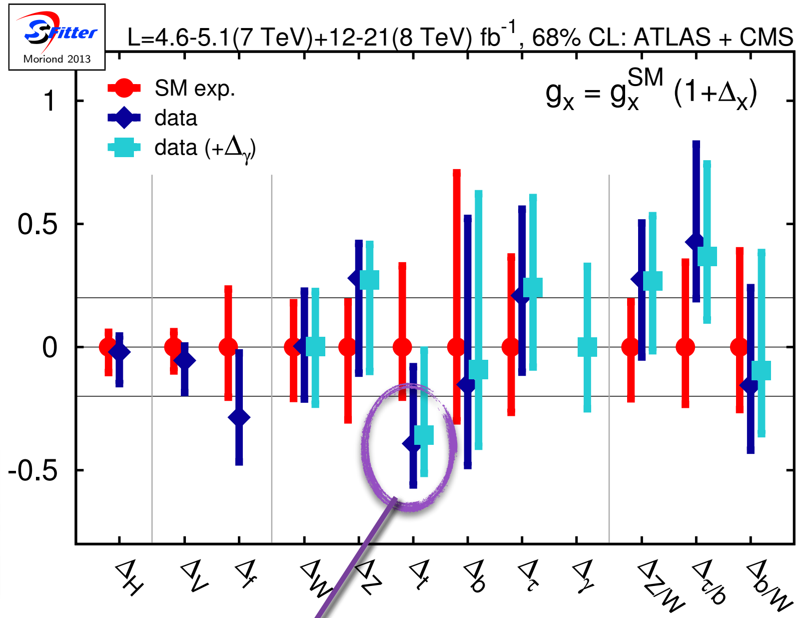
Klute, Lafaye, Plehn, Rauch, Zerwas (2012)

Strategy of Higgs analysis

- Higgs–gauge couplings can be extracted from precise tree–level information
- Higgs-fermions couplings largely relies on loop–induced couplings

→ Limited and model–dependent understanding of the top Yukawa coupling

→ Its measurement from ttH challenging



Important for Higgs production

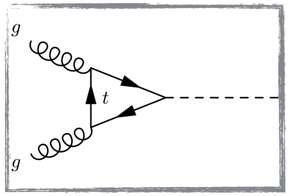
- Can we use kinematical information to direct probe the Yukawa coupling in ggH?

→ Let’s look at the structure of the ggH coupling

Heavy quark mass effects in Higgs production

- Higgs interacts with gluons via a loop-induced coupling

$$\mathcal{L}_{ggH} \supset g_{ggH} \frac{H}{v} G^{\mu\nu} G_{\mu\nu}$$



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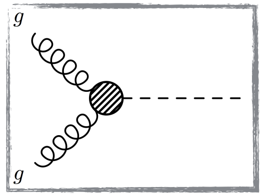


$$\frac{g_{ggH}}{v} = \frac{\alpha_s}{8\pi} \frac{1}{v} \tau \left[1 + (1-\tau) f(\tau)\right] \qquad f(\tau) \overset{\text{on-shell}}{=} \left(\arcsin\sqrt{\frac{1}{\tau}}\right)^2 \overset{\tau\to\infty}{=} \frac{1}{\tau} + \frac{1}{3\tau^2} + \mathcal{O}\left(\frac{1}{\tau^3}\right)$$

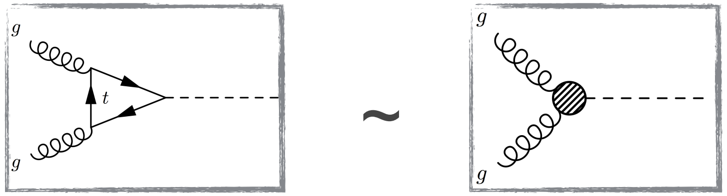
- HEFT is an excellent approximation for Higgs production $\tau = 4m_t^2/m_H^2$
- The exact N...LO calculations available are done in the HEFT framework
- It is a misconception to say that HEFT is equivalent to $m_t \to$ infinity

  Notice that we can get the finite top mass dependence in the HEFT

  → Very simple functional… arcsin!

Heavy quark mass effects in Higgs production

- Higgs interacts with gluons via a loop-induced coupling



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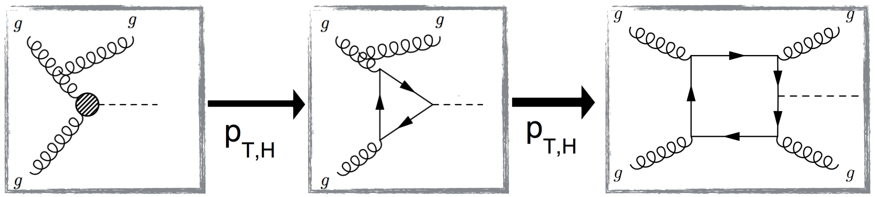
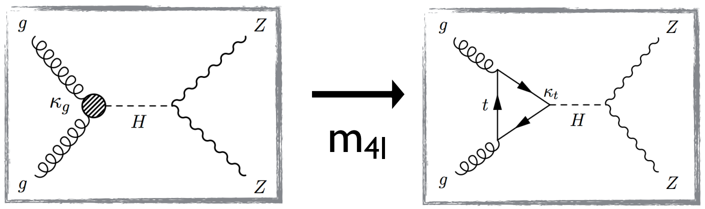
- HEFT is an excellent approximation for Higgs production $\tau = 4m_t^2/m_H^2$
- The exact N...LO calculations available are done in the HEFT framework
- However, it does not work so well if external particles go off-shell.
  I.e., we start to direct probe the loop structure!

- Boosted Higgs:



- Off-shell Higgs:



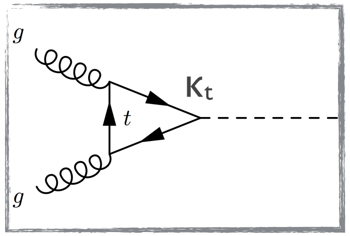
Framework

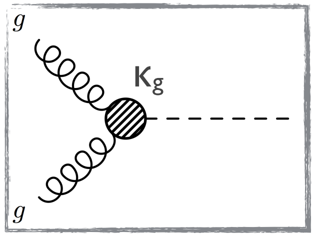
- Dim-6 operators with Yukawa coupling in the top loop no longer decouple
  Instead, coupling strengths with finite value in the limit of large quark masses.
- Is the Y_t responsible for the ggH coupling or are there BSM contributions?

Relevant CP-even BSM operators to GF:

$$\mathcal{O}_g = \frac{\alpha_s}{12\pi v^2}|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_y = \frac{y_t}{v^2}|H|^2 \bar{Q}_L \tilde{H} t_R$$

$$\mathcal{L}_{ggH} \supset -\kappa_t \frac{m_t}{v} \bar{t}th + \kappa_g \frac{\alpha_s}{12\pi} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu\, a}$$





Hj:
Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant (2014)
Banfi, Martin, Sanz (2013)
Azatov, Paul (2014)
Grojean, Salvioni, Schlaffer Weiler (2013)
Hjj:
Buschman, Englert, DG, Plehn,Spannowsky (2014)
H+jets with NLO Merging+...:
Buschman, DG, Krauss, Kuttimalai, Schonherr, Plehn

- Disentangle κ_t and κ_g satisfying Higgs total rate $\sigma \sim |\kappa_t + \kappa_g|^2 \rightarrow \kappa_t + \kappa_g = 1$

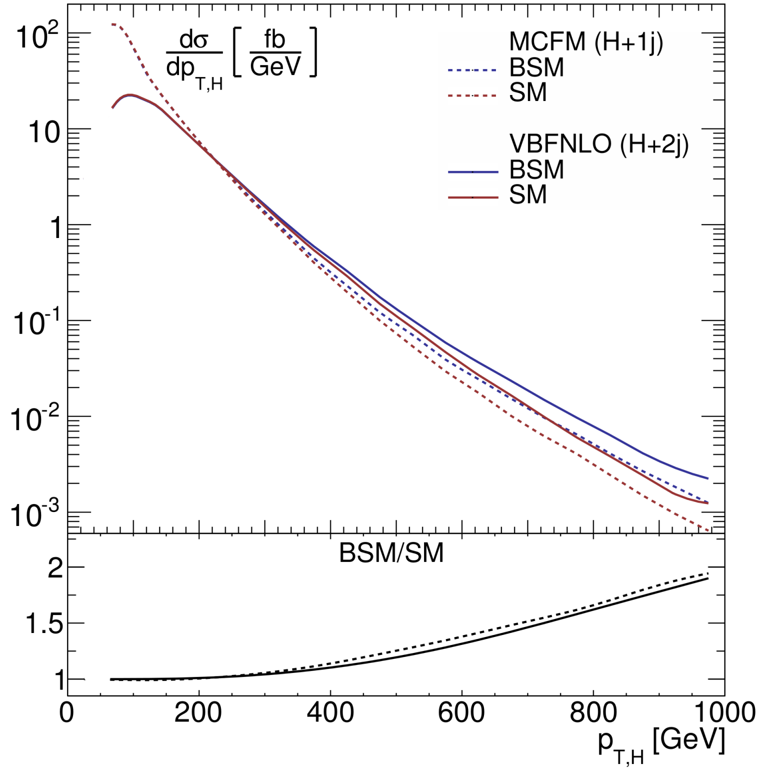
$$\mathcal{M} = \kappa_t \mathcal{M}_t + \kappa_g \mathcal{M}_g$$

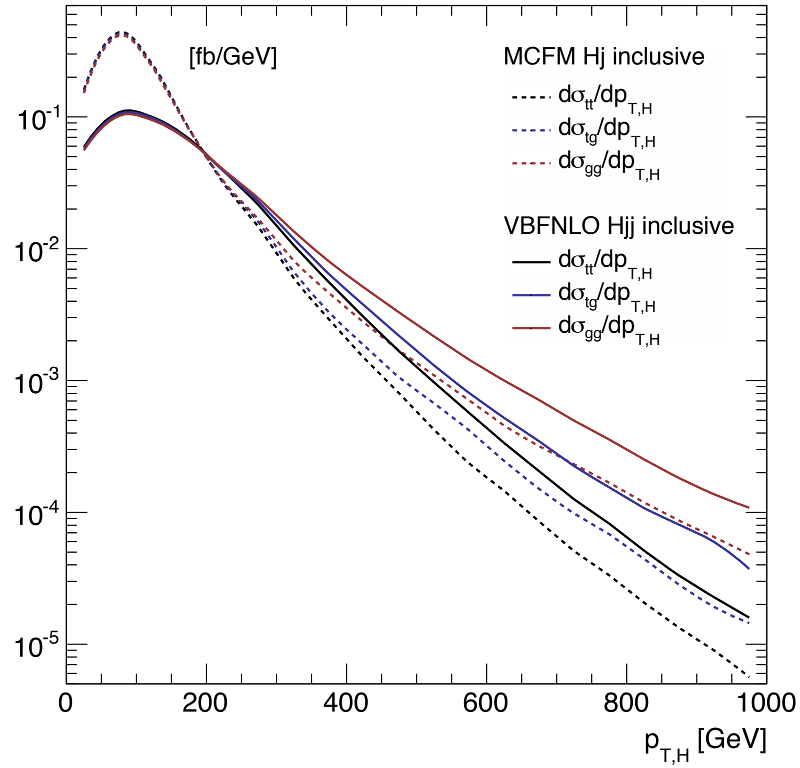
$$(\kappa_t, \kappa_g)_{\text{SM}} = (1,0) \qquad (\kappa_t, \kappa_g)_{\text{HEFT}} = (0,1) \qquad (\kappa_t, \kappa_g)_{\text{BSM}} = (0.8, 0.2)$$

Boosted Higgs

- Log mass effects for Hj and Hjj have the same origin
- For boosted Higgs production: $|\mathcal{M}_{Hj(j)}|^2 \propto m_t^4 \, \log^4 \frac{p_{T,H}^2}{m_t^2}$

$$\mathcal{M} = \kappa_t \mathcal{M}_t + \kappa_g \mathcal{M}_g \quad \longrightarrow \quad \frac{d\sigma}{d\mathcal{O}} = \kappa_t^2 \frac{d\sigma_{tt}}{d\mathcal{O}} + \kappa_t \kappa_g \frac{d\sigma_{tg}}{d\mathcal{O}} + \kappa_g^2 \frac{d\sigma_{gg}}{d\mathcal{O}}$$

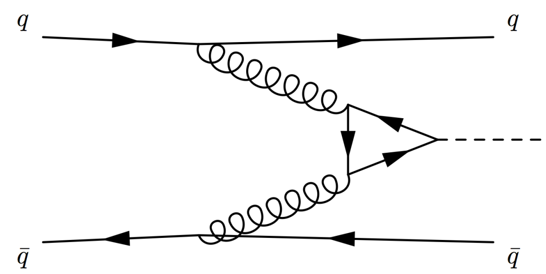




Buschman, Englert, DG, Plehn,Spannowsky (2014)

Boosted Higgs

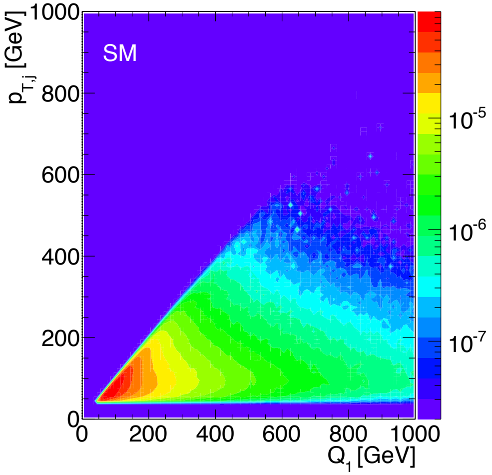
- H+1j: $\sigma_{gg\to Hg} \propto m_t^4 \ln^4\left(\frac{p_T^2}{m_t^2}\right)$
- H+2j: $\sigma_{q\bar{q}\to Hq\bar{q}} \propto \frac{m_t^4}{(Q_1^2-Q_2^2)^2}\left[\ln^2\left(\frac{Q_1^2}{m_t^2}\right) - \ln^2\left(\frac{Q_2^2}{m_t^2}\right)\right]^2 \overset{Q_1 \gg Q_2}{=} \frac{m_t^4}{Q_1^4}\ln^4\left(\frac{Q_1^2}{m_t^2}\right)$

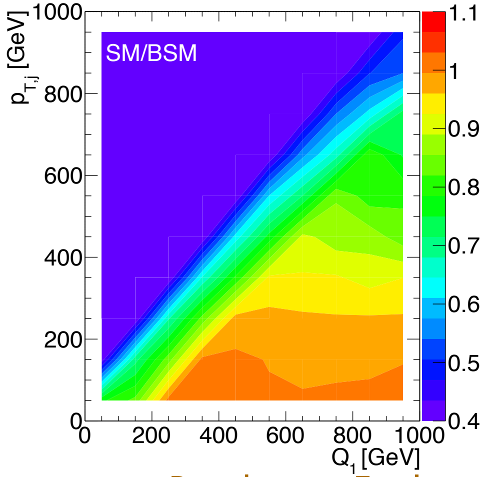


In the limit of one significantly harder tagging jet $Q_1 >> Q_2$

$$\sigma_{q\bar{q}\to Hq\bar{q}} \propto m_t^4 \ln^4\left(\frac{p_{T,j}^2}{m_t^2}\right) \sim m_t^4 \ln^4\left(\frac{p_{T,H}^2}{m_t^2}\right)$$

- Logs at Hj and Hjj have the same origin. I.e., the top mass effects
- From kinematics $p_{Tj} > Q_1$ for the Hjj

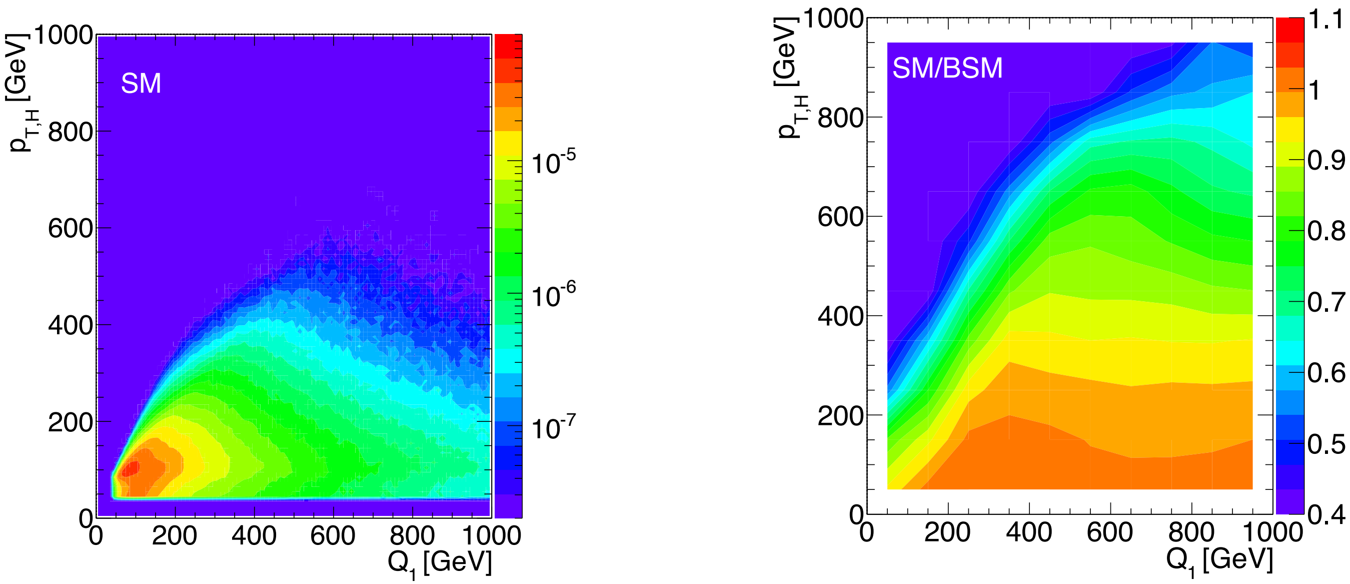




Buschman, Englert, DG, Plehn,Spannowsky (2014)

Boosted Higgs

- For given $p_{T,j}$ values SM/BSM independent of the virtuality.
- While the virtuality is fixed by the steep gluonic parton densities the top mass logarithm feeds on the $p_{z,j}$ jet momentum in the beam direction
- $p_{Tj}>Q_1$ bound is washed out for P_{TH}. Boost from the second jet

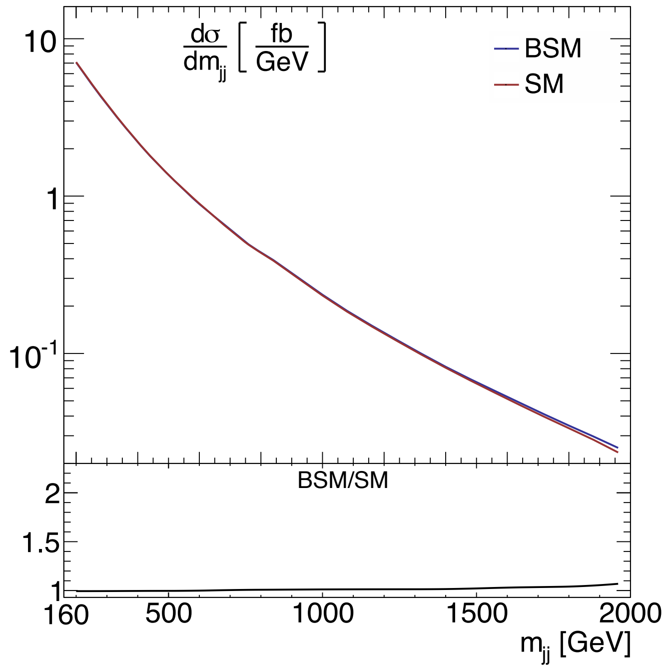


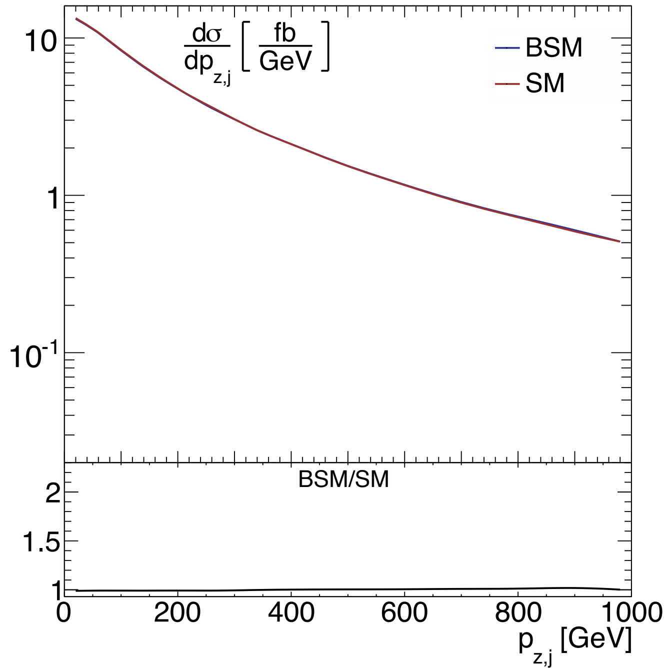
→ Log in the second jet too. Higgs simultaneously captures 1 and 2-jets info

Buschman, Englert, DG, Plehn, Spannowsky (2014)

Hunting the mass effects

- WBF requires large m_{jj} to suppress the GF. If we get also a factor 4-5 wrong there too all the HEFT predictions are wrong!





➡ m_{jj} (ultimately $p_{z,j(H)}$) is a very robust observable for HEFT <-> Full theory

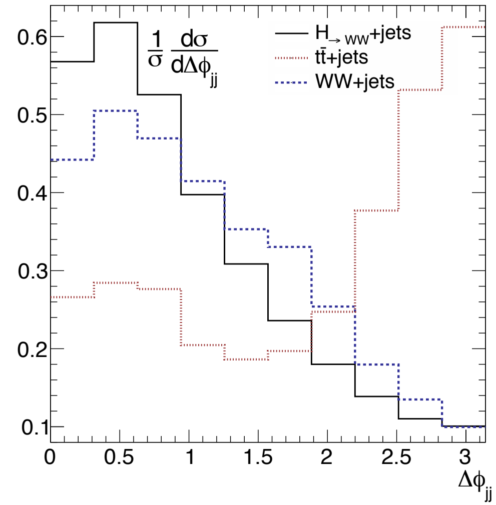
It does not have the same enhancements as p_{TH}. Ufs!

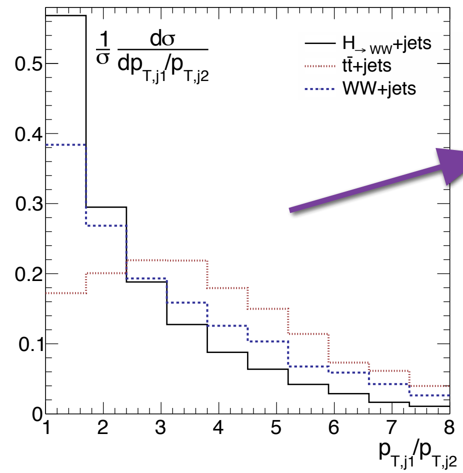
- p_{TH} is the most sensitive distribution… but can we see this BSM @LHC?

Buschman, Englert, DG, Plehn,Spannowsky (2014)

Signal-Background analysis

- We chose the two most promising channels $H \to WW$ & $H \to \tau\tau$





H+2 very hard jets mercedes-like topology

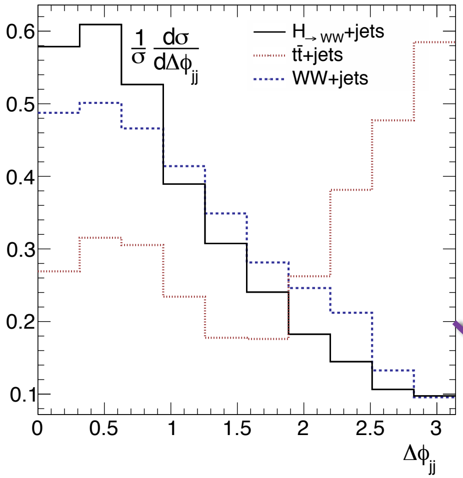
Buschman, Englert, DG, Plehn,Spannowsky (2014)

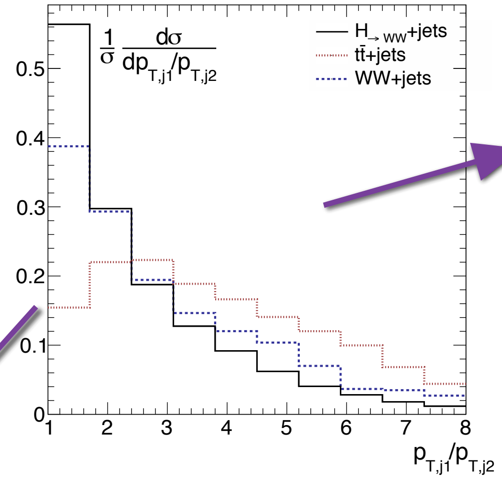
	$Hj \to (WW)j$ inclusive			$Hjj \to (WW)jj$ inclusive		
cuts	H+jets	WW+jets	$t\bar{t}$+jets	H+jets	WW+jets	$t\bar{t}$+jets
$p_{T,j} > 40$ GeV, $\lvert y_j \rvert < 4.5$ $p_{T,\ell} > 20$ GeV, $\lvert y_\ell \rvert < 2.5$	35.5	524	14770	17.3	90.7	7633
$N_b = 0$	33.3	515	4920	15.2	87.4	1690
$m_{\ell\ell} \in [10, 60]$ GeV	28.3	106	1060	13.0	17.2	351
$\not{E}_T > 45$ GeV	21.4	92.9	930	10.6	15.9	309
$\Delta\phi_{\ell\ell} < 0.8$	14.3	49.8	479	8.14	10.3	162
$m_T < 125$ GeV	14.2	26.6	220	8.09	6.14	76.2
$p_{T,H} > 300$ GeV	0.59	2.73	5.18	1.06	1.39	3.28
$\Delta\phi_{jj} < 1.8$				0.87	1.05	1.33
$p_{T,j1}/p_{T,j2} < 2.5$				0.57	0.53	0.53

- mjj cut doesn't enhance signal and not needed
- Similar strategy for the $H \to \tau\tau$
- The second jet described by ME reduces backgrounds by ~ 1/5 when compared to the Hj

Signal-Background analysis

- We chose the two most promising channels H → WW & H → ττ





H+2 very hard jets
mercedes-like topology

Buschman, Englert, DG, Plehn, Spannowsky (2014)

Very similar distributions for both channels mostly (ISR)

- Collinear approximation for taus

$$m_{\tau\tau} = \frac{m_{\rm vis}}{\sqrt{x_1 x_2}} \quad \text{with} \quad x_{1,2} = \frac{p_{{\rm vis}1,2}}{p_{{\rm vis}1,2} + p_{{\rm miss}1,2}}$$

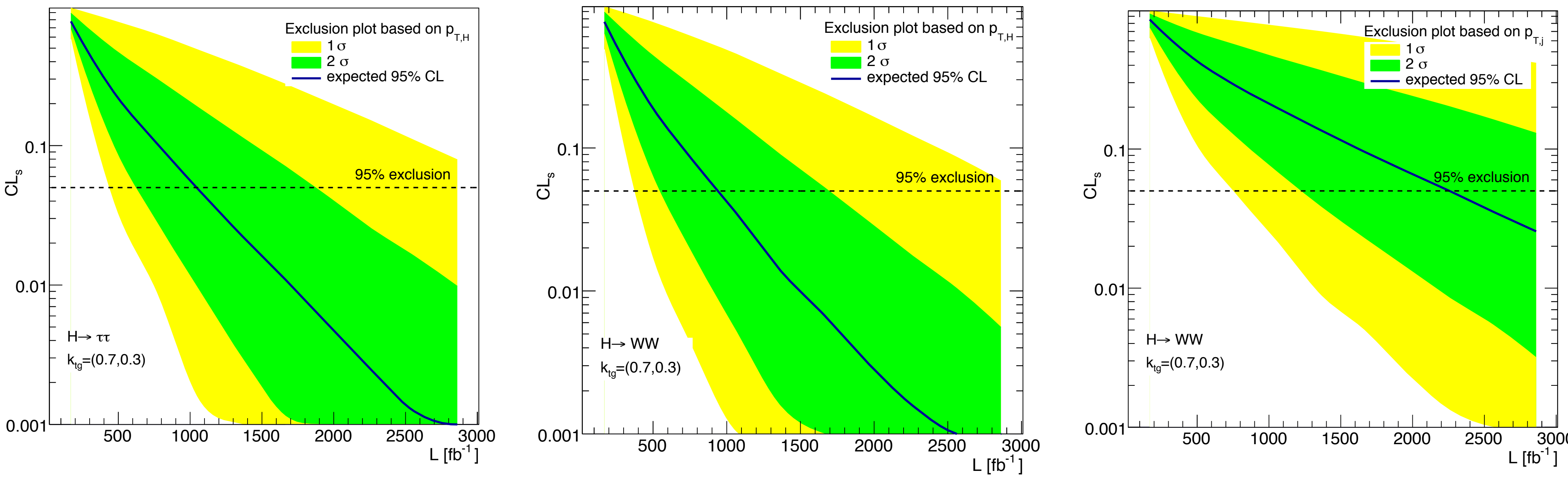
$$|m_{\tau\tau} - m_H| < 20 \text{ GeV} \quad \text{with} \quad x_{1,2} \in [0.1, 1]$$

$$p_{T,H} \sim p_{T,\ell_1} + p_{T,\ell_2} + \not{p}_T > 300 \text{ GeV}$$

	$Hj \to (\tau\tau)j$ inclusive				$Hjj \to (\tau\tau)jj$ inclusive			
cuts	H+jets	Z/γ^*+jets	WW+jets	$t\bar{t}$+jets	H+jets	Z/γ^*+jets	WW+jets	$t\bar{t}$+jets
$p_{T,j} > 40$ GeV, $\|y_j\| < 4.5$ $p_{T,\ell} > 20$ GeV, $\|y_\ell\| < 2.5$	9.82	162303	524	14770	5.10	27670	90.7	7633
$N_b = 0$	9.21	148221	515	4920	4.50	23218	87.4	1690
$m_{\ell\ell} \in [10, 60]$ GeV $m_{\ell\ell'} \in [10, 100]$ GeV	6.59	10466	179	1616	3.41	1832	28.3	541
$\not{E}_T > 45$ GeV	6.24	38.1	166	1616	3.31	0.65	27.0	541
$\|m_{\tau\tau} - m_H\| < 20$ GeV	5.88	2.84	6.28	45.9	3.10	0.11	1.18	16.0
$p_{T,H} > 300$ GeV	0.23	0.013	0.40	0.87	0.41	0.004	0.20	0.56
$\Delta\phi_{jj} < 1.8$					0.33	0	0.15	0.22
$p_{T,j1}/p_{T,j2} < 2.5$					0.22	0	0.076	0.086

→ S/B better than in the WW case. But lower cross-section.

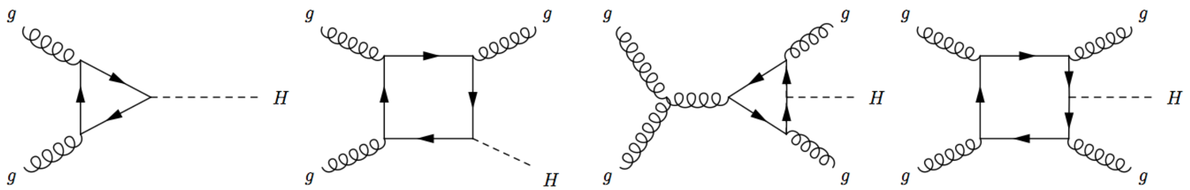
Log-likelihood analysis

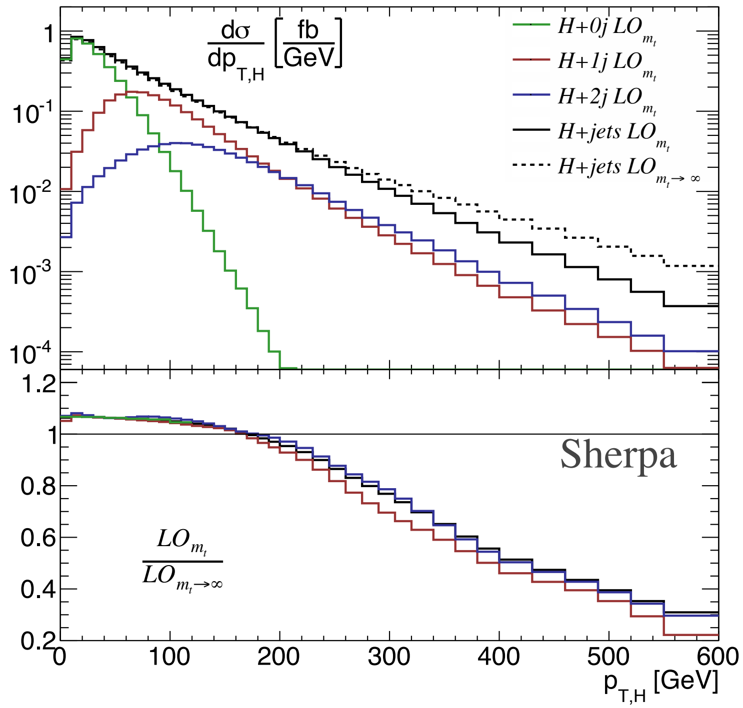


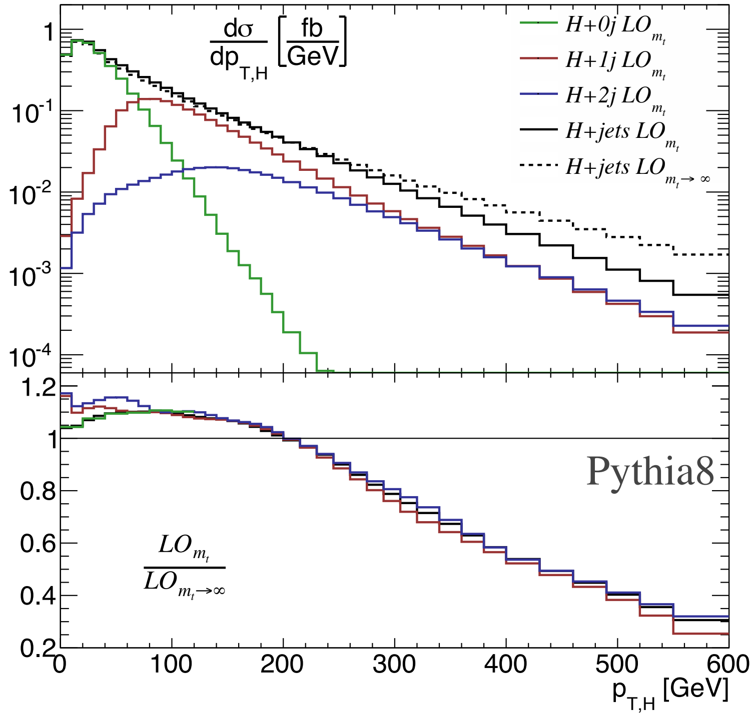
- H → WW is the most promising channel
- The Higgs transverse momentum is indeed more sensitive than the jet
- Both signatures H → WW & H → ττ appear feasible
- Better sensitivity should appear for Hj and Hjj together → Let's "merge" them

Buschman, Englert, DG, Plehn, Spannowsky (2014)

Top mass effects: H+jets CKKW merging



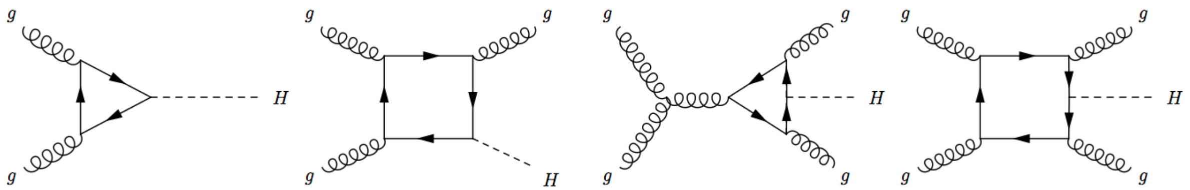


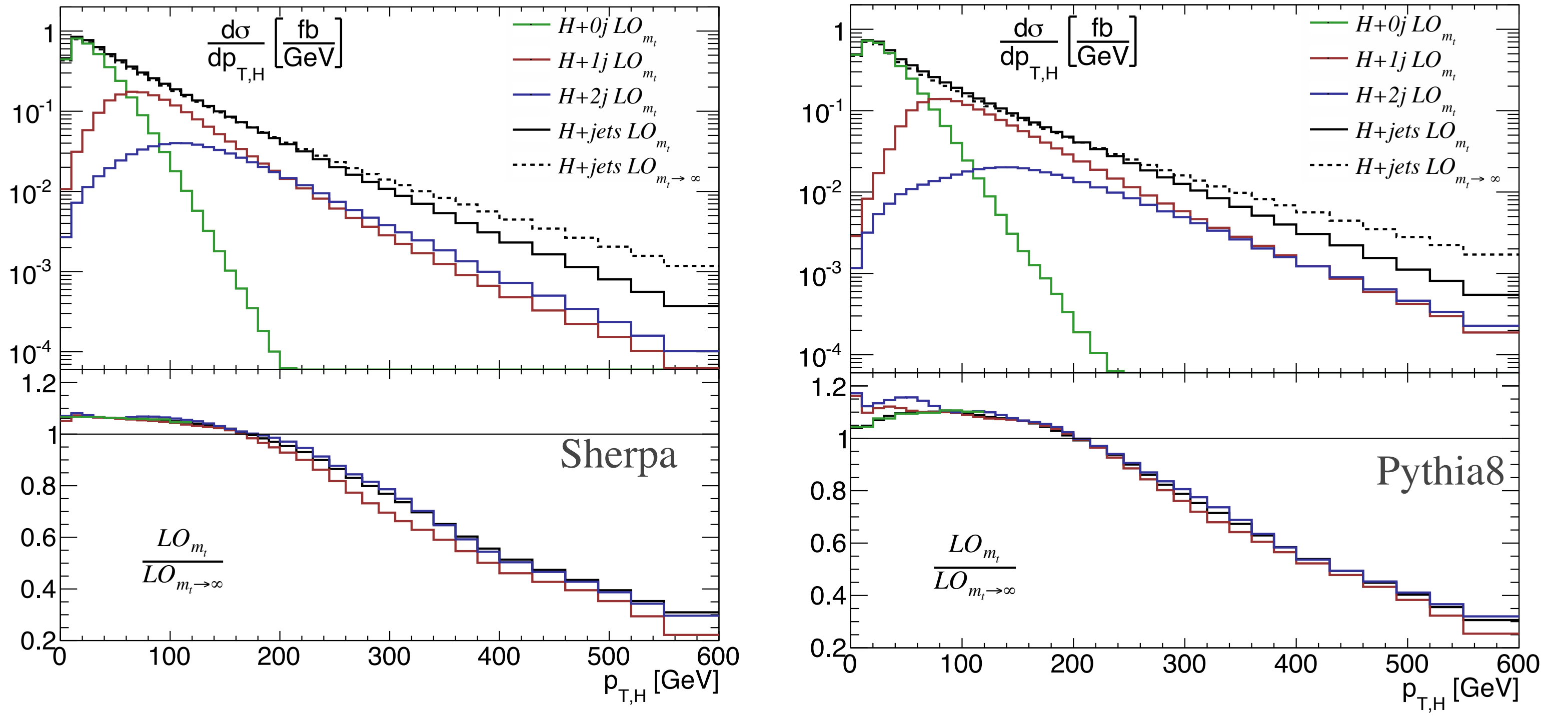


In preparation: M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn

- Hj and Hjj signal have about the same size for boosted Higgs
- HEFT and Full scale on the same way for $p_{T,H} < m_t$
- $p_{T,H} < m_t \rightarrow$ constant scaling factor 1.065 for the Higgs–gluon coupling

Top mass effects: H+jets CKKW merging





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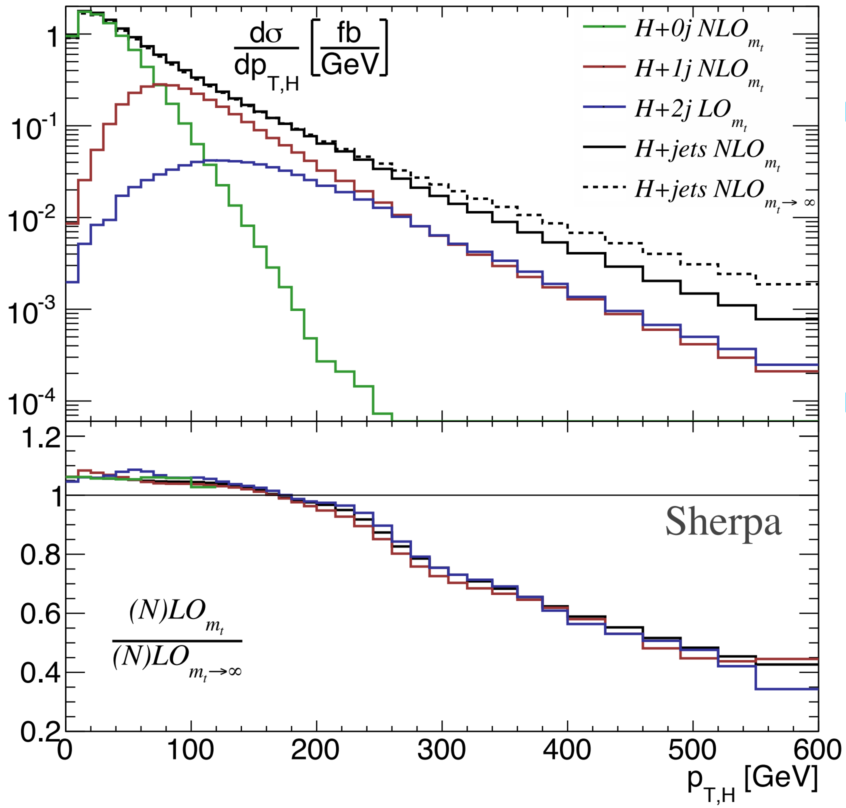
- Top mass effects fundamental for boosted H: correction of O(4) at p_{TH}~600 GeV
- Each jet multiplicity has approximately same top mass correction
- Consequently the same happens for the merged result

Top mass effects: H+jets MEPS@NLO merging

- Reweighting HEFT amplitudes with Openlops ME: $r_t^{(n)} = \frac{|\mathcal{M}^{(n)}(m_t)|^2}{|\mathcal{M}^{(n)}(m_t \to \infty)|^2}$

$$d\sigma^{\text{S-MC@NLO}} = d\Phi_n\, r_t^{(n)} \left[\mathcal{B} + \mathcal{V} + \int d\Phi_1\, \mathcal{D}\right] \left(\Delta(t_0) + \int d\Phi_1 \frac{\mathcal{D}}{\mathcal{B}} \Delta(t)\right) + d\Phi_{n+1} \left[r_t^{(n+1)}\mathcal{R} - r_t^{(n)}\mathcal{D}\right]$$



→ MEPS@NLO need to take into account the heavy quark mass effects at the boosted regime

→ Similarly to LO merging the top mass effects factorise at NLO merging for each jet bin

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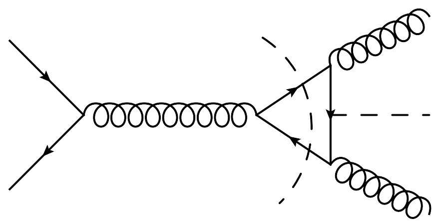
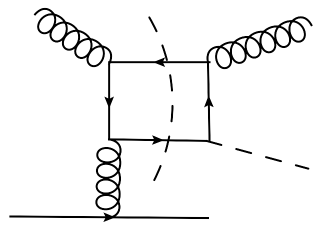
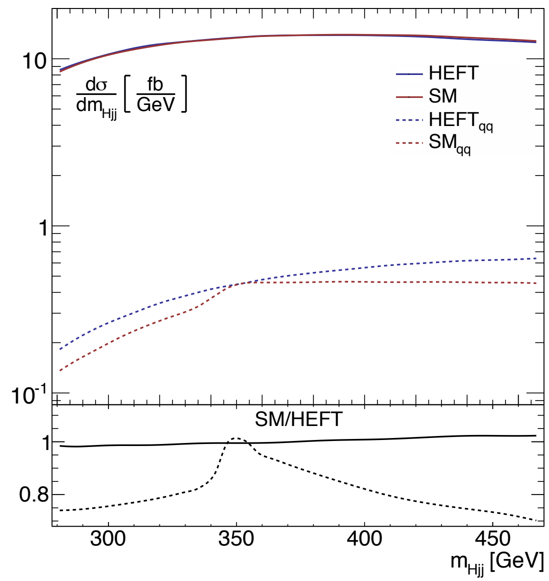
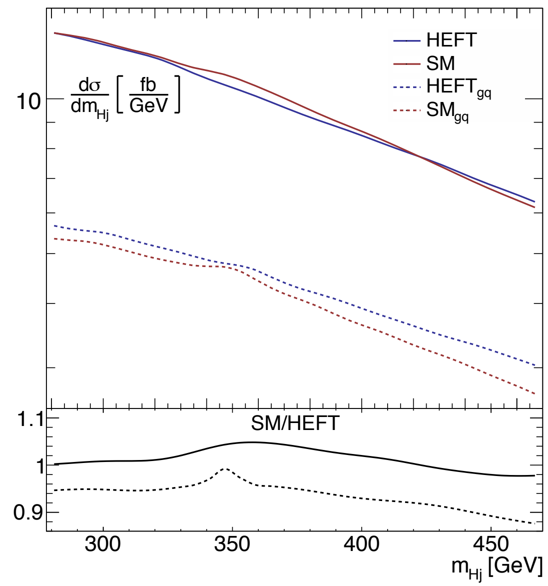
Absorptive terms

- We can see these loop effects via reconstructed masses







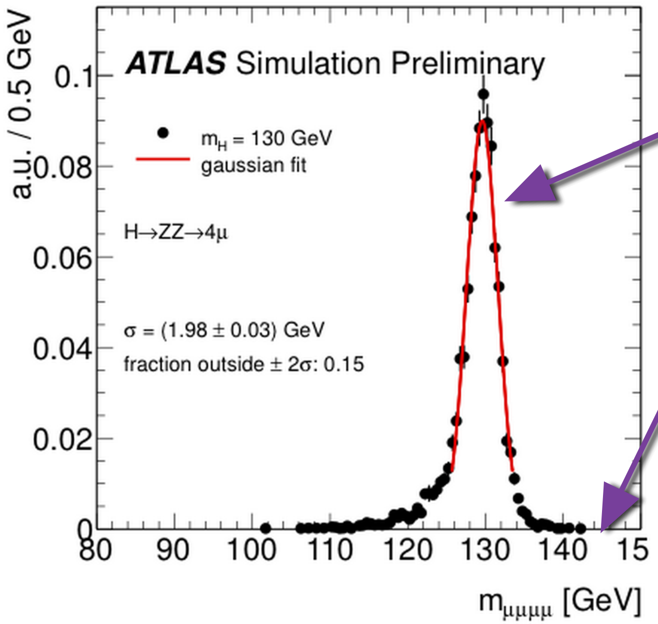


- Very small absorptive terms. This will hardly allow us to make a qualitative statement about the origin of the effective Higgs–gluon coupling, not even talking about a measurement of κ_t and κ_g.

Buschman, Englert, DG, Plehn,Spannowsky (2014)

Off-Shell Higgs Production

- How to probe the off-shell Higgs effects given that it is a very narrow resonance?



$$\frac{d\sigma}{dm_{4l}} \sim \frac{(g_i g_f)^2}{\Gamma_H}$$

$$\frac{d\sigma}{dm_{4l}} \sim \frac{(g_i g_f)^2}{(m_{4l}^2 - m_H^2)^2}$$

- Almost all signal only events are in the on-shell region

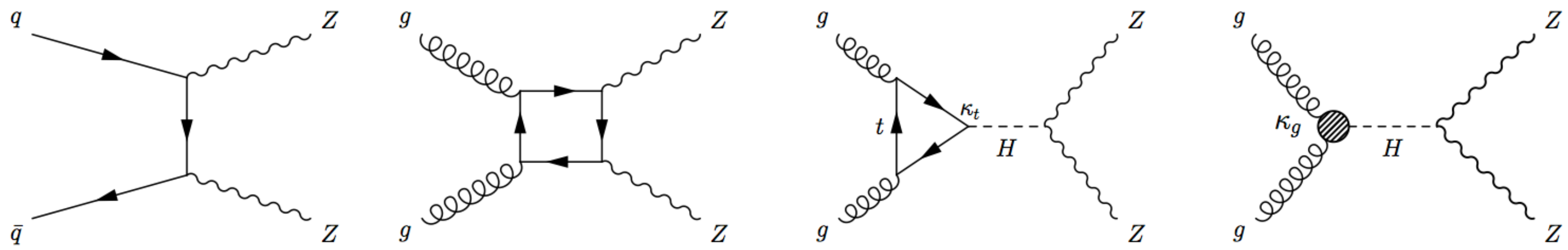
→ Solution: interfere with a background that has a very large rate for $m_{4l} >> m_H$

→ That is the case for $gg \to H^* \to ZZ$ with $gg \to ZZ$

Off-Shell Higgs Production

- Carries information on the Higgs couplings at different energy scales

CMS collaboration, PRL B 736, 64 (2014)



➡ Probe energy dependence from the higher dimensional operators

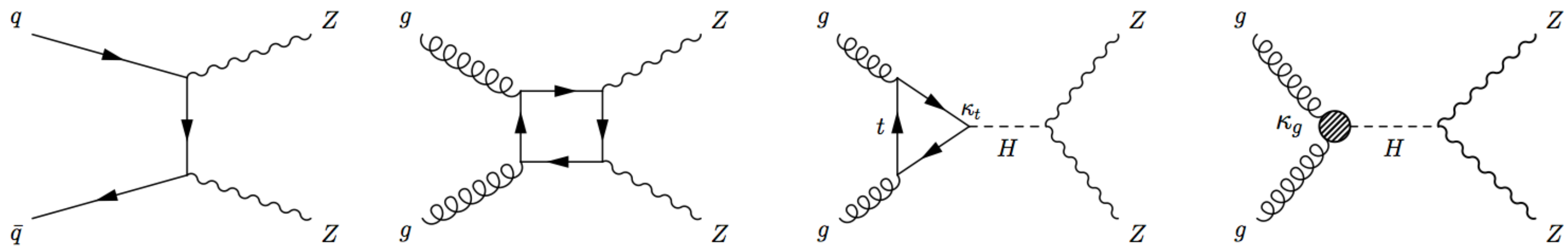
- $$\mathcal{M}_t^{++00} = -2\,\frac{m_{4\ell}^2 - 2m_Z^2}{m_Z^2}\,\frac{m_t^2}{m_{4\ell}^2 - m_H^2 + i\Gamma_H m_H}\left[1 + \left(1 - \frac{4m_t^2}{m_{4\ell}^2}\right) f\left(\frac{4m_t^2}{m_{4\ell}^2}\right)\right]$$
- $$\mathcal{M}_g^{++00} \approx -\frac{m_{4\ell}^2}{2m_Z^2} \qquad \text{with } m_t \gg m_{4\ell} \gg m_H, m_Z$$
- $$\mathcal{M}_t^{++00} \approx +\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{4\ell}^2}{m_t^2} \qquad \text{with } m_{4\ell} \gg m_t \gtrsim m_H, m_Z$$
- $$\mathcal{M}_c^{++00} \approx -\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{4\ell}^2}{m_t^2} \qquad \text{with } m_{4\ell} \gg m_t \gtrsim m_Z\,.$$

➡ Full top mass: destructive interference

➡ Low-energy limit: constructive interference

Off-Shell Higgs Production

- Carries information on the Higgs couplings at different energy scales



- qq→ ZZ generated already at tree level. We generate it @NLO
- gg→ ZZ only know @LO.
- Signal and signal-background interference have very similar NLO & NNLO enhancement

Bonvini, Caola, Forte, Melnikov, Ridolfi (2013)

→ Include QCD effects by equal K-factor for signal, signal-background interference & background

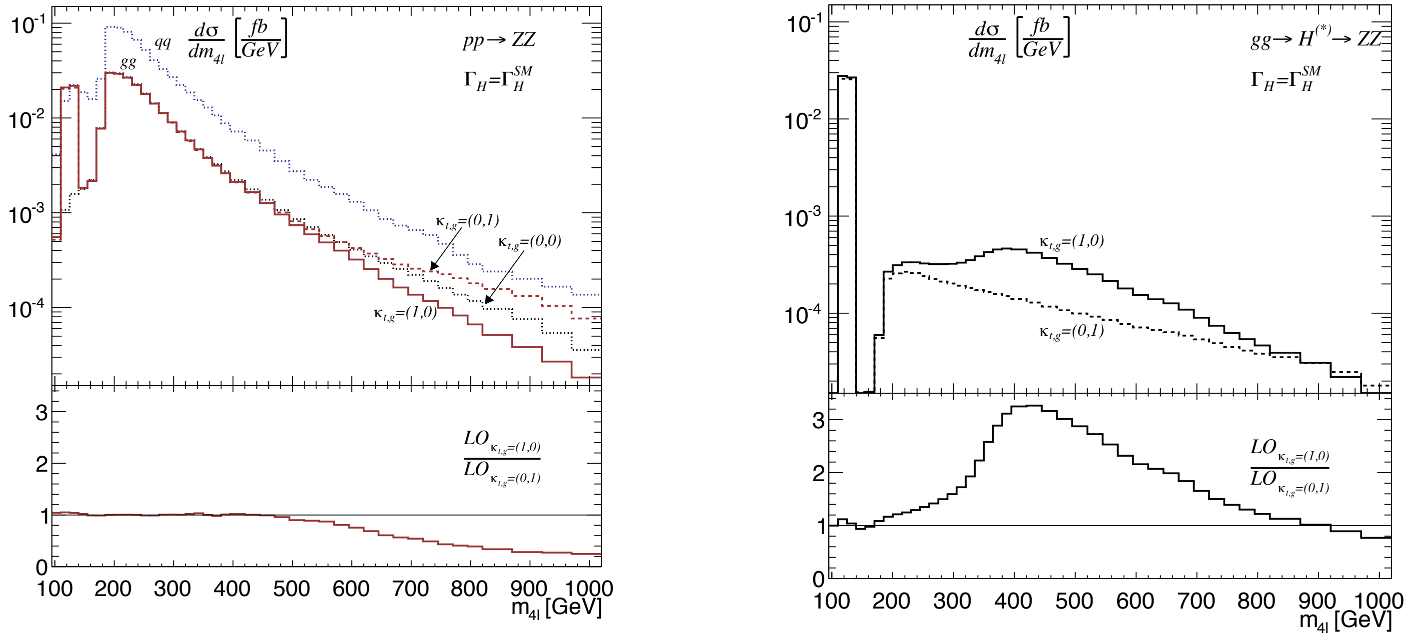
→ We include these effects through a differential NLO reweighing obtained from HEFT signal

Off-Shell Higgs Production

- Large off-shell tail m_{4l}>300GeV: O(15%) of the total rate

$$\mathcal{M}_{ZZ} = \kappa_t \mathcal{M}_t + \kappa_g \mathcal{M}_g + \mathcal{M}_c$$

$$\frac{d\sigma}{dm_{4\ell}} = \frac{d\sigma_c}{dm_{4\ell}} + \kappa_t \frac{d\sigma_{tc}}{dm_{4\ell}} + \kappa_g \frac{d\sigma_{gc}}{dm_{4\ell}} + \kappa_t^2 \frac{d\sigma_{tt}}{dm_{4\ell}} + \kappa_t \kappa_g \frac{d\sigma_{tg}}{dm_{4\ell}} + \kappa_g^2 \frac{d\sigma_{gg}}{dm_{4\ell}}$$

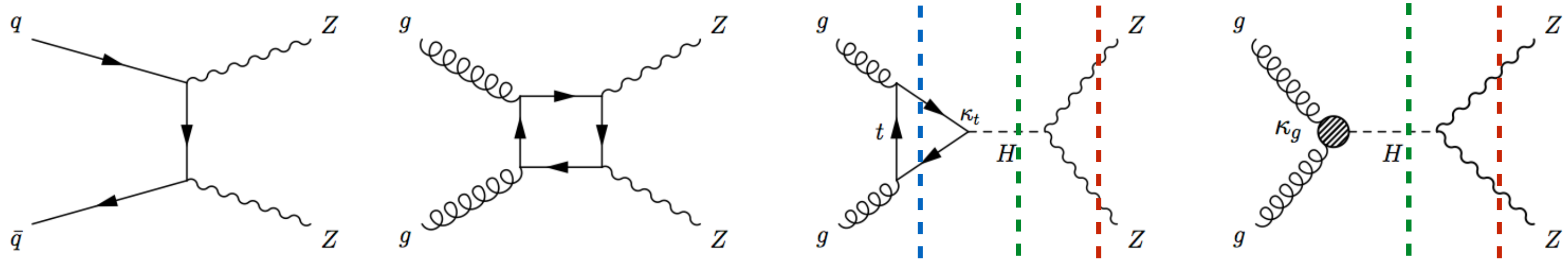


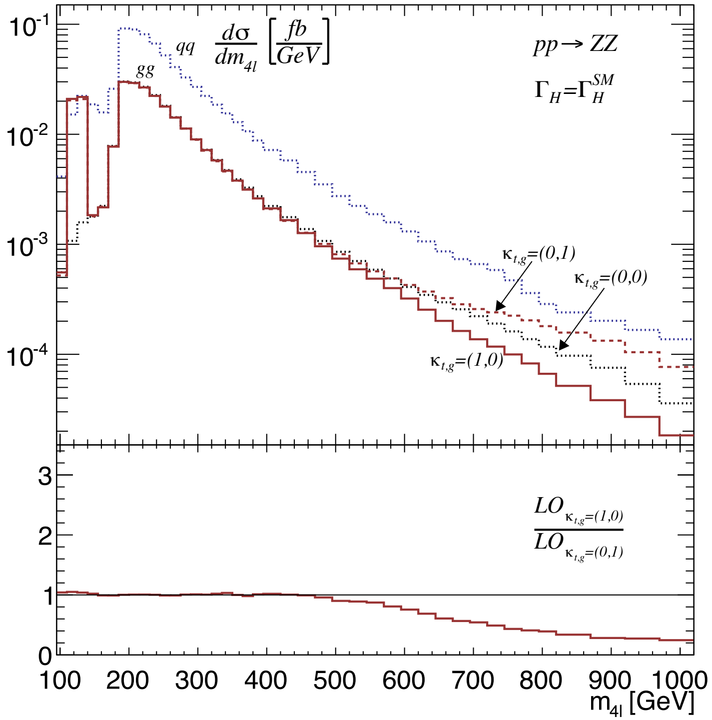
- qq→ ZZ generated already at tree level
- qq→ ZZ one order of magnitude larger than gg → ZZ
- Enhancement on the tail for low-energy limit and suppression of the full top mass result

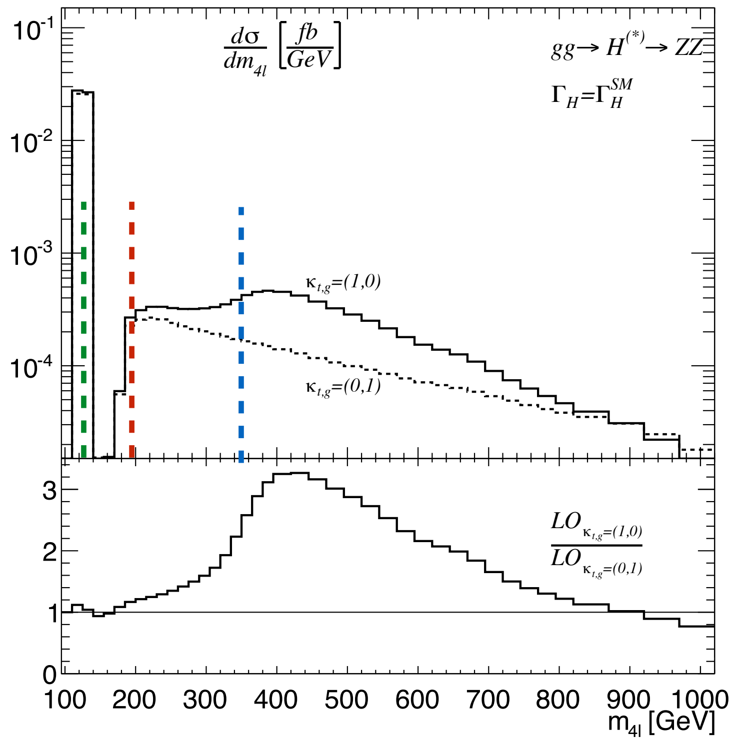
In preparation: M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn

Off-Shell Higgs Production

- Large off-shell tail m_{4l}>300GeV: O(15%) of the total rate



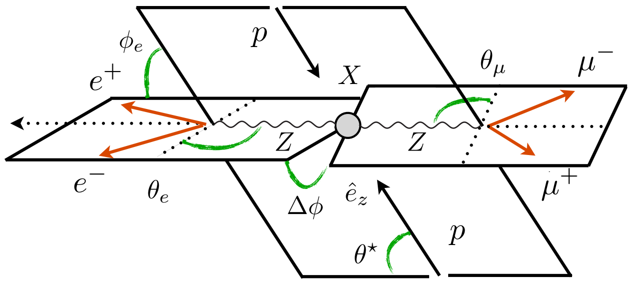




In preparation: M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn

Nelson angles

- Signal only: info on HZZ operator

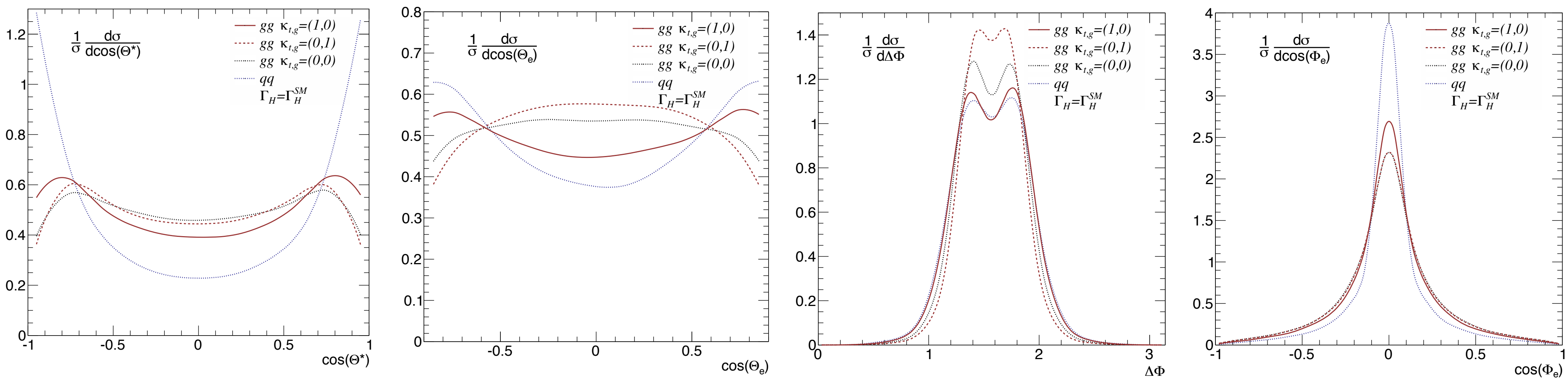


Cabibbo and Maksymowicz (1965)
Dell'Aquila and Nelson (1986)

Gao, Gritsan, Guo, Melnikov, Schulze, Tran (2010)
Englert, DG, Mawatari, Plehn (2012)
Englert, DG, Nail, Spannowsky (2013)

- Signal-background interference gets spin correlation:

→ info on the Higgs production and decay operators



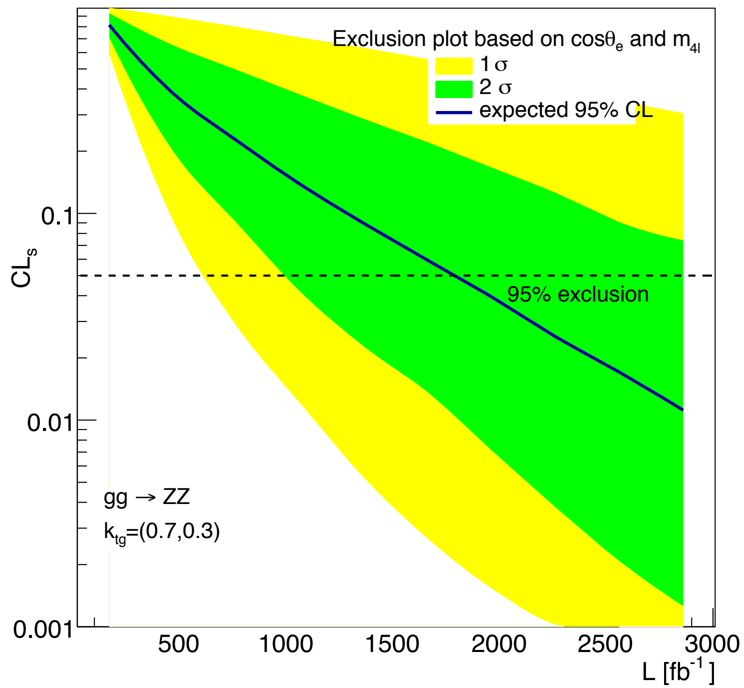
In preparation: M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn

Log-likelihood analysis

- Following the CMS cut flow analysis for the off-shell H→ZZ measurement

1) suppress the qq→ZZ background by requiring that $|\cos\Theta^*| < 0.7$

2) 2-D CLs analysis - $(\cos\theta_e, m_{4l})$.



→ Exclusion of our BSM hypothesis need a few inverse attobarns

→ Boosted Higgs more promising

In preparation: M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn

Higgs width measurement

- SM prediction $\Gamma_H \sim 4$MeV

→ Best limit from direct measurement $H \to ZZ$ $\Gamma_H < 3.4$ GeV

- New idea: combine on-shell & off-shell rates to break the ξ-degeneracy

$$\sigma^{\text{On-Shell}}_{i\to H\to f} \propto \frac{g_i^2(m_H) g_f^2(m_H)}{\Gamma_H}\,, \qquad g_{i,f}(m_H) = \xi g^{SM}_{i,f}(m_H)\,, \qquad \Gamma_H = \xi^4 \Gamma_H$$

→ Sub-leading dependence on Γ_H in the off-shell regime

$$\sigma^{\text{Off-Shell}}_{i\to H^*\to f} \propto g_i^2(\sqrt{\hat{s}}) g_f^2(\sqrt{\hat{s}})$$

Caola, Melnikov (2013)
Kauer, Passarino (2012)
Campbell, Ellis, Williams (2014)

- While interesting idea, clearly not a model independent width measurement

Englert, Spannowsky (2014)

Higgs width measurement

- Model dependency ultimately reflect the non-trivial ggH momentum running

  Our framework is a prime example of it:

$$\sigma^{\text{On-Shell}}_{gg\to H\to ZZ} \propto (\kappa_t + \kappa_g)^2 \frac{g^2_{ggH}(m_H) g^2_{HZZ}(m_H)}{\Gamma_H}$$ → k_t & k_g factorize

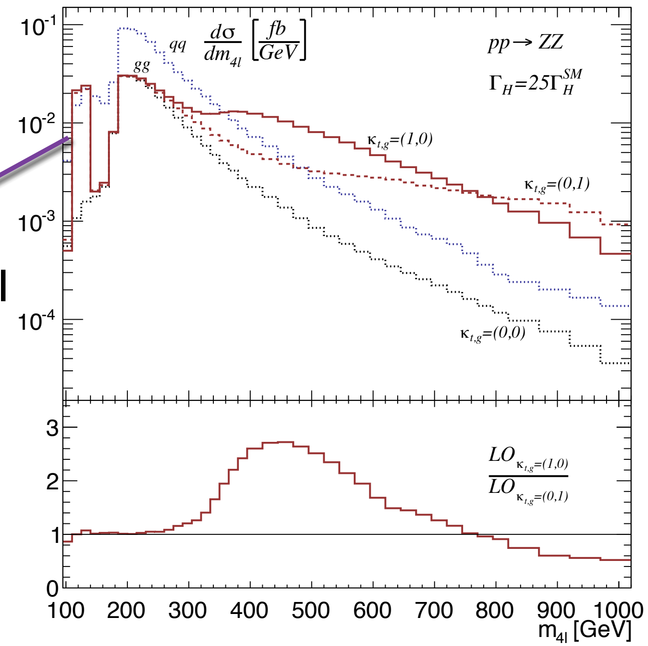
$$\sigma^{\text{Off-Shell}}_{gg\to H^*\to ZZ} \propto \left(k_t g_{ggH}(m_{4\ell}) + k_g g_{ggH}(m_H)\right)^2 g^2_{HZZ}(m_{4\ell})$$ → non-trivial k_t & k_g dependence

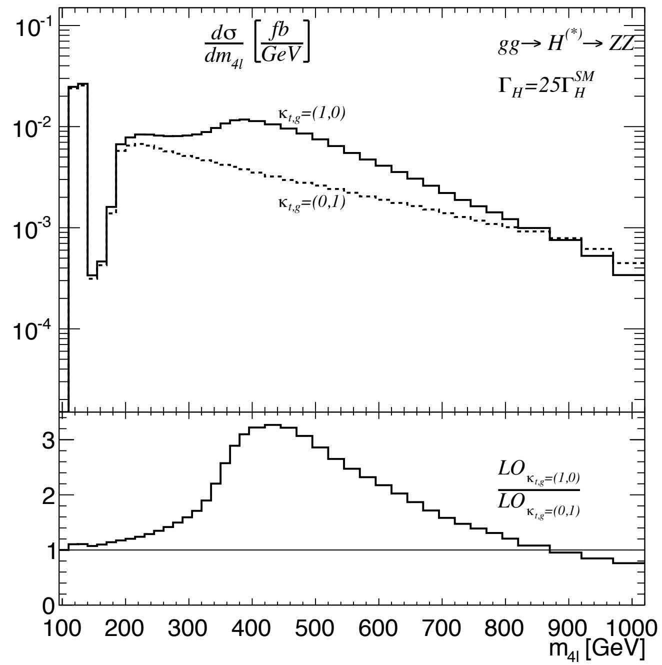
In preparation: M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn

- Example: $\xi^4 = 25 \quad \rightarrow \quad \Gamma_H = 25\Gamma_H^{\text{SM}}$

Signal strength still

$\mu_{\text{on-shell}} = 1$





Summary

- Top mass effects in $p_{T,H}$ are large and can be described in combination with NLO-merging
  - Top mass effects factorize for each jet bin
  - Reweighting function $W(p_{TH})$ top mass effects
  - Complementary way to extract information on the Yukawa coupling

- Off-shell Higgs effects can be described in the same framework
- Exact top mass dependence is a crucial assumption in the Higgs width measurement