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
arXiv: 1410.5806 M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn

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Outline

Heavy quark mass effects in Higgs production:

- The state of the art of event simulation including the heavy quark masses: Higgs + jets MEPS merging @LO & @NLO$_{\text{approx.}}$

- Looking for BSM effects: Boosted and Off-shell Higgs production

- Higgs width measurement

Motivation

- After the Higgs discovery the SM is a complete theory
  → All the particle degrees of freedom have been discovered

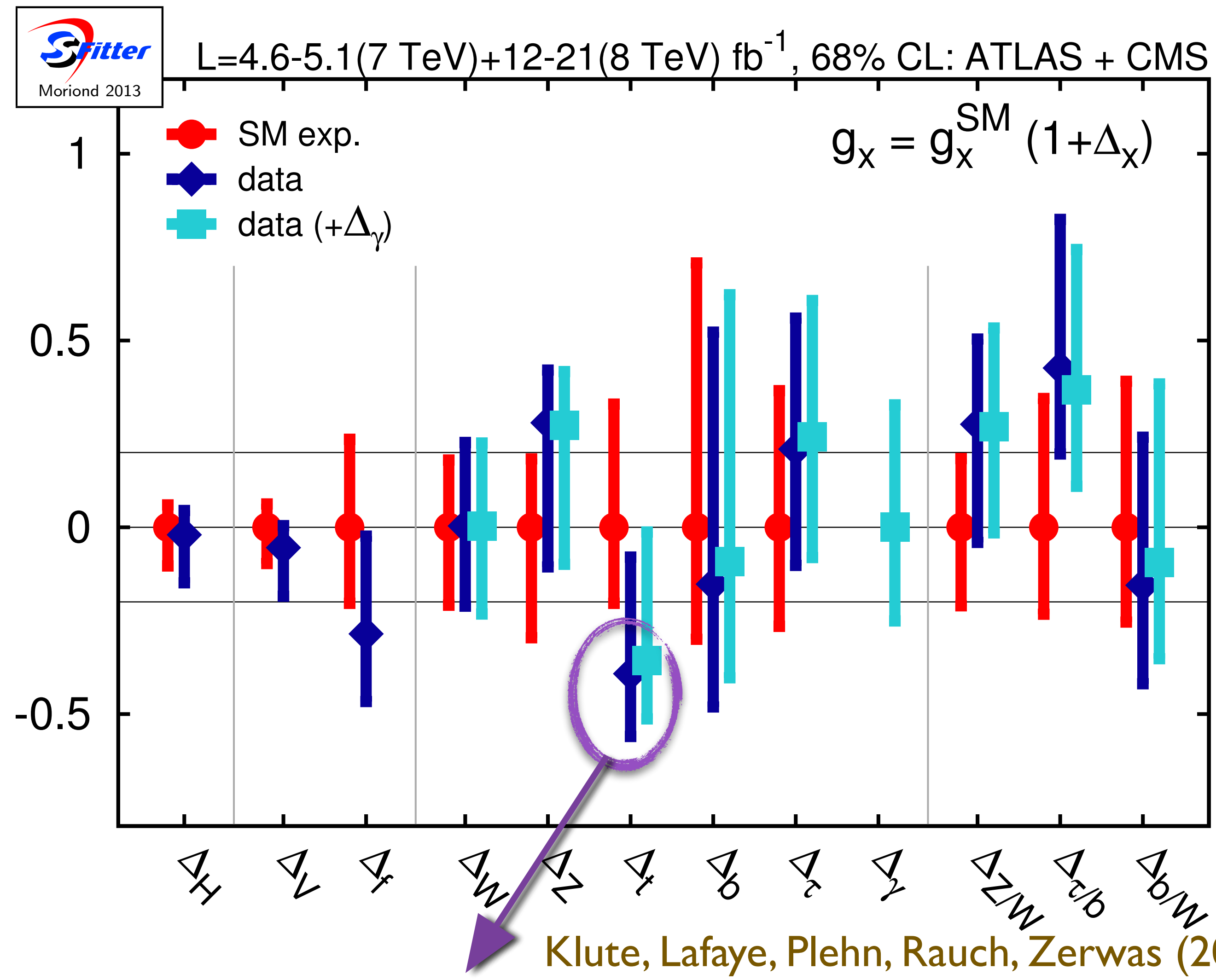
- But we are still left with plenty of problems and without a "no-lose theorem"
  → DM, neutrino oscillation, inflation, hierarchy problem…

- Where should we search for BSM in the absence of any clear BSM signal?
  → Higgs couplings… in special the top Yukawa might be a good place

Motivation

- Is it really the SM Higgs boson? Strategy of Higgs analysis:

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



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

Important for Higgs production

Higgs-fermions couplings largely relies on loop–induced couplings

→ Limited and model–dependent understanding of y_t

→ Measurement from ttH is challenging

Motivation

- Is it really the SM Higgs boson? Strategy of Higgs analysis:

Unique resonance?

↓

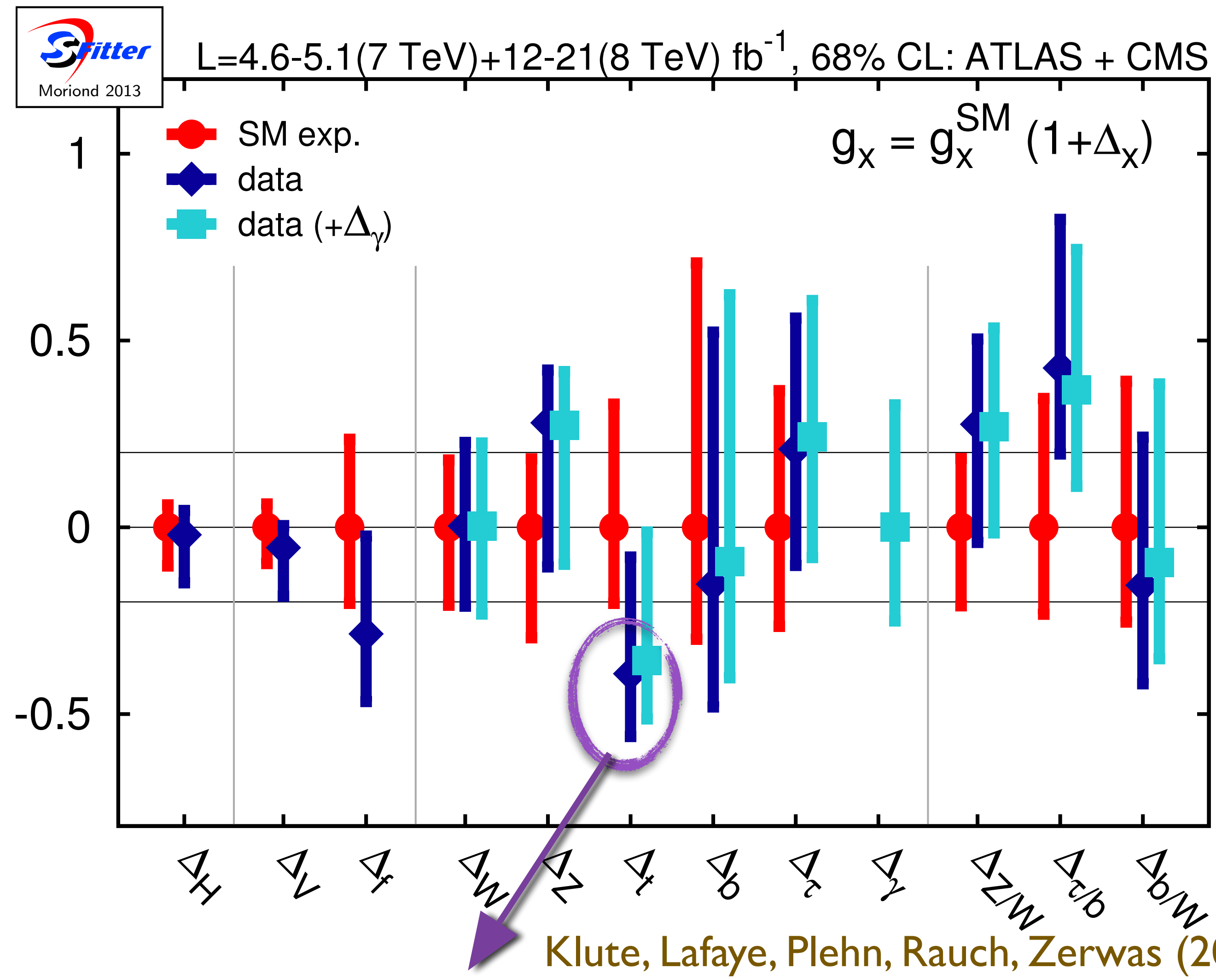
Spin/CP?

↓

Lagrangian?

↓

Coupling strength?



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

Important for Higgs production

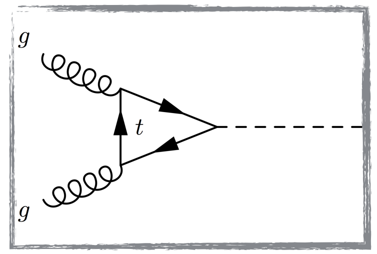
Can we use any kinematical information to direct probe y_t in ggH?

→ Let's look at the structure of the ggH coupling in the SM

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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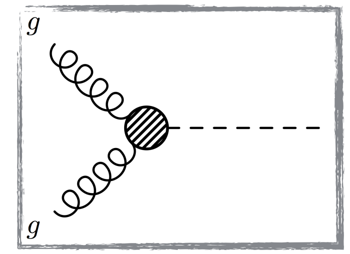


$$\frac{g_{ggH}}{v} = \frac{\alpha_s}{8\pi} \frac{1}{v} \tau \left[1 + (1-\tau) f(\tau)\right]$$

$$f(\tau) \overset{\text{on-shell}}{=} \left(\arcsin \sqrt{\frac{1}{\tau}}\right)^2 \overset{\tau\to\infty}{=} \frac{1}{\tau} + \frac{1}{3\tau^2} + \mathcal{O}\left(\frac{1}{\tau^3}\right)$$

$$\tau = 4m_t^2/m_H^2$$

- HEFT is an excellent approximation for Higgs production

- All present exact N...LO calculations are done in the HEFT framework
  E.g., that is what MG, MC@NLO, POWHEG,… do

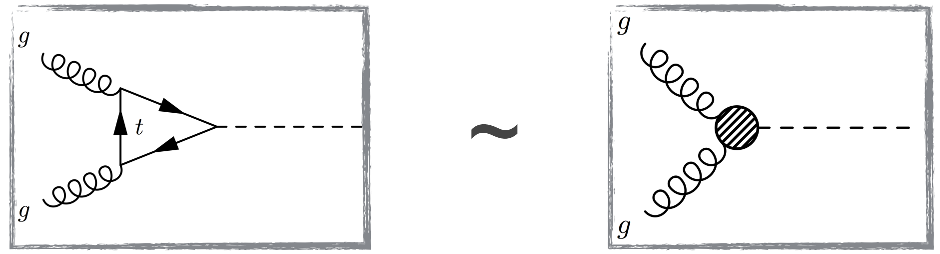
- It is a misconception to say that HEFT is equivalent to $m_t \to$ infinity
  Notice that we can get the finite top mass dependence in the HEFT

- In general a “loop” is not a fixed number. QCD corrections are dynamic.

Heavy quark mass effects in Higgs production

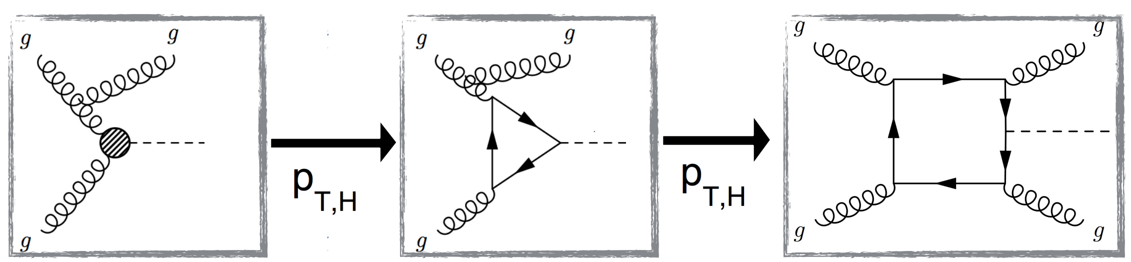
- Higgs interacts with gluons via a loop-induced coupling

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

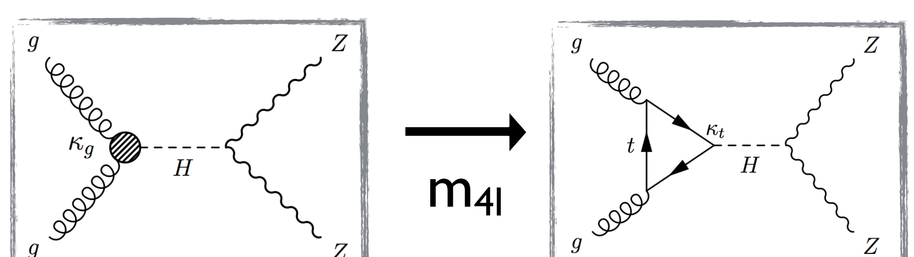


$$\frac{g_{ggH}}{v} = \frac{\alpha_s}{8\pi} \frac{1}{v} \tau \left[1 + (1-\tau) f(\tau)\right] \qquad f(\tau) \overset{\text{on-shell}}{=} \left(\arcsin\sqrt{\frac{1}{\tau}}\right)^2 \overset{\tau\to\infty}{=} \frac{1}{\tau} + \frac{1}{3\tau^2} + \mathcal{O}\left(\frac{1}{\tau^3}\right)$$

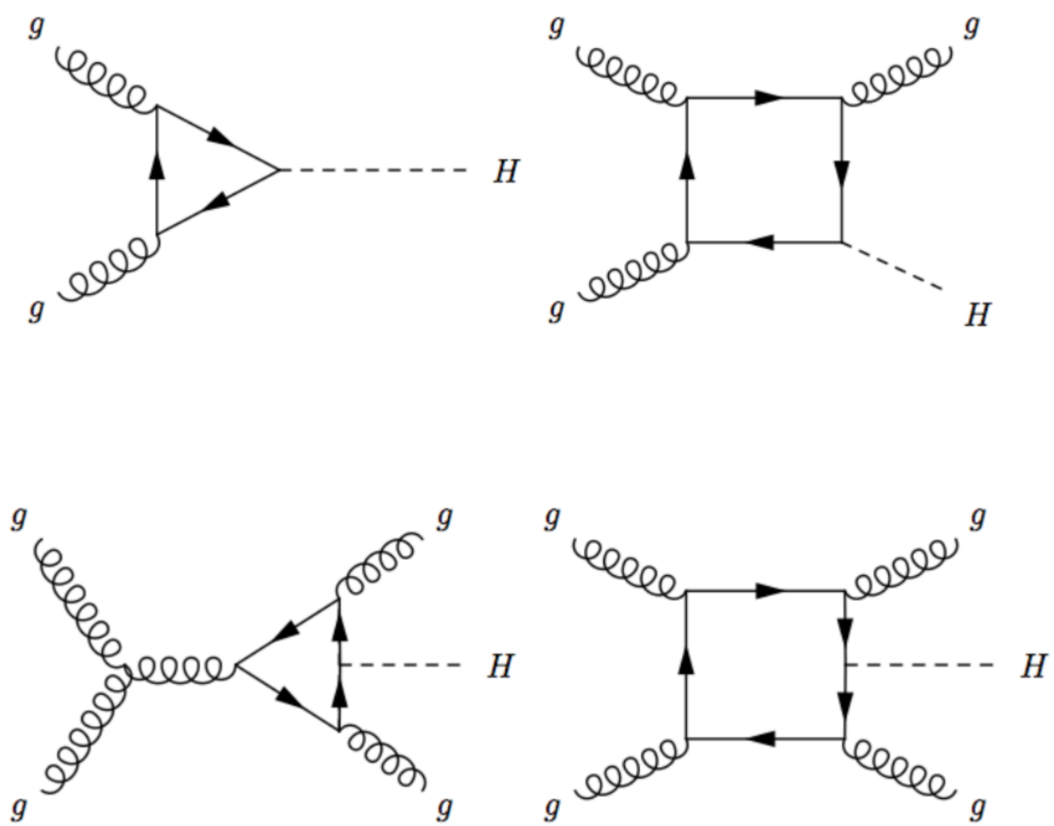
- HEFT is an excellent approximation for Higgs production $\quad \tau = 4m_t^2/m_H^2$
- All present exact N...LO calculations are done in the HEFT framework
- HEFT approx. does not work so well if external particles go off-shell.
  I.e., we start to direct probe the loop structure!
  - Boosted Higgs:

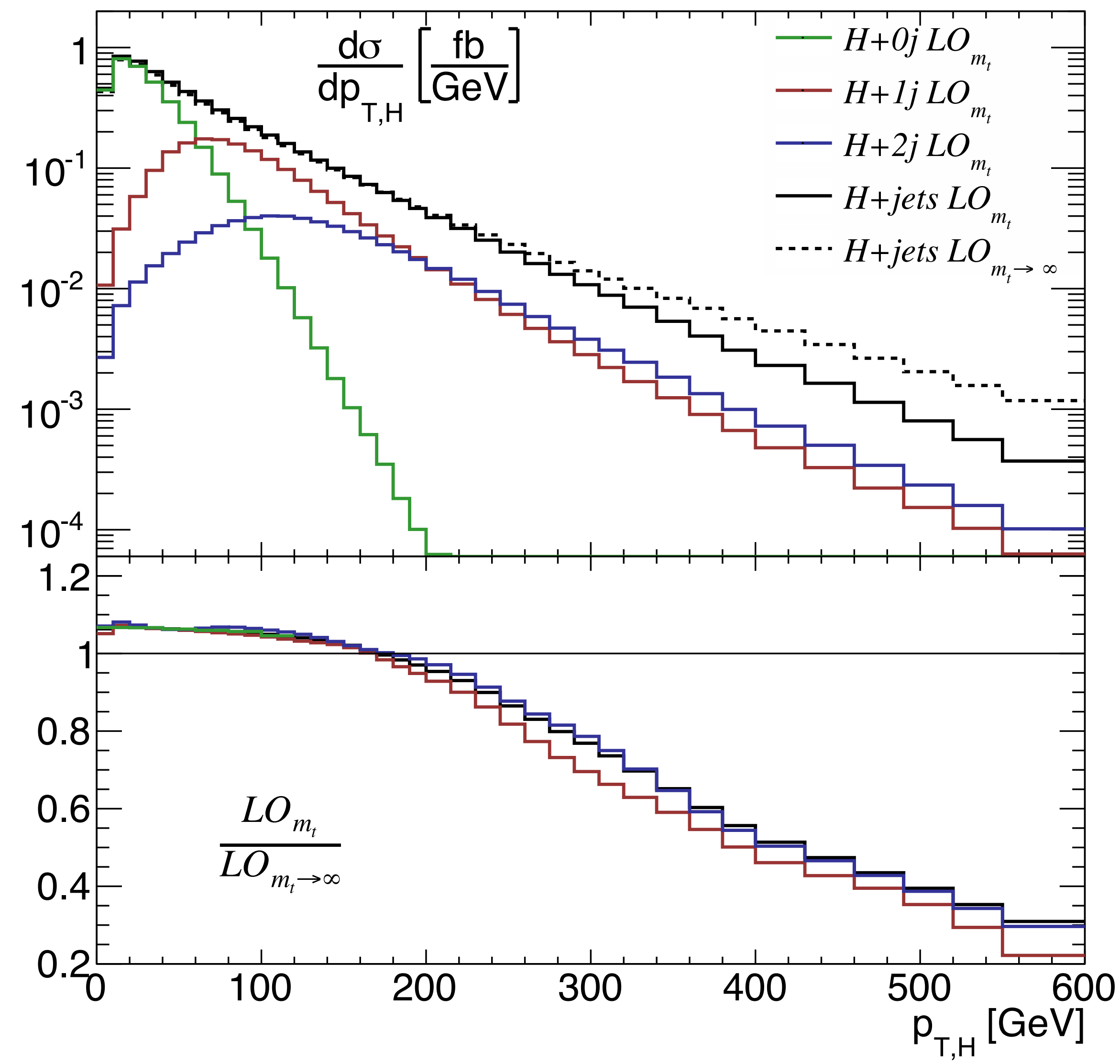


  - Off-shell Higgs:



Top mass effects: H+jets CKKW merging





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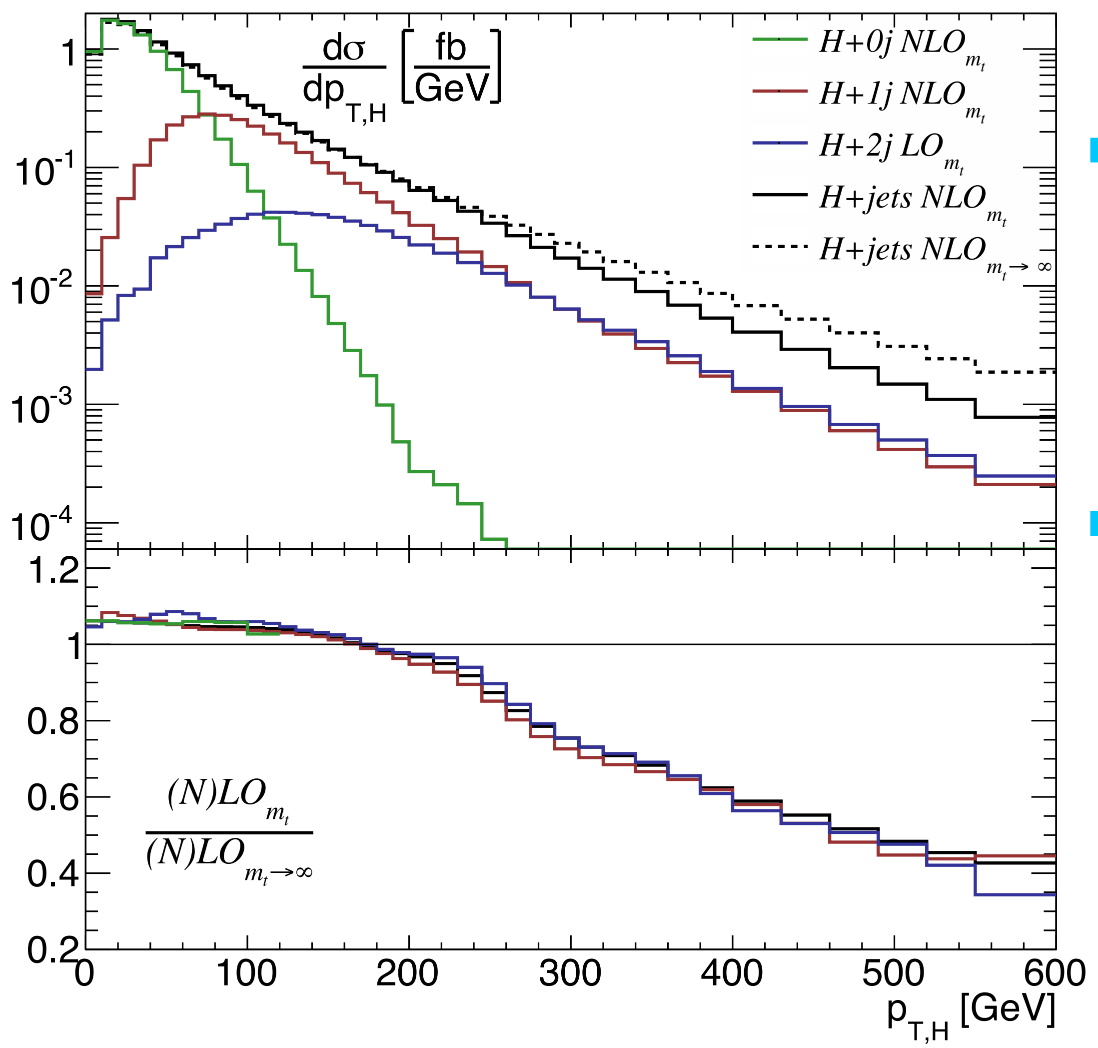
- Top mass effects fundamental for boosted H: correction of O(4) at p_{TH}~600 GeV
- Each jet multiplicity has approximately same top mass correction
- Consequently the same happens for the merged result

Top mass effects: H+jets MEPS@NLO merging

- Reweighting HEFT amplitudes with OpenLoops 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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Framework

- Is the Y_t responsible for the ggH coupling or are there BSM contributions?

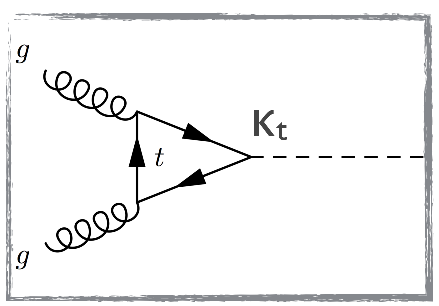
$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right) + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} + \ldots$$

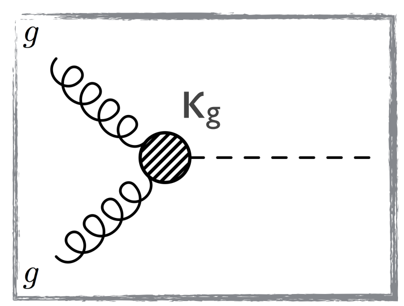
Relevant CP-even BSM operators to GF:

$$\mathcal{O}_g = \frac{\alpha_s}{12\pi v^2}|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_y = \frac{y_t}{v^2}|H|^2 \bar{Q}_L \tilde{H} t_R \qquad \mathcal{O}_H = \frac{1}{2v^2}\partial_\mu |H|^2 \partial^\mu |H|^2$$

At linear order: $k_t = 1 - \frac{c_H}{2} - \text{Re}(c_y) \qquad k_g = c_g$

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





Hj:

Azatov, Paul (2014)

Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant (2014)

Banfi, Martin, Sanz (2013)

Grojean, Salvioni, Schlaffer Weiler (2013)

Hjj:

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

H+jets with NLO Merging+...:

Buschman, DG, Krauss, Kuttimalai, Schonherr, Plehn

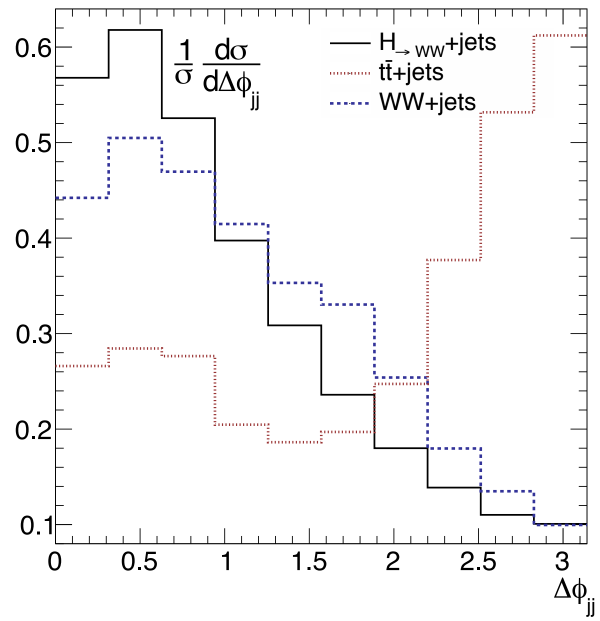
- Disentangle κ_t and κ_g satisfying Higgs total rate $\sigma \sim |\kappa_t + \kappa_g|^2 \rightarrow \kappa_t + \kappa_g = 1$

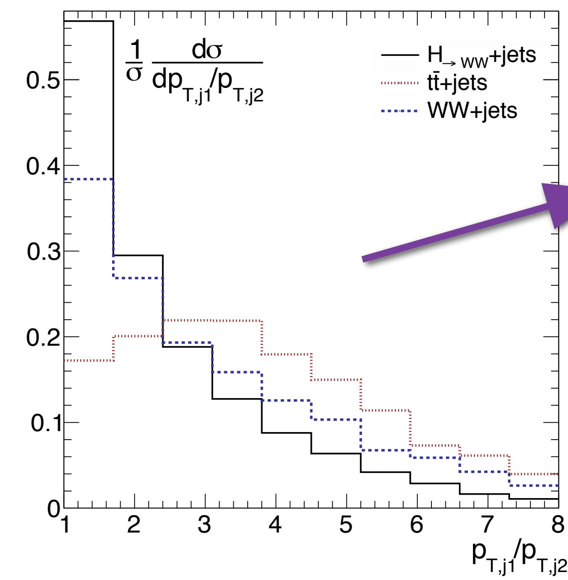
$$\mathcal{M} = \kappa_t \mathcal{M}_t + \kappa_g \mathcal{M}_g$$

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

Signal-Background analysis

- $(\kappa_t, \kappa_g)_{\rm SM} = (1,0)$ VS $(\kappa_t, \kappa_g)_{\rm BSM} = (0.8, 0.2)$
- We chose the two most promising channels $H \to WW$ & $H \to \tau\tau$





H+2 very hard jets mercedes-like topology

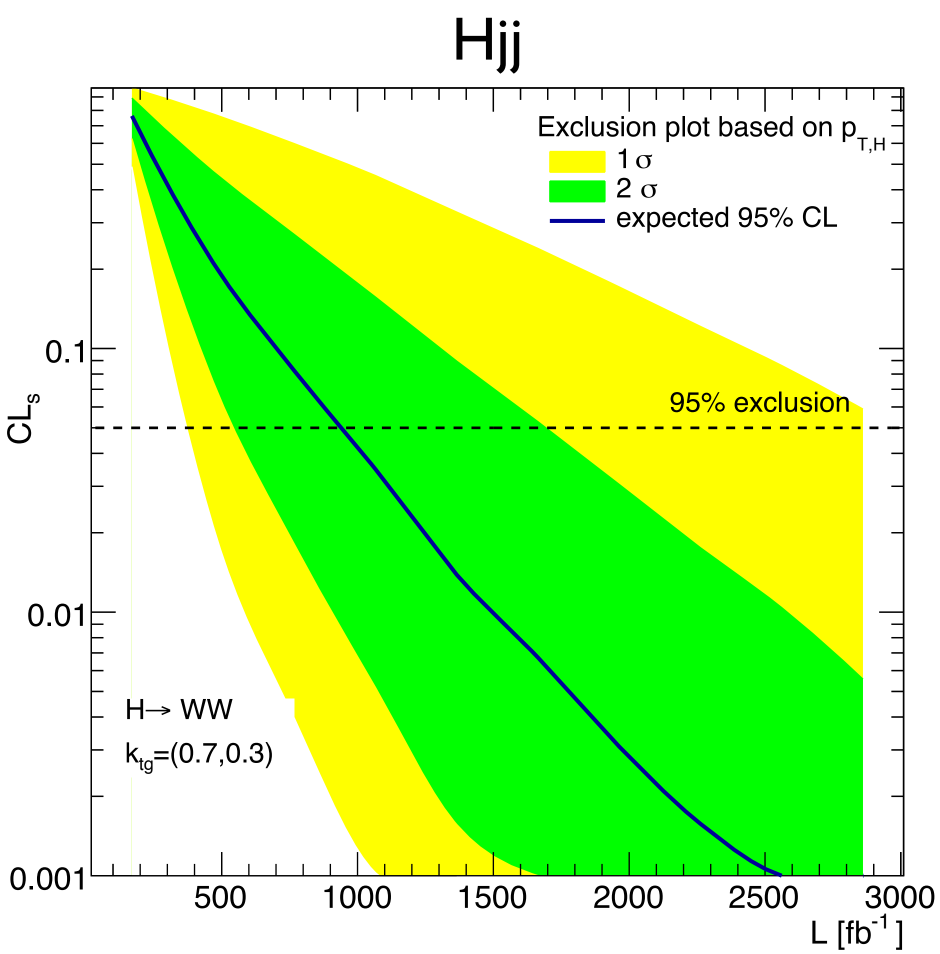
	$Hj \to (WW)j$ inclusive			$Hjj \to (WW)jj$ inclusive		
cuts	H+jets	WW+jets	$t\bar{t}$+jets	H+jets	WW+jets	$t\bar{t}$+jets
$p_{T,j} > 40$ GeV, $\lvert y_j\rvert < 4.5$ $p_{T,\ell} > 20$ GeV, $\lvert y_\ell\rvert < 2.5$	35.5	524	14770	17.3	90.7	7633
$N_b = 0$	33.3	515	4920	15.2	87.4	1690
$m_{\ell\ell} \in [10, 60]$ 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

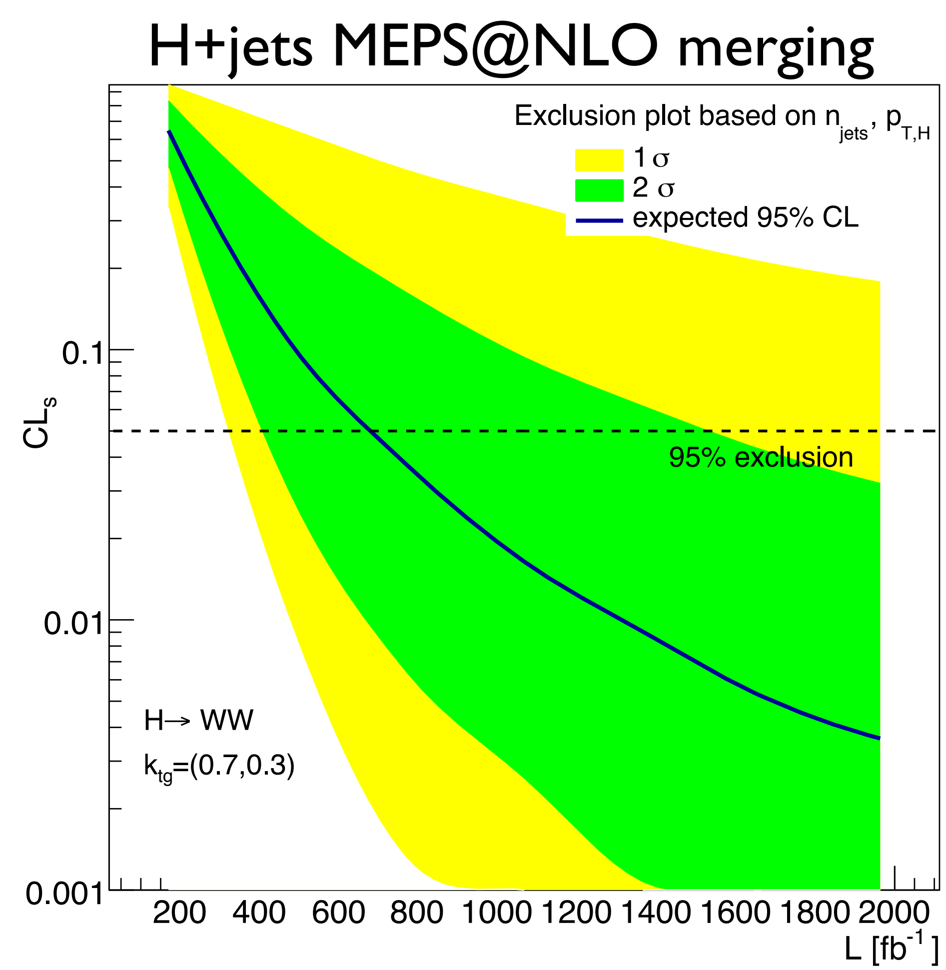
- mjj cut doesn't enhance signal and not needed
- Similar strategy for the $H \to \tau\tau$
- The second jet described by ME reduces backgrounds by ~ 1/5 when compared to the Hj

Log-likelihood analysis

- The merged distributions capture the info from the first and second jet bin

→ Better constrains for the merged sample:





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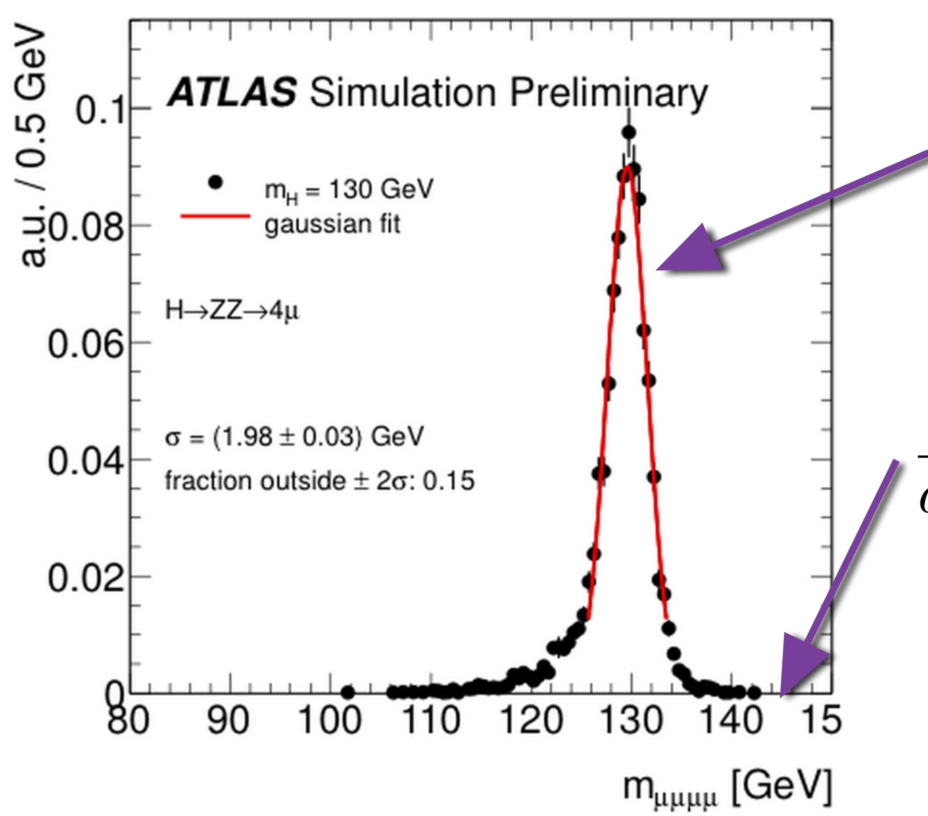
Off-Shell Higgs Production

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



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

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

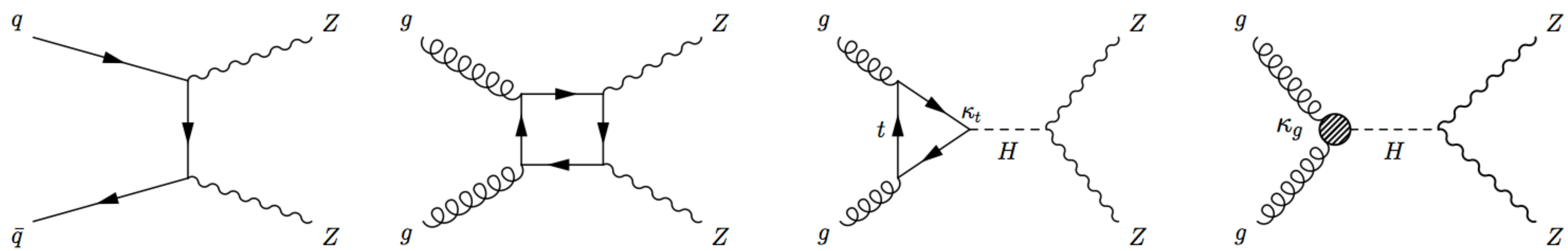
- Almost all signal only events are in the on-shell region

→ Solution: interference 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



→ Probe energy dependence from the higher dimensional operators

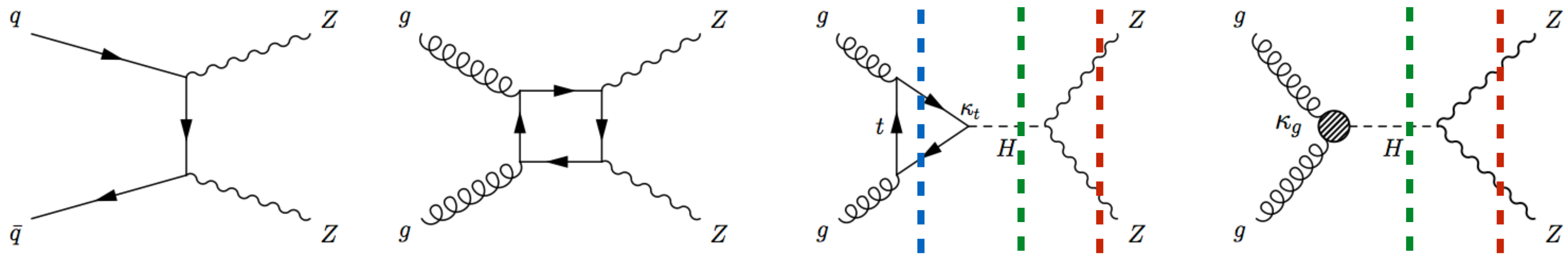
- $\mathcal{M}_g^{++00} \approx -\frac{m_{4\ell}^2}{2m_Z^2}$ with $m_t \gg m_{4\ell} \gg m_H, m_Z$
- $\mathcal{M}_t^{++00} \approx +\frac{m_t^2}{2m_Z^2} \log^2 \frac{m_{4\ell}^2}{m_t^2}$ with $m_{4\ell} \gg m_t \gtrsim m_H, m_Z$
- $\mathcal{M}_c^{++00} \approx -\frac{m_t^2}{2m_Z^2} \log^2 \frac{m_{4\ell}^2}{m_t^2}$ with $m_{4\ell} \gg m_t \gtrsim m_Z$.

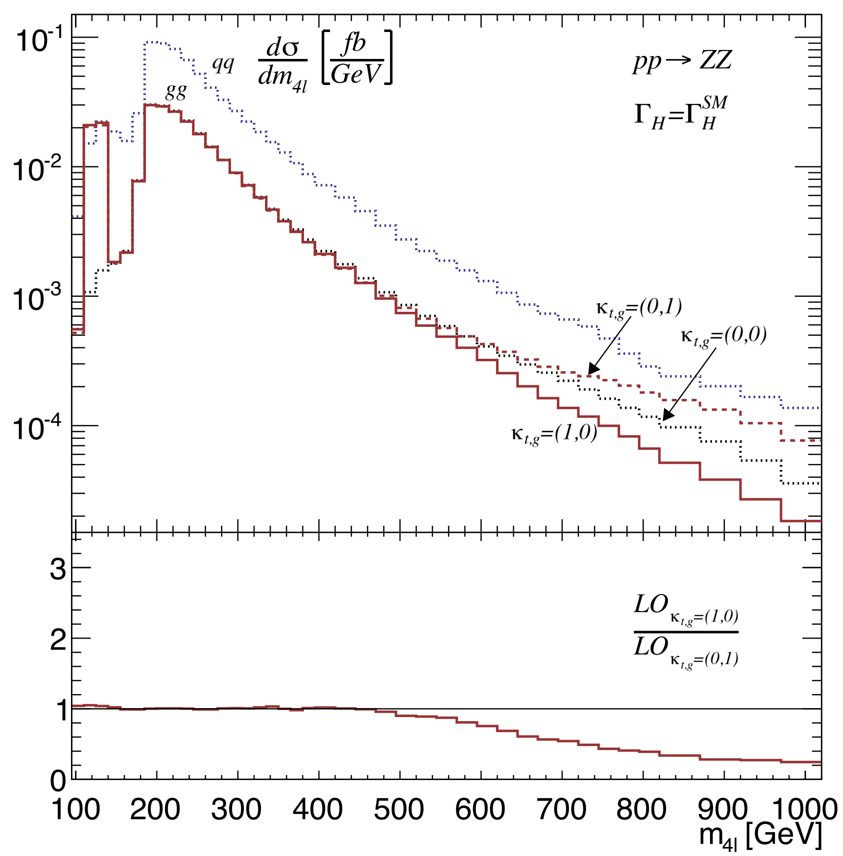
→ Full top mass: destructive interference

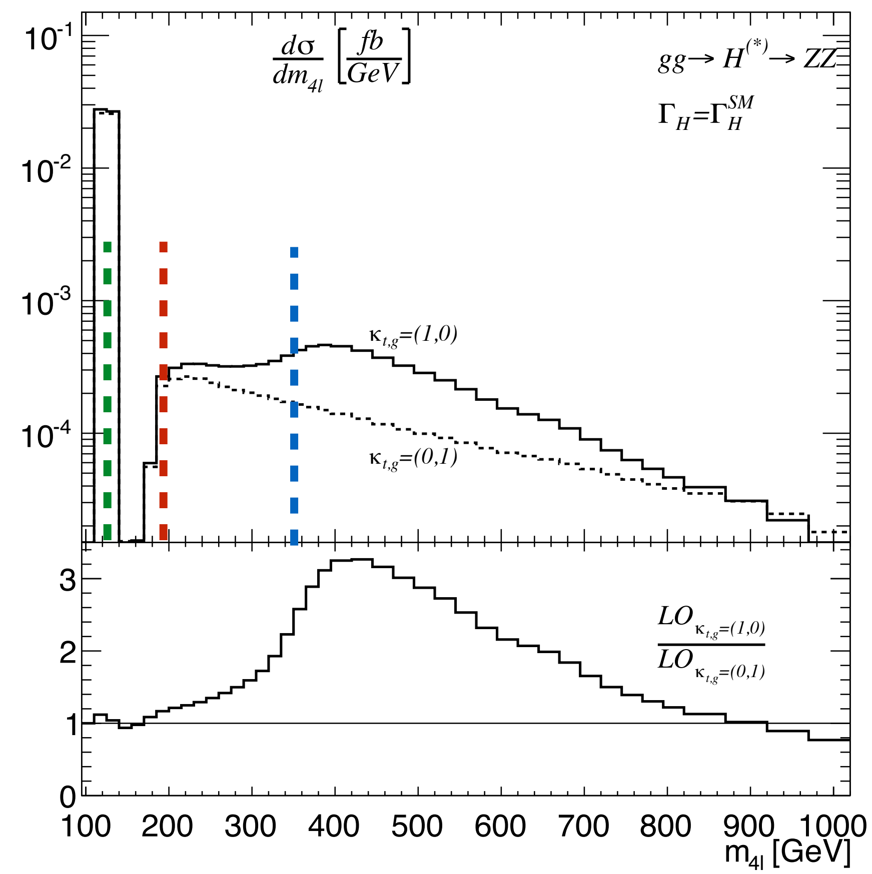
→ Low-energy limit: constructive interference

Off-Shell Higgs Production

- Large off-shell tail m_{4l}>300GeV: O(15%) of the total rate $\mathcal{M}_{ZZ} = \kappa_t \mathcal{M}_t + \kappa_g \mathcal{M}_g + \mathcal{M}_c$







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

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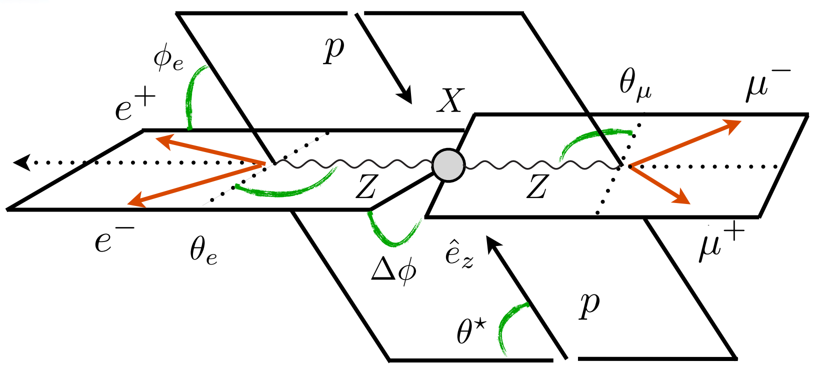
Nelson angles

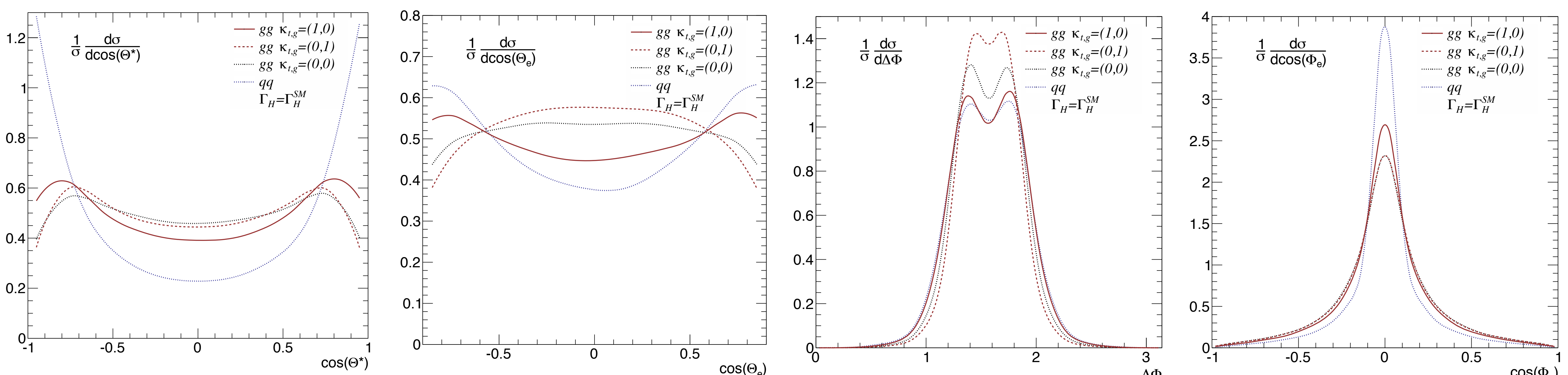
- Signal only: info on HZZ operator



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)
Djouadi, Godbole, Mellado, Mohan (2013)

- Signal-background interference gets spin correlation:

→ info on the Higgs production and decay operators



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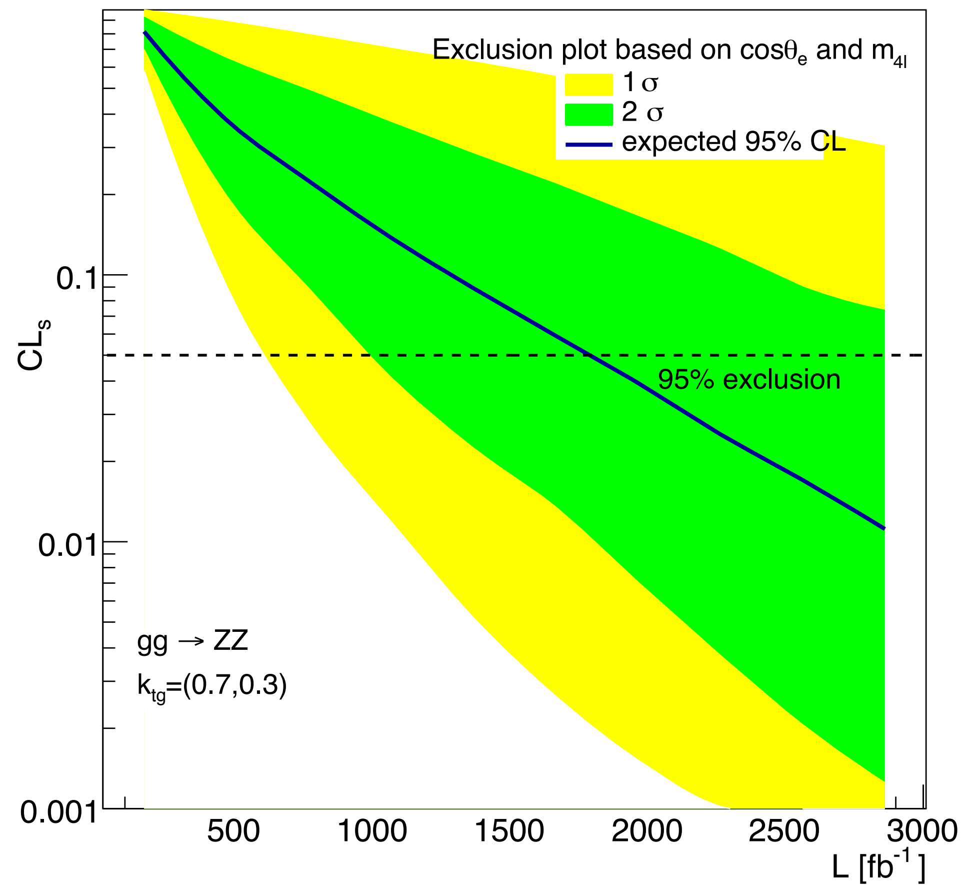
Log-likelihood analysis

- 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

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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

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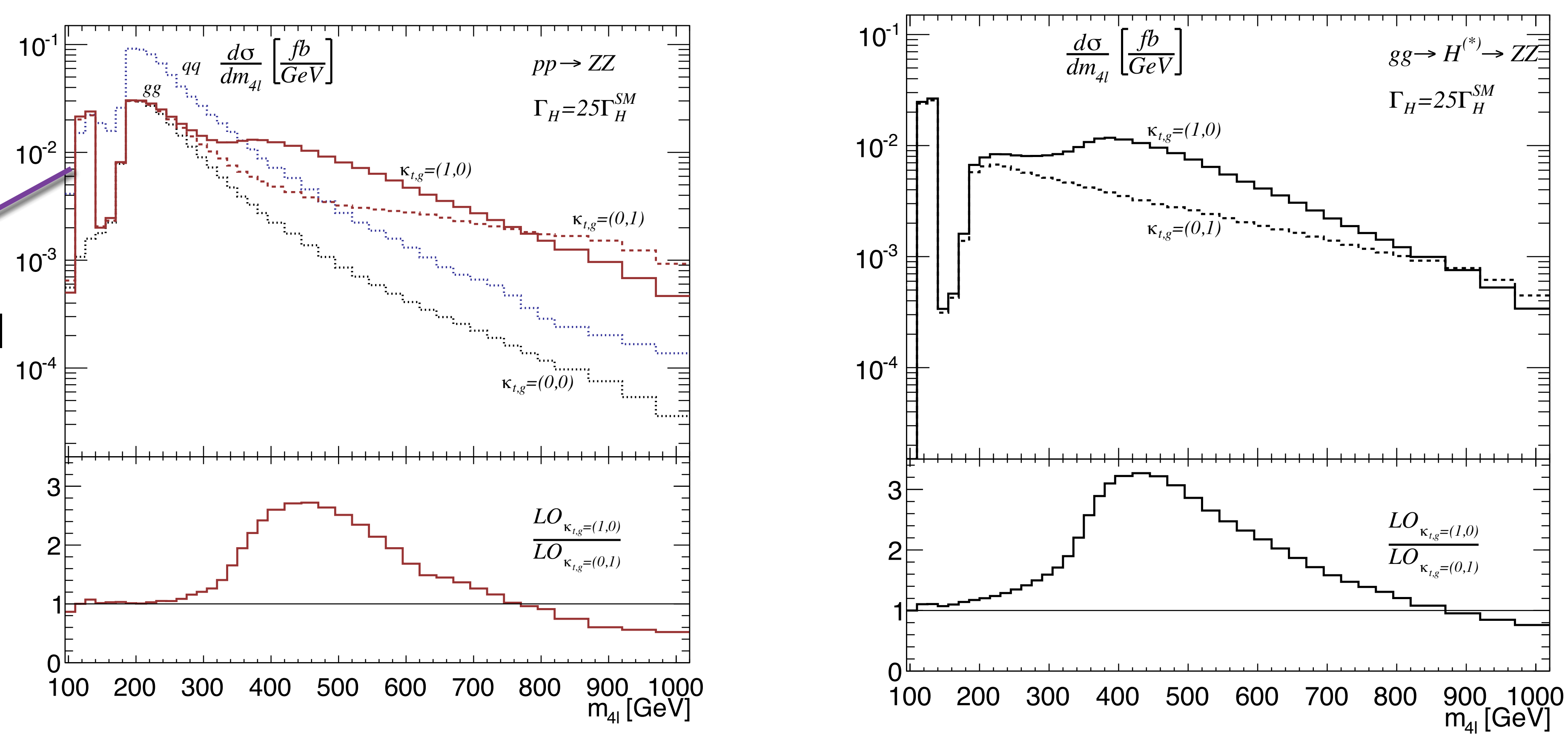
- Example: $\xi^4 = 25 \quad \rightarrow \quad \Gamma_H = 25\Gamma_H^{SM}$

Signal strength still

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



Summary

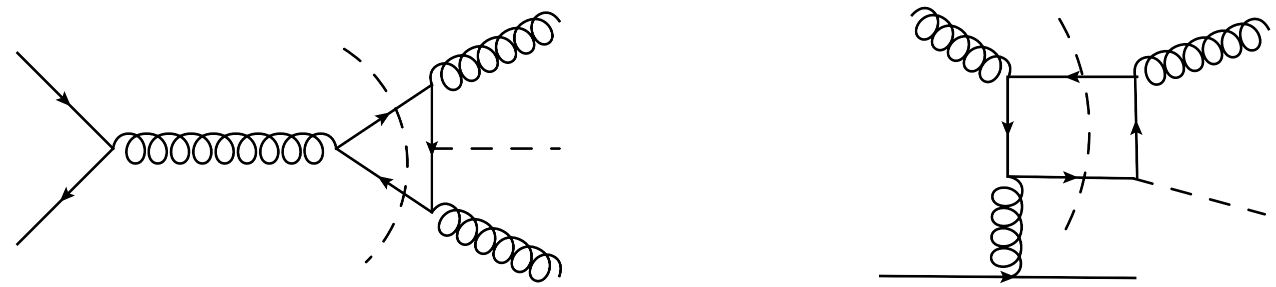
- Boosted/off-shell Higgs production can provide an alternative access to the top Yukawa coupling and provide information about the fields circulating in the gluon fusion loop

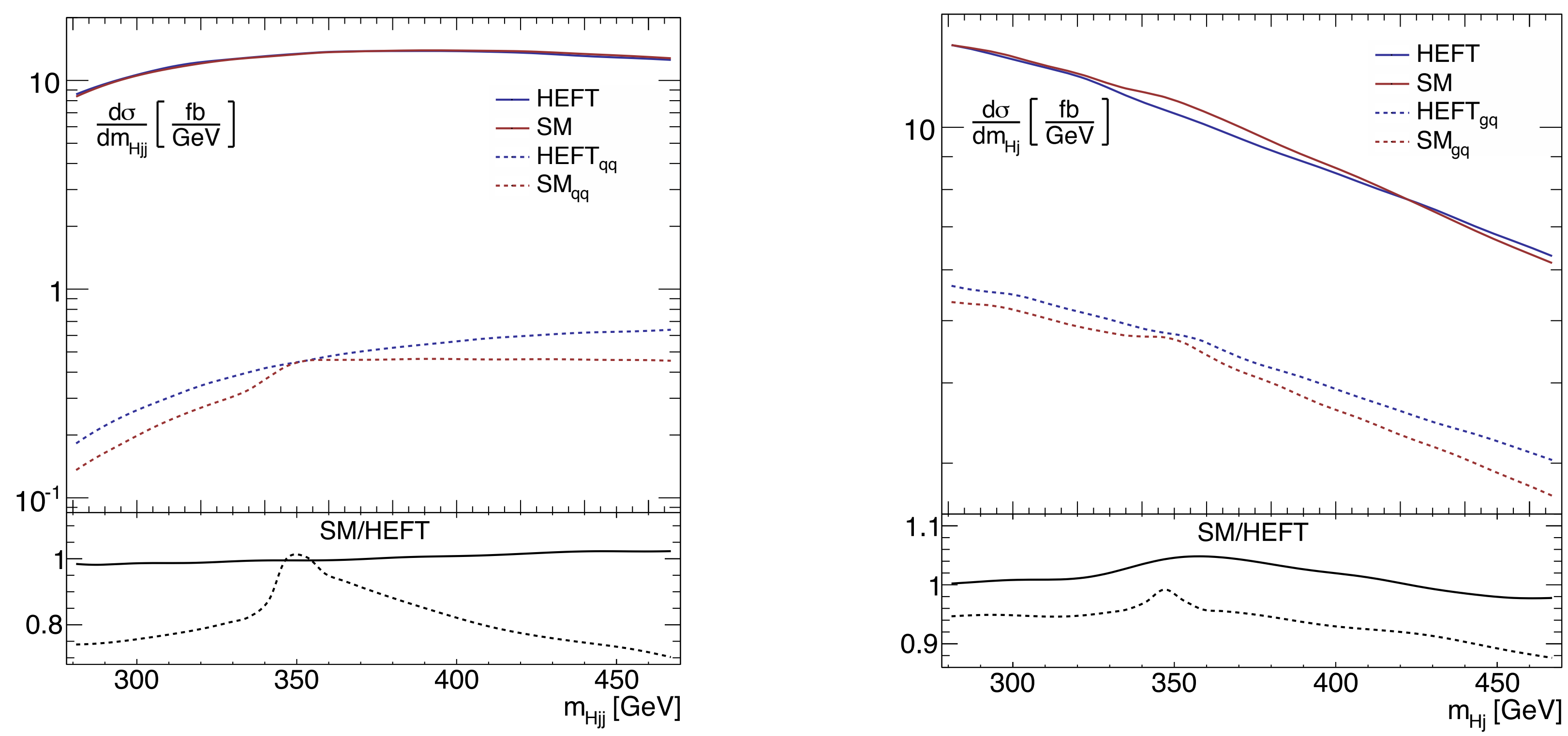
- Top mass effects in $p_{T,H}$ are large and can be described in combination with NLO-merging
  - Top mass effects factorize for each jet bin

- Current width measurement is not model independent.
  Our framework is a prime example of it

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.

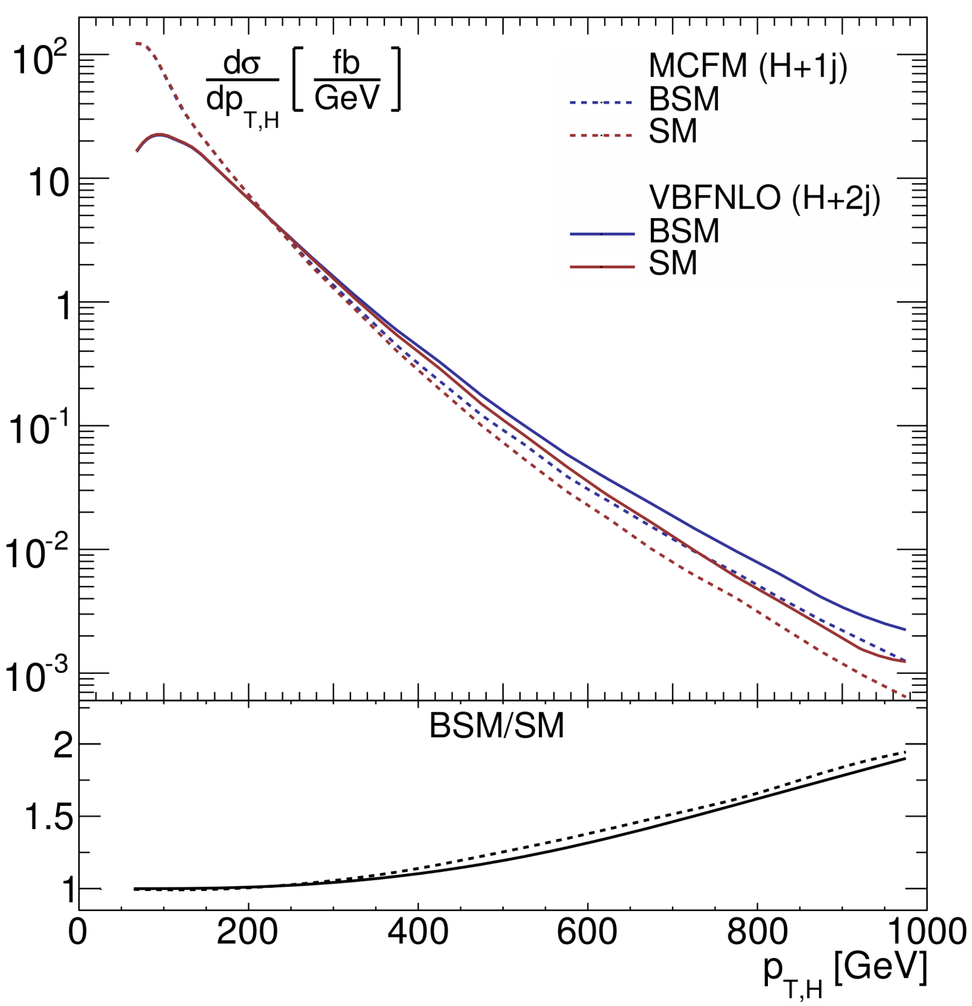
Buschman, Englert, DG, Plehn, Spannowsky (2014)

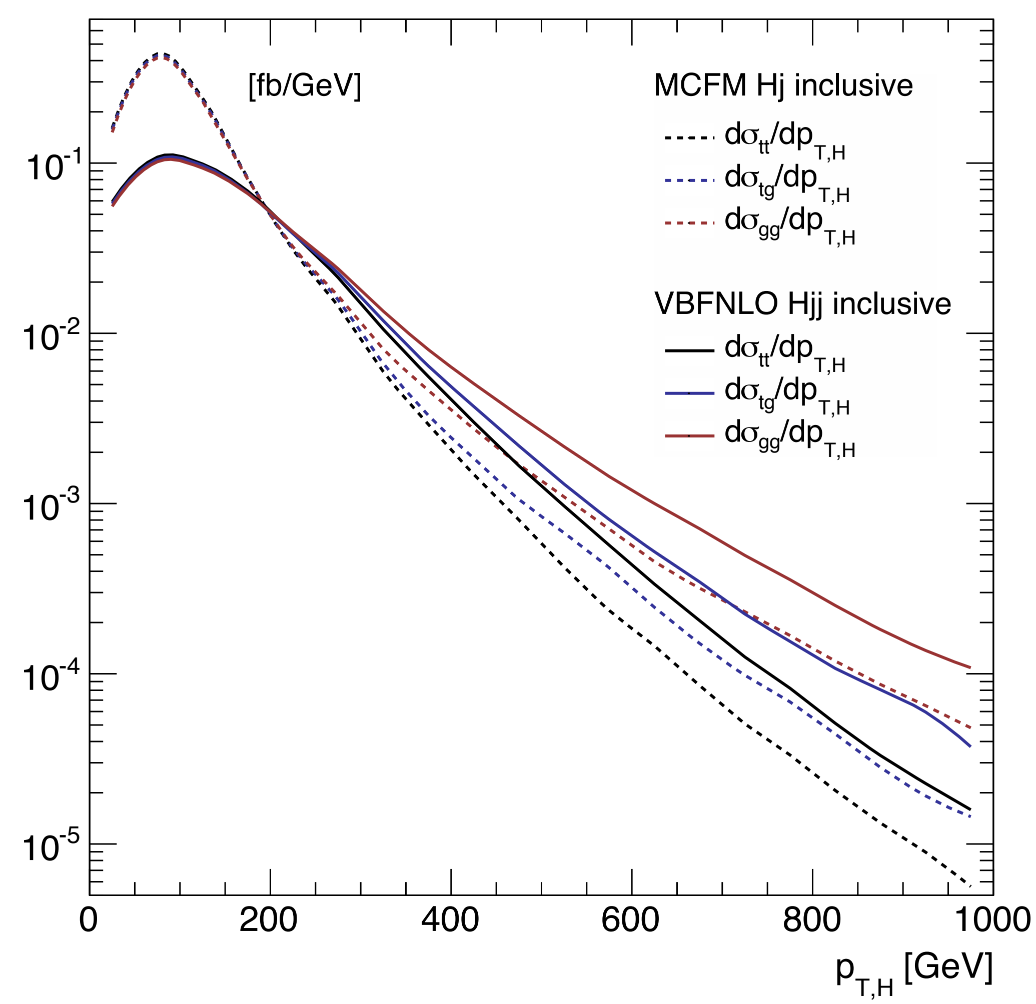
Boosted Higgs

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

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

$$\frac{d\sigma}{d\mathcal{O}} = \kappa_t^2 \frac{d\sigma_{tt}}{d\mathcal{O}} + \kappa_t \kappa_g \frac{d\sigma_{tg}}{d\mathcal{O}} + \kappa_g^2 \frac{d\sigma_{gg}}{d\mathcal{O}}$$

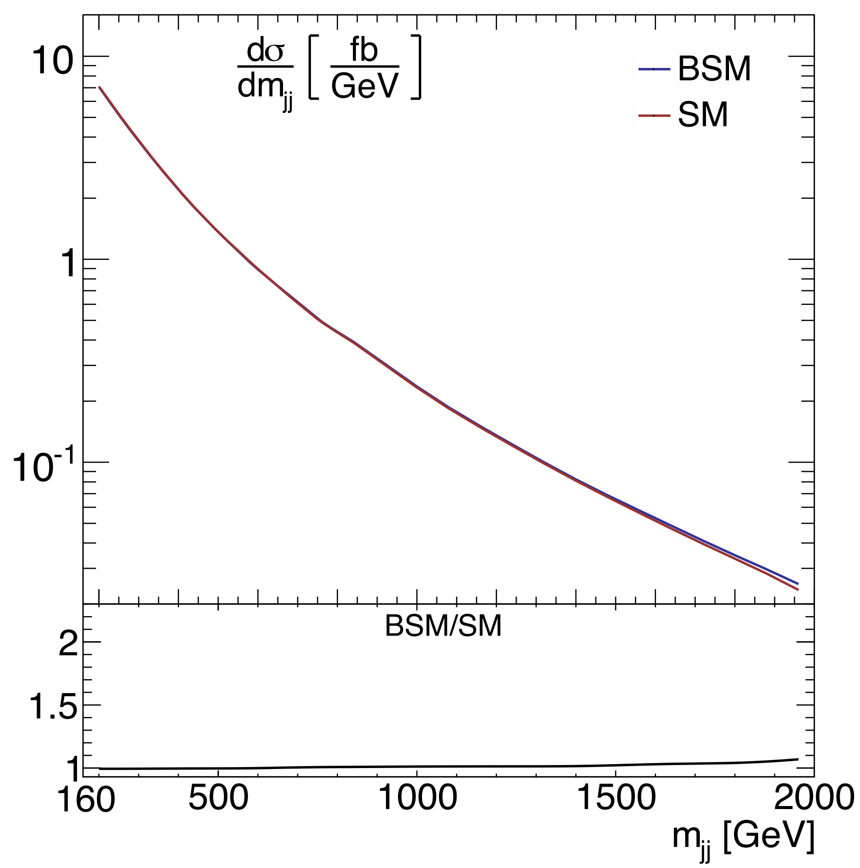


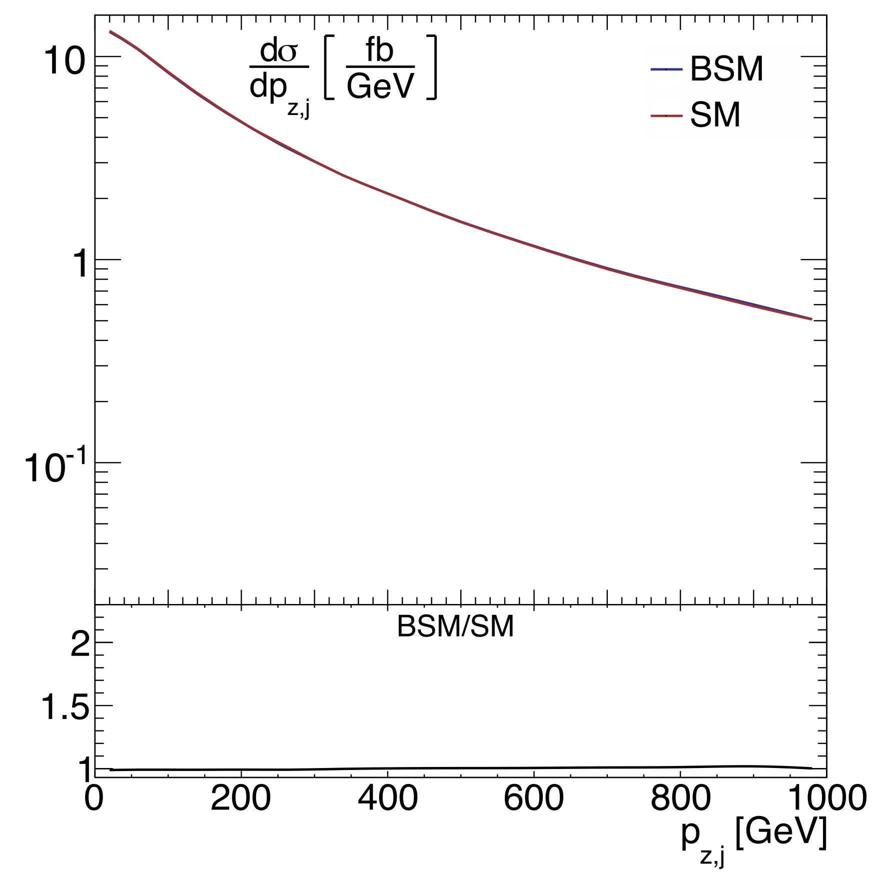


Buschman, Englert, DG, Plehn,Spannowsky (2014)

Hunting the mass effects

- WBF requires large m_{jj} to suppress the GF. If we get also a factor 2 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

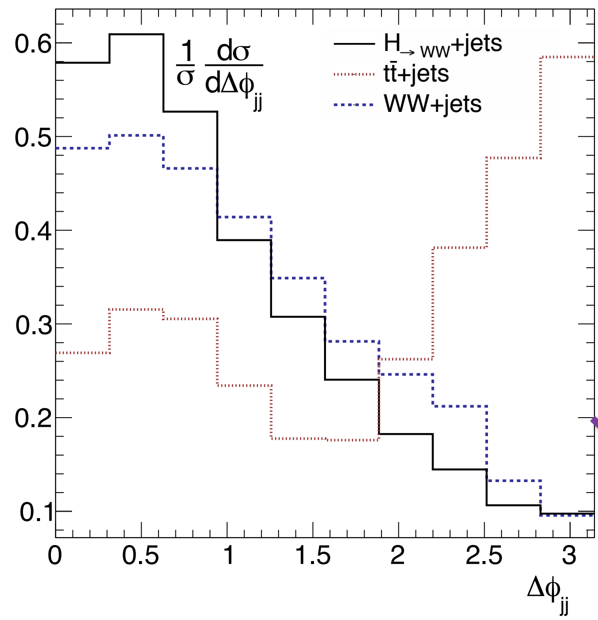
It does not have the same enhancements as p_{TH}.

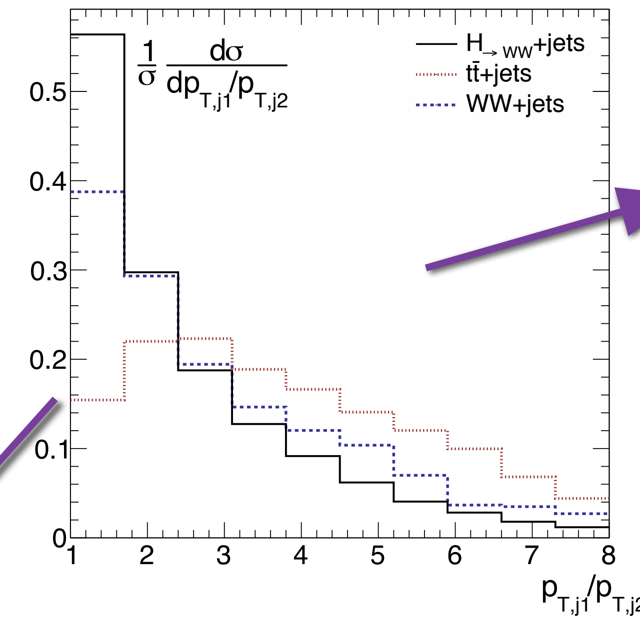
- p_{TH} is the most sensitive distribution… What about the merged sample - H+jets?

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

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

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

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

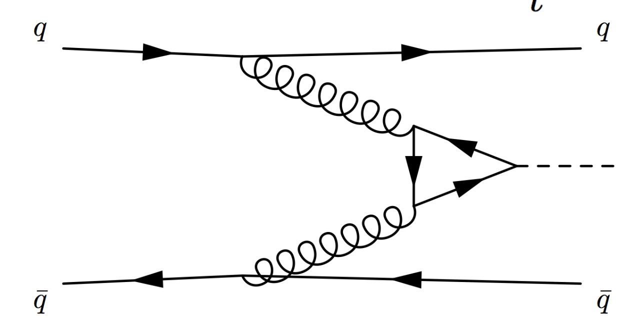
$$p_{T,H} \sim p_{T,\ell_1} + p_{T,\ell_2} + \not{p}_T > 300 \text{ GeV}$$

	$Hj \to (\tau\tau)j$ 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, $\lvert y_j\rvert < 4.5$ $p_{T,\ell} > 20$ GeV, $\lvert y_\ell\rvert < 2.5$	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
$\lvert m_{\tau\tau} - m_H\rvert < 20$ 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

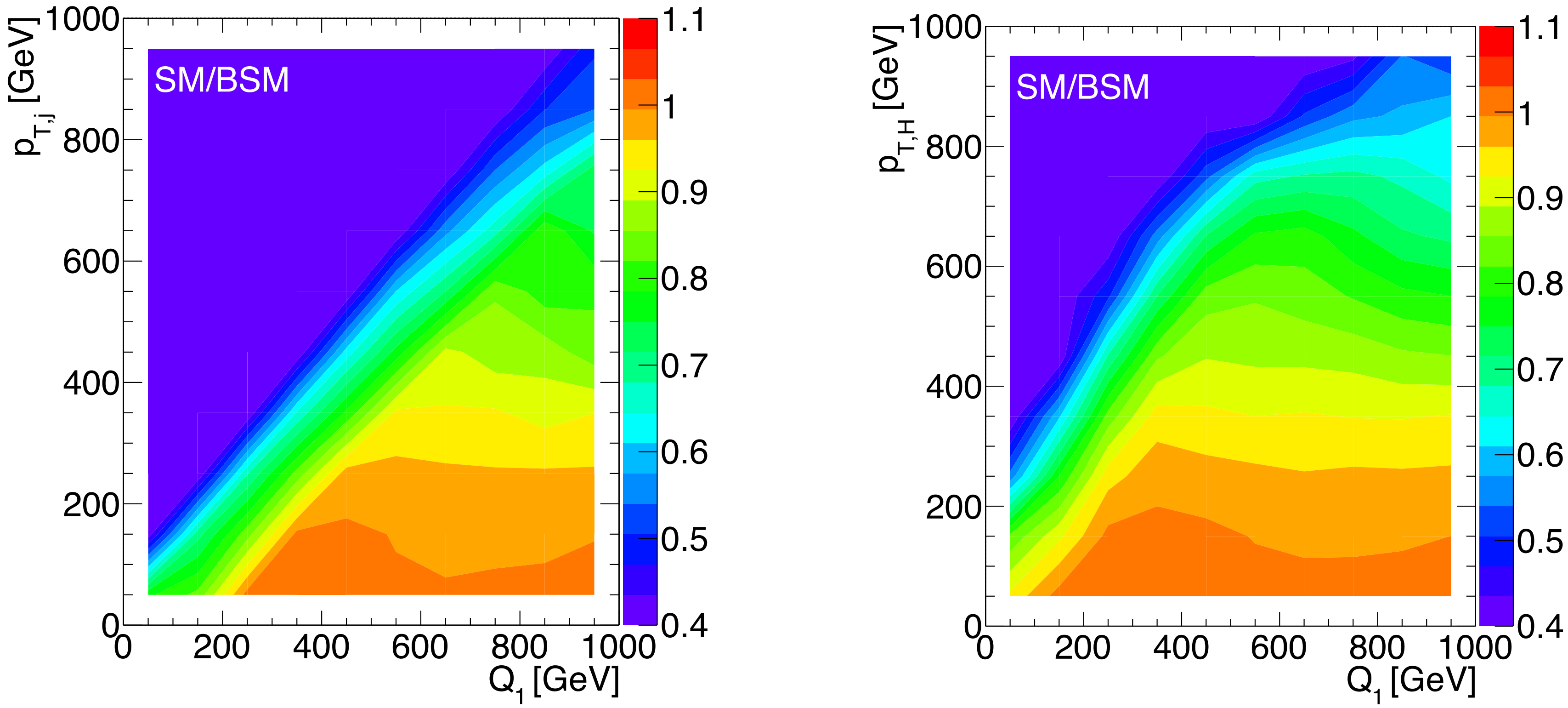
→ S/B better than in the WW case. But lower cross-section.

Boosted Higgs

- Logs at Hj and Hjj have the same origin. I.e., the top mass effects: $|\mathcal{M}_{Hj(j)}|^2 \propto m_t^4 \, \log^4 \frac{p_{T,H}^2}{m_t^2}$



- 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

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

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