Off-Shell Higgs Production at the LHC

HEFT 2015
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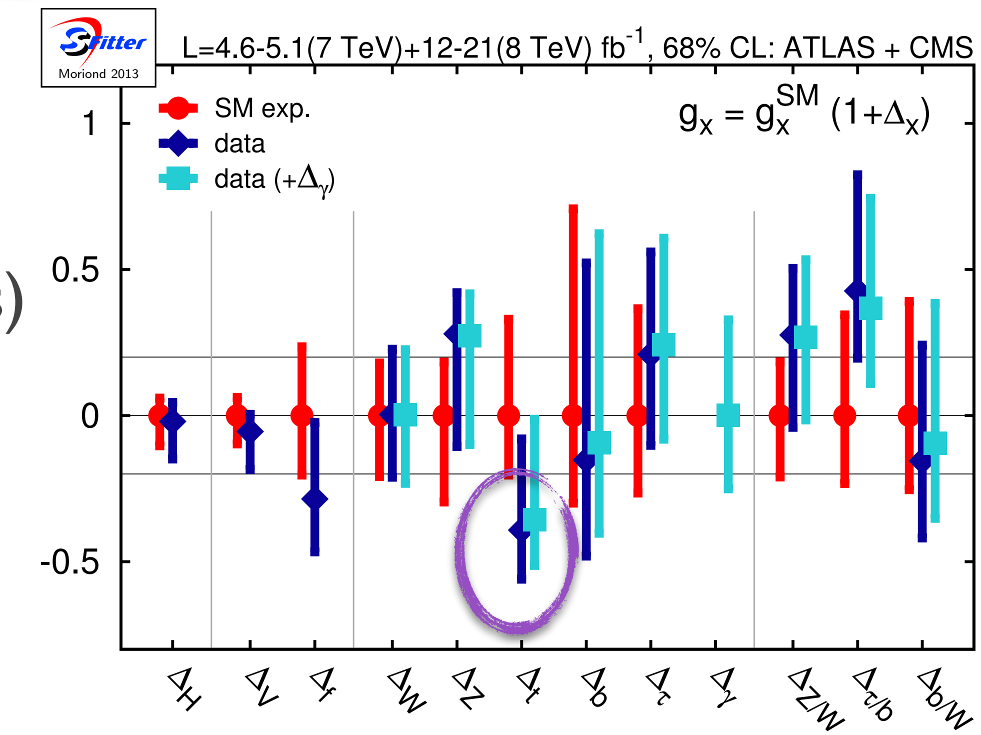
Motivation



- Run I tells that we are seeing the SM
  (with large error bars and several degeneracies in the fits)

- We expect a big improvement in the current Run:

  More data and energy

  And very importantly more distributions

- If there is new physics a the the TeV scale it is most likely to be sitting on "the tail" of some distributions

→ Boosted

→ Off-Shell

Experimentally: clean measurement (leptonic final state)

Theoretically: allows to probe the operator structures at different energy scales

→ Might help to overcome our limited understanding of y_t

Motivation

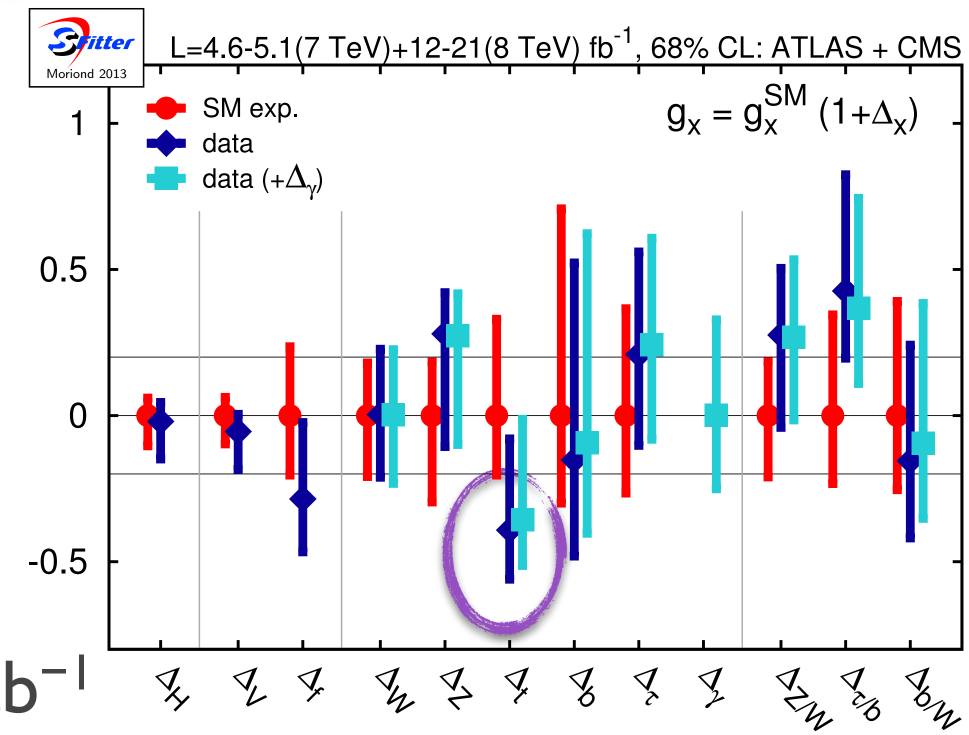
- Higgs–gauge couplings - extracted from precise tree–level information

- Higgs-fermions couplings - largely relies on loop–induced couplings

→ Limited and model–dependent

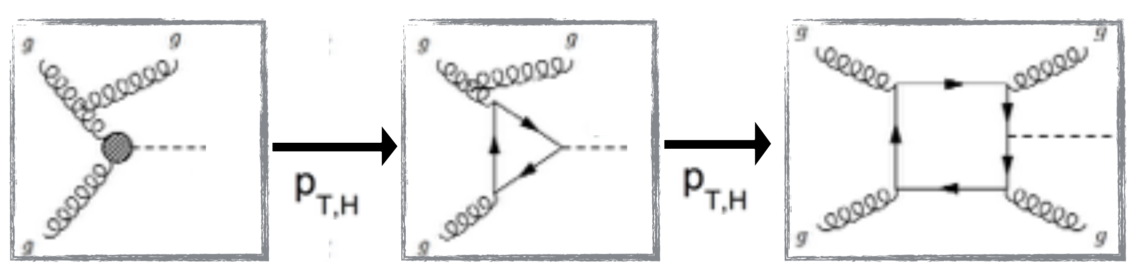
→ ttH measurement challenging: y_t at 20% needs ~$3ab^{-1}$

(Moretti, Petrov, Pozzorini, Spannowsky)

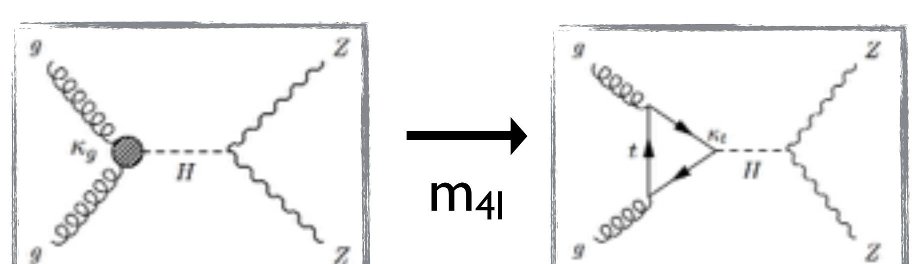


- In general a "loop" is not a fixed number. QCD corrections are dynamic

- Boosted Higgs:



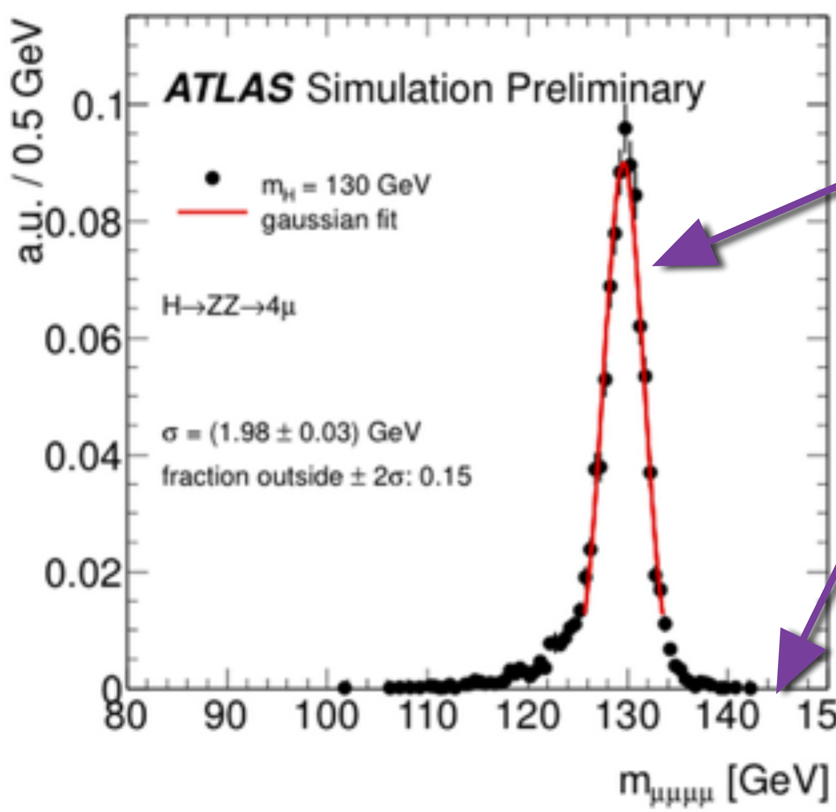
- Off-shell Higgs:



Off-Shell Higgs Production

- Just recently, we start to recognize the importance of the Off-Shell Higgs

→ since $\Gamma_H/m_H \sim 3 \times 10^{-5}$ one naively expects very small off-shell rates



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

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

- However, at least 15% of the cross-section comes from m_{4l}>300 GeV

Narrow Width Approximation fails spectacularly - unitarizing property of Higgs

→ Interference with background: gg→H^*→ZZ with gg→ZZ ;

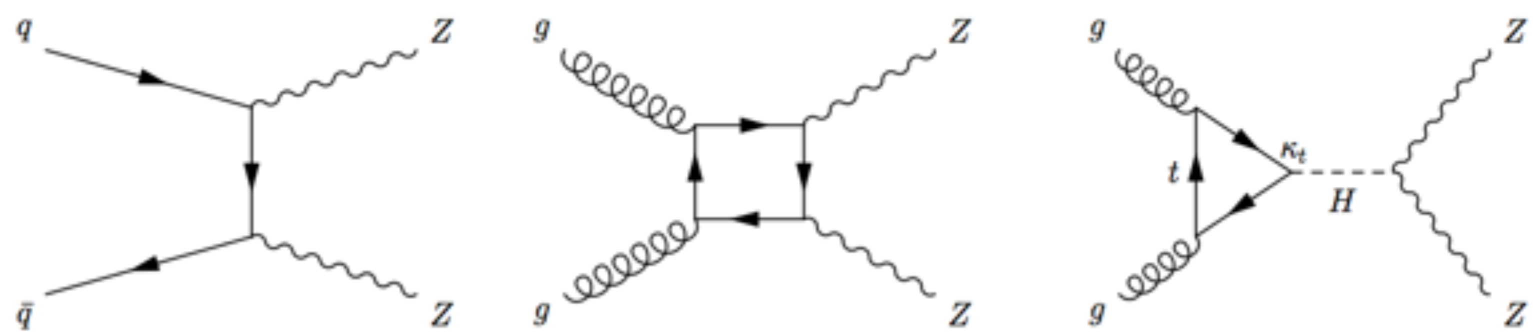
→ ZZ Threshold;

→ and top mass effects change our naive expectation

Kauer, Passarino 2012
Caola, Melnikov 2013
Campbell, Ellis, Williams 2013

Theoretical ingredients

- Signal and background components:



(a) (b) (c)

→ $|a|^2$ - Background component: generated already at tree level (large) known at NNLO

(Cascioli *et. al*. 2014)

→ $|b|^2$ - Continuum background known at LO only. Internal masses make it a non-trivial multi-scale problem; Big uncertainties; Very important calculation for Run II

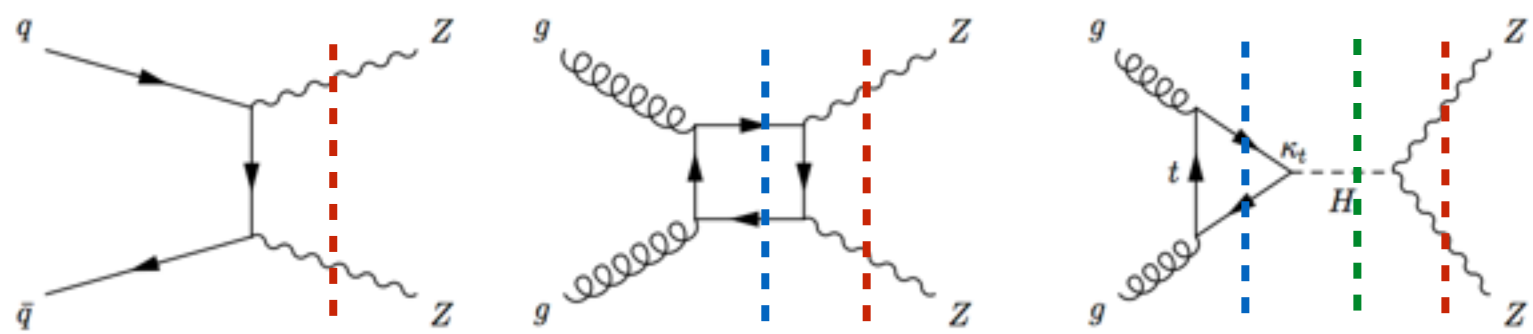
→ $|c|^2$ - signal (loop-induced) known at NNLO

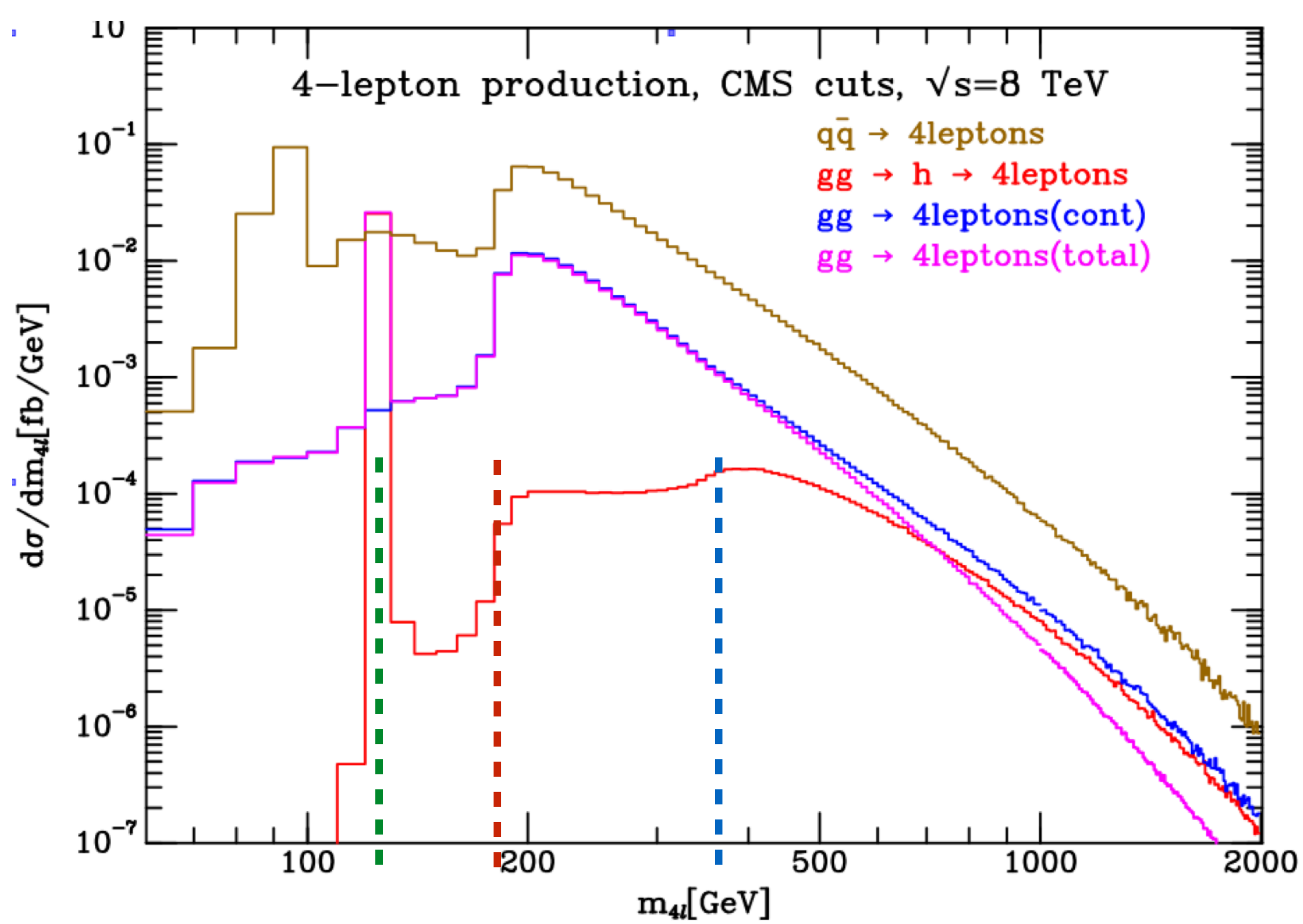
→ b*c - Signal/background interference. Large and destructive at large invariant mass. $|c|^2$ and b*c present similar perturbative QCD enhancement: $K^{NLO}_{b*c} \sim K^{NLO}_{|c|^2}$

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

Theoretical ingredients

- Signal and background components:





Campbell, Ellis, Williams 2013

Theoretical ingredients

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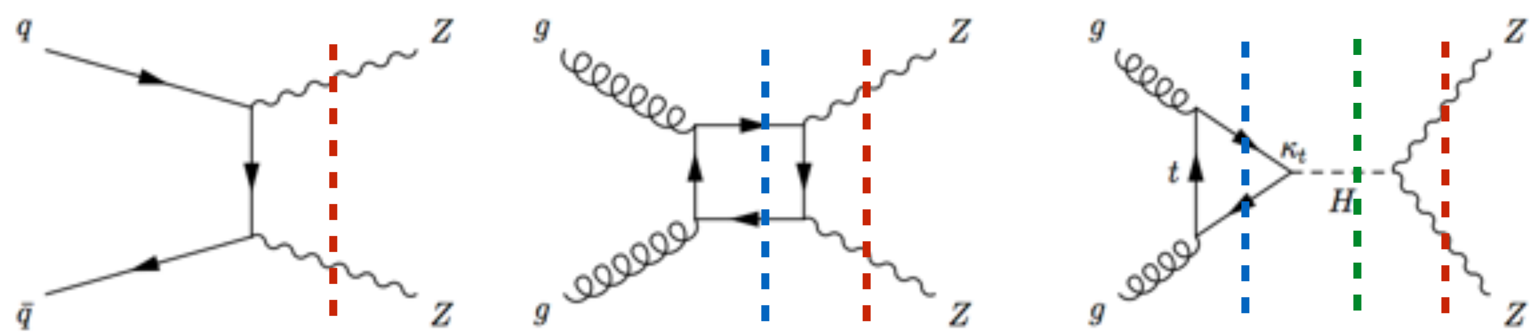


$$\mathcal{M}_t^{++00} = -2\frac{m_{4\ell}^2 - 2m_Z^2}{m_Z^2} \frac{m_t^2}{m_{4\ell}^2 - m_H^2 + i\Gamma_H m_H} \left[1 + \left(1 - \frac{4m_t^2}{m_{4\ell}^2}\right) f\left(\frac{4m_t^2}{m_{4\ell}^2}\right)\right]$$

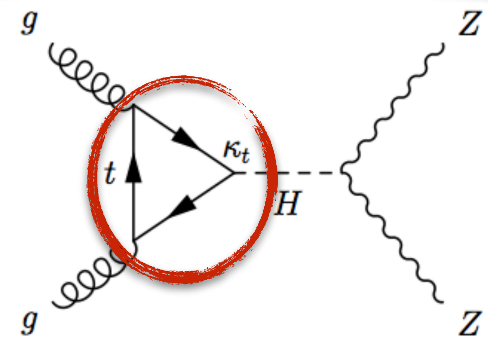
→ Top mass effects in Higgs production

- $\mathcal{M}_t^{++00} \approx +\frac{m_t^2}{2m_Z^2} \log^2 \frac{m_{4\ell}^2}{m_t^2}$ 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

→ The Higgs does what he is expected to do! (Quigg, Lee, Thacker 1977)

Framework



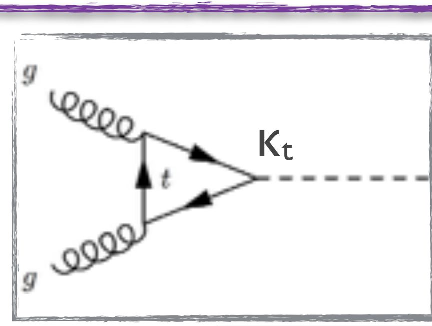
- Higgs production: Is the y_t responsible for the ggH coupling or are there BSM contributions?

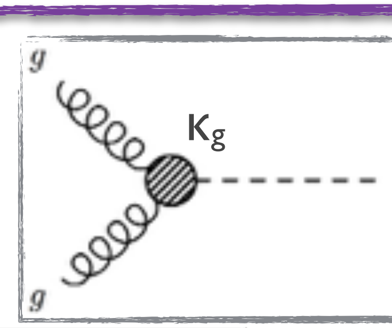
Relevant CP-even dim6 operators to GF:

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

$$k_t = 1 - \frac{c_H}{2} - \mathrm{Re}(c_y) \qquad k_g = c_g$$

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



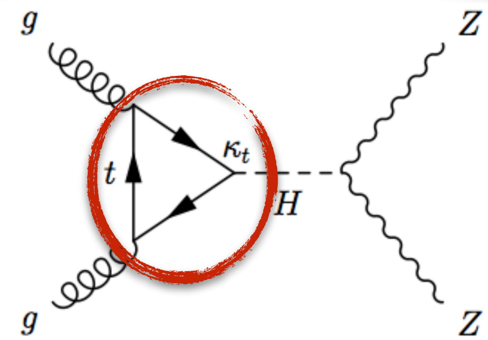


$$\mathcal{M} = \kappa_t \mathcal{M}_t + \kappa_g \mathcal{M}_g$$

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

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

Framework



- Higgs production: Is the y_t responsible for the ggH coupling or are there BSM contributions?

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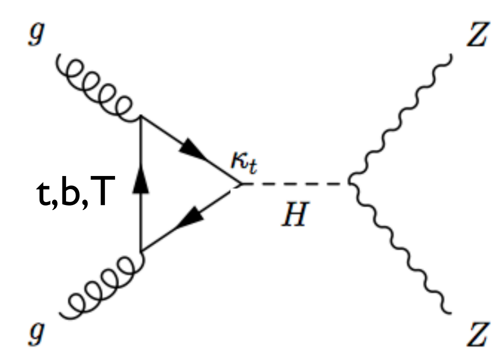
- Top partners - Prototype model inducing this degeneracy

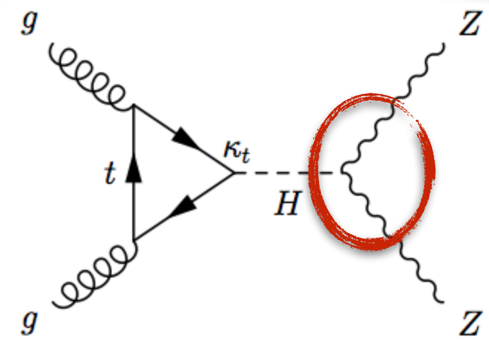
$$\mathcal{L} = -y\bar{Q}_L t_R H - M\bar{T}T - Y_T\bar{Q}_L T_R H$$



→ Heavy fermion loops generate k_g and mixing modifies y_t (k_t)

Dawson, Furlan (2014); Chen, Dawson, Lewis (2014)

Framework



- Higgs decays - the dim6 operators give rise to the following Higgs interactions:

$$\mathcal{L}^{HVV} = g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu} \partial^{\nu} + g^{(2)}_{HZZ} H Z_{\mu\nu} Z^{\mu\nu} + g^{(3)}_{HZZ} H Z_{\mu} Z^{\mu}$$

→ The additional operators $Z_{\mu\nu} Z^{\mu} \partial^{\nu}$ and $H Z_{\mu\nu} Z^{\mu\nu}$ affect the longitudinal Z polarisation

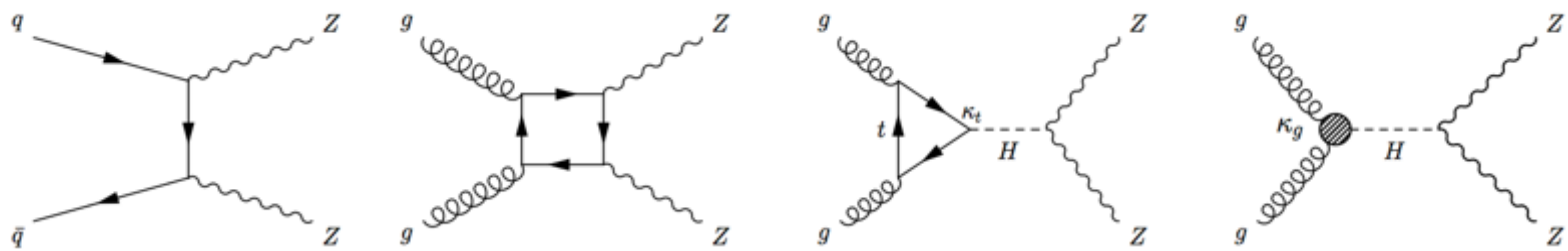
→ So they lead to similar m_{4l} kinematics as the SM $H Z_{\mu} Z^{\mu}$
We consider only $g^{(3)}_{HZZ}$ in our analysis

Gainer, Matchev, Mrenna, Park (2014)
Azatov, Grojean, Paul, Salvioni (2014)

→ On-Shell H>ZZ Nelson angles provide a better probe to the decays than off-shell measurement. More data and better kinematic sensitivity. Off-shell mostly probes the energy growth

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 known @LO

- Since signal and signal-background interference have very similar QCD enhancements

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

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

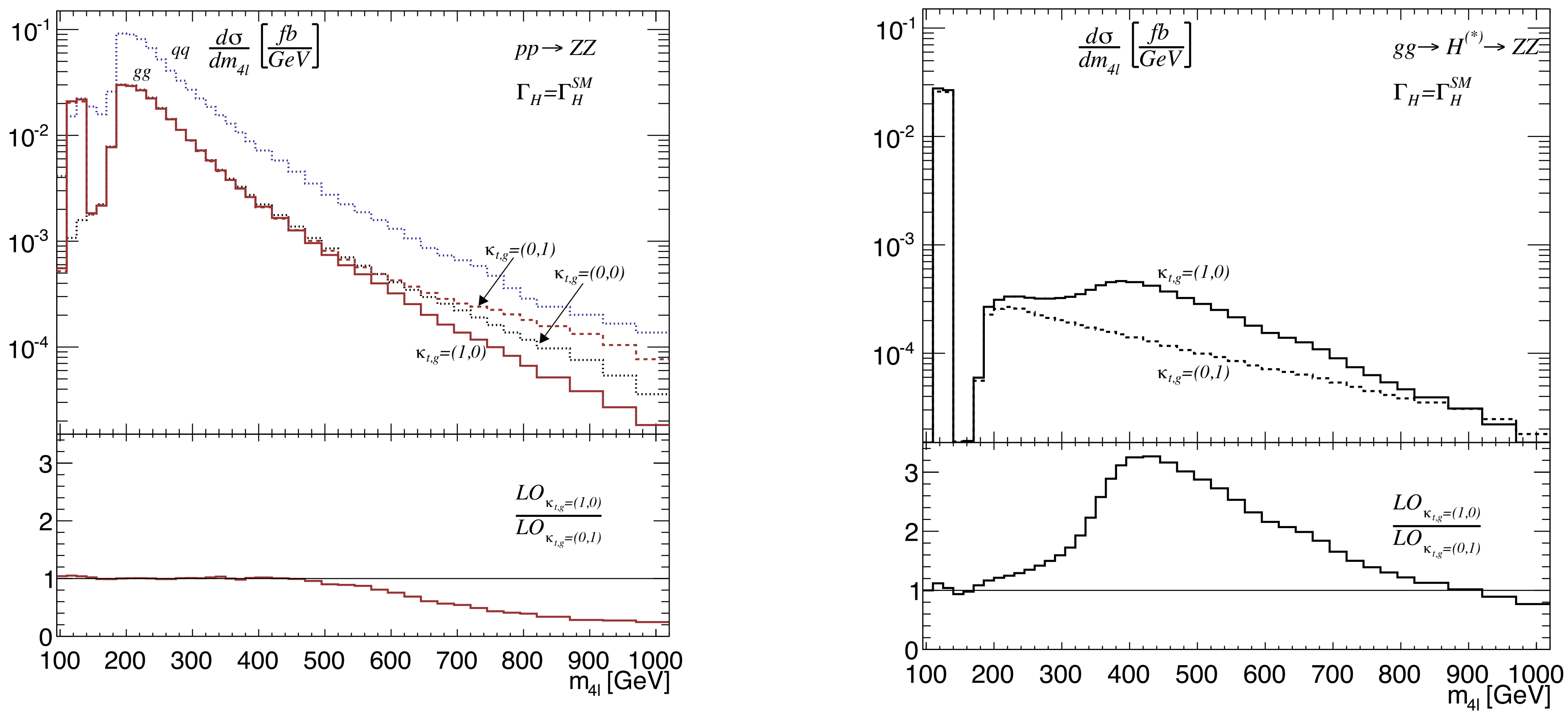
➡ We include these effects through a differential NLO reweighing obtained from the signal

Off-Shell Higgs Production

- Carries information on the Higgs couplings at different energy scales

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

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

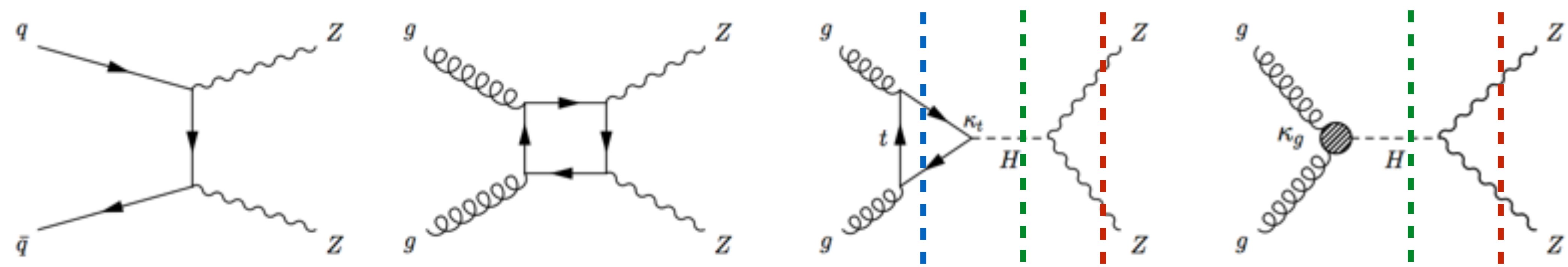


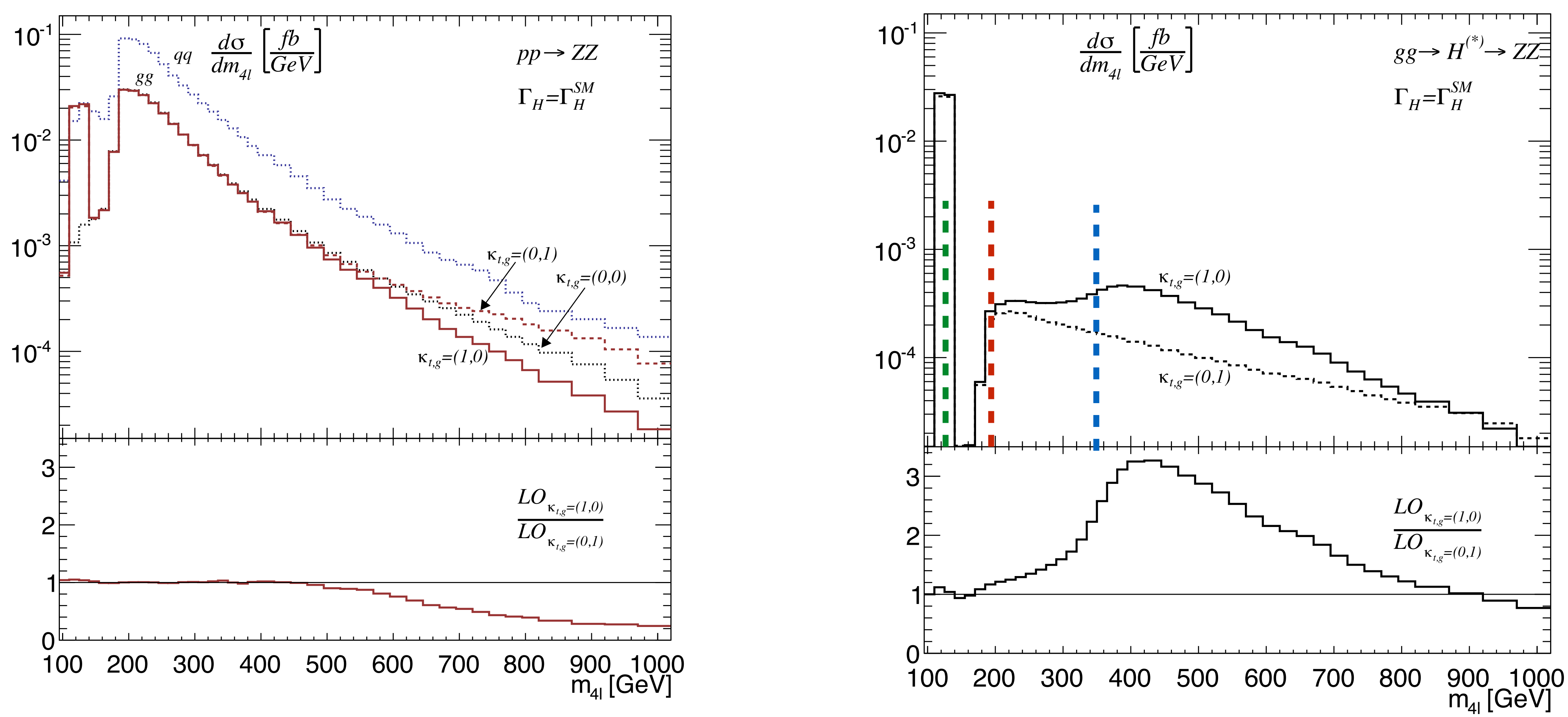
- qq→ ZZ generated already at tree level. Much larger than gg → ZZ
- Enhancement on the tail for low-energy limit and suppression of the full top mass result

Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

Off-Shell Higgs Production

- Carries information on the Higgs couplings at different energy scales

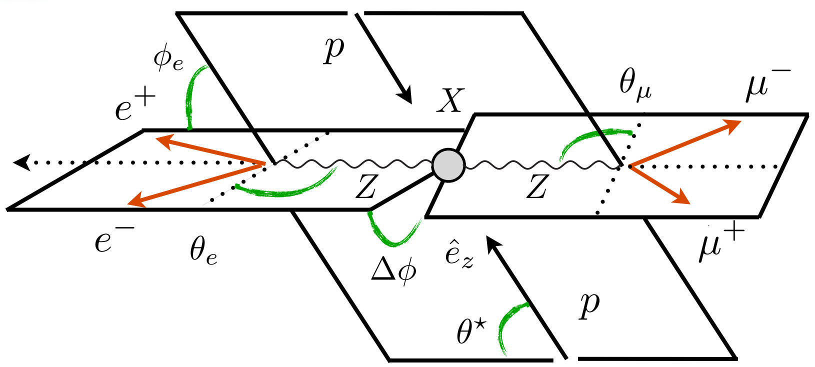




Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

Nelson angles

- Signal only: info on HZZ operator

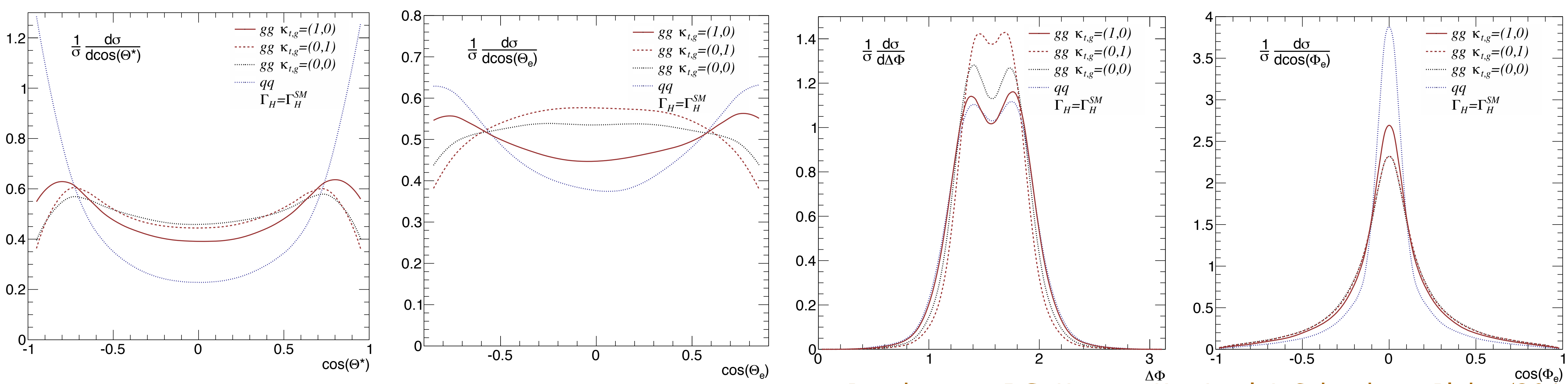


Cabibbo and Maksymowicz (1965)
Dell'Aquila and Nelson (1986)

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
suppress the background and distinguish the signal hypothesis

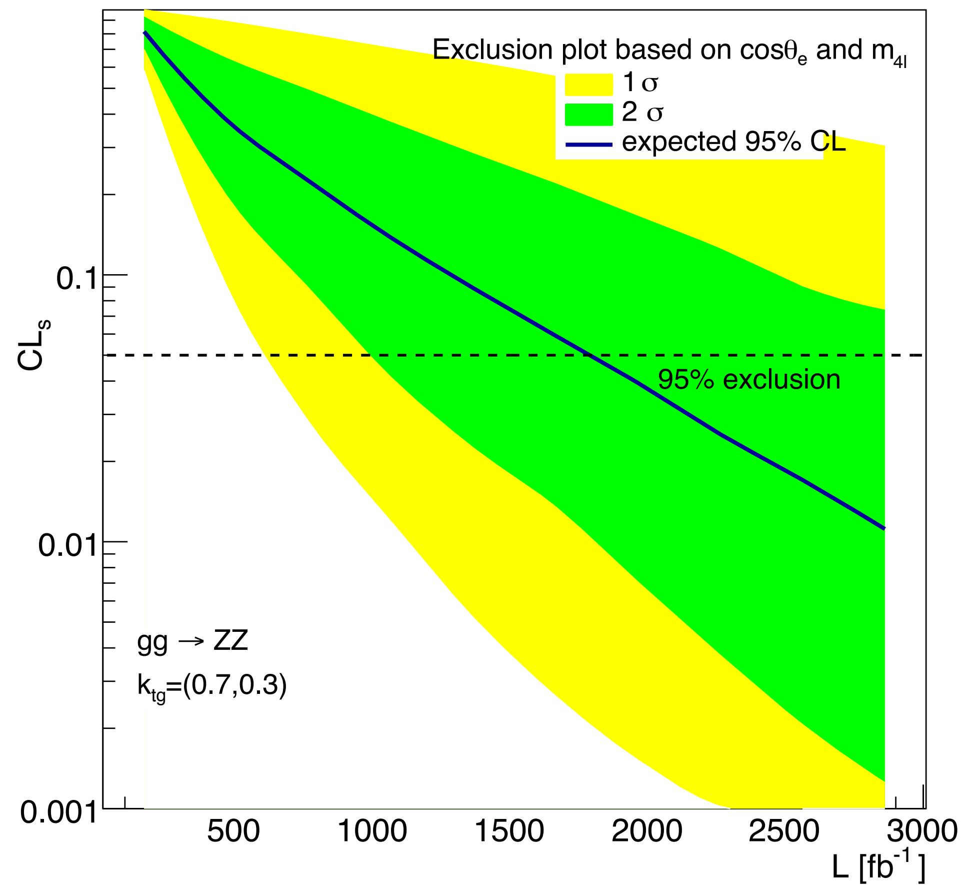


Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

Log-likelihood analysis

- CMS cut flow analysis for the off-shell $H \to ZZ$ measurement plus:

1) Suppress the $qq \to ZZ$ background by requiring that $|\cos\Theta^*| < 0.7$
2) 2D CLs analysis - ($\cos\theta_e$,m_{4l}).



➡ Exclusion of our BSM hypothesis need a few inverse attobarns
There is a room for significant improvement: E.g., MEM

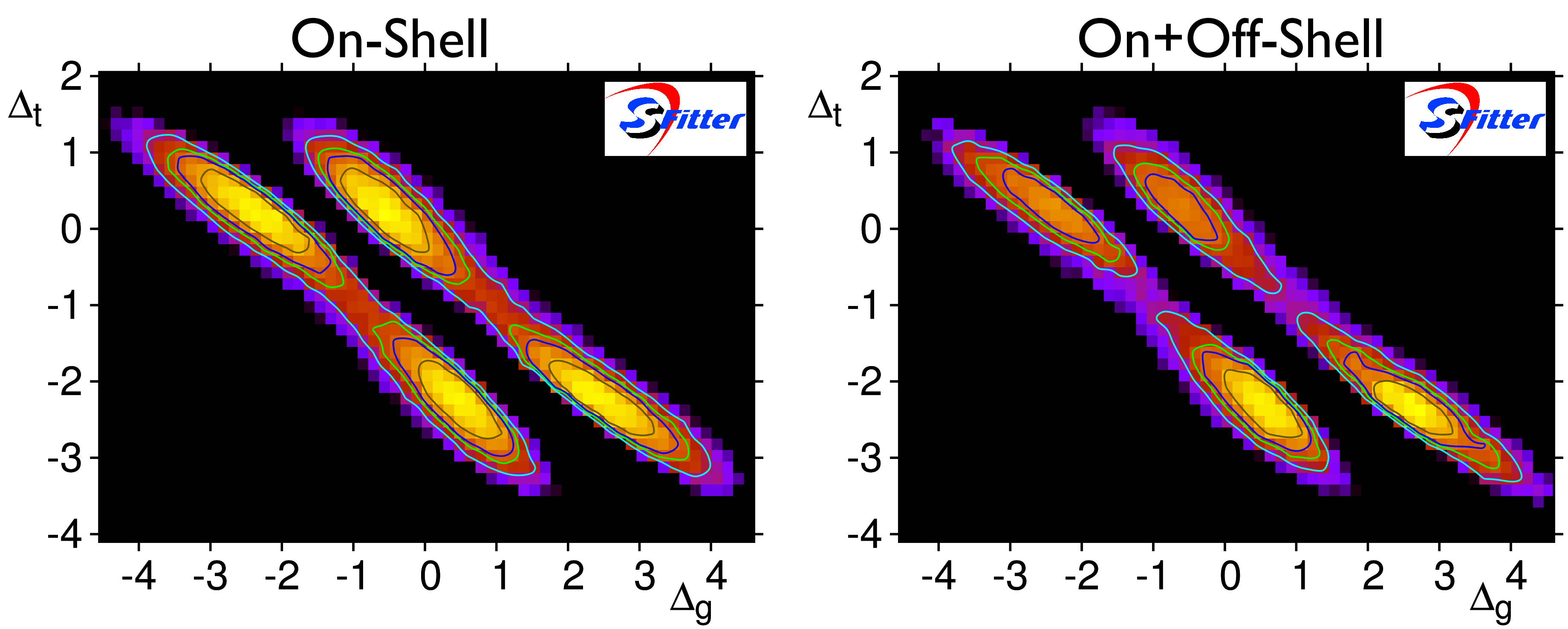
Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

Off-Shell Measurements: Sfitter results

- Full coupling fit to the ATLAS+CMS Run I data:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$

$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu}$$



➡ The Run I CMS results present an excess of events in the off-shell tail

➡ Atlas sees the opposite, however it has much less statistics for this measurement

➡ This gives a slight preference to the negative solutions in our fit

More on the dim6 fits with Run-I results: see talk by Oscar Eboli

Higgs width measurement

- SM prediction $\Gamma_H \sim 4\text{MeV}$

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

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

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

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

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

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

- While interesting idea, it is not a model independent width measurement

Englert, Spannowsky (2014)
Englert, Soreq, Spannowsky (2014)

Higgs width measurement

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

  This 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

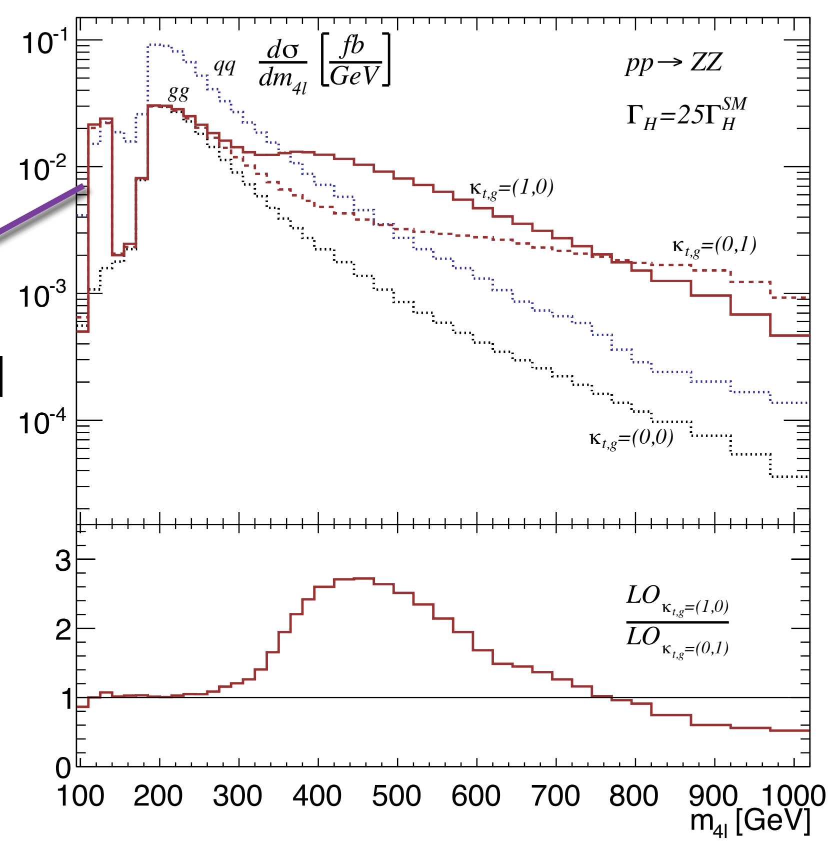
$$\sigma^{\text{Off-Shell}}_{gg\to H^*\to ZZ} \propto \left(k_t g_{ggH}(m_{4\ell}) + k_g g_{ggH}(m_H)\right)^2 g^2_{HZZ}(m_{4\ell})$$ → non-trivial k_t & k_g dependence

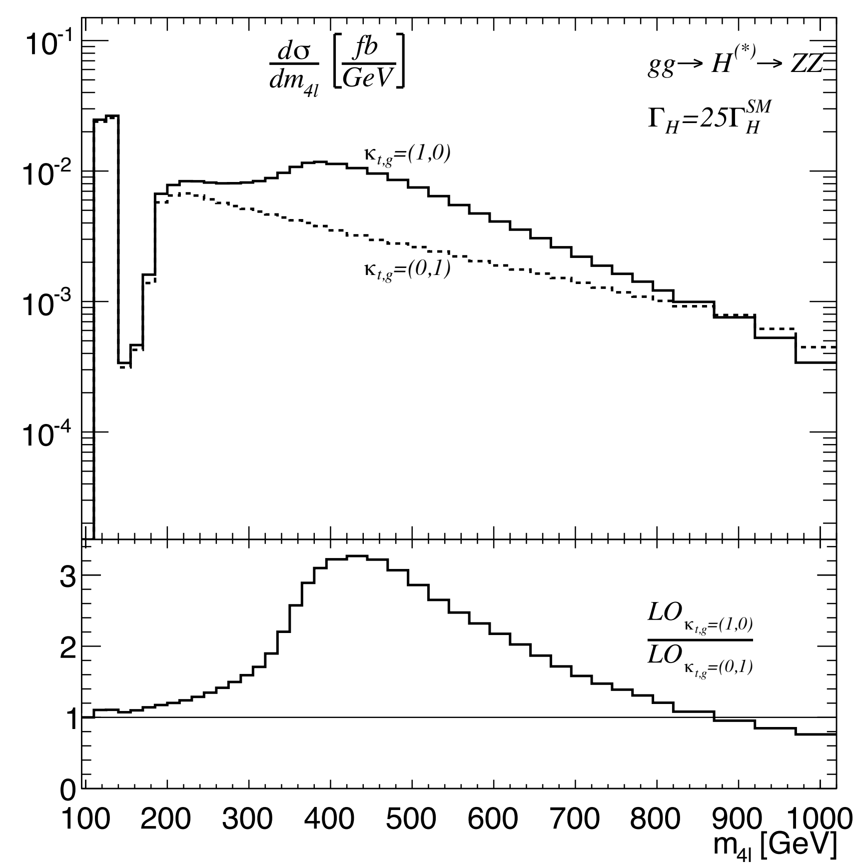
- Example: $\xi^4 = 25 \quad \rightarrow \quad \Gamma_H = 25\Gamma_H^{SM}$

Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

Signal strength still

μon-shell = 1



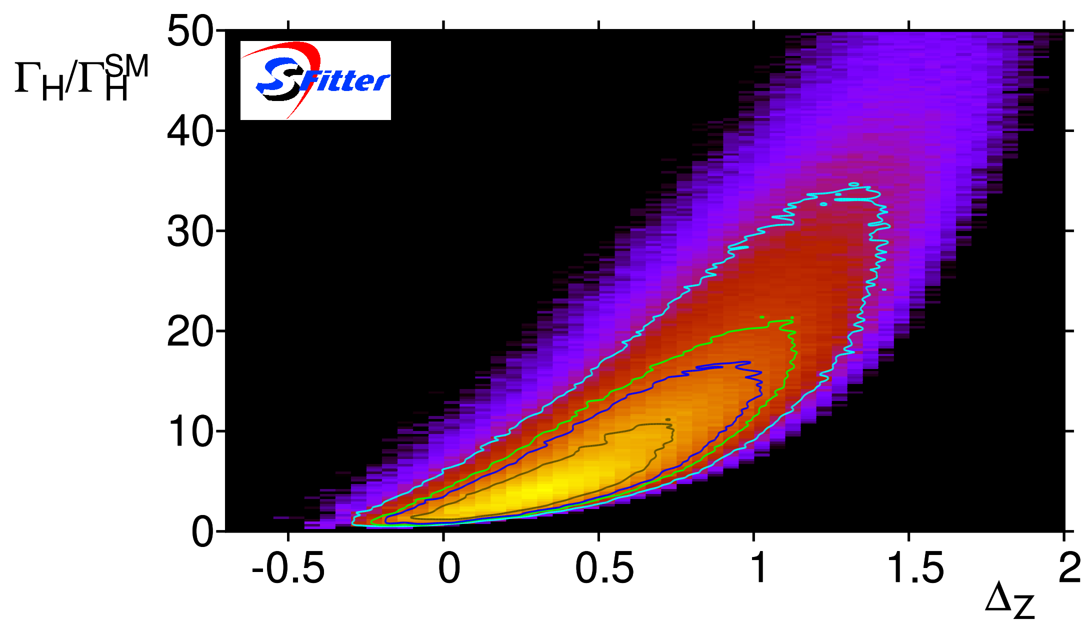


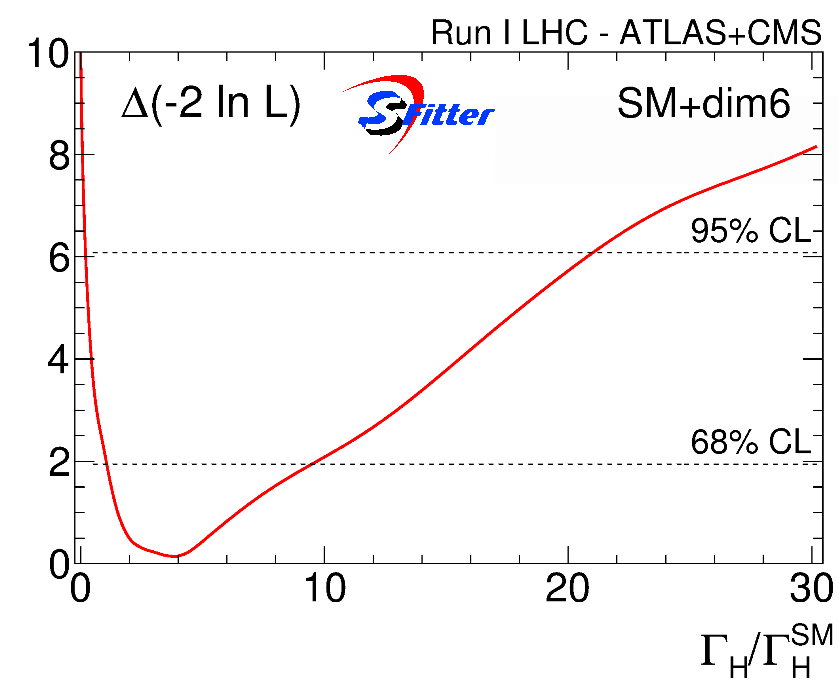
Higgs width measurement

- Leaving the Higgs width as a free parameter in the SFitter setup:

➡ Total width measurement - combination of Off+On-Shell measurements. But now accounting for the full m_{4l} profile

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible decays} + \text{unobservable decays}$$





➡ For $\Gamma_H/\Gamma^{SM} \gg 1$ Higgs production and decay rates scale like $g_X{}^4/\Gamma_H$

As expected, for $\Gamma_H/\Gamma^{SM} \sim 30 \sim 2.3^4$ we have $\Delta Z \sim 1.3$

Higgs width measurement

- Leaving the Higgs width as a free parameter in the SFitter setup:

→ Total width measurement - combination of Off+On-Shell measurements. But now accounting for the full m_{4l} profile

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + {\rm h.c.} \right)$$

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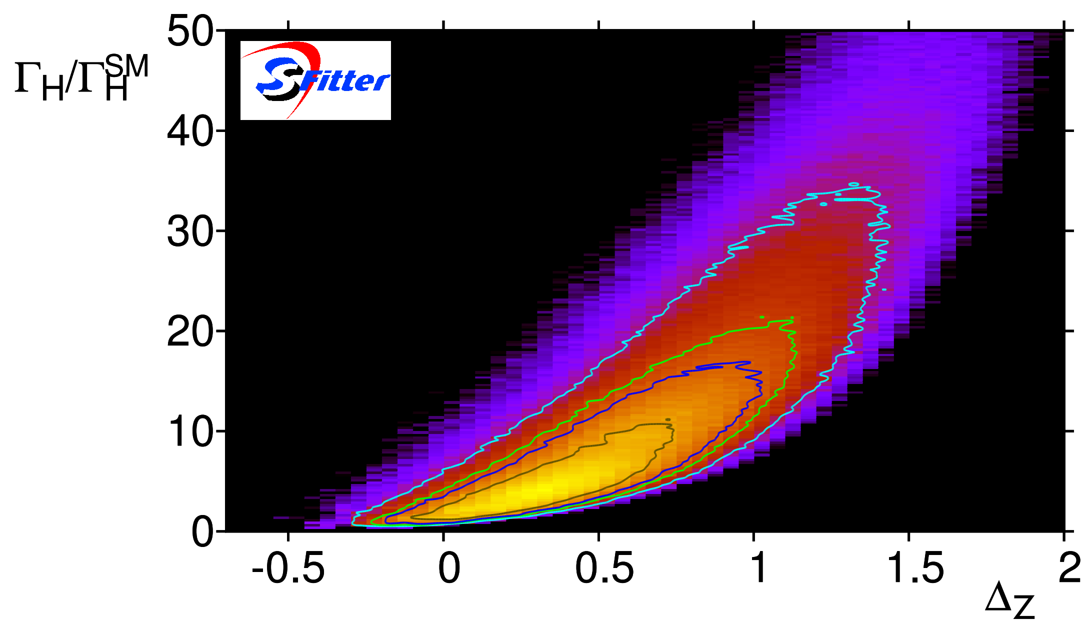
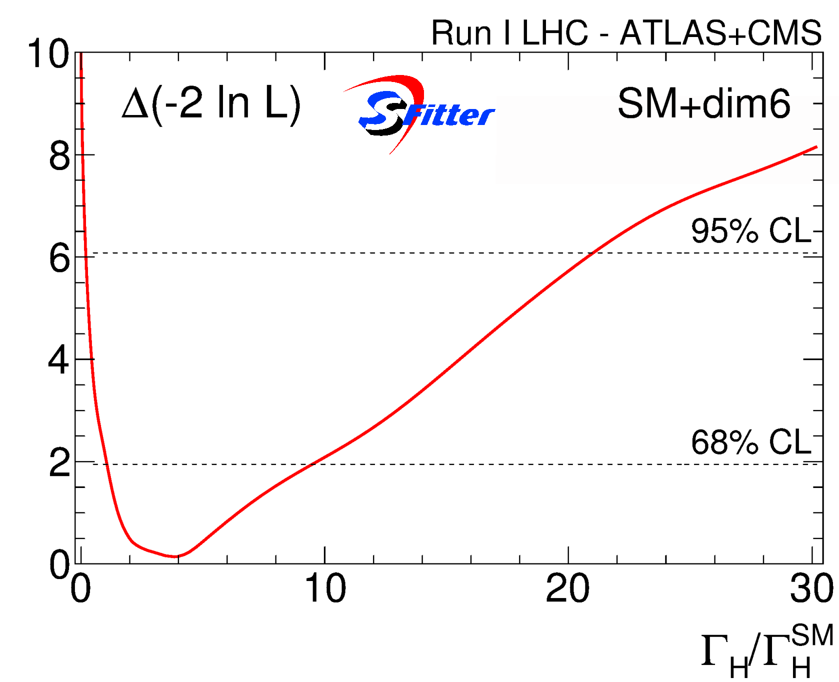


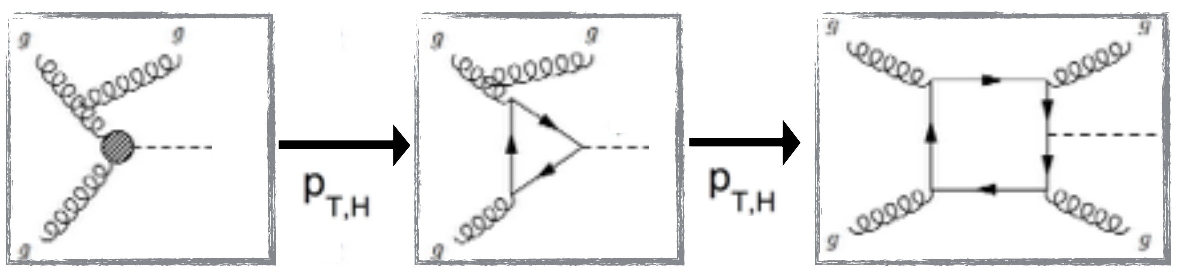


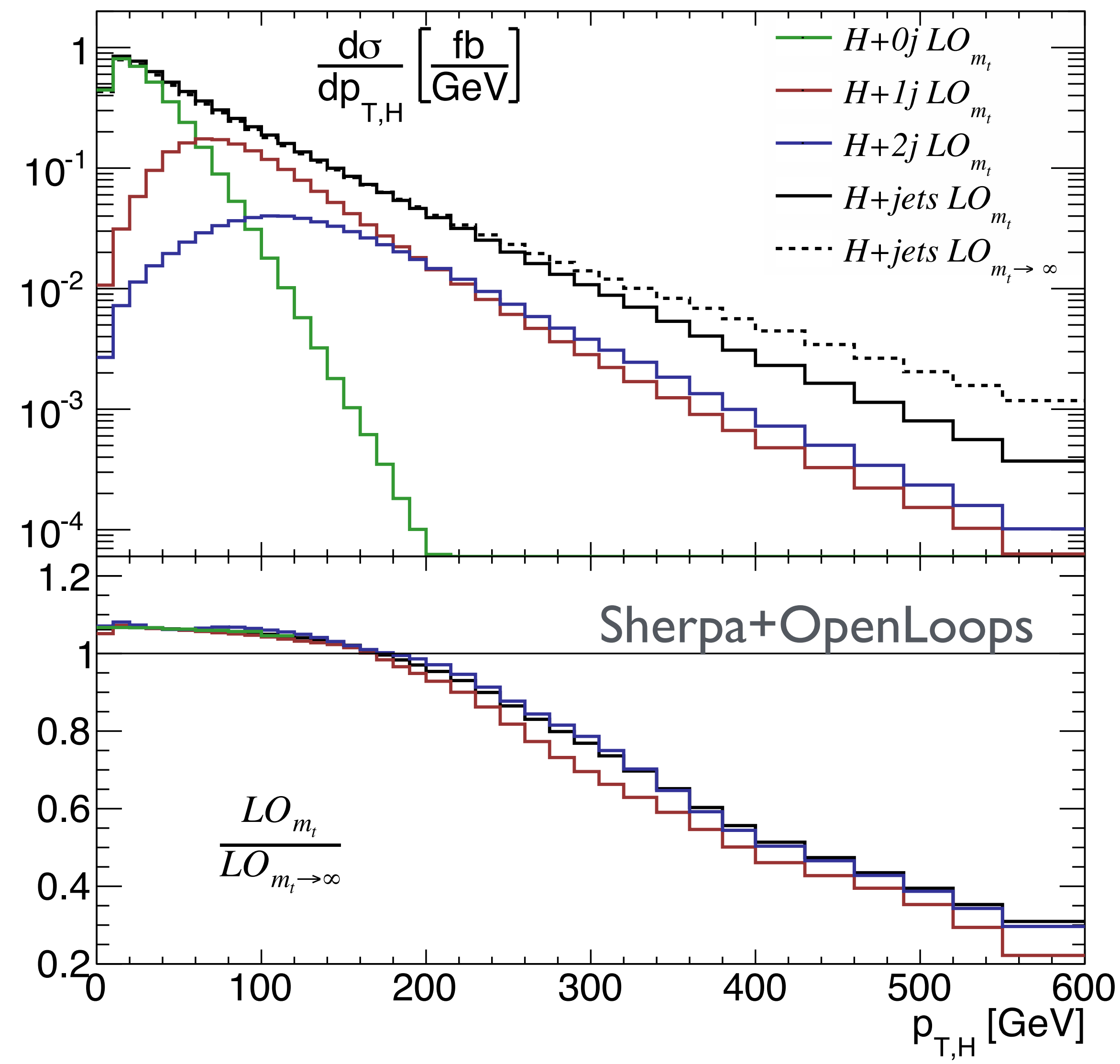
→ $\Gamma_H < 9.3\Gamma^{SM}$ at 68% CL. While our width constraint was obtained considering possible BSM operators, our bound is still competitive to other analysis that account only to SM-like interactions

→ Key ingredient: full m_{4l} profile

Complementary approaches

- H+jets CKKW merging





Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

➡ How many jets do we need to account for?

As many as we can add!

➡ 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

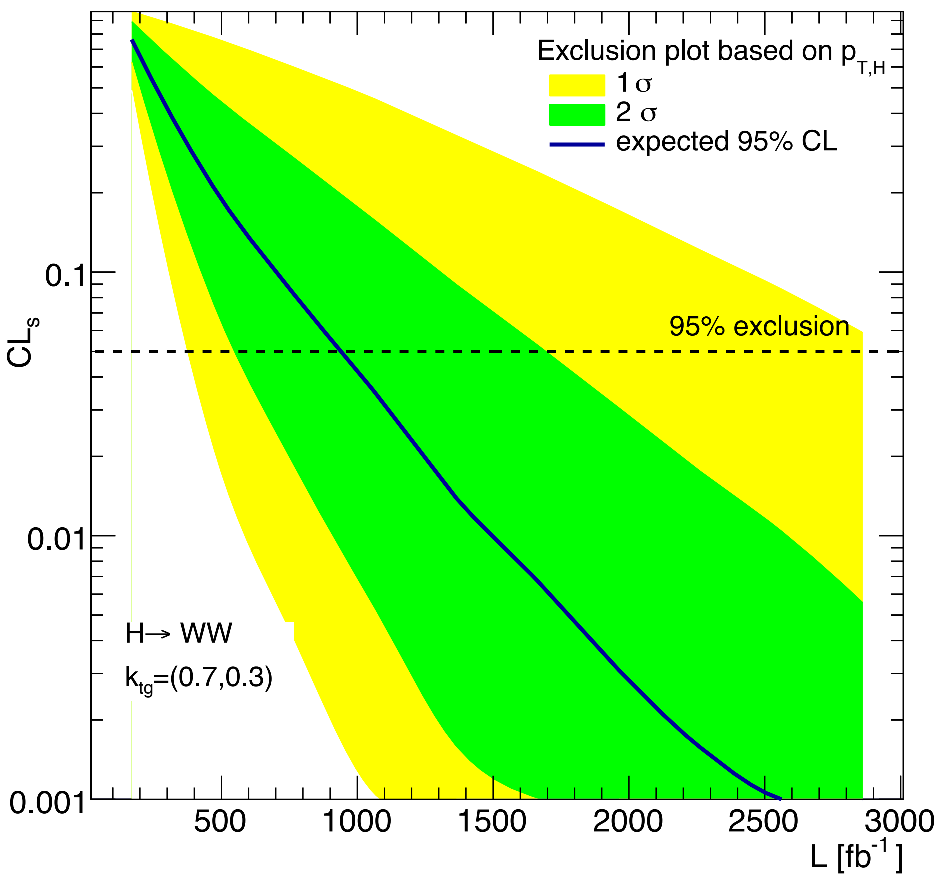
➡ Consequently the same happens for the merged result

Complementary approaches

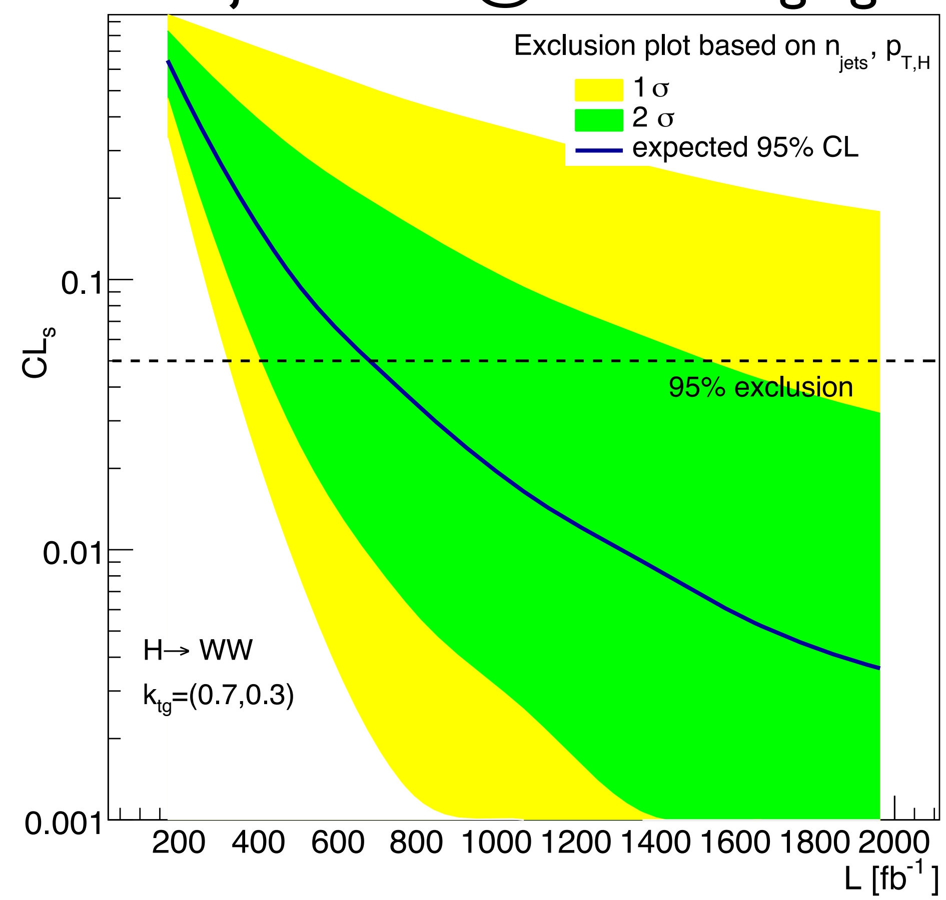
- The merged distributions capture the info from the first and second jet bin

➡ Better constraints for the merged sample:

Hjj



H+jets MEPS@NLO merging



Buschman, DG, Krauss, Kuttimalai, Schonherr, Plehn (2015)

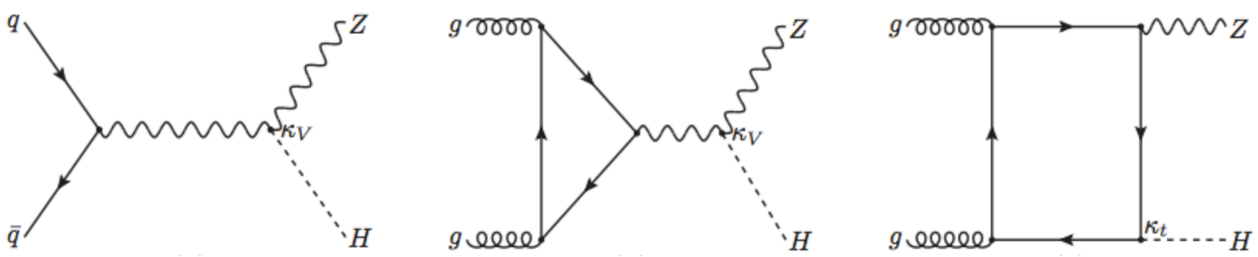
➡ CLs uses (njet, p_{TH}) to maximizes the sensitivity.
Only possible/reliable via multijet merging

Azatov, Paul (2014)
Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant (2014)
Banfi, Martin, Sanz (2013)
Grojean, Salvioni, Schlaffer Weiler (2013)
Buschman, Englert, DG, Plehn,Spannowsky (2014)
Dawson, Lewis, Zeng (2014) ...

More on boosted H+jets: see talk by Ian Lewis

Complementary approaches

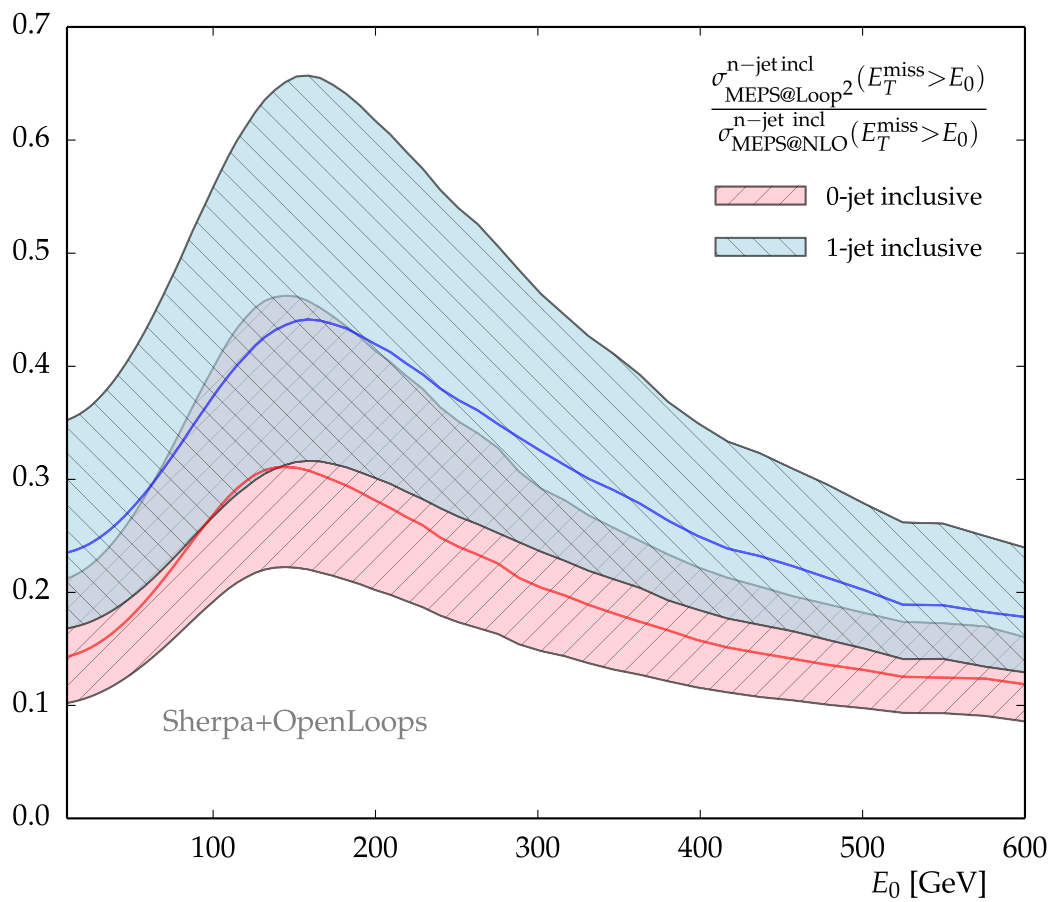
- Higgs-Strahlung: H(bb)Z(ll) via jet-substructure



$$\mathcal{M} = \kappa_t \mathcal{M}_t + \kappa_V \mathcal{M}_V$$

$$\frac{d\sigma}{dp_{TH}} = \kappa_t^2 \frac{d\sigma_{tt}}{dp_{TH}} + \kappa_t \kappa_V \frac{d\sigma_{tV}}{dp_{TH}} + \kappa_V^2 \frac{d\sigma_{VV}}{dp_{TH}}$$

- Boosted kinematics enhances loop-induced component



DG, Krauss, Kuttimalai, Maierhoefer (2015)

Most of Run I LHC analysis neglect this component

Note that this might change:

→ The invisible bounds from Z(ll)H

→ And y_b from Z(ll)H(bb)

Hespel, Maltoni, Vryonidou (2015)
DG, Krauss, Kuttimalai, Maierhoefer (2015)
Englert, McCullough, Spannowsky (2014)
Altenkamp, Dittmaier, Harlander, Rzehak, Zirke (2013)
Craig, Farina, McCullough, Perelstein (2014)

Complementary approaches

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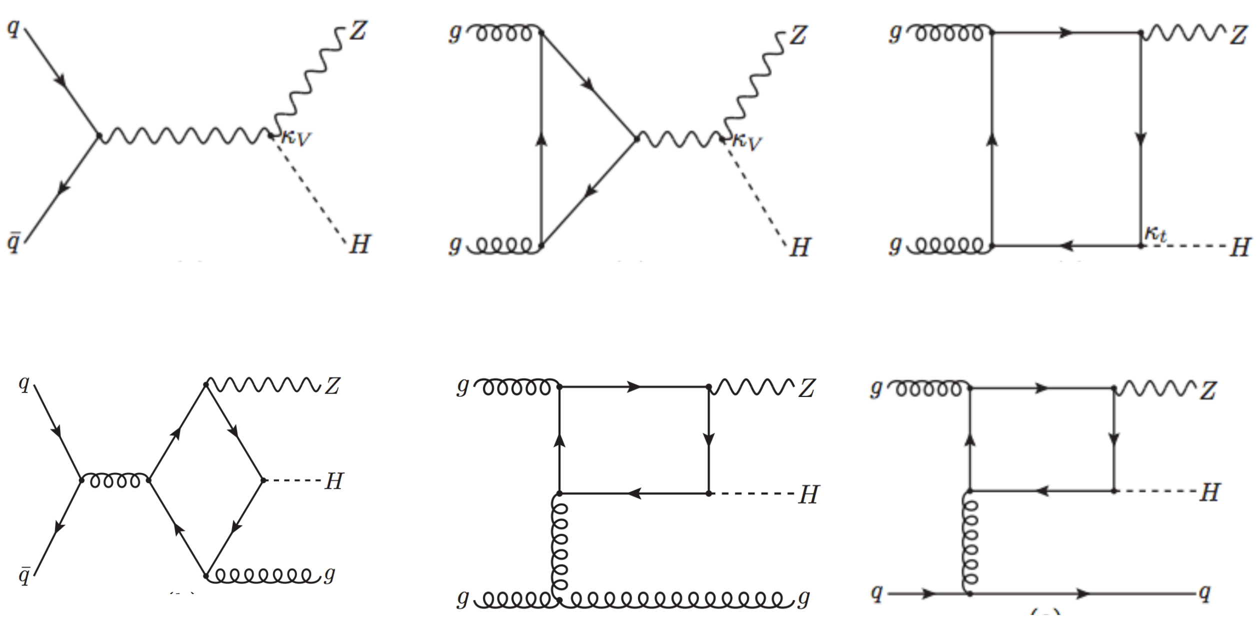
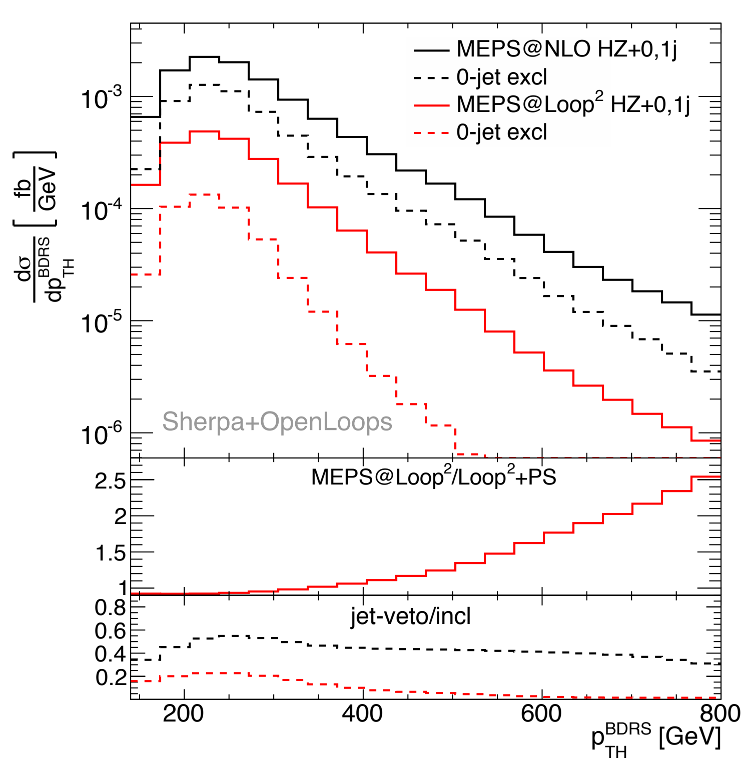
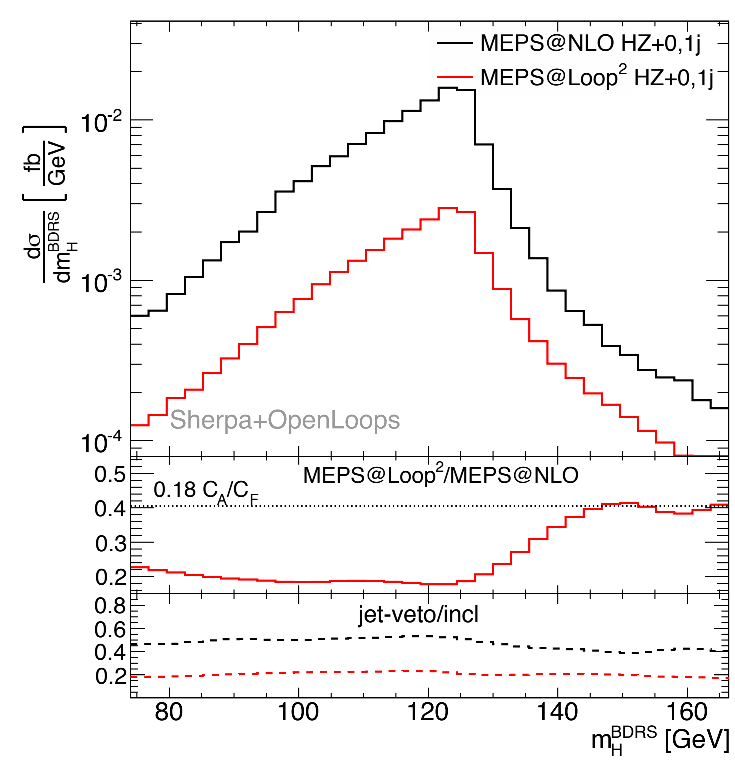


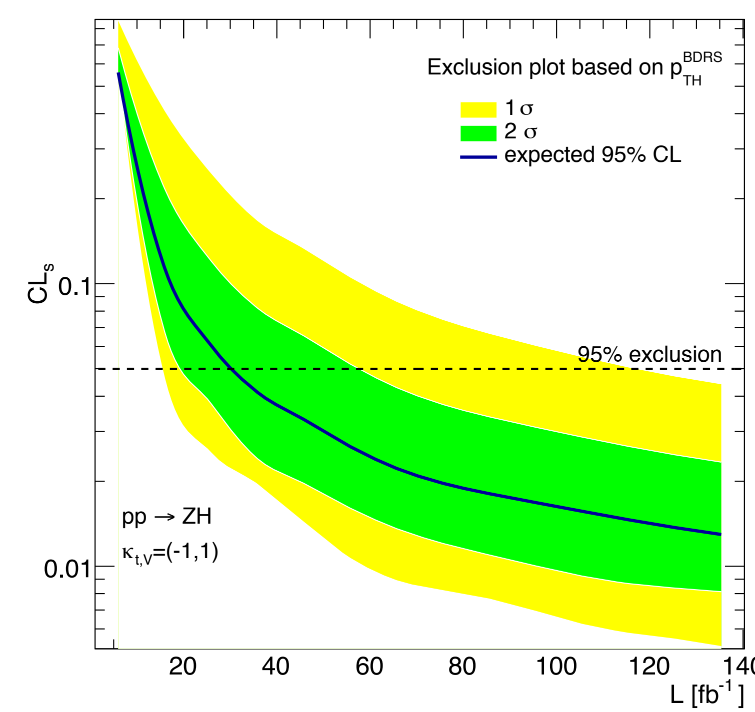
Merging up to one jet (Sherpa+OpenLoops):
MEPS@NLO - DY
MEPS@Loop2 - GF

→ GF changes p_{TH} and m_H^{BDRS} profiles

→ Relevant constraints for the y_t







DG, Krauss, Kuttimalai, Maierhoefer (2015)

Summary

- LHC Run II will give very energetic Higgses with significant statistics

- Off-shell, boosted (H+jets, HZ+jets…) will be very important to further explore the TeV scale

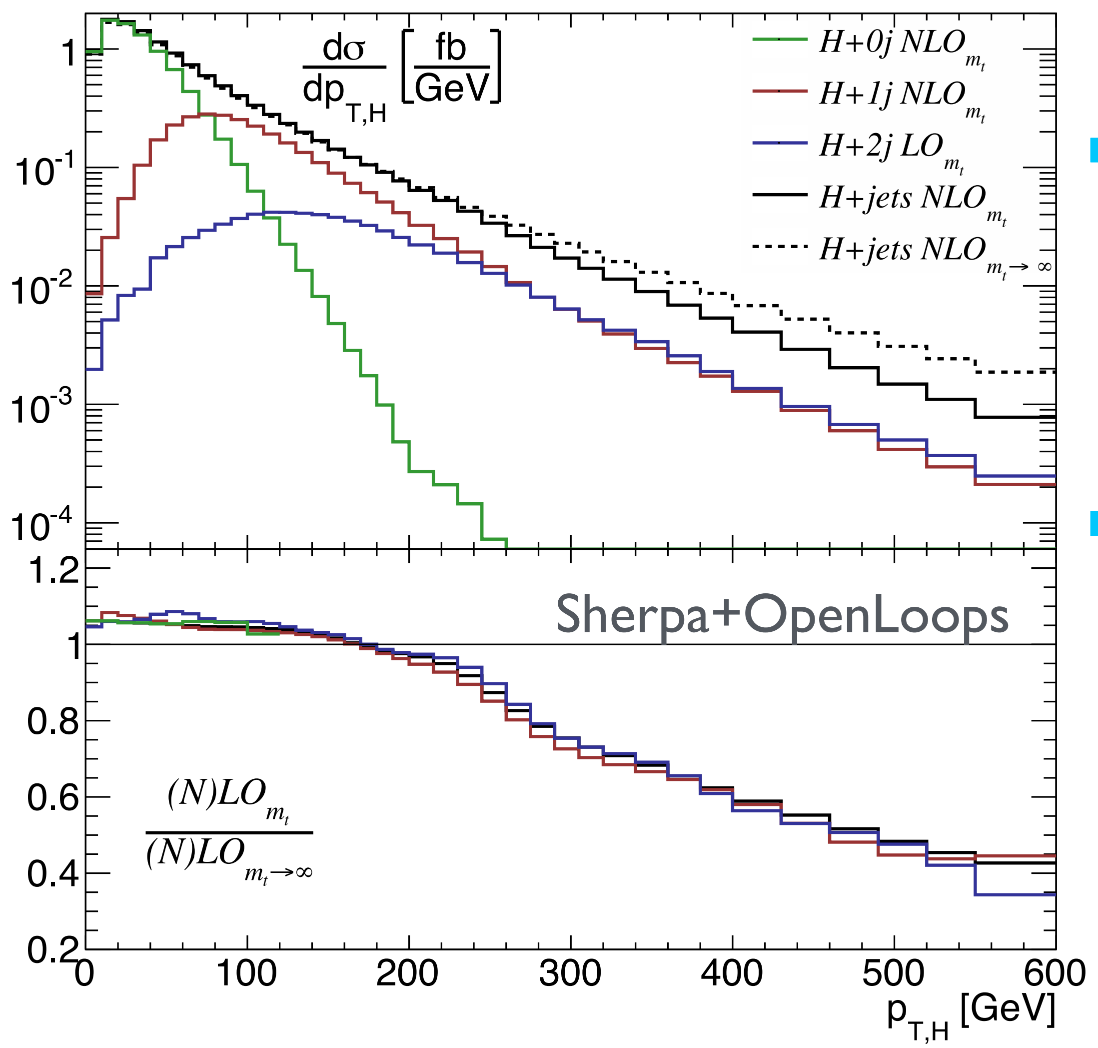
- Higher order calculation accounting for heavy quark mass effects are becoming even more important

- We should go beyond the total rate information. Distribution profiles significantly improve our constraints and should be added to the coupling fits

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

M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn (2014)