Higgs-Strahlung: Merging the NLO DY and Loop-Induced 0+1 jet Multiplicities

DG, F. Krauss, S. Kuttimalai, P. Maierhöfer (arxiv:1509.01597)

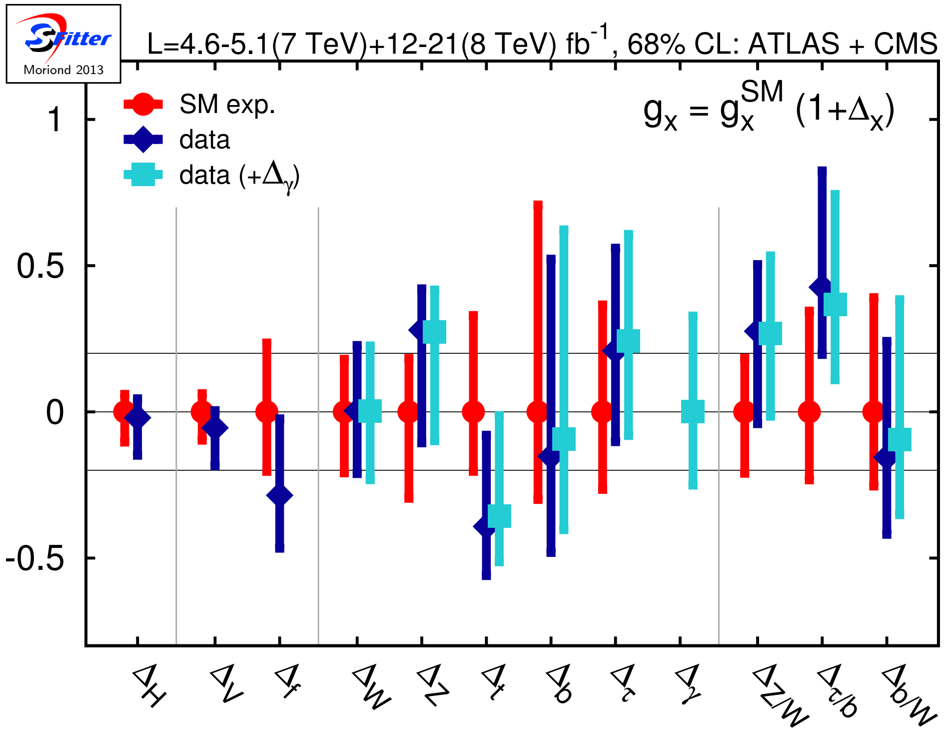
Theoretical Particle Physics Seminar
Universität Zürich - 24.11.2015

Dorival Gonçalves

Outline

- Calculation setup
- Z(ll)H(inv) & Z(ll)H(bb)
- Impact on general distribution profiles
- Impact on coupling fits

Motivation

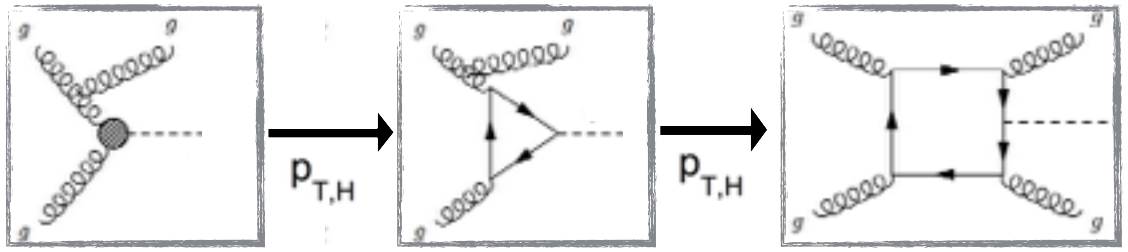


- Run I tells that we are seeing the SM
  (with large error bars and several degeneracies in the fits)

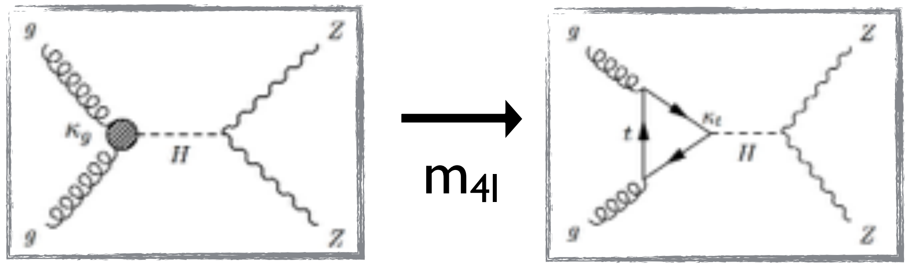
- We expect a big improvement in the current Run:
  More data and energy
  And very importantly more distributions

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

- Boosted Higgs:



- Off-shell Higgs:

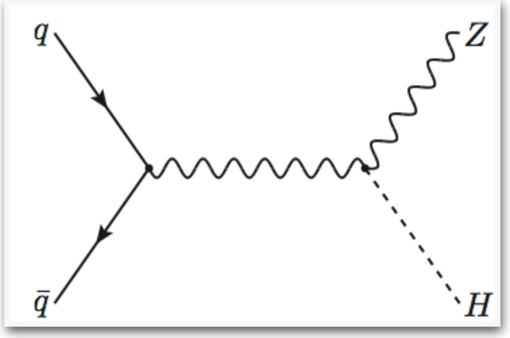


→ Might help to overcome our limited understanding of $y_{t(b)}$

Motivation

- $pp \to ZH$: Prominent path for accurate understanding of Higgs boson couplings

→ $H \to b\bar{b}$: Largest, yet most challenging Higgs decay (overwhelming QCD backs)



- Leading channels, GF and VBF, fail due to huge QCD backs
- Z(ll)H(bb) supplemented by jet substructure technics can succeed

  First hints in the Run-I by ATLAS and CMS but not fully stablished yet

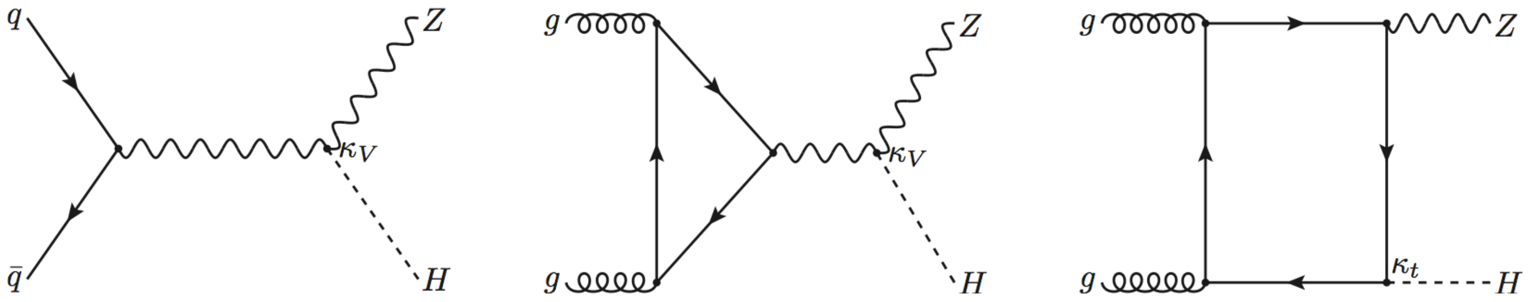
  Butterworth, Davison, Rubin, Salam (2008)

→ Z(ll)H(inv): Invisible Branching ratio constraints

- One of the strongest bounds: $BR(H \to inv) < 0.75\ (0.58)$ for ATLAS (CMS)

Higgs-Strahlung Production

- In the SM, ZH production is dominated by DY-like mode. At LO~O(α_{EW}^2)
- Gluon Fusion, loop-induced process mediated by quark loops. At LO~O($\alpha_S^2\alpha_{EW}^2$)



→ GF and DY sub-processes do not interfere

→ GF leads to O(10%) corrections to the total rate

Altenkamp, Dittmaier, Harlander, Rzehak, Zirke (2013)
Brein, Harlander, Wiesemann, Zirke (2011)
Englert, McCullough, Spannowsky (2014)
Hespel, Maltoni, Vryonidou (2015)
Ferrera, Grazzini, Tramontano (2014)

- There are four major factors that guarantee GF larger than the anticipated naive $\alpha_S^2 \approx 1\%$

→ Larger gluon PDF

→ Larger initial state colour factor

→ Top Yukawa coupling appears in the place α_{EW} factors: $y_t \sim O(1)$

→ Threshold enhancement at $m_{ZH} \sim 2m_t$, which gives rise to relevant rates at the boosted regime $p_{TH} \sim m_t$

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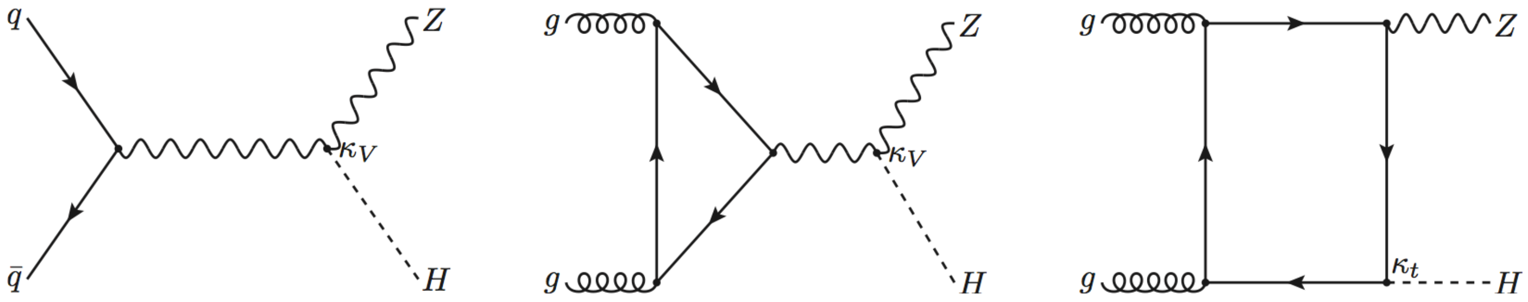

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- On the phenomenological side, and in particular in the framework of Higgs boson coupling fits, loop-induced provides an additional probe to the size and the sign of the top-quark Yukawa coupling

$$y_t = \kappa_t y_t^{SM}, \qquad g_{HVV} = \kappa_V g_{HVV}^{SM}$$

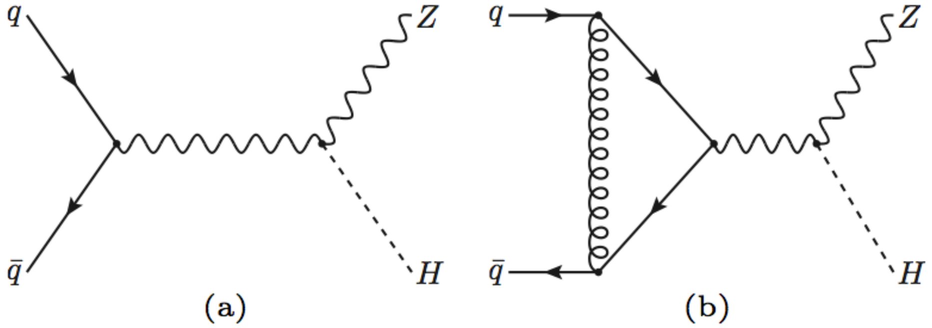
On the other hand, $qq \to ZH$ probes only κ_V

Higgs-Strahlung Production

- Higher-order corrections, multi-jet merging, and simulation set-up:
- SHERPA event generator (“Swiss knife”): LO, dipole subtraction, merging, hadronization…
- OpenLoops: Loop contributions
- Collier: evaluation of tensor integrals
- Finite width effects and spin correlations from Z decay are fully accounted for

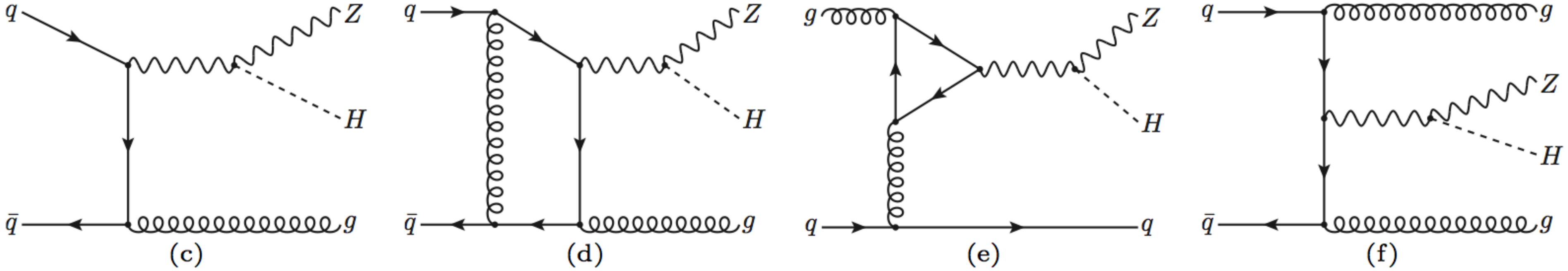
DY-like pp→HZ(ll)+0, 1 jets at NLO accuracy in QCD merged into a inclusive sample (MEPS@NLO)

ZH:



(a) (b)

ZHj:



(c) (d) (e) (f)

Higgs-Strahlung Production

- Higher-order corrections, multi-jet merging, and simulation set-up:
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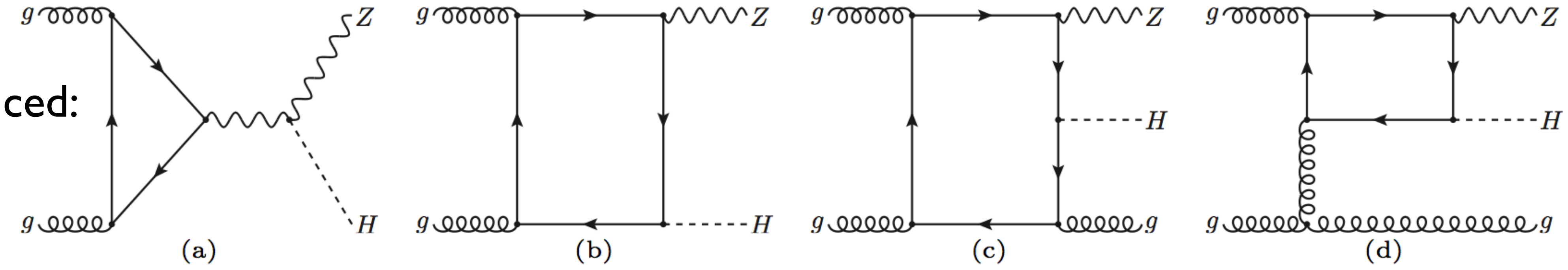
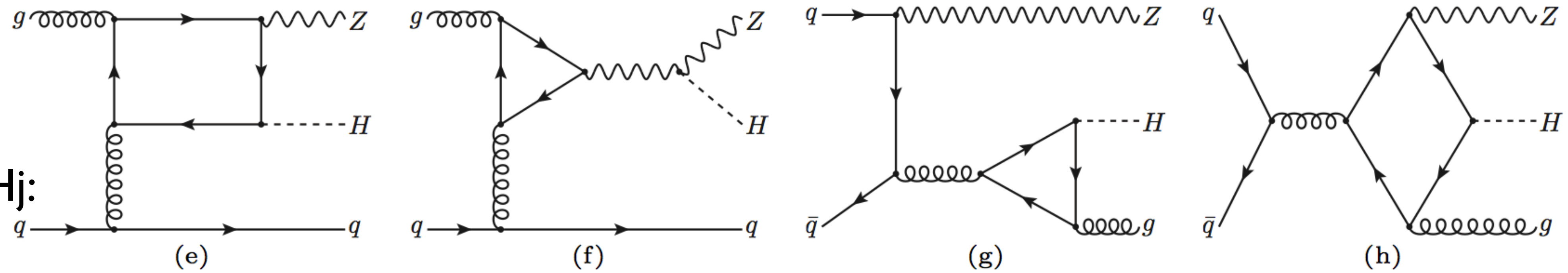
  - Collier: evaluation of tensor integrals
  - Finite width effects and spin correlations from Z decay are fully accounted for

GF pp → HZ(ll) + 0, 1 jets at LO accuracy in QCD merged into a inclusive sample (MEPS@Loop2)

Purely loop induced:



Finite & gauge invariant subset of NNLO to ZHj:



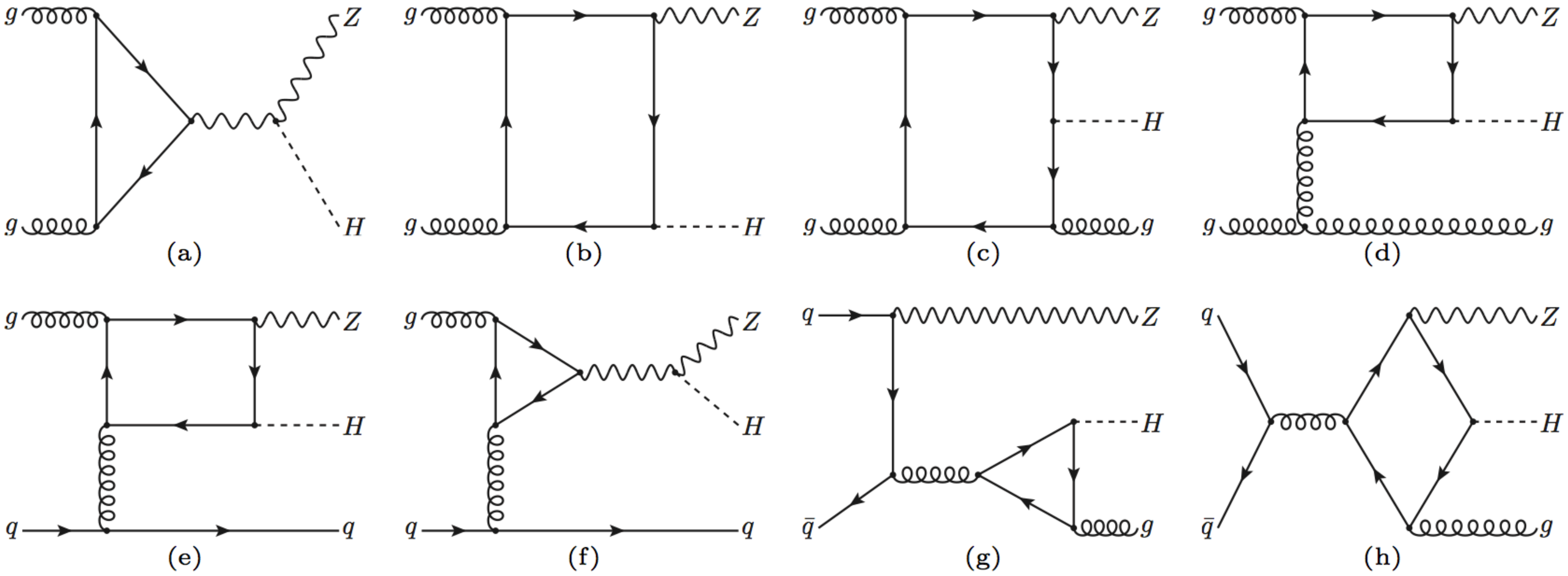
Higgs-Strahlung Production

- Similarly to gg>ZZ and gg>HH, presence of many scales makes it a non-trivial NLO calculation

→ Probably the most important fixed order calculation missing in the literature.

- Only estimates of NLO corrections in the infinite top mass limit exist and they are large K~2 (we use it)

Altenkamp, Dittmaier, Harlander, Rzehak, Zirke (2013)

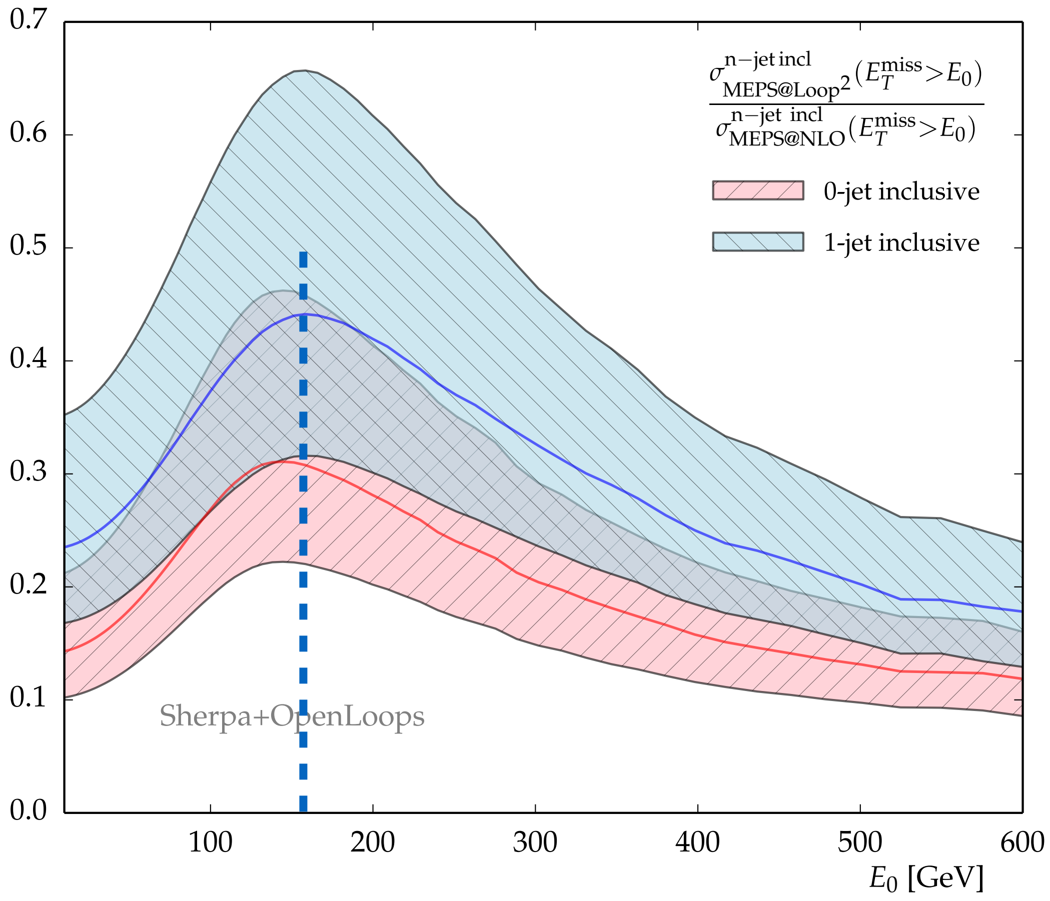


DG, Krauss, Kuttimalai, Maierhoefer (2015)

Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert (2014)

Higgs-Strahlung: invisible searches

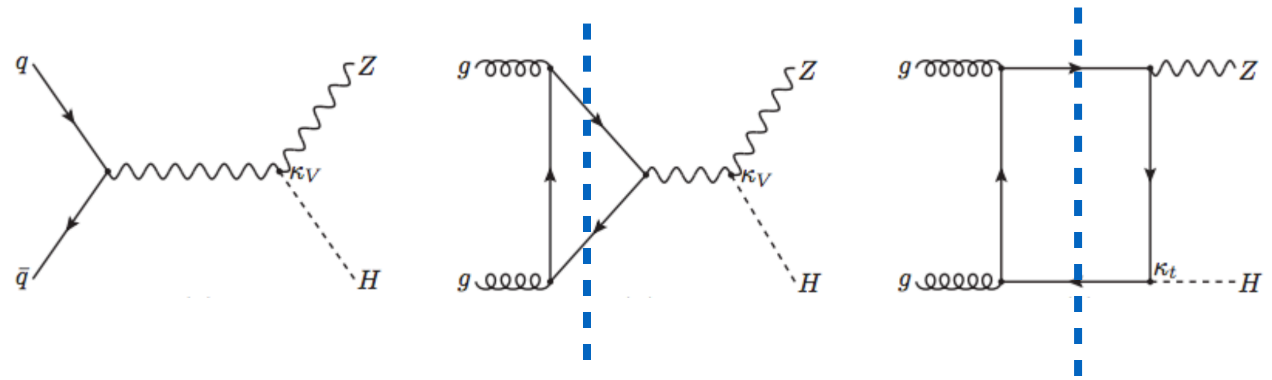
- Invisible Higgs decays - so called "Higgs-portal" models: Higgs is a mediator between the SM and Dark Matter sector
- Z(ll)H(inv) provides a very clean signature: Large MET recoiling against boosted Z(ll)



DG, Krauss, Kuttimalai, Maierhoefer (2015)

→ Total cross section dominated by DY: GF corresponds to only O(10%)

→ Top mass threshold: $m_{ZH} \sim 2m_t$ (MET~m_t)

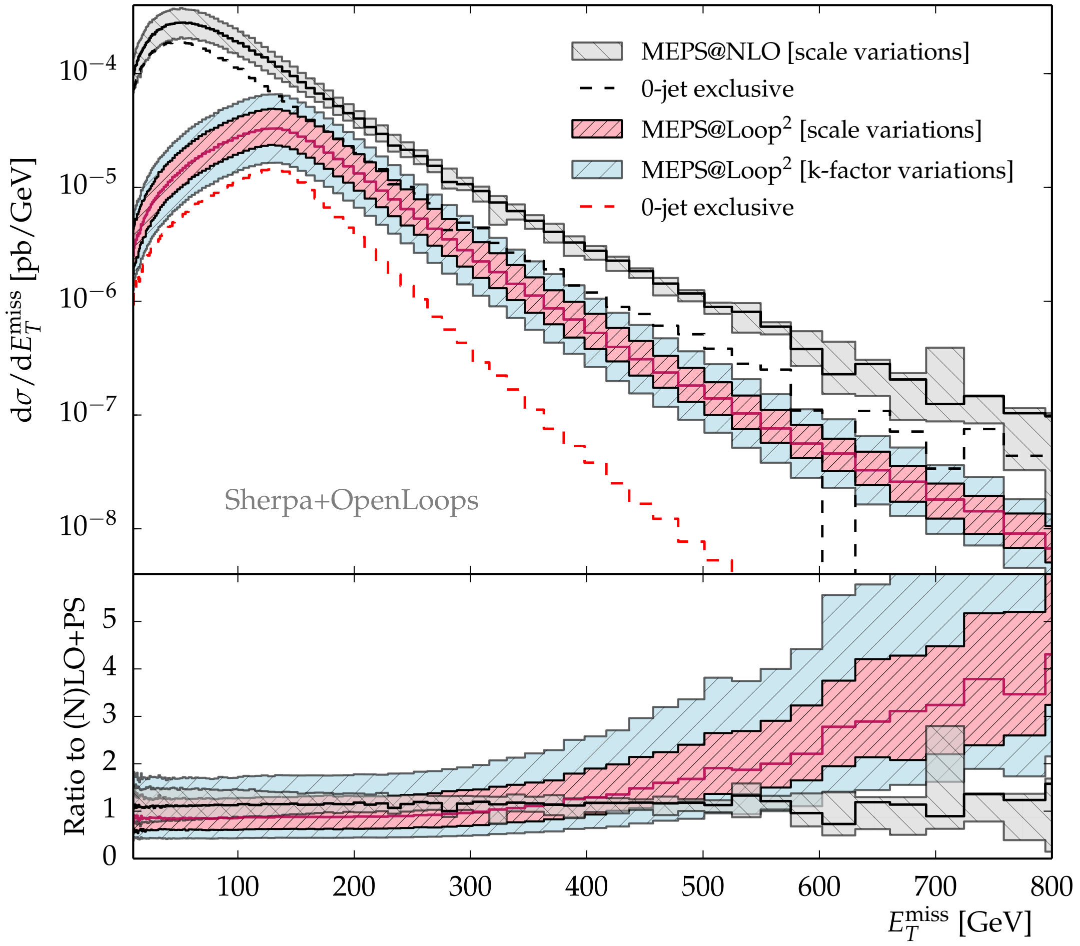


→ GF corresponds to ~30% (~40%) for the 0- (1-)jet bin

→ This might change invisible bounds from Z(ll)H(inv)

Higgs-Strahlung: invisible searches

- DY does not feature threshold enhancement but rather show the typical s-channel suppression for large energies



→ DY presents the typical 10-20% uncertainty

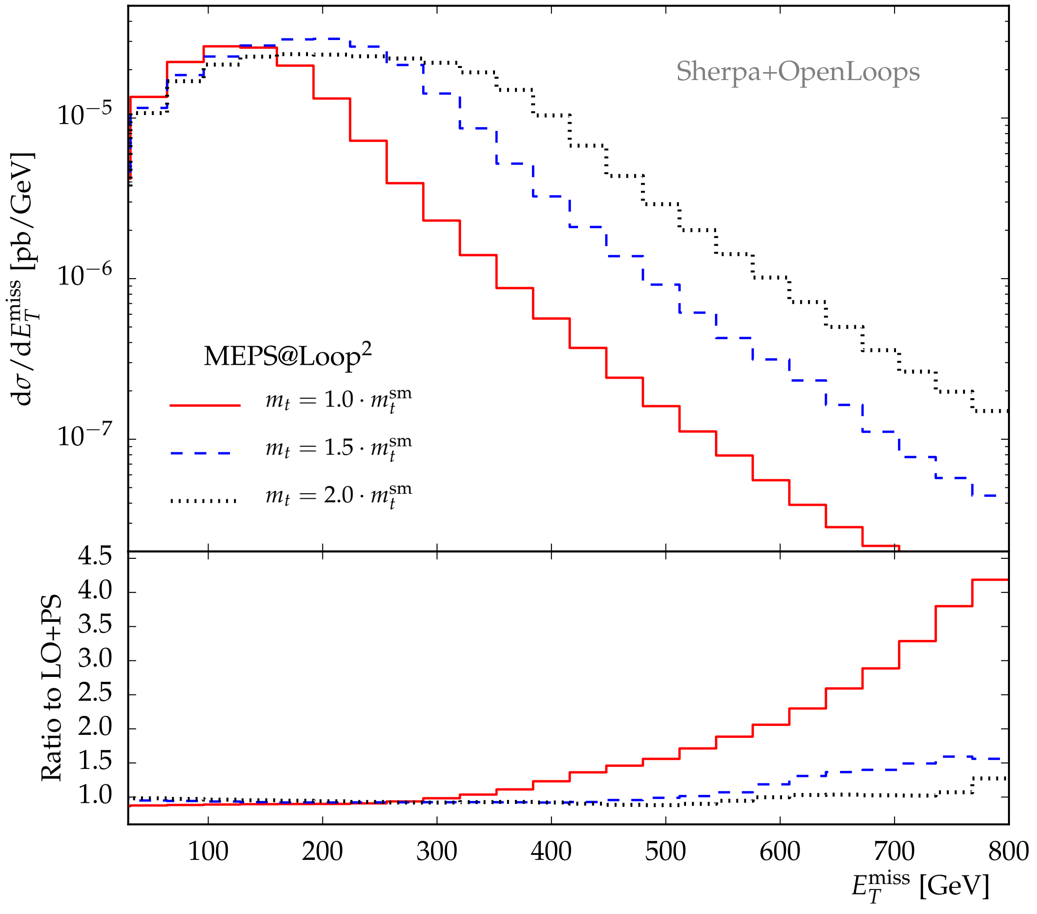
→ GF presents O(30%) - Typical for merging at LO

→ K-factor variation - translates into uncertainty, twice as large as the effect of the standard scale variation in the GF mode

→ MEPS@NLO/MC@NLO~1 for MET distrib.

→ Loop^2+PS significantly undershoots the merged result at the boosted regime

Higgs-Strahlung: invisible searches

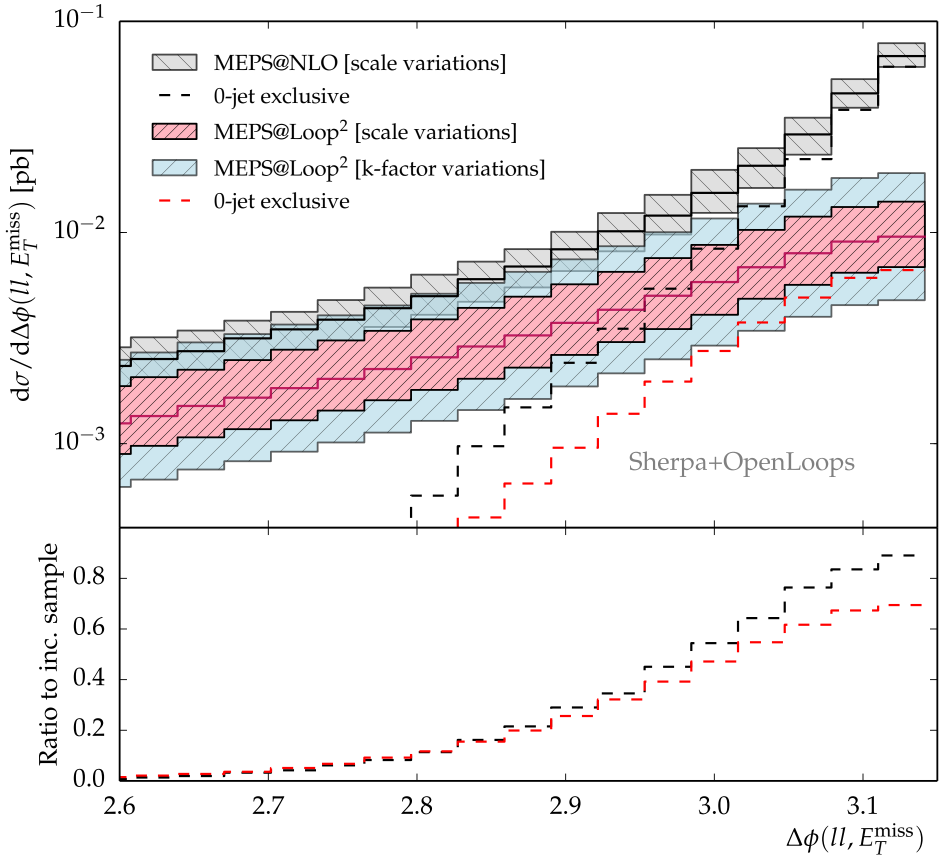


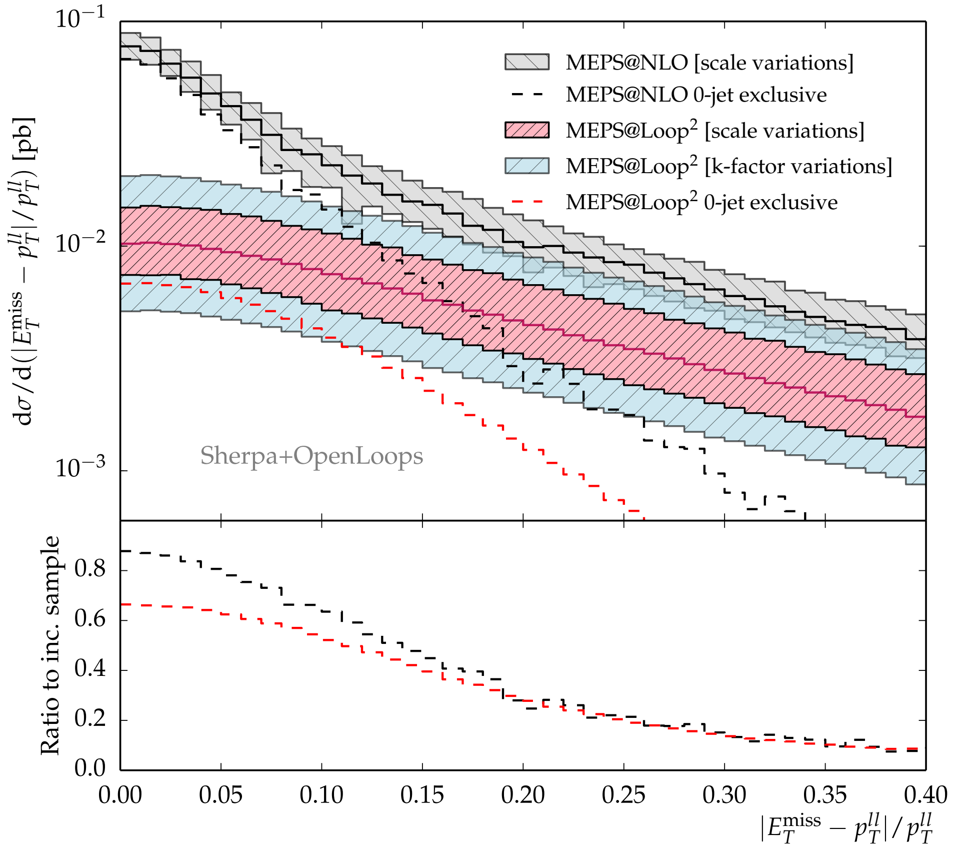
- Loop^2+PS significantly undershoots the merged result at the boosted regime
- Larger m_t pushes effect to higher energies Similar to the H+jets case (HEFT vs Full)
- Effects induced by higher jet multiplicity ME beyond the scope of conventional PS alone
- Multijet merging correctly fill these phase space regions

- As the GF becomes a significant player in the boosted regimes a proper modelling is of vital importance

Higgs-Strahlung: invisible searches

- Useful distributions for pheno analysis:
- At large E_T^{miss}, Z and E_T^{miss} are almost back to back $\Delta\phi_{ll,E_T^{miss}}$ and $|p_T(ll) - E_T^{miss}|/p_T(ll)$ become useful distributions for the background suppression

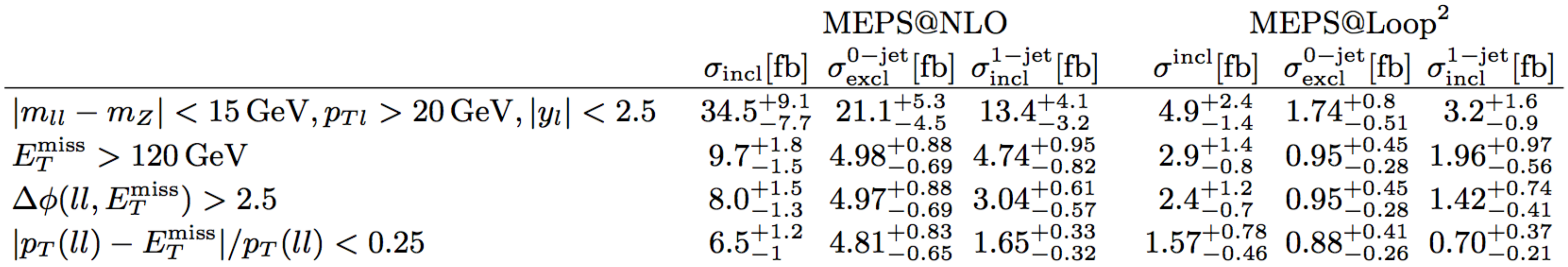




→ GF contribution suppressed for small angles:
0-jet is the biggest component - almost no extra recoil

Higgs-Strahlung: invisible searches

- GF relevant even after all the selection cuts:



	MEPS@NLO			MEPS@Loop^2		
	$\sigma_{\text{incl}}[\text{fb}]$	$\sigma^{0-\text{jet}}_{\text{excl}}[\text{fb}]$	$\sigma^{1-\text{jet}}_{\text{incl}}[\text{fb}]$	$\sigma^{\text{incl}}[\text{fb}]$	$\sigma^{0-\text{jet}}_{\text{excl}}[\text{fb}]$	$\sigma^{1-\text{jet}}_{\text{incl}}[\text{fb}]$
$\lvert m_{ll} - m_Z\rvert < 15\,\text{GeV}, p_{Tl} > 20\,\text{GeV}, \lvert y_l\rvert < 2.5$	$34.5^{+9.1}_{-7.7}$	$21.1^{+5.3}_{-4.5}$	$13.4^{+4.1}_{-3.2}$	$4.9^{+2.4}_{-1.4}$	$1.74^{+0.8}_{-0.51}$	$3.2^{+1.6}_{-0.9}$
$E_T^{\text{miss}} > 120\,\text{GeV}$	$9.7^{+1.8}_{-1.5}$	$4.98^{+0.88}_{-0.69}$	$4.74^{+0.95}_{-0.82}$	$2.9^{+1.4}_{-0.8}$	$0.95^{+0.45}_{-0.28}$	$1.96^{+0.97}_{-0.56}$
$\Delta\phi(ll, E_T^{\text{miss}}) > 2.5$	$8.0^{+1.5}_{-1.3}$	$4.97^{+0.88}_{-0.69}$	$3.04^{+0.61}_{-0.57}$	$2.4^{+1.2}_{-0.7}$	$0.95^{+0.45}_{-0.28}$	$1.42^{+0.74}_{-0.41}$
$\lvert p_T(ll) - E_T^{\text{miss}}\rvert / p_T(ll) < 0.25$	$6.5^{+1.2}_{-1}$	$4.81^{+0.83}_{-0.65}$	$1.65^{+0.33}_{-0.32}$	$1.57^{+0.78}_{-0.46}$	$0.88^{+0.41}_{-0.26}$	$0.70^{+0.37}_{-0.21}$

- $(\text{GF/DY})_{0\text{-jet}}$~20% & $(\text{GF/DY})_{1\text{-jet}}$~40%

- However, GF was not accounted in some Run-I searches:

  Some analyses account for 1-jet bin separately, thereby retaining even larger sensitivity to GF

- Maybe we should take some of these bounds with a grain of salt

Hadronic decays Z(ll)H(bb)

- Higgs candidate is part of a multi-jet system: decay products+ FSR
- This simple picture is blurred by ISR and additional particles from the underlying event "splashing" into the fat-jet system stemming from the Higgs decay

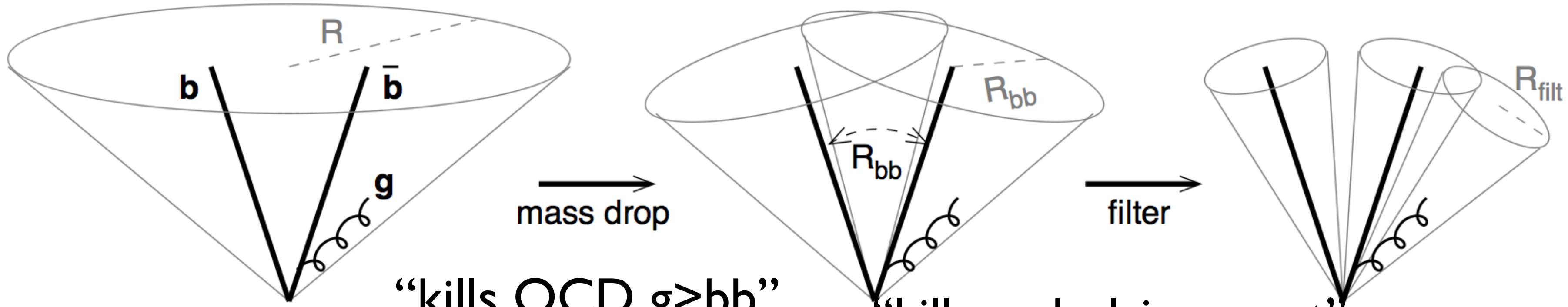
Underlying event: $\langle \delta m_j^2 \rangle \simeq \Lambda_{\mathrm{UE}}\, p_{T,j} \left(\frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)$, with $\Lambda_{UE} \sim 10\ GeV$

Dasgupta, Magnea, Salam (2007)

→ Proper modelling of the QCD emissions indispensable requirement for robust analysis

Butterworth, Davison, Rubin, Salam (2008) - BDRS method

Fatjet C/A:
R~2m$_H$/p$_T$~1.2



"kills QCD g>bb"

"kills underlying event"

Mass drop: $m_{j1} < 0.66 m_j$

Not too asymmetric: $\frac{\min(p_{tj_1}^2, p_{tj_2}^2)}{m_j^2} \Delta R^2_{j_1,j_2} > y_{\mathrm{cut}}$

Take 3 hardest subjets

b-tagging on the 2 hardest

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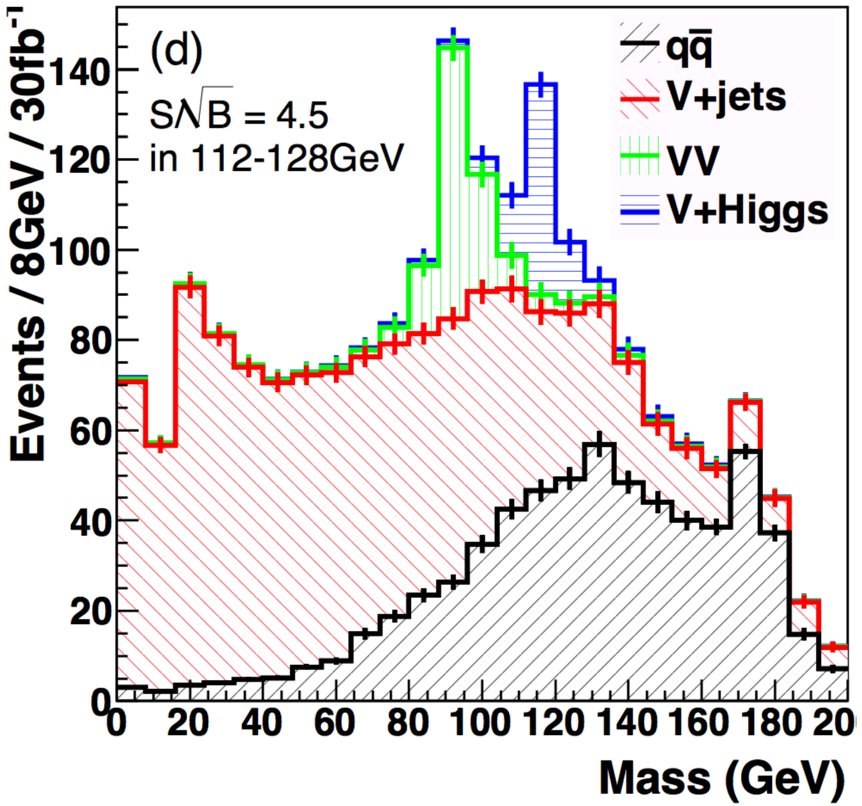

→ BDRS result: LHC 14 TeV and 30 fb^{-1}

→ Combination of HZ and HW channels

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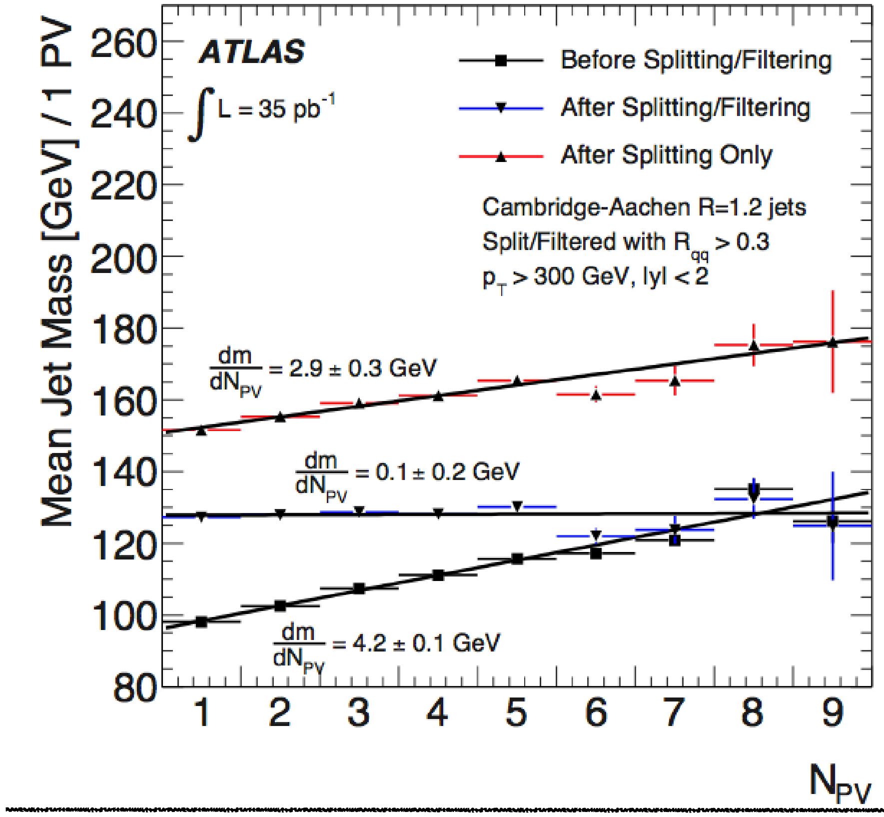


→ Tested on LHC data!

→ Jet mass as a function of the number of primary vertices N_{PV} (amount of pileup)

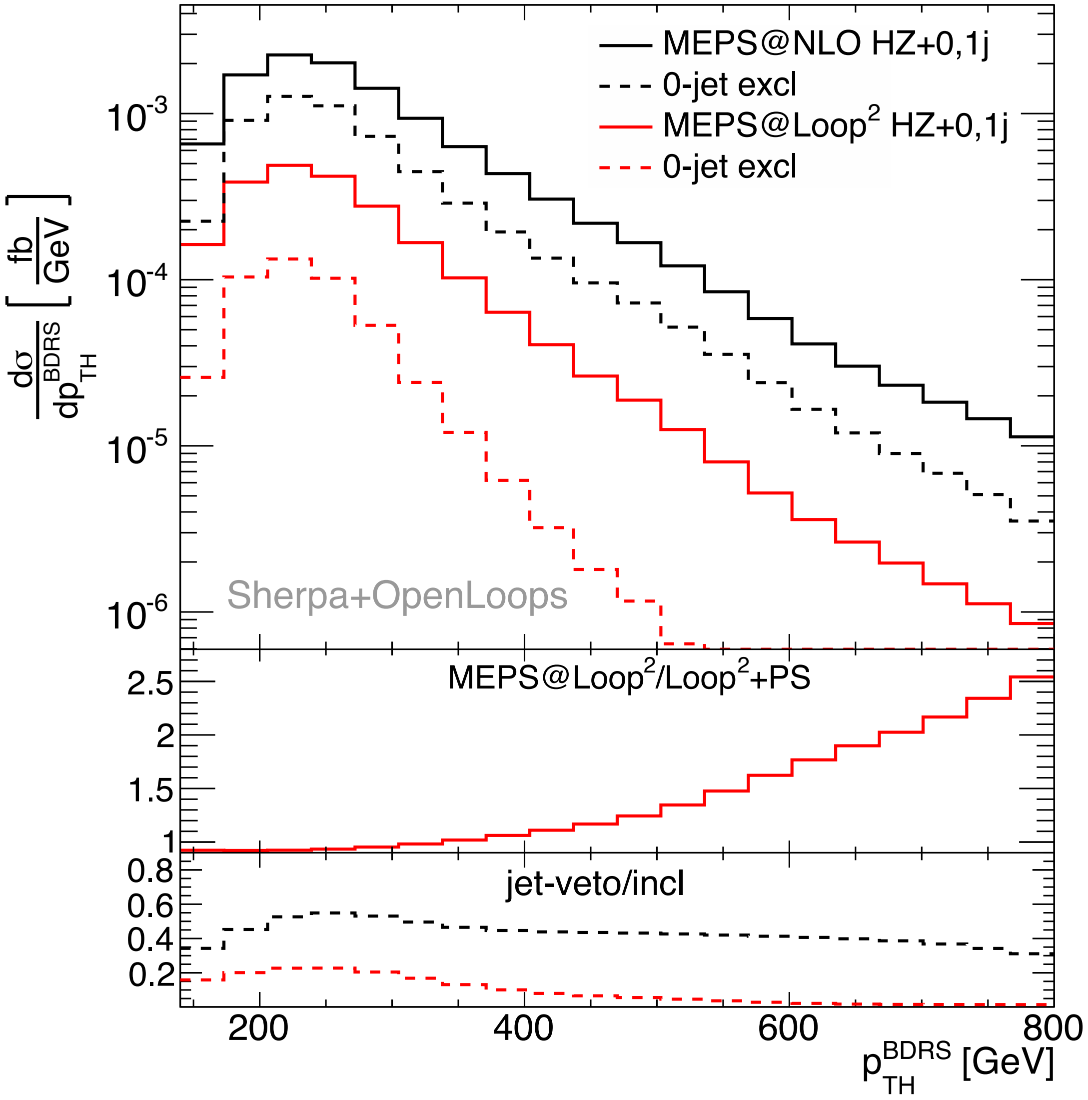
→ After filtering, jet mass has little to no dependence on N_{PV}

→ Filtering successfully isolate the hard process.

ATLAS Collaboration, arxiv:1203.4606

Hadronic decays Z(ll)H(bb)

- In analogy to E_T^{miss} in Z(ll)H(inv), MEPS@Loop^2 presents enhancement with respect to ZH Loop^2+PS



➡ Effect noticeably smaller than in Z(ll)H(inv)

$p_{TZ(H)} > 200\ GeV$ offers smaller phase space region to PS

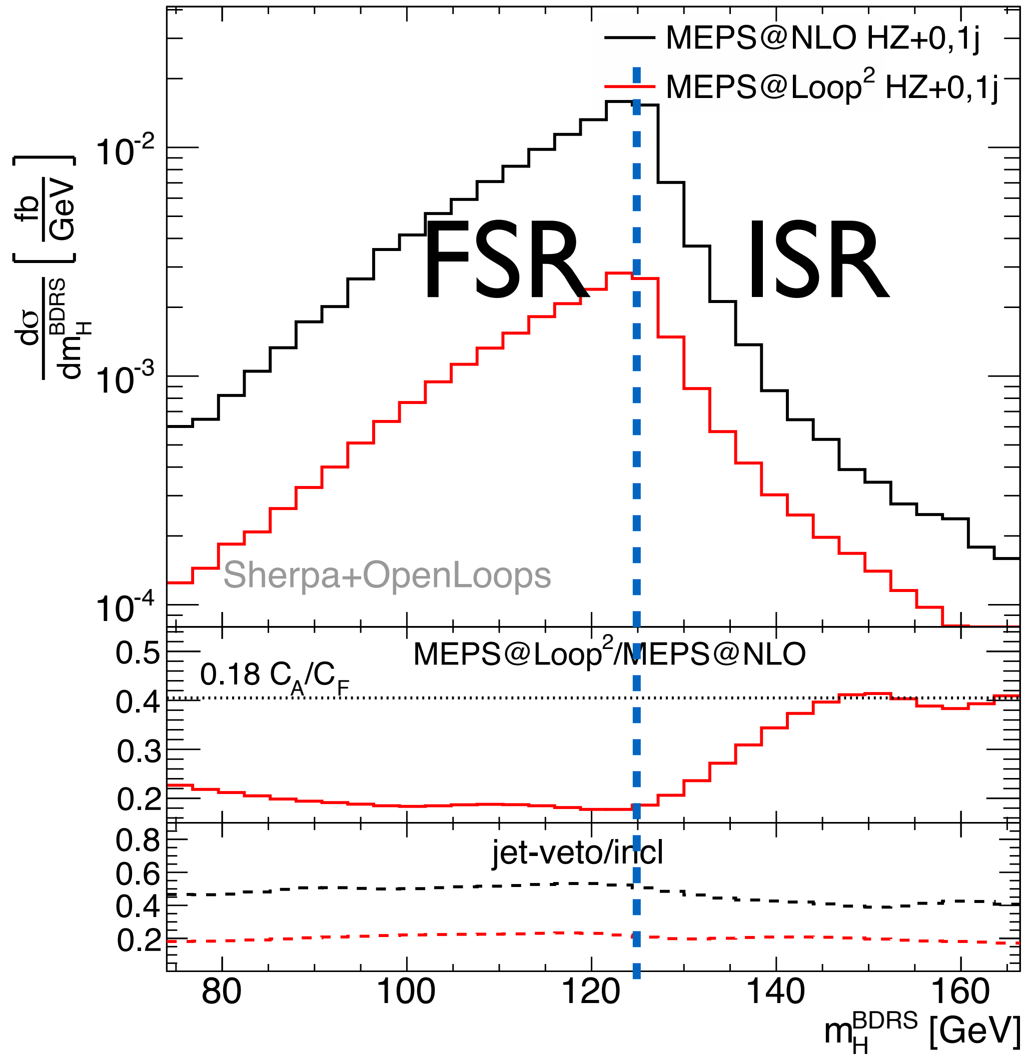
Besides, the H(bb) is more sensitive to QCD radiation which induces extra differences

DG, Krauss, Kuttimalai, Maierhoefer (2015)

Ferrera, Grazzini, Tramontano (2014)

Hadronic decays Z(ll)H(bb)

- GF changes the invariant mass profile for the filtered Higgs:



→ $m_{BDRS}<125$: FSR
PS radiation off the bb pair

→ $m_{BDRS}>125$: ISR
MEPS@NLO and MEPS@Loop^2

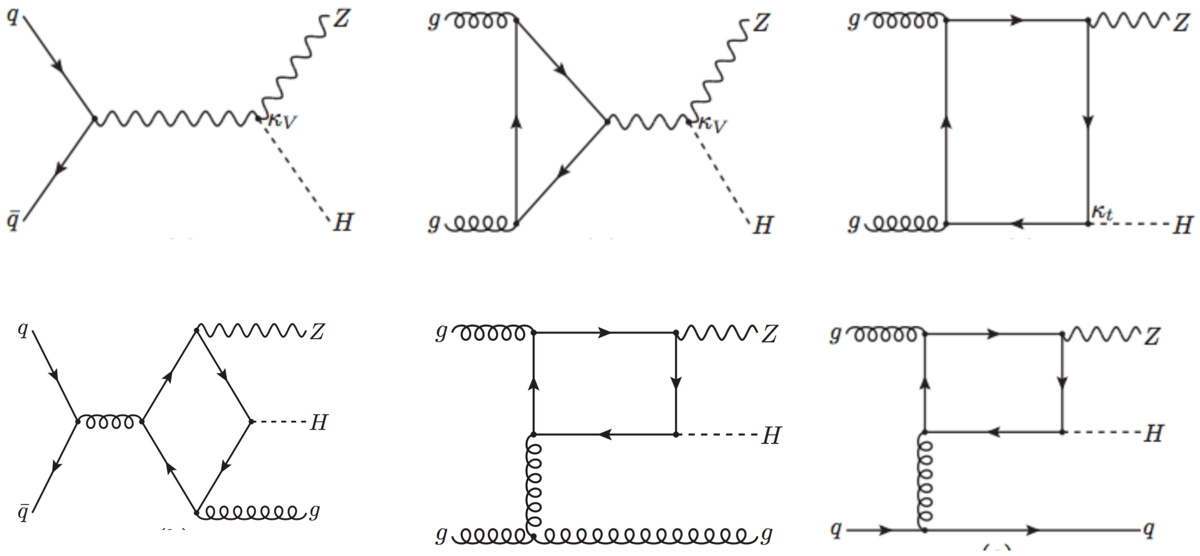
- Big enhancement that goes from O(18%) to O(40%) of DY rate: $0.18\times C_A/C_F \sim 0.4$

- Higgs is genuinely part of a multi-jet system

DG, Krauss, Kuttimalai, Maierhoefer (2015)
Ferrera, Grazzini, Tramontano (2014)

ZH Boosting Coupling Constraints

- DY+Loop-induced contributions access the size and sign of y_t:



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

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

sign

- To estimate the LHC sensitivity towards these coefficients, we consider the major backgrounds:

tt, Zbb, and ZZ_{EW} + jets

Besides these standard contributions, we also accounted for GF ZZ_{GF} production

cuts	ZH_{GF} $\kappa_t = -1$	ZH_{GF}	ZH_{DY}	$t\bar{t}$+jets	$Zb\bar{b}$+jets	ZZ_{EW}	ZZ_{GF}
BDRS reconstruction	1.48	0.07	0.37	0.29	13.83	0.79	0.10
$\|m_H^{\rm BDRS} - m_H\| < 10$ GeV	0.63	0.03	0.16	0.02	0.35	0.02	0.002

→ Main background: Zbb+jets

DG, Krauss, Kuttimalai, Maierhoefer (2015)

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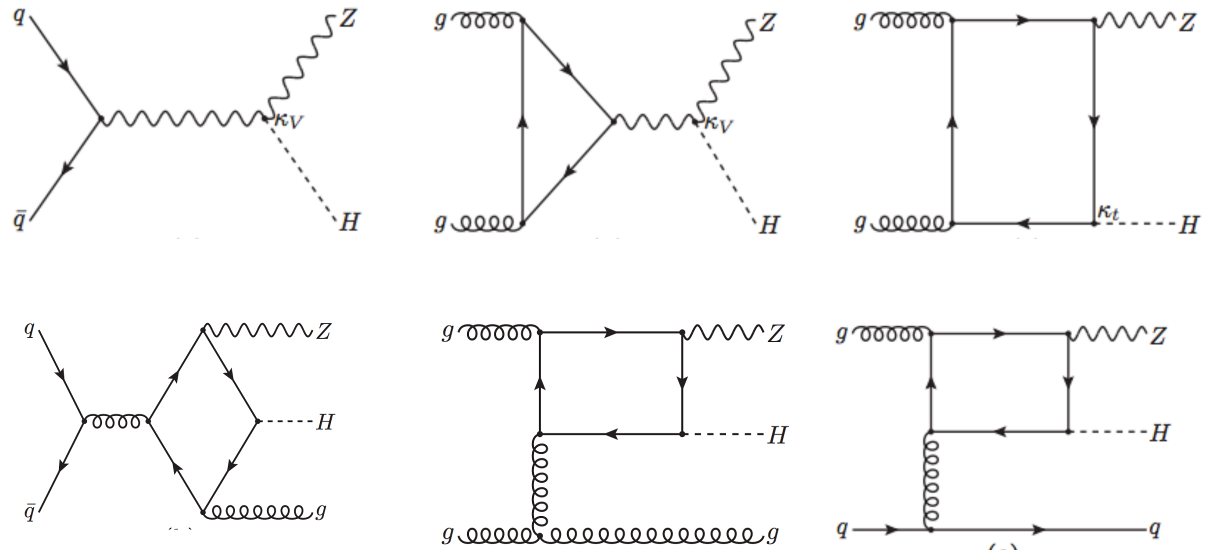

$$\mathcal{M} = \kappa_t \mathcal{M}_t + \kappa_V \mathcal{M}_V$$

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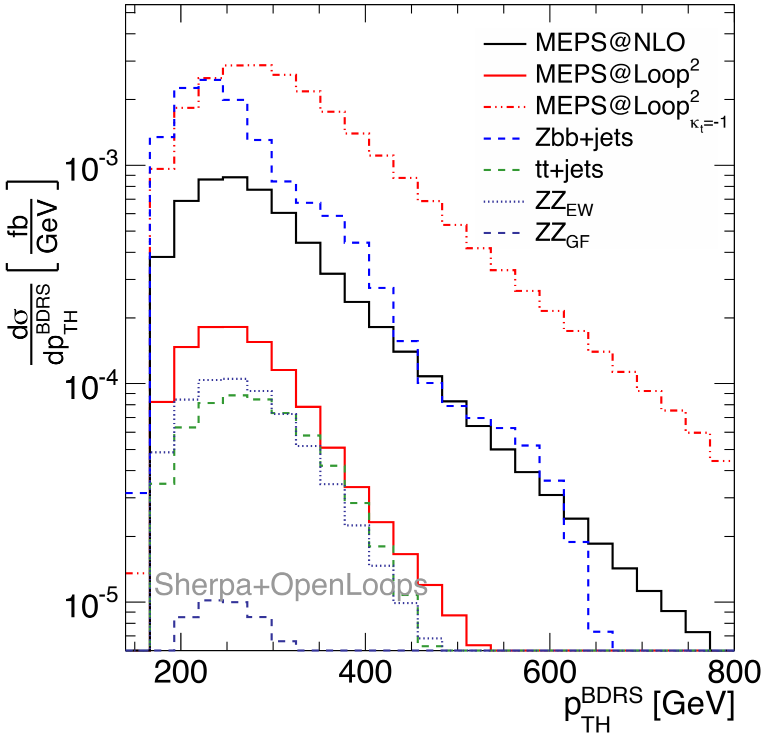
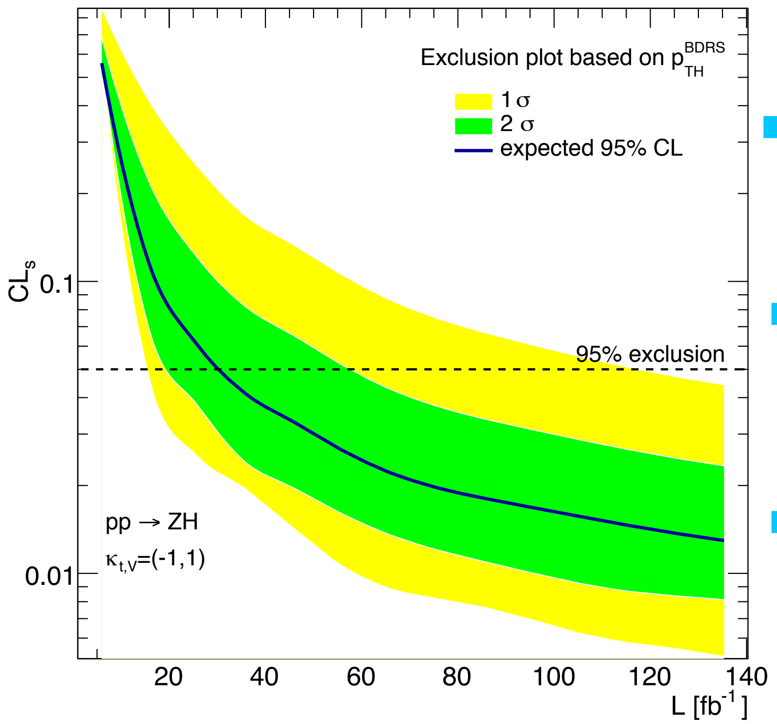


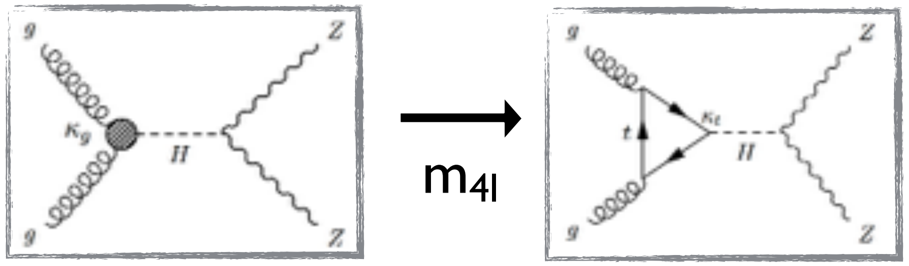


- Benefits from σ_{tV} that presents destructive interference in the full p_T distribution
- Conservative systematic uncertainty of 50% to GF (unknown higher order corrections)
- BSM hypothesis excluded with ~30 fb^{-1} of data

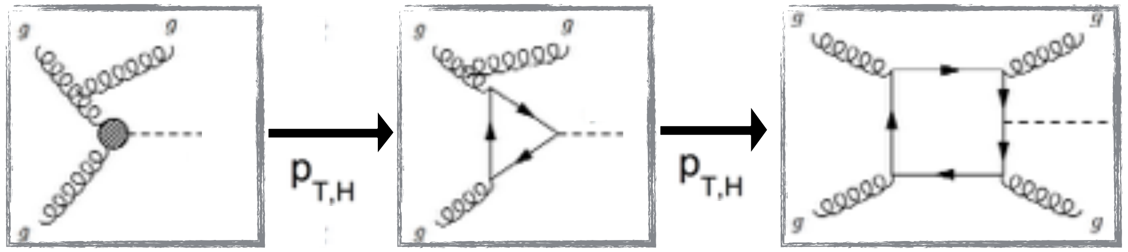
DG, Krauss, Kuttimalai, Maierhoefer (2015)

Complementary approaches

- Complementary approaches to measure the y_t effects via loop-induced processes:
  - Off-shell Higgs:



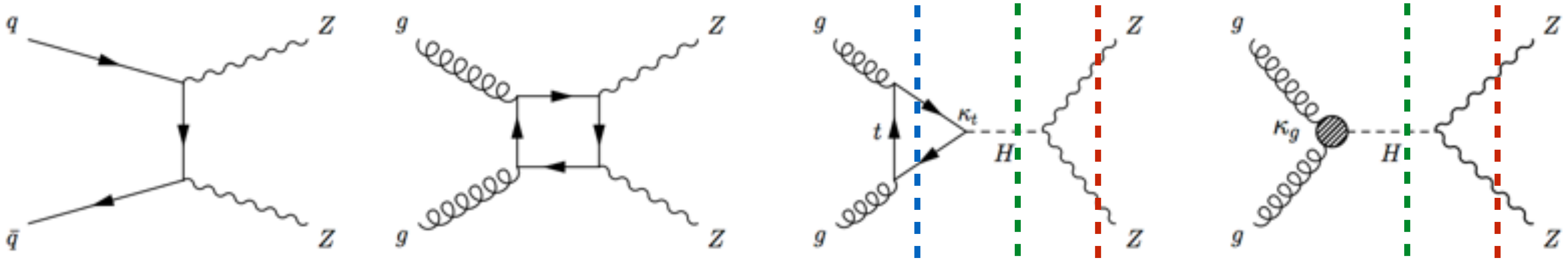
  - Boosted Higgs:

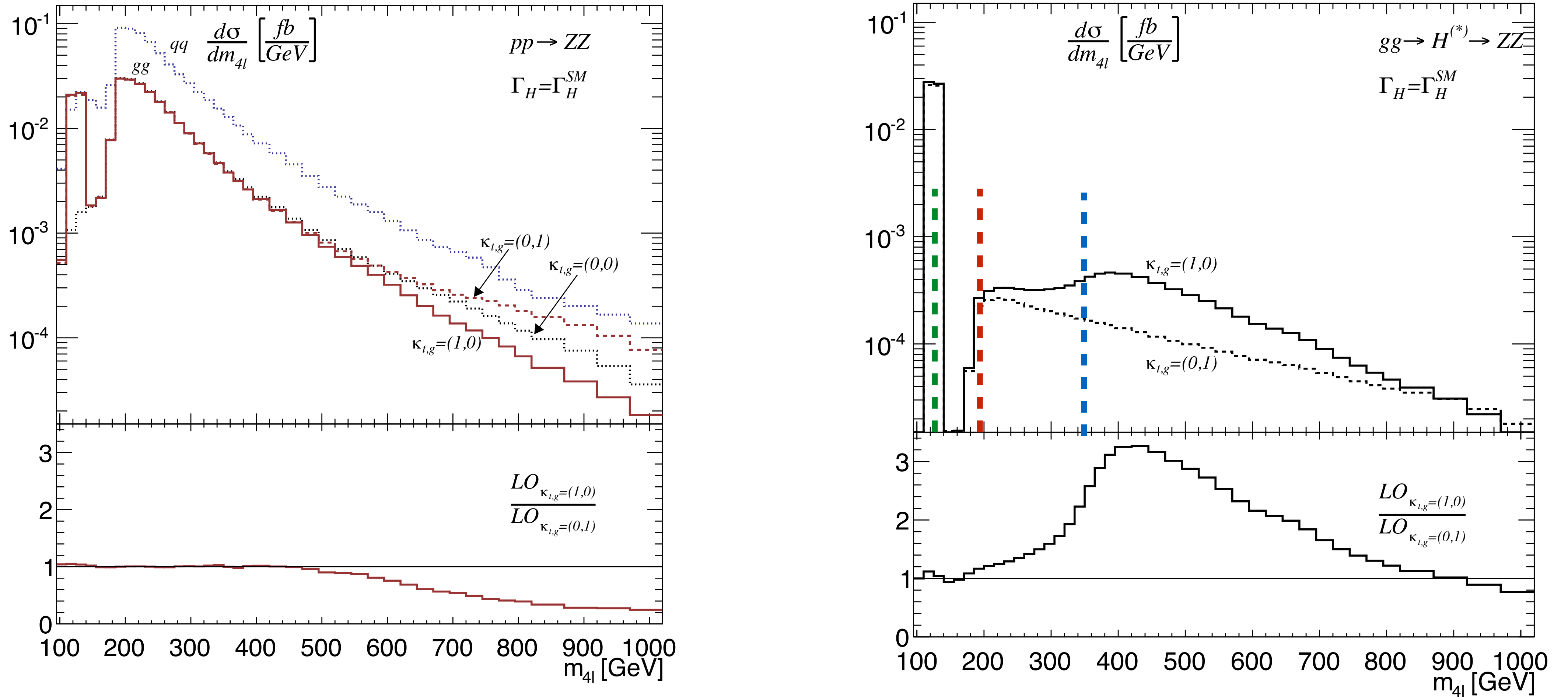


Off-Shell Higgs Production

- Carries information on the Higgs couplings at different energy scales

  At least 15% of the rate comes from $m_{4l}>300$ GeV





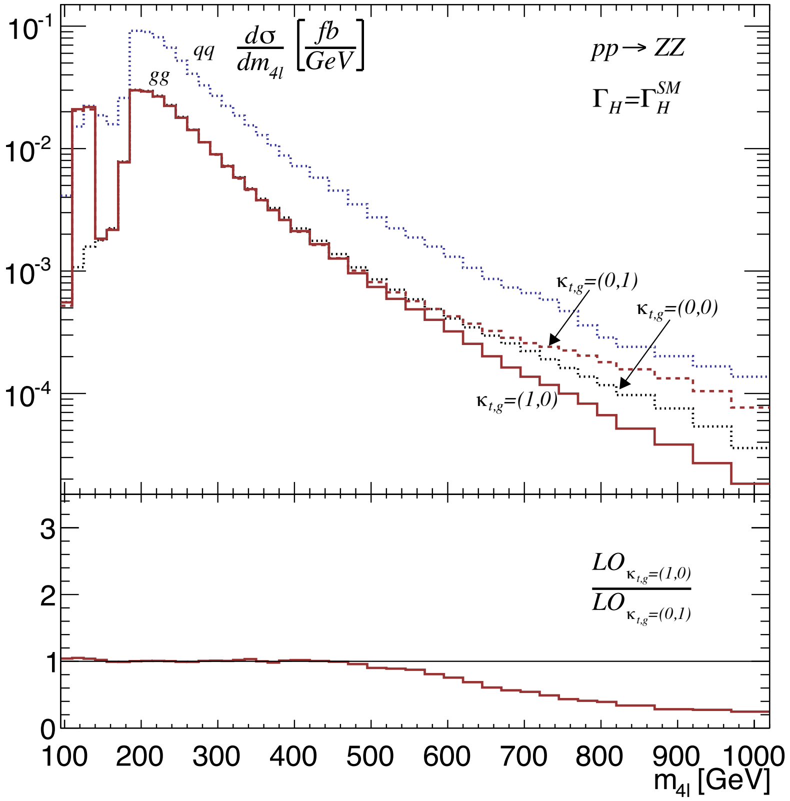
Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

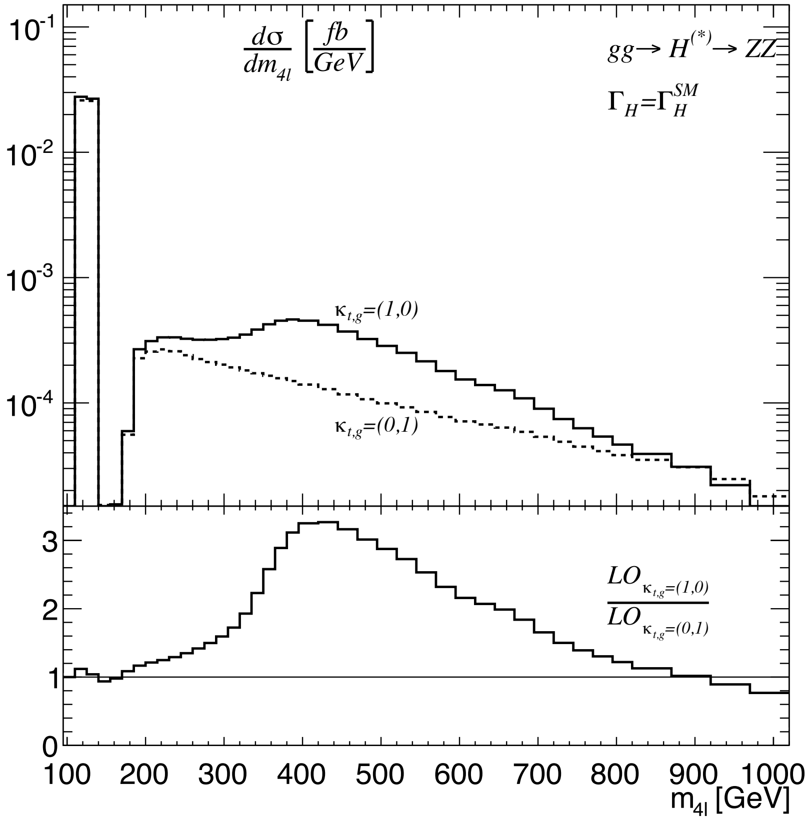
Off-Shell Higgs Production

- Carries information on the Higgs couplings at different energy scales

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

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



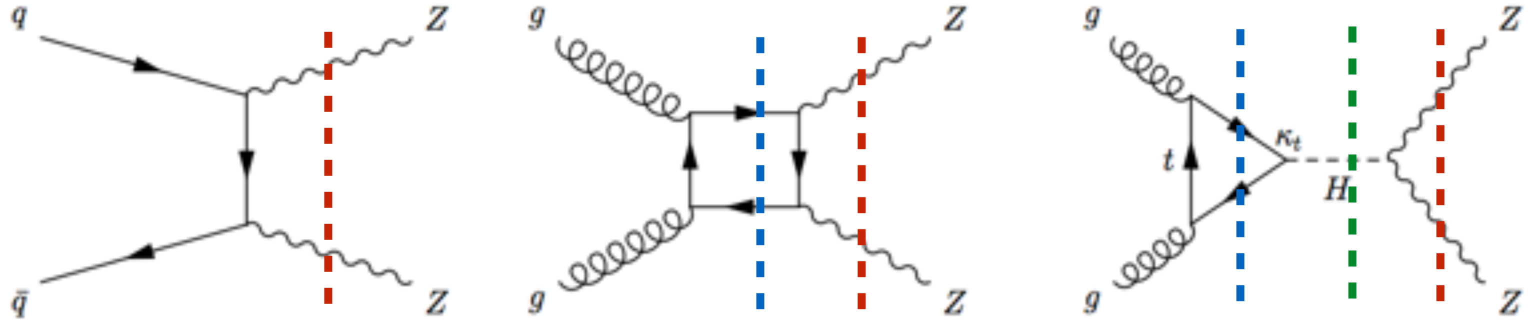


- qq → ZZ generated already at tree level. Much larger than gg → ZZ
- Enhancement on the tail for low-energy limit and suppression of the full top mass result

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

Theoretical ingredients

- Signal and background components:



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

→ 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

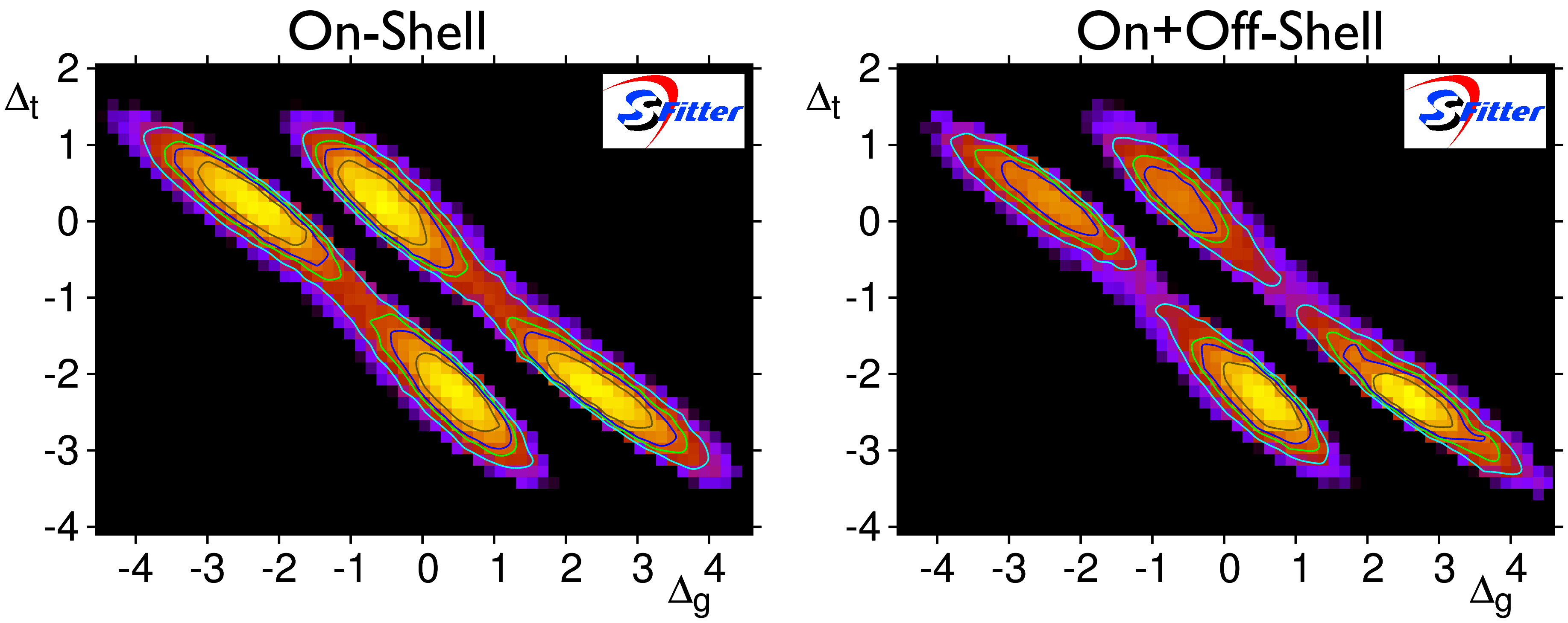
→ The Higgs does what he is expected to do! (Quigg, Lee, Thacker 1977)

Off-Shell Measurements: Sfitter results

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

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

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



→ 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

Corbett, Eboli, DG, Gonzalez-Fraile, Plehn, Rauch (2015)

Higgs width measurement

- SM prediction $\Gamma_H \sim 4$MeV

→ Best limit from direct measurement H → 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, 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:

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

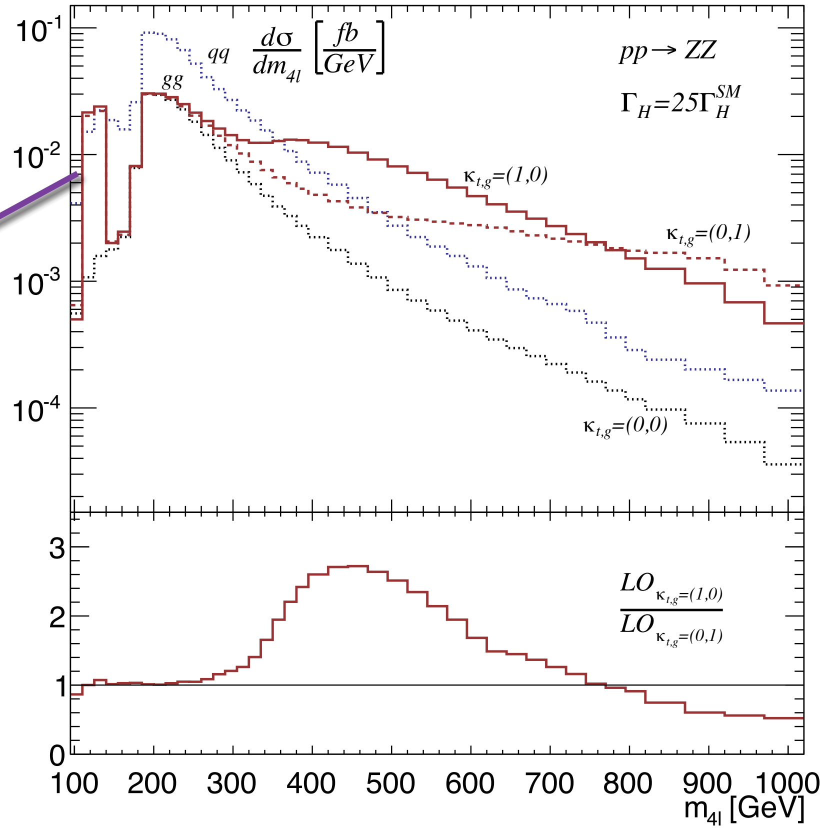
→ k_t & k_g factorize

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

→ non-trivial k_t & k_g dependence

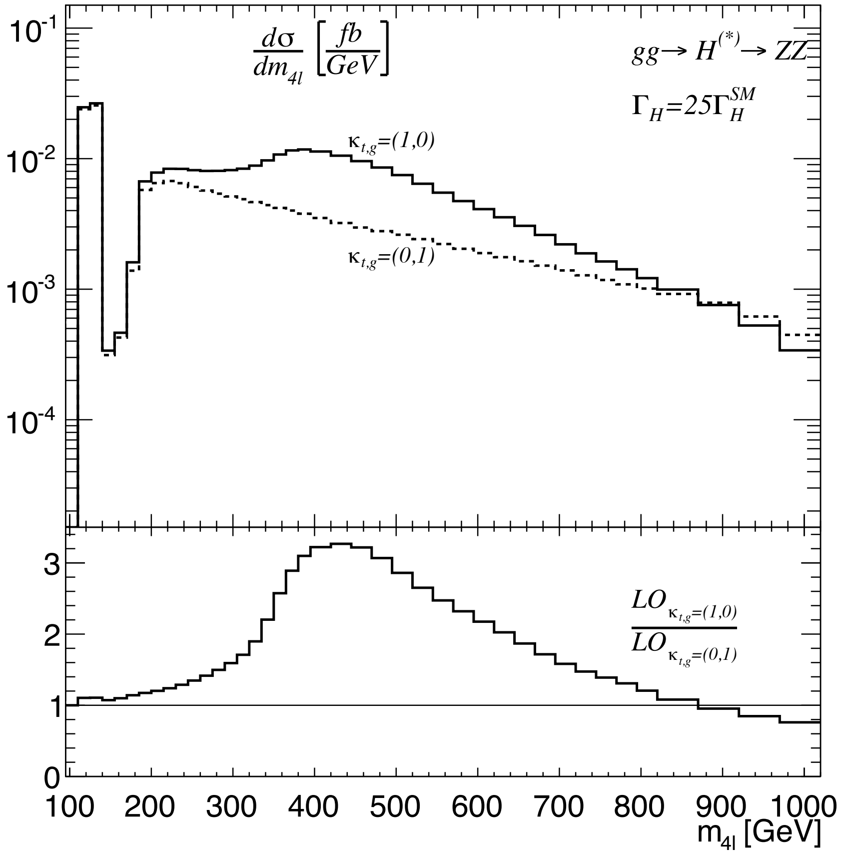
- Example: $\xi^4 = 25 \quad \rightarrow \quad \Gamma_H = 25\Gamma_H^{SM}$

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



Signal strength still

μon-shell = 1



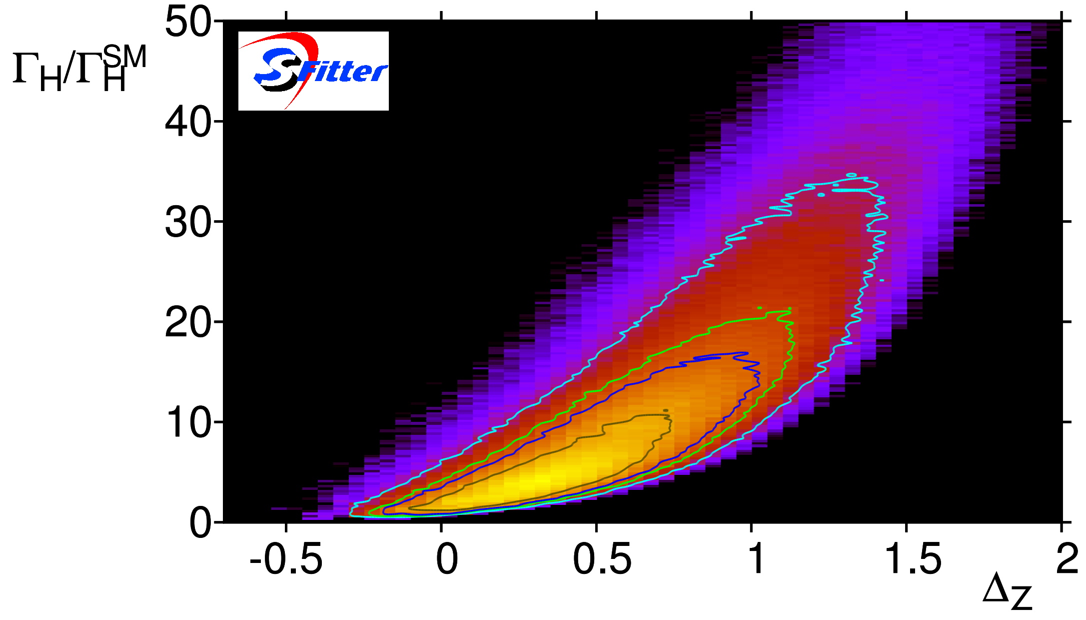
Higgs width measurement

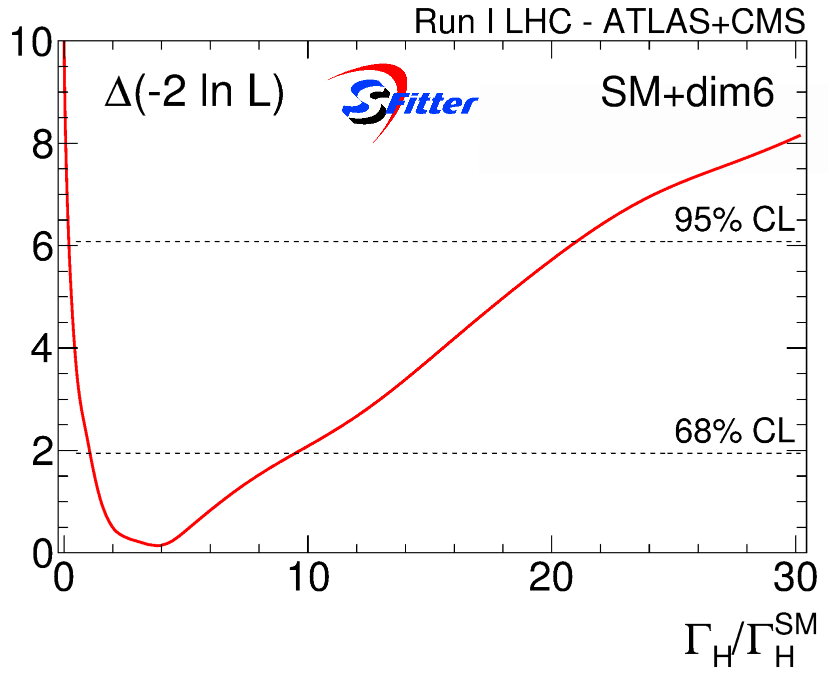
- Leaving the Higgs width as a free parameter in the SFitter setup:

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

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

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





Corbett, Eboli, DG, Gonzalez-Fraile, Plehn, Rauch (2015)

➡ 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 $\Delta Z \sim 1.3$

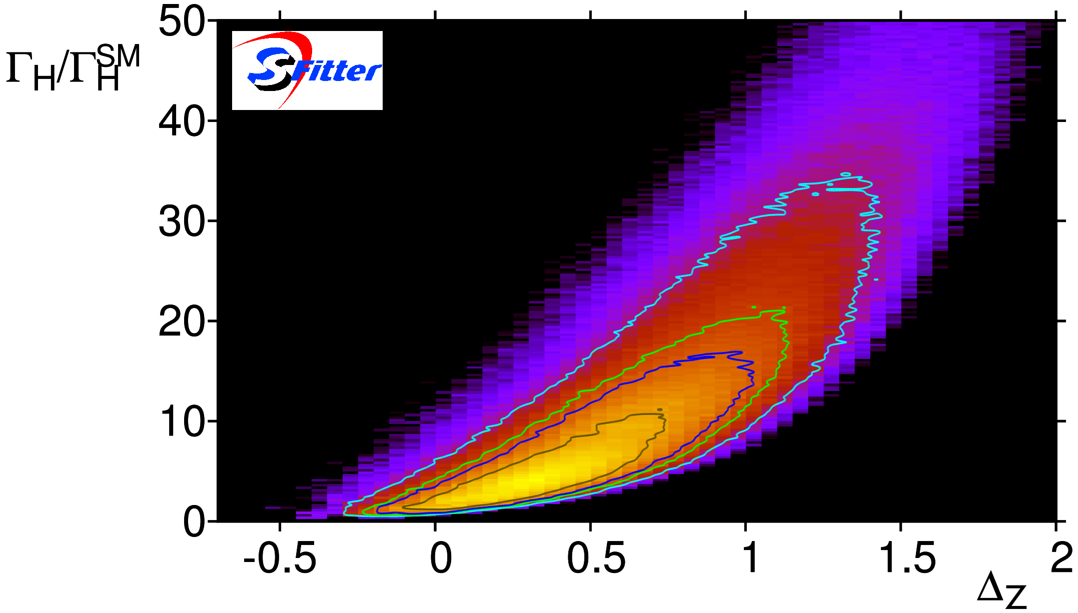
Higgs width measurement

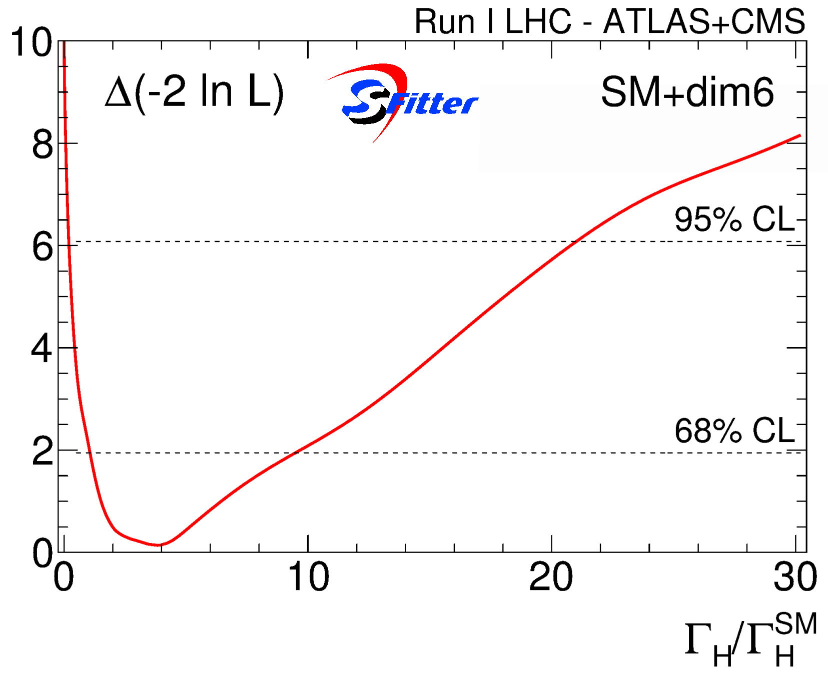
- Leaving the Higgs width as a free parameter in the SFitter setup:

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

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

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





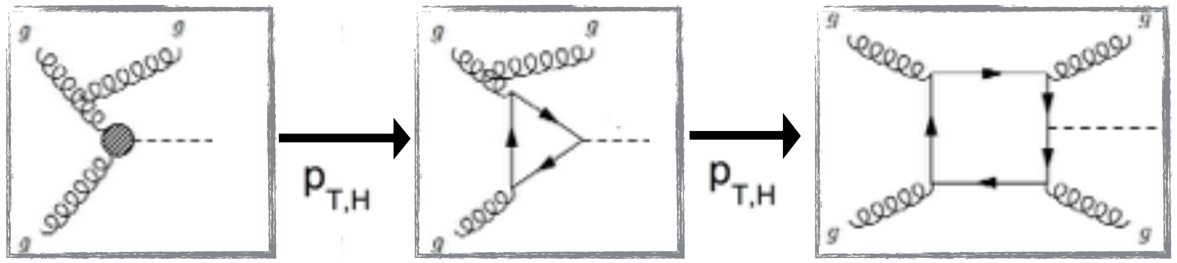
➡ $\Gamma_H < 9.3\Gamma^{SM}$ at 68% CL. While our width constraint was obtained considering possible BSM operators, our bound is still competitive to other analysis that account only to SM-like interactions

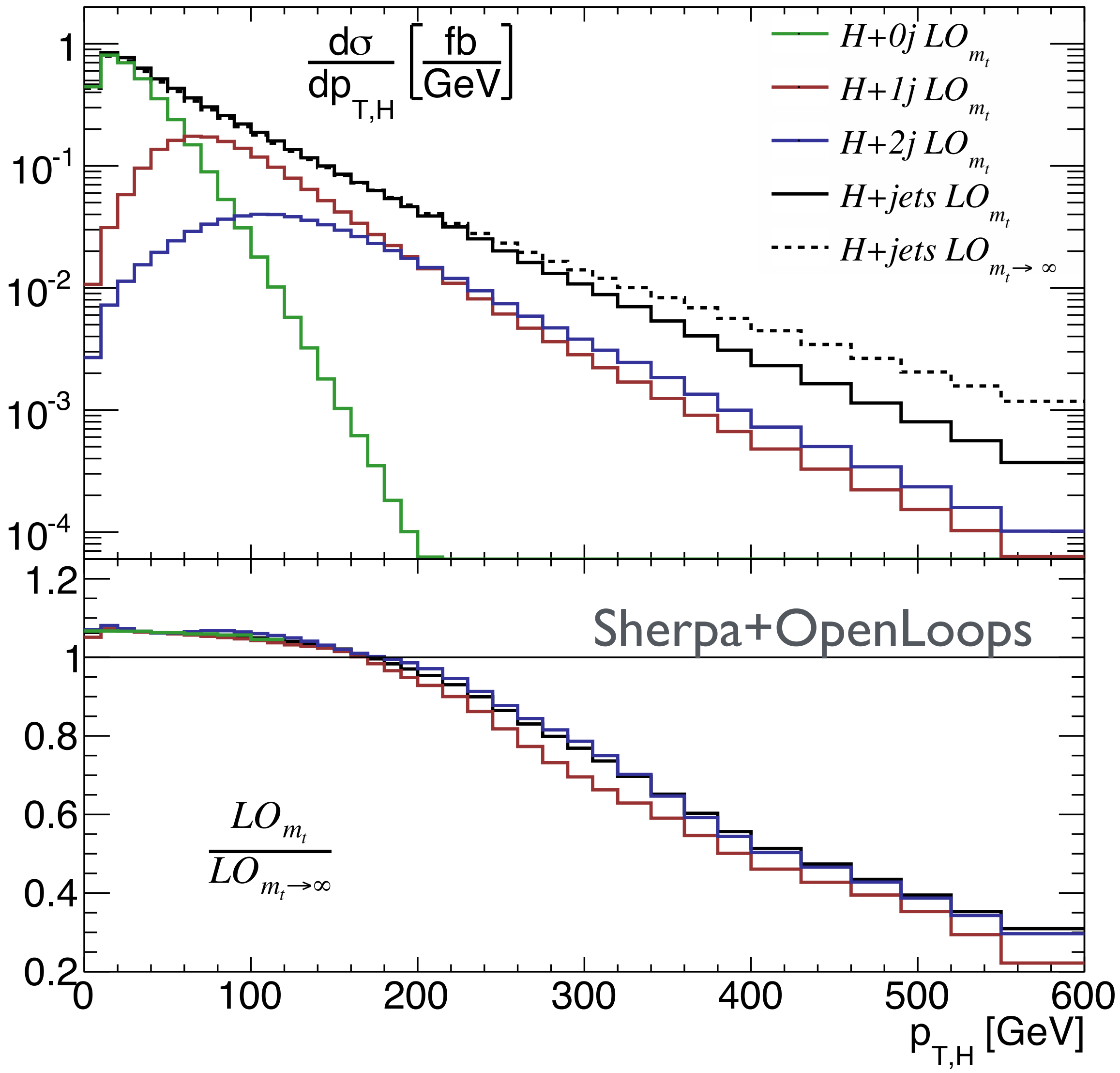
➡ Key ingredient: full m_{4l} profile

Corbett, Eboli, DG, Gonzalez-Fraile, Plehn, Rauch (2015)

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

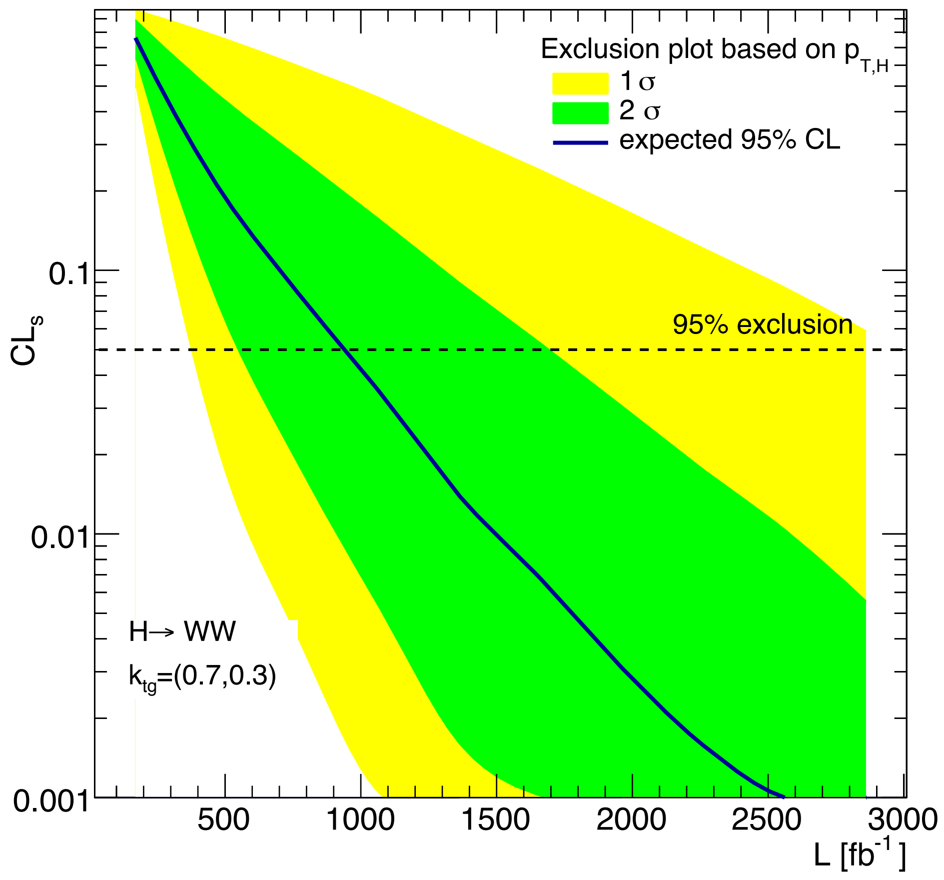
→ Consequently the same happens for the merged result

Complementary approaches

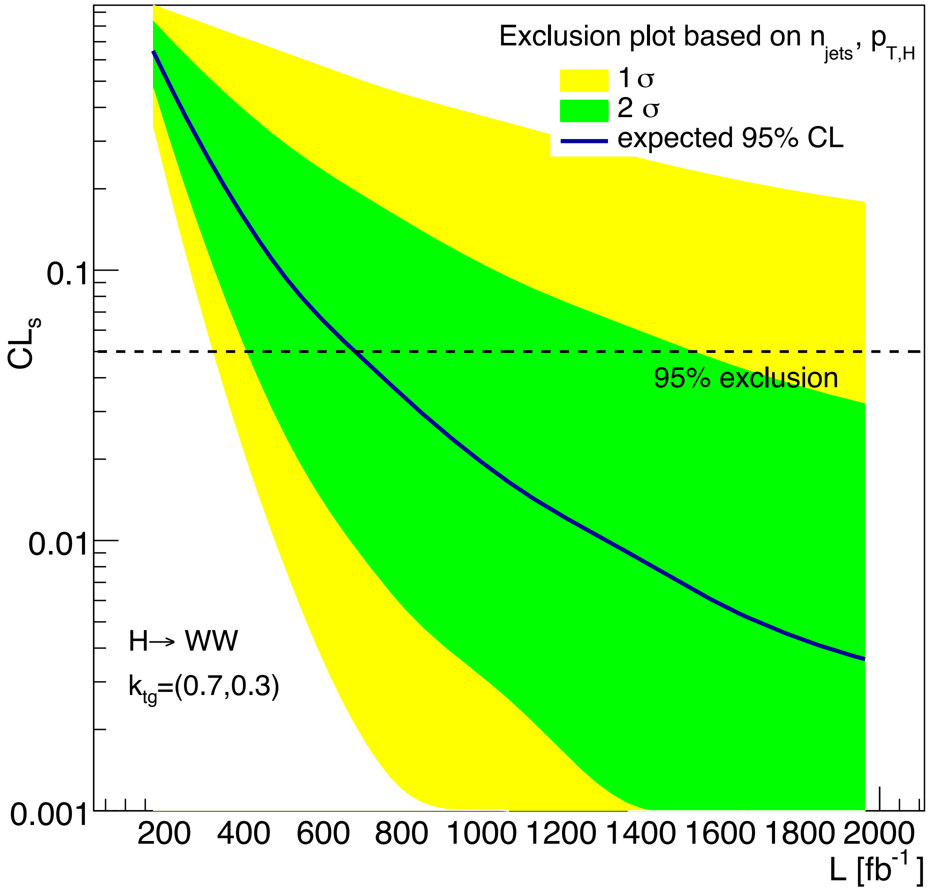
- The merged distributions capture the info from the first and second jet bin

➡ 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

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

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) ...

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 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