Exploring the Higgs-top coupling at the LHC

Fermilab

Fermilab - 02.02.2017

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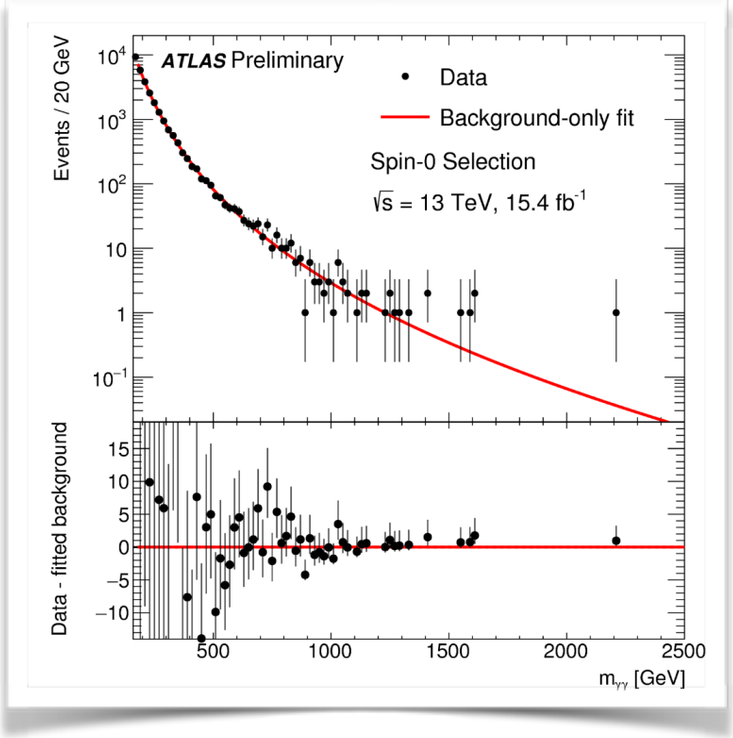
Motivation

- LHC is killing the hopes for a quick new fundamental particle discovery:
  - Diboson anomaly: gone
  - Diphoton anomaly: gone
  - SUSY: even the compressed spectra is becoming "compressed" by data
- Should we get desperate and look for bumps on ALEPH?

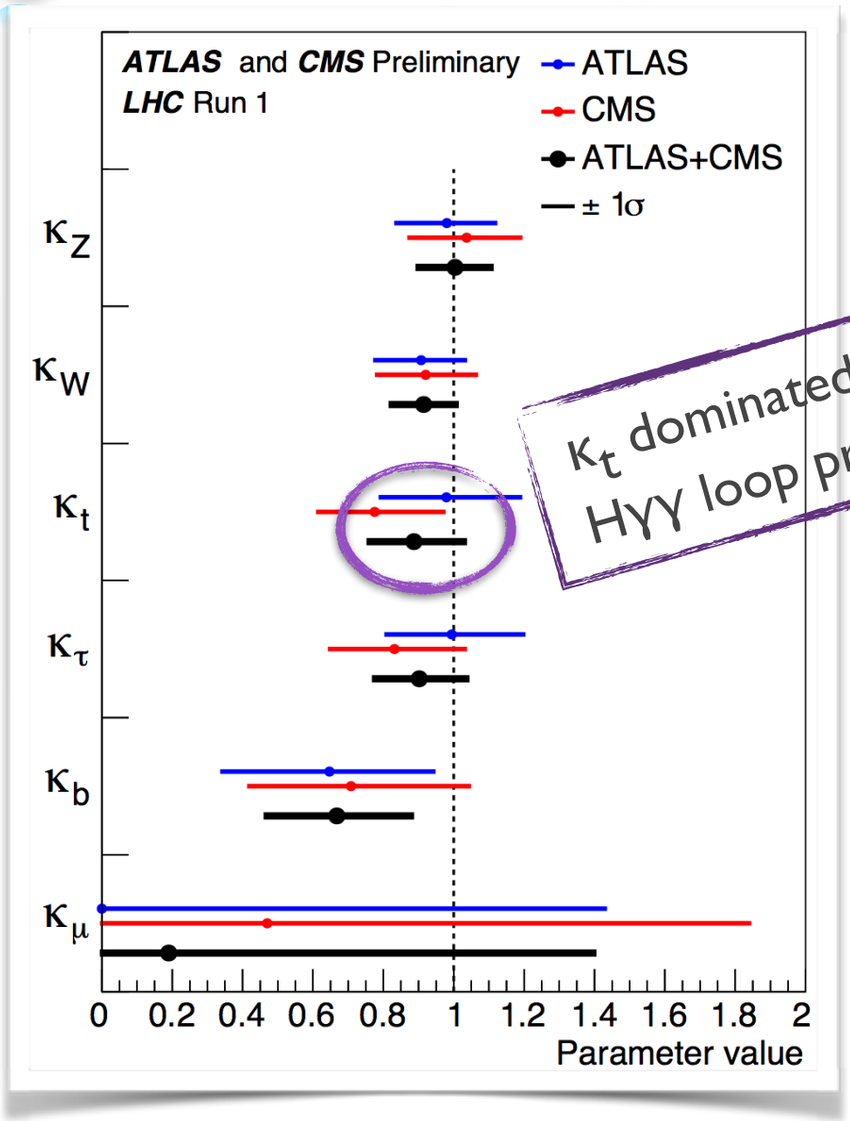


- Maybe it is time to further focus on the Higgs. We still have plenty to learn:

We will have many discoveries soon at Run-II!
- H→bb: 58% of BR(H)
- VH
- ttH

Motivation

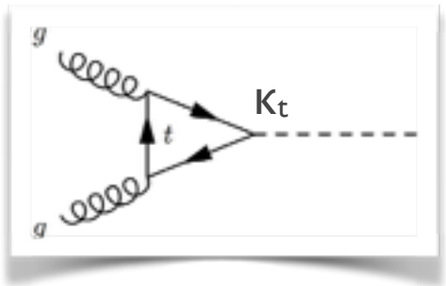
- We see the SM Higgs so far (with large error bars and several fit's degeneracies)

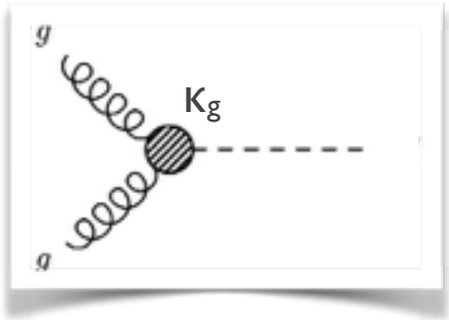


- Higgs–gauge couplings: extracted from precise tree–level information
- Higgs-fermions couplings: largely rely on loop–induced couplings

→ Limited and model–dependent

- What if BSM provides simultaneous modifications of both Higgs-top Yukawa and Higgs-gluon couplings?

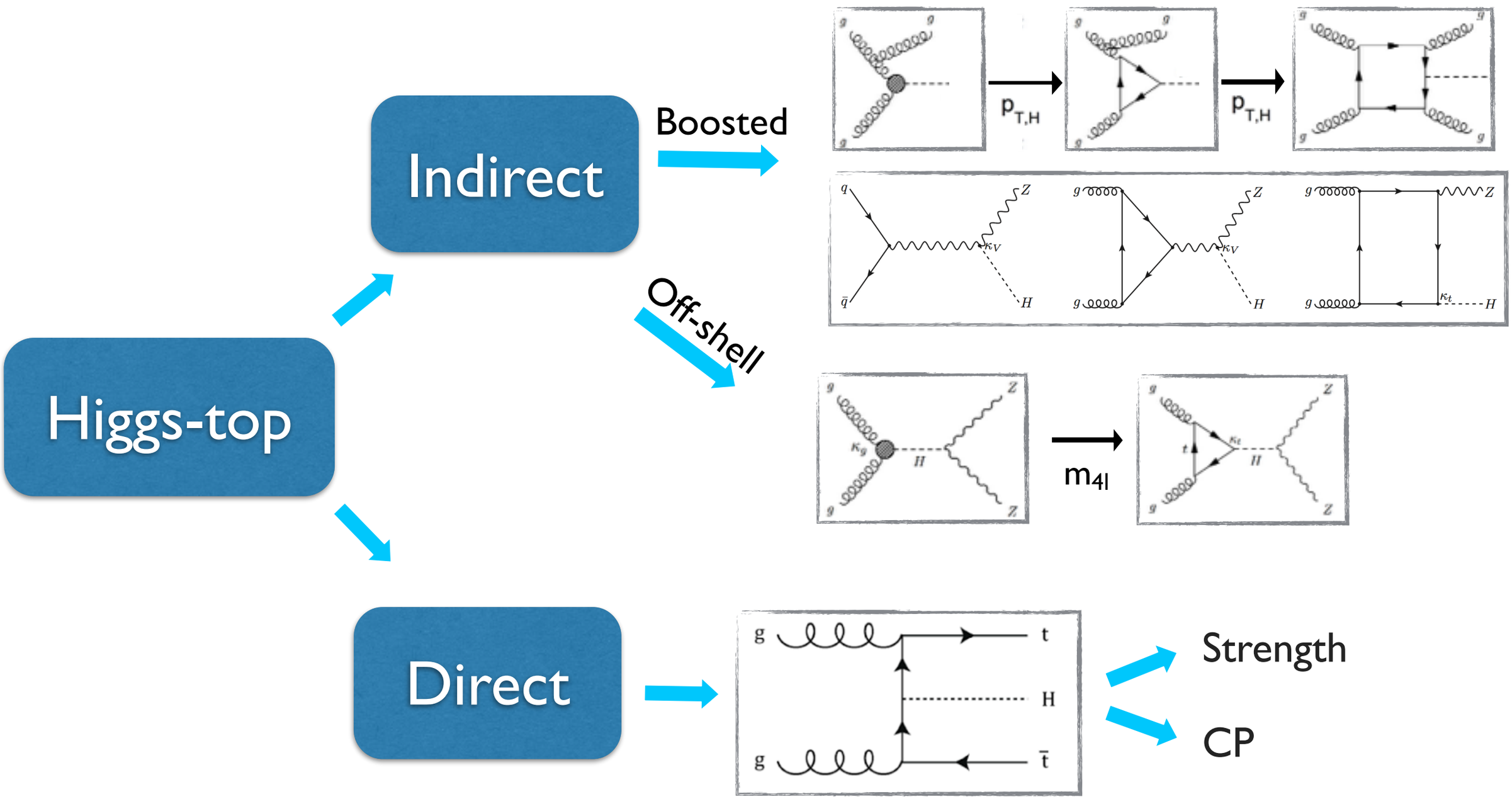




- What about Higgs-top CP-structure?

Motivation

- More energy and data will let us go far beyond the signal strength measurement



Framework for Higgs coupling analysis

Complexity

Full theory

New Lorentz structures
New degrees of freedom
Very complex/many parameters
But if correct gives predictability!

Simplified models

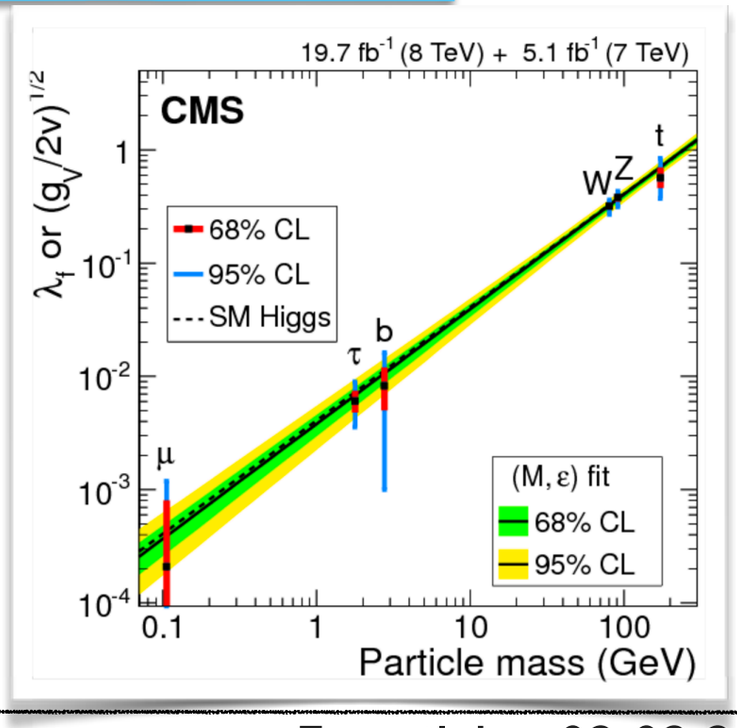
New Lorentz structures (interesting subset)
New degrees of freedom (interesting subset)

EFT

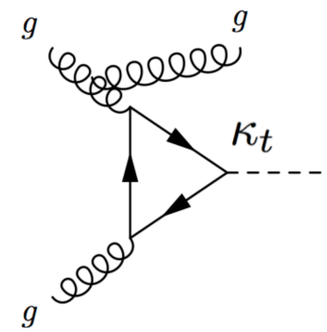
Same symmetries of the SM
New Lorentz structures
No new degrees of freedom

kappa formalism
(Run I paradigm)

Simple coupling rescaling
No new Lorentz structures
No new degrees of freedom



GF Higgs production

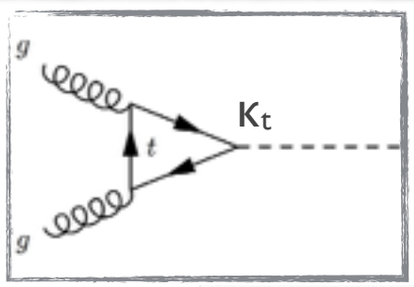


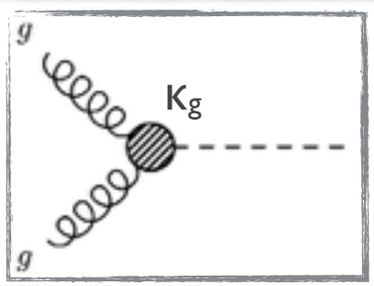
- Relevant CP-even dim6 operators to GF:

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

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

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



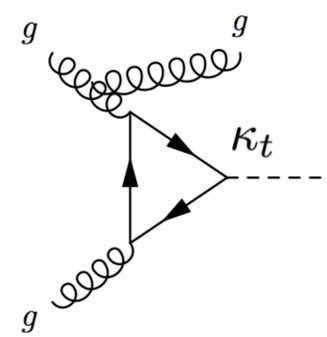


$$\mathcal{M} = \kappa_t\mathcal{M}_t + \kappa_g\mathcal{M}_g$$

Hj:
Azatov, Paul (2014)
Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant (2014)
Banfi, Martin, Sanz (2013)
Grojean, Salvioni, Schlaffer Weiler (2013)
Harlander, Neumann (2013)
Hjj:
Buschmann, Englert, DG, Plehn,Spannowsky (2014)
H+jets with NLO^{approx} Merging+...:
Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2015)

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

GF Higgs production



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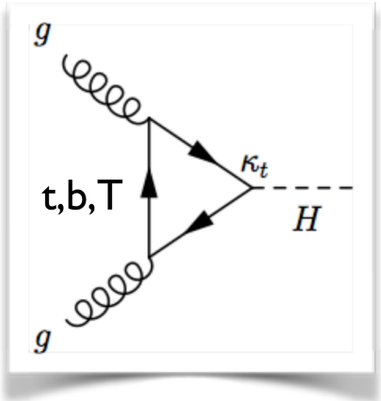
- Top partners - Prototype model inducing this degeneracy

$$\mathcal{L} = -yQ_Lt_RH - MTT - Y_TQ_LT_RH$$



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

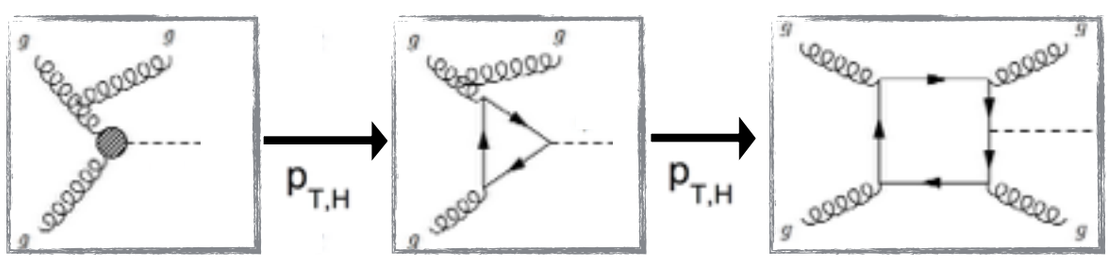
Dawson, Furlan (2014); Chen, Dawson, Lewis (2014)

Boosted Higgs

- Distributions are fundamental to break the degeneracy: $\sigma \sim |\kappa_t + \kappa_g|^2 \rightarrow \kappa_t + \kappa_g \sim 1$

  This information is missed in the rate analysis

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



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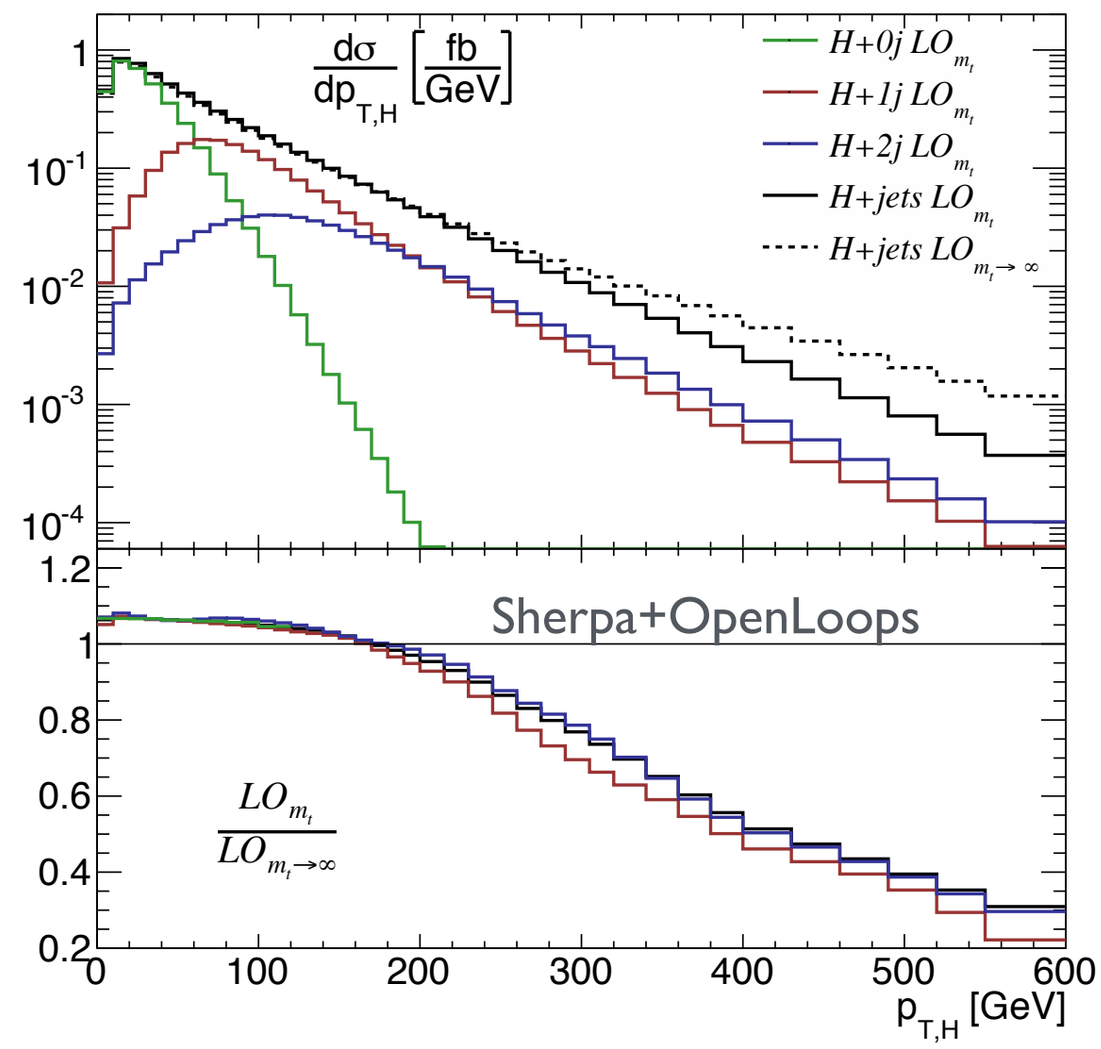

➡ Top mass effects fundamental for boosted H: correction of O(4) at p_{TH}~600 GeV

Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)
Caola, Stefano Forte, Marzani, Muselli, Vita (2016)
Neumann, Ciaran (2016); Baur, Glover (1990)

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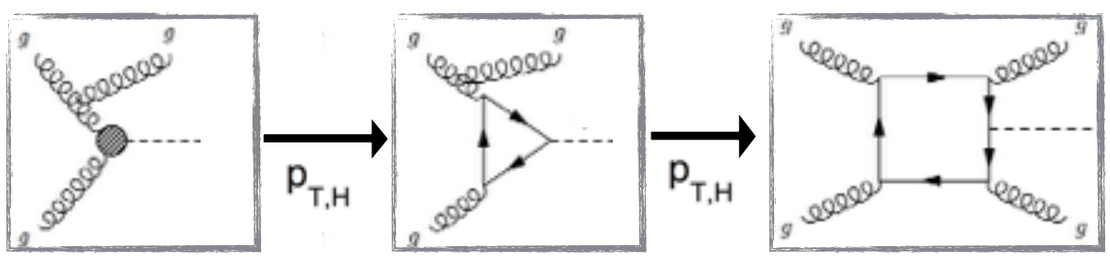

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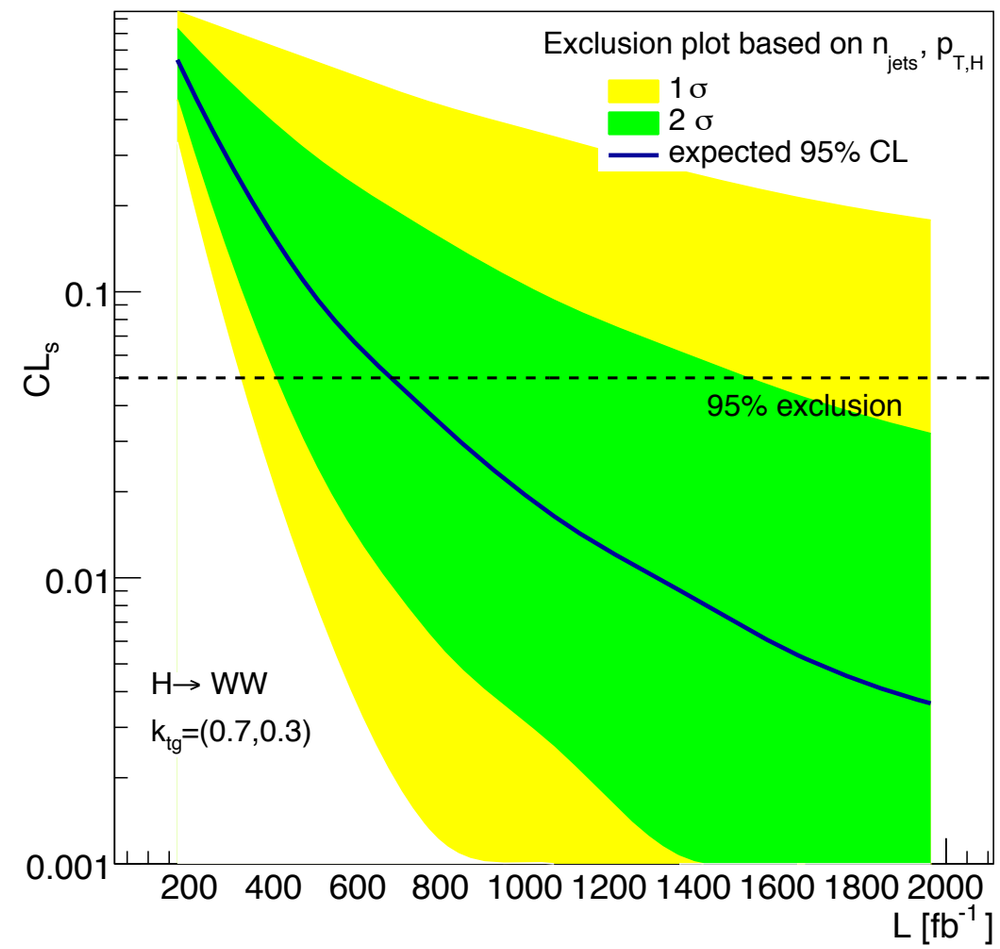


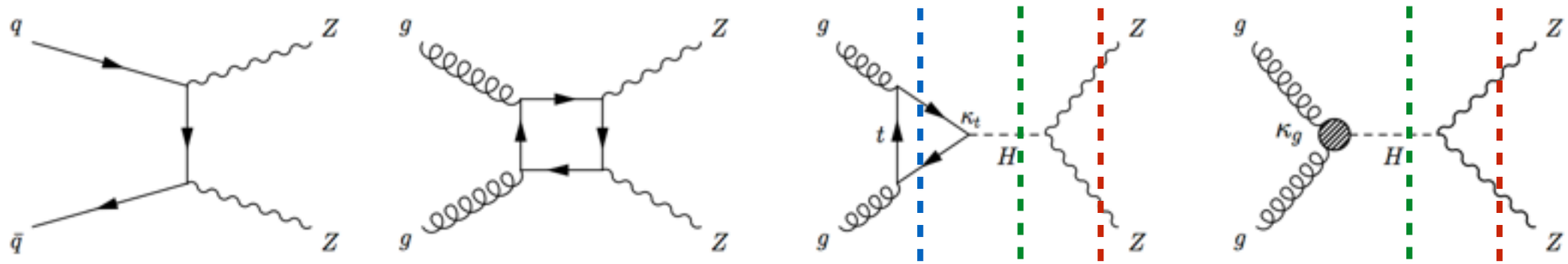
Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

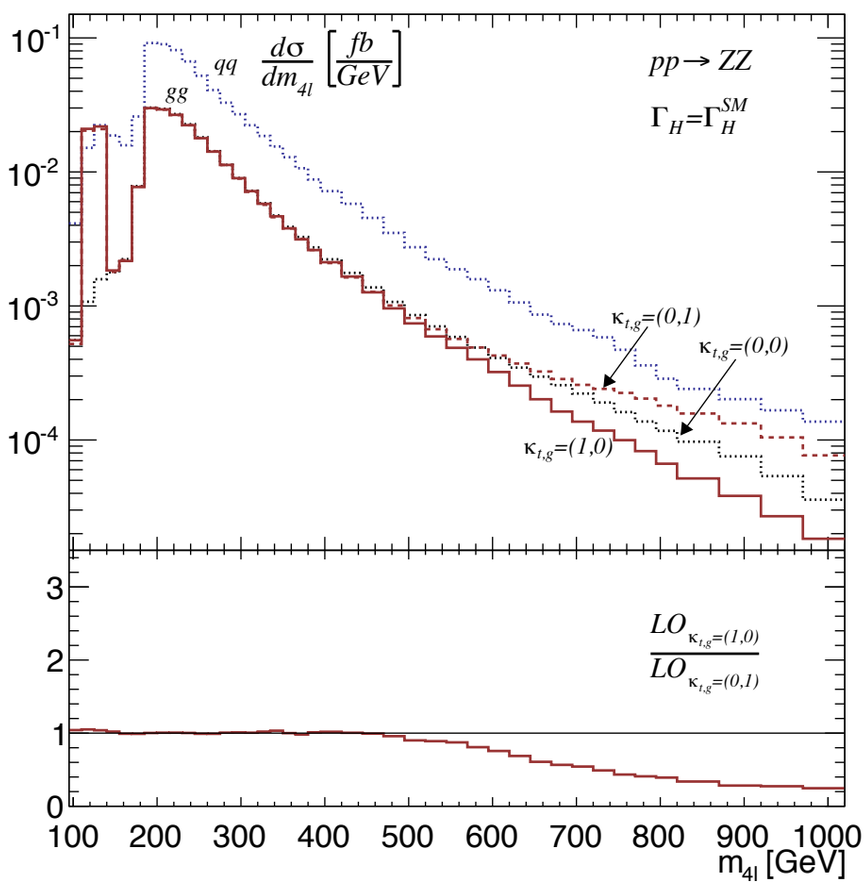
→ Top mass effects fundamental for boosted H: correction of O(4) at p_{TH}~600 GeV

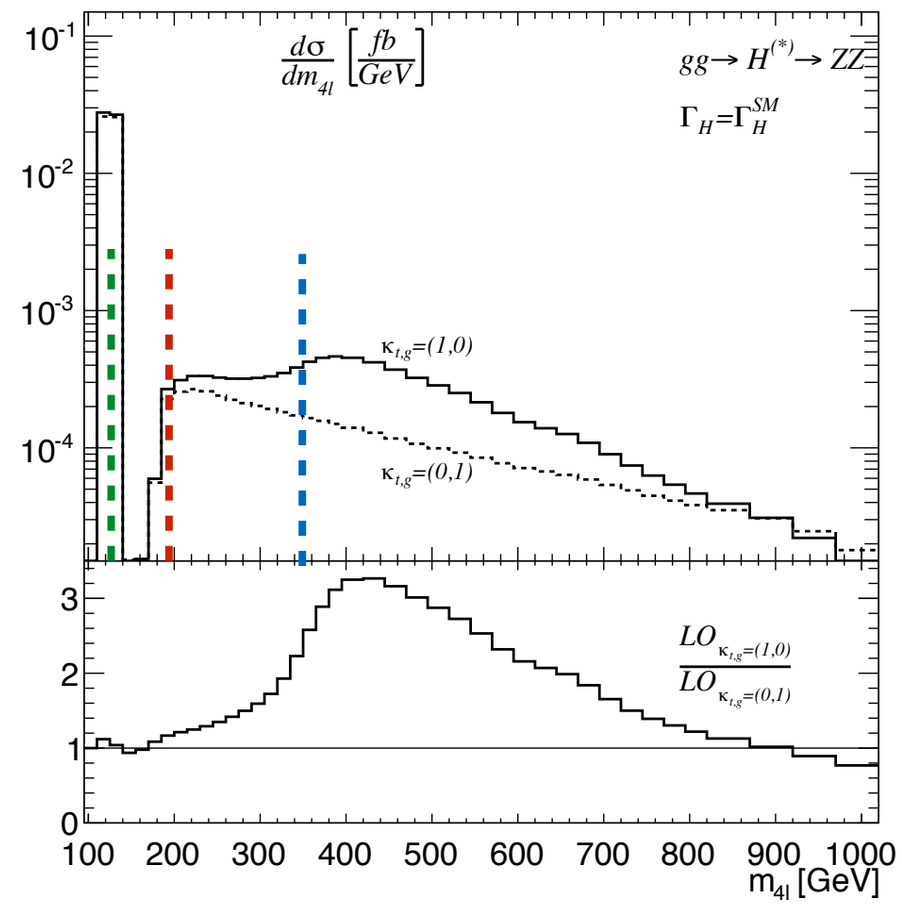
- δy_t~10-15% with ~3ab^{-1} from ttH

Off-Shell Higgs Production

- Signal and background components:







- 15% of cross-section comes from m_{4l}>140 GeV

Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)
Campbell, Ellis, Williams (2013); Azatov Grojean, Salvioni (2014)
Lykken, Matchev, Mrenna, Gainer (2014)

Off-Shell Higgs Production

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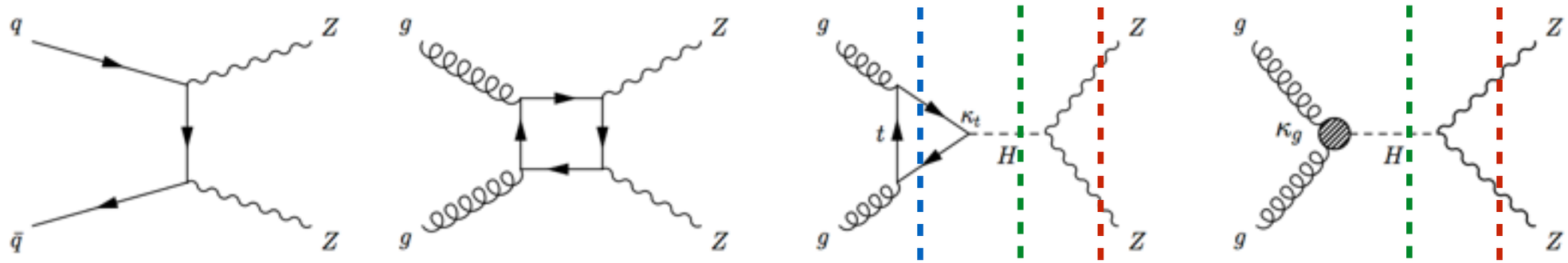

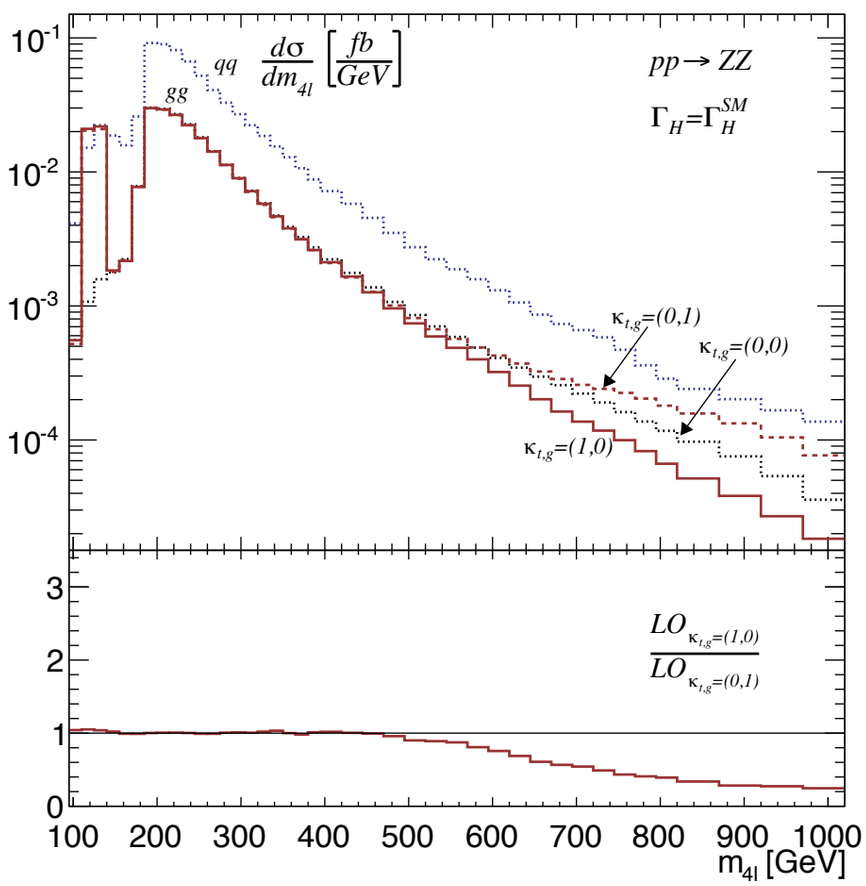

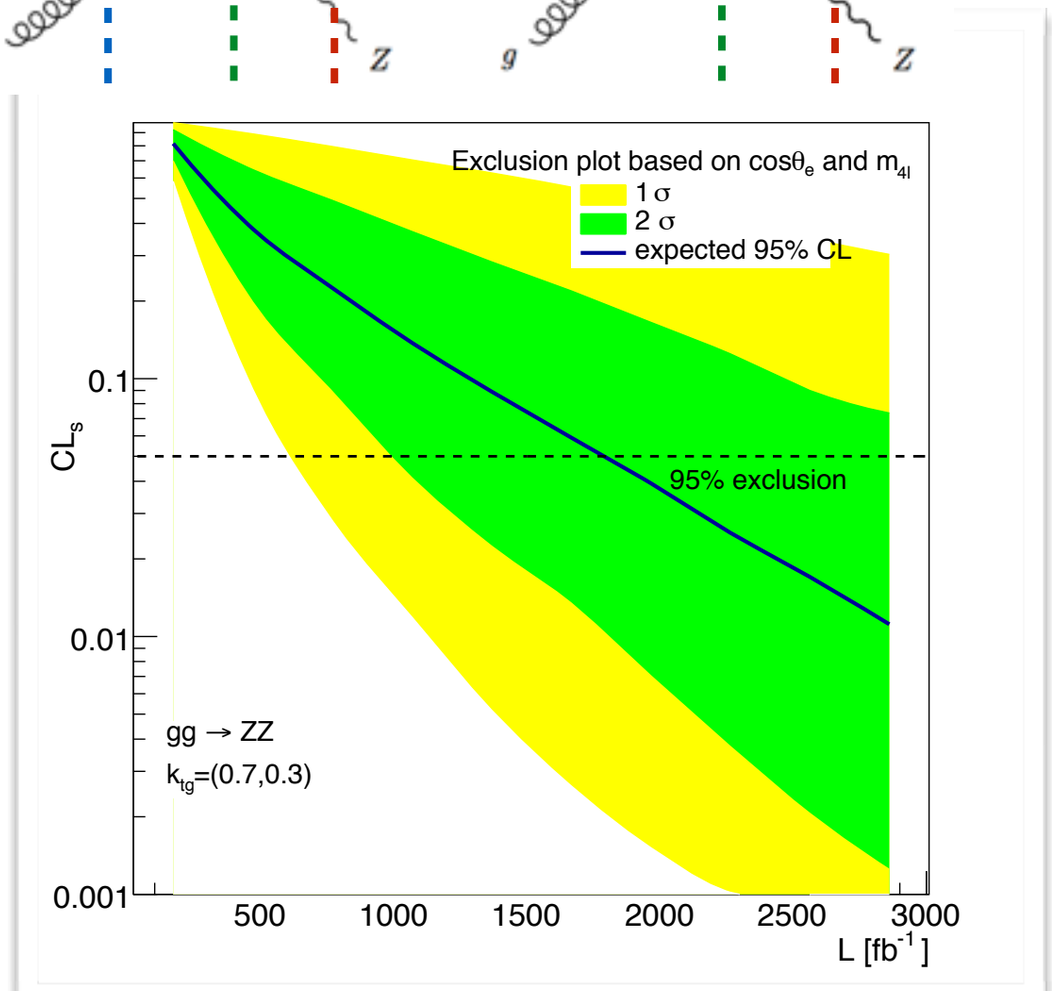

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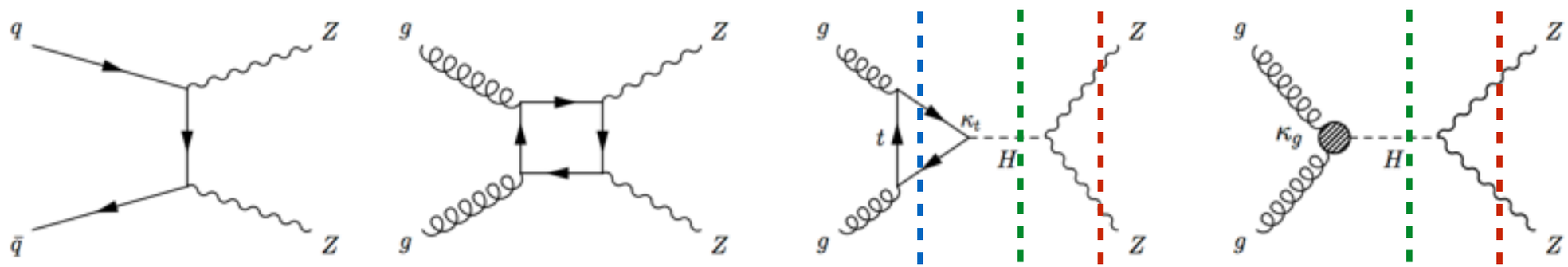


$$\mathcal{M}_t^{++00} = -2\,\frac{m_{4\ell}^2 - 2m_Z^2}{m_Z^2}\,\frac{m_t^2}{m_{4\ell}^2 - m_H^2 + i\Gamma_H m_H}\left[1 + \left(1 - \frac{4m_t^2}{m_{4\ell}^2}\right) f\left(\frac{4m_t^2}{m_{4\ell}^2}\right)\right]$$

→ 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)

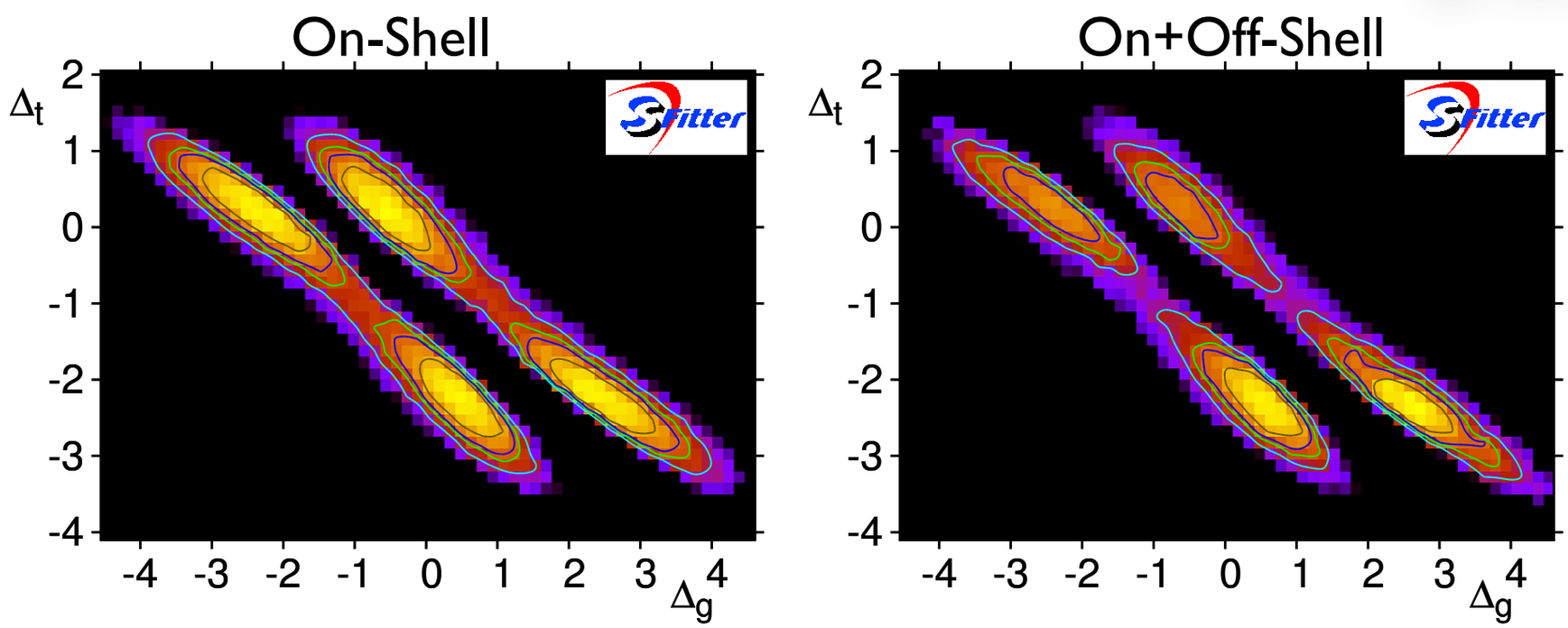
Off-Shell Higgs Production: SFitter results

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

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

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

$$g = (1+\Delta) g_{SM} = \kappa g_{SM}$$



- 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 the fit

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

Higgs width measurement

- SM prediction $\Gamma_H \sim 4.2$MeV
  - → Best limit from direct measurement $H \to ZZ$: $\Gamma_H < 2.6$ (3.5)GeV obs (exp) ATLAS
  - The ultimate reach is expected to be ~1GeV

- 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 (2013)

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

Englert, Spannowsky (2014)

Higgs width measurement

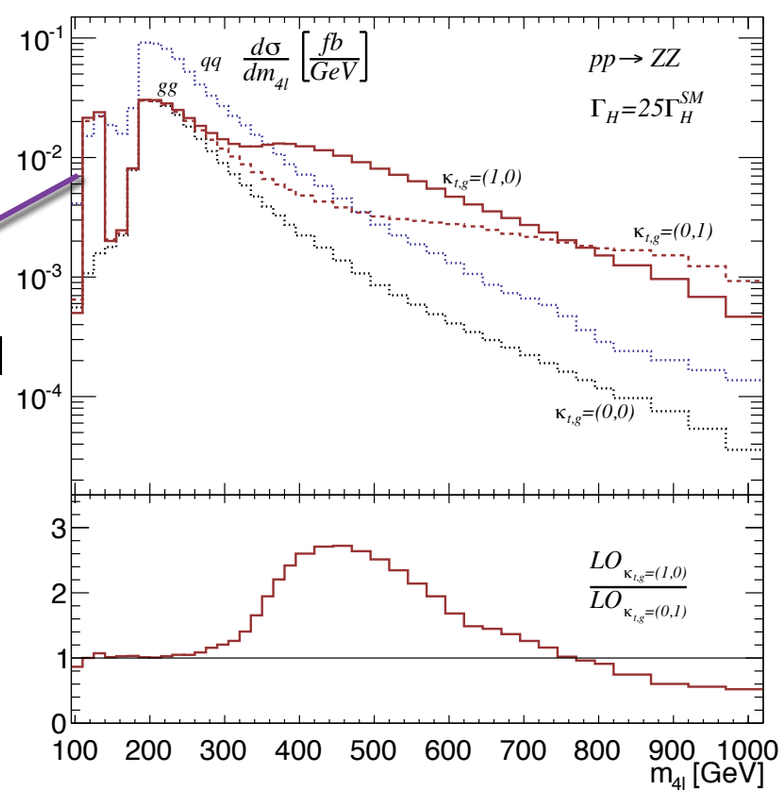
- Model dependency ultimately reflect the non-trivial ggH momentum running

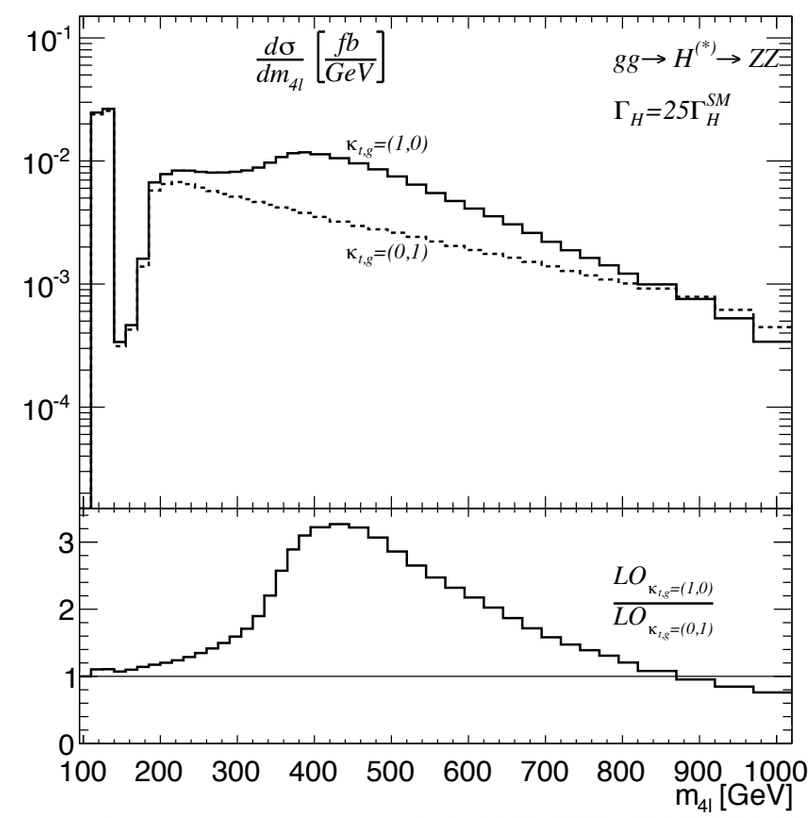
  Our setup is a prime example of it:

$$\sigma^{\text{On-Shell}}_{gg\to H\to ZZ} \propto (\kappa_t+\kappa_g)^2 \frac{g^2_{ggH}(m_H)g^2_{HZZ}(m_H)}{\Gamma_H}$$ → 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: $\xi^4 = 25 \quad \rightarrow \quad \Gamma_H = 25\Gamma_H^{\text{SM}}$





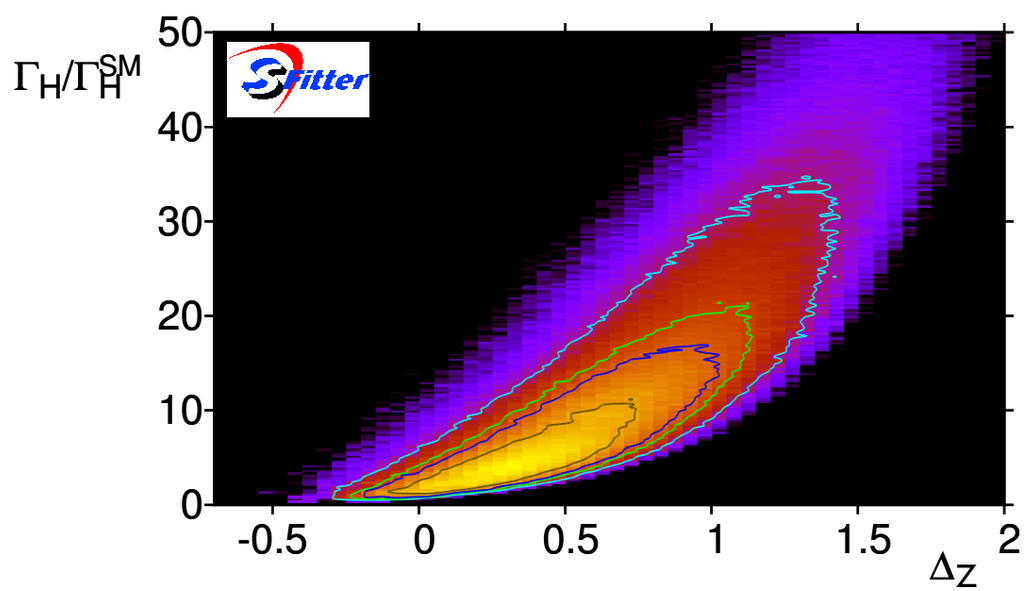
Signal strength still

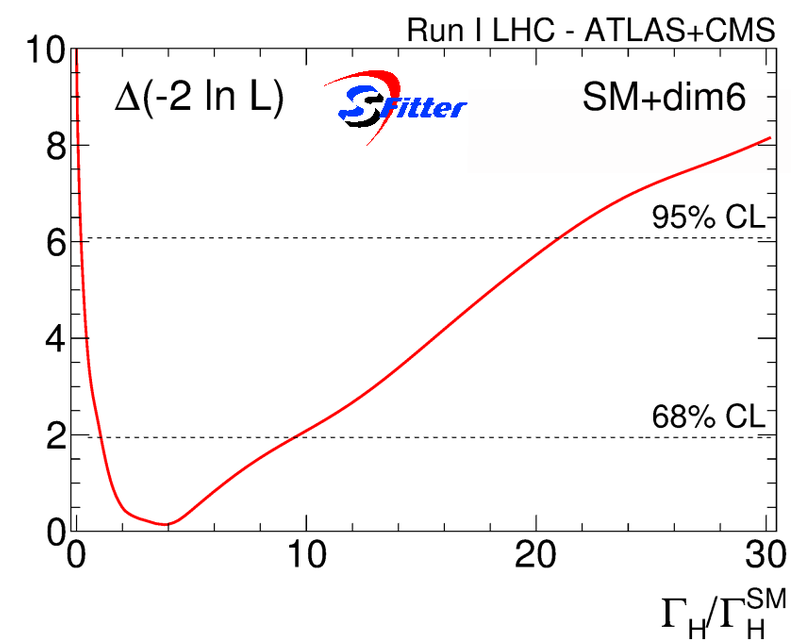
$\mu_{\text{on-shell}} = 1$

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

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



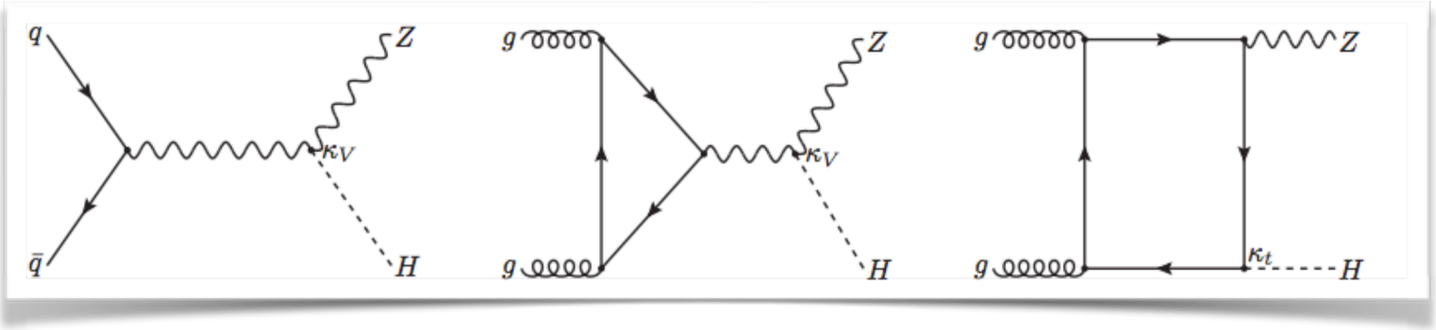


  - $\Gamma_H < 9.3\Gamma^{SM}$ at 68% CL. While this width constraint was obtained considering possible BSM operators, the bound is still competitive to other analysis that account only to SM-like interactions
  - Key ingredient: full m_{4l} profile

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

ZH Production

- ZH signal components:



@LO~O(α_{EW}^2) @LO~O($\alpha_s^2\alpha_{EW}^2$)

Altenkamp, Dittmaier, Harlander, Rzehak, Zirke (2013)
Englert, McCullough, Spannowsky (2013)
Hespel, Maltoni, Vryonidou (2015)
Campbell, Ellis, Williams (2016)

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

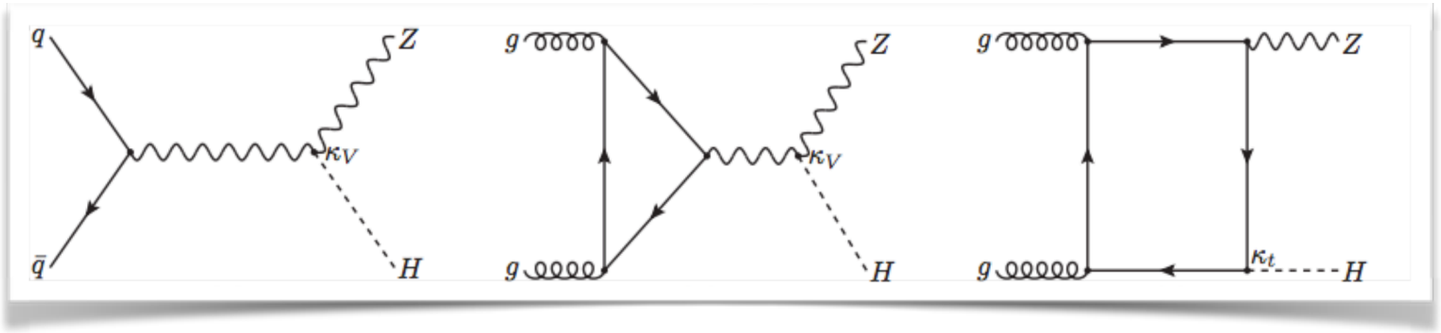
$$\frac{d\sigma}{dp_{TH}} = \kappa_t^2 \frac{d\sigma_{tt}}{dp_{TH}} + \kappa_t \kappa_V \frac{d\sigma_{tV}}{dp_{TH}} + \kappa_V^2 \frac{d\sigma_{VV}}{dp_{TH}}$$

- 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 $p_{TH} \sim m_t$

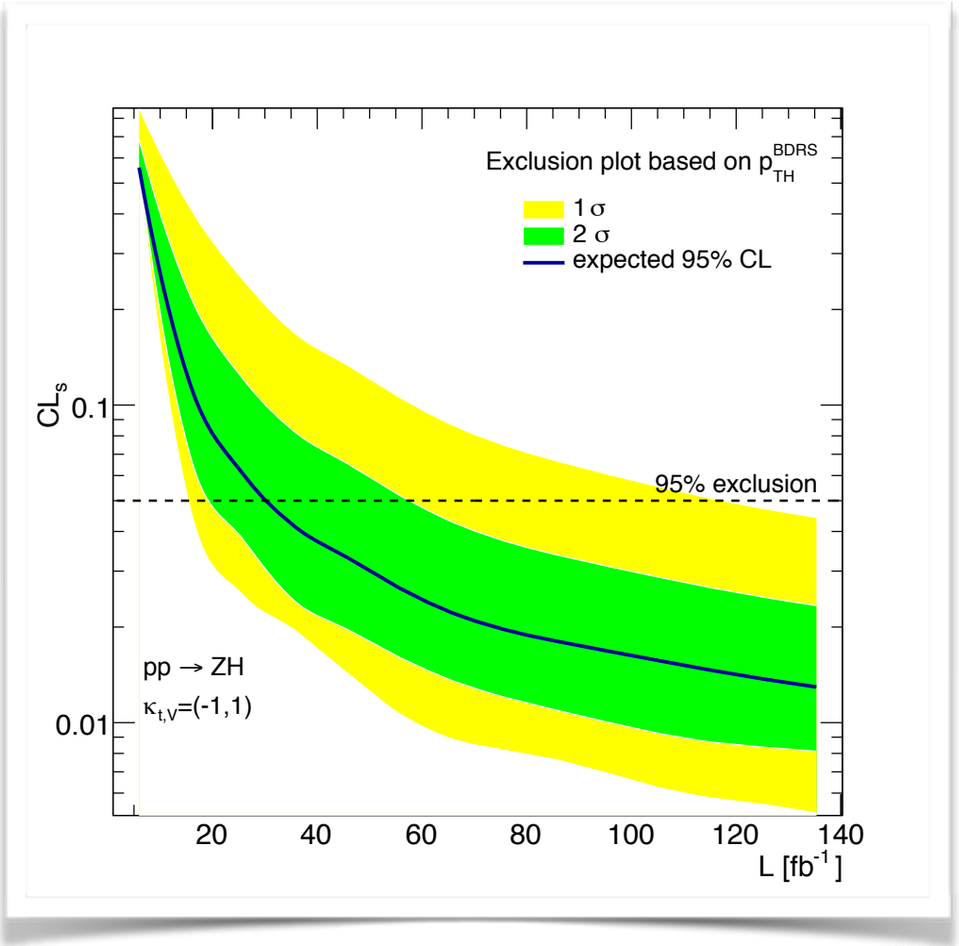
DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

ZH Production

- ZH signal components:



@LO~O(α_{EW}^2) @LO~O($\alpha_s^2\alpha_{EW}^2$)



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

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

sign

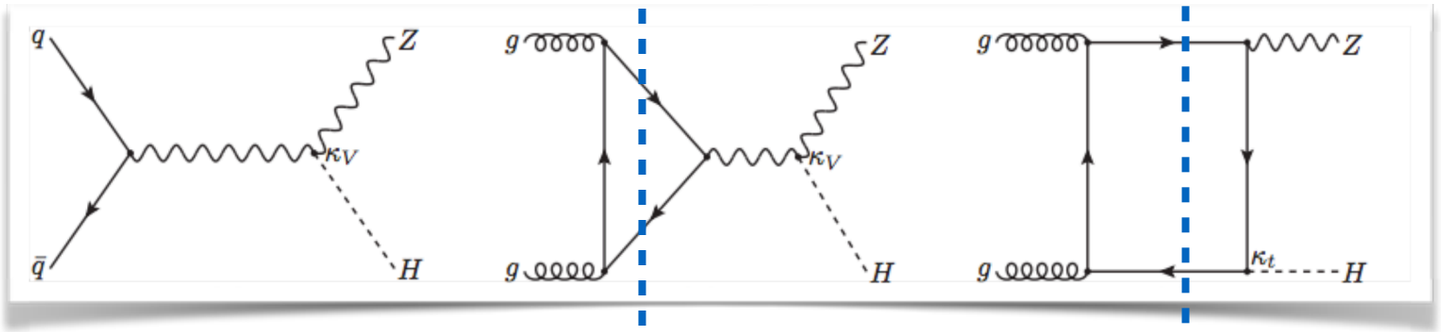
- SM σ_{tV} presents large destructive interference
- We can exclude k_t=-1 with ~30 fb^{-1} of data:

  The LHC has already enough data for it

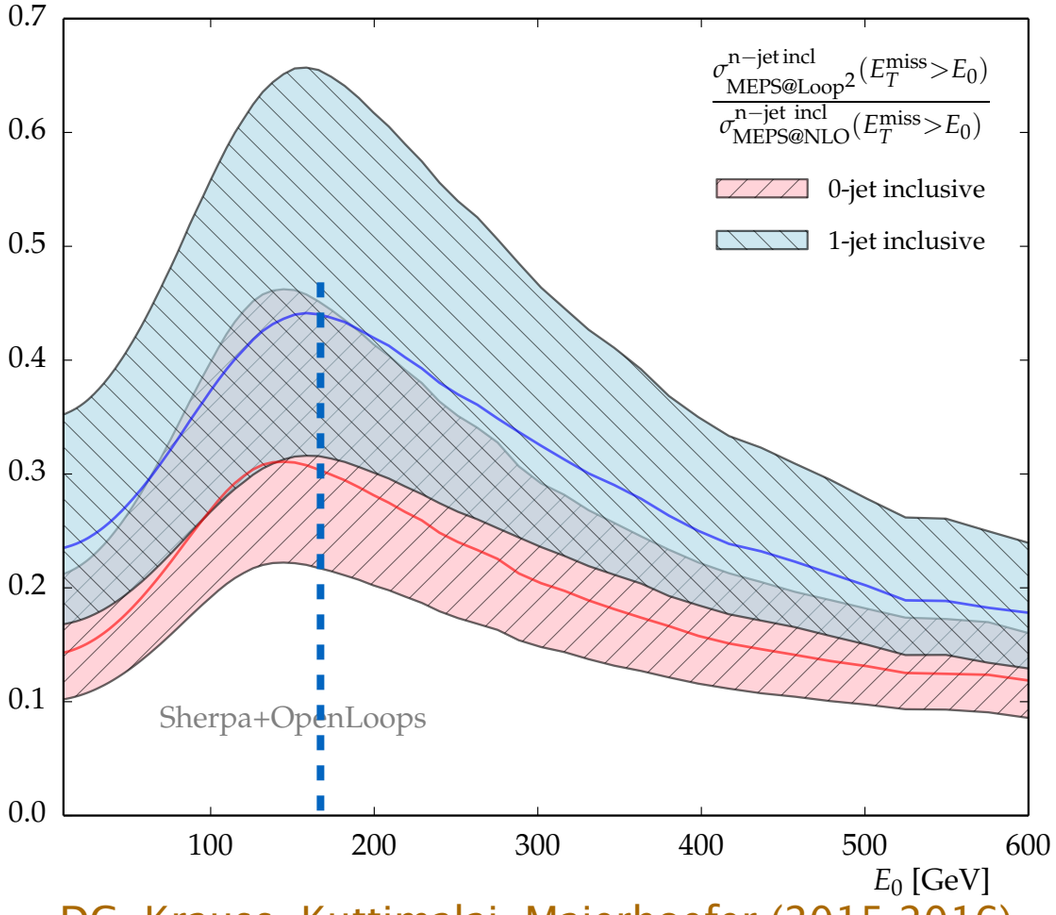
DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

ZH Production

- ZH signal components:



- Boosted kinematics enhances loop-induced component



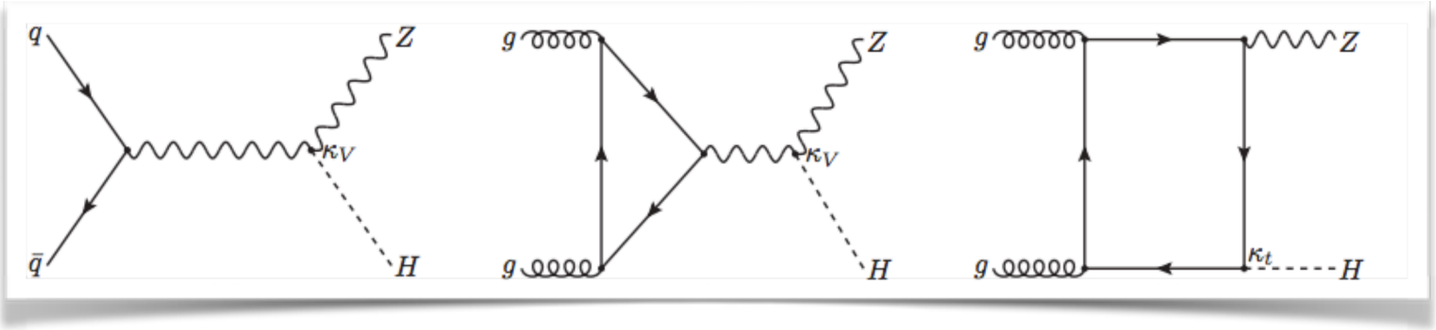
DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

This impacts on:

- Invisible bounds from Z(ll)H(inv)
- And y_b from Z(ll)H(bb)

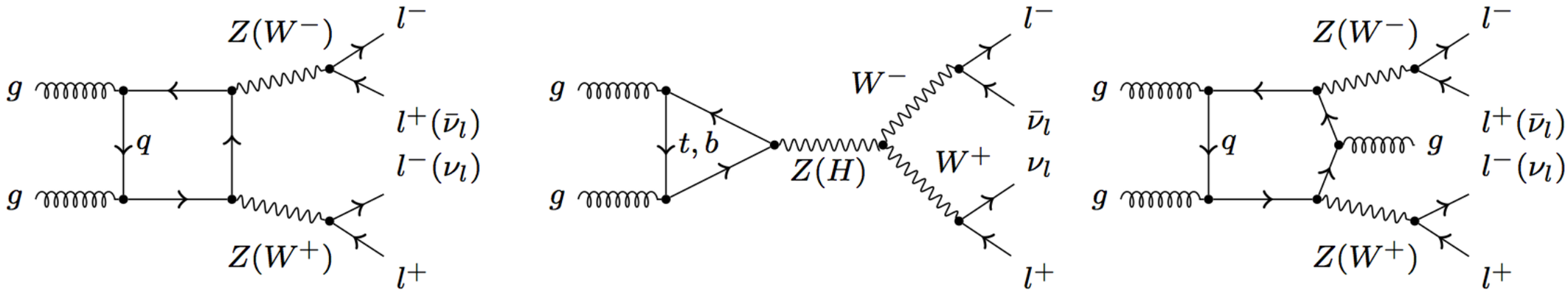
ZH Production

- ZH signal components:



- By the same arguments, we should also consider the loop-induced background contributions

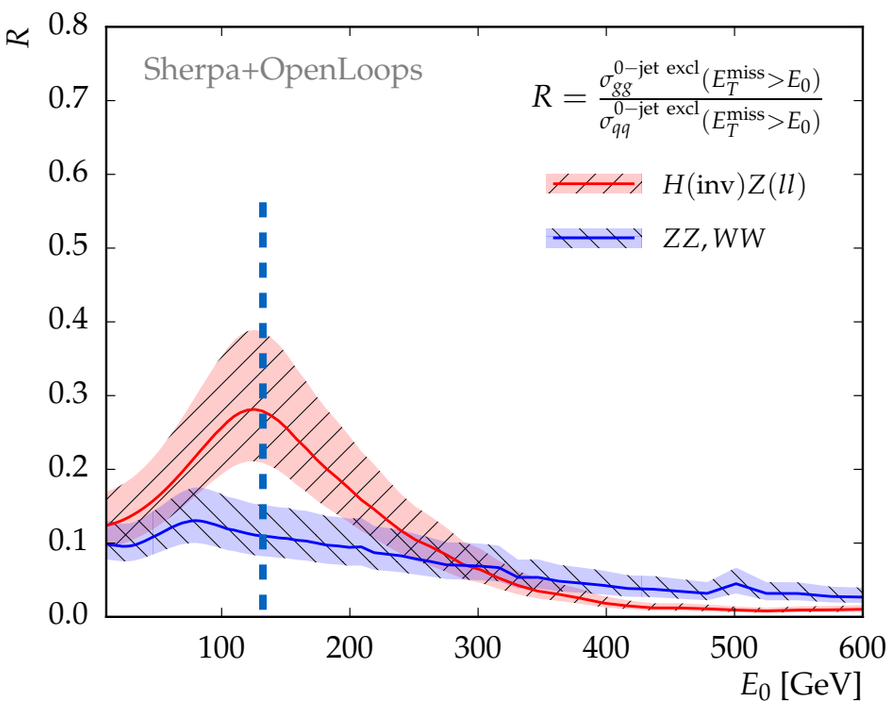
  E.g., the major backgrounds for Invisible searches VV' also present relevant loop-induced components

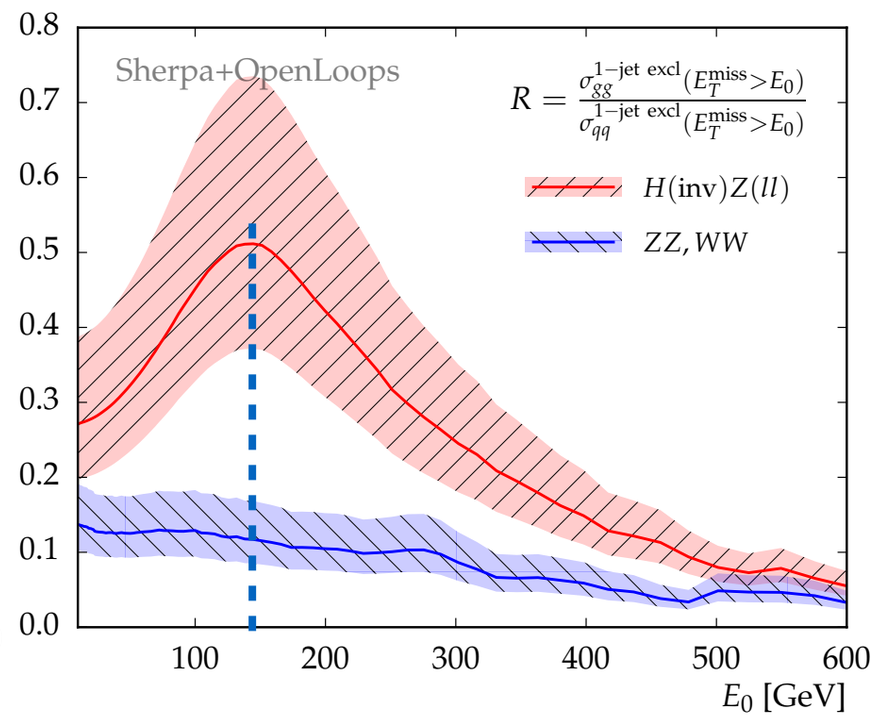


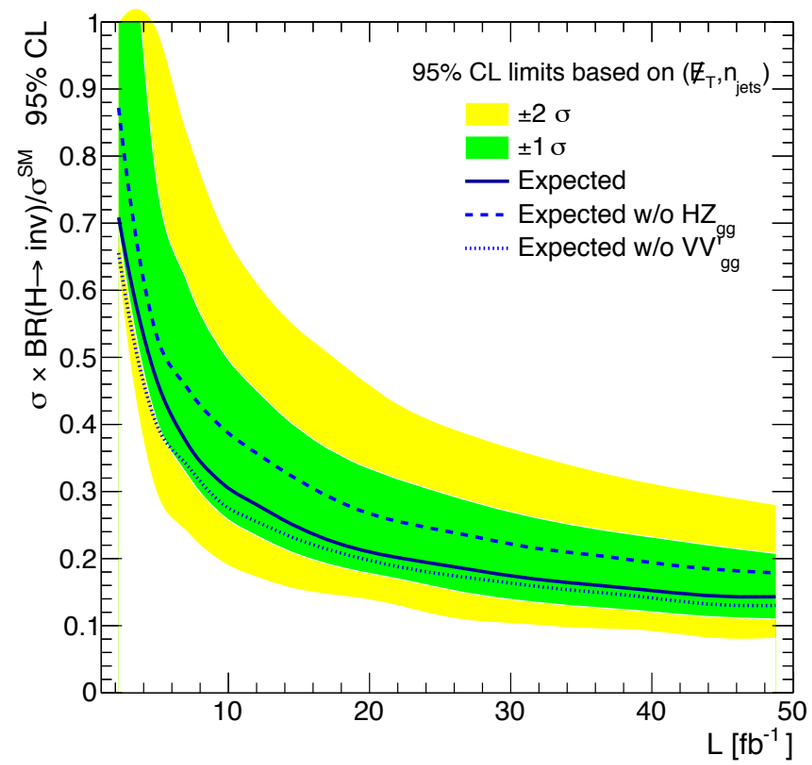
DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

ZH: invisible searches

- Constraining power to BR(H>inv) for the Run-II LHC:
  - Jet vetoes set under control tt+jets background
  - Multi-jet merging accounts for detailed QCD emissions in each jet sample







DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

- $\mathcal{BR}(H \to inv) < 0.3$ with only 10 fb^{-1}
- $\mathcal{BR}(H \to inv) < 0.4$ disregarding HZ_{GF} at the same luminosity

  HZ_{GF} makes the bound stronger by more than 30%

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

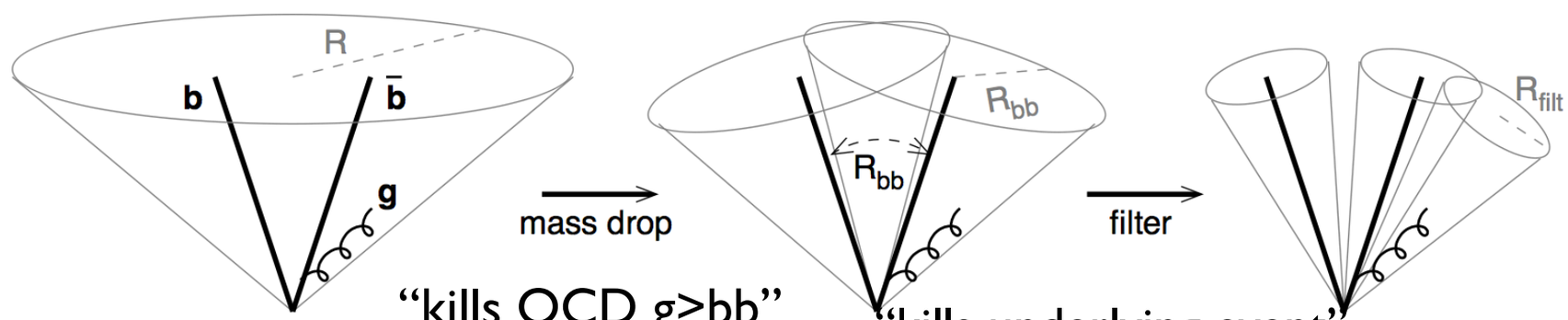
Underlying event: $\langle \delta m_j^2 \rangle \simeq \Lambda_{\rm UE}\, p_{T,j} \left(\frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)$, with $\Lambda_{UE} \sim 10\ GeV$

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: $R \sim 2m_H/p_T \sim 1.2$



"kills QCD g>bb"

"kills underlying event"

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

Take 3 hardest subjets

b-tagging on the 2 hardest

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

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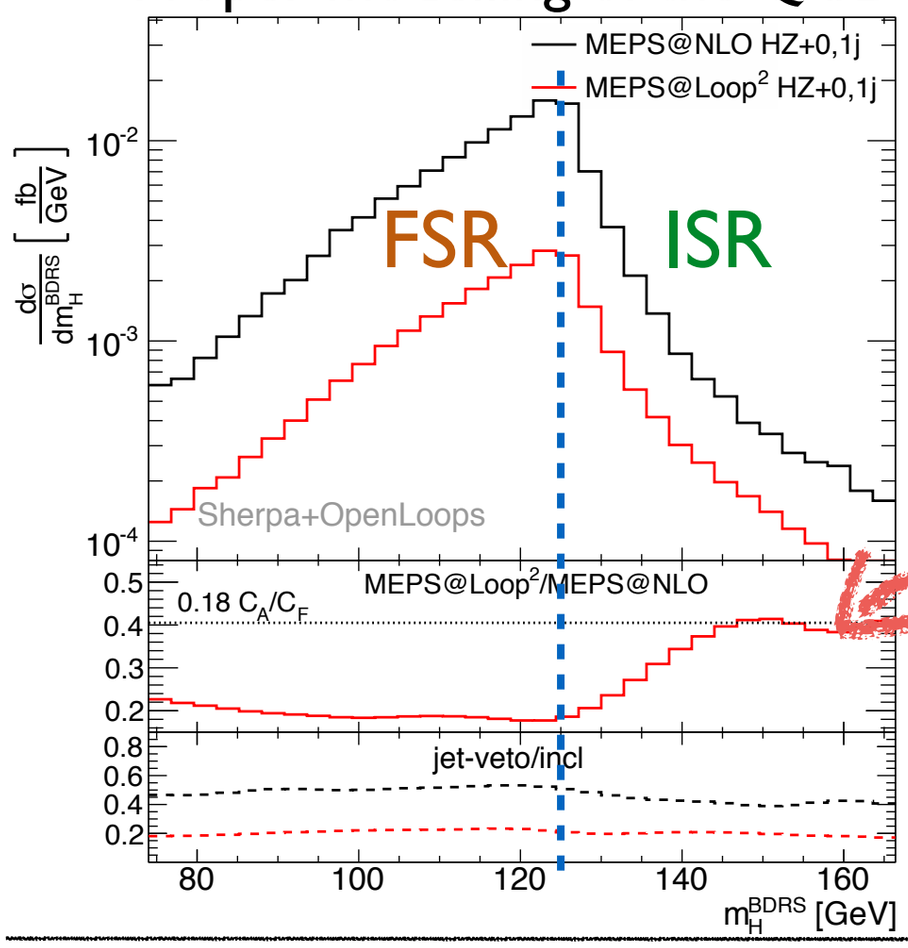
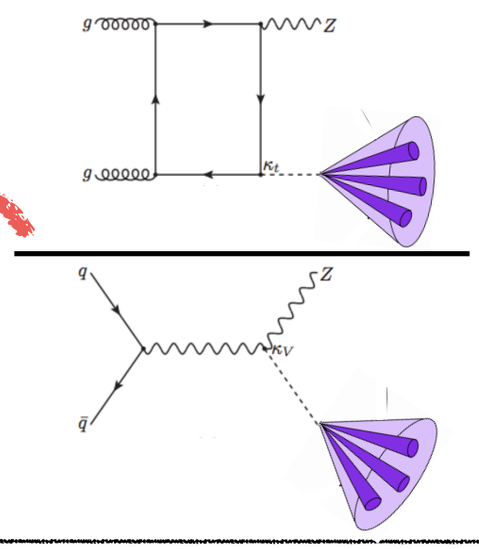


- GF changes the invariant mass profile for the filtered Higgs:
  - → m_{BDRS}<125GeV: FSR - PS radiation off the bb pair
  - → m_{BDRS}>125GeV: ISR - MEPS@NLO and MEPS@Loop²

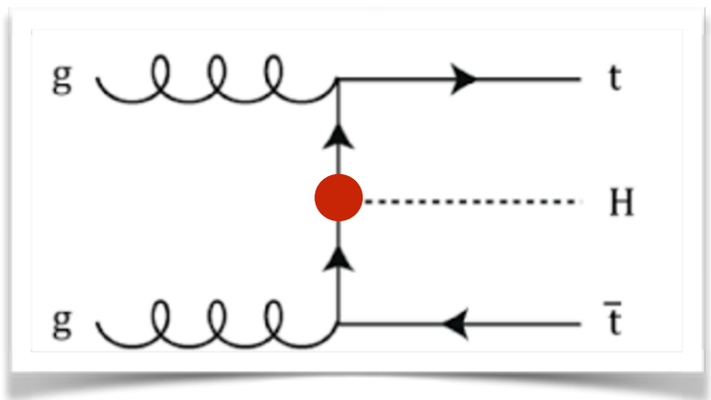


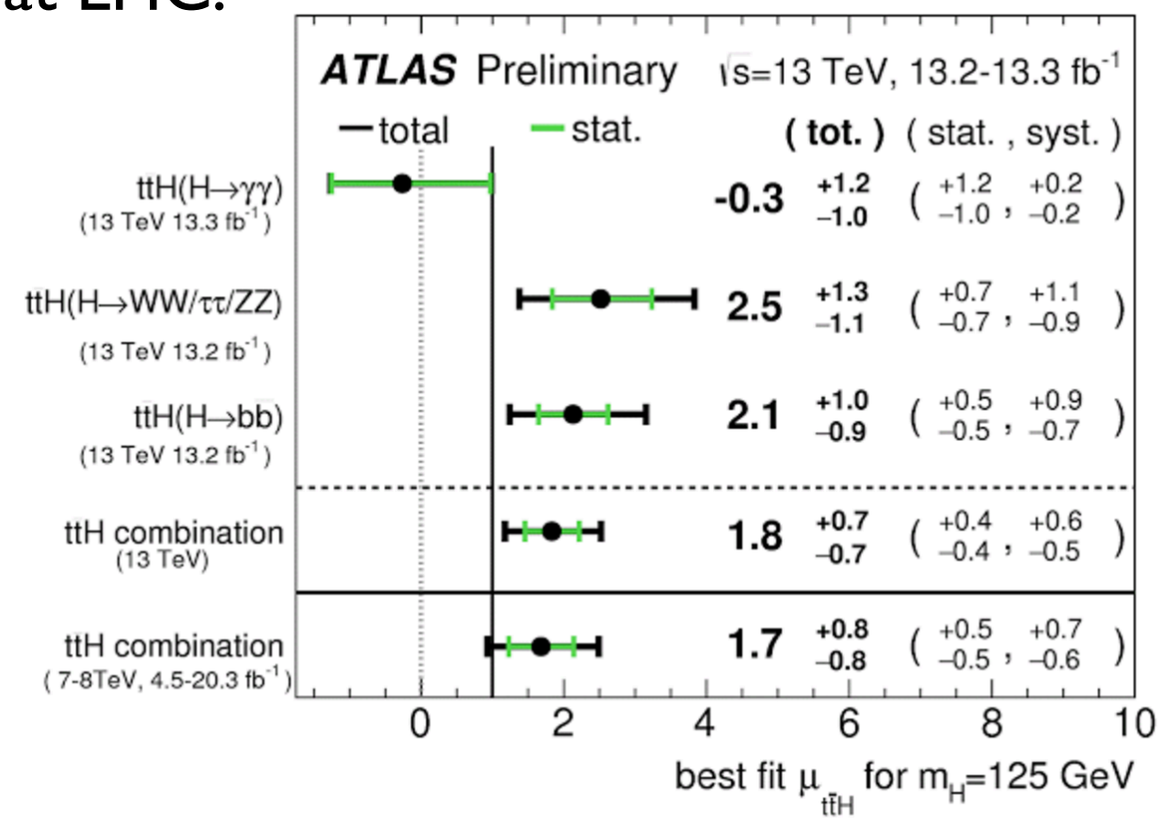
Higgs is genuinely part of a multi-jet system

DG, Krauss, Kuttimalai, Maierhoefer (2015)

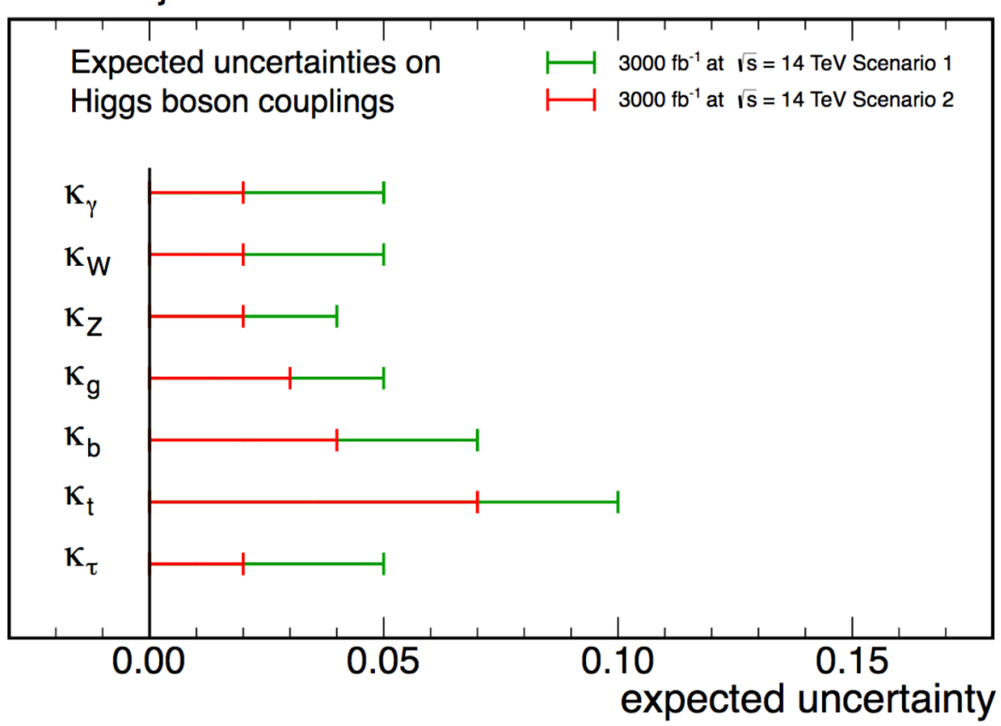
Exciting opportunities ahead!

- ttH channel is around the corner at LHC:





CMS Projection



- Expected precisions
  - Scenario I: systematic uncertainties same as now
  - Scenario II: theoretical uncertainty divided by 1/2 and systematic by 1/sqrt(L)

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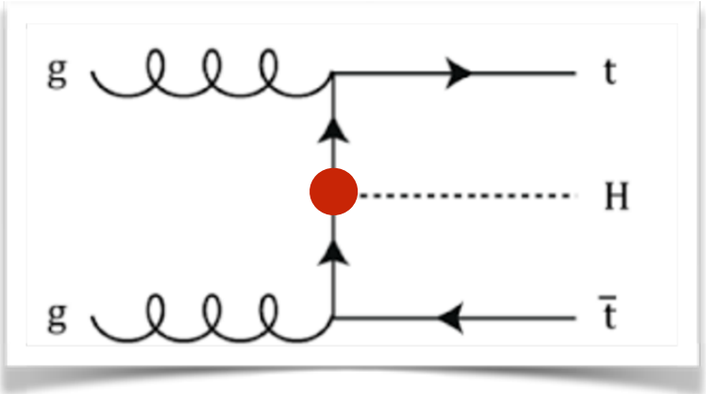
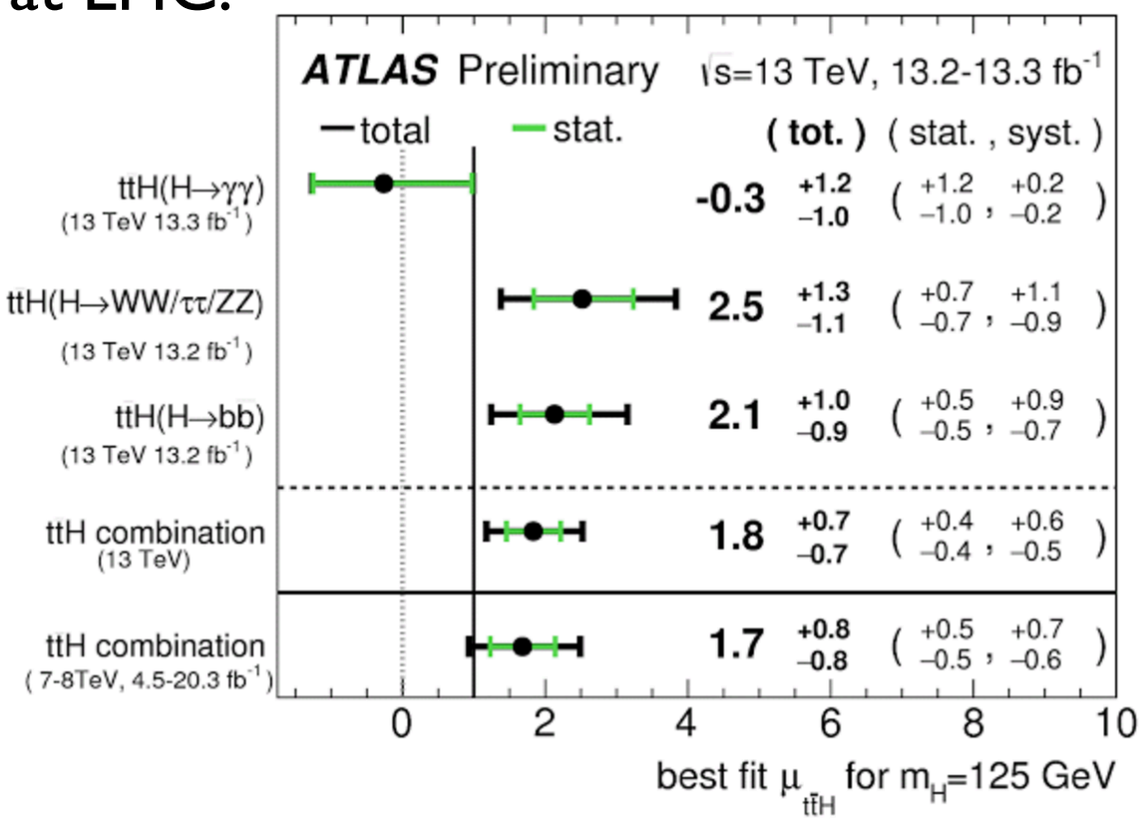




- Can we <u>directly</u> measure Higgs-top CP structure at the LHC?

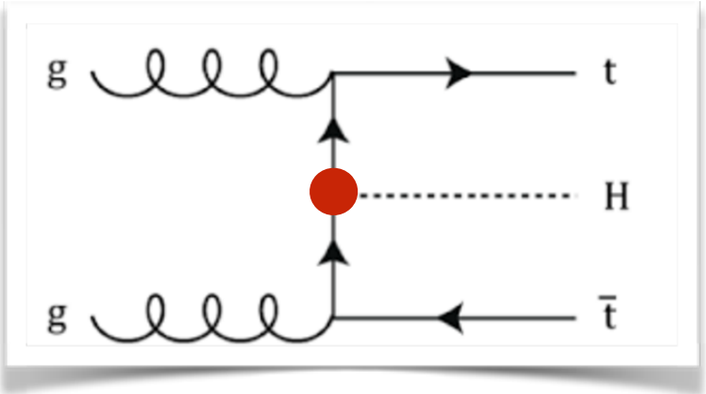
$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$

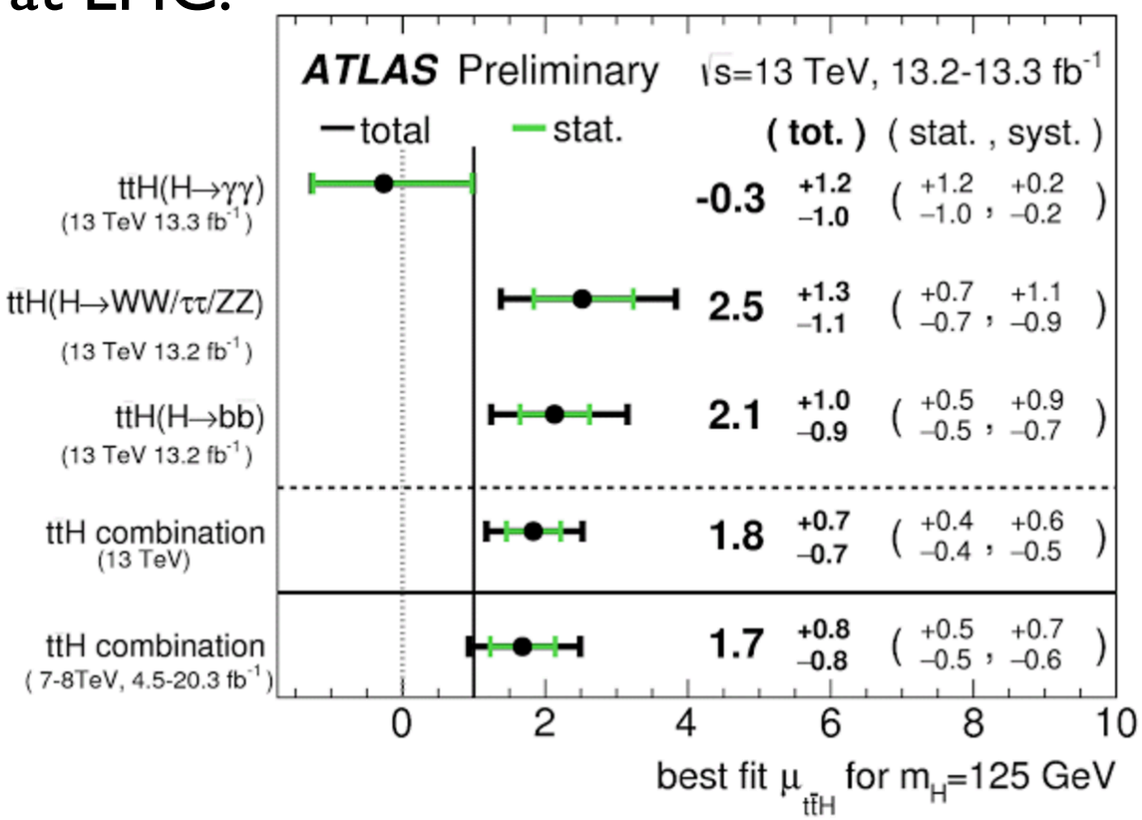
J. Ellis, Hwang, Sakurai, Takeuchi (2014)
Boudjemaa, Godbole, Guadagnoli,Mohan (2015)
Buckley, DG (2015)

- While CP-odd H-V appears only at dim-6 or higher, CP-odd H-f can manifest at tree-level
- Mixture possible in some models, e.g., 2HDM
- Not excluded from Higgs measurements

Exciting opportunities ahead!

- ttH channel is around the corner at LHC:





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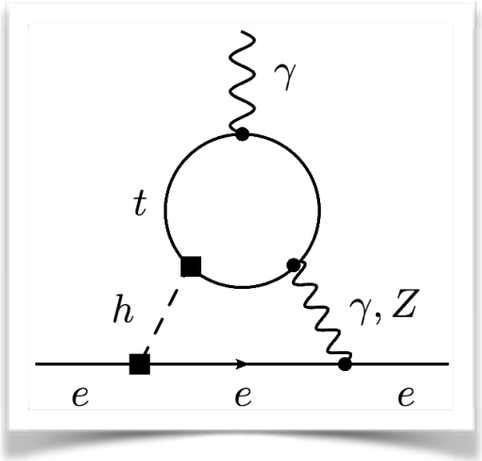

- Indirect constraints from eEDM very strong, yet assume:
  - Coupling strength/structure to light fermions
  - No other states in the spectrum

Directly Measuring $t\bar{t}H$

- Spin correlations of top and anti-top affected by nature of interaction

  $\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$:

  Parke, Mahlon (2010)

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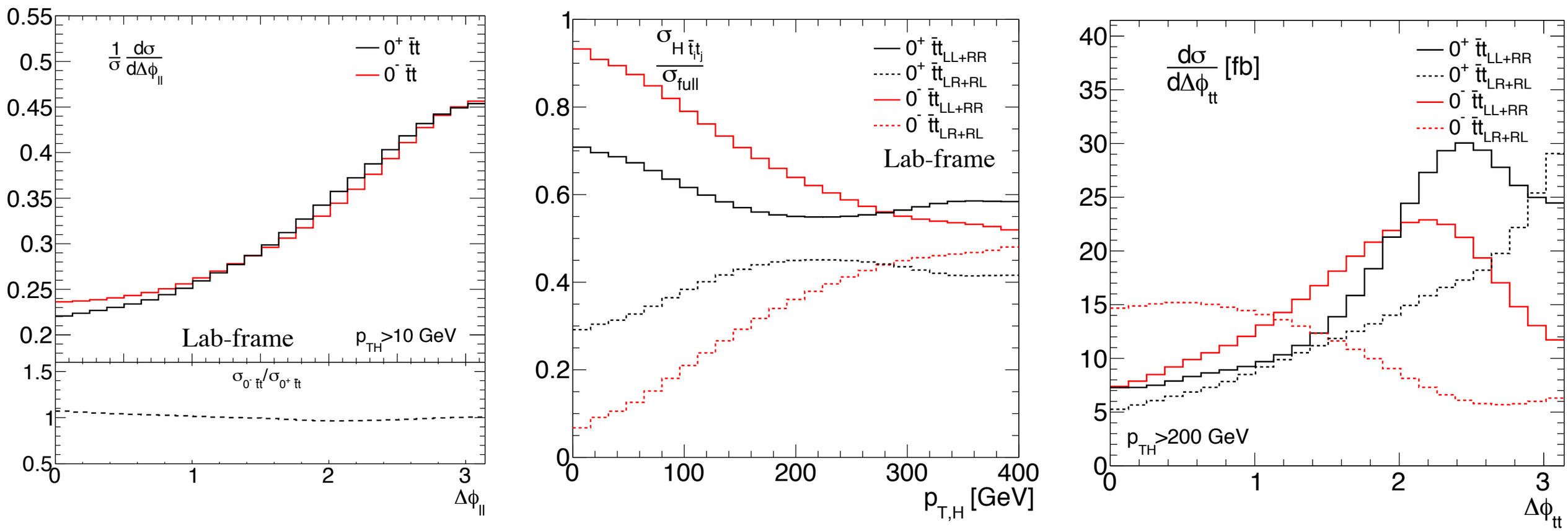

Buckley, DG (2015)

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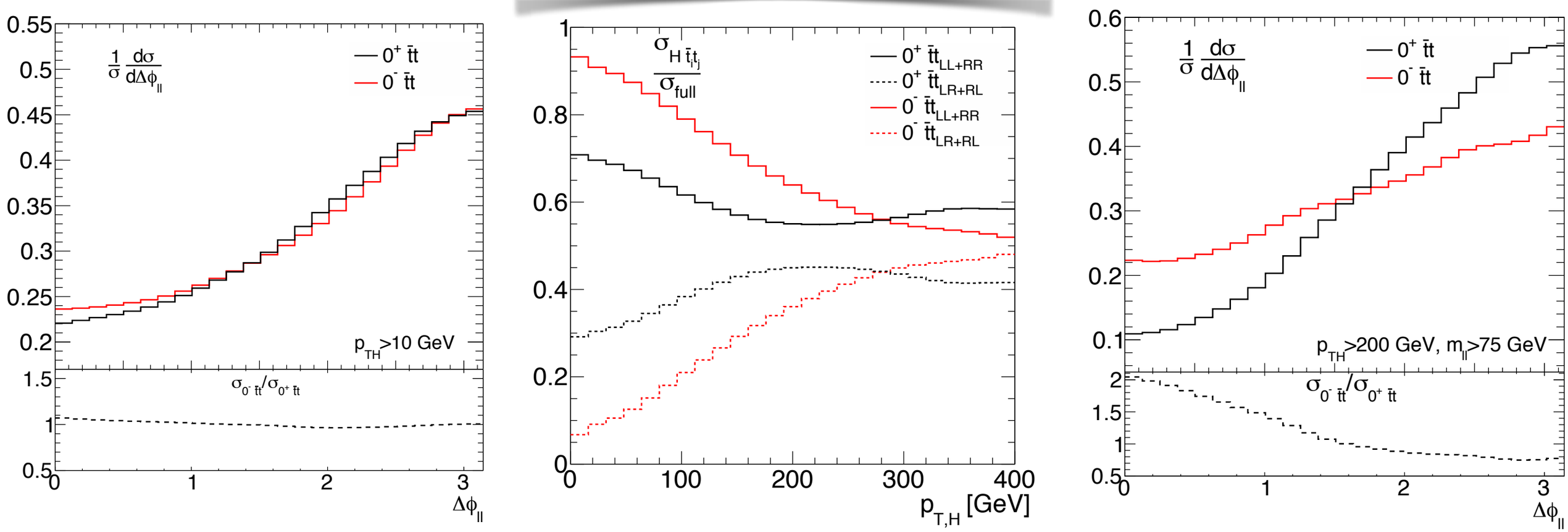


- Boosted Higgs (p_{TH}>200GeV) nicely match with H>bb BDRS algorithm
- No previous study with dileptonic ttH(bb) via BDRS in the literature.
  First, we have to show that we can at least see the signal!!

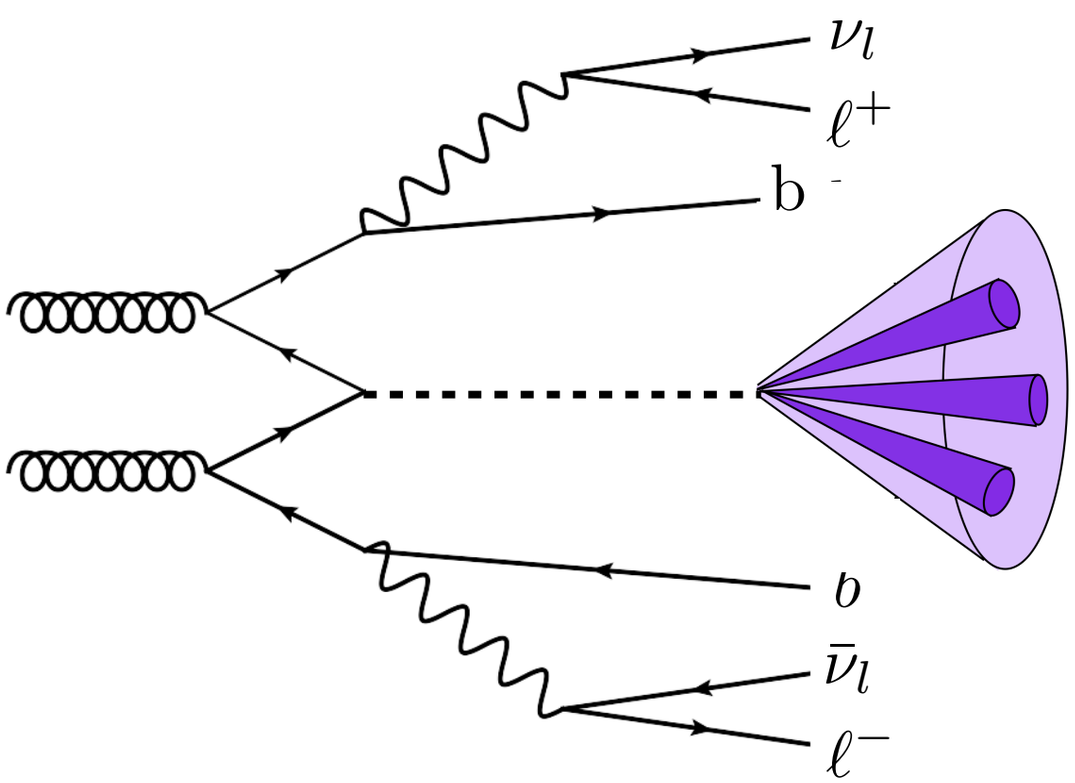
Buckley, DG (2015)
Plehn, Salam, Spannowsky (2009)

Directly Measuring $t\bar{t}H$

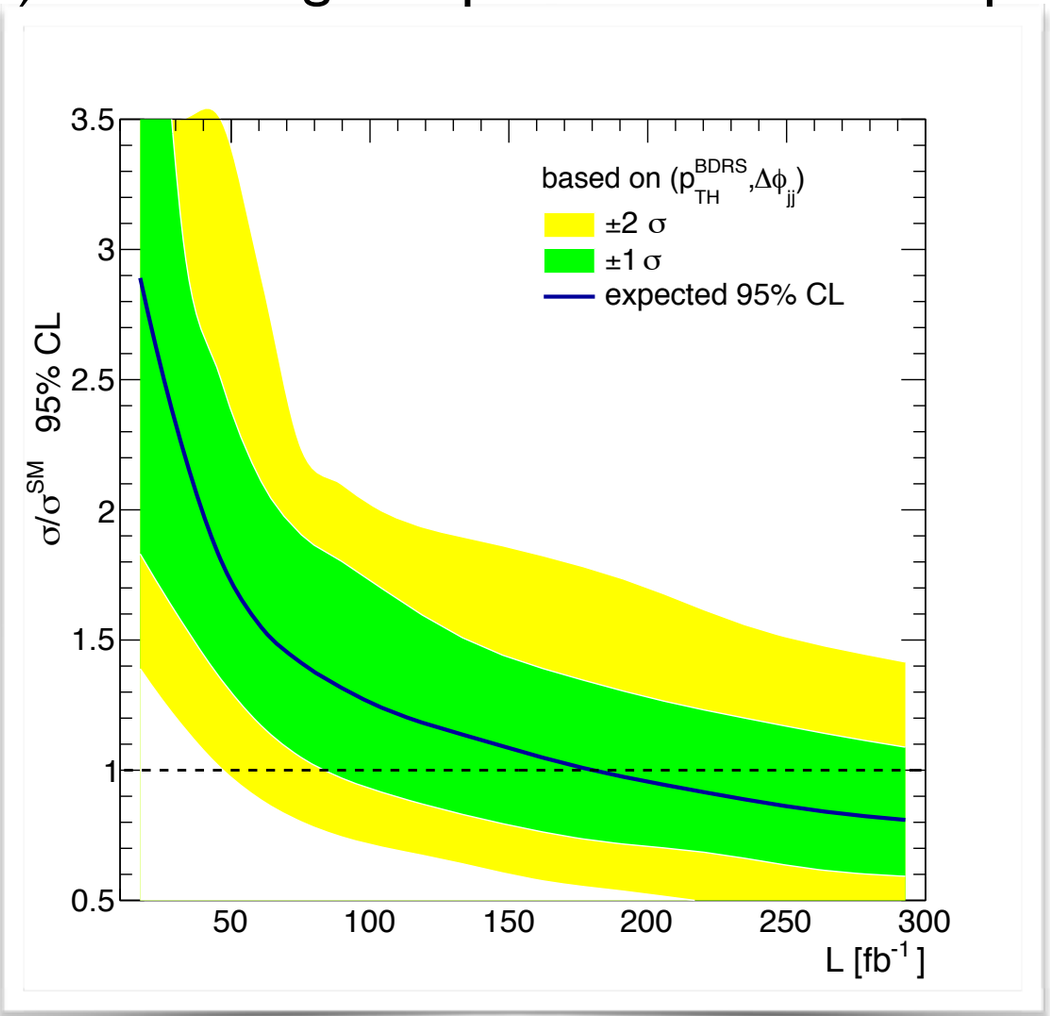
- Higgs candidate is genuinely <u>part of a multi-jet system:</u>

  Proper modelling of the QCD emissions indispensable requirement for robust analysis

➡ Signal & backgrounds are @NLO (MC@NLO), accounting for spin correlation on top decays



BDRS H-tag, $p_{T\ell} > 15$ GeV, $|\eta_\ell| < 2.5$
$p_{Tj} > 30$ GeV, $|\eta_j| < 2.5$, $n_j \geq 2$, $n_l = 2$
two extra b-tags (four in total)
$|m_H^{\rm BDRS} - m_H| < 10$ GeV, $m_{b\bar{b}} > 110$ GeV



- We can see the ttH with L~175 fb^{-1} @95% CL

Buckley, DG (2015)

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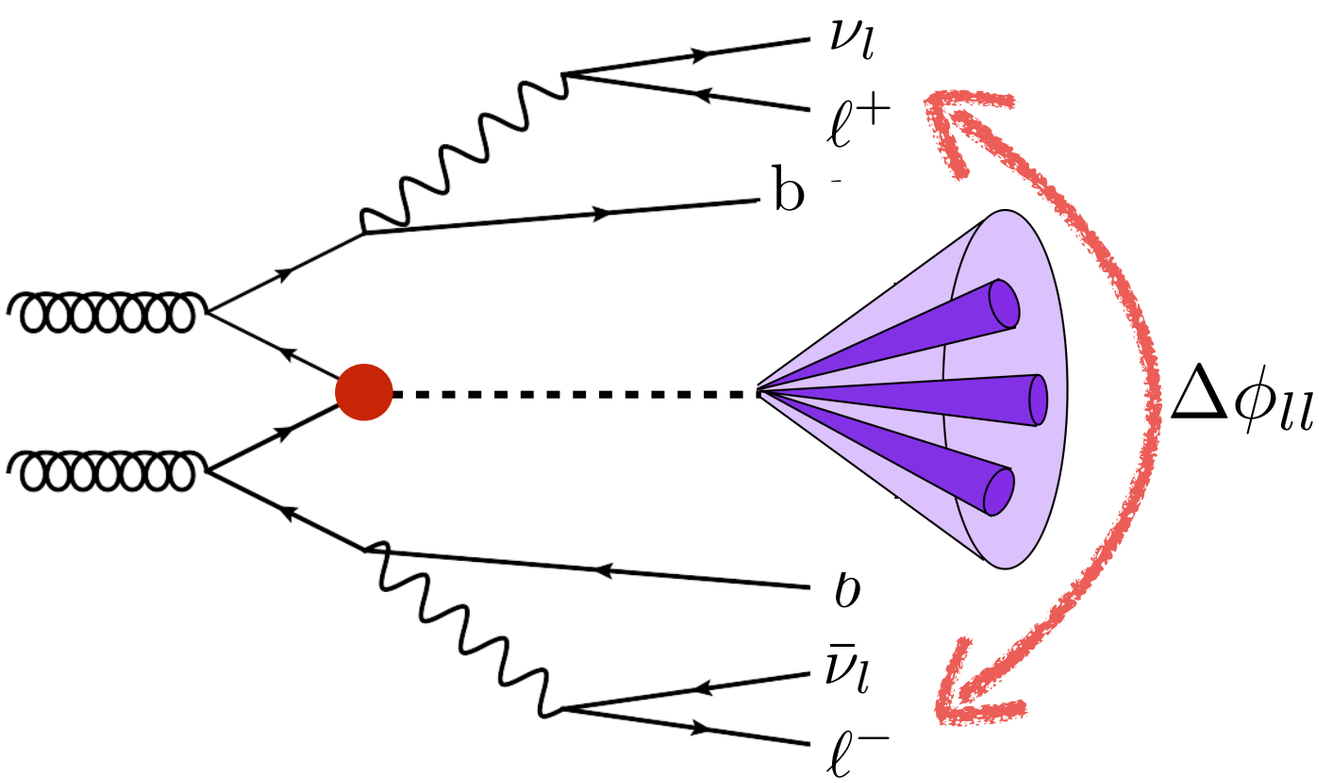

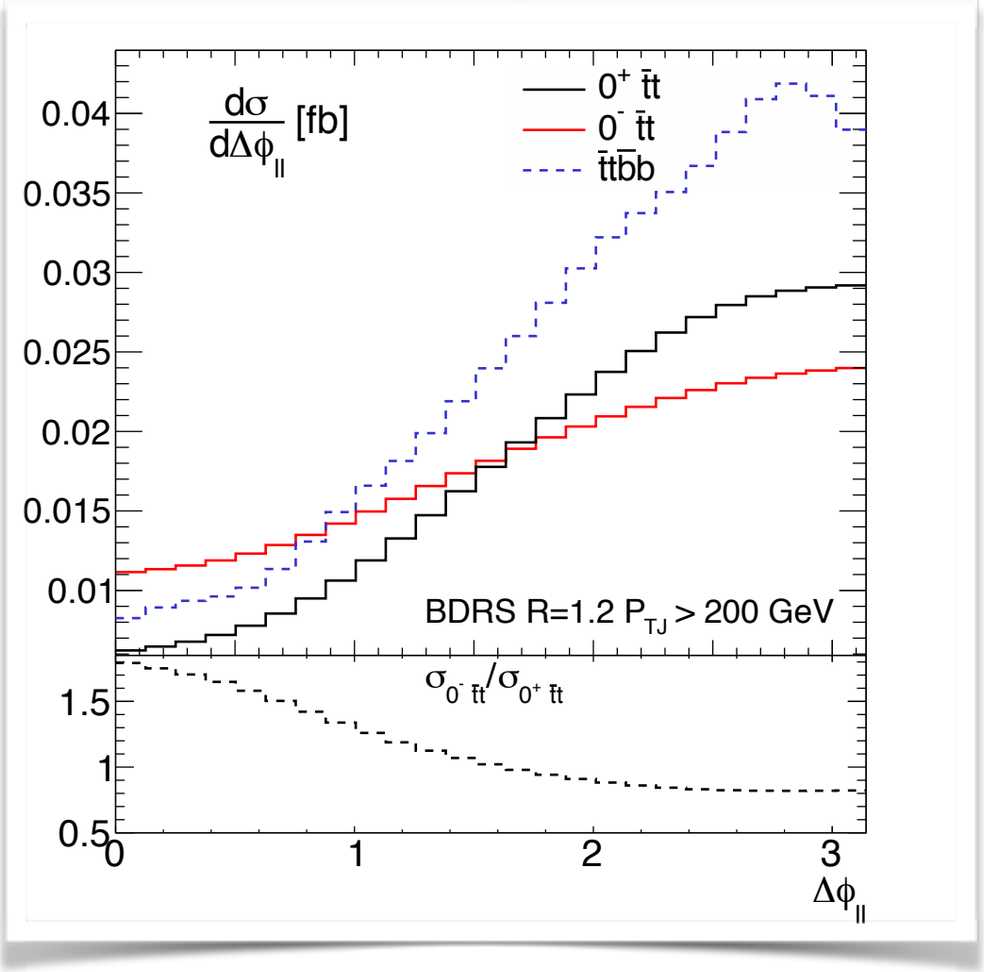

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- The full analysis and higher-order effects did not degrade our observable!

Buckley, DG (2015)

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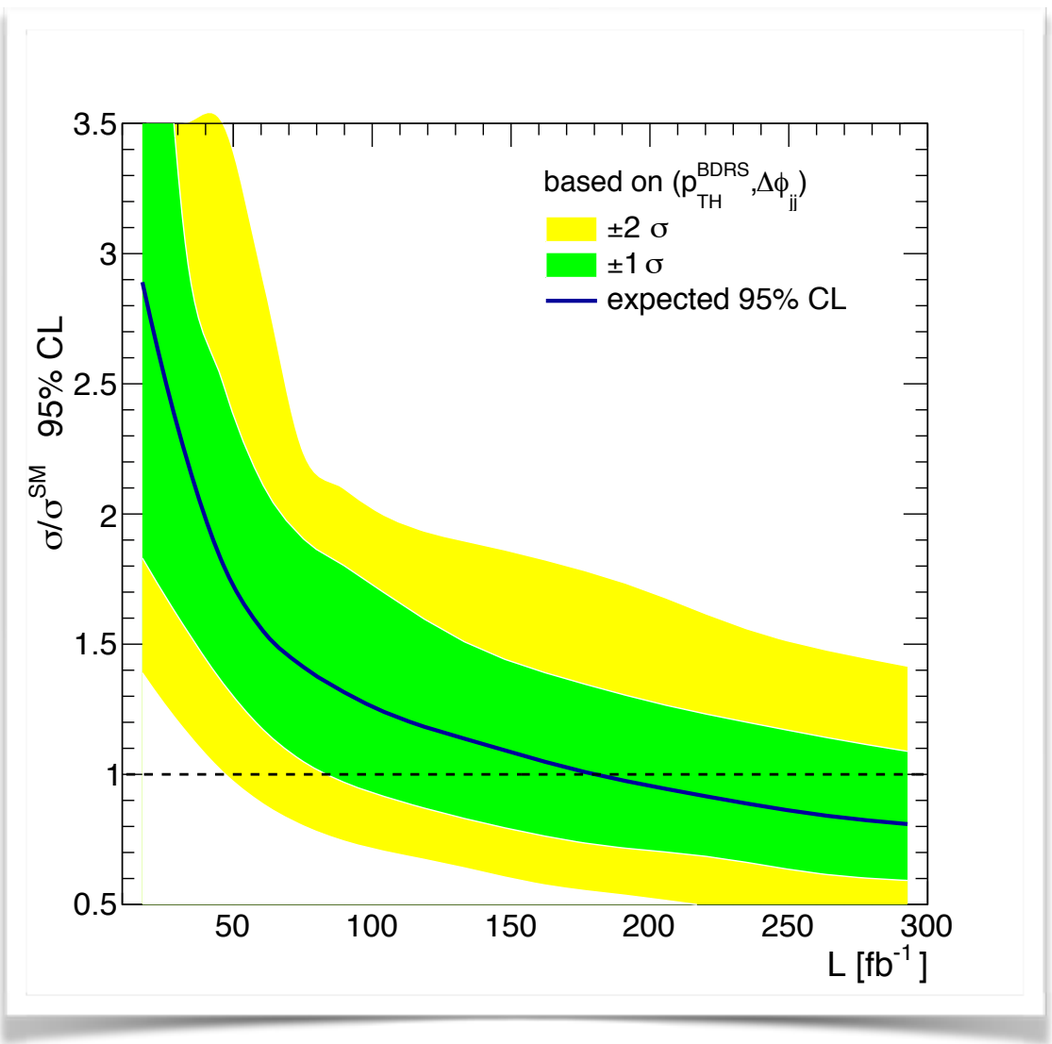

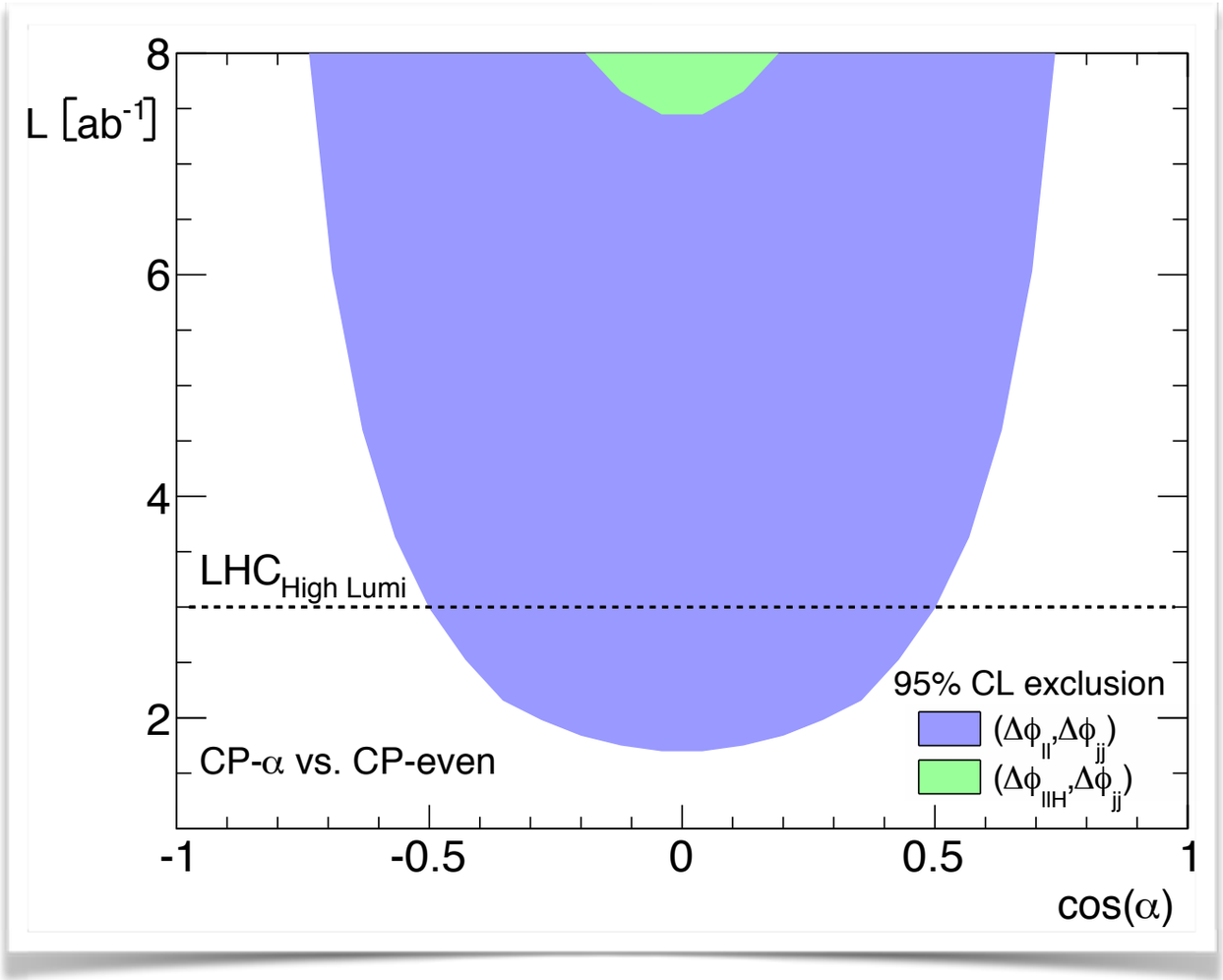

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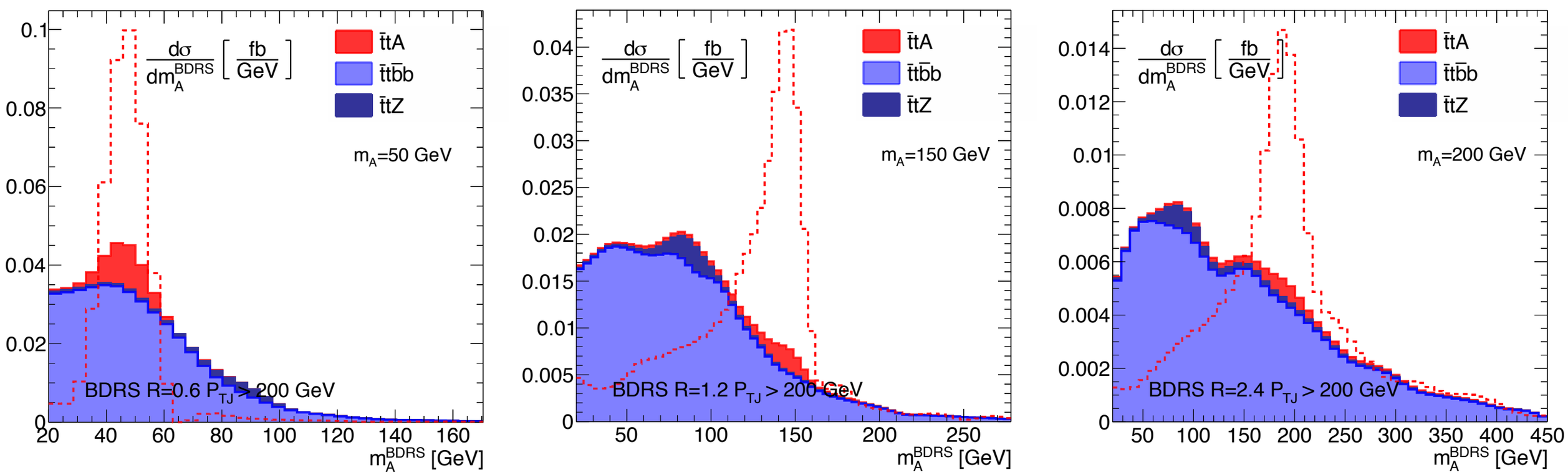
- Seeking for light pseudoscalars: ttA(bb) can <u>direct</u> access the Yukawa and explore low m_A

  Tailoring the BDRS analysis for different m_A ranges: $R \sim 2m_A/p_{TA}$



Lopez-val, DG (2016); Carena, Liu (2016)

Kozaczuk, Martin (2015); Casolino,Spannowsky(2015)

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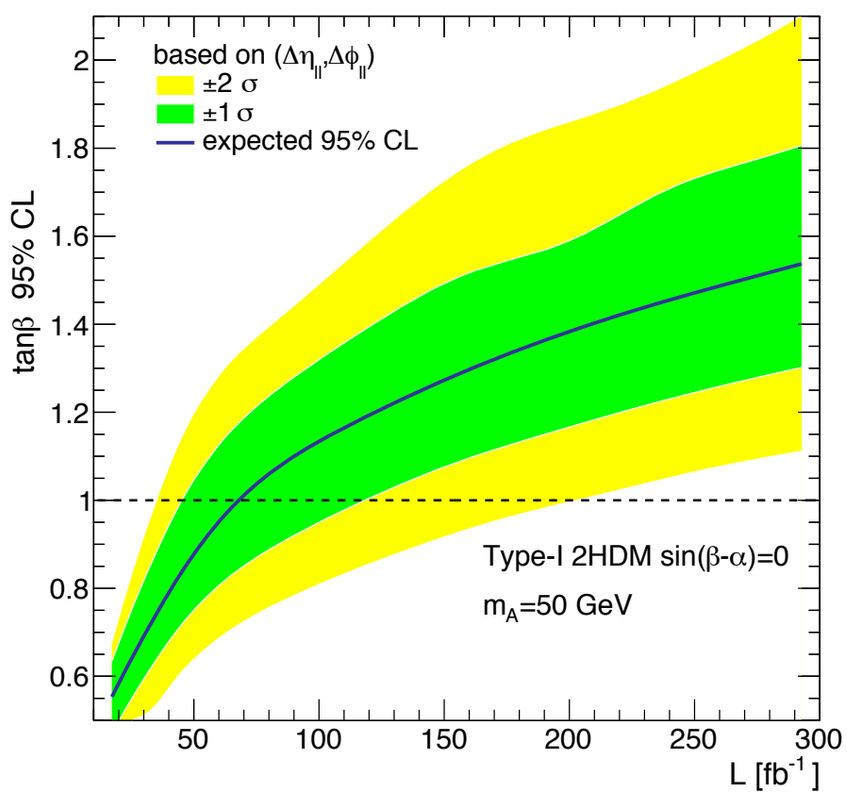

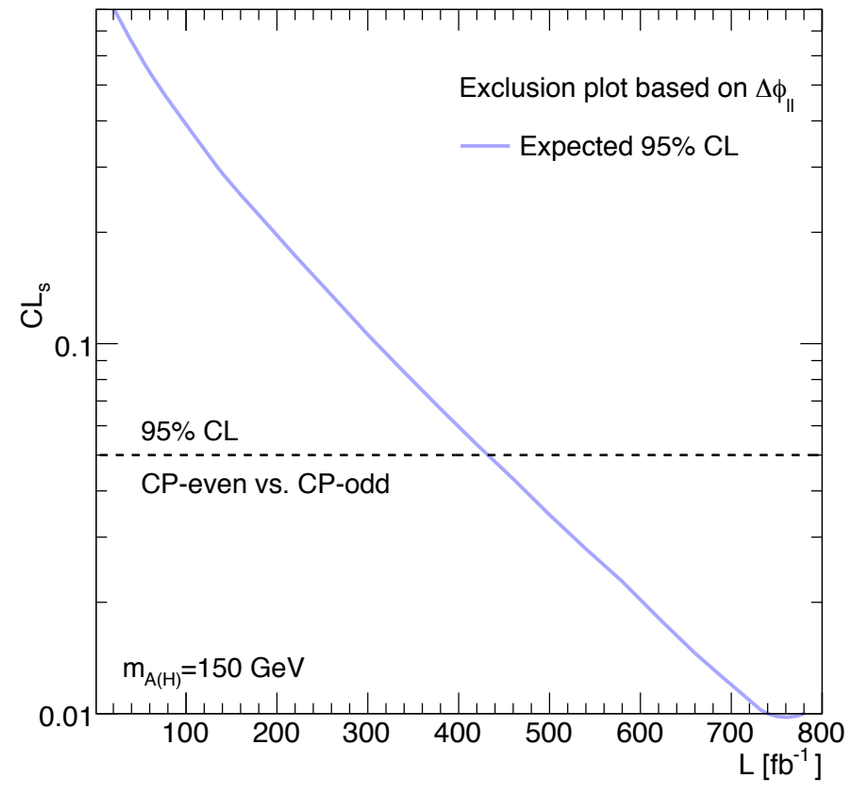

Lopez-val, DG (2016)

Summary

- LHC Run II will give very energetic Higgses with significant statistics
- Off-shell, boosted (H+jets, HZ+jets) will be important to coupling and Γ_H determination
  Distribution profiles significantly improve y_t constraints and should be added to coupling fits
- It is possible to access the Higgs-top CP-structure via angular correlations in ttH
  Boosted Higgs analysis nicely match with CP-structure measurement

Thank you for your attention!