HH production from VBS: an efficient test of the Higgs selfcoupling at the LHC

María Herrero

Instituto de Física Teórica, Universidad Autónoma de Madrid

maria.herrero@uam.es

Higgs Couplings Conference,
Tokyo, Nov 29th 2018

Based on [arXiv:1807.09736]

E. Arganda, C. Garcia-Garcia, M.J. Herrero

Introduction/Motivation

Aim

- Measure the Higgs self-coupling λ
- Check SM relation between λ and mH
- Test BSM alternatives of λ

Current status and sensitivity to λ at the LHC

- Studies focus on gluon gluon fusion (dominant) HH production

  See references [11-39] for theoretical studies and [40-46] for experimental searches in [arXiv:1807.09736]

- Different ggF channels considered (th. and exp.): $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\bar{\tau}$...
- Current sensitivity: exp. global analysis constrains $\lambda \in [-5.0, 12.1]\ \lambda_{SM}$ at 95% C.L.

  [ATLAS-CONF-2018-043]

Future prospects at linear colliders

- e+e- linear colliders (ILC, CLIC) will allow for most precise λ_{SM} measurements

  [Abramowicz et al, Eur. Phys. J. C77 (2017) 475]

- Still far (and/or unknown) in the future!!

$$\Delta\lambda/\lambda = 40\% \text{ at } \sqrt{s} = 1.4\,\text{TeV},$$
$$\Delta\lambda/\lambda = 22\% \text{ at } \sqrt{s} = 3\,\text{TeV}.$$

Our proposal: VBS to test λ BSM at the LHC

ggF: $gg \to HH$

$\sigma_{\rm ggF}(14\ {\rm TeV}, \kappa = \lambda/\lambda_{\rm SM} = 1) \sim 32\ {\rm fb}$

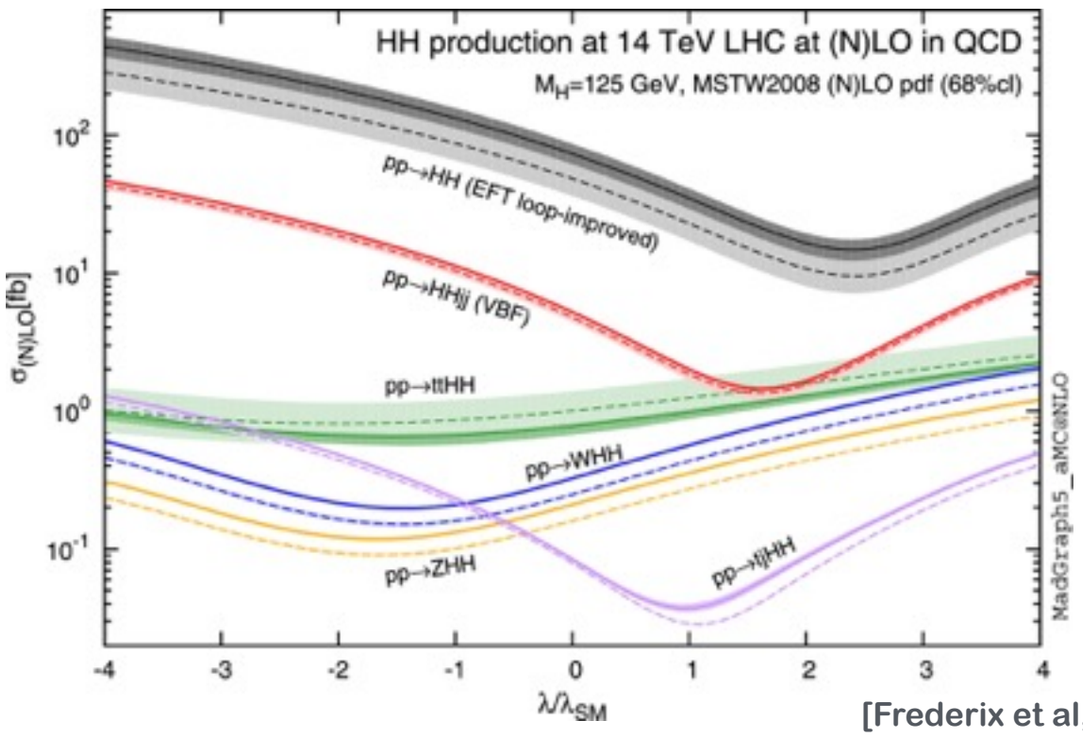
- 1-loop + top physics involved
- Largest cross section near $t\bar{t}$ threshold
- Sizable NLO corrections: big uncertainties
- Less specific kinematics

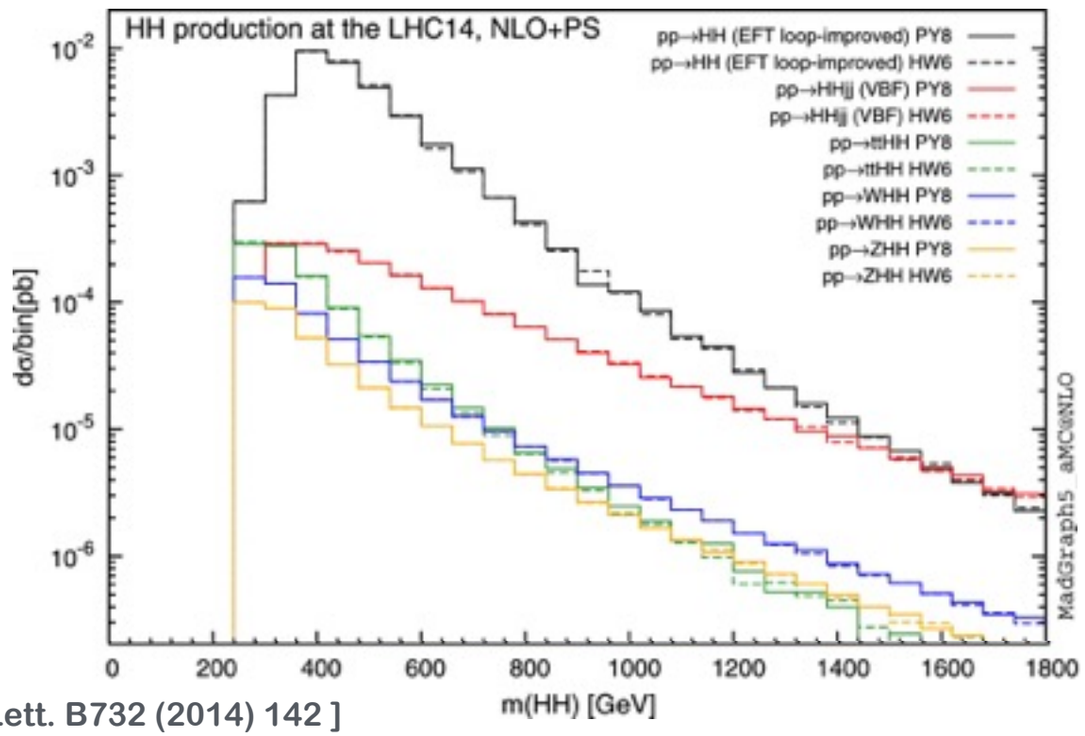
VBS: $q_1 q_2 \to HH q_3 q_4$

$\sigma_{\rm VBS}(14\ {\rm TeV}, \kappa = \lambda/\lambda_{\rm SM} = 1) \sim 2\ {\rm fb}$

- Tree level + no top physics involved
- Largest cross section near HH threshold
- Small NLO corrections, more accurate
- Very characteristic kinematics

VBS smaller cross section than ggF , but with interesting features





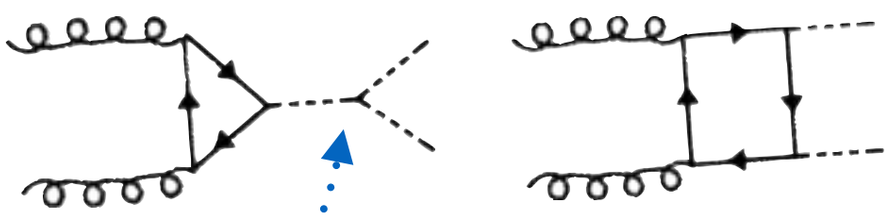
[Frederix et al, Phys. Lett. B732 (2014) 142]

ggF and VBS : both have negative interference of diagram containing λ and the rest

More on comparing VBS and ggF

ggF: $gg \to HH$

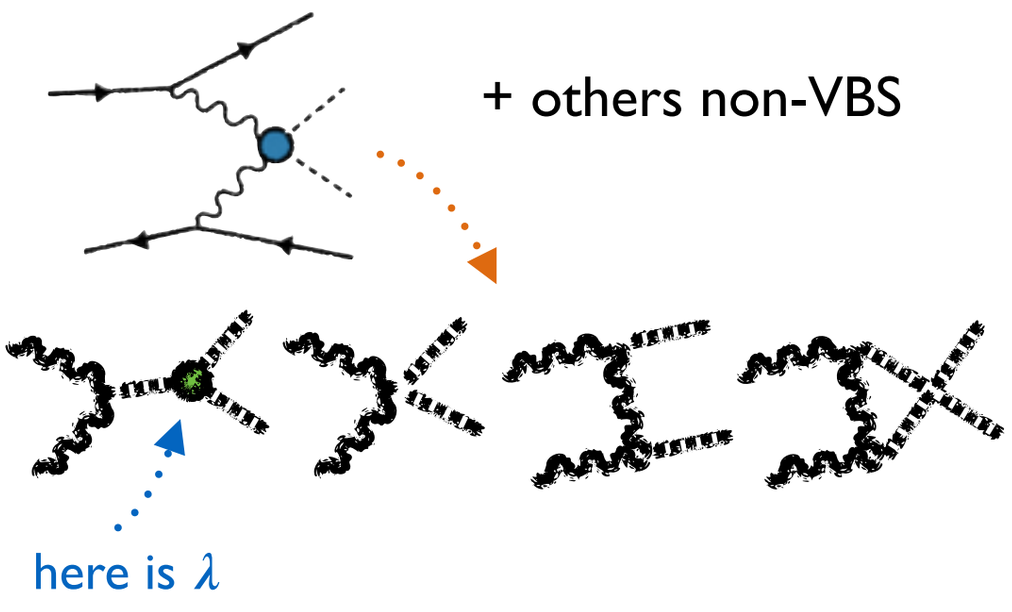
$$\sigma_{\mathrm{ggF}}(14\ \mathrm{TeV}, \kappa = \lambda/\lambda_{\mathrm{SM}} = 1) \sim 32\ \mathrm{fb}$$



BUT : ggF and VBS different final state

VBS: $q_1 q_2 \to HHq_3 q_4$

$$\sigma_{\mathrm{VBS}}(14\ \mathrm{TeV}, \kappa = \lambda/\lambda_{\mathrm{SM}} = 1) \sim 2\ \mathrm{fb}$$



$W_L^+ W_L^- \to HH$ probes Φ^4 at high energy

ggF: $gg \to HHjj$

$$\sigma_{\mathrm{ggF}}^{\mathrm{HHjj}}(14\ \mathrm{TeV}, \kappa = \lambda/\lambda_{\mathrm{SM}} = 1) \sim 5.5\ \mathrm{fb}$$

[Dolan et al, Phys. Rev. Lett. 112 (2014) 101802]

[Dolan et al, Eur. Phys. J. C75 (2015) 387]

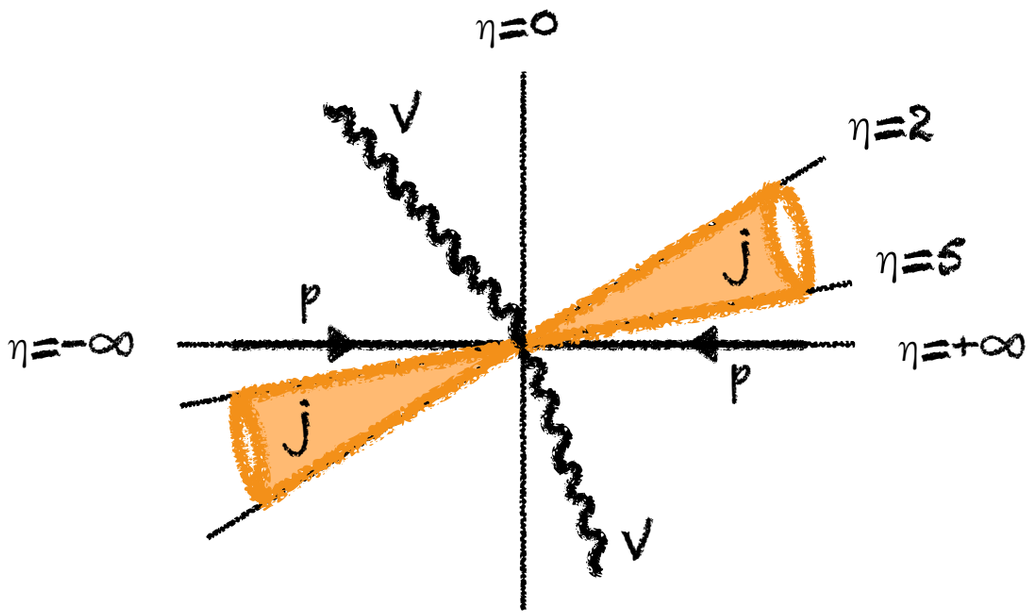
- Contributes to our signal: same final state and it is also sensitive to λ
- But: our VBS selection cuts reduce cross section below pure VBS one
  For instance for Mjj>500 GeV → ggF<1/20 VBS
- Not taken into account in the present work

Defining our signal at the LHC: pp → HHjj

Signal: prediction of $q_1q_2 \to HHq_3q_4$ for given $\lambda \neq \lambda_{SM}$

We consider $\lambda \in [-10,10]\ \lambda_{SM}$

All our LHC estimates are computed using MadGraph5



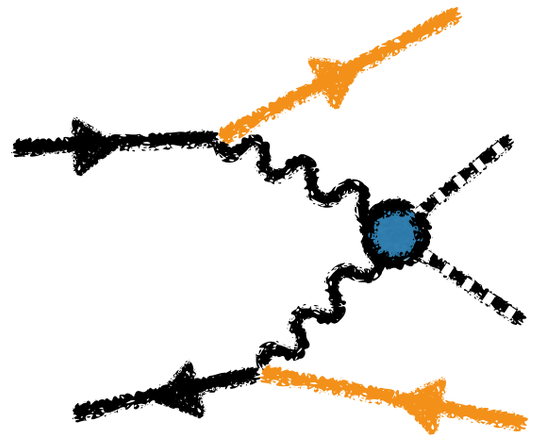
Extra jets identify VBS configurations among all contributing diagrams

Two opposite-side forward/backward jets with large pseudorapidity gap required

$$|\Delta\eta_{jj}| \equiv |\eta_{j_1} - \eta_{j_2}|$$

and with large invariant masses

$$M_{jj}$$



Defining VBS selection cuts

Our benchmark is (for others see arXiv:1807.09736) :

$$|\Delta\eta_{jj}| > 4$$

$$M_{jj} > 500\ \text{GeV}$$

Basic detection cuts: $p_{T_j} > 20\ \text{GeV}\,, \quad |\eta_j| < 5\,, \quad \Delta R_{jj} > 0.4\,, \quad |\eta_H| < 2.5$

Chacterization of VBS: $\Delta\eta_{jj}$ and M_{jj}

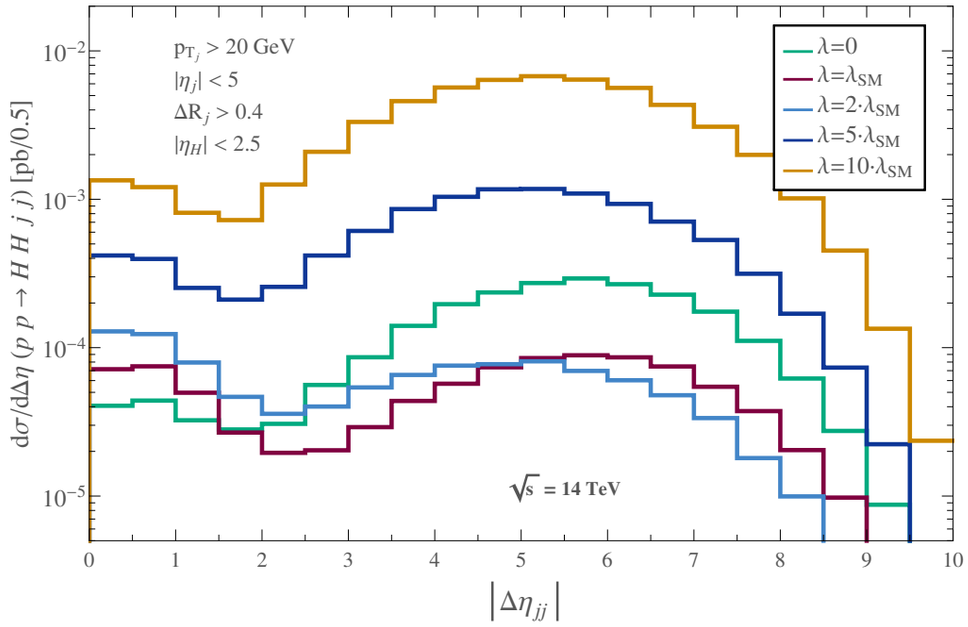
How VBS-dominated is our signal?

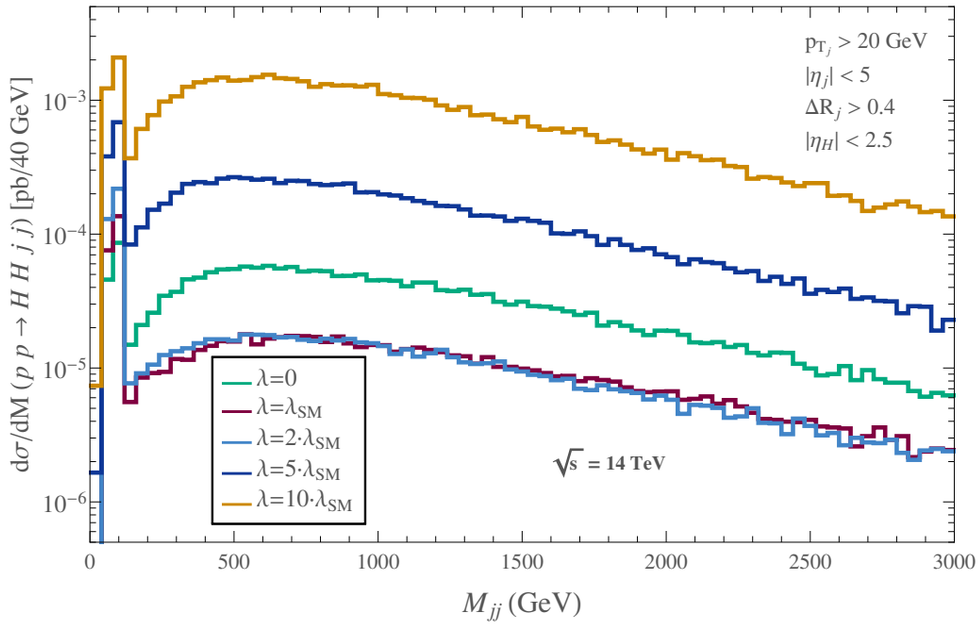
All our LHC estimates are computed using MadGraph5

VERY MUCH (for all λ) !!!

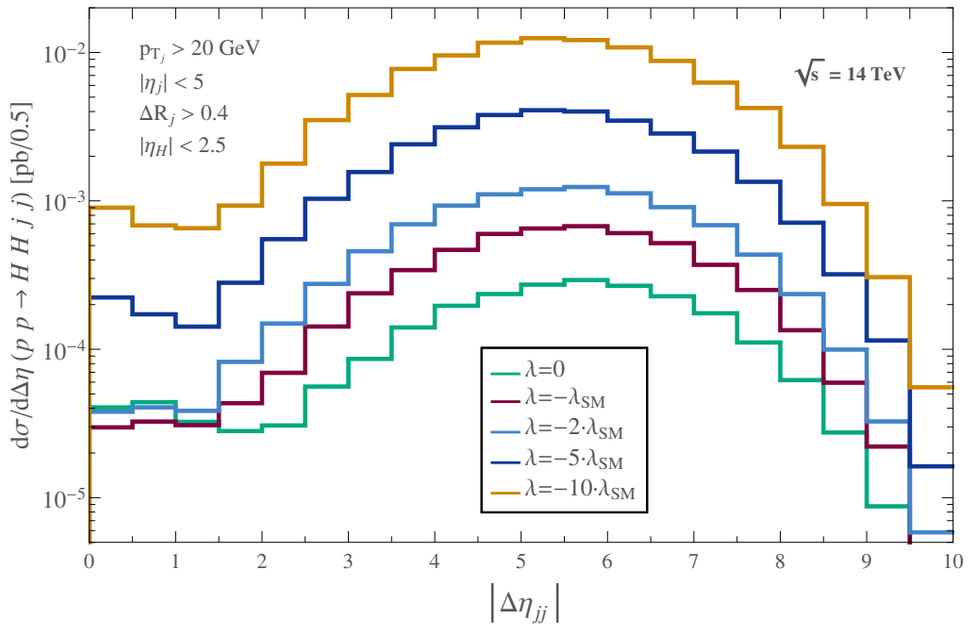
- **Checked: 55-75% of $q_1q_2 \to HHq_3q_4$ events occur through VBS**

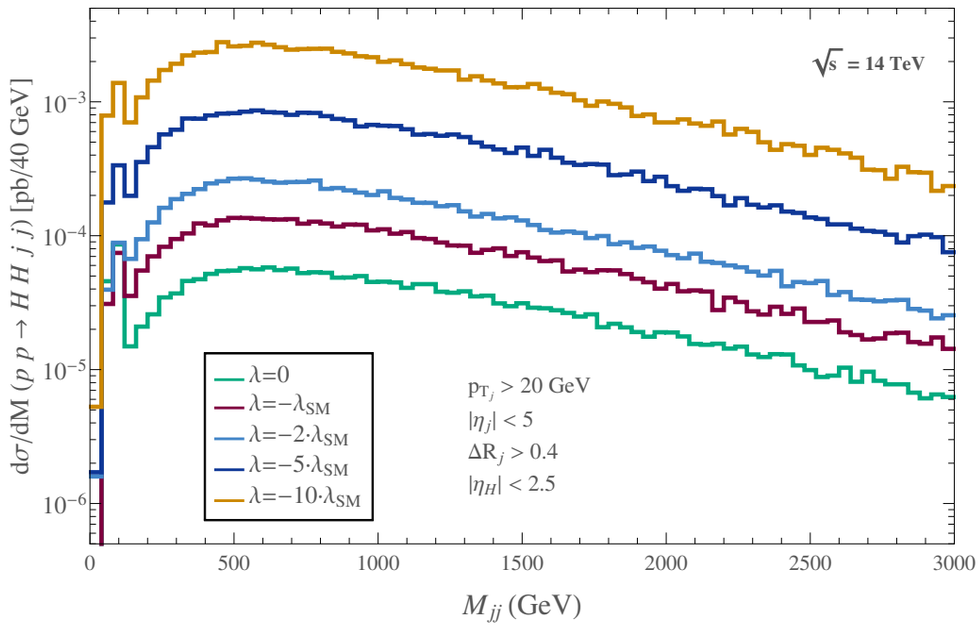
$\lambda \geq 0$





$\lambda \leq 0$





Our signal after Higgs decays

- HH production observed through Higgs decay products
- Two decays considered: $H \to b\bar{b}$ and $H \to \gamma\gamma$

$pp \to HHjj \to b\bar{b}b\bar{b}jj$ $(q_1q_2 \to b\bar{b}b\bar{b}q_3q_4)$

Highest rates due to large BR($H \to b\bar{b}$) ~ 60 %

Large backgrounds

$pp \to HHjj \to b\bar{b}\gamma\gamma jj$ $(q_1q_2 \to b\bar{b}\gamma\gamma q_3q_4)$

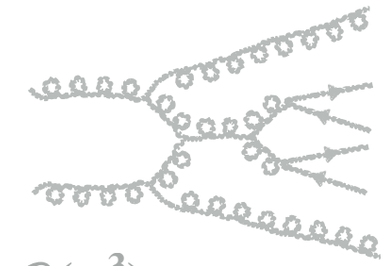
Much cleaner channel. Small and controllable backgrounds

Lower statistics due to small BR($H \to \gamma\gamma$) ~ 0.2 %

$pp \to b\bar{b}b\bar{b}jj$ backgrounds

multijet QCD $pp \to b\bar{b}b\bar{b}jj$

Estimated with MG5
Checked with AlpGen

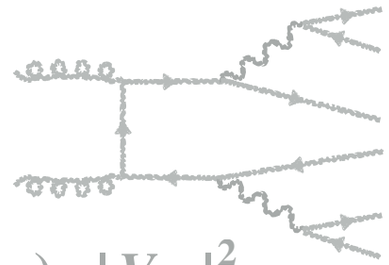


$\mathcal{O}(\alpha_S^3)$

+ …

- **Dominant** background by many **orders of magnitude**
- **Additional** selection **cuts** apart from **VBS** required

$t\bar{t} \to bW^+\bar{b}W^- \to b\bar{b}b\bar{b}jj$

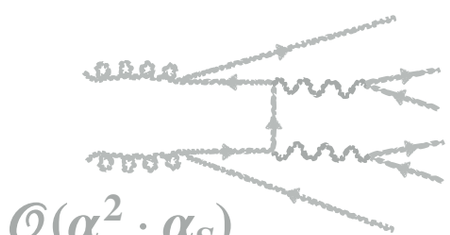


$\mathcal{O}(\alpha^2 \cdot \alpha_S) \cdot |V_{qb}|^2$

+ …

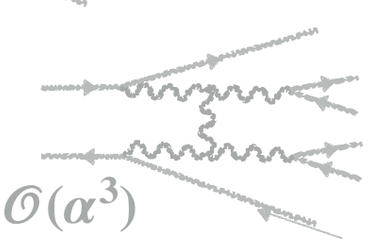
- **CKM suppressed**
- Radically **different kinematics** respect to **VBS**
- **Under control** (negligible after VBS cuts)

$pp \to ZZjj \to b\bar{b}b\bar{b}jj$ & $pp \to ZHjj \to b\bar{b}b\bar{b}jj$



$\mathcal{O}(\alpha^2 \cdot \alpha_S)$

+ …



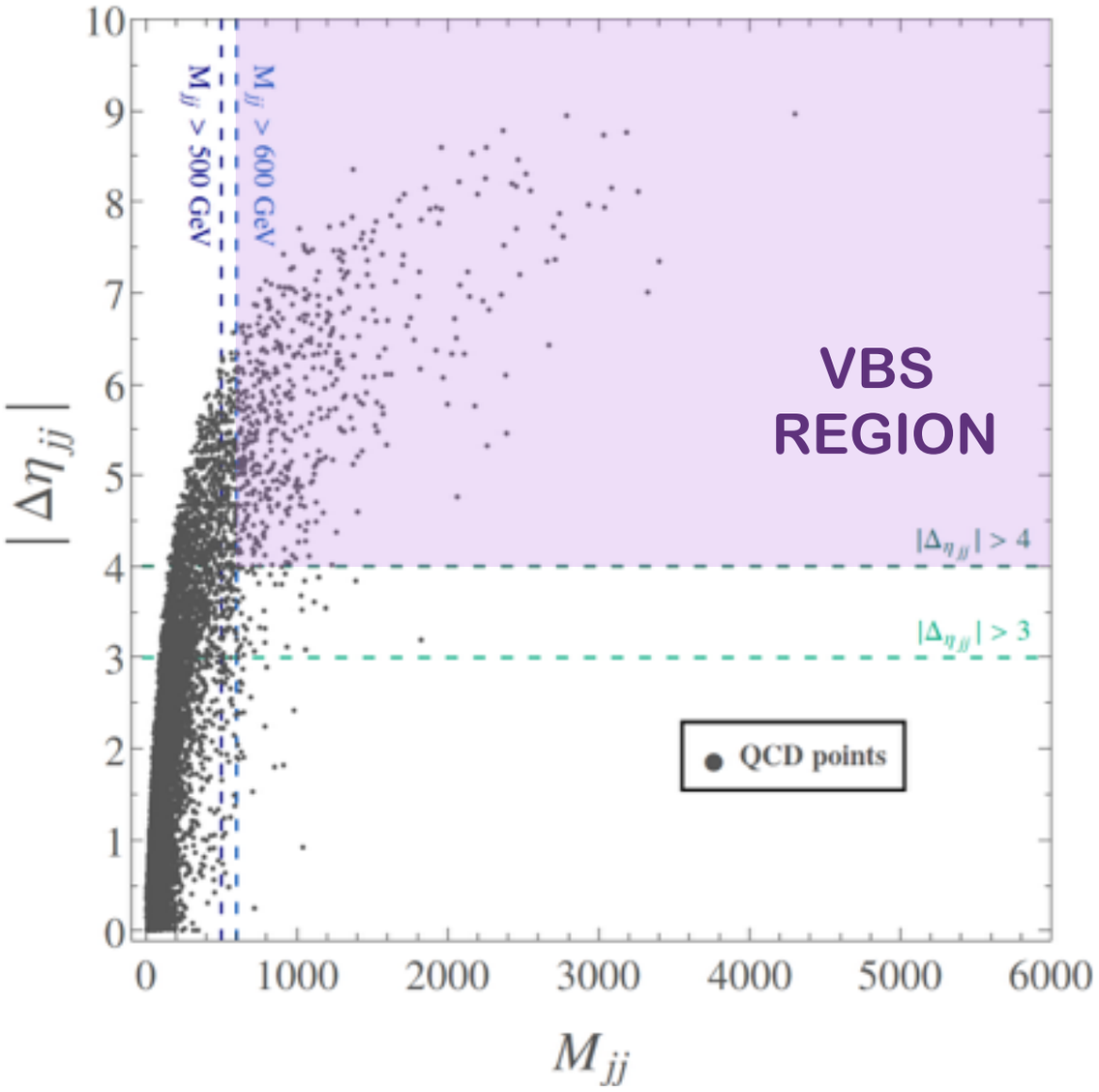
$\mathcal{O}(\alpha^3)$

- Take place **in part** through **VBS** configurations
- **Additional** selection **cuts** apart from **VBS** required

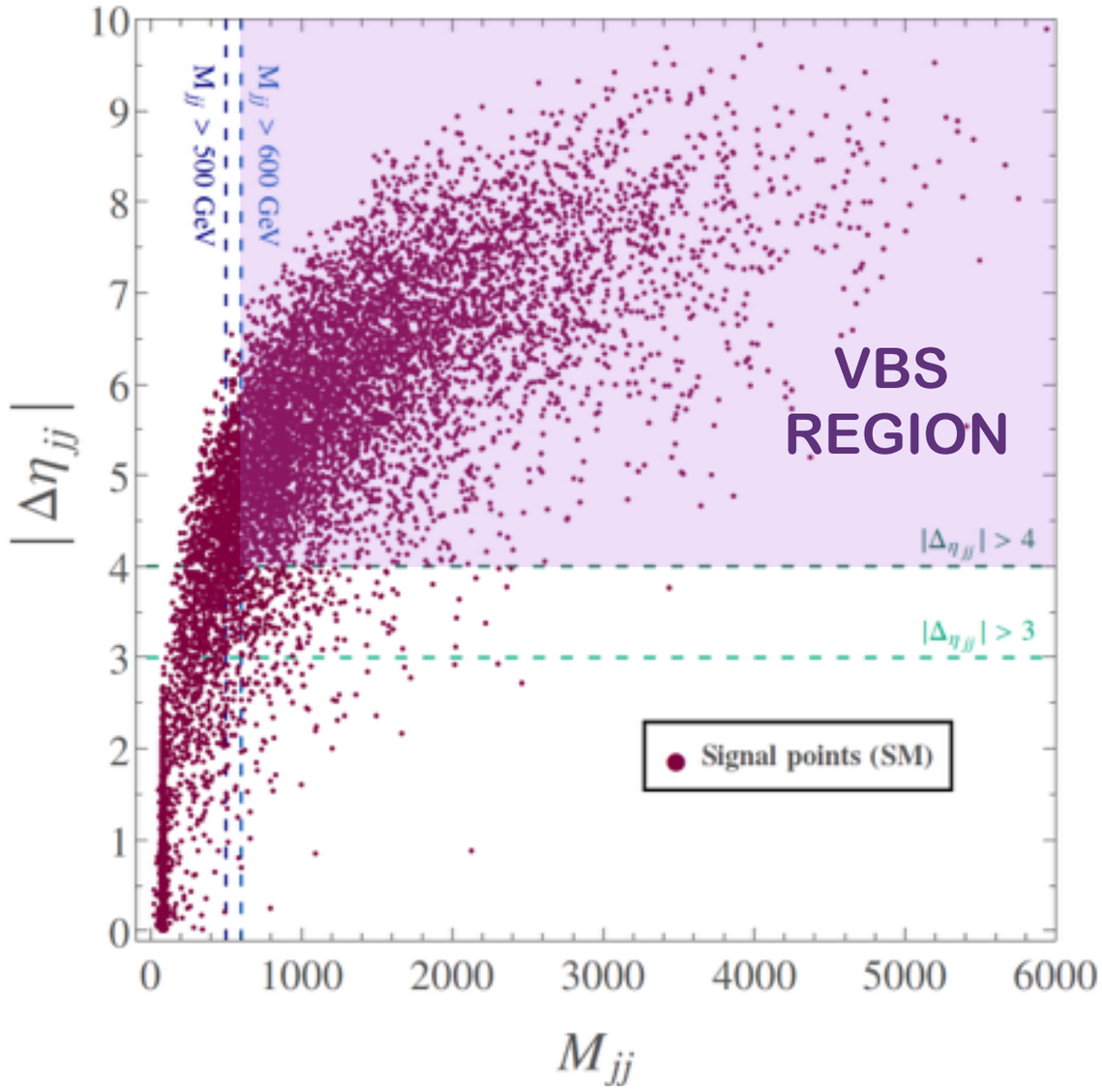
Signal versus QCD-bkg in $b\bar{b}b\bar{b}jj$: VBS

Signal & QCD bkg populate different kinematical regions

Multijet QCD characterized by



Most of signal events in VBS kin. region



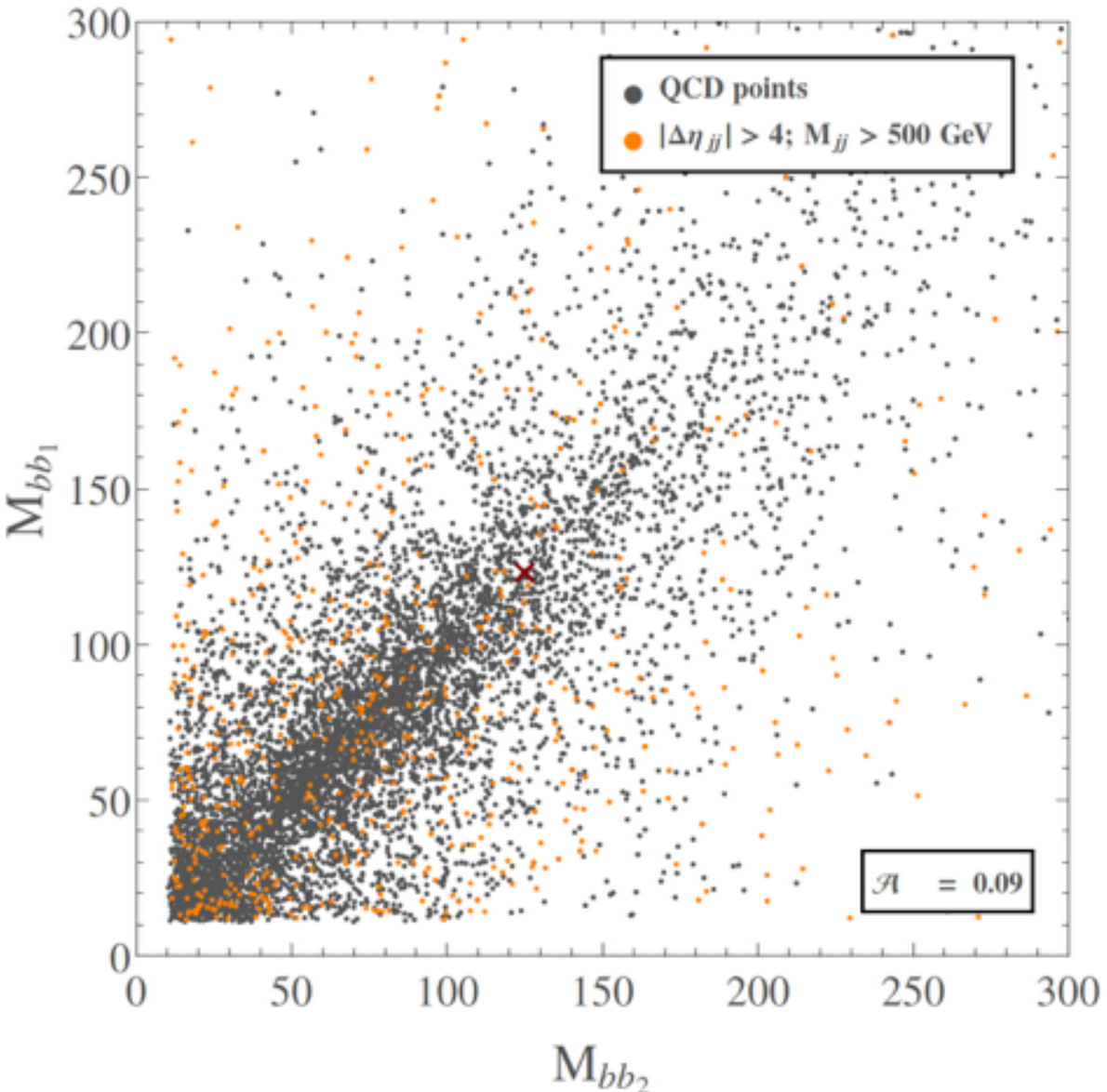
VBS cuts tried. Our benchmark choice is : $|\Delta\eta_{jj}| > 4 \quad M_{jj} > 500$ GeV

Signal versus QCD-bkg in $b\bar{b}b\bar{b}jj$: HH

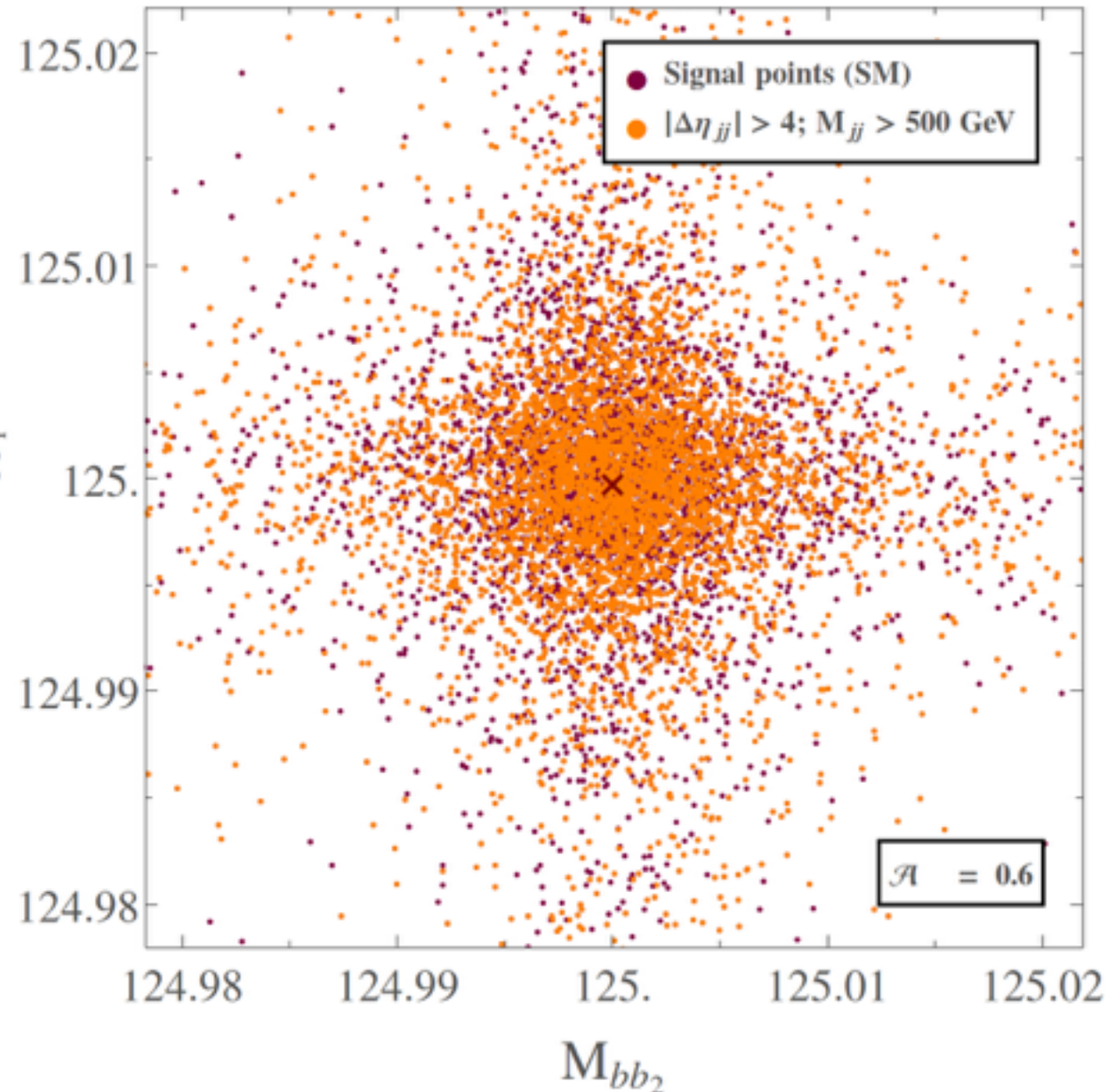
Signal & QCD bkg populate different (Mbb1,Mbb2) regions

- b-quarks paired as HH candidates: pairing minimizing $|M_{bb1} - M_{bb2}|$

Multijet QCD background events lie mainly at low $[M_{bb1}, M_{bb2}]$



Signal events lie near $[M_{bb1}, M_{bb2}] \sim [M_H, M_H]$



HH candidate cuts in $b\bar{b}b\bar{b}jj$

b-quark pairs identified as HH decays

- **HH candidate cuts:**

  We follow recent cuts proposed by ATLAS [arXiv: 1804.06174] and CMS [CMS-PAS-HIG-16-026]

$p_{T_b} > 35\ \text{GeV}$

Small angular separation between Higgs decay products

$$\hat{\Delta}R_{bb} \equiv \begin{cases} 0.2 < \Delta R_{bb^l} < \dfrac{653}{M_{4b}\,\text{GeV}} + 0.475\,;\ 0.2 < \Delta R_{bb^s} < \dfrac{875}{M_{4b}\,\text{GeV}} + 0.35\,,\ M_{4b} < 1250\ \text{GeV} \\ 0.2 < \Delta R_{bb^l} < 1\,;\ 0.2 < \Delta R_{bb^s} < 1\,,\ M_{4b} > 1250\ \text{GeV} \end{cases}$$

$$\hat{p}_{T_{bb}} \equiv p_{T_{bb^l}} > M_{4b}/2 - 103\,\text{GeV}\,;\ p_{T_{bb^s}} > M_{4b}/3 - 73\,\text{GeV}$$

$[M_{bb1}, M_{bb2}] \sim [M_H, M_H]$

$$\chi_{HH} \equiv \sqrt{\left(\frac{M_{bb^l} - m_H}{0.05\,m_H}\right)^2 + \left(\frac{M_{bb^s} - m_H}{0.05\,m_H}\right)^2} < 1$$

Efficiency of the selection cuts in $b\bar{b}b\bar{b}jj$

In addition to the basic detection cuts:

$$p_{T_{j,b}} > 20 \text{ GeV} ; \ |\eta_j| < 5 ; \ |\eta_b| < 2.5 ; \ \Delta R_{jj,jb} > 0.4 ; \ \Delta R_{bb} > 0.2$$

Combined HH candidate and VBS cuts

Cut	σ_{QCD} [pb]	$\sigma_{ZHjj,ZZjj}$ [pb]	$\sigma_{\text{Signal};\kappa=1}$ [pb]
Basic detection cuts	602.72	0.028	$5.1{\cdot}10^{-4}$
$p_{T_b} > 35$ GeV	98.31	0.01	$3.0{\cdot}10^{-4}$
$\hat{\Delta}R_{bb}$	33.80	$6.3 \cdot 10^{-3}$	$1.1{\cdot}10^{-4}$
$\hat{p}_{T_{bb}}$	29.77	$5.8{\cdot}10^{-3}$	$9.0{\cdot}10^{-5}$
$\chi_{HH} < 1,$	$7.9 \cdot 10^{-2}$	$8.6{\cdot}10^{-6}$	$9.0{\cdot}10^{-5}$
VBS cuts in	$6.8 \cdot 10^{-3}$	$5.5{\cdot}10^{-6}$	$4.1{\cdot}10^{-5}$

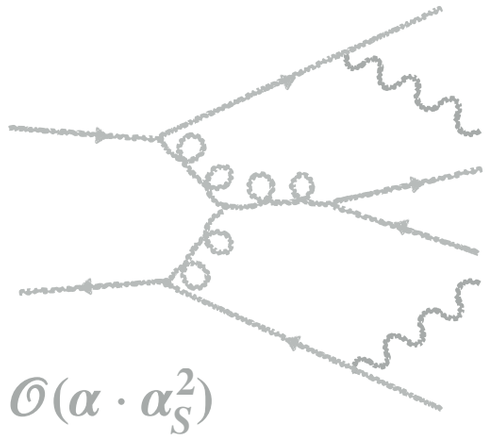
Cuts subsequently applied

- **Signal mildly reduced ; similar results for other** $\kappa = \lambda/\lambda_{\text{SM}} \neq 1$
- **Very reduced backgrounds!!!**

$pp \to b\bar{b}\gamma\gamma jj$ backgrounds and selection cuts

mixed QCDEW $pp \to b\bar{b}\gamma\gamma jj$

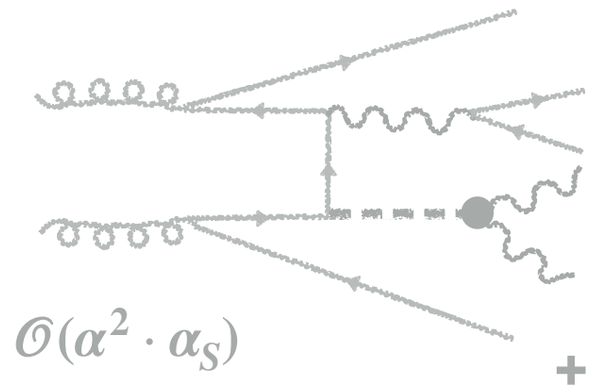
- **Dominant** background but easy to control
- **Additional** selection **cuts** apart from **VBS** required



$\mathcal{O}(\alpha \cdot \alpha_S^2)$ + ...

$pp \to ZHjj \to b\bar{b}\gamma\gamma jj$

- Take place **in part** through **VBS** configurations
- **Additional** selection **cuts** apart from **VBS** required



$\mathcal{O}(\alpha^2 \cdot \alpha_S)$ + ...

Selection cuts

VBS cuts + HH candidate $p_{T_{\gamma_l}}/M_{\gamma\gamma} > 1/3\,; \quad p_{T_{\gamma_s}}/M_{\gamma\gamma} > 1/4; \quad \chi_{HH} = \sqrt{\left(\frac{M_{bb} - m_H}{0.05\, m_H}\right)^2 + \left(\frac{M_{\gamma\gamma} - m_H}{0.05\, m_H}\right)^2} < 1$

VERY REDUCED BACKGROUNDS!

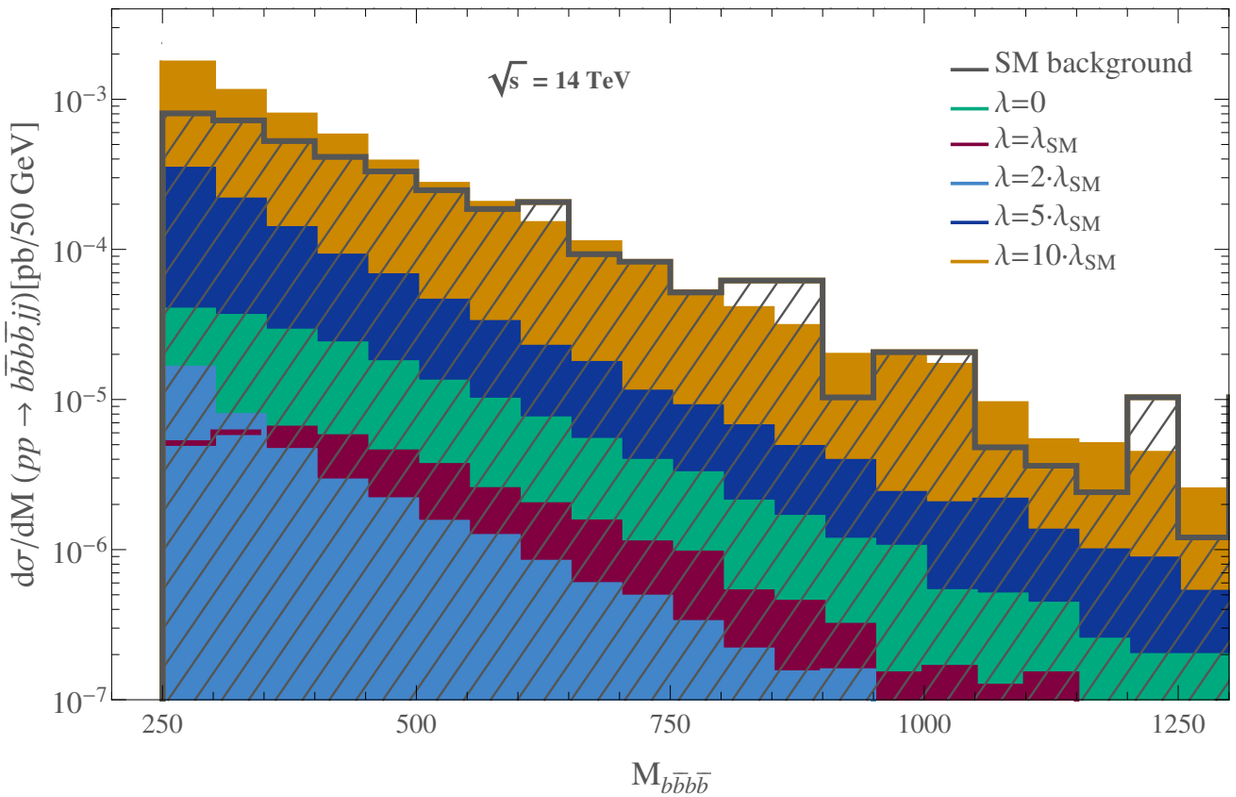
Basic detection cuts: $p_{T_{j,b}} > 20\ \text{GeV}\,; \; p_{T_\gamma} > 18\ \text{GeV}\,; \; |\eta_j| < 5\,; \; |\eta_{b,\gamma}| < 2.5\,; \; \Delta R_{jj,jb,\gamma\gamma,\gamma b,\gamma j} > 0.4\,; \; \Delta R_{bb} > 0.2, p_{T_{\gamma^l}}$

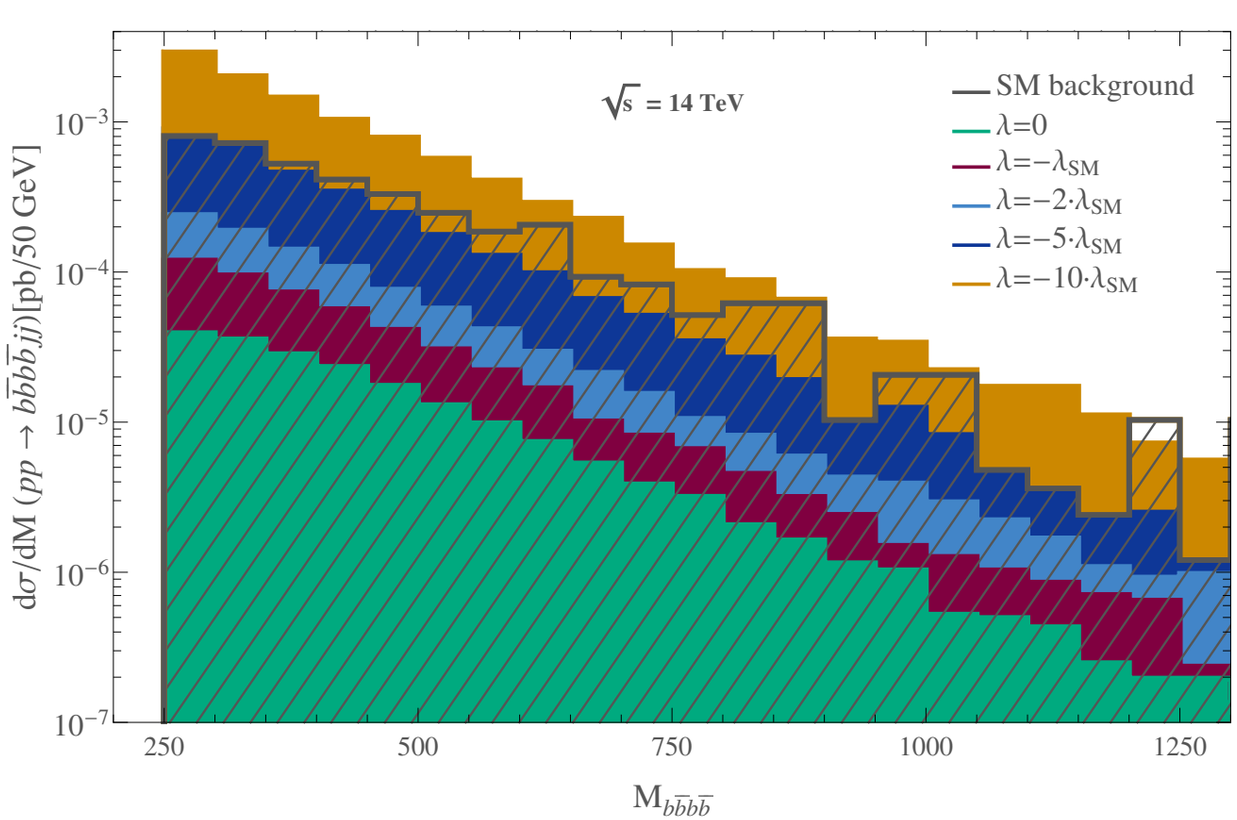
Results for pp → $b\bar{b}b\bar{b}jj$: M4b distributions

Signal = $q_1q_2 \to HHq_3q_4 \to b\bar{b}b\bar{b}q_3q_4$ (sensitive to λ)

SM Background = multijet QCD + ZHjj + ZZjj leading to $b\bar{b}b\bar{b}jj$

- **Clear deviations for** $\lambda \neq \lambda_{SM}$ **respect the SM bkg and the** λ_{SM} **prediction**
- **Largest sensitivity near HH production threshold. More sensitivity to negative** λ





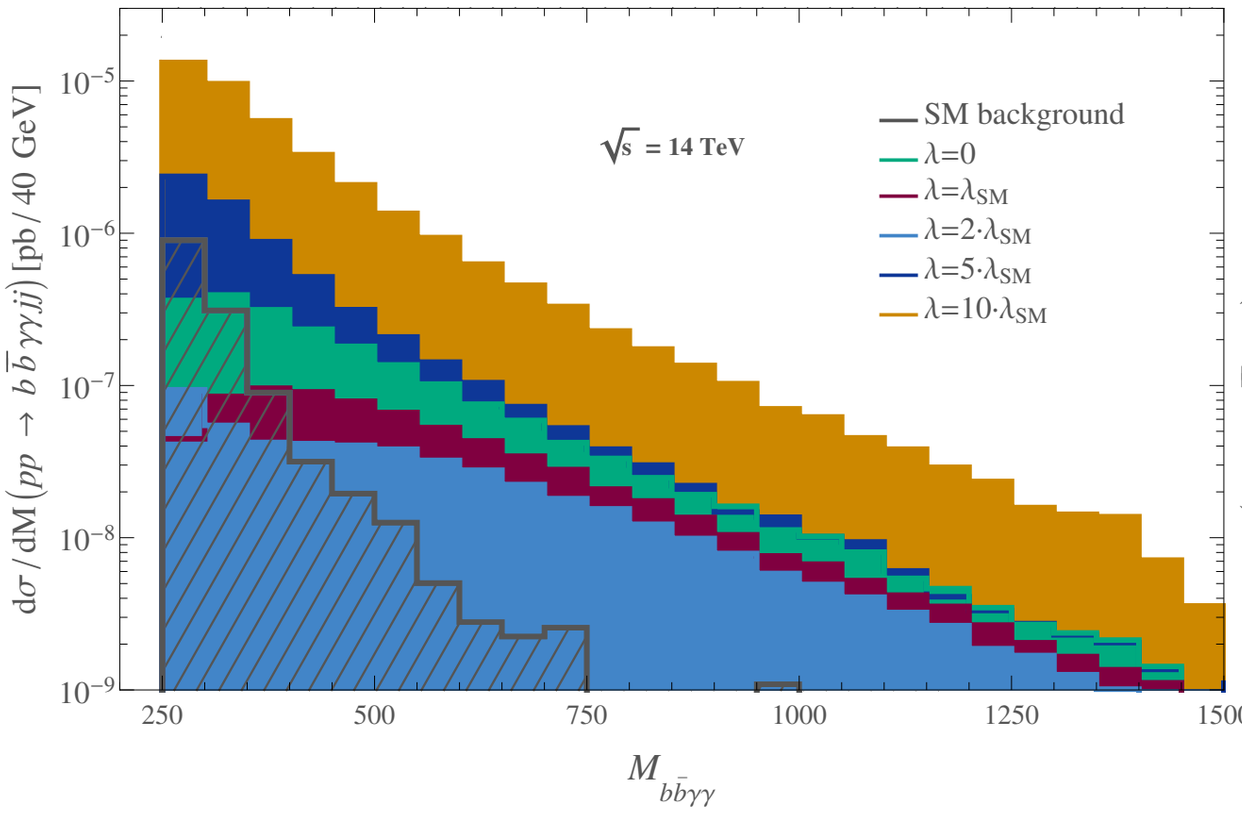
- **Some predictions (**λ **= -10** λ_{SM}**) even above backgrounds!**

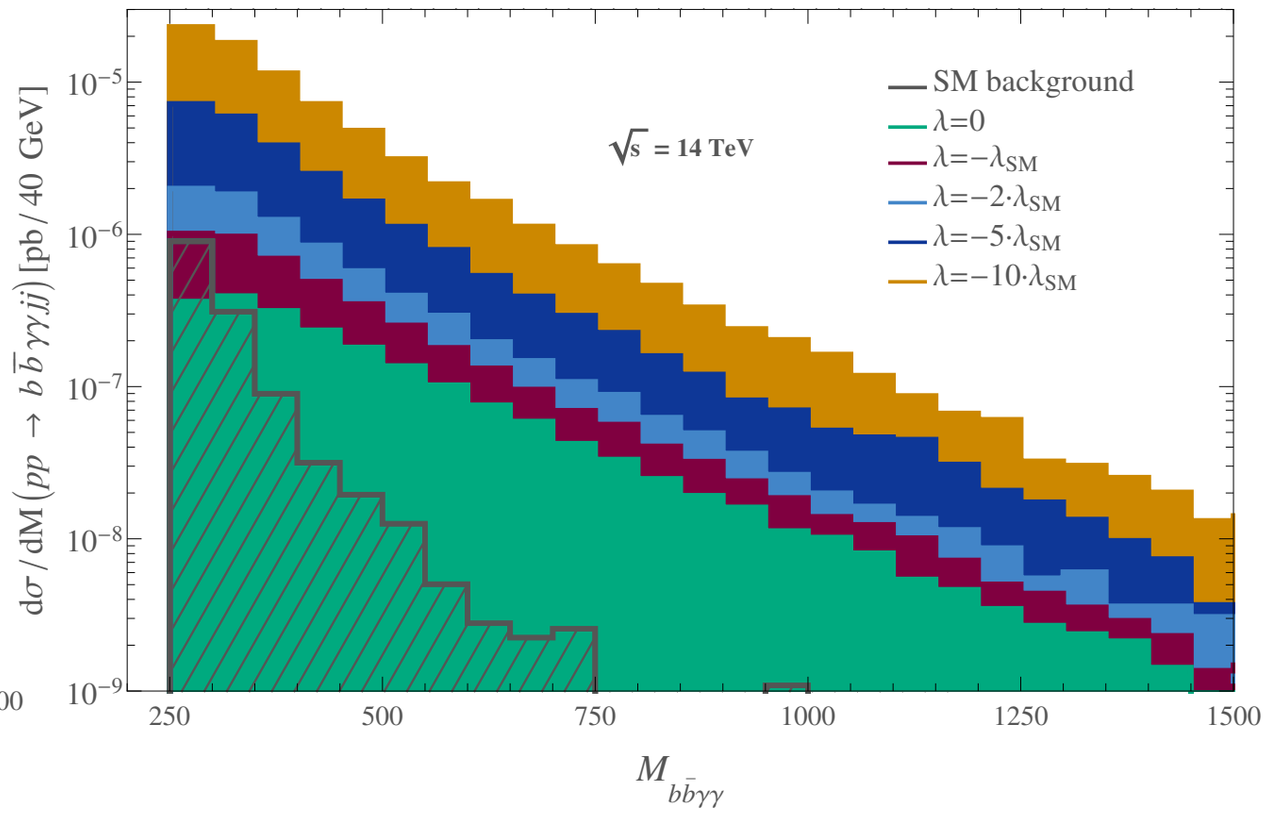
Results for pp → $b\bar{b}\gamma\gamma jj$: M2b2γ distributions

Signal = $q_1q_2 \to HHq_3q_4 \to b\bar{b}\bar{\gamma}\bar{\gamma}q_3q_4$ (sensitive to λ)

SM Background = mixed QCDEW + ZHjj events leading to $b\bar{b}\gamma\gamma jj$

- Similar results as in pp → $b\bar{b}b\bar{b}jj$ varying λ but with smaller rates
- Again clear deviations respect to the background and the λ_{SM} prediction





- Very reduced and steeper backgrounds
- All tested values of λ above background!

Results: Sensitivity to λ in $b\bar{b}b\bar{b}jj$ and $b\bar{b}\gamma\gamma jj$

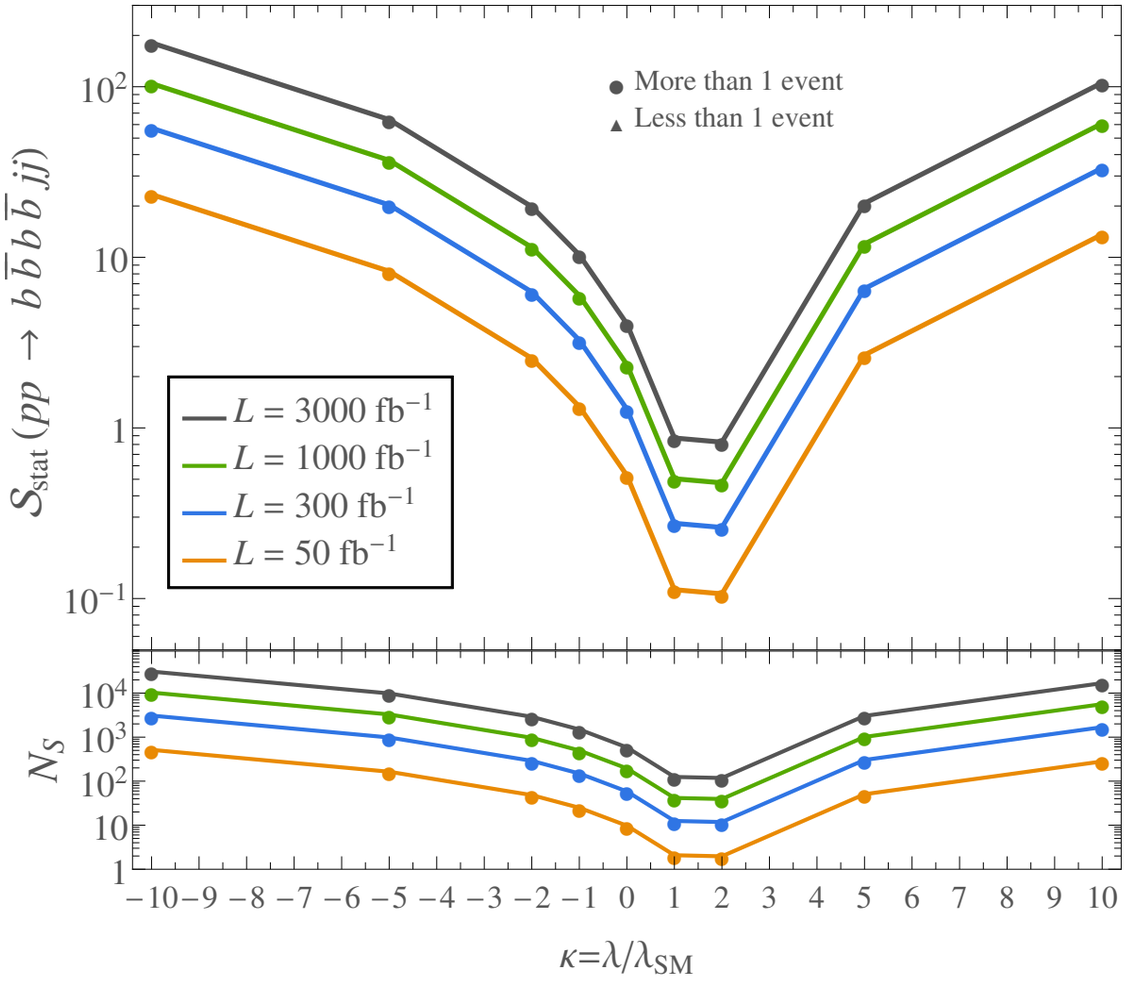
Statistical significance : $S_{\rm stat}$

for different λ values and different luminosities

$$\mathcal{S}_{\rm stat} = \sqrt{-2\left((N_S+N_B)\log\left(\frac{N_B}{N_S+N_B}\right)+N_S\right)} \longrightarrow \frac{N_S}{\sqrt{N_B}}$$

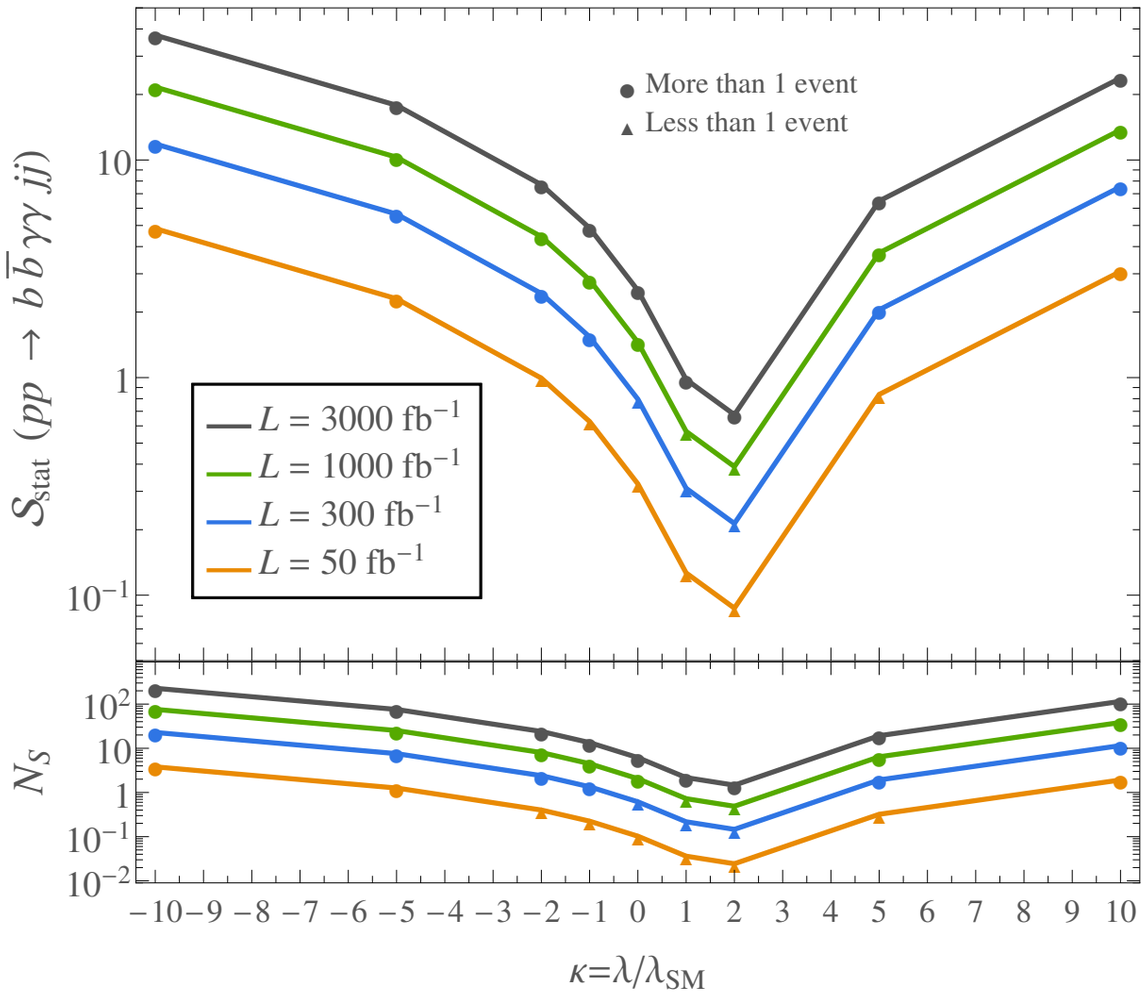
$b\bar{b}b\bar{b}jj$:

High sensitivity, even for the lowest luminosity. High signal rates N_S !!!



$b\bar{b}\gamma\gamma jj$:

Modest sensitivity, lower signal rates N_S , but cleaner



Results: Accesible λ BSM in $b\bar{b}b\bar{b}jj$ and $b\bar{b}\gamma\gamma jj$

Which λ intervals can we probe through VBS?

- **$b\bar{b}b\bar{b}jj$: very promising and competitive !!!**

3σ (5σ) intervals in $\kappa \equiv \lambda/\lambda_{SM}$

$L\ [\mathrm{fb}^{-1}]$	50	300	1000	3000
$\kappa > 0$	$\kappa > 5.4\ (7.0)$	$\kappa > 4.3\ (4.8)$	$\kappa > 3.7\ (4.2)$	$\kappa > 3.2\ (3.7)$
$\kappa < 0$	$\kappa < -2.4\ (-3.8)$	$\kappa < -1.0\ (-1.7)$	$\kappa < -0.3\ (-0.8)$	$\kappa < 0\ (-0.2)$

Very broad intervals probed even for low luminosities!

HL-LHC: able to test small deviations and be sensitive to all $\lambda < 0$ values

- **$b\bar{b}\gamma\gamma jj$: more modest, need HL**

$L\ [\mathrm{fb}^{-1}]$	50	300	1000	3000
$\kappa > 0$	$\kappa > 9.9\ (14.2)$	$\kappa > 6.4\ (8.4)$	$\kappa > 4.6\ (6.0)$	$\kappa > 3.8\ (4.7)$
$\kappa < 0$	$\kappa < -6.7\ (-10.0)$	$\kappa < -2.7\ (-4.6)$	$\kappa < -1.1\ (-2.3)$	$\kappa < -0.2\ (-1.0)$

*WARNING!: Naive results. Hadronization and detector effects not taken into account

Conclusions

VBS is an efficient channel to test large BSM λ at the LHC !!!

- **We find competitive sensitivities in VBS to λ :**
  in two decay channels after VBS and HH candidate selection

  - $pp \to \bar{b}b\bar{b}bjj$: **large rates but large backgrounds**

    High and promising sensitivities already for $L = 50\ \mathrm{fb}^{-1}$

    HL-LHC could probe small deviations : $\lambda = (3-5)\lambda_{\rm SM}$

    Better if $\lambda < 0$

  - $pp \to b\bar{b}\gamma\gamma jj$: **small rates but very controlled backgrounds**

    Modest but interesting sensitivities. Need to go to $L \geq 300\ \mathrm{fb}^{-1}$

- **Promising results !!! BUT PARTON LEVEL YET**
  Deserve further study including hadronization and detector effects!!!

Starting a project in collaboration with exp. group to perform a realistic study including these effects

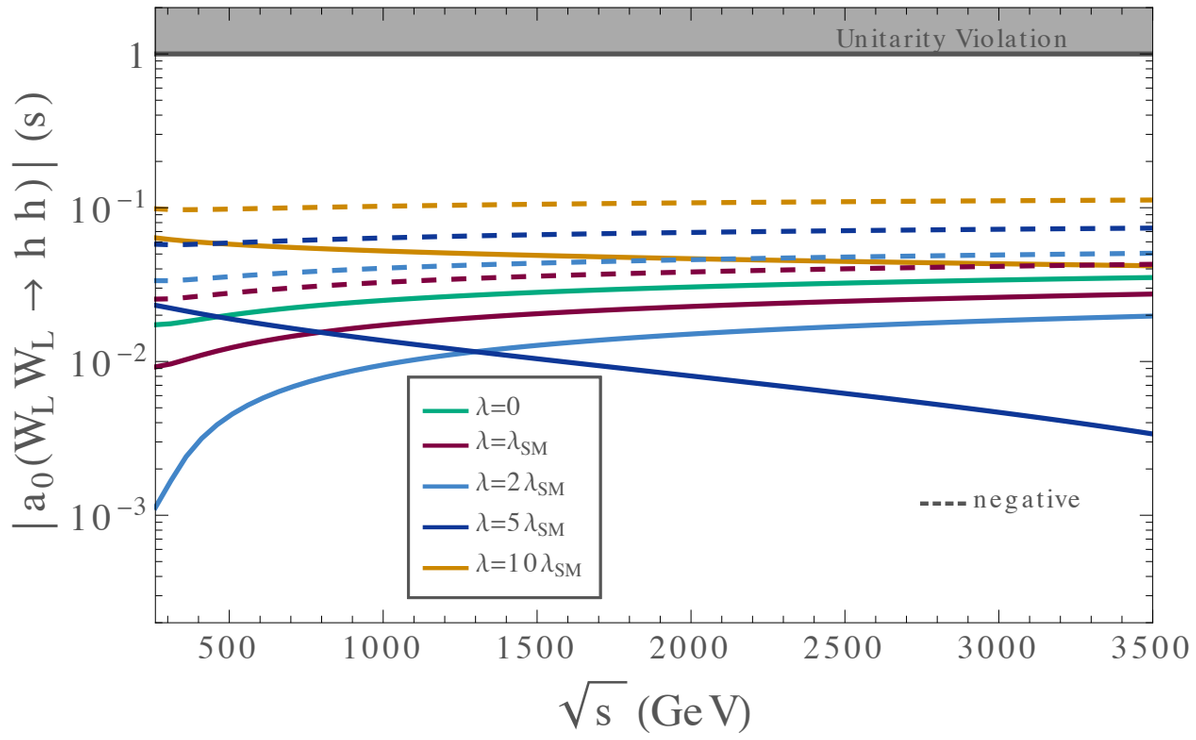
Back up slides

(No) Unitarity violation problems

- Definition of unitarity violation: absolute value of Jth (angular momentum) partial wave of VV → HH becomes 1

$$|a_J| = \left| \frac{1}{64\pi} \int_{-1}^{1} d\cos\theta \, A(VV \to HH) \, P_J(\cos\theta) \right| > 1$$

- We have checked that all our partial waves for $\lambda \in$ [-10,10] λ_{SM} are below 0.1
- No unitarity violation in this channel

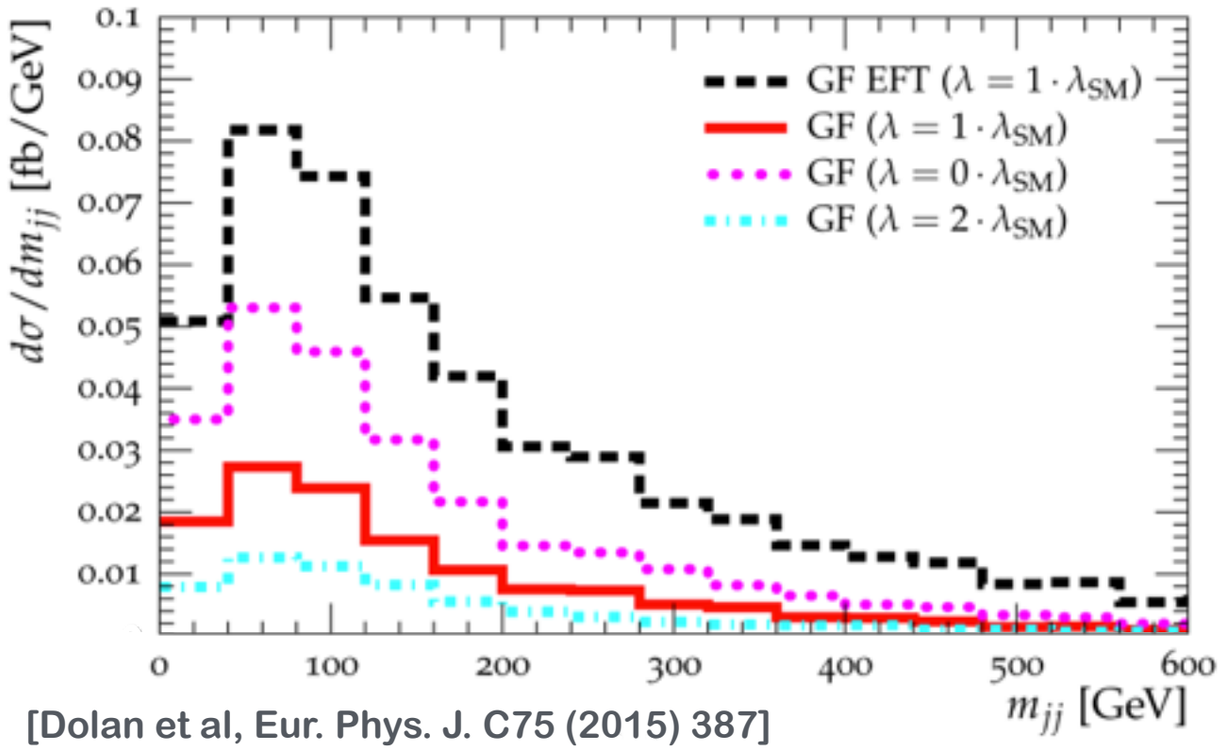


- Other channels such as HH HH might violate unitarity for κ ~7 values at low energies

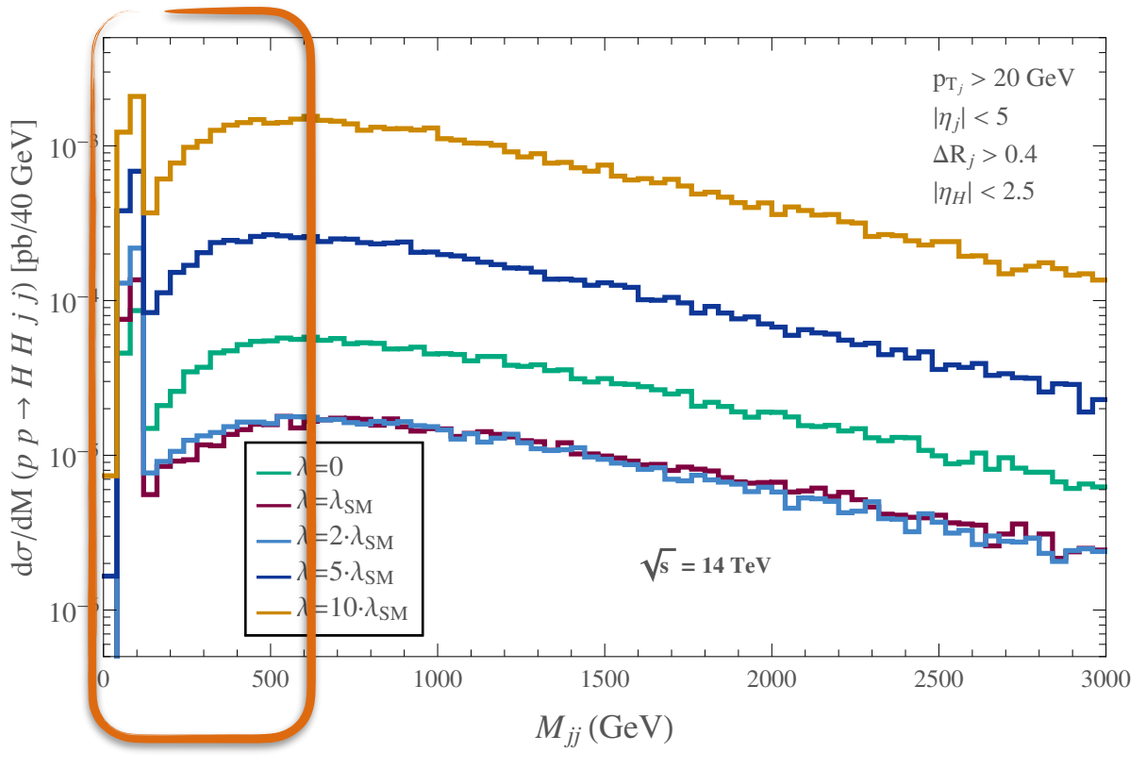
[Di Luzio et al, Eur.Phys.J. C77 (2017) no.11, 788]

“Pollution” from ggF HHjj production?

- Initial cross section twice as big as pure VBS
- After [Dolan et al, Eur. Phys. J. C75 (2015) 387] selection cuts based on $\Delta\eta_{jj}$ ggF amounts to 1/3 of VBS
- They also impose cuts on low M_{HH} masses near threshold where most of VBS signal lies
- Checked: VBS cut on Mjj > 500 GeV leads to a strong reduction ggF < 1/20 VBS



[Dolan et al, Eur. Phys. J. C75 (2015) 387]



Comment on tagging efficiencies effects

- Results modified taking into account b and γ tagging efficiencies

Current values: b-tagging eff. ~ 70% γ-tagging eff. ~ 95%

	Number of events reduction	Significance reduction
bbbbjj	$N_{eff}/N \sim 0.25$	$S_{eff}/S \sim 0.5$
bbγγjj	$N_{eff}/N \sim 0.5$	$S_{eff}/S \sim 0.7$

- Examples of accesible values of λ for L = 1000 fb^{-1} without and with efficiencies

	κ > 0	κ > 0 (eff)
bbbbjj	κ > 3.7 (4.2)	κ > 4.3(4.9)
bbγγjj	κ > 4.6 (6.0)	κ > 6.0 (8.0)

- These efficiencies might improve! Easy way to apply the new ones!

Features of sensitivity to λ at different $\sqrt{s}$

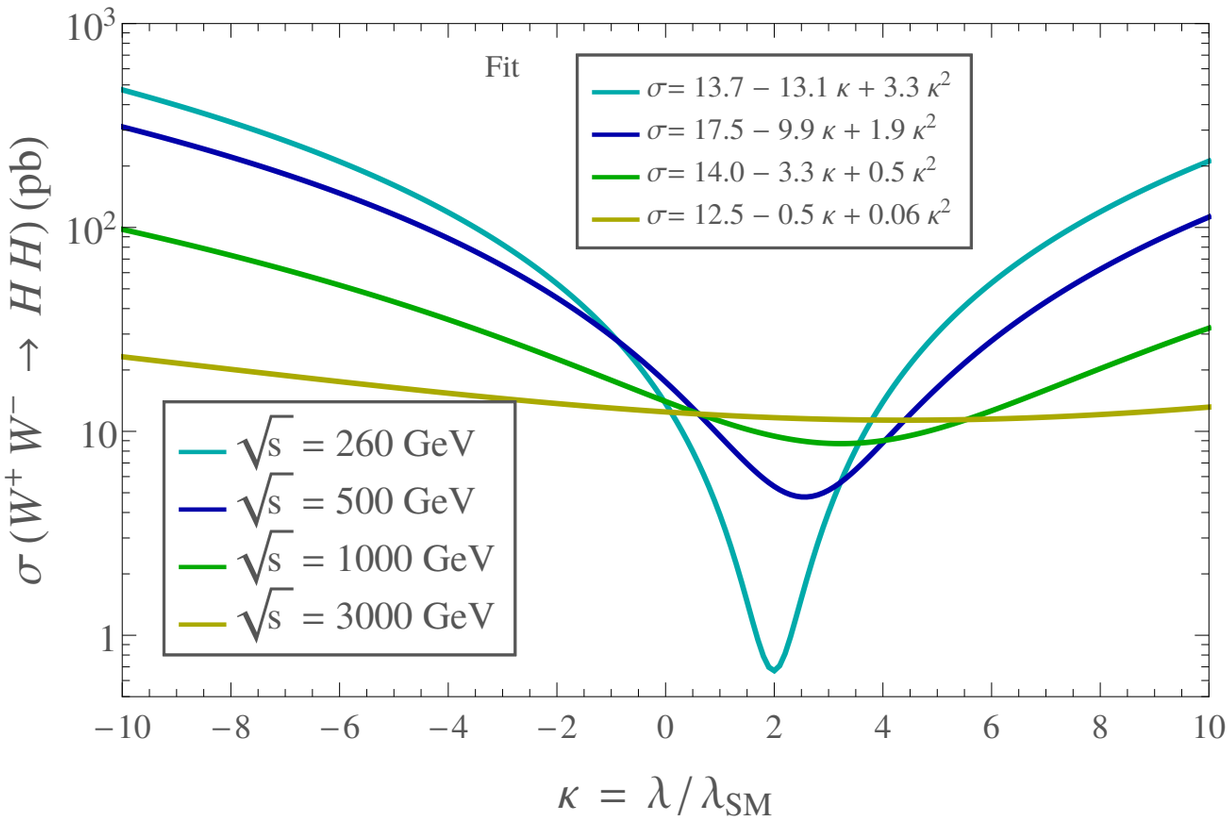
Interplay between diagrams

- $\lambda > 0$: negative interference
- $\lambda < 0$: positive interference

Sensitivity to $\lambda > 0$ and to $\lambda < 0$ different!

Better sensitivity for $\lambda < 0$ for same $|\lambda|$

Cancellations and analytical sensitivity to λ depend on energy and λ value



Highest sensitivity outside the interval around minimum

Largest cross section and sensitivity near the HH threshold

Study of VBS cuts in pp → $b\bar{b}b\bar{b}jj$

- We analyze the fraction of events that satisfy different sets of VBS cuts
- Signal dominated by VBS topologies
- QCD background reduced in 1-1.5 orders of magnitude

Acceptance

$$\mathscr{A}_{\rm VBS} \equiv \frac{\sigma(pp \to b\bar{b}b\bar{b}jj)|_{\rm VBS}}{\sigma(pp \to b\bar{b}b\bar{b}jj)}$$

Set of VBS cuts	$\mathcal{A}_{\rm VBS}^{\rm QCD}$	$\mathcal{A}_{\rm VBS}^{{\rm Signal};\kappa=1}$
$\|\Delta\eta_{jj}\| > 4,\ M_{jj} > 500$ GeV	0.086	0.631
$\|\Delta\eta_{jj}\| > 4,\ M_{jj} > 600$ GeV	0.066	0.597
$\|\Delta\eta_{jj}\| > 4,\ M_{jj} > 700$ GeV	0.054	0.558
$\|\Delta\eta_{jj}\| > 3,\ M_{jj} > 500$ GeV	0.098	0.669
$\|\Delta\eta_{jj}\| > 3,\ M_{jj} > 600$ GeV	0.071	0.626
$\|\Delta\eta_{jj}\| > 3,\ M_{jj} > 700$ GeV	0.057	0.580

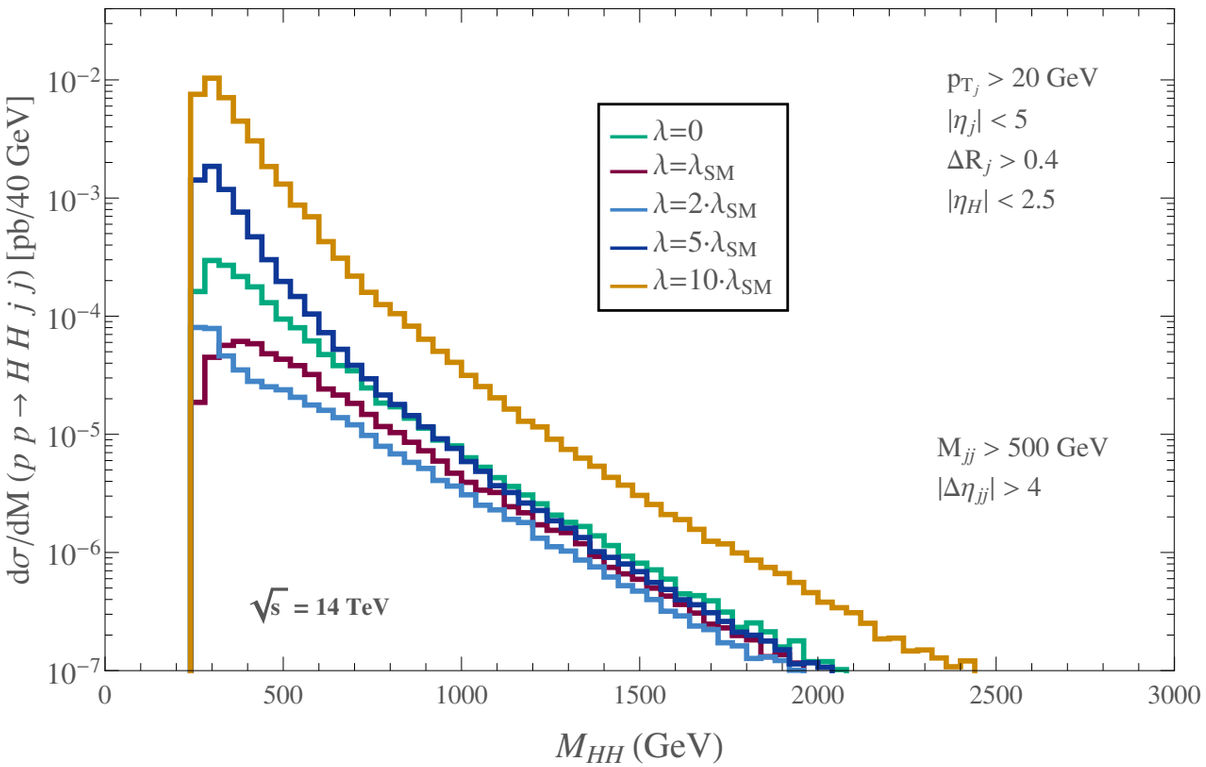
- Different sets give similar results → We stick to: $|\Delta\eta_{jj}| > 4$, $M_{jj} > 500$ GeV

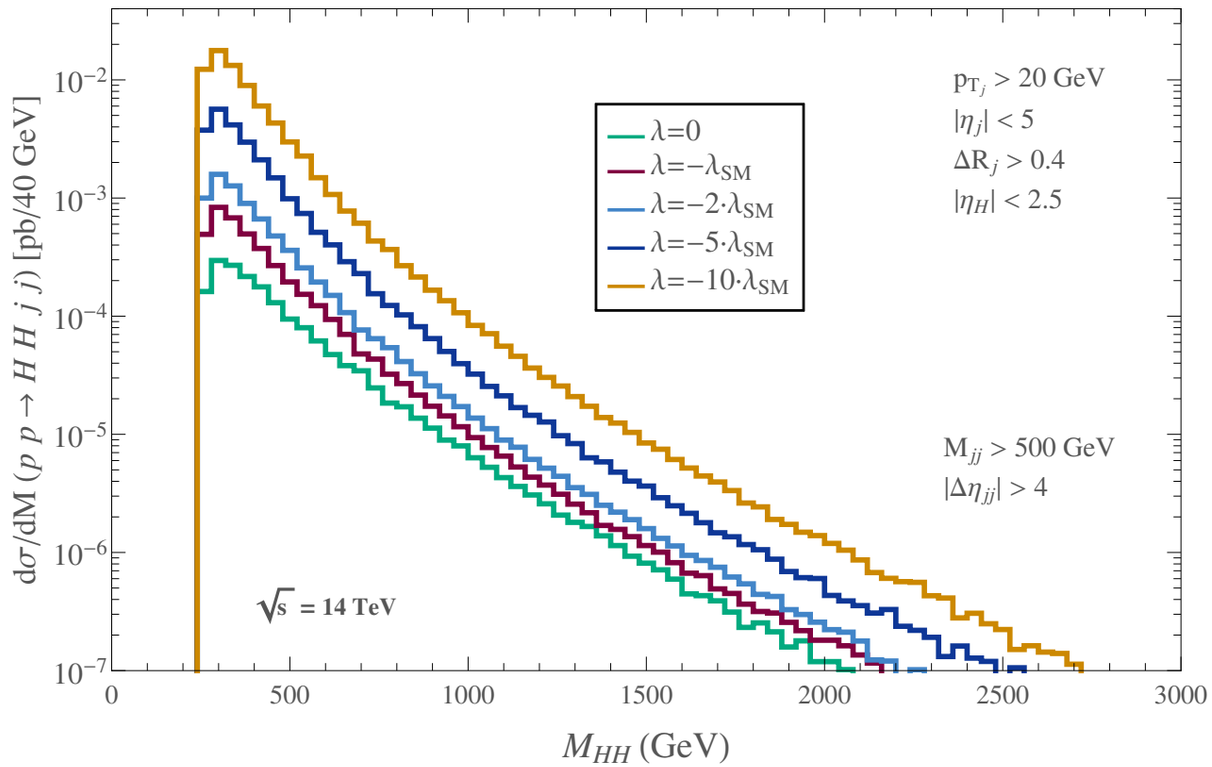
Basic detection cuts: $p_{T_{j,b}} > 20$ GeV ; $|\eta_j| < 5$; $|\eta_b| < 2.5$; $\Delta R_{jj,jb} > 0.4$; $\Delta R_{bb} > 0.2$

Sensitivity to λ in HHjj: MHH distributions

- pp → HHjj VBS-dominated → direct translation form subprocess results

- **Visible deviations** respect to the SM!!!





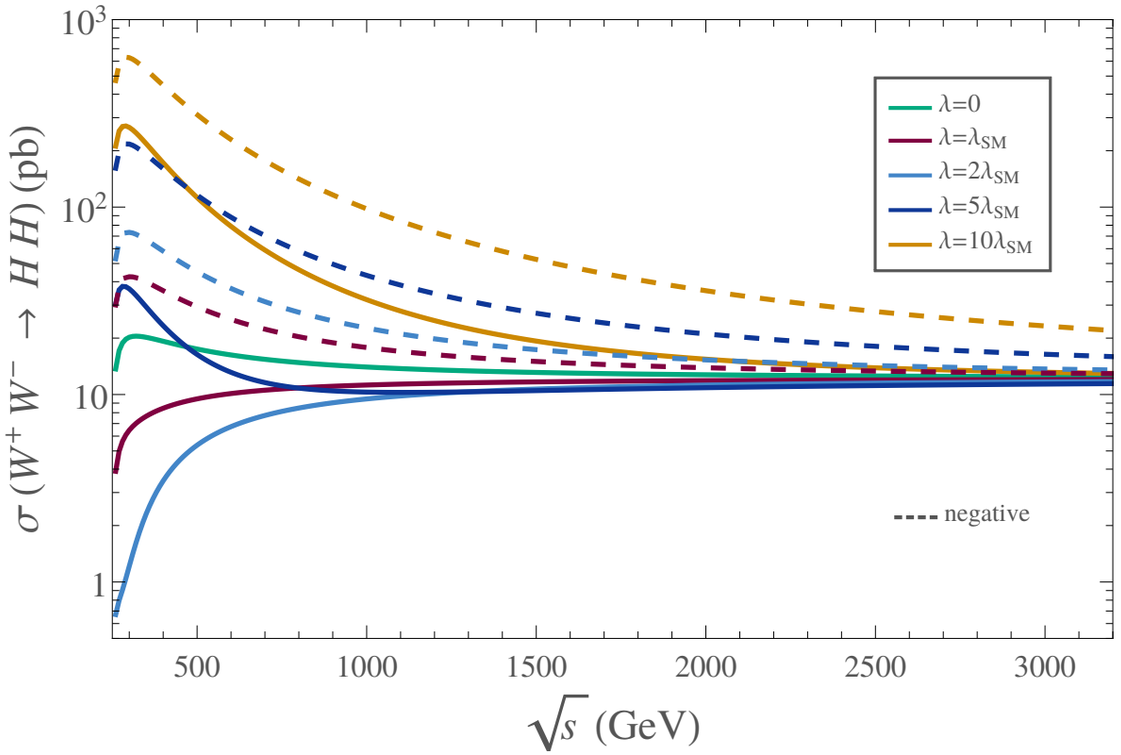
- **Different sensitivity to $\lambda > 0$ and to $\lambda < 0$ remains**
  positive interference for $\lambda < 0$, negative for $\lambda > 0$

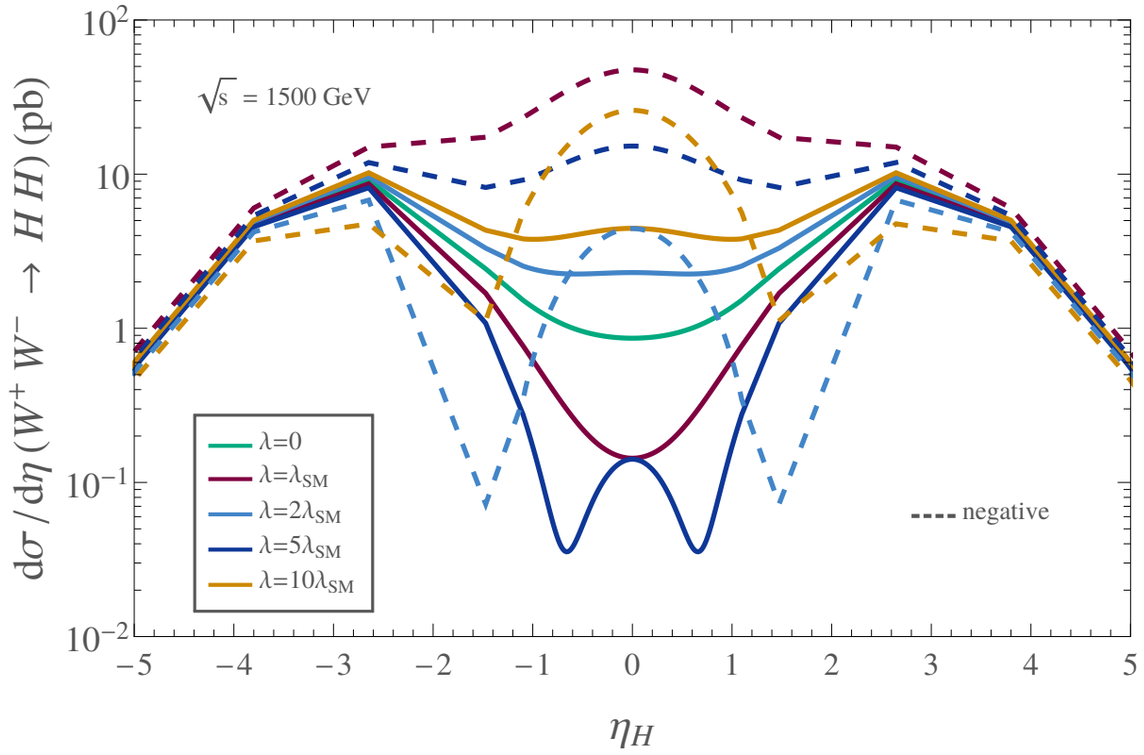
- **Largest sensitivity still near HH production threshold**

BSM distortions varying $\kappa = \lambda/\lambda_{SM}$

- We study $\lambda \in$ [-10,10] λ_{SM}

- Energy and angular behaviour change when varying λ





- $\lambda \neq \lambda_{SM}$ leads to sizable (exp. observable) deviations from the SM

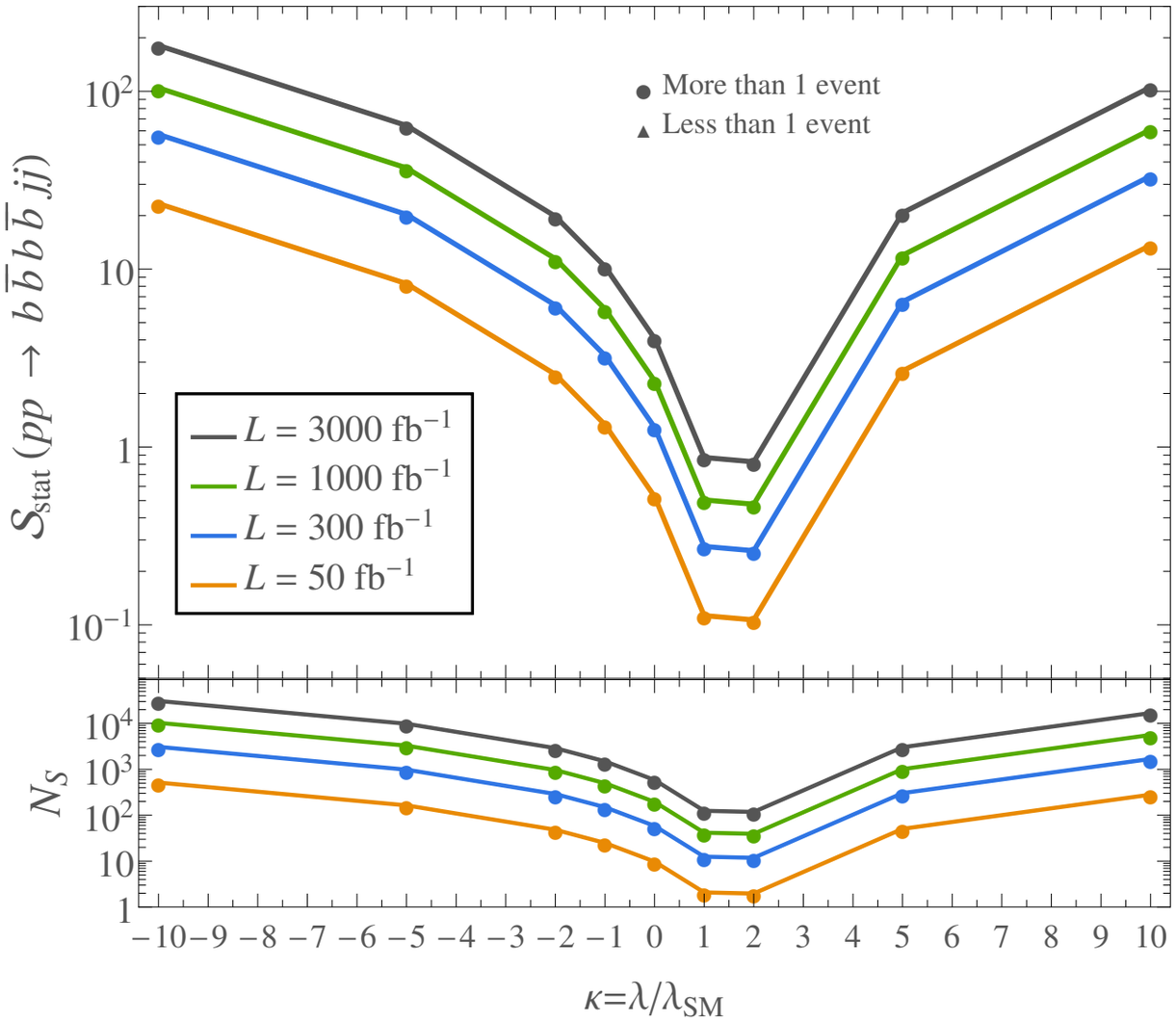
- Largest deviations near HH production threshold

Sensitivity to λ in pp → $b\bar{b}b\bar{b}jj$

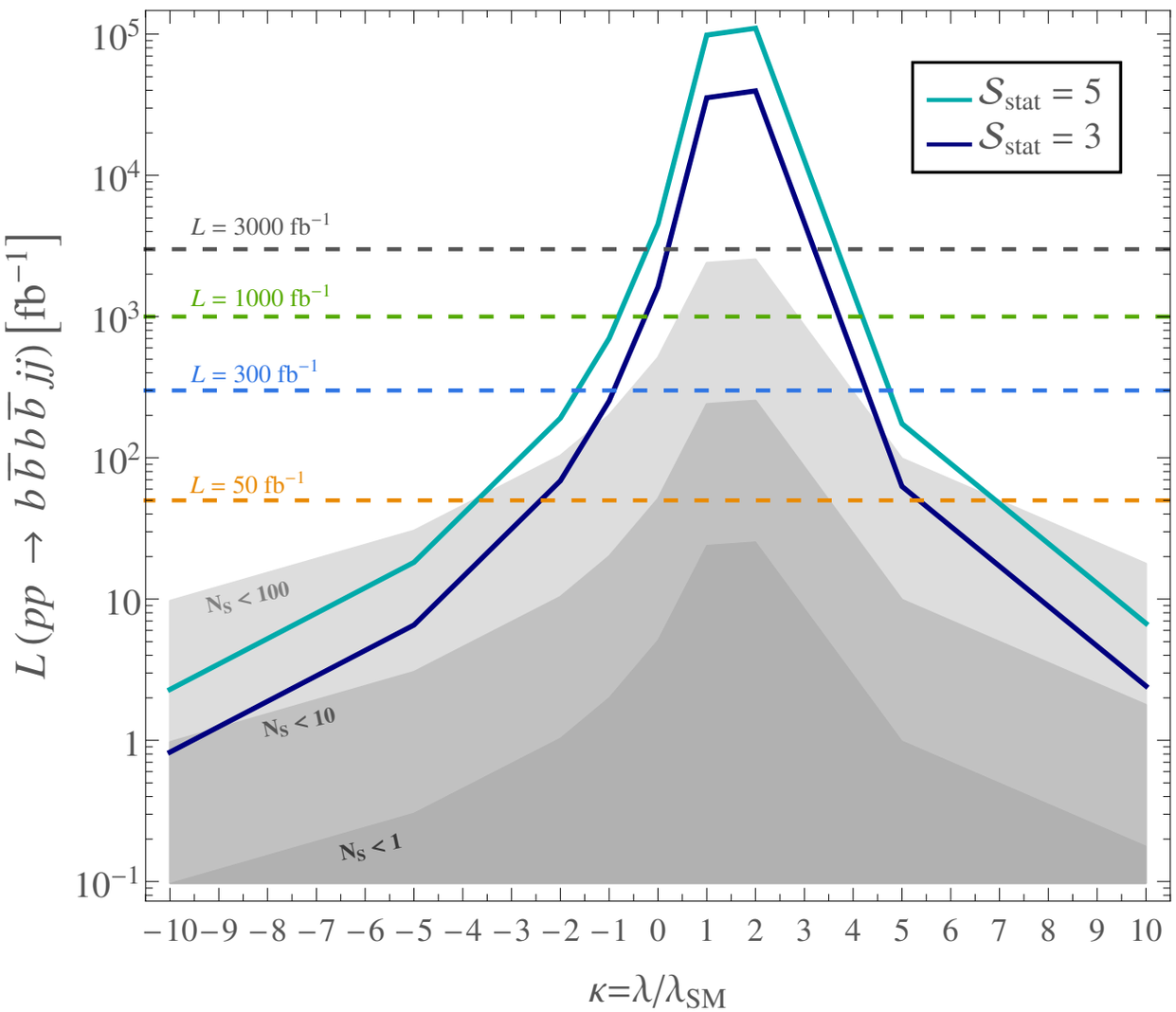
High sensitivity to BSM λ even for the lowest luminosities!!!

$$\mathcal{S}_{\text{stat}} = \sqrt{-2\left((N_S + N_B)\log\left(\frac{N_B}{N_S + N_B}\right) + N_S\right)}$$

Statistical significance for different λ values and different luminosities



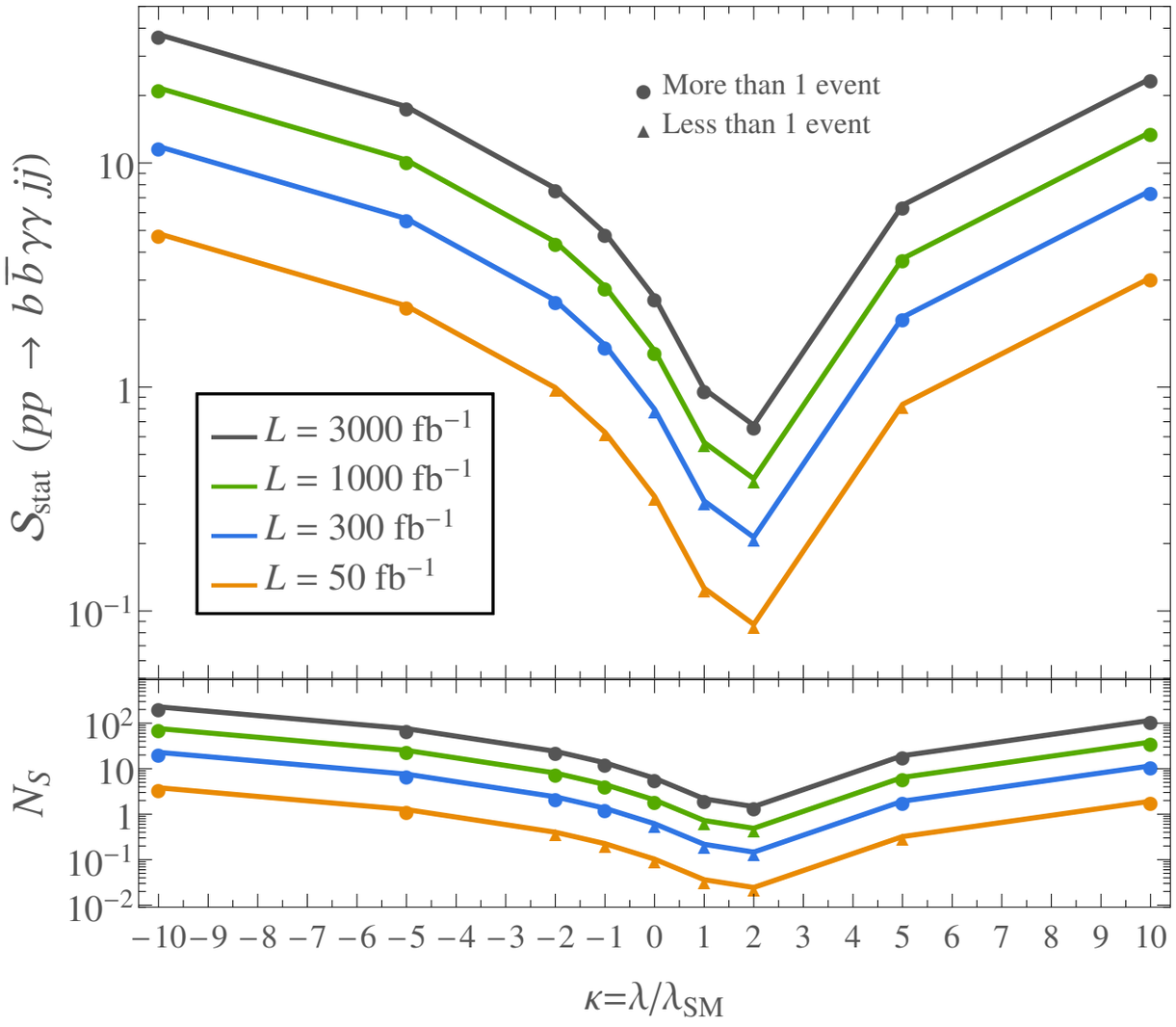
Luminosity required to observe a λ value at 3σ and 5σ



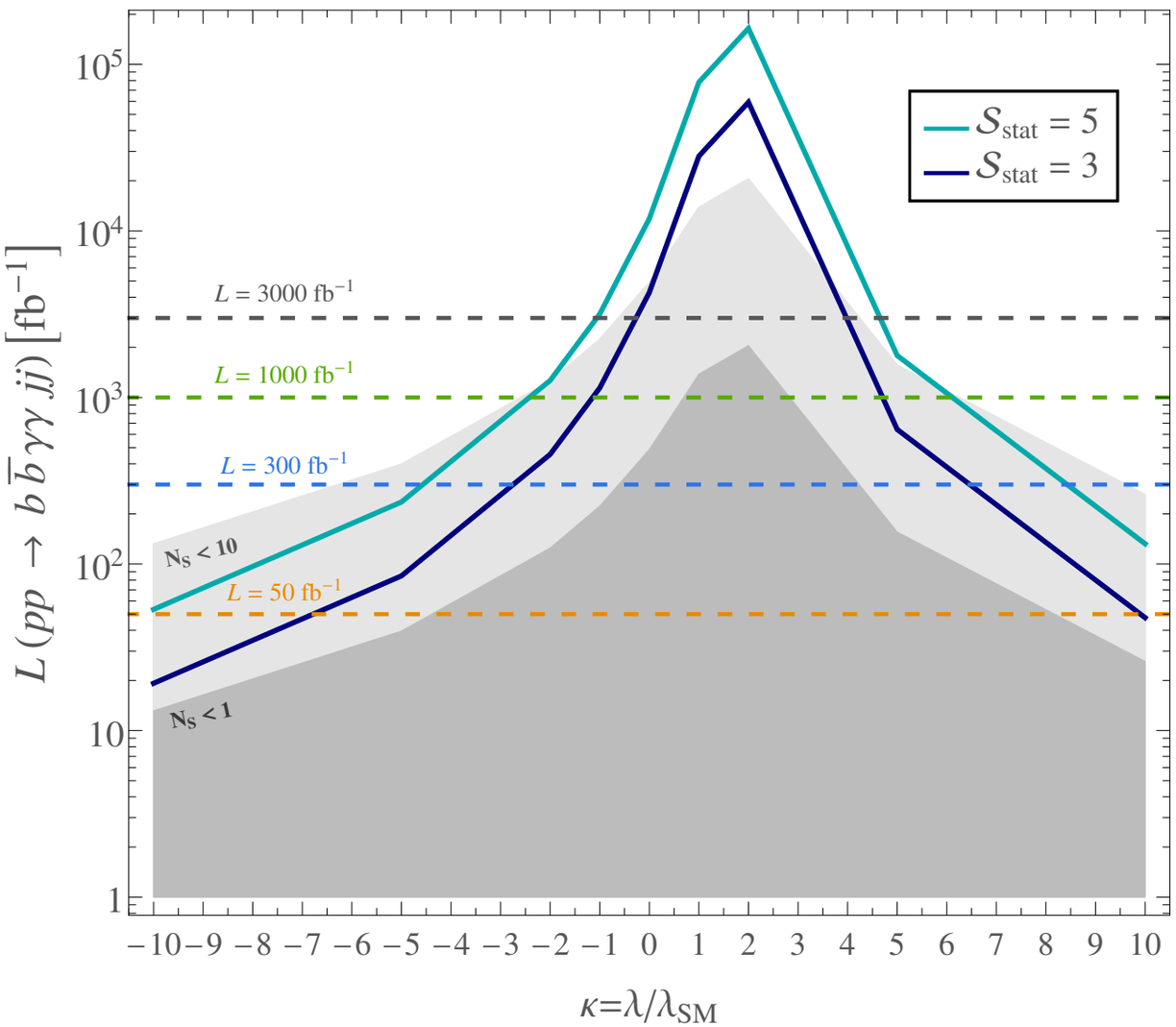
Sensitivity in pp → bb̄γγjj

Modest but interesting channel to probe the H self-coupling

Statistical significance for different λ values and different luminosities

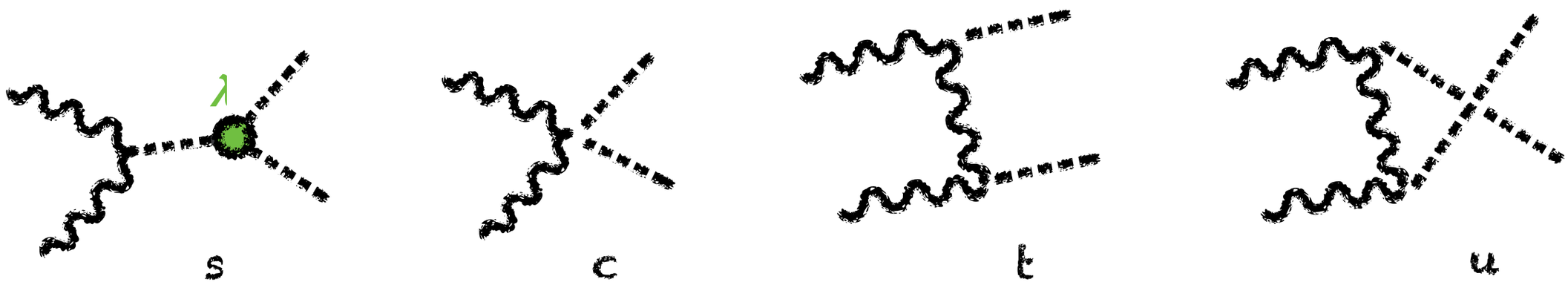


Luminosity required to observe a λ value at 3σ and 5σ

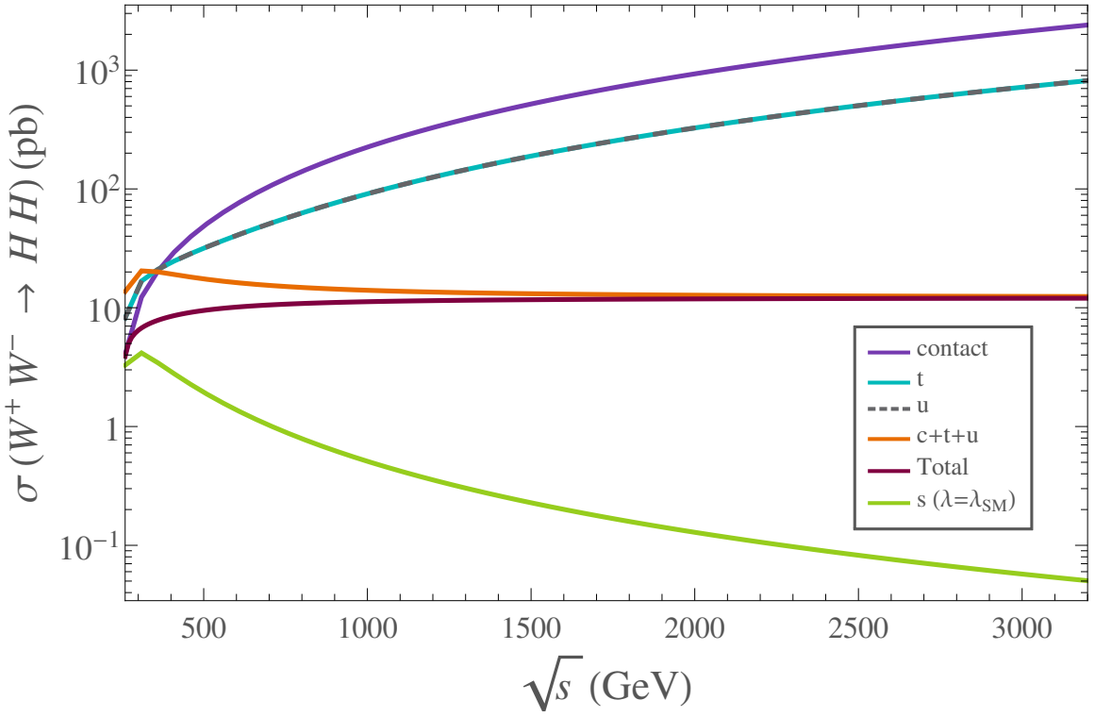


Learning from SM subprocess VV→HH

Diagrams that contribute:



(similar behaviour for WW and ZZ)



- **λ present only in s-channel**
- **Cross section dominated by $V_LV_L \to HH$**
- **λ contribution subleading in SM**
- **Main c+t+u cancellations lead to σ flatness at high √s**
- **Negative interference between λ diagram and the rest. More relevant near HH threshold**

$\lambda \neq \lambda_{SM}$ leads to sizable (exp. observable) deviations from the SM !!!

See next how to look for these deviations at the LHC