The Higgs self-coupling at the LHC: can we probe it through HH production via VBS?

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Based on [arXiv:1807.09736]

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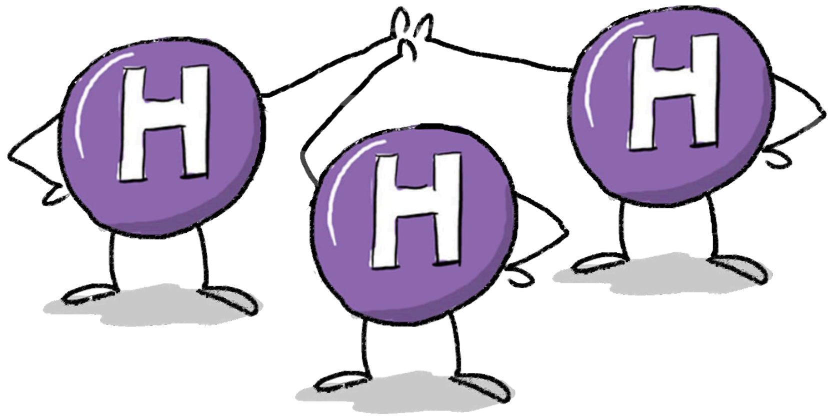
Introduction to the topic

Aim



- Measure accurately the Higgs self-coupling λ
- Understand the BEH mechanism
- Check BSM alternatives of λ

Current status and sensitivity 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

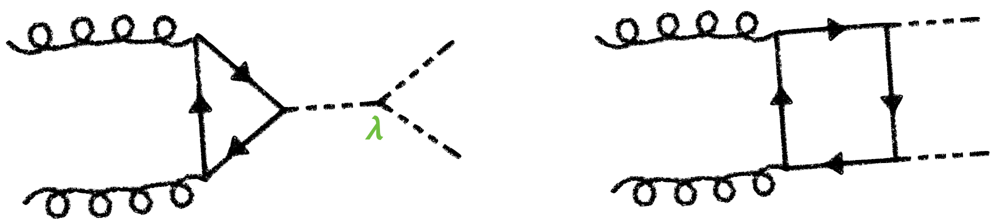
  [Abramowicz et al, Eur. Phys. J. C77 (2017) 475]
- Still far (and/or unknown) in the future!!

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

VBS to access λ at the LHC

ggF: $gg \to HH$

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



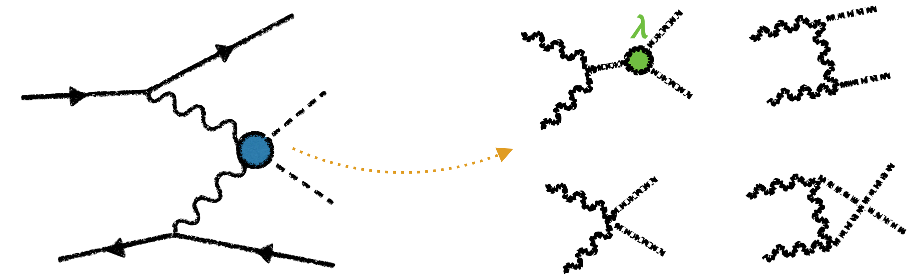
1-loop + Top mass + scale choice + sizeable NLO

Less specific kinematics

Only sensitive to HHH coupling

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 + small scale unc. + small NLO

Very characteristic kinematics

$V_L V_L \to HH$ probes Φ^4 at high energy

ggF: $gg \to HHjj$?

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

Contributes to our signal: same final state & sensitive to λ

VBS selection cuts reduce cross section below pure VBS one

Not taken into account in the present work

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

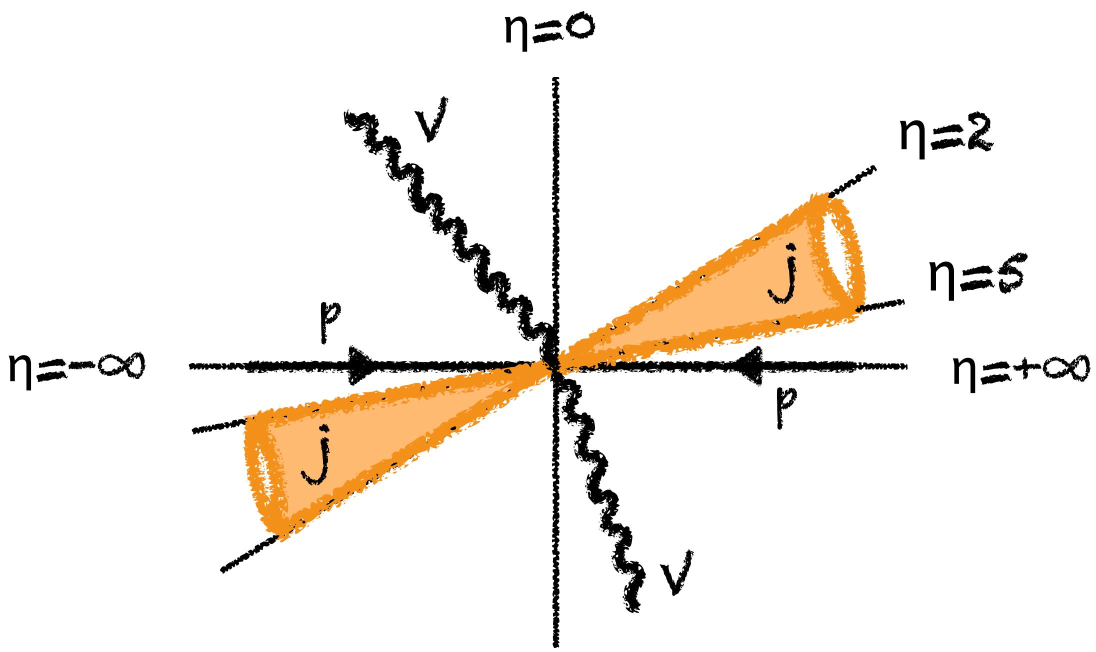
[Dolan et al, Eur. Phys. J. C75 (2015) 387]

Defining our signal @ the LHC: pp → HHjj

Signal: prediction of $q_1q_2 \to HHq_3q_4$ events for given λ

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

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

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

with large invariant masses

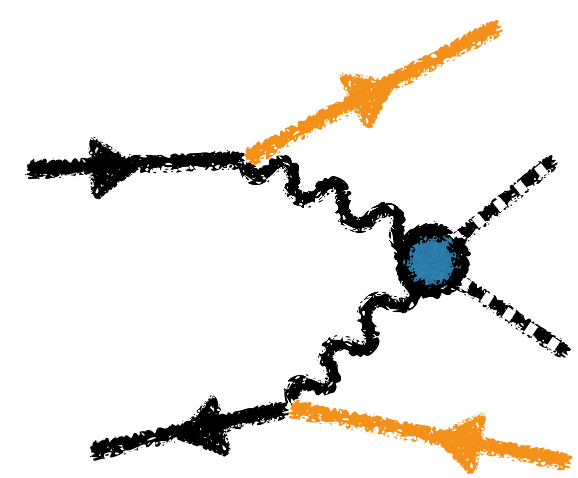
$$M_{jj}$$

Defining VBS selection cuts

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

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

pp → HHjj
VBS-dominated !!



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

1st signal after Higgs decays: $pp \to HHjj \to b\bar{b}b\bar{b}jj$

Highest rates : $BR(H \to bb) \sim 60\ \%$

Large **backgrounds**

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

Estimated with MG5
Checked with AlpGen

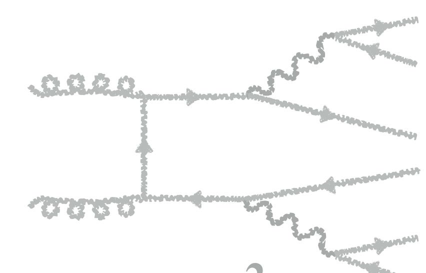
- **Dominant** background by many **orders of magnitude**
- **Additional** selection **cuts** apart from **VBS** required?

+ …

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

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

- **CKM suppressed**
- Radically **different kinematics** respect to **VBS**
- **Under control**

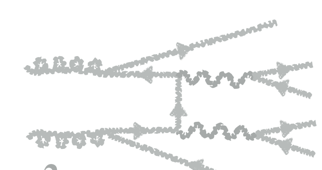


+ …

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

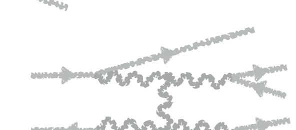
$pp \to ZZjj \to b\bar{b}b\bar{b}jj$ & $pp \to ZHjj \to b\bar{b}b\bar{b}jj$

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



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

+



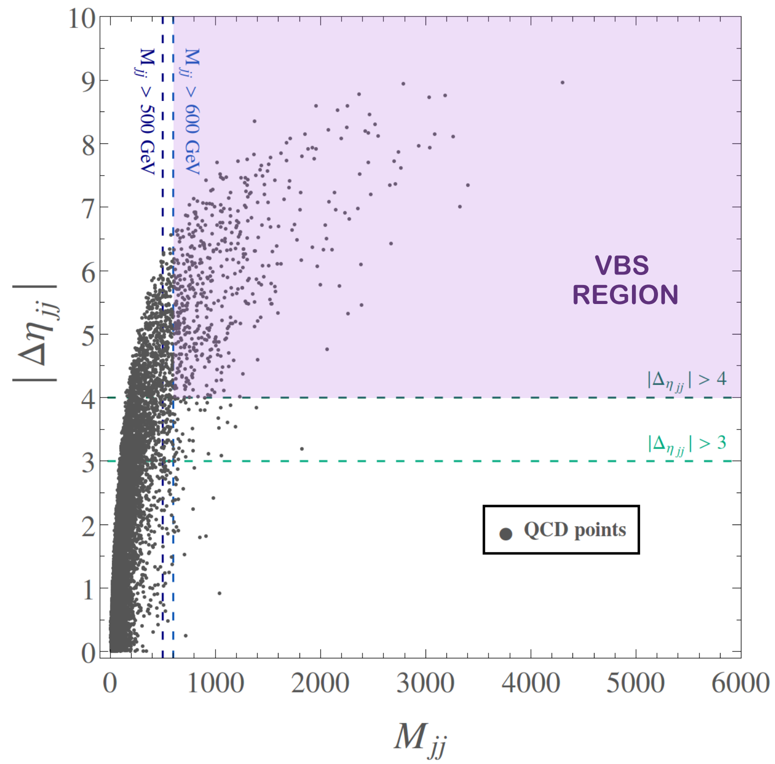
$\mathcal{O}(\alpha^3)$

Signal and QCD background kinematics

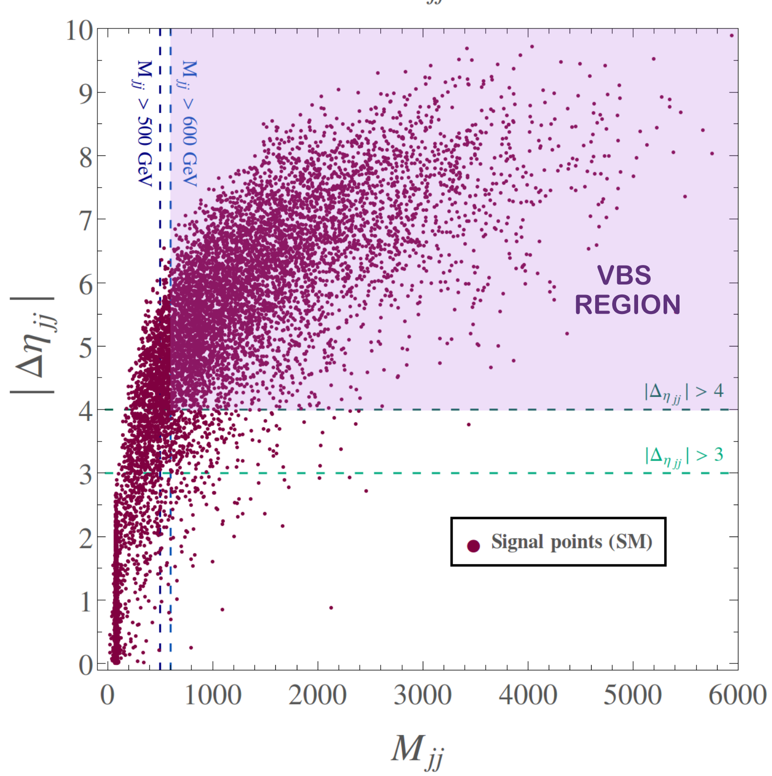
Signal & QCD bkg populate different kinematical regions

In VBS variables

Multijet QCD characterized by **small $\Delta\eta_{jj}$** and **small M_{jj}**

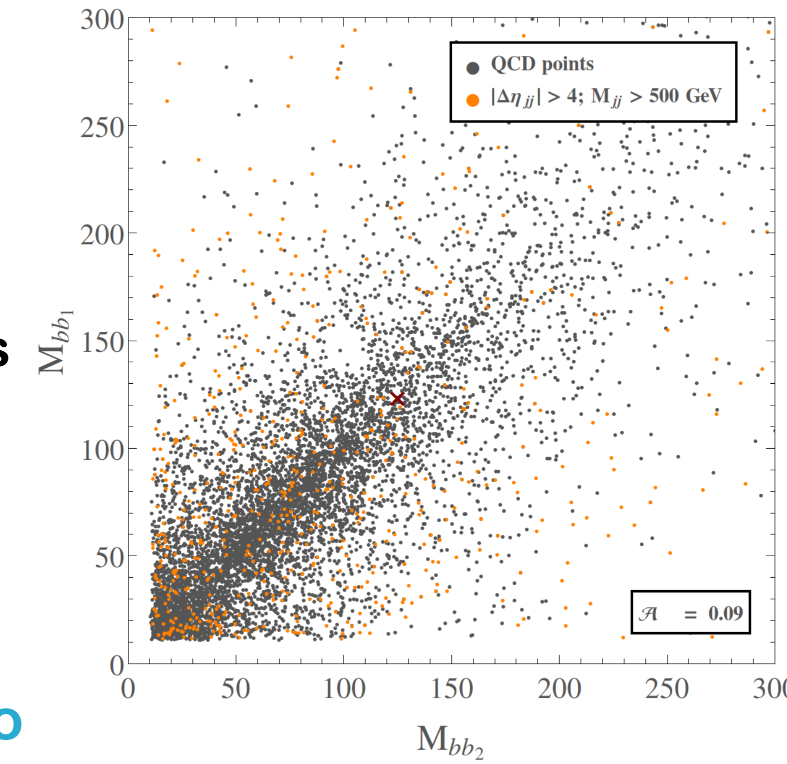


Most of **signal** events in **VBS** kin. region



In bb variables

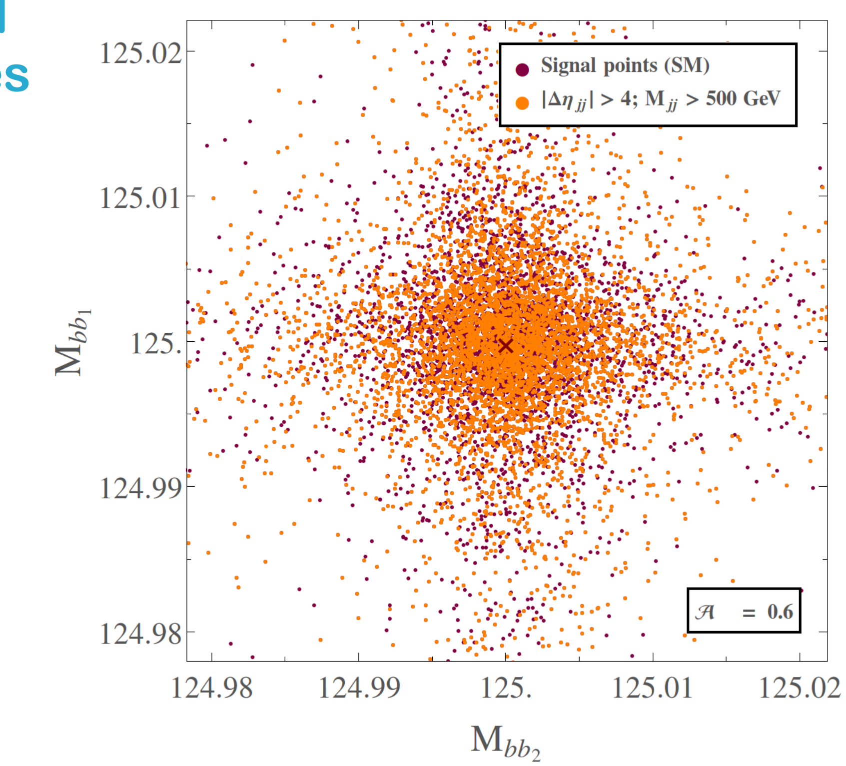
Multijet QCD **background** events lie mainly at **low [M_{bb1}, M_{bb2}]**



We profit from Higgs decays info

b-quarks paired as HH candidates

Signal events lie near **[M_H,M_H]**



HH candidate identification and cut efficiency

- **HH candidate cuts** (inspired in ATLAS [arXiv: 1804.06174] and CMS [CMS-PAS-HIG-16-026])

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

Small angular separation between Higgs decay products

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

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

[Mbb1, Mbb2] ~[MH,MH]

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

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

- **Efficiency of Basic* + VBS + HH candidate cuts**

Cut	σ_{QCD} [pb]	$\sigma_{ZHjj,ZZjj}$ [pb]	$\sigma_{\text{Signal};\kappa=1}$ [pb]
Basic only	602.72	0.028	$5.1\cdot10^{-4}$
Basic + VBS + HH	$6.8\cdot10^{-3}$	$5.5\cdot10^{-6}$	$4.1\cdot10^{-5}$

Very reduced backgrounds!!!

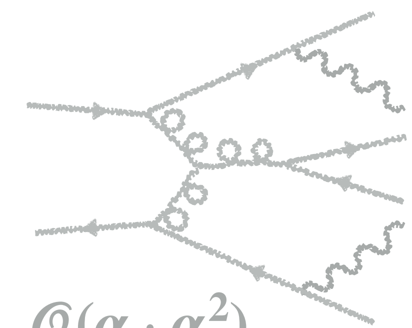
2nd signal after Higgs decays: $pp \to HHjj \to b\bar{b}\gamma\gamma jj$

Small and controlable backgrounds

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

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

VERY REDUCED BACKGROUNDS!

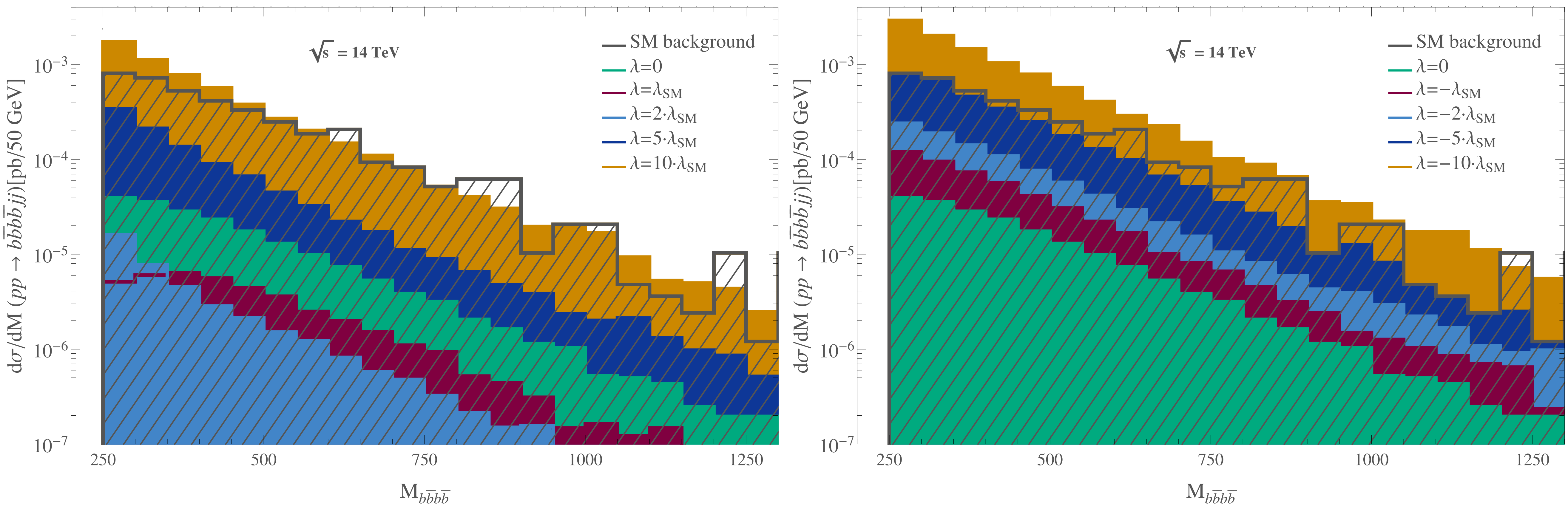
Basic detection cuts: $p_{T_{j,b}} > 20$ GeV ; $p_{T_\gamma} > 18$ GeV ; $|\eta_j| < 5$; $|\eta_{b,\gamma}| < 2.5$; $\Delta R_{jj,jb,\gamma\gamma,\gamma b,\gamma j} > 0.4$; $\Delta R_{bb} > 0.2, p_{T_{\gamma_l}}$

Results of pp → $b\bar{b}b\bar{b}jj$: M_{4b} 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 respect the background and the λ_{SM} prediction



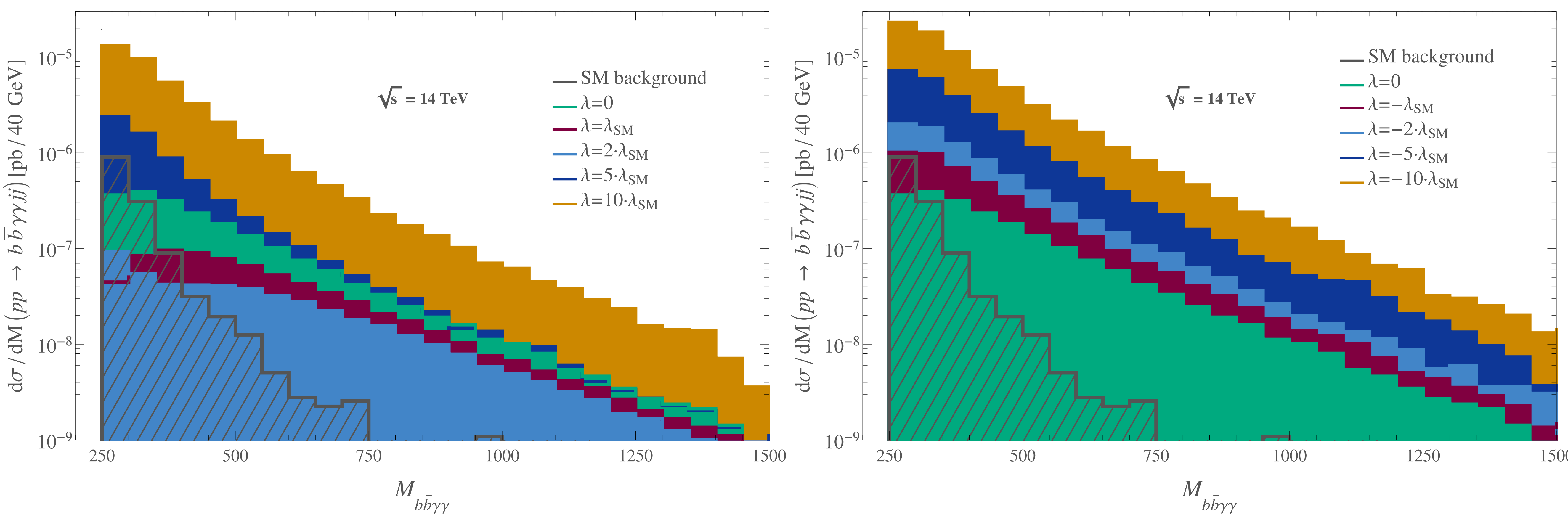
- Some predictions (κ = -10) even above backgrounds!

Results of $pp \to b\bar{b}\gamma\gamma jj$: $M_{2b2\gamma}$ distributions

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

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

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



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

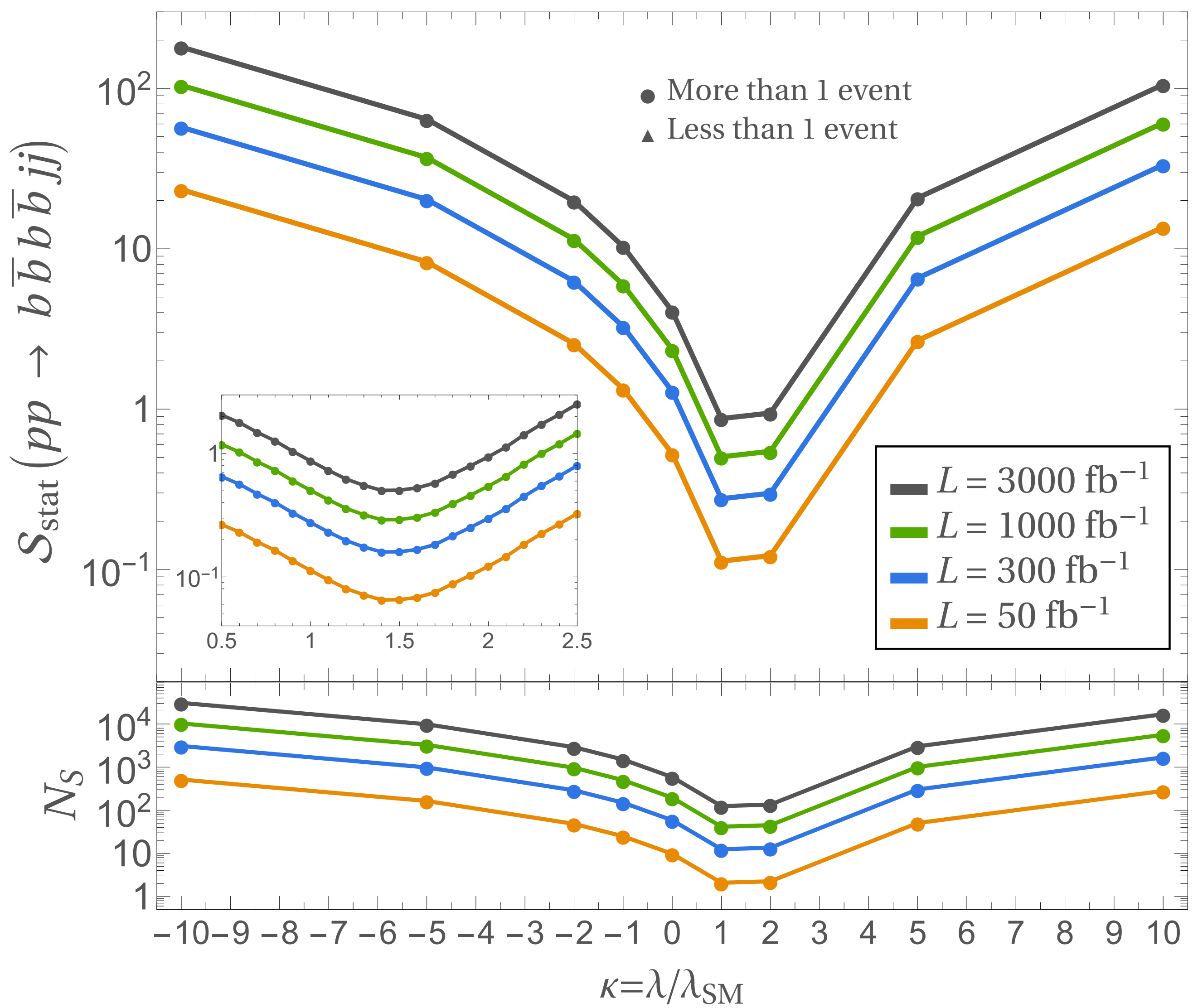
Results: Sensitivity to λ in $b\bar{b}b\bar{b}jj$ & $b\bar{b}\gamma\gamma jj$

Statistical significance for different λ values and different luminosities

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

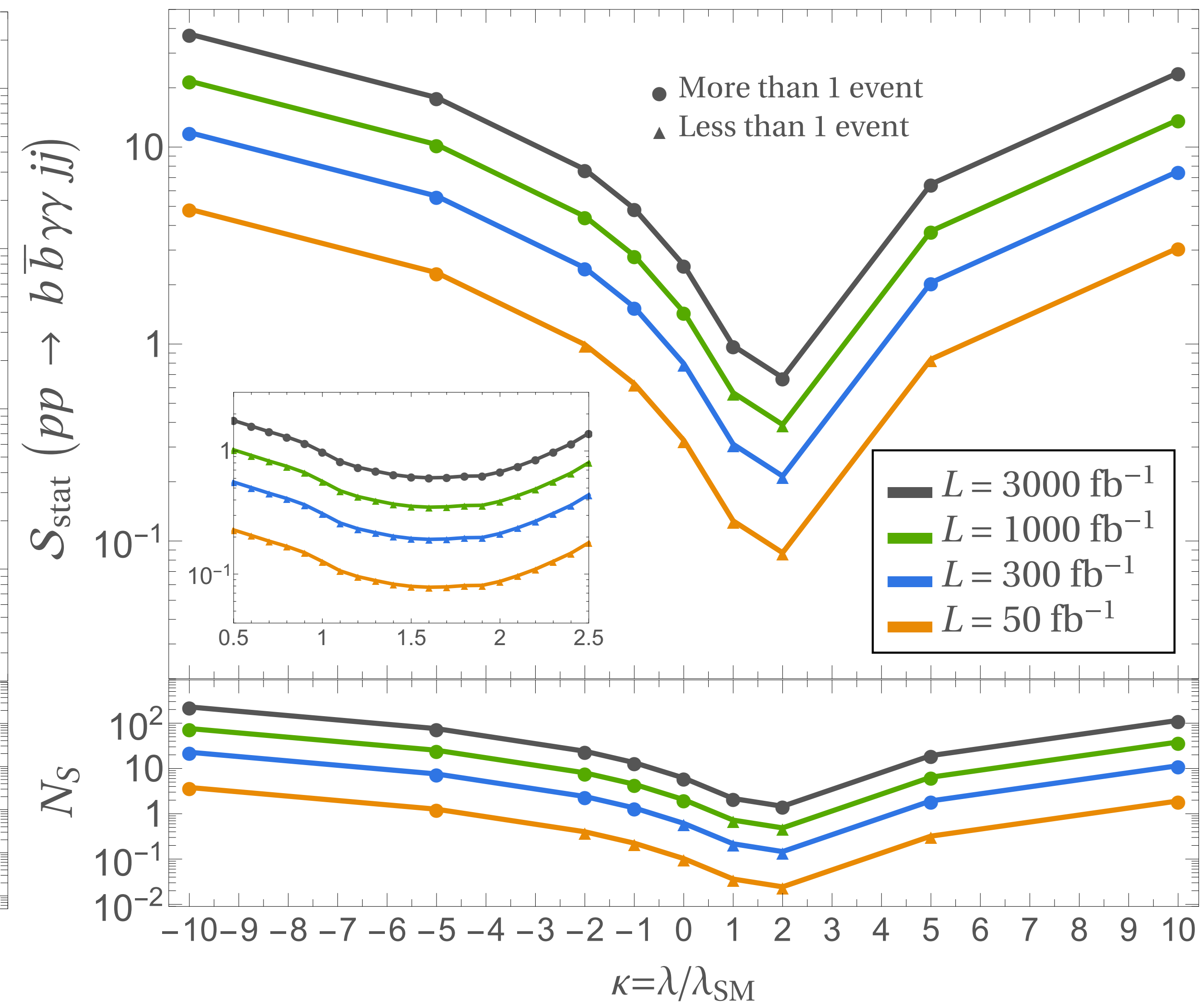
$b\bar{b}b\bar{b}jj$

High sensitivity to BSM λ even for the lowest luminosity



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

Modest sensitivity to BSM λ, smaller rates but cleaner



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

Which λ intervals can we probe through VBS?

$b\bar{b}b\bar{b}jj$ Very promising and competitive

3σ (5σ) intervals

L [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

$b\bar{b}\gamma\gamma jj$ Modest, require High Luminosity

3σ (5σ) intervals

L [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)

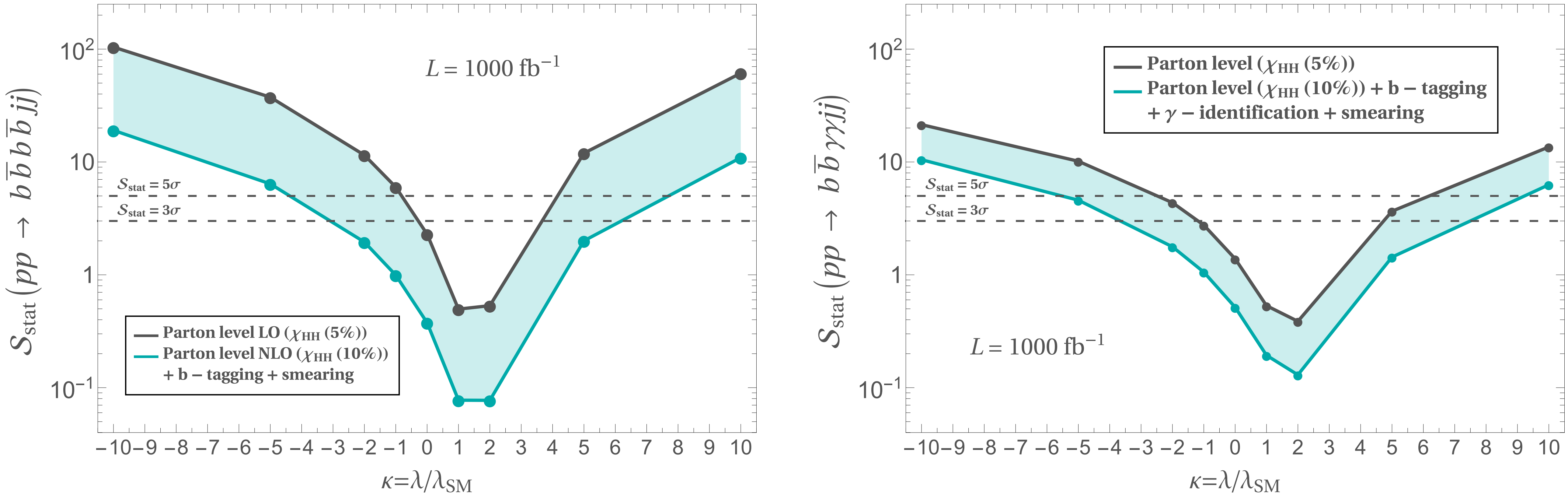
*WARNING!: Naive results. Hadronization and detector not taken into account

First look at beyond parton level

More to come!
We are improving these results!

Additional considerations might affect results…

- **b - tagging** (70%) and **γ identification** efficiencies (95%)
- More up-to-date **Higgs mass reconstruction** efficiency (10%)
- **Detector** effects
- **NLO** corrections



… but not much!

For benchmark L = 1000 fb^{-1}

Signal	Original	With additional considerations
$b\bar{b}b\bar{b}jj$	$\kappa > 3.7\,(4.2)$	$\kappa > 6.2\,(7.7)$
$b\bar{b}\gamma\gamma jj$	$\kappa > 4.6\,(6.0)$	$\kappa > 7.7\,(9.4)$

Conclusions

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

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

  - pp → $b\bar{b}b\bar{b}jj$: large rates but large backgrounds

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

    HL-LHC could probe small deviations: $\lambda \sim (3 - 5)\ \lambda_{SM}$ (Even better for $\lambda < 0$)

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

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

    HL-LHC could probe small deviations very efficiently

- Taking into account tagging and identification efficiencies, up-to-date Higgs mass reconstruction, detector effects and NLO corrections does not change predictions much!

- Promising results deserve further study!!!

Conclusions

THANK YOU!!! :)

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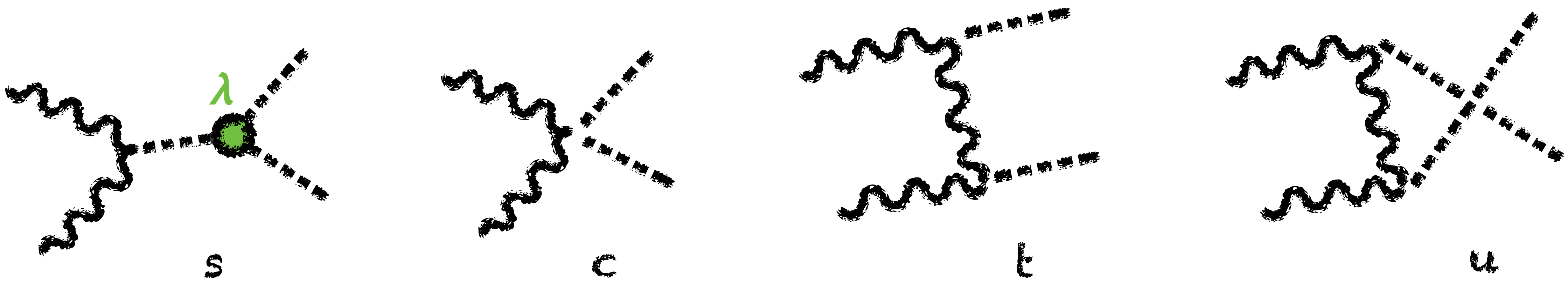
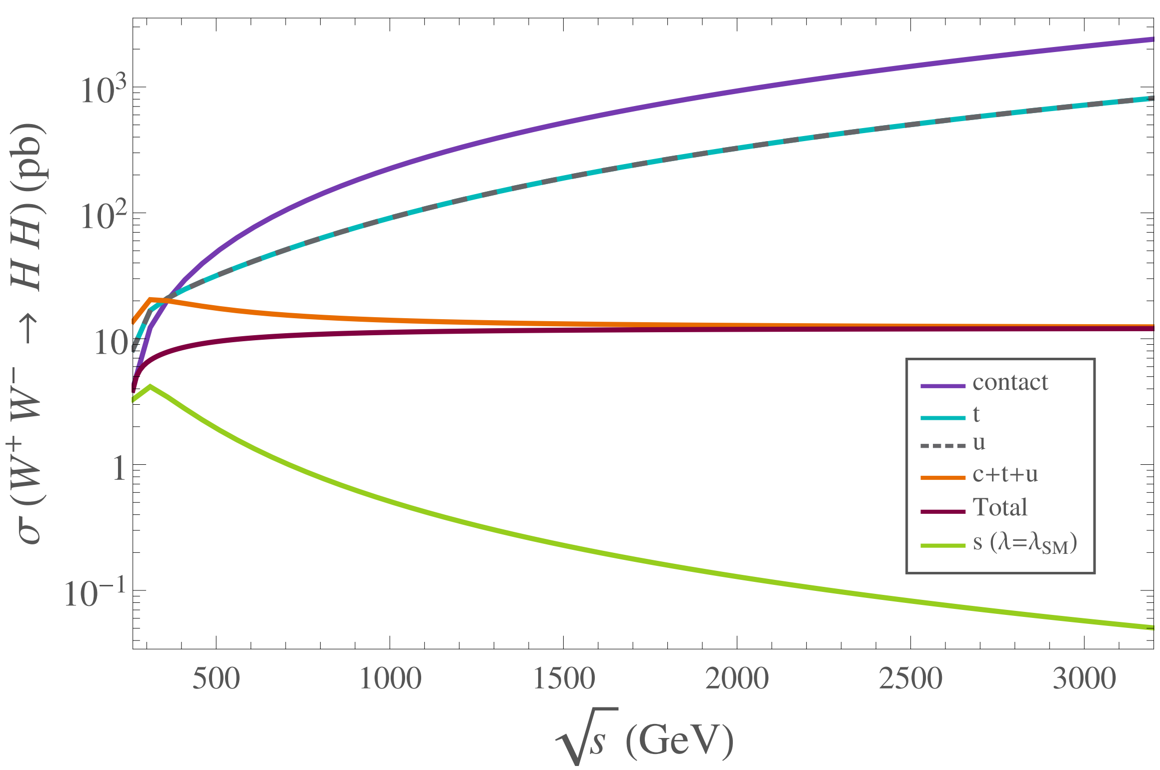
Back up slides

Learning from SM subprocess VV→HH

Diagrams that contribute:



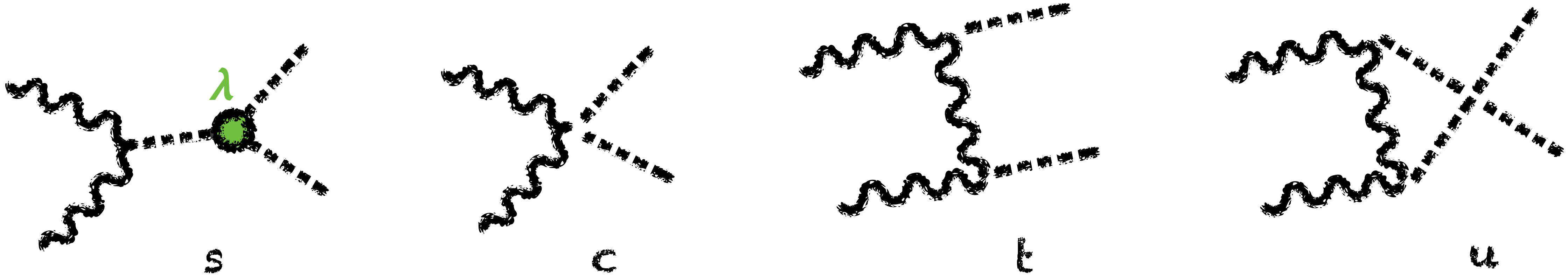
Reminder of main facts in the SM



- λ present only in s-channel
- Cross section dominated by $V_L V_L \to HH$
- 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 only relevant near HH threshold

Learning from SM subprocess VV→HH

Diagrams that contribute:



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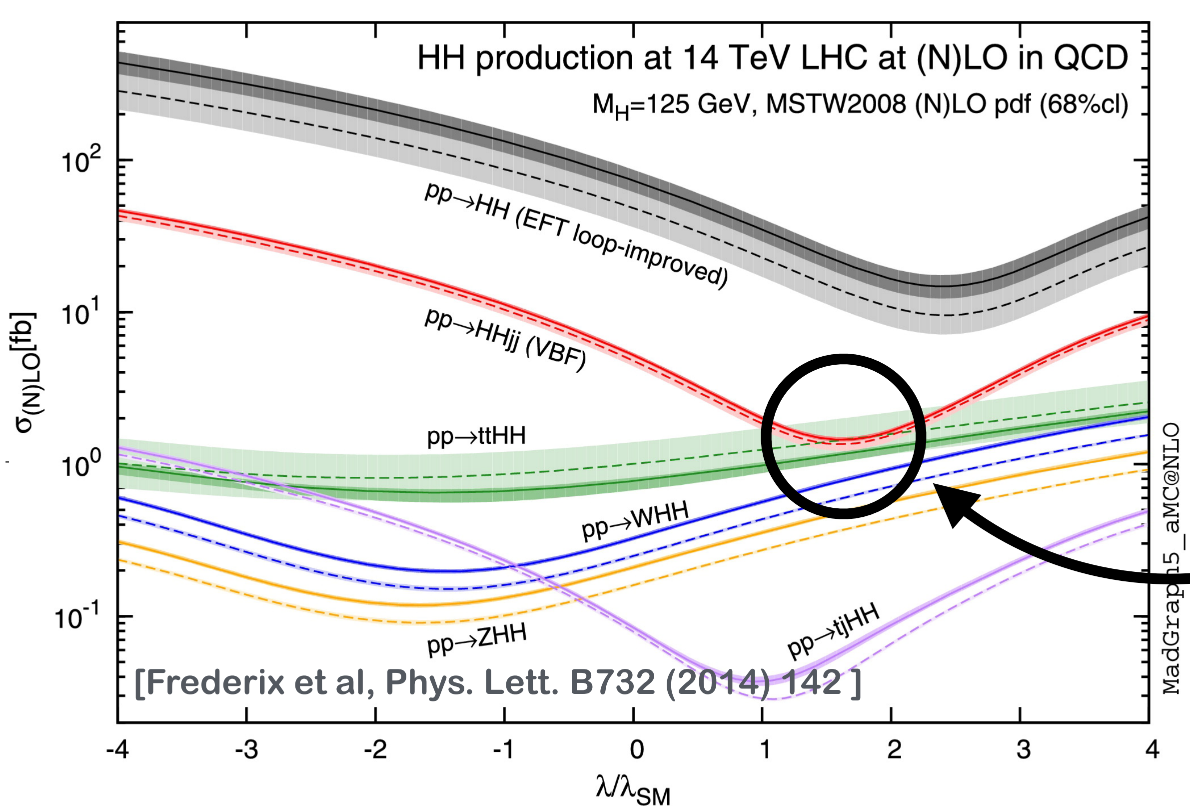

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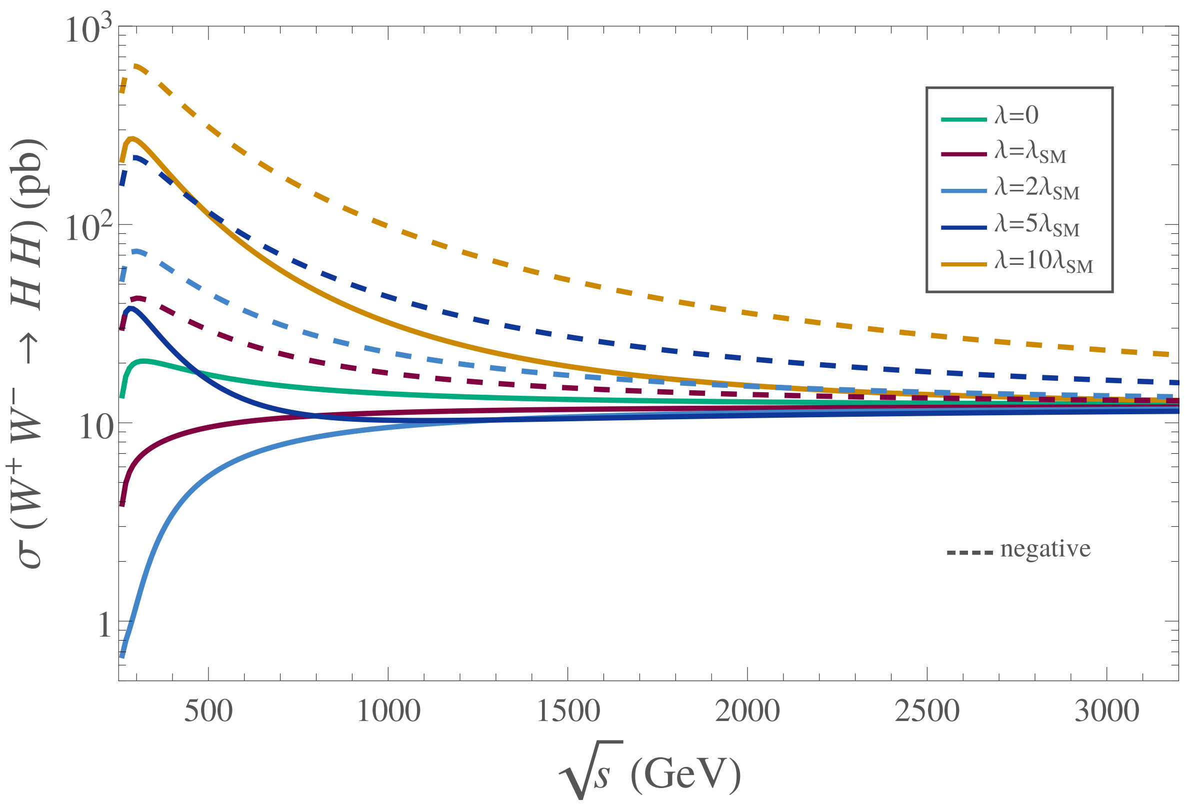
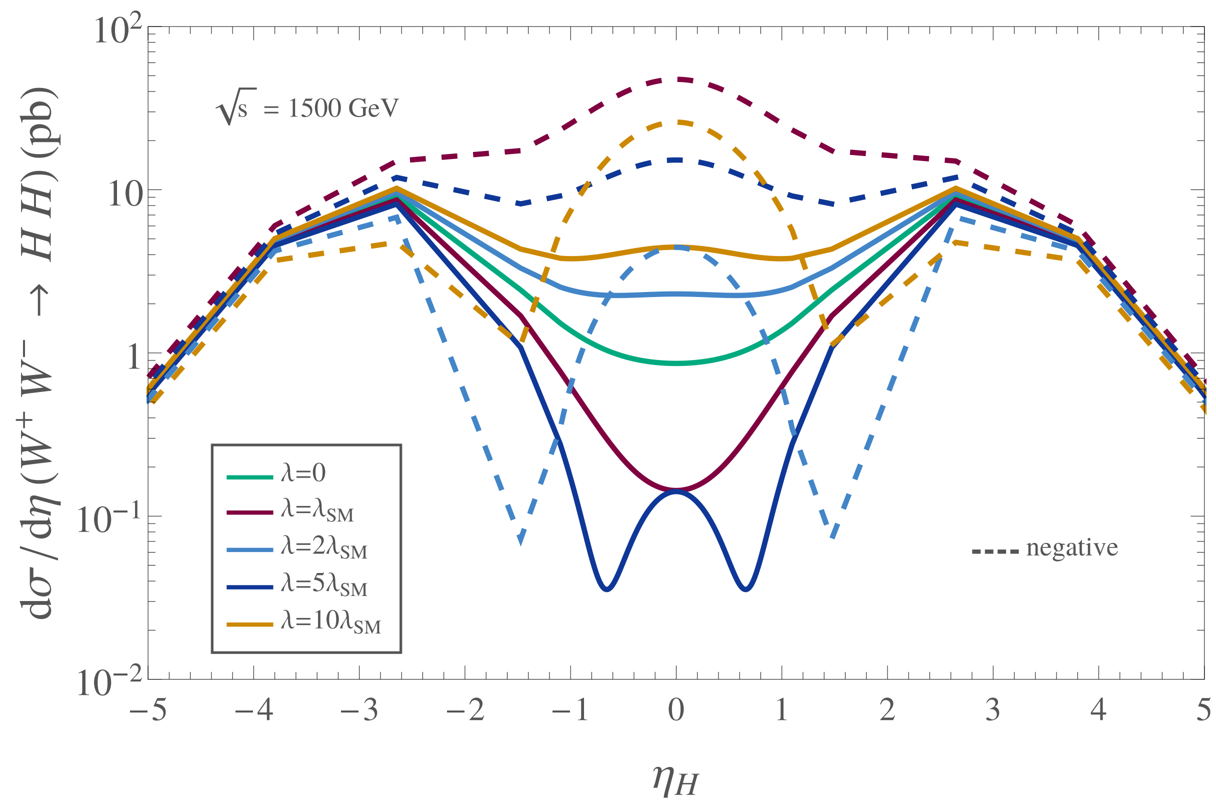
BSM distortions varying $\kappa = \lambda/\lambda_{SM}$

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

- Energy and angular behavior change when varying λ





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

- Largest deviations near HH production threshold

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

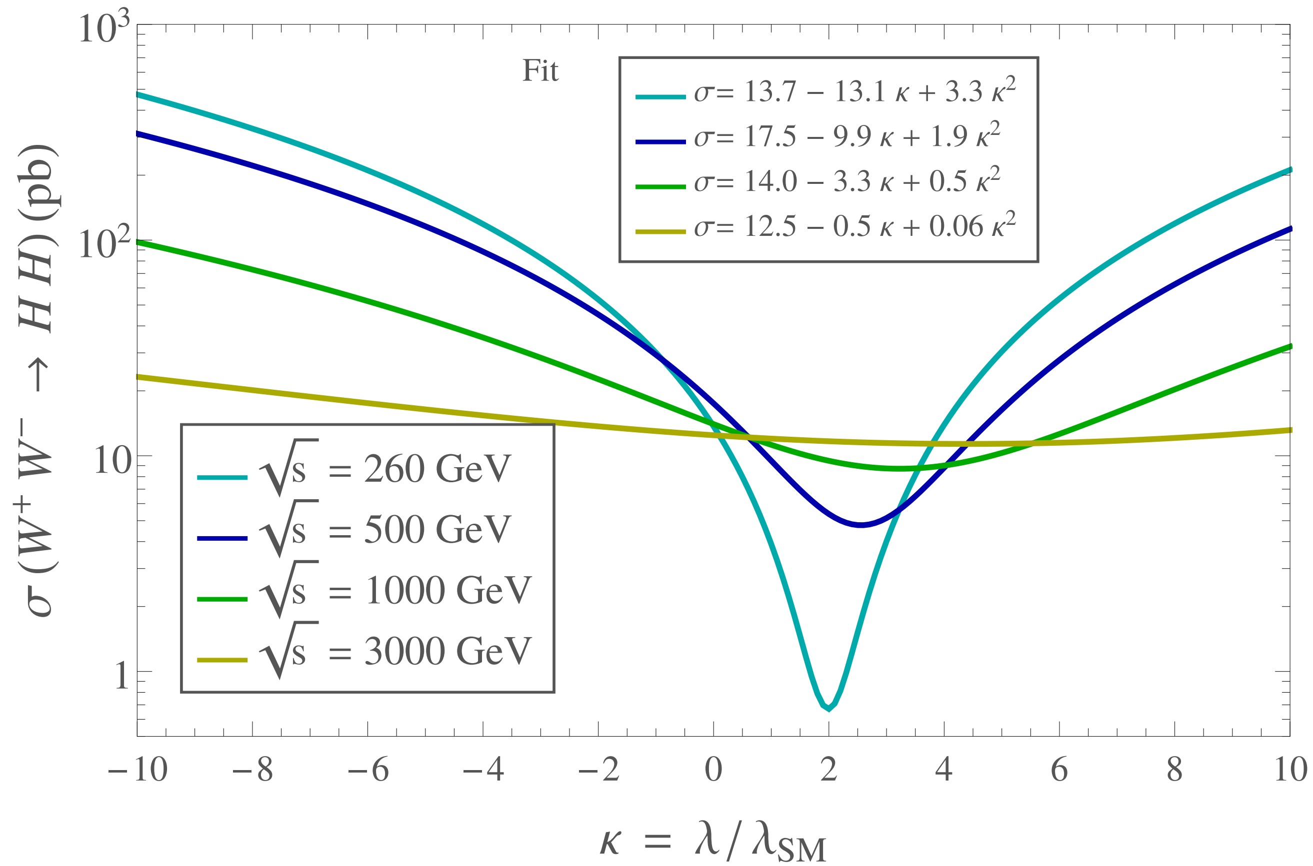
Interplay between diagrams

- $\lambda > 0$: 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

pp → HHjj characterization

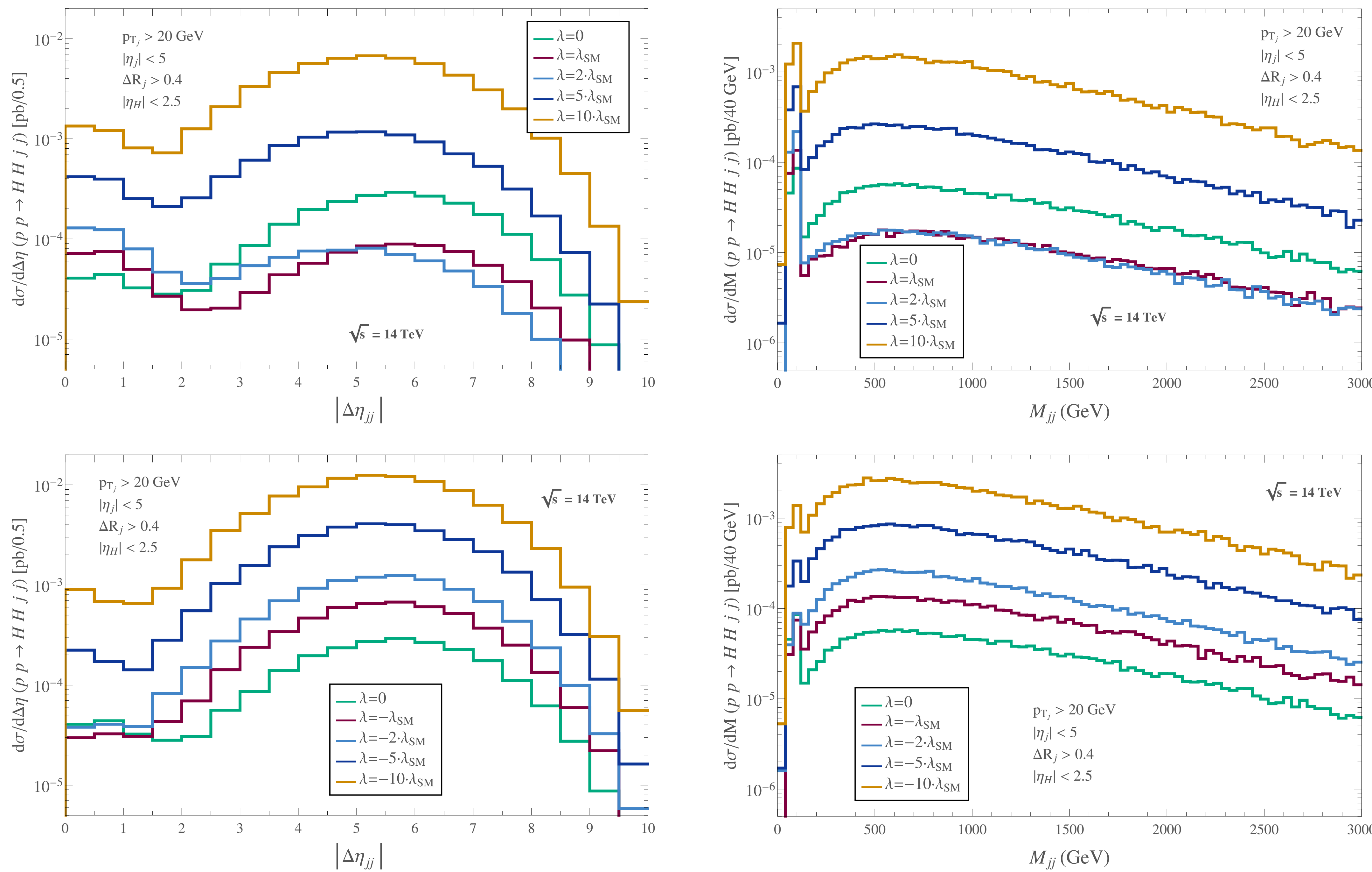
All our LHC estimates are computed using MadGraph5

How VBS-dominated is our signal?

- **VERY!!!** 55-75% of $q_1 q_2 \to HHq_3 q_4$ events occur through VBS

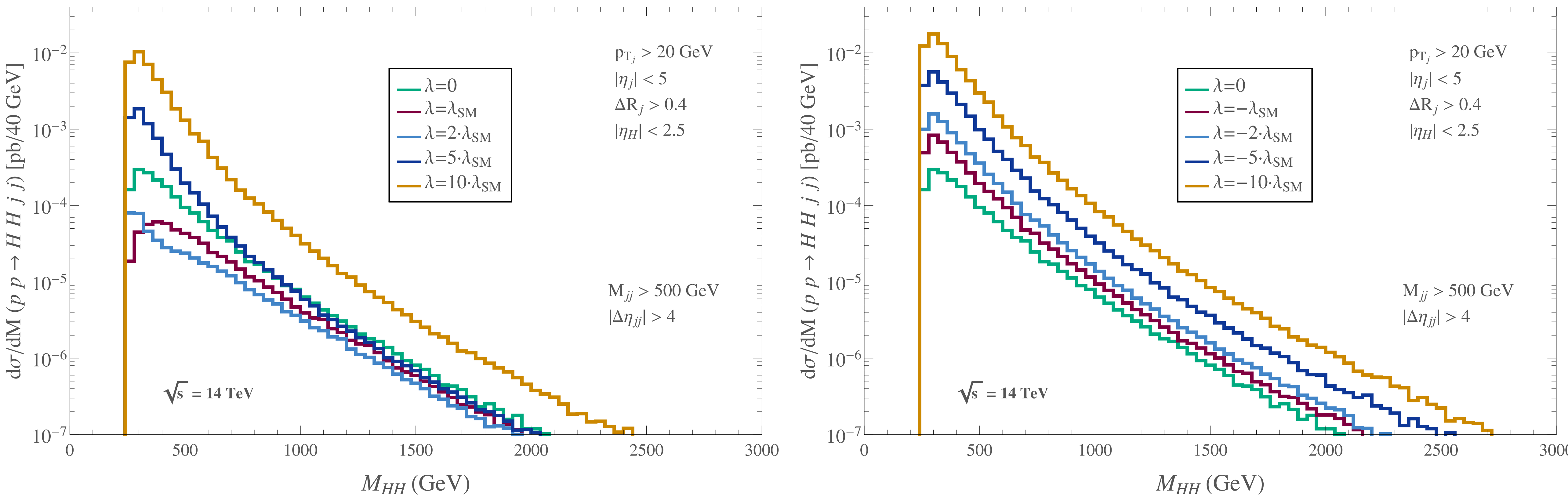
$\lambda \geq 0$

$\lambda \leq 0$



Varying κ at the LHC in pp → HHjj

- pp → HHjj VBS-dominated ⟶ direct translation form subprocess results
- **Visible deviations** respect to the SM!!!



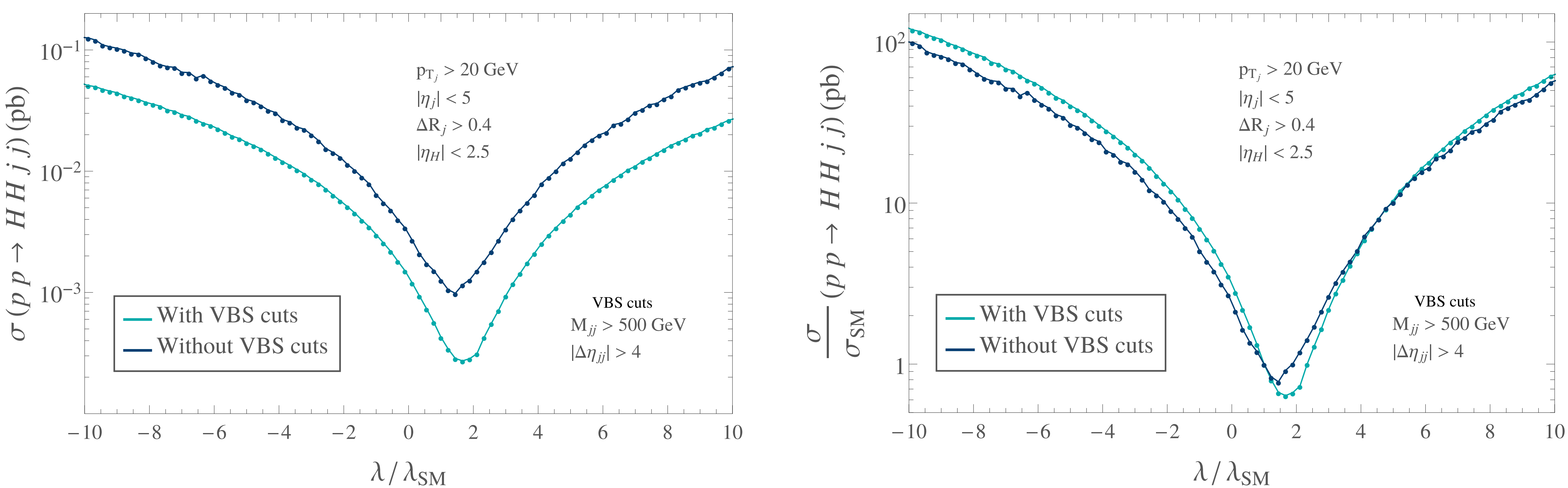
- Different sensitivity to $\lambda > 0$ and to $\lambda < 0$ remains

- Largest sensitivity still near HH production threshold

Sensitivity at the LHC vs subprocess

Does interference play the same role in pp → HHjj?

- Minimum appears in different place?
  - LHC cross section dominated by region close to HH threshold
  - Applying VBS cuts moves minimum
  - VBS selection improves sensitivity away from minimum



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	$\mathcal{A}_{\rm VBS}^{\rm QCD}$	$\mathcal{A}_{\rm VBS}^{\rm Signal;\kappa=1}$
$\lvert\Delta\eta_{jj}\rvert > 4,\ M_{jj} > 500$ GeV	0.086	0.631
$\lvert\Delta\eta_{jj}\rvert > 4,\ M_{jj} > 600$ GeV	0.066	0.597
$\lvert\Delta\eta_{jj}\rvert > 4,\ M_{jj} > 700$ GeV	0.054	0.558
$\lvert\Delta\eta_{jj}\rvert > 3,\ M_{jj} > 500$ GeV	0.098	0.669
$\lvert\Delta\eta_{jj}\rvert > 3,\ M_{jj} > 600$ GeV	0.071	0.626
$\lvert\Delta\eta_{jj}\rvert > 3,\ M_{jj} > 700$ 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 ; $|\eta_j| < 5$; $|\eta_b| < 2.5$; $\Delta R_{jj,jb} > 0.4$; $\Delta R_{bb} > 0.2$

Efficiency of the selection cuts

Combined HH candidate and VBS cuts

- **Signal mildly reduced**

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

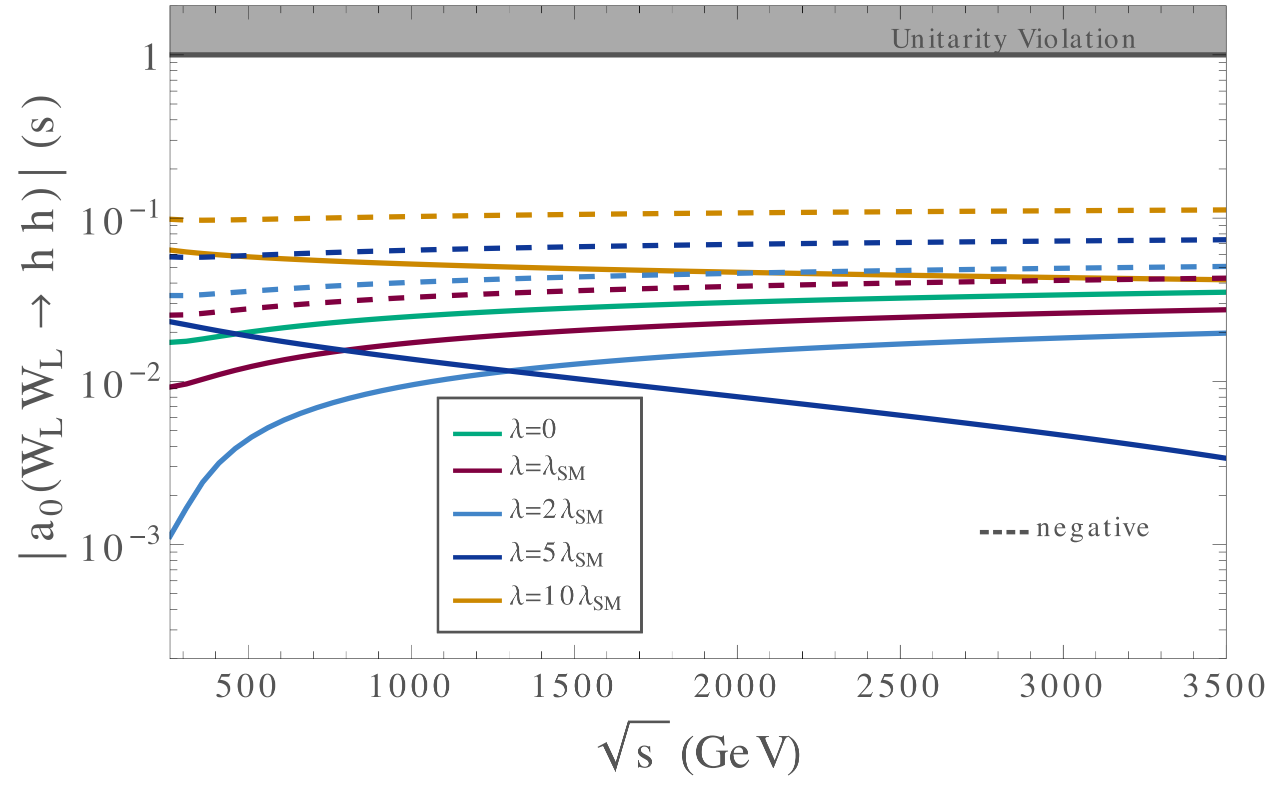
- **Very reduced backgrounds!!!**

(No) Unitarity violation problems

- Definition of unitarity violation: absolute value of J[th] (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 $\lambda \in [-10,10]\ \lambda_{SM}$ are below 0.1
- No unitarity violation in this channel

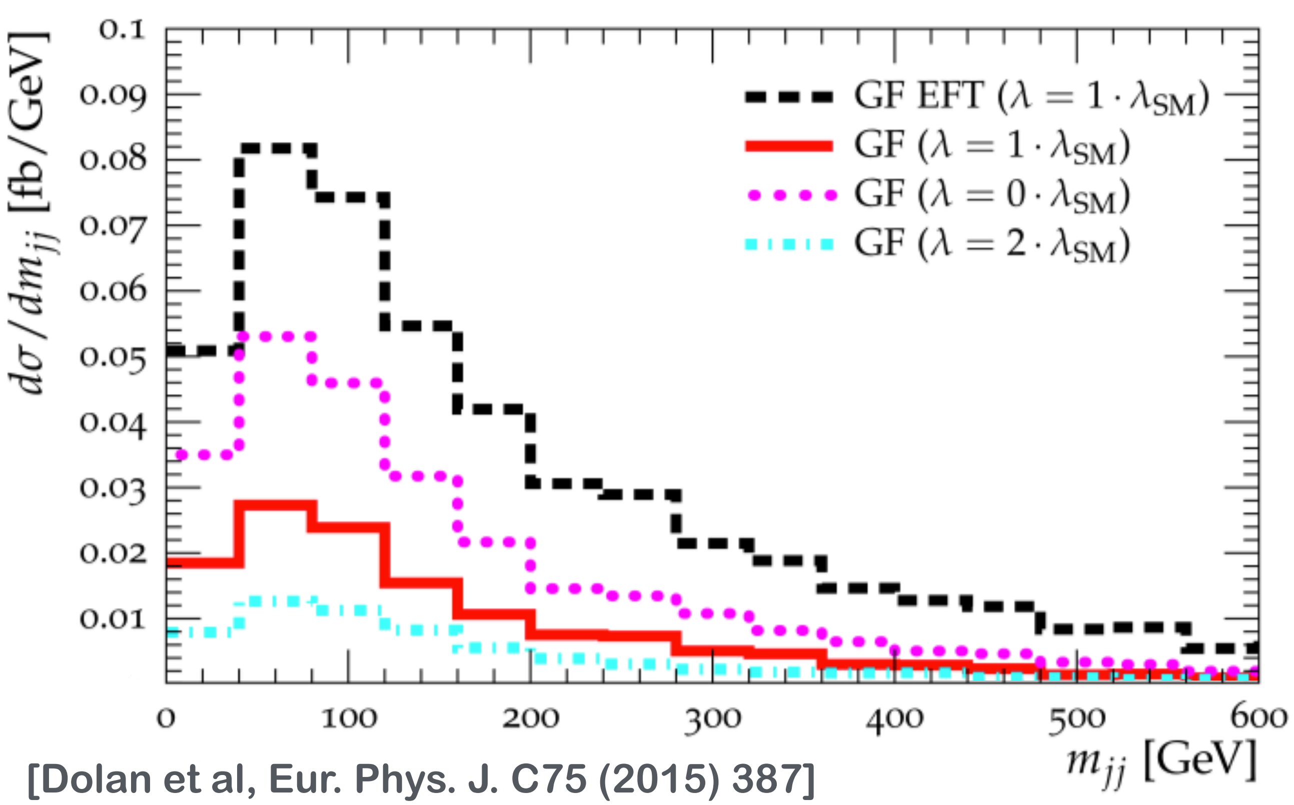


- Other channels such as HH HH might violate unitarity for κ ~7 values at low energies

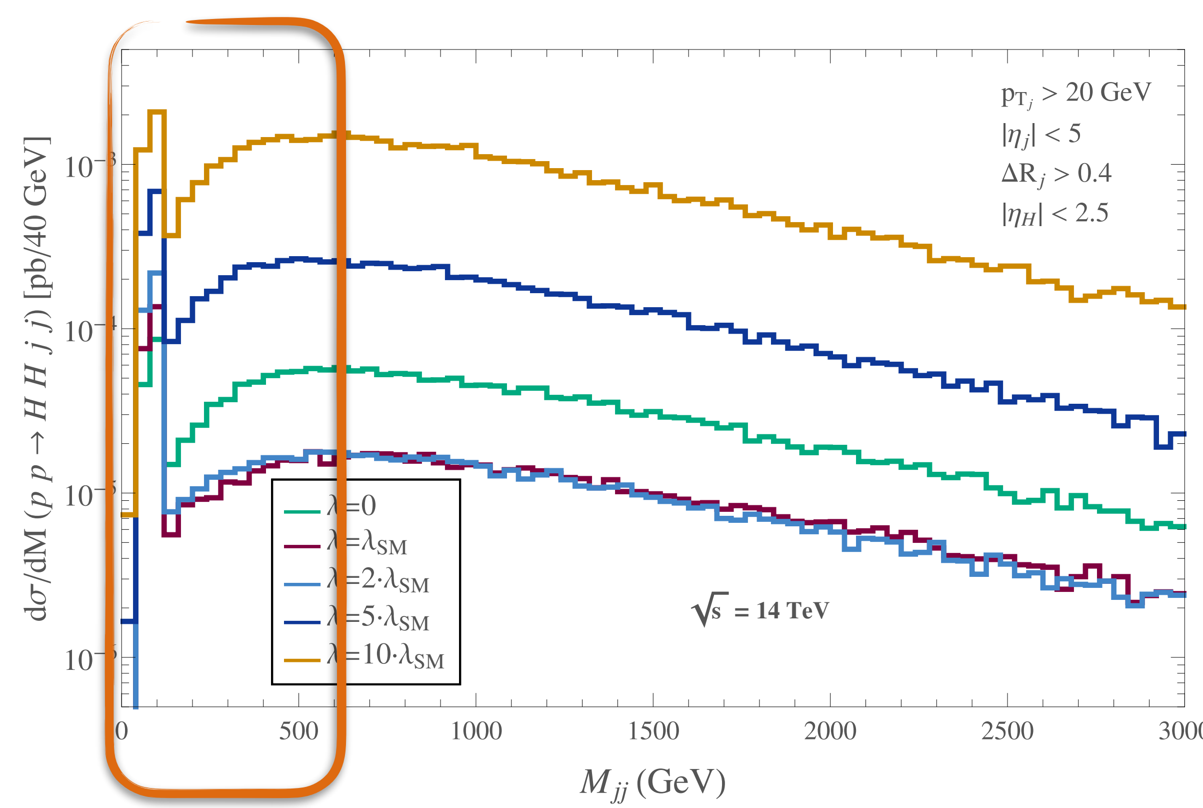
[Di Luzio et al, Eur.Phys.J. C77 (2017) no.11, 788]

"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**
- **More sophisticated VBS cuts, such as our M_{jj}, will improve this rate favoring 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 $L = 3000\ fb^{-1}$ with and without efficiencies

	$\kappa > 0$	$\kappa > 0$ (eff)	$\kappa < 0$	$\kappa < 0$ (eff)
bbbbjj	$\kappa > 3.2$ (3.7)	$\kappa > 3.8$ (8.7)	$\kappa < 0$ (-0.2)	$\kappa < -0.6$ (-1.0)
bbγγjj	$\kappa > 3.8$ (4.7)	$\kappa > 4.7$ (5.4)	$\kappa < -0.2$ (-1.0)	$\kappa < -0.9$ (-2.3)

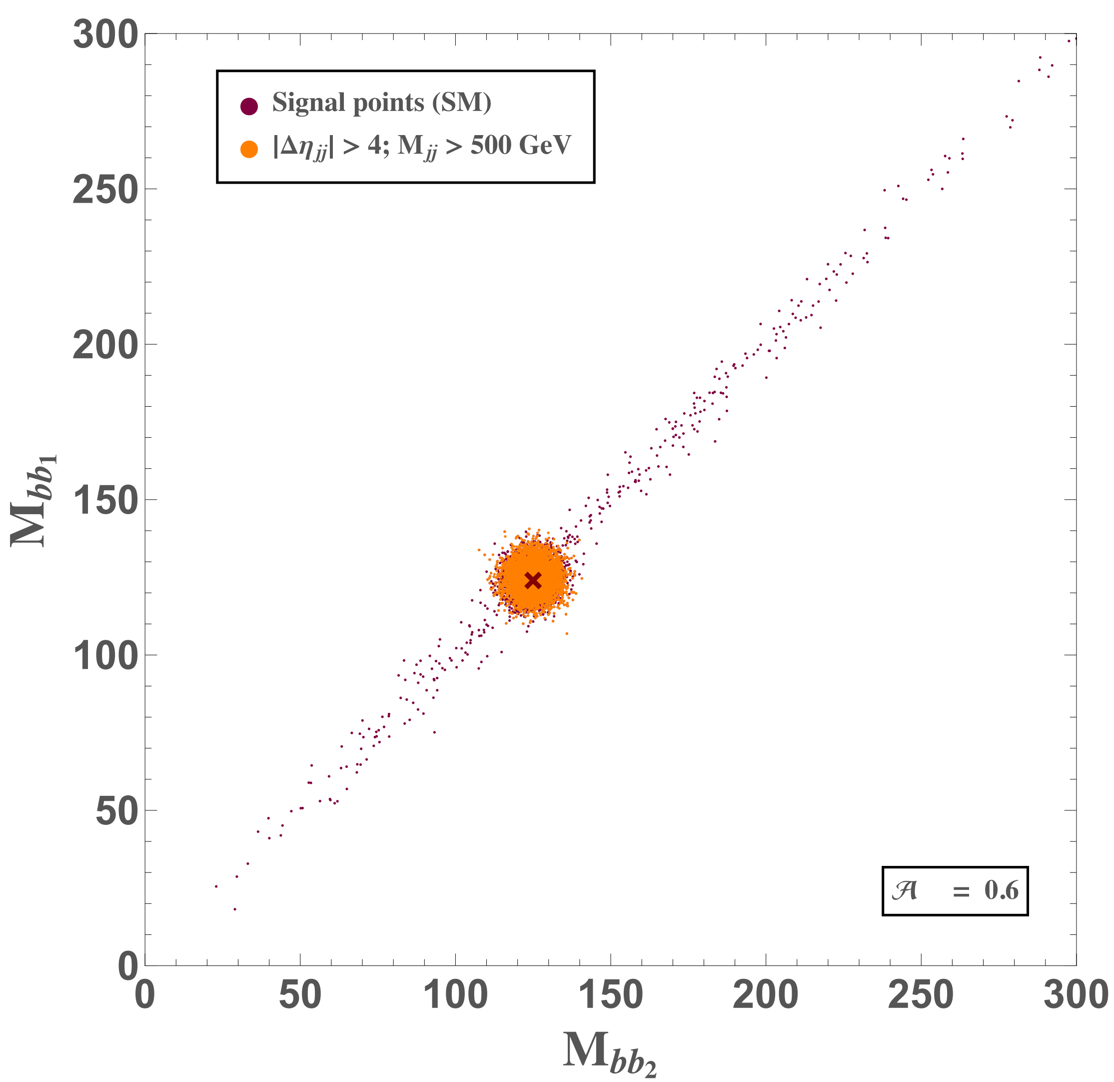
- These efficiencies might improve! Easy way to apply the new ones!

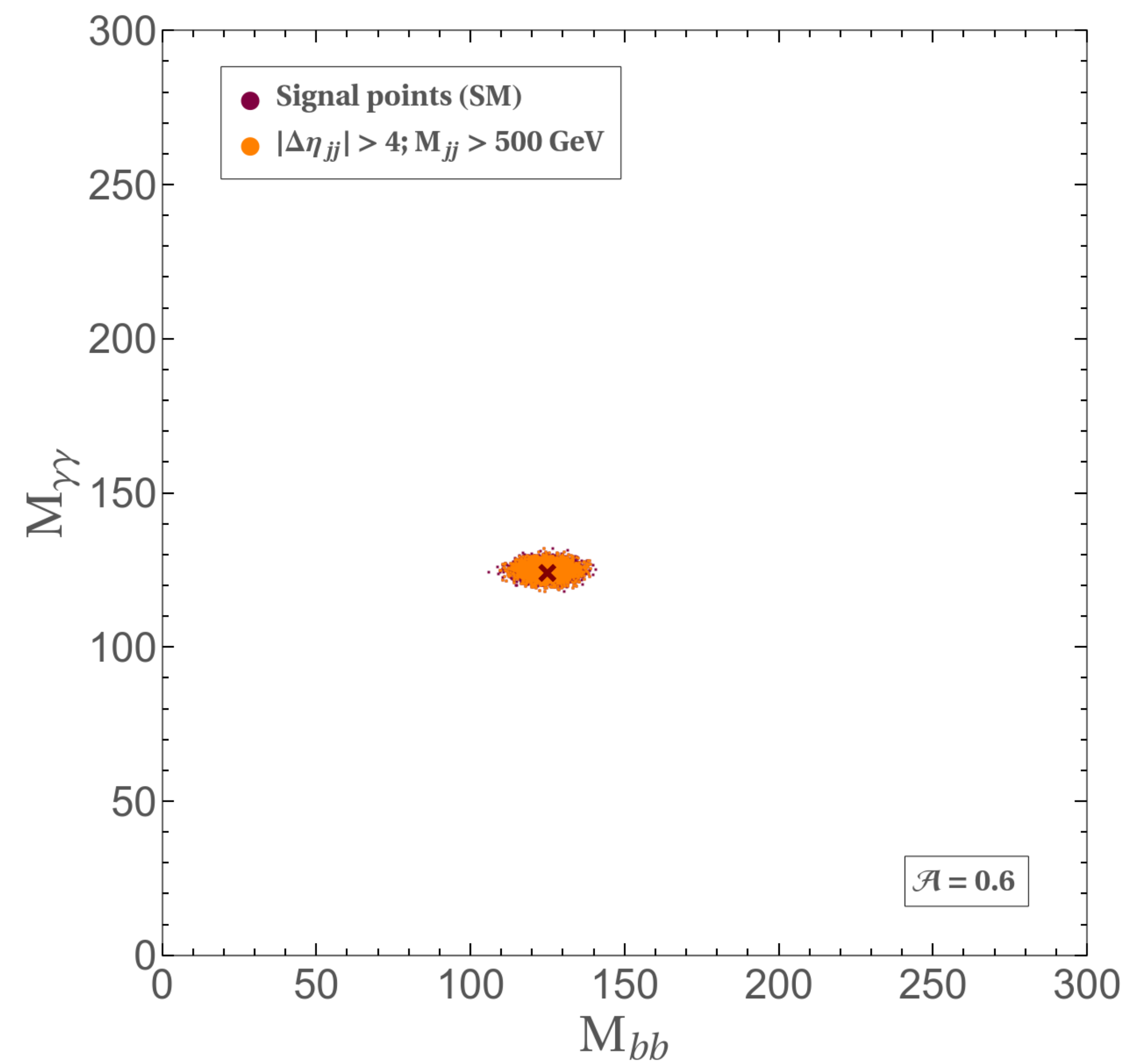
Detector effects

- We simulate detector effects applying a gaussian smearing to all final state particle energies

$$E' = E + 1/\sqrt{2\pi\sigma} \cdot e^{-x^2/(2\sigma^2)} \qquad \sigma = 0.05 \cdot E_{j,b}$$

- This changes the distribution of events in the relevant variables and thus the cut efficiencies



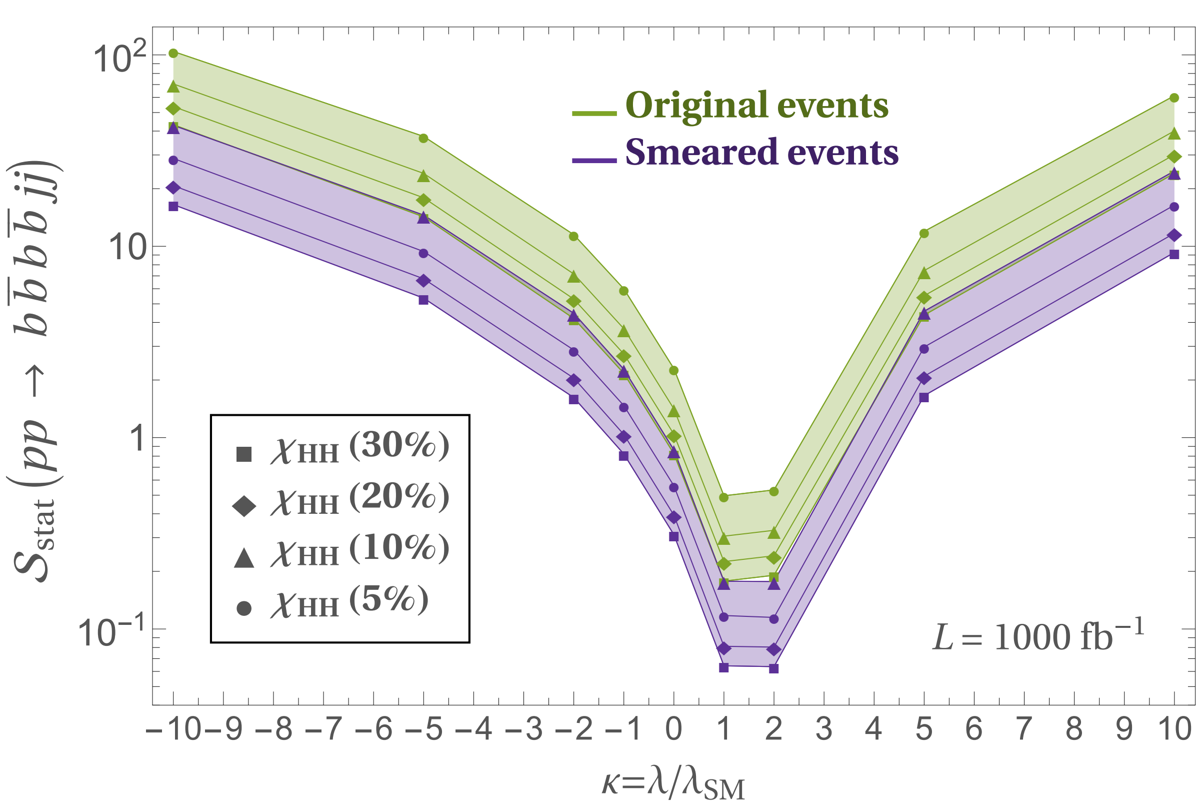


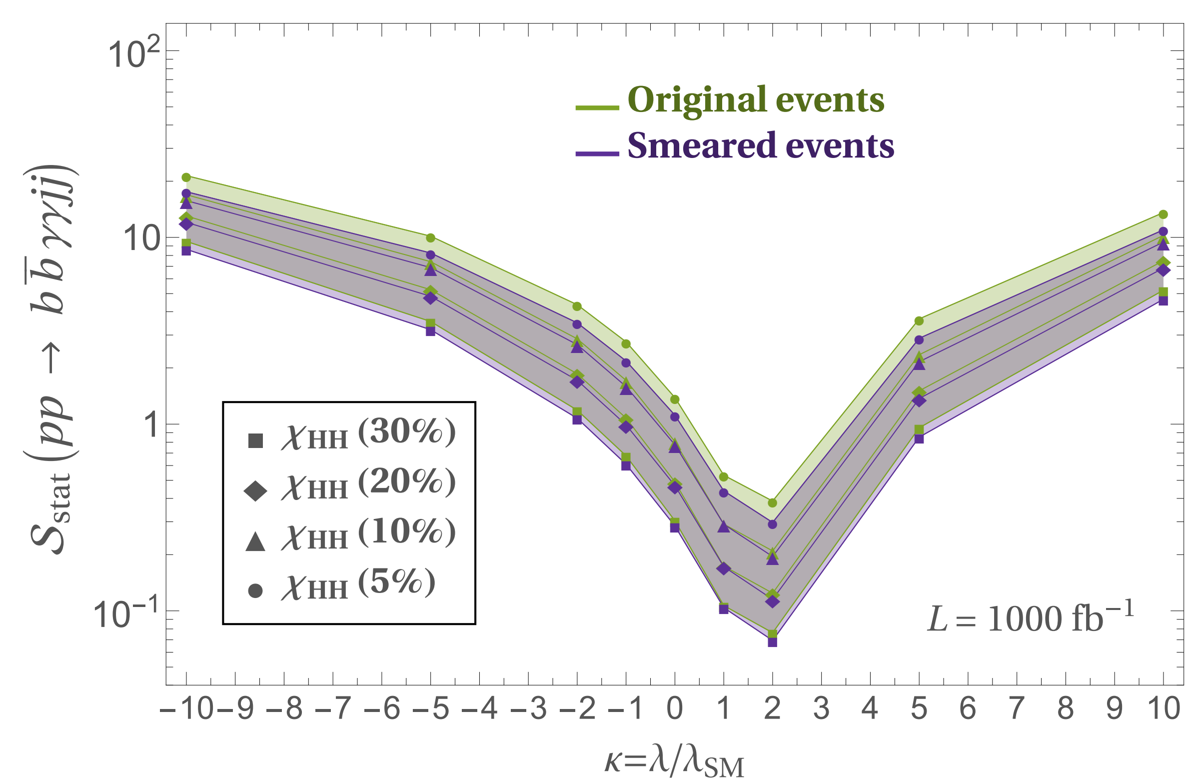
Higgs mass reconstruction & detector effects

- We study different Higgs mass reconstruction efficiencies

$$\chi_{HH} \equiv \sqrt{\left(\frac{M_{bb^l} - m_H}{\Delta_E\, m_H}\right)^2 + \left(\frac{M_{bb^s} - m_H}{\Delta_E\, m_H}\right)^2} < 1; \quad \Delta_E = (0.05, 0.1, 0.2, 0.3)$$

- Also including detector effect through gaussian smearing





- In original events: factor 0.4 reduction from ΔE = 0.05 to ΔE = 0.3
- From upper green to upper purple: factor 0.4 reduction as well