WW scattering at colliders: a window to new Higgs Physics

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Various BSM Higgs studies via WW scattering (=WBF)

Access to λ_{HHH}, V_{HWW}, V_{HHWW} in HH at e+e-

Access to λ_{HHH} and λ_{HHHH} in HHH at e+e-

2011.13195, EPJC 81 (2021)3, 260, González-López, Herrero, Martínez-Suárez

Access to λ_{HHH} in HH at LHC

1807.09736, Nucl.Phys.B 945 (2019) 114687, Arganda, García-García, Herrero

FIRST proposal, predictions and HL-LHC prospects for κ_λ via WBF were done in our work 3 years ago.
Other works focused only on GGF.

Recently, LHC collaborations testing this sensitivity to κ_λ via WBF and setting improved constraints.

Non-resonant

Studied in EFT

Access to λ_{hhh}, λ_{hhH}, λ_{hHH}, λ_{hAA} in h_ih_j at e+e-

2106.11105, EPJC 81 (2021)10, 913, Arco, Heinemeyer, Herrero

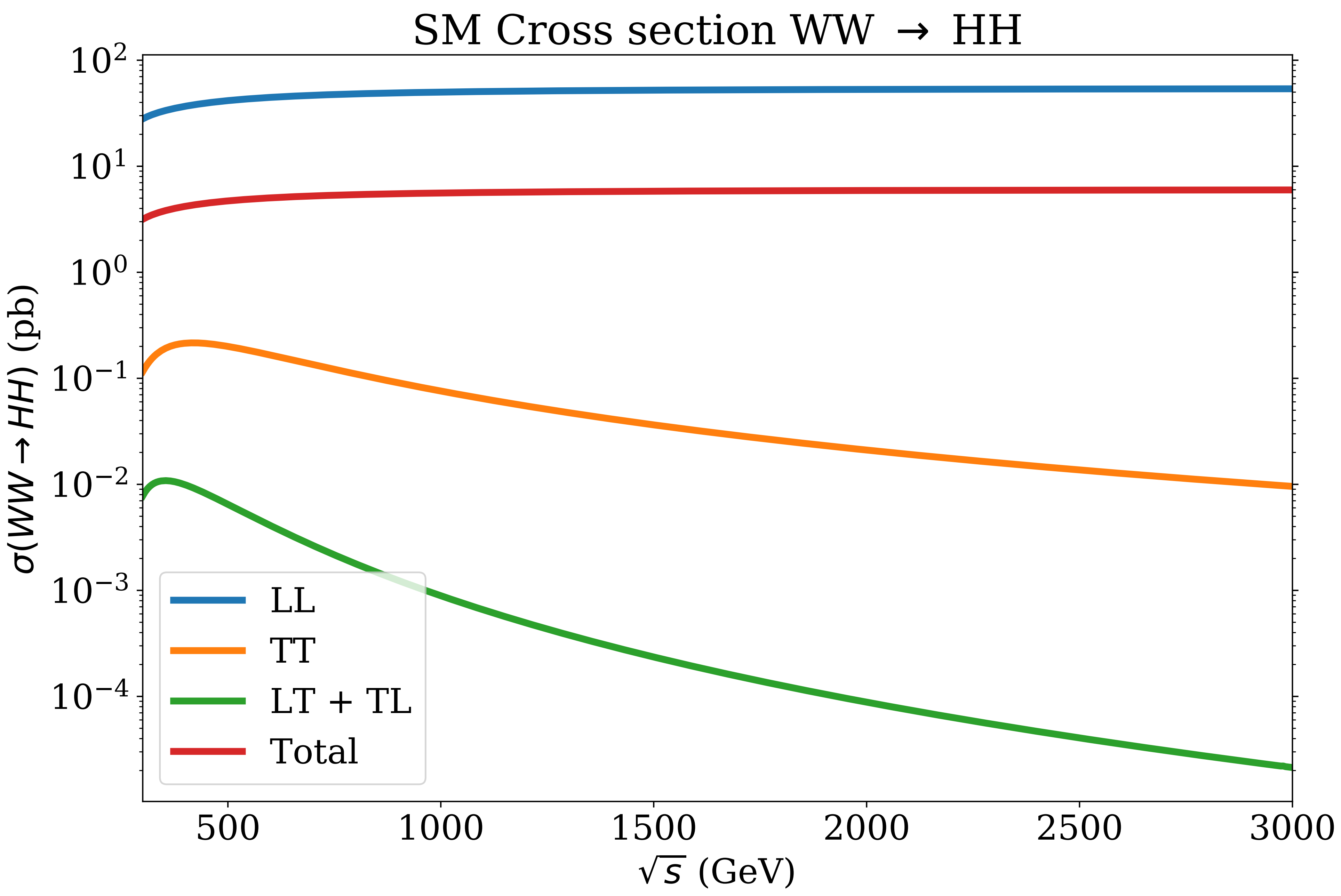
Heavy H in 2HDM is resonant in WW → hh : efficient window to λ_{hhH}

Resonant

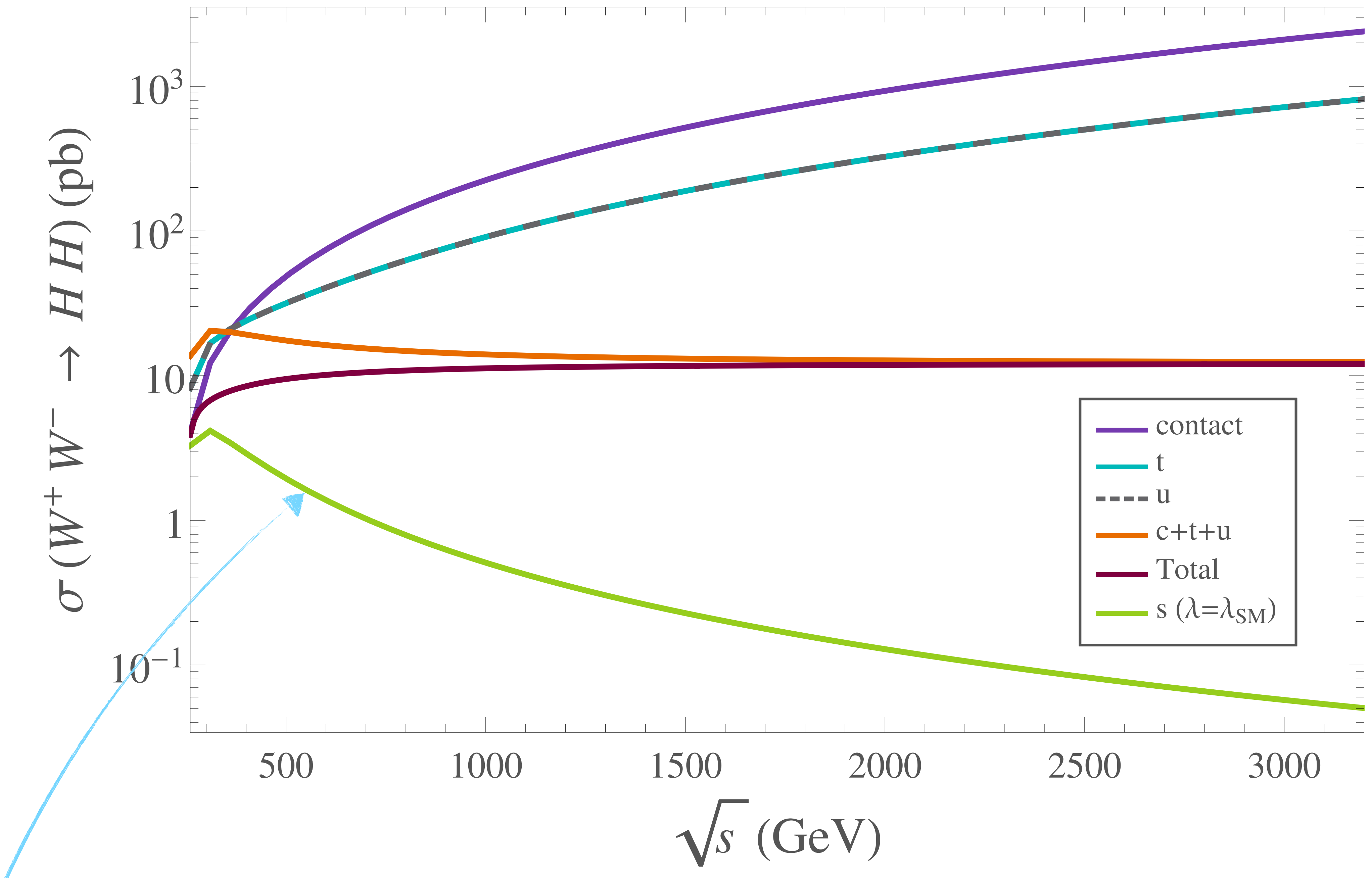
Studied In 2HDM

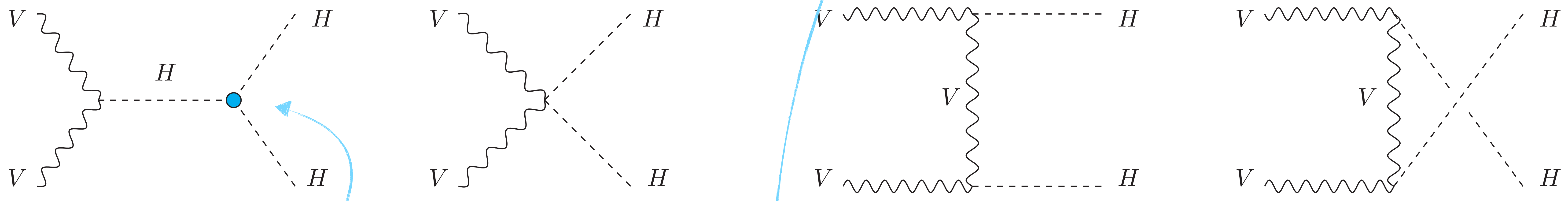
Also recent work ongoing with Roberto Morales, Daniel Domenech, Maria Ramos: NLO EFT in WW scattering: HEFT and SMEFT

WW $\longrightarrow$ HH in SM



Very subtle cancellations at TeV among channels





Equivalence Theorem: OK at TeV

$$|\mathbf{T}(\mathbf{W}_L^+\mathbf{W}_L^- \to \mathbf{HH})| \simeq |\mathbf{T}(\phi^+\phi^- \to \mathbf{HH})|$$

Clear LL dominance explaining the flat behavior with energy : LL >TT >LT+TL :

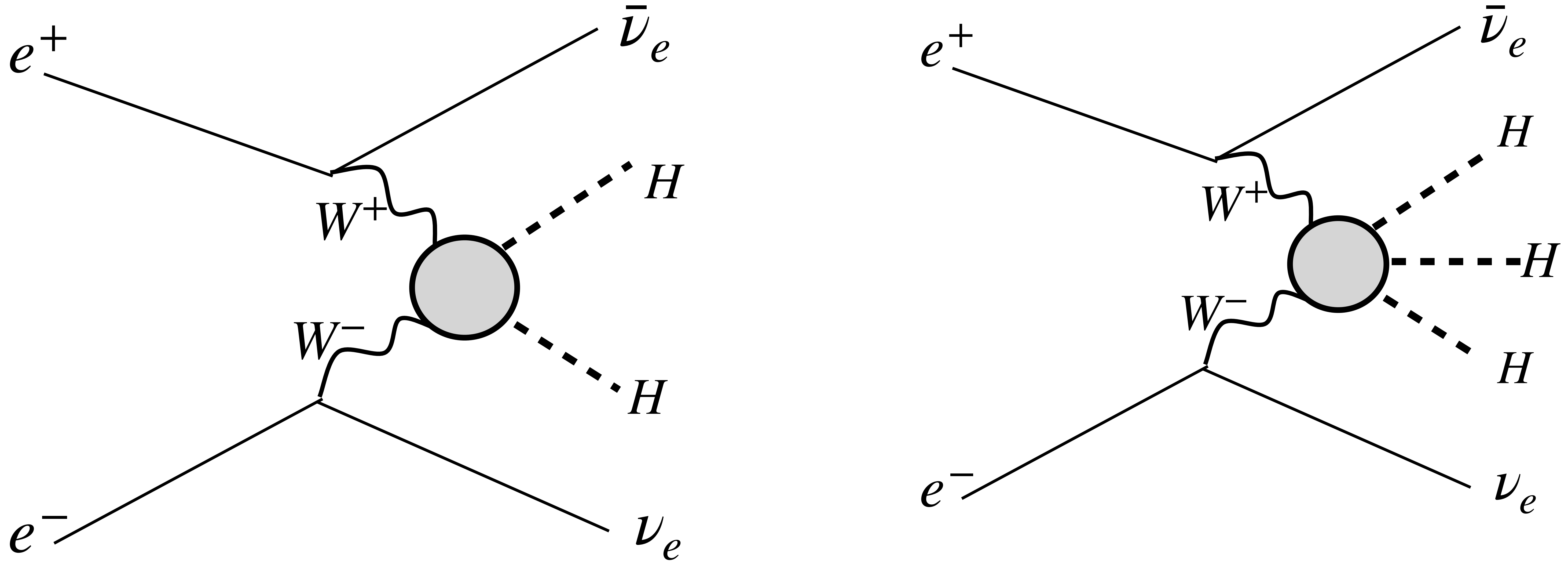
Sensitivity to λ_{HHH} only in s-channel: main effects manifest at the region close to HH threshold

HH and HHH production at colliders via VBS (=WBF)

2011.13195, EPJC 81 (2021)3, 260, González-López, Herrero, Martínez-Suárez

For e+e-: other HH and HHH production mechanisms suppressed at TeV respect to WW

e^+e^-colliders



Similar mechanism
At LHC with leptons
replaced by quarks

Finding correlation/uncorrelation between HHH and HHHH
is one of the Golden Tasks for future colliders (ee and LHC)

λ_{HHH} involved in WW ⟶ HH and in WW ⟶ HHH

λ_{HHHH} only involved in WW ⟶ HHH

Remember that within SM : $V_{HWW} = v\, V_{HHWW}$ and $V_{HHH} = v\, V_{HHHH}$ due to H in a doublet

Any deviation to these correlations may indicate physics BSM

BSM: WW ⟶ HH (and HHH) with LO-HEFT (chi-dim=2)

2011.13195, EPJC 81 (2021)3, 260, González-López, Herrero, Martínez-Suárez

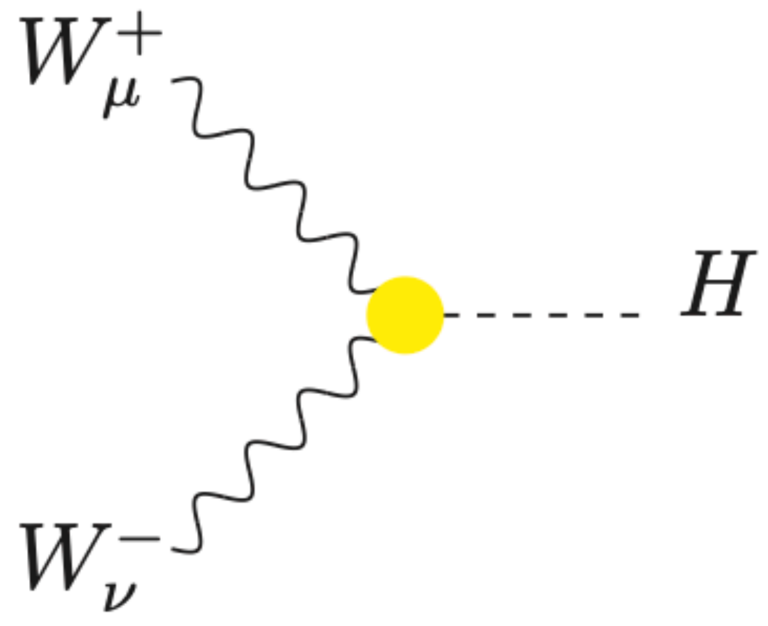
$$\mathscr{L}^{\rm LO}_{\rm EChL} = \frac{v^2}{4}\left[1 + 2\boxed{a}\left(\frac{H}{v}\right) + \boxed{b}\left(\frac{H}{v}\right)^2 + \dots\right] {\rm Tr}\left[D_\mu U^\dagger D^\mu U\right] - \boxed{\kappa_3}\lambda v H^3 - \frac{1}{4}\boxed{\kappa_4}\lambda H^4 + \dots..$$

SM: $\mathbf{a} = \mathbf{b} = \kappa_3 = \kappa_4 = 1$

Anomalous couplings: parametrize possible BSM effects to LO-HEFT

$U(\pi^a) = e^{i\pi^a\tau^a/v}$

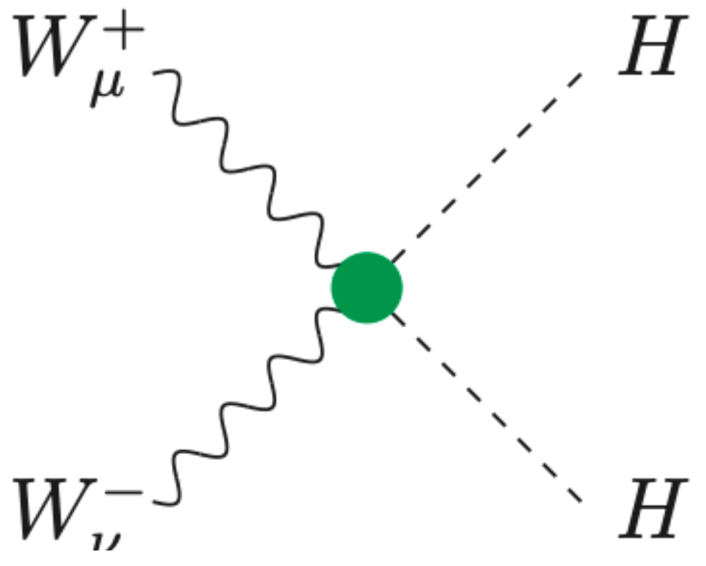
Non-Linear GBs



$a = \kappa_V$

$$V_{WWH} = iagm_W g_{\mu\nu}$$

$a^{\rm exp} \in [0.97, 1.13]^{[1]}$



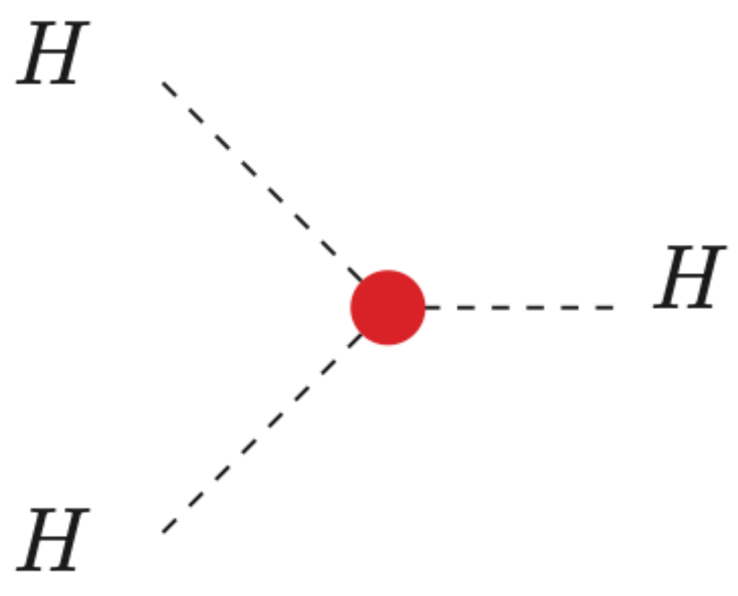
$b = \kappa_{2V}$

$$V_{WWHH} = \frac{ibg^2}{2} g_{\mu\nu}$$

$b^{\rm exp} \in [-0.76, 2.90]^{[2]}$

H

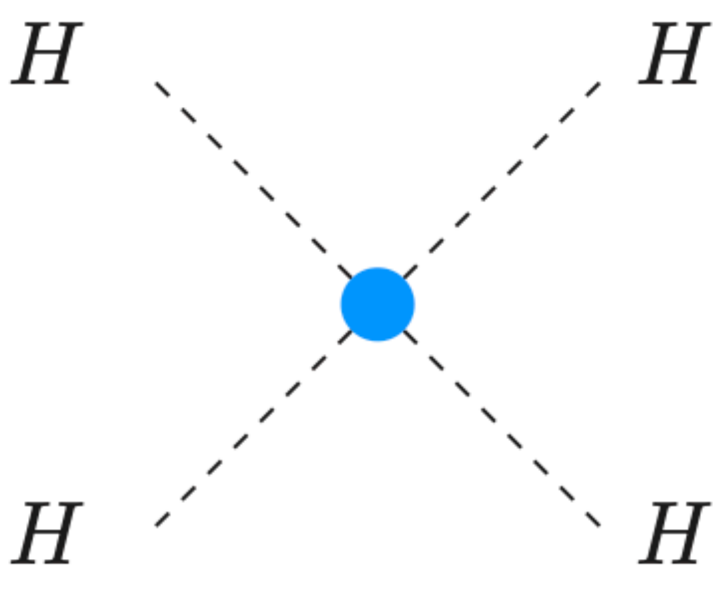
Higgs is singlet



$\kappa_3 = \kappa_\lambda$

$$V_{HHH} = -i\kappa_3 6\lambda v$$

$\kappa_3^{\rm exp} \in [-2.3, 10.3]^{[3]}$



$$V_{HHHH} = -i\kappa_4 6\lambda$$

$\kappa_4^{\rm exp}$ unconstrained

Uncorrelated coeffs.

a versus b

κ_3 versus κ_4

In contrast to SM and SMEFT
(where H is in a doublet)

[1a] ATLAS, Phys. Rev. D **101** (2020) [1909.02845]

[1b] ATLAS-CONF-2020-027. Best fit $\kappa_V = a = 1.03 \pm 0.03$

[2a] ATLAS, JHEP **07** (2020) [2001.05178]

[2b] CMS (2022) [2202.09617] $\kappa_{2V} = b \in [-0.1, 2.2]$
($bbbb$ events)

[3a] ATLAS-CONF-2019-049

[3b] CMS (2021) [2011.12373] $\kappa_\lambda = \kappa_3 \in [-3.3, 8.5]$
($bb\gamma\gamma$ events)

Behavior with energy (LO-HEFT)

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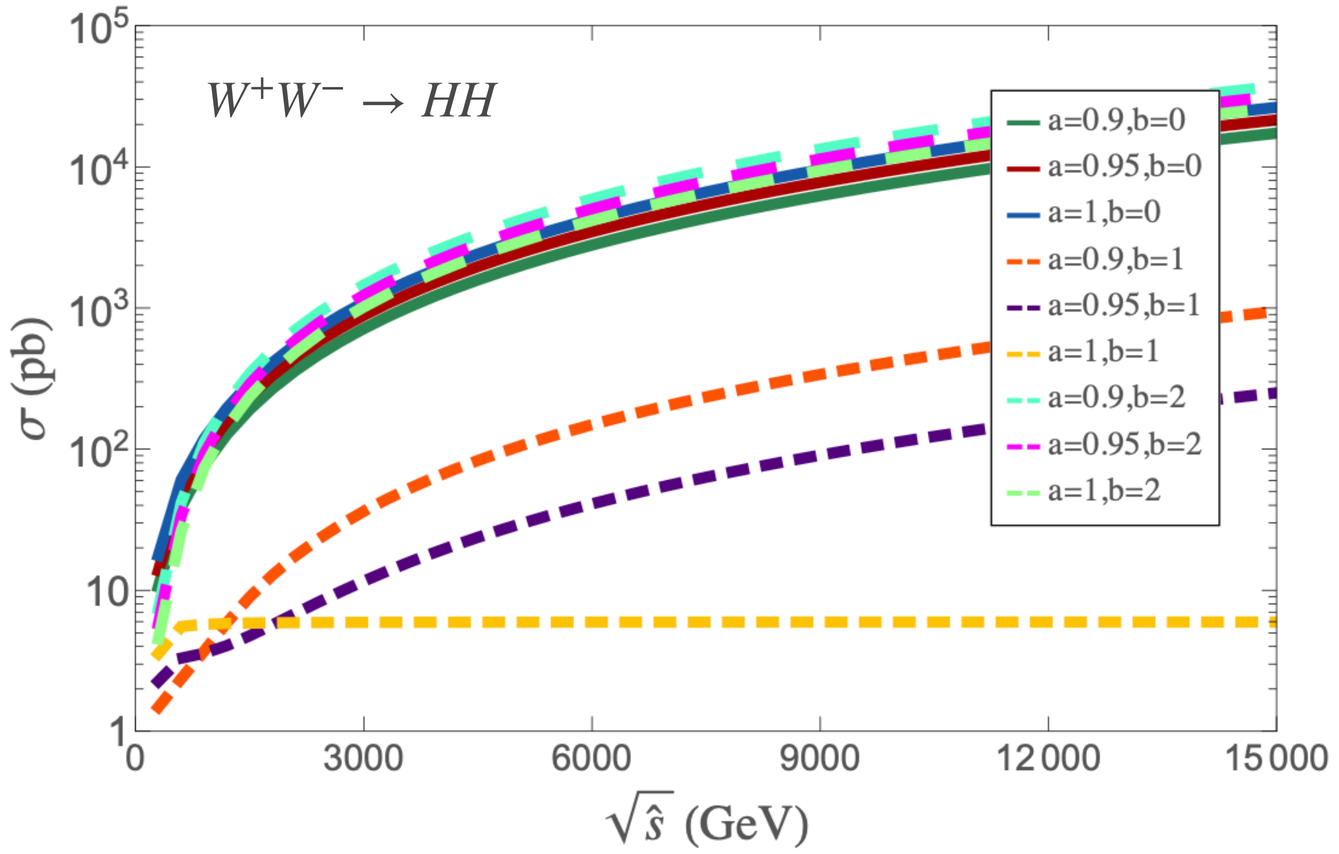
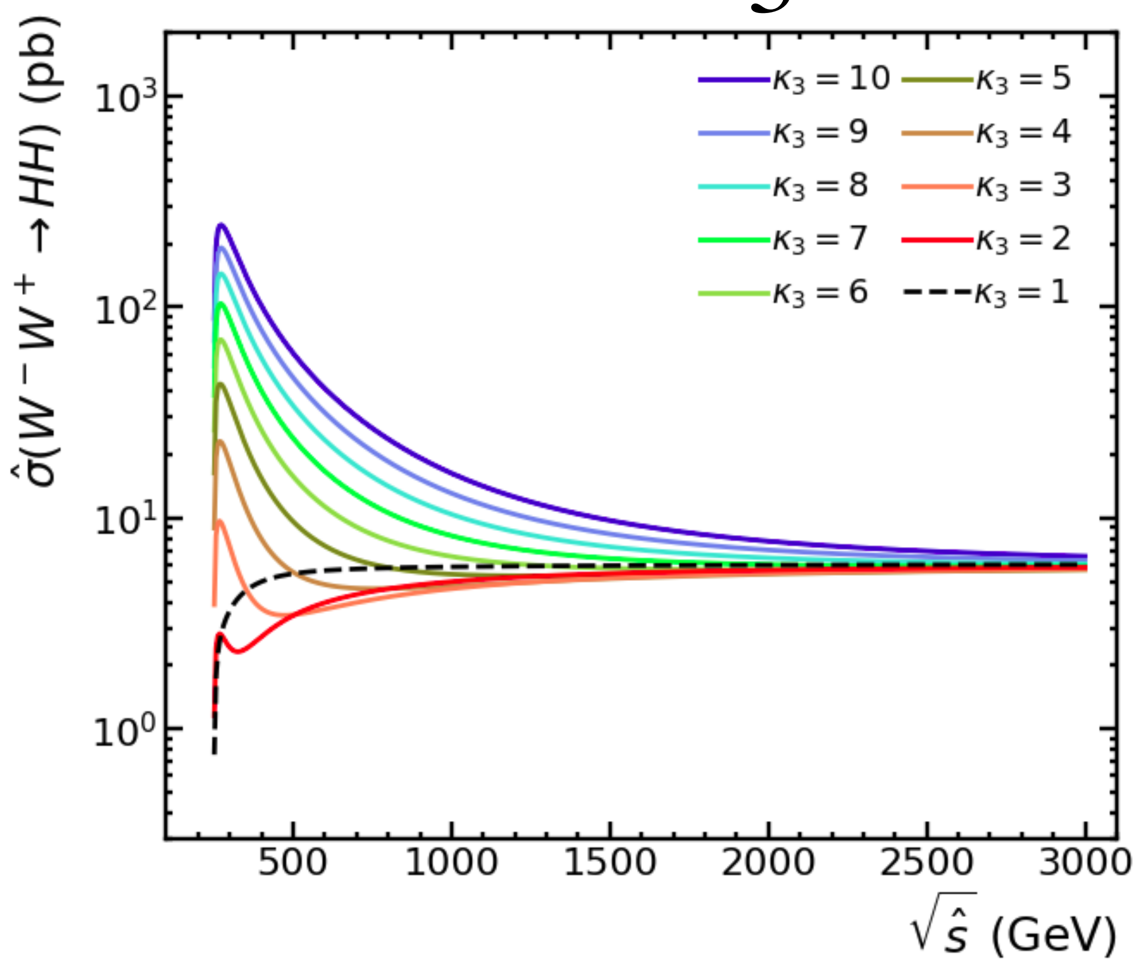
Subprocess level

$WW \to HH$

$b \neq a^2$

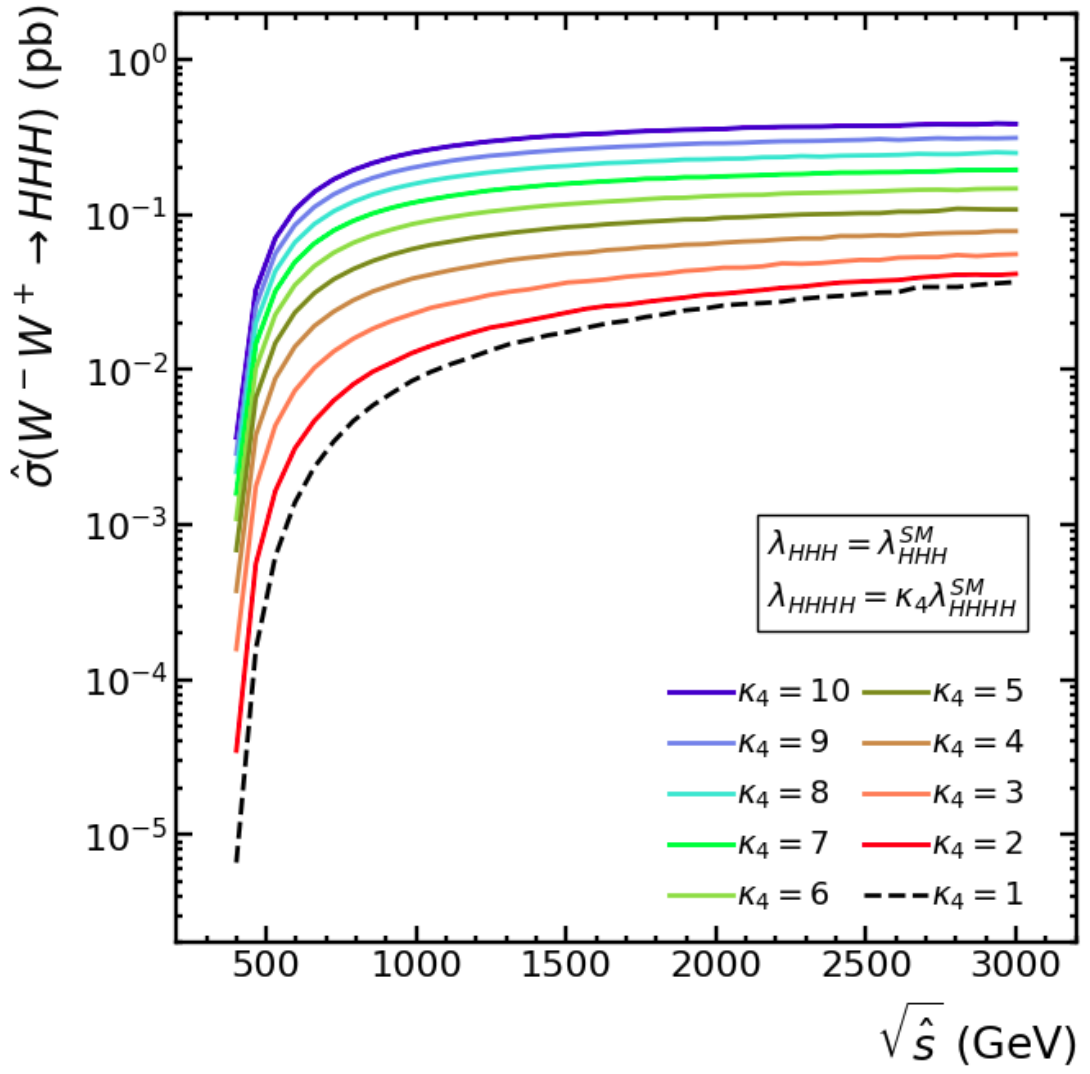


κ_3

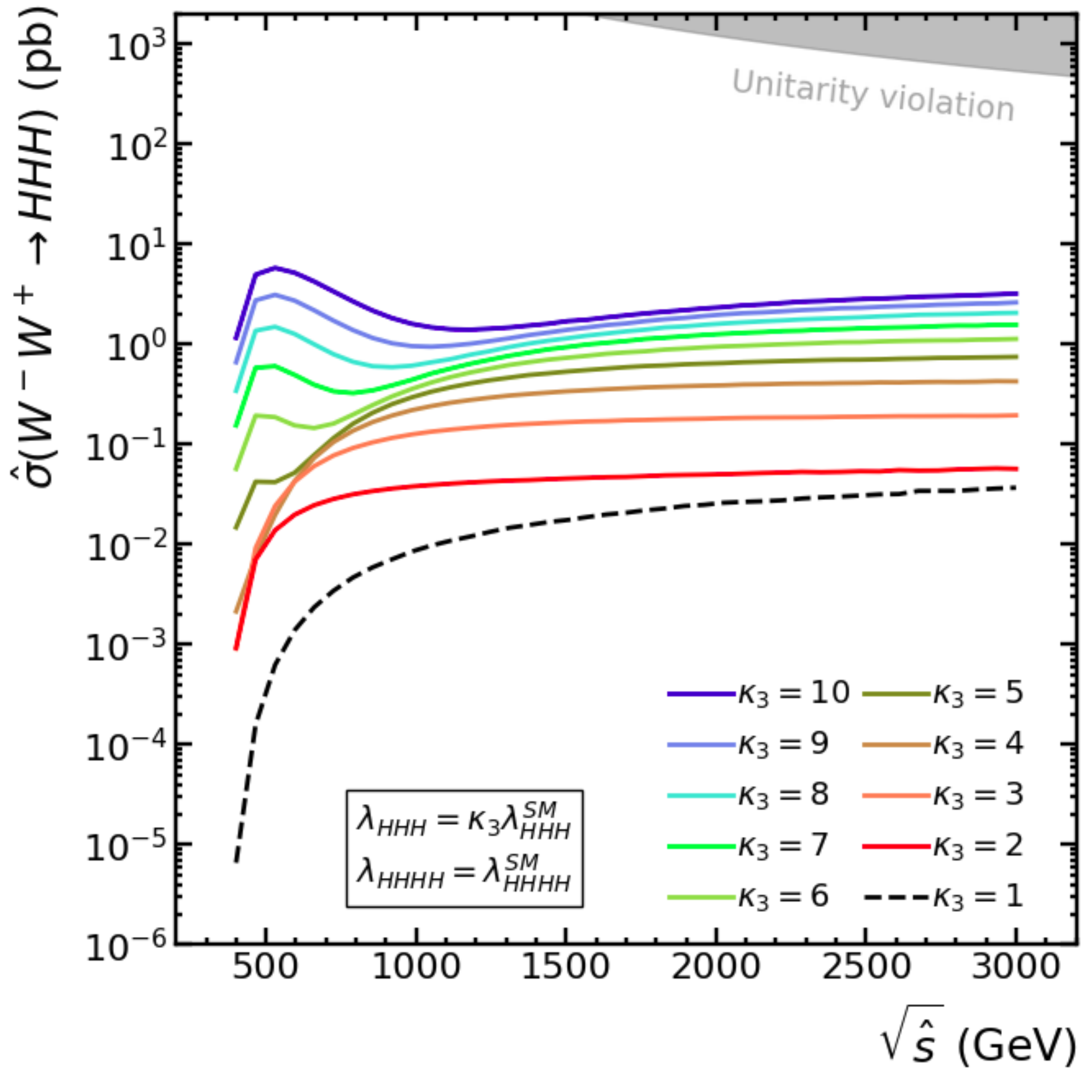


Largest deviations
respect to SM
in LL modes

$WW \to HHH$

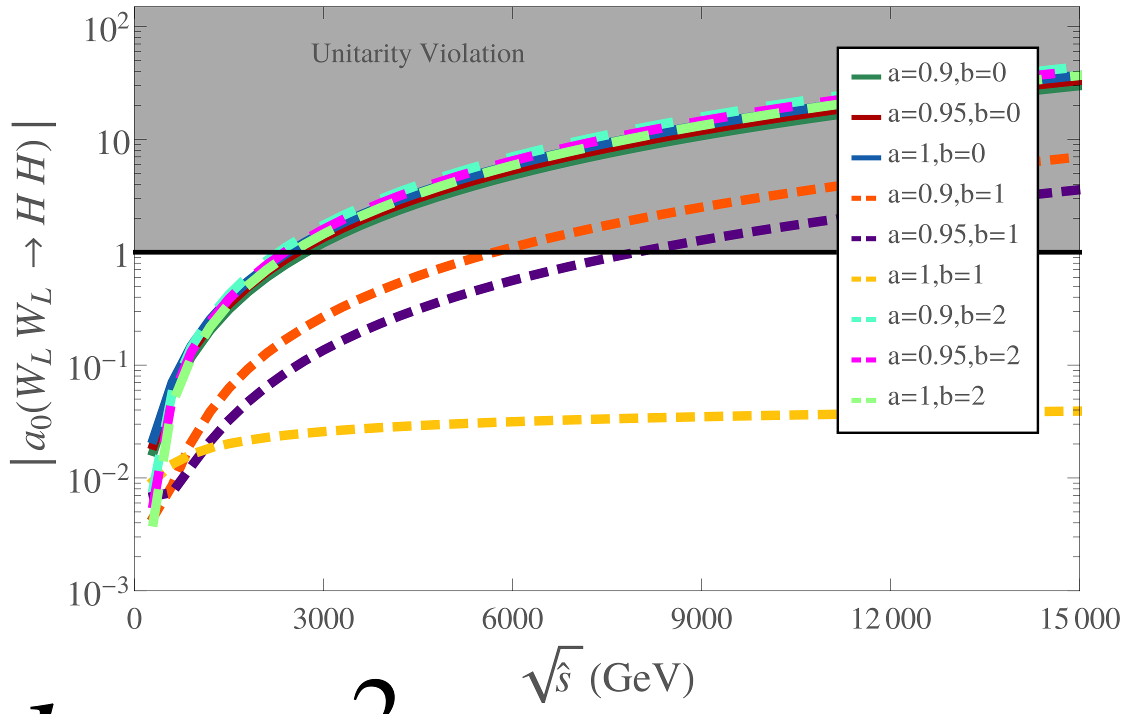


κ_4

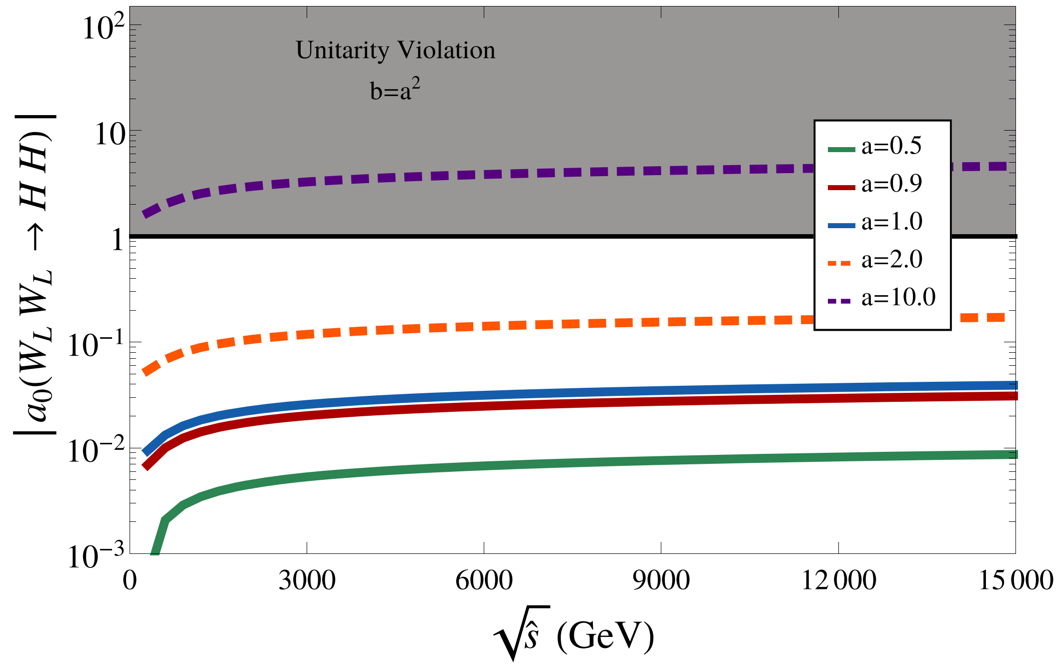


κ_3

$b \neq a^2$



$b = a^2$



HH : Strong enhancement
at large $\sqrt{s}$ for $b \neq a^2$
Unitarity violation above few TeV
Warning: $\kappa_{2V} = 0$ violates unitarity
Sensitivity to κ_3 close to threshold

HHH : Similar behavior at large
$\sqrt{s}$ as in the SM (shifted upwards)
No unitarity constraints on κ_3, κ_4
Max sensitivity to κ_3 close to
threshold

Sensitivity to LO-HEFT coeffs at e^+e^- : $\mathrm{CLIC}\ 3\,\mathrm{TeV}\,,5\,\mathrm{ab}^{-1}$ (also ILC, see paper)

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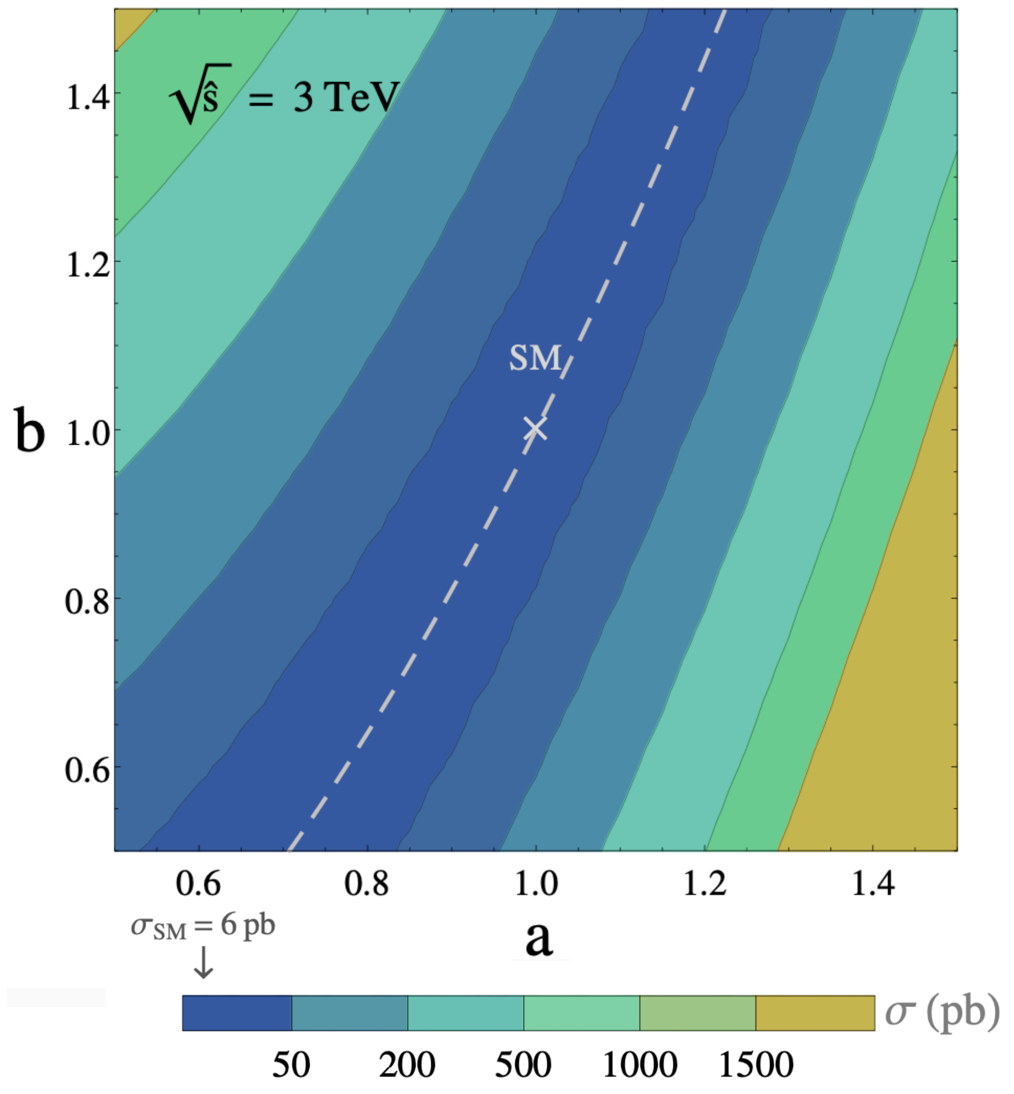
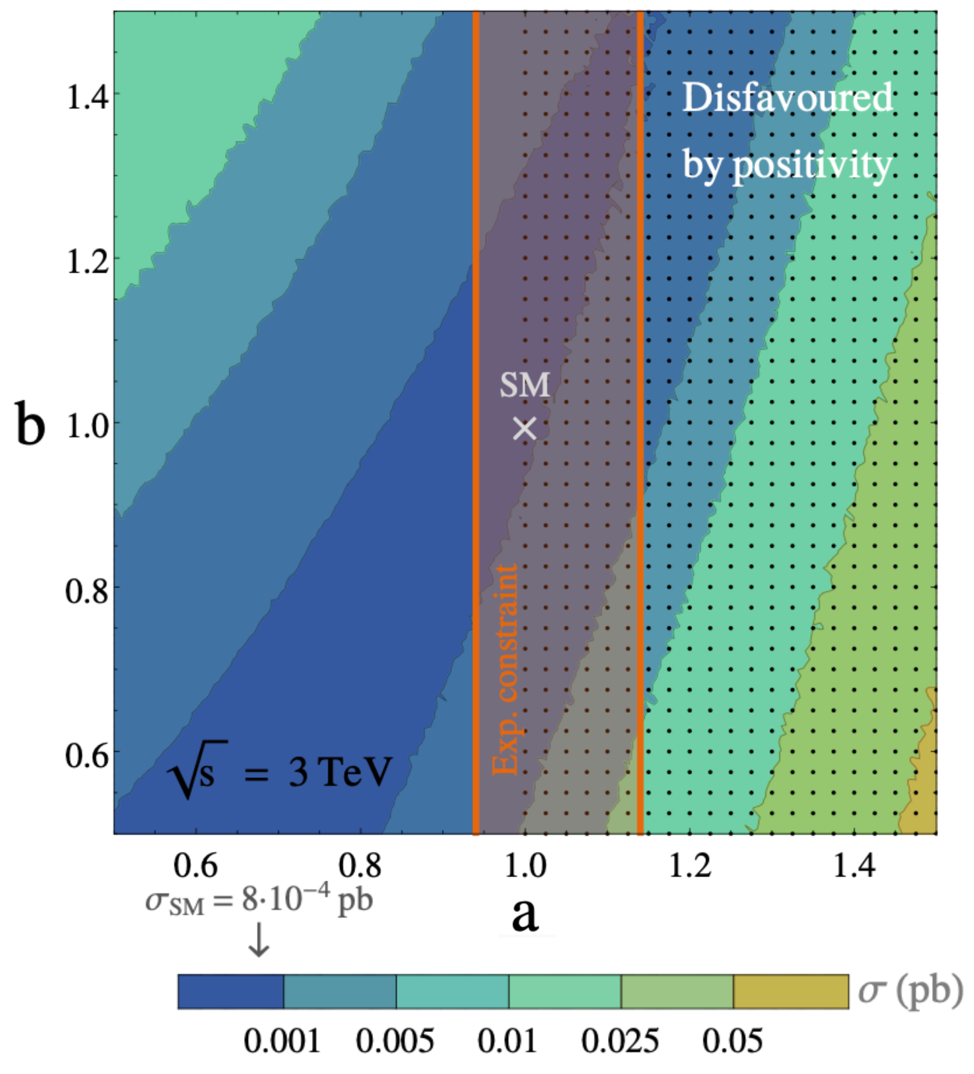
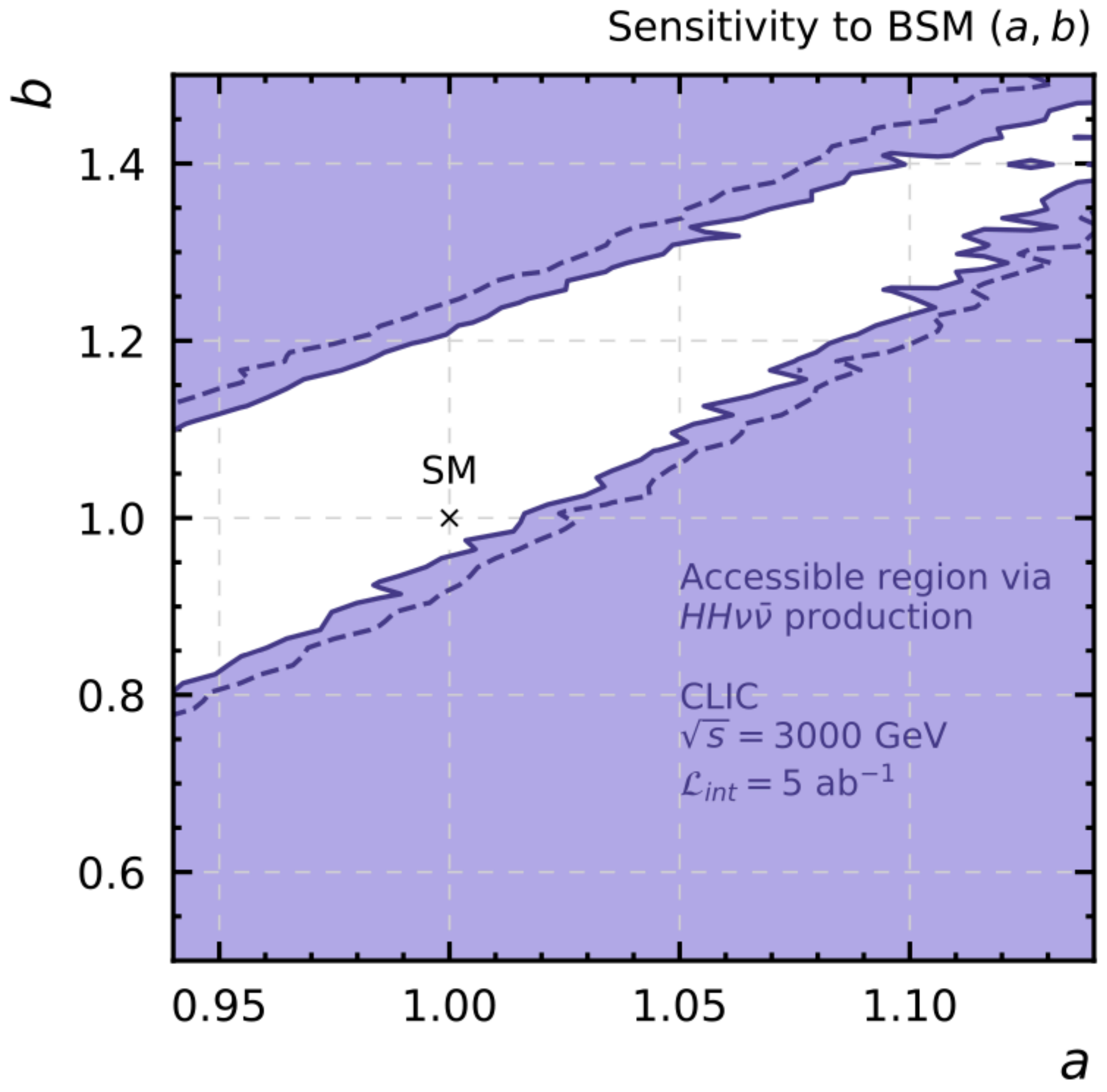
$W^+W^- \to HH$



$e^+e^- \to HH\bar{\nu}_e\nu_e$





$$e^+e^- \to 4b + E_T^{\rm mis}$$

4-btagged jets

$\epsilon_b = 0.8$

✓ $p_T^j > 20$ GeV ✓ $\Delta R_{jj} > 0.4$

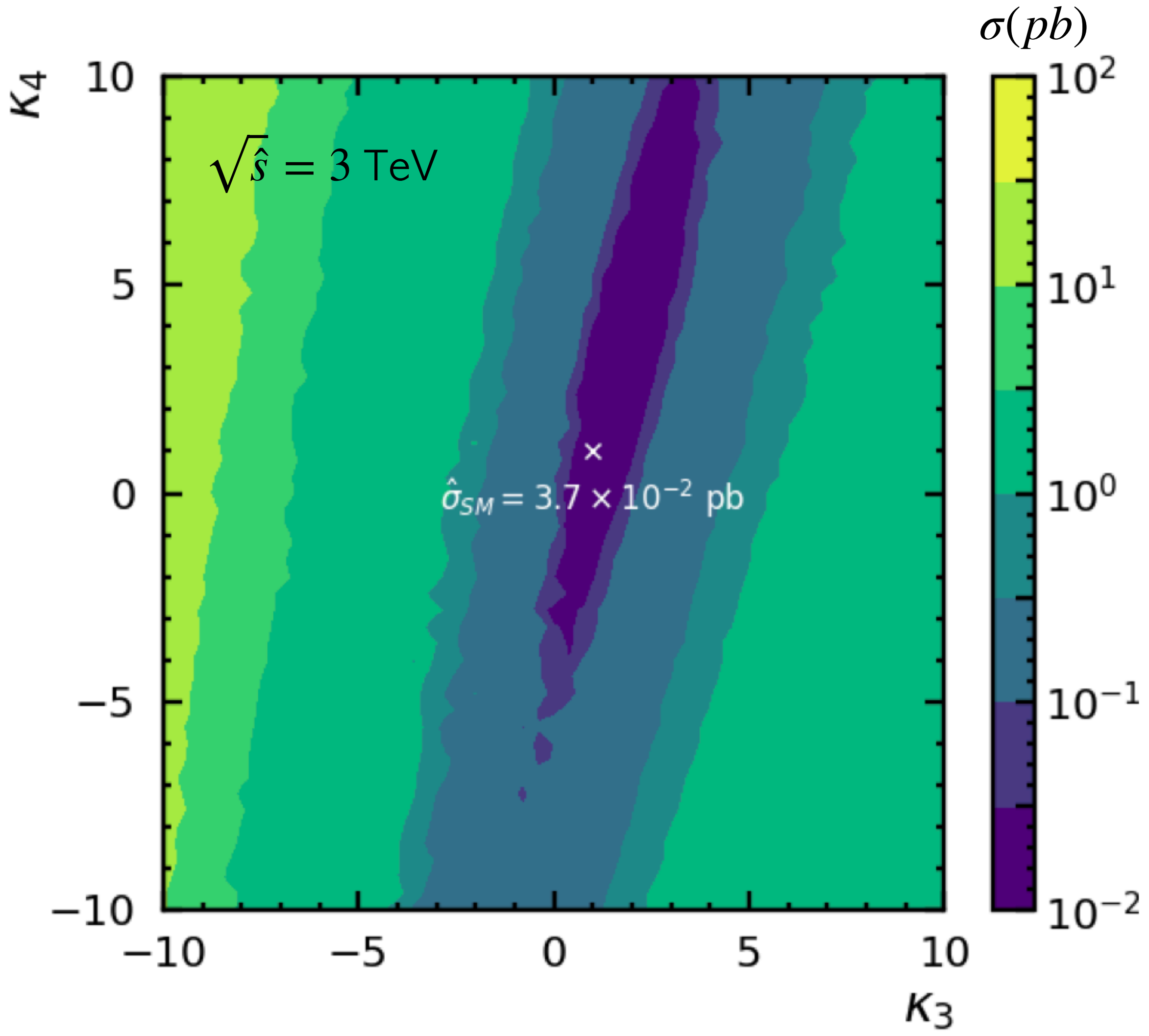
✓ $|\eta^j| < 2$ ✓ $E_T^{\rm mis} > 20$ GeV

Solid (dashed) lines bound regions with $R < 5\,(10)$, with $R = (N_{\rm BSM} - N_{\rm SM})/\sqrt{N_{\rm SM}}$.

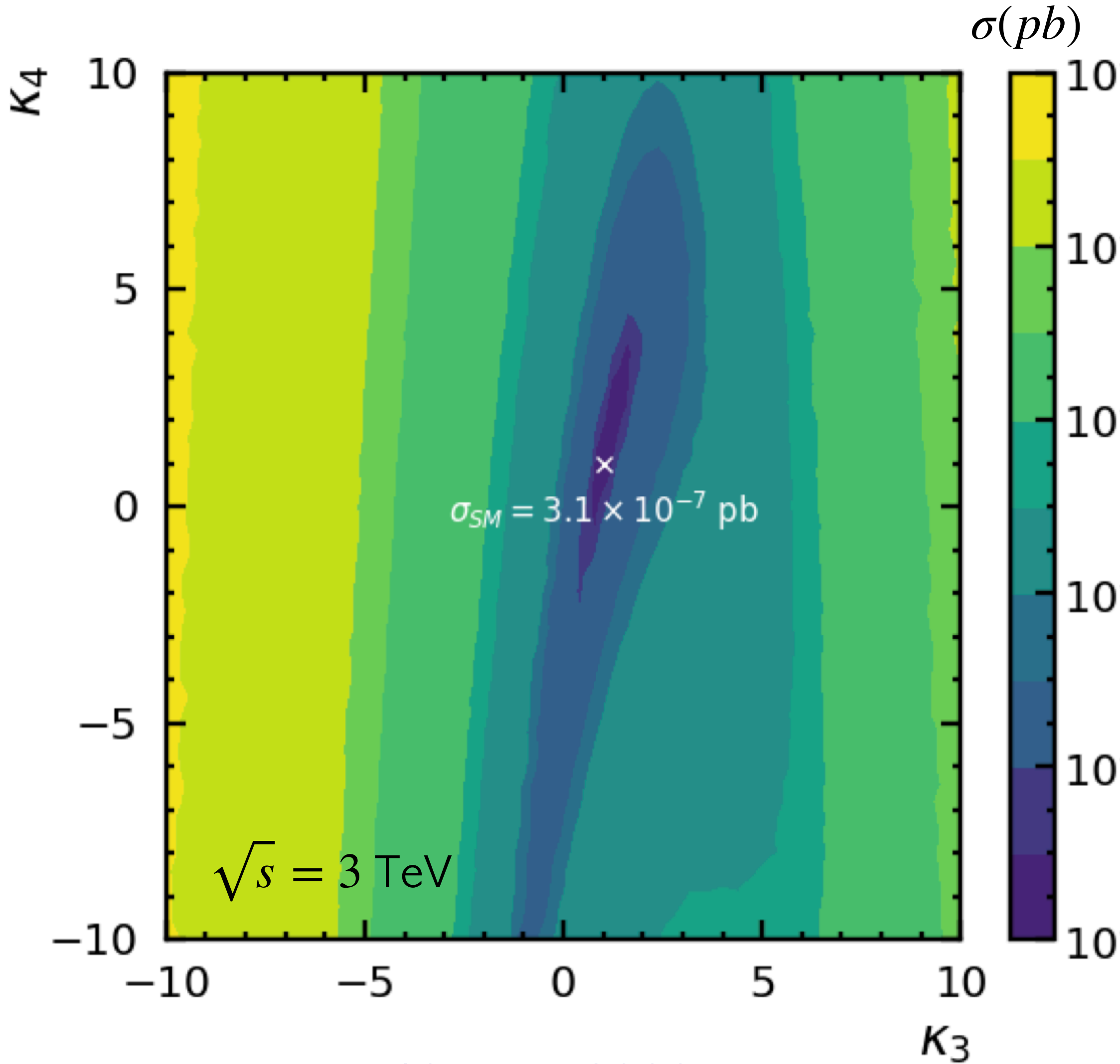
Large accessible regions in (a,b)

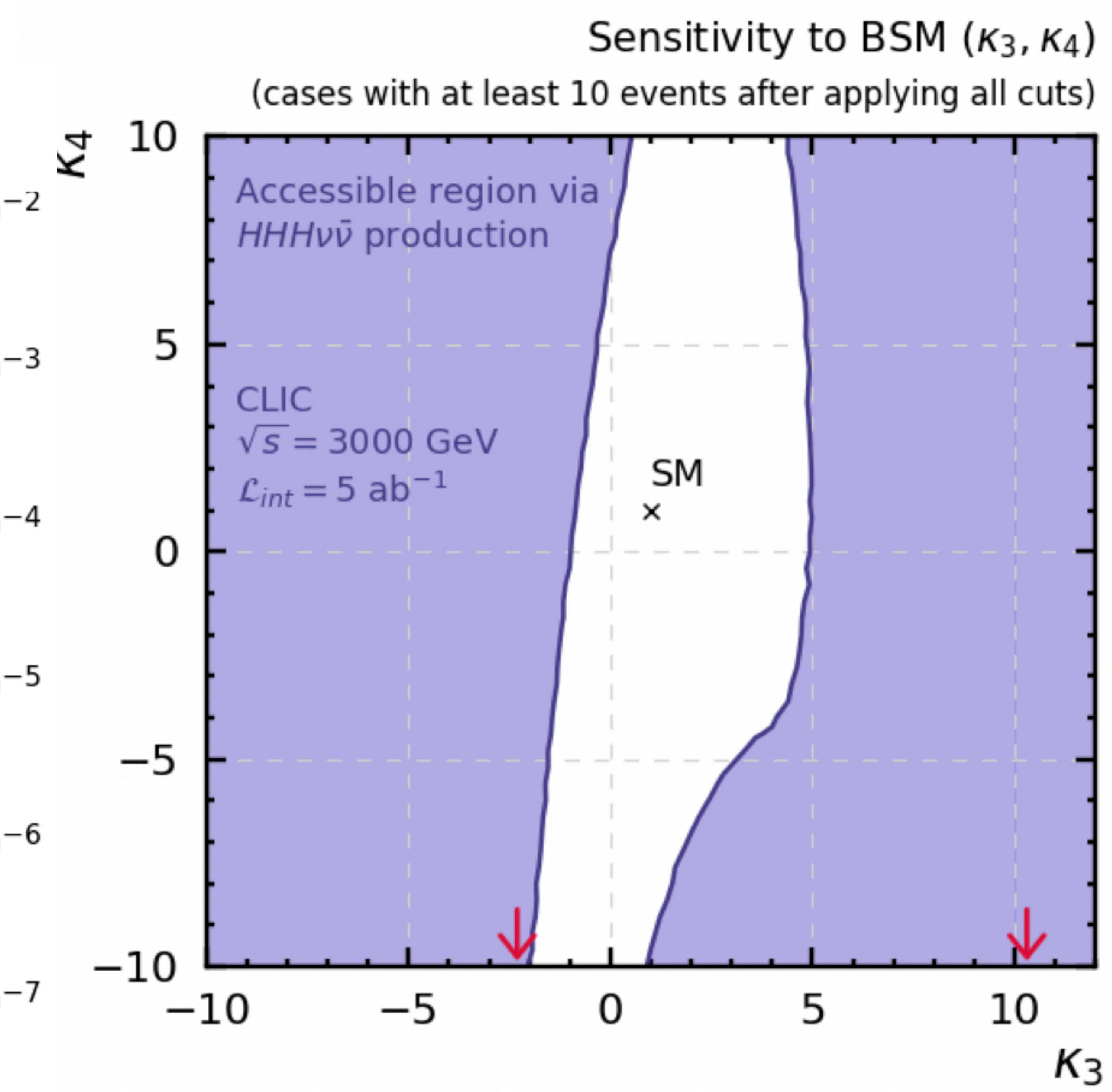
Smaller regions for $\mathrm{ILC}\ 1\,\mathrm{TeV}\ 8\,\mathrm{ab}^{-1}$, see paper

$W^+W^- \to HHH$



$e^+e^- \to HHH\bar{\nu}_e\nu_e$





$$e^+e^- \to 6b + E_T^{\rm mis}$$

At least 5-btagged jets

$\epsilon_b = 0.8$

✓ $p_T^j > 20$ GeV ✓ $N_j \geq 6$

✓ $|\eta^j| < 2.72$ ✓ $E_T^{\rm mis} > 20$ GeV

10 events required for accessibility

Sensitivity at CLIC to both κ_3 and κ_4

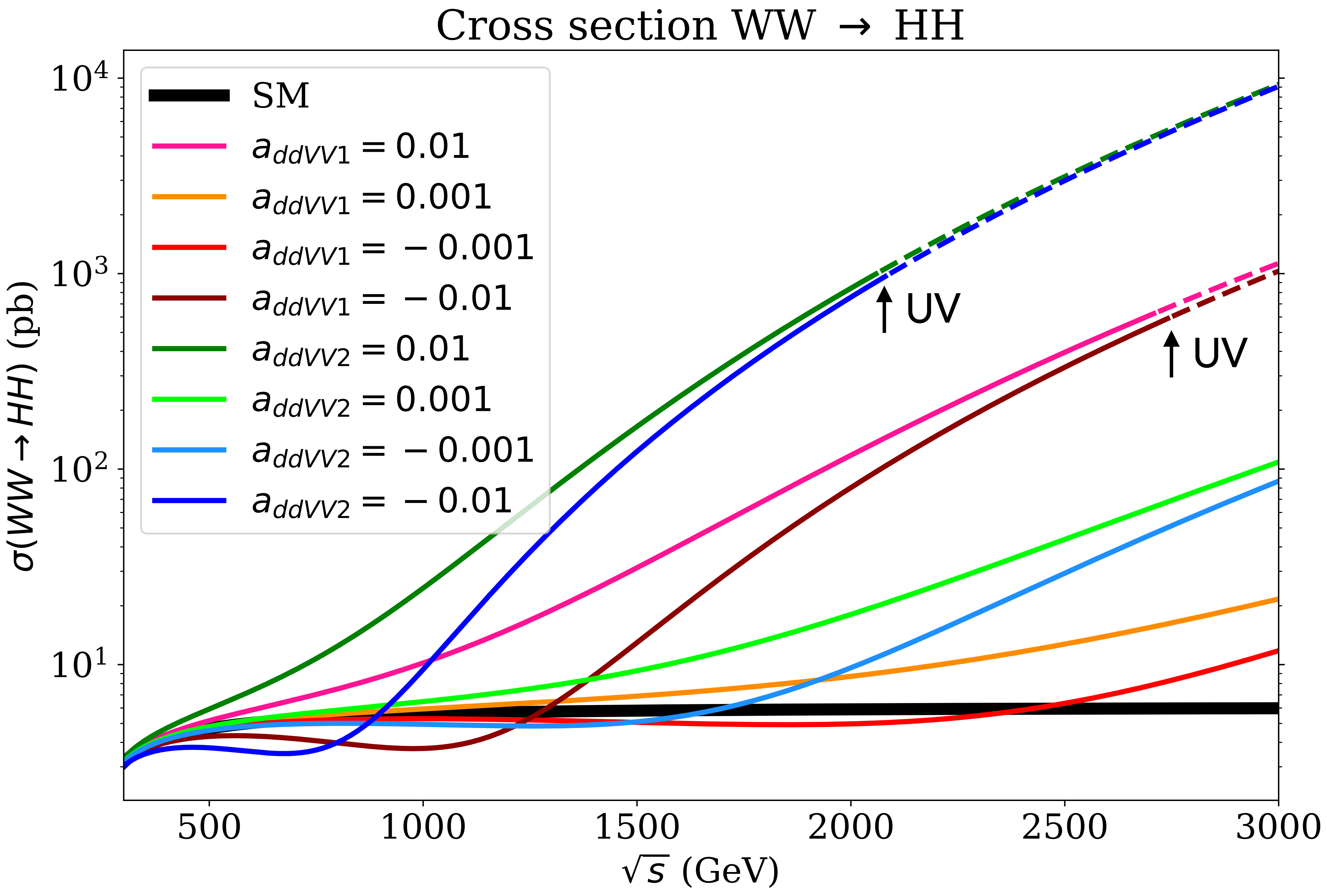
(Madgraph5 used for all collider cross section predictions)

Behavior with energy (NLO-HEFT, chi-dim=4)

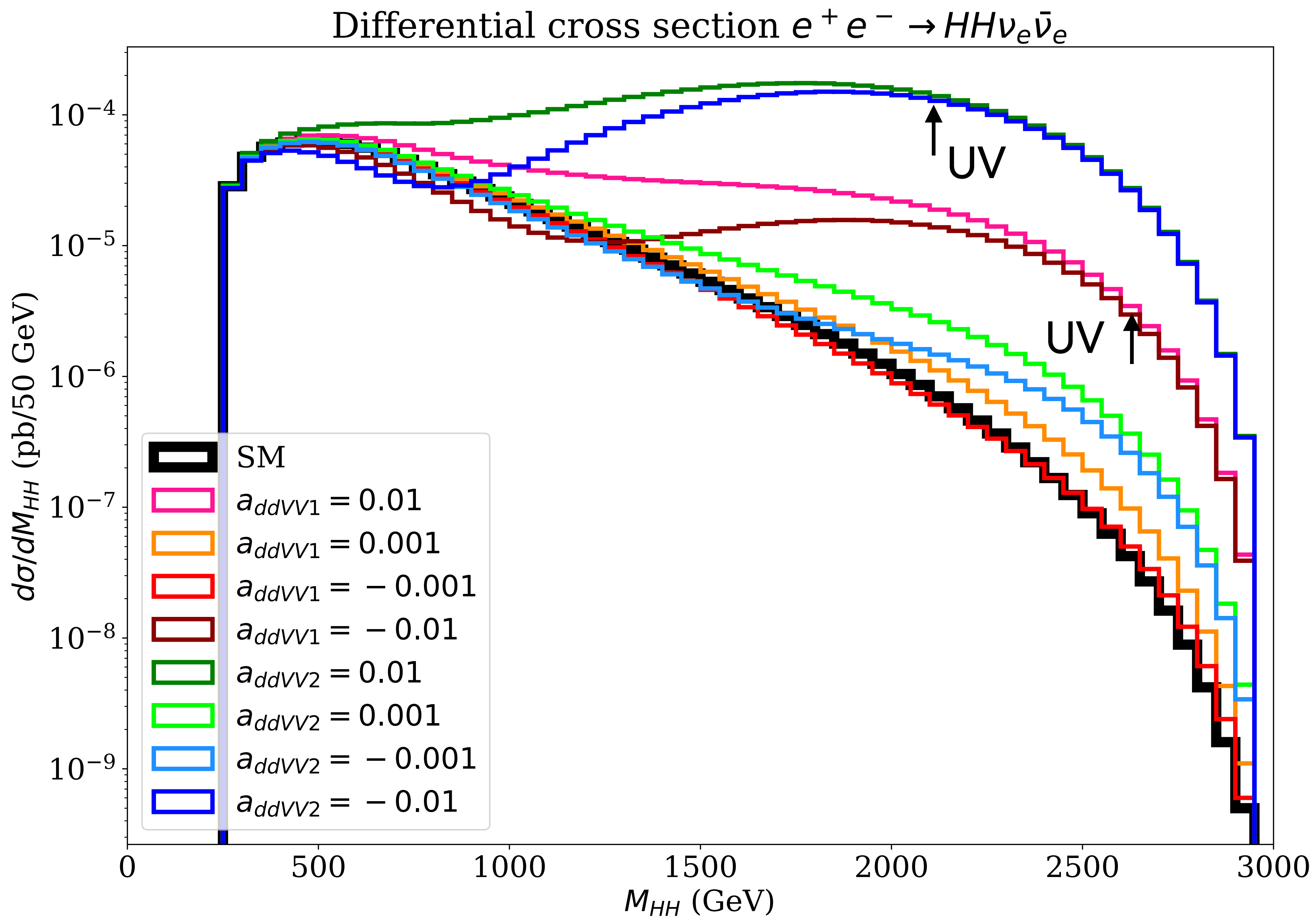
Some preliminary results (D. Domenech, M. Herrero, R. Morales, M. Ramos, 2022)

$$\mathscr{L}^{\rm NLO}_{\rm EChL} = \ \ldots + \underbrace{a_{ddVV1}}_{=\eta=\,e} (1/v^2)\, \partial^\mu H \partial^\nu H\, {\rm Tr}\left[(D_\mu U^+)\,(D_\nu U)\right] + \underbrace{a_{ddVV2}}_{=\delta=\,d} (1/v^2)\, \partial^\mu H \partial_\mu H\, {\rm Tr}\left[(D^\nu U^+)\,(D_\nu U)\right] + \ldots$$

WW subprocess



e^+e^- process



enhancement in $WW \to HH$ at large $\sqrt{s}$ $\Rightarrow$ enhancement in $e^+e^- \to HH\bar{\nu}_e\nu_e$ at large invariant mass M_{HH}

↑ UV= to the right of this point prediction enters in the Unitarity Violating region

Largest deviations respect to SM in LL modes

Comparing SMEFT and HEFT : LO and NLO

$WW \to HH$ subprocess

Some preliminar results (D. Domenech, M. Herrero, R. Morales, M. Ramos, 2022)

$$\mathcal{L}_6 \supset c_{\phi^6}(\phi^\dagger\phi)^3 + c_{\phi\Box}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + c_{\phi D}(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi) + c_{\phi W}(\phi^\dagger\phi)W^a_{\mu\nu}W^{a\mu\nu}$$

$c_i \equiv a_i/\Lambda^2$

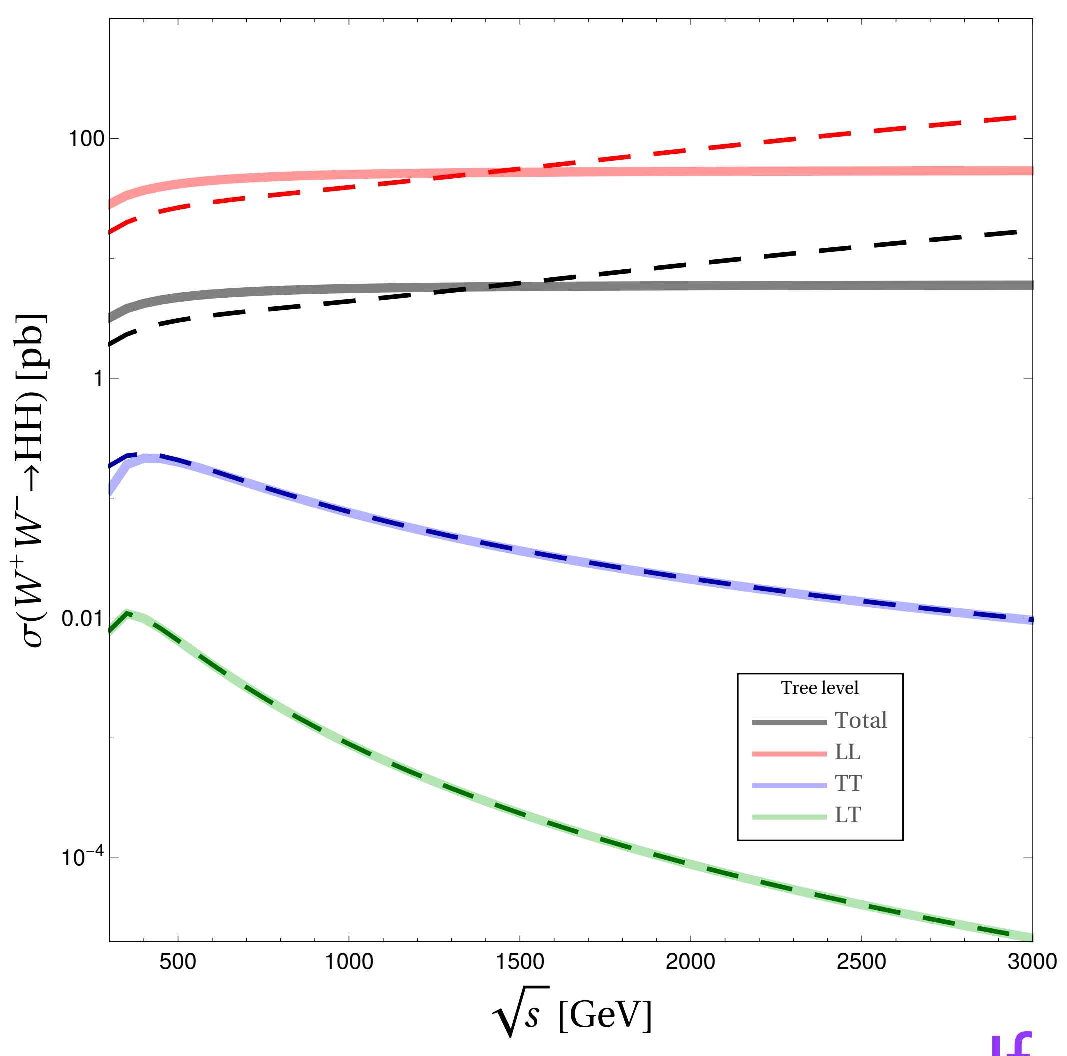
$$\mathcal{L}_8 \supset c^{(1)}_{\phi^4}(D_\mu\phi^\dagger D_\nu\phi)(D^\nu\phi^\dagger D^\mu\phi)+c^{(2)}_{\phi^4}(D_\mu\phi^\dagger D_\nu\phi)(D^\mu\phi^\dagger D^\nu\phi)+c^{(3)}_{\phi^4}(D_\mu\phi^\dagger D_\mu\phi)(D^\nu\phi^\dagger D^\nu\phi)+\ldots$$

$c_i \equiv a_i/\Lambda^4$

Again: the largest BSM deviations in Longitudinal modes $W_L W_L \to HH$ Transverse modes are less affected. At TeV: dim8 compete with dim6 !!

$\Lambda = 1\,\text{TeV}$
In these plots

$a_{\phi\Box} = 1.0$



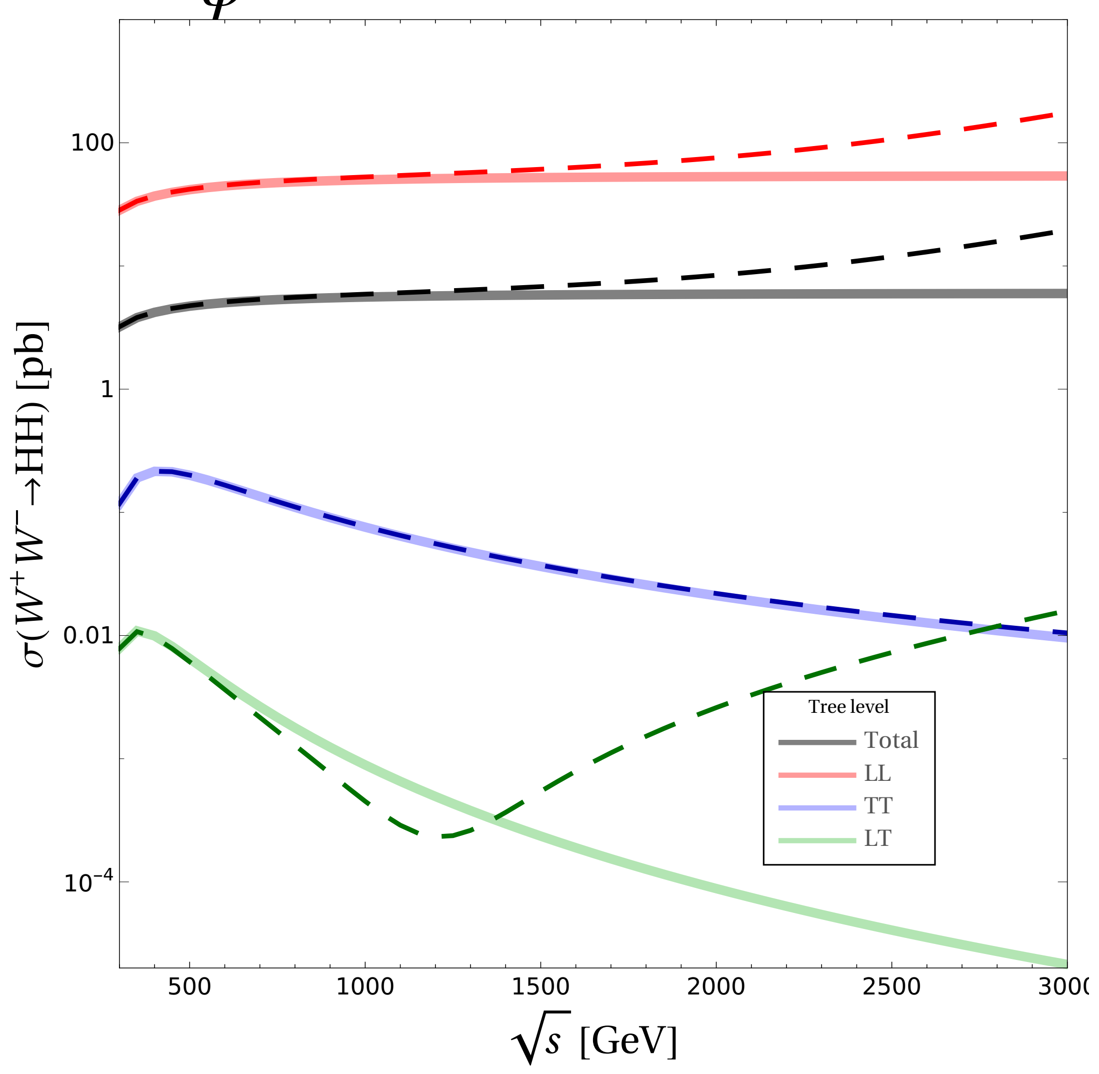
dim 6

$a_{\phi\Box}$

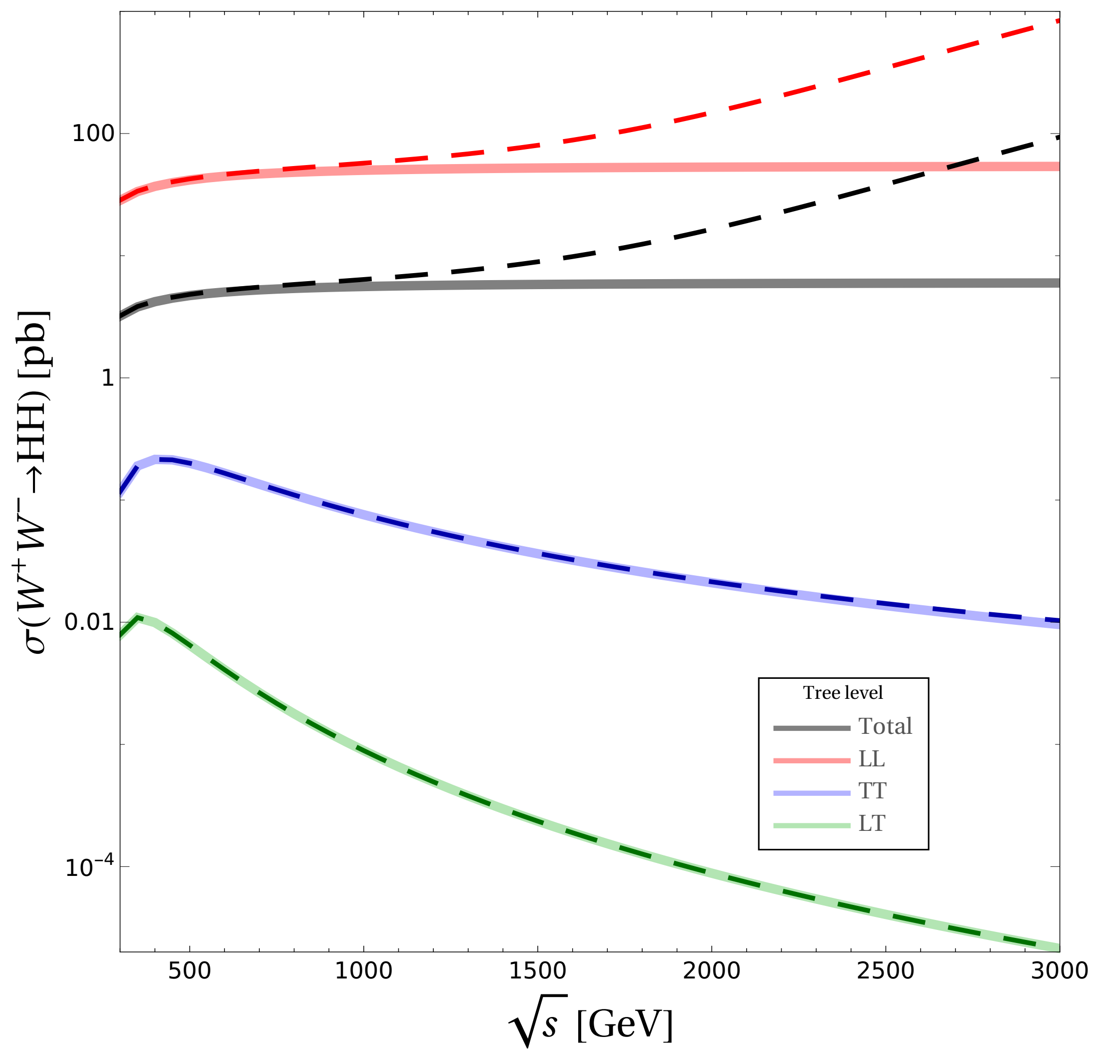
compares to

$a\,(\kappa_V)$ **and** $b\,(\kappa_{2V})$

$a^{(1)}_{\phi^4} = 1.0$



$a^{(3)}_{\phi^4} = 1.0$



dim 8

$a^{(1)}_{\phi^4}, a^{(3)}_{\phi^4}$

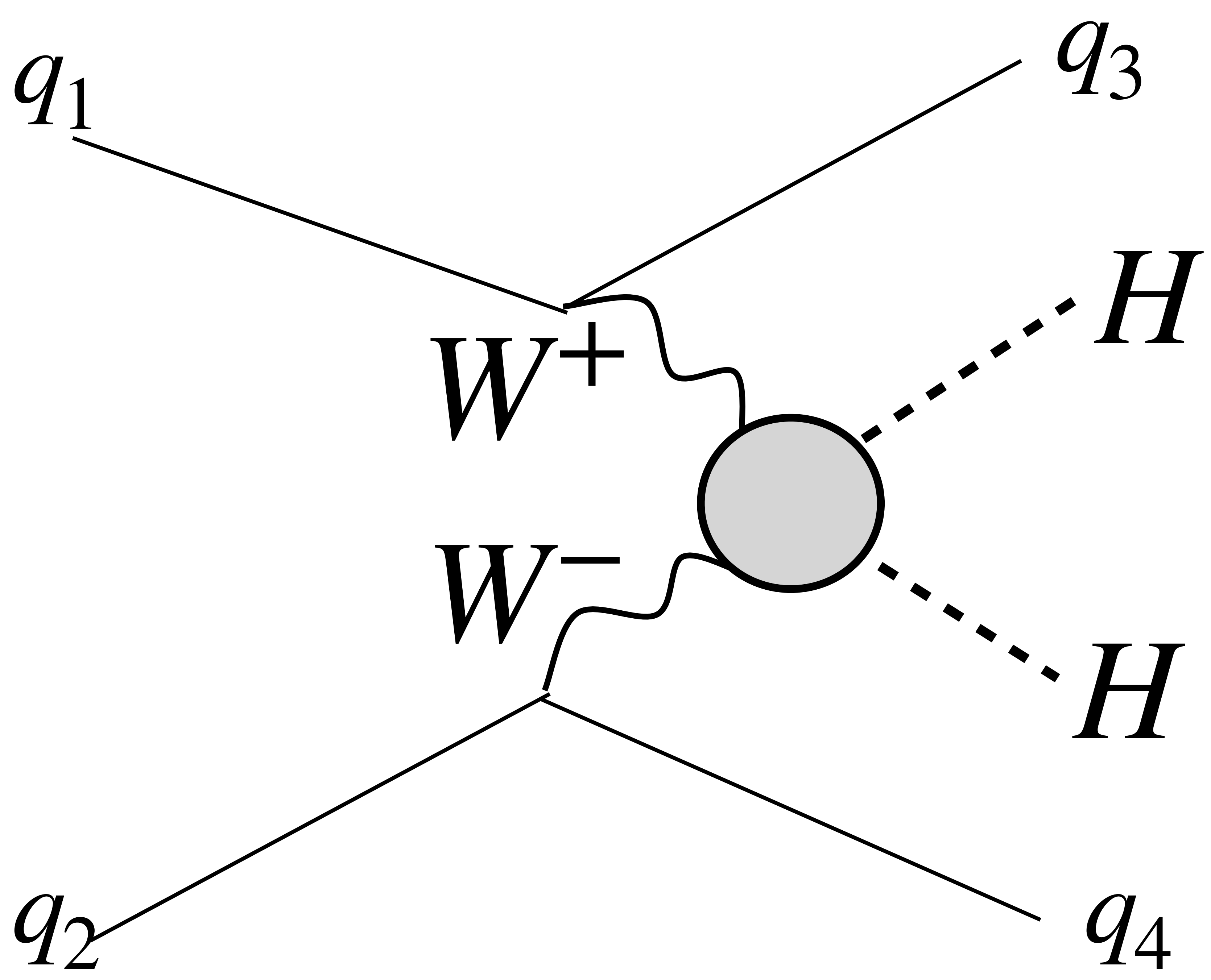
compare to

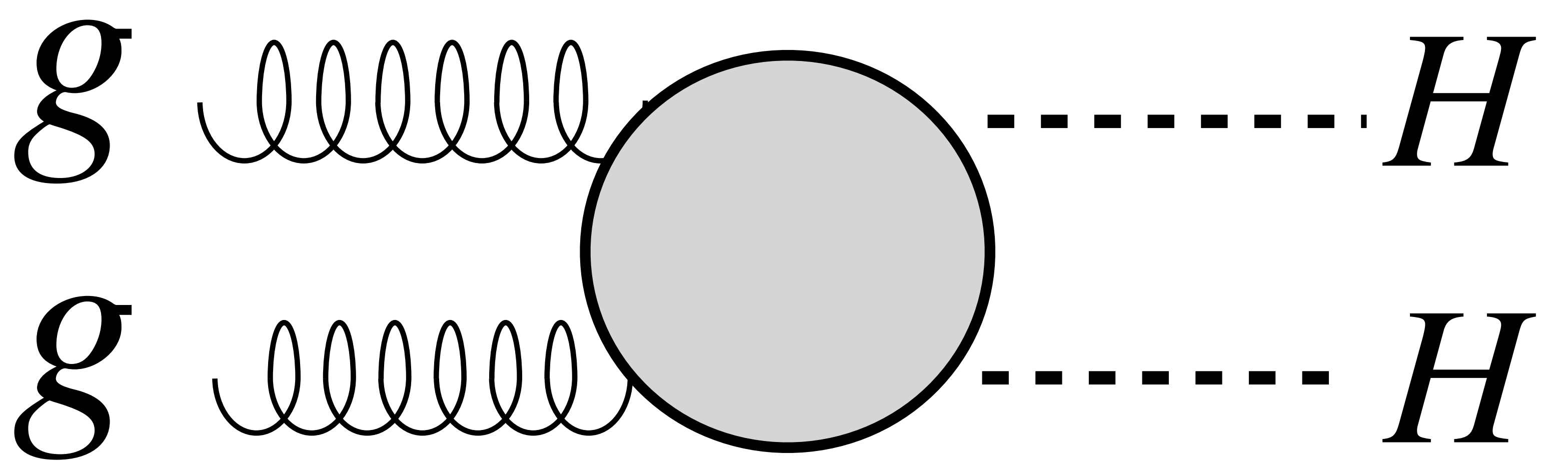
a_{ddVV1}, a_{ddVV2}

If matching in amplitudes according to behavior with energy: SMEFT dim 8 (6) <—> HEFT chi-dim 4 (2)

HH production also at LHC via WW scattering

1807.09736, Nucl.Phys.B 945 (2019) 114687, Arganda, García-García, Herrero





gg dominates WW:
difficult search at LHC

'To Extract' WW: impose cuts on jets from q3 and q4

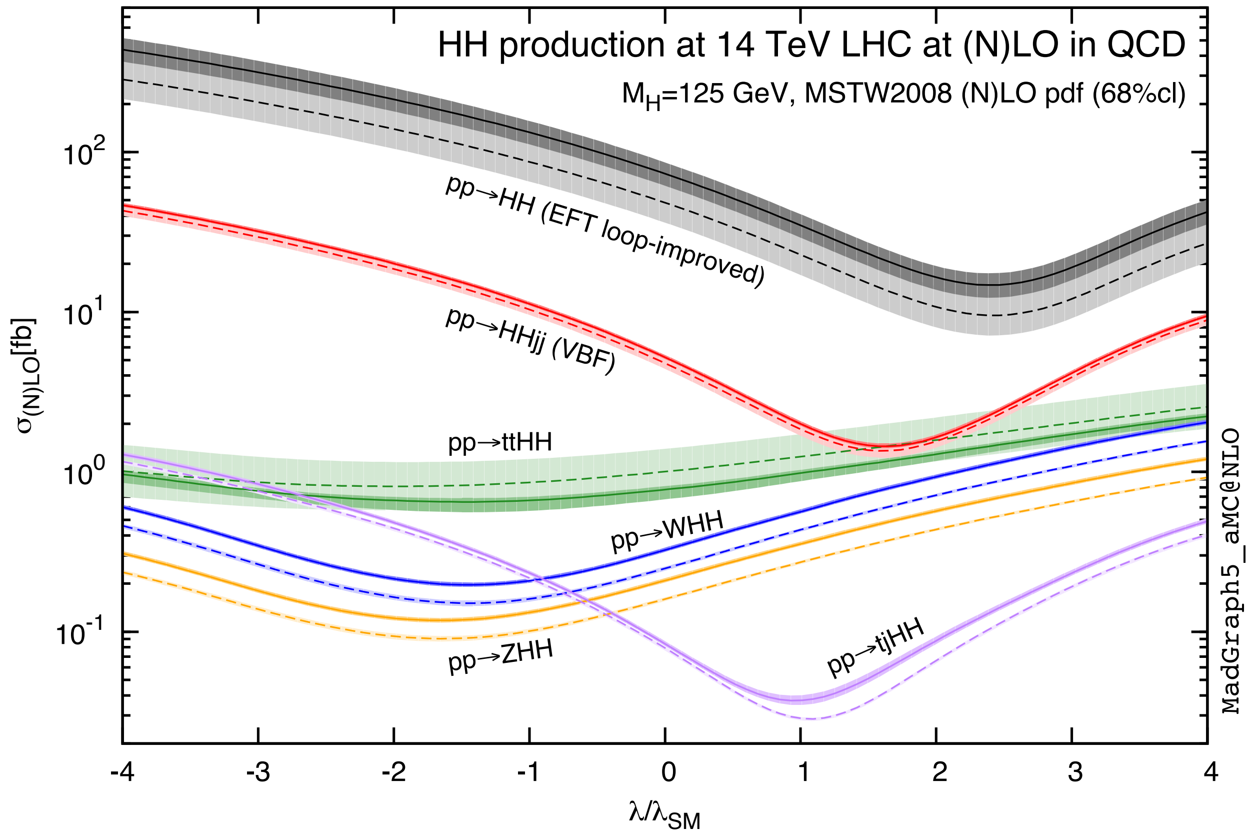
Two opposite-sided forward/backward jets with large pseudorapidity gap and large invariant mass, typically, $\Delta\eta_{jj} > 4$, $M_{jj} > 500$ GeV , VBS cuts

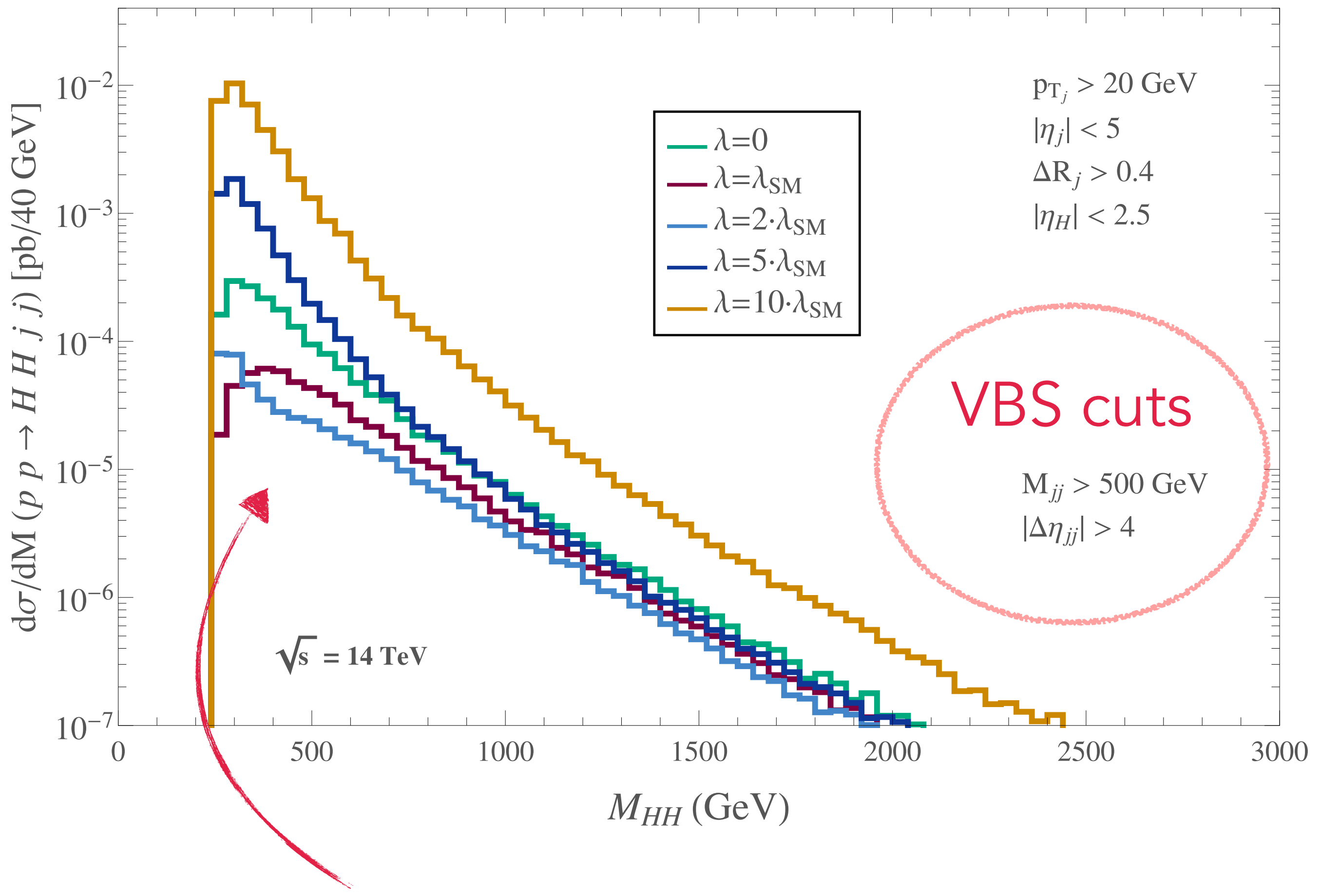
Our work: first proposal, predictions λ_{HHH} at LHC via $WW \to HH$ and prospects for HL-LHC

1807.09736, Nucl.Phys.B 945 (2019) 114687, Arganda, García-García, Herrero

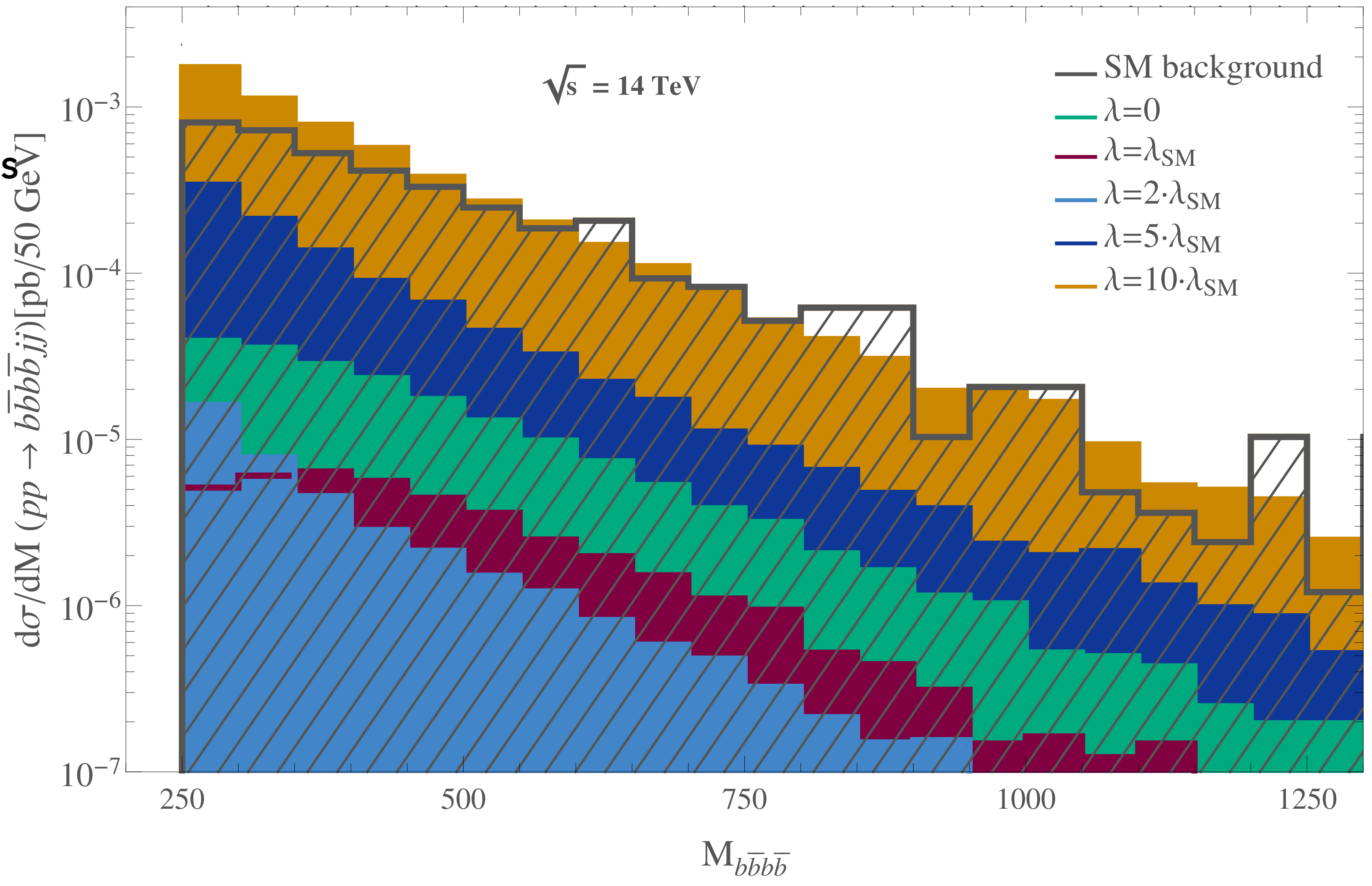
$\sigma_{ggF}(14\ \mathrm{TeV}, \kappa = \lambda/\lambda_{SM} = 1) \sim 32$ fb 1-loop, large uncertainties

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





Larger sensitivity to λ_{HHH} near HH threshold region



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

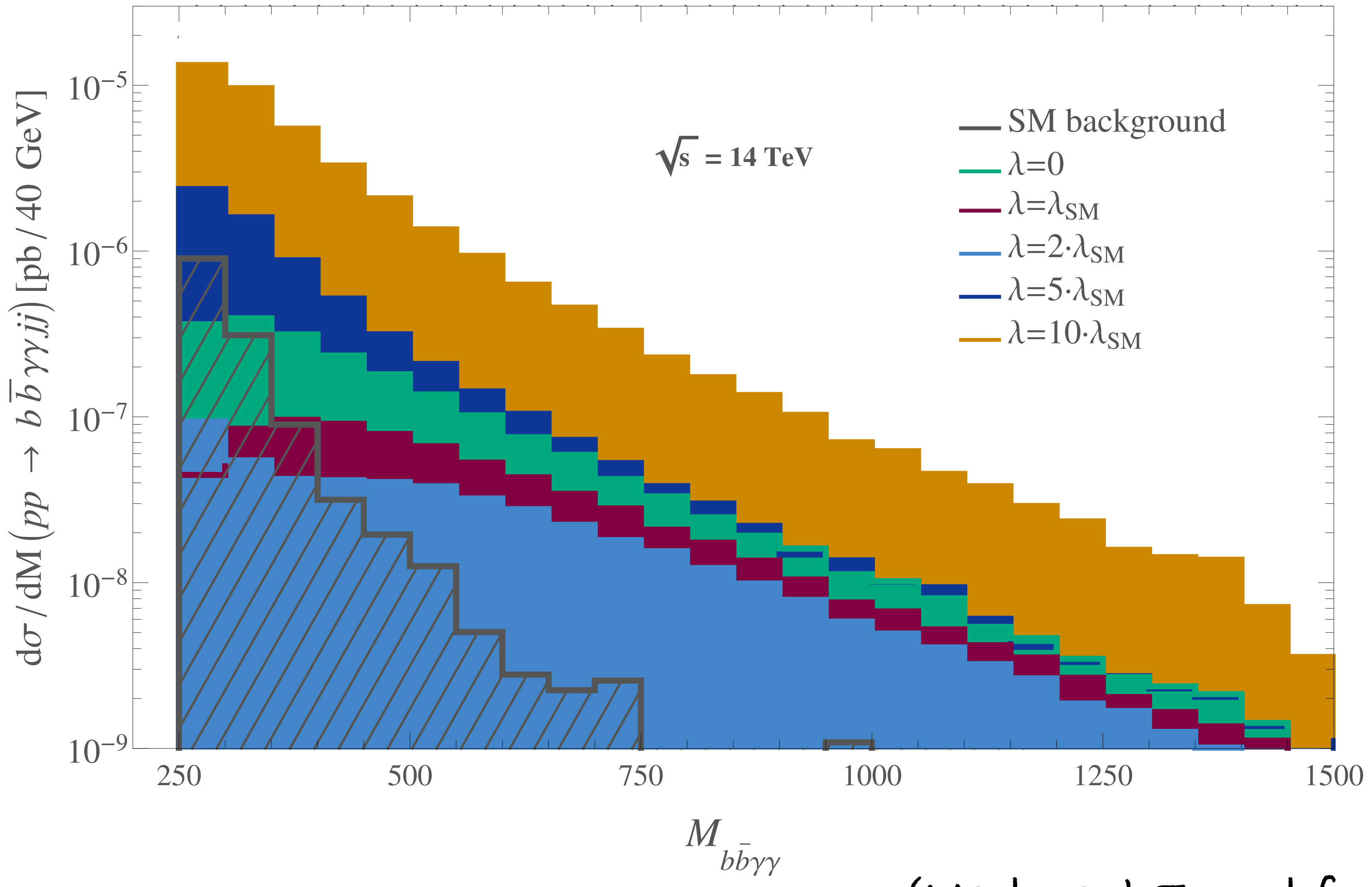
Large SM back: multijets QCD+ZHjj+ZZjj

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

$$\hat{\Delta}R_{bb} \equiv \begin{cases} 0.2 < \Delta R_{bb^l} < \frac{653}{M_{4b}} + 0.475\,;\ 0.2 < \Delta R_{bb^s} < \frac{875}{M_{4b}} + 0.35\,,\ M_{4b} < 1250\ \mathrm{GeV}\,, \\ 0.2 < \Delta R_{bb^l} < 1\,;\ 0.2 < \Delta R_{bb^s} < 1\,,\ M_{4b} > 1250\ \mathrm{GeV}\,, \end{cases} \qquad p_{T_b} > 35\ \mathrm{GeV}$$

$$\text{VBS CUTS}: \quad |\Delta\eta_{jj}| > 4\,, \quad M_{jj} > 500\ \mathrm{GeV} \qquad \chi_{HH} \equiv \sqrt{\left(\frac{M_{bb^l} - m_H}{0.05\,m_H}\right)^2 + \left(\frac{M_{bb^s} - m_H}{0.05\,m_H}\right)^2} < 1$$

VBS+HH candidate cuts very efficient
$[M_{bb1}, M_{bb2}] \sim [M_H, M_H]$ etc (for details see paper)



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

Lower statistics but cleaner signal

$B(H \to \gamma\gamma) \sim 0.2\,\%\,,\ B(H \to b\bar{b}) \sim 60\,\%$

Small SM back: mixed QCDEW+ZHjj

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

$$\text{VBS CUTS}: \quad |\Delta\eta_{jj}| > 4\,, \quad M_{jj} > 500\ \mathrm{GeV}$$

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

VBS+HH candidate cuts very efficient
$[M_{bb1}, M_{gaga}] \sim [M_H, M_H]$ etc (for details see paper)

(Madgraph5 used for all collider cross section predictions)

Sensitivity to BSM λ_{HHH} at LHC via $\mathbf{WW} \to \mathbf{HH}$: (parton level) predictions for HL-LHC

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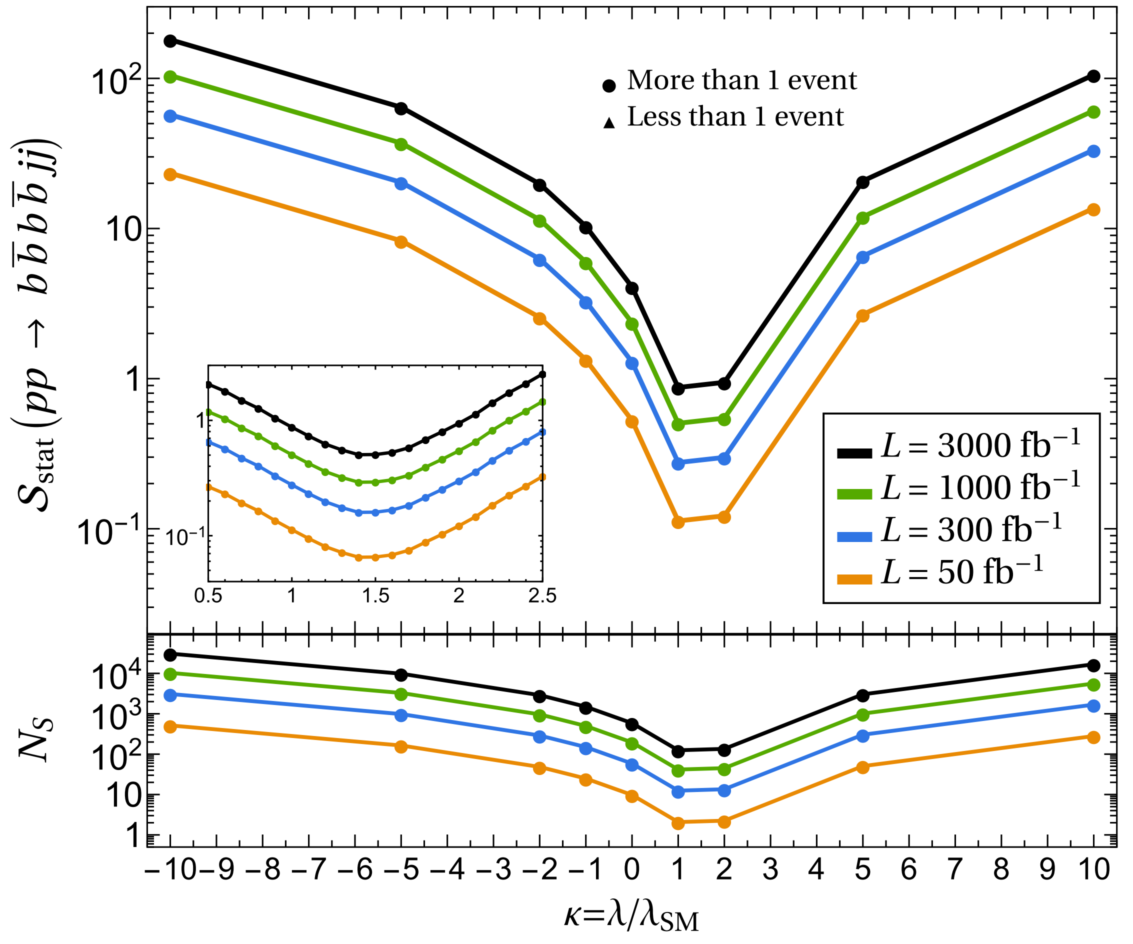
*bbbb*jj events



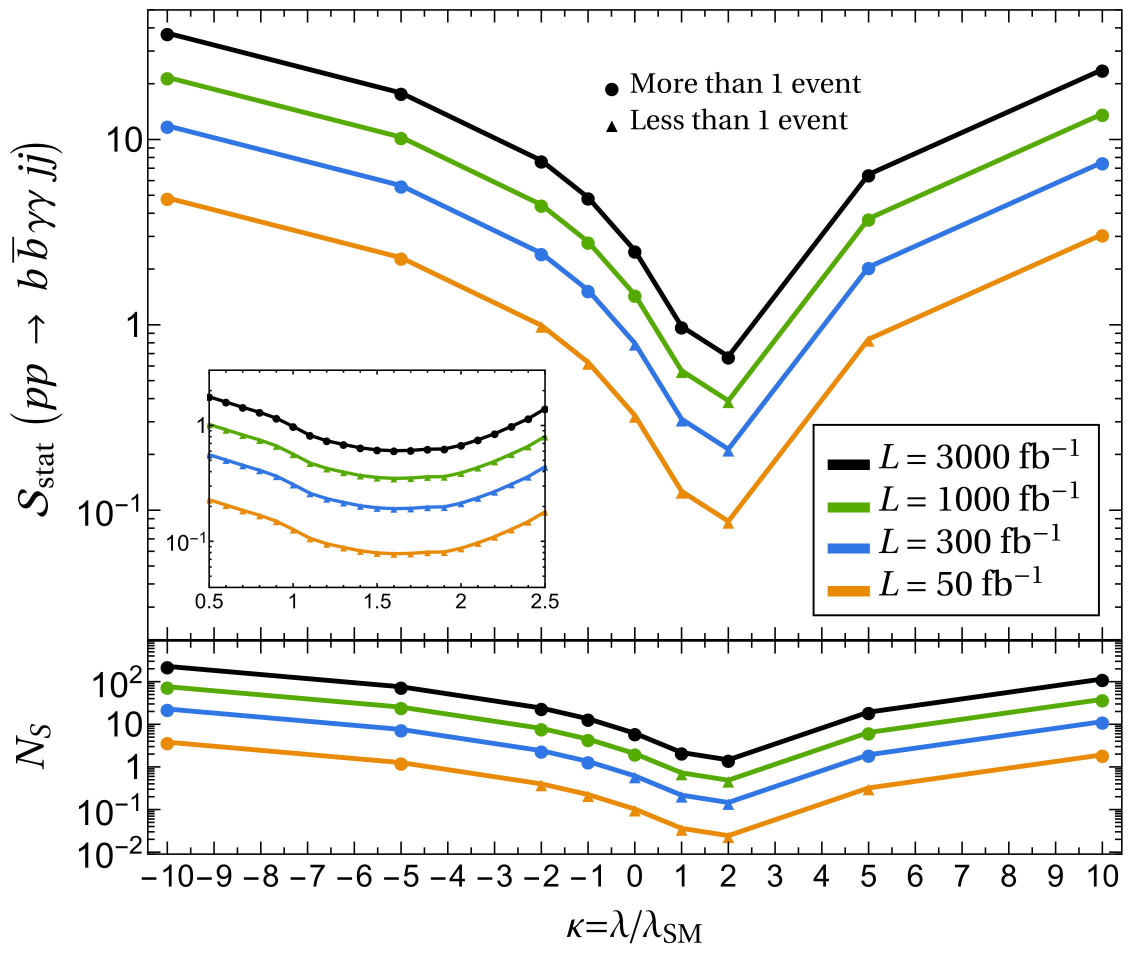
$$\mathcal{S}_{\rm stat} = \sqrt{-2\left((N_S+N_B)\log\left(\frac{N_B}{N_S+N_B}\right)+N_S\right)}$$

$3\sigma(5\sigma)$

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)

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)

*bbγγ*jj events



modified slightly by additional considerations (NLO, b-tagging 0.7, γ identification 0.95, χ_{HH} 0.05-0.1, see paper)

Example: for benchmark L = 1000 fb^{-1}

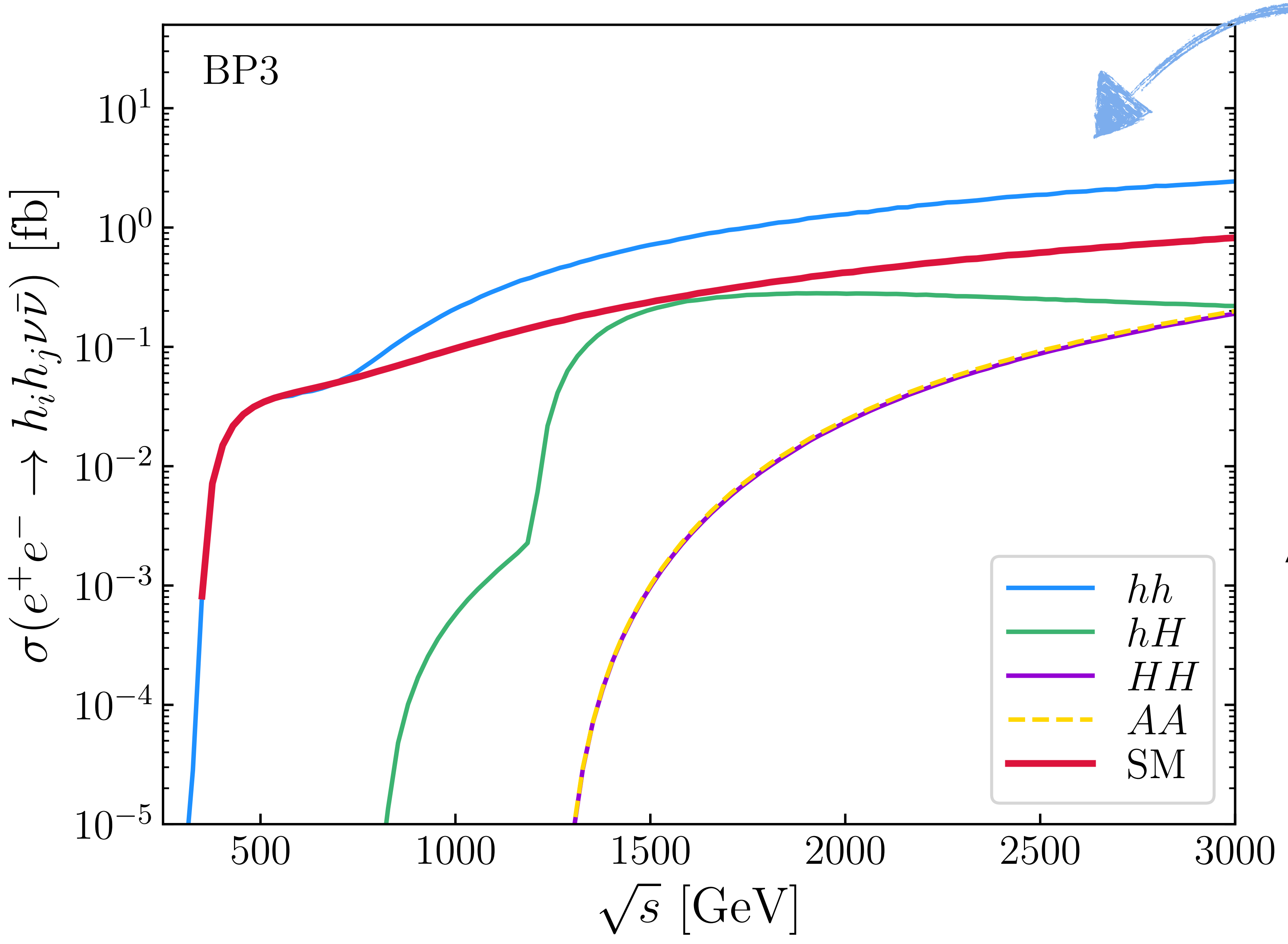
Signal	Original	With additional considerations
$b\bar{b}b\bar{b}jj$	$\kappa > 3.7\,(4.2)$	$\kappa > 6.2\,(7.7)$
$b\bar{b}\gamma\gamma jj$	$\kappa > 4.6\,(6.0)$	$\kappa > 7.7\,(9.4)$

Our study was the first one indicating that WBF at LHC was indeed sensitive to BSM κ_λ (in addition to GGF)

Our predictions for this sensitivity are in concordance with the recent CMS (2021) [2011.12373] and CMS (2022) [2202.09617] improved constraints to κ_λ from WBF analysis with real data at LHC using *bbγγ* and *bbbb* events

Access to 2HDM triple couplings via WW scattering

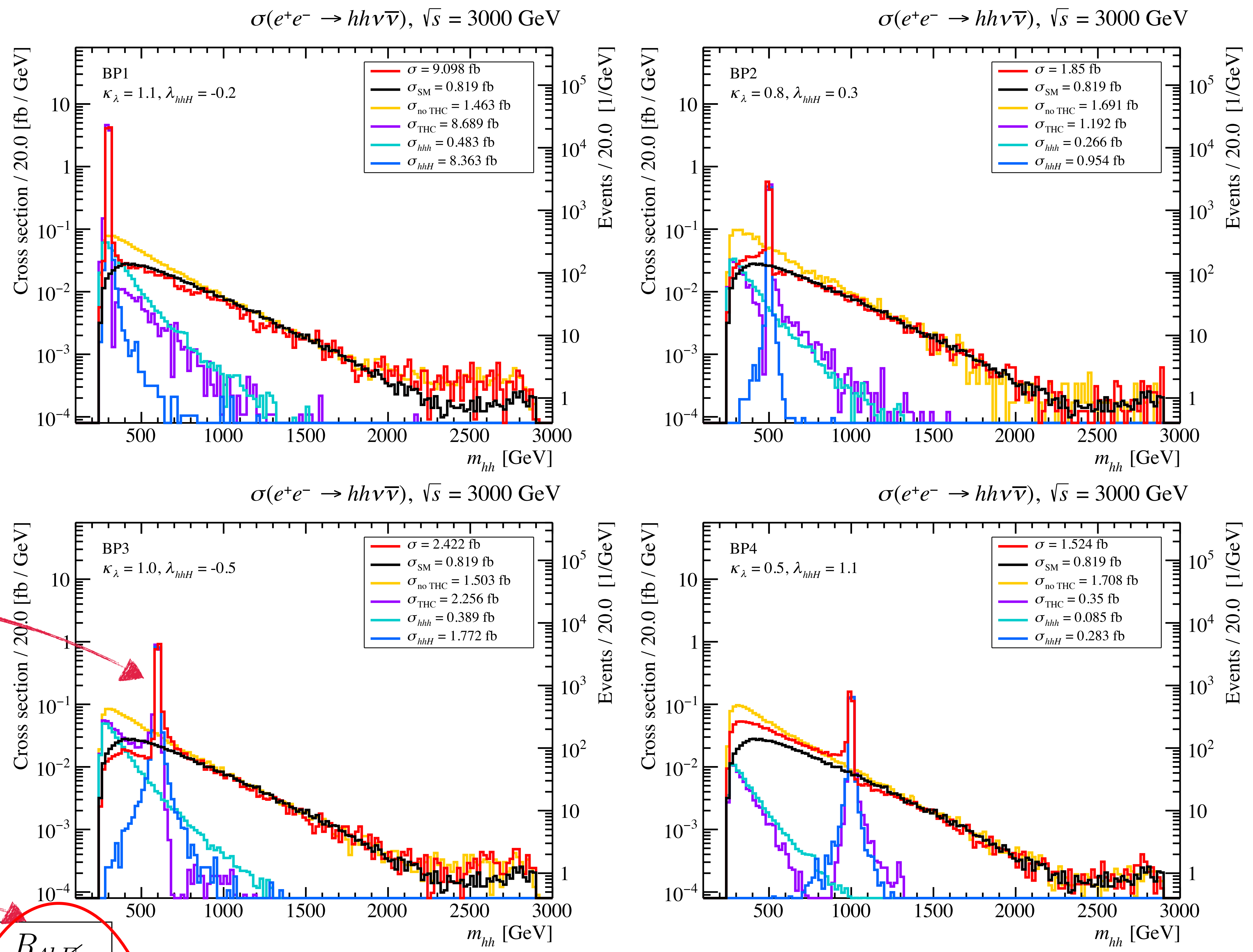
2106.11105, EPJC 81 (2021)10,913, Arco, Heinemeyer, Herrero



In hh production

1) Non-Resonant

Access to λ_{hhh} at the low m_{hh} region close to hh threshold Similarly to the SM case



2) Resonant

Access to λ_{hhH} via the resonant peak at $m_{hh} \sim m_H$ Viable for a wide range of m_H and $c_{\beta-\alpha}$ values

CLIC (3TeV, 5ab^{-1}) offers the best access to λ_{hhH}

We find large sensitivity in (4-bjets + missing E_T) events

$$R = \frac{\bar N^R - \bar N^C}{\sqrt{\bar N^C}}$$

$$\bar N = N \times A \times (\epsilon_b)^4$$

$$\epsilon_b = 0.8$$

$c_{\beta-\alpha}$	λ_{hhH}	Γ_H [GeV]	$\sigma_{\rm 2HDM}$ [fb]	$\bar N^R_{4b\not{E}_T}$ / $\bar N^C_{4b\not{E}_T}$ / $\bar N^{\rm SM}_{4b\not{E}_T}$	$R_{4b\not{E}_T}$
0.1	0.30	1.24	1.434	167 / 7 / 2	60
0.12	0.23	1.51	1.253	97 / 7 / 2	34
0.14	0.10	1.88	0.972	17 / 3 / 1	8
0.16	-0.06	2.48	0.908	15 / 3 / 1	7
0.18	-0.27	3.47	1.369	195 / 13 / 5	50
0.2 (BP3)	-0.52	5.08	2.422	577 / 30 / 11	100

$p_T^b > 20\,{\rm GeV}$; $|\eta^b| < 2$; $p_T^Z > 20\,{\rm GeV}$; $\Delta R_{bb} > 0.4$; $E_T^{\rm miss} > 20\,{\rm GeV}$,

Point	Type	m_H	$\tan\beta$	$c_{\beta-\alpha}$	m_{12}^2
BP1	I	300	10	0.25	Eq. (8)
BP2	I	500	7.5	0.1	32000
BP3	I	600	10	0.2	Eq. (8)
BP4	I	1000	8.5	0.08	Eq. (8)

For other colliders ILC .. see paper

Conclusions

WW scattering at colliders
is an efficent window to new Higgs Physics

Multiple Higgs production (HH, HHH,..) will test the most relevant quantities defining the Higgs potential, and will clarify possible correlations:
V_{HWW} / V_{HHWW}, λ_{HHH} / λ_{HHHH} ,...

WW scattering will also give access to new resonances, like extra heavy scalar particles, vector resonances, etc..

Back up slides

VBS: An efficient way to test the Higgs Sector of EW Theory within SM and BSM

Equivalence Theorem:

$$|\mathbf{T}(\mathbf{V}_L^1\mathbf{V}_L^2 \to \mathbf{V}_L^3\mathbf{V}_L^4)| \simeq |\mathbf{T}(\phi^1\phi^2 \to \phi^3\phi^4)| + \mathcal{O}(\mathbf{m}_V/\sqrt{\mathbf{s}})^n$$

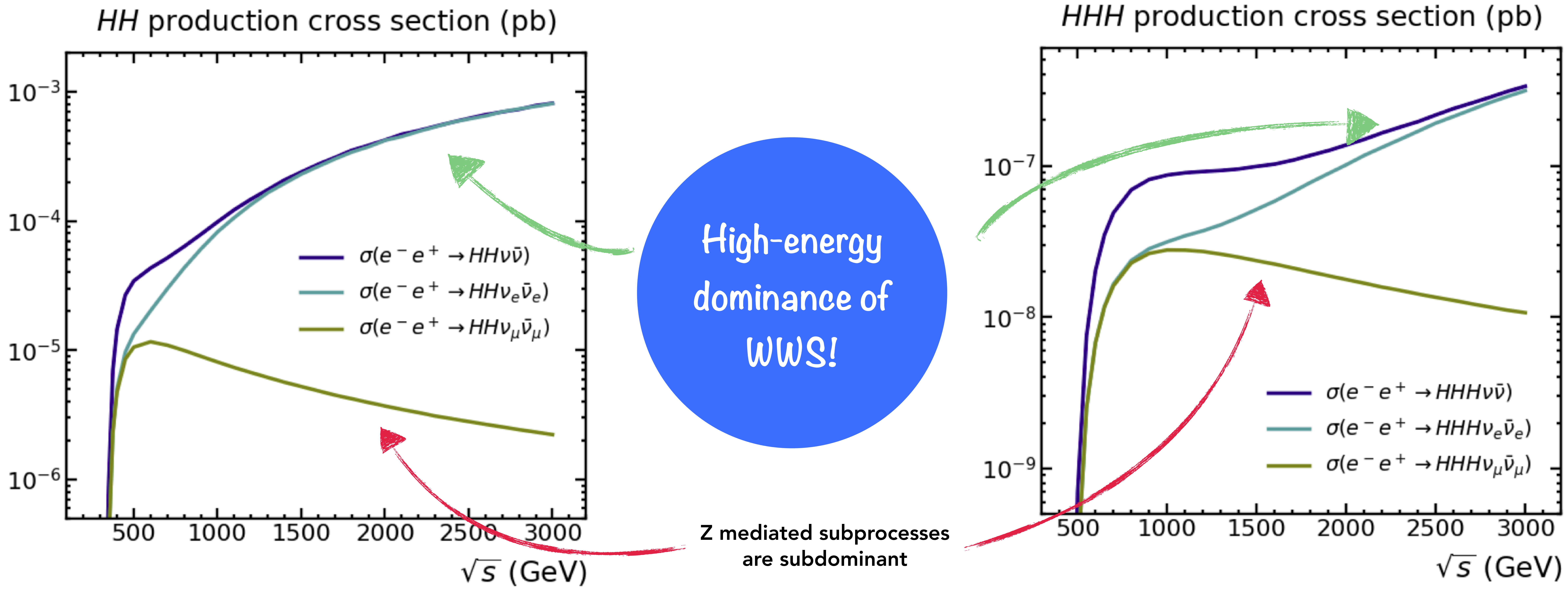
At high energies, longitudinal gauge bosons behave as Goldstone bosons

Examples:

$$|\mathbf{T}(\mathbf{W}_L^+\mathbf{W}_L^- \to \mathbf{W}_L^+\mathbf{W}_L^-)| \simeq |\mathbf{T}(\phi^+\phi^- \to \phi^+\phi^-)| \quad |\mathbf{T}(\mathbf{W}_L^+\mathbf{Z}_L \to \mathbf{W}_L^+\mathbf{Z}_L| \simeq |\mathbf{T}(\phi^+\phi^0 \to \phi^+\phi^0)|$$

$$|\mathbf{T}(\mathbf{W}_L^+\mathbf{W}_L^- \to \mathbf{HH})| \simeq |\mathbf{T}(\phi^+\phi^- \to \mathbf{HH})| \qquad |\mathbf{T}(\mathbf{W}_L^+\mathbf{W}_L^- \to \mathbf{HHH})| \simeq |\mathbf{T}(\phi^+\phi^- \to \mathbf{HHH})|$$

SM: HH and HHH: Dominance of WW scattering



High-energy dominance of WWS!

Z mediated subprocesses are subdominant

2011.13195, EPJC 81 (2021)3, 260, González-López, Herrero, Martínez-Suárez

$W_L W_L$ dominates $W_T W_T$ and $W_L W_T$

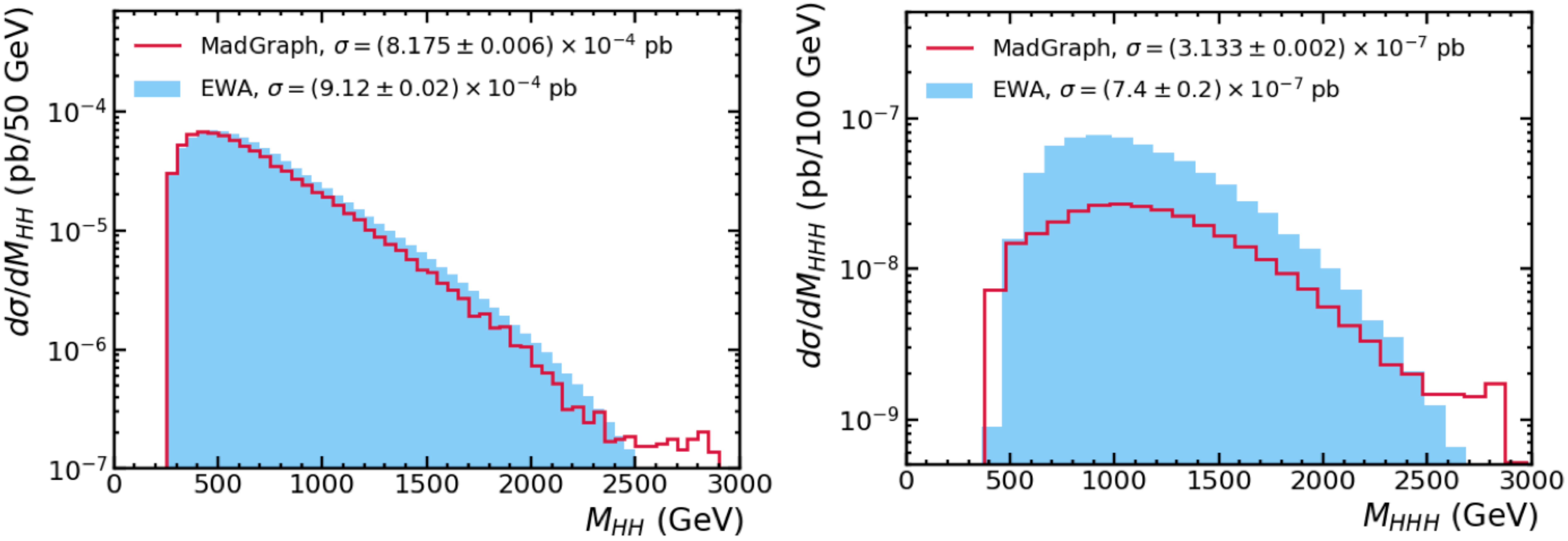
(Madgraph5 used for all collider cross section predictions)

The effective W approximation for WW->HH in e+e-: SM

W's are treated as partons inside electrons. Their "PDFs" allow to compute full cross sections from subprocess.[4]

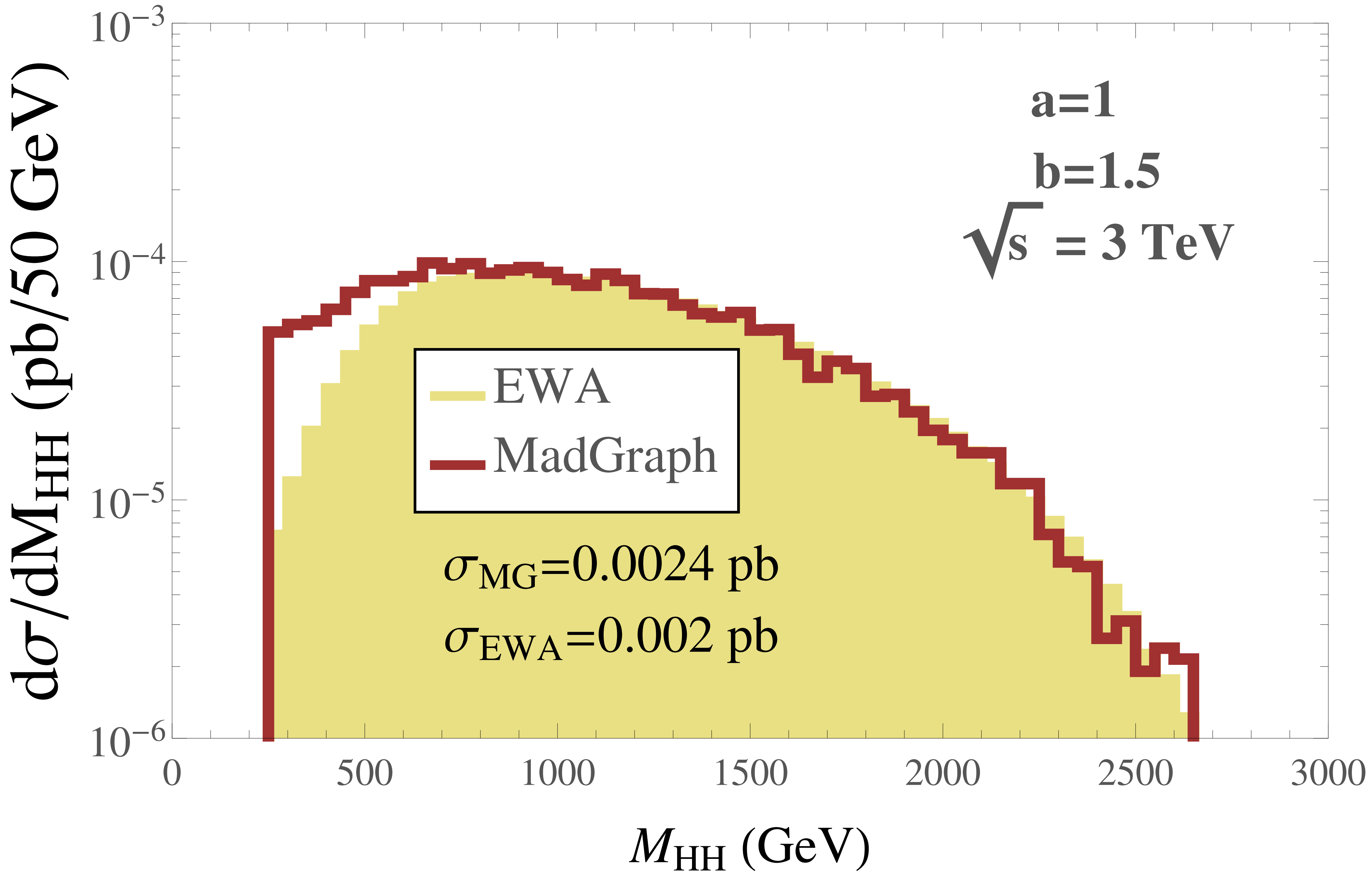
[4] S. Dawson, Nucl. Phys. B **249** (1985)

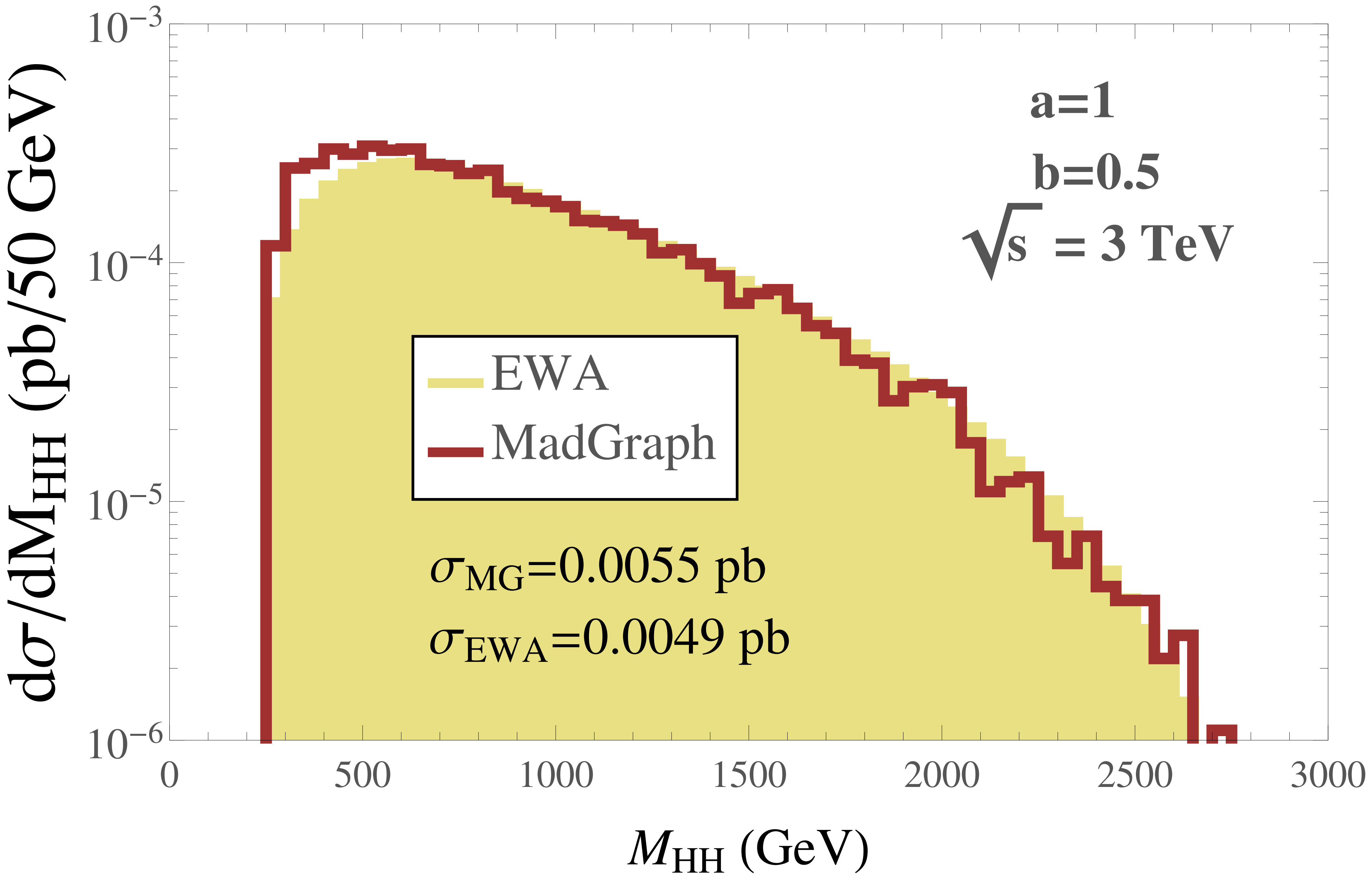
$$\sigma(e^+e^- \to HH\nu\bar{\nu}) = \int dx_1 \int dx_2 f(x_1) f(x_2) \hat{\sigma}(W^+W^- \to HH)$$



Good approximation for HH, not so good for HHH

The effective W approximation for WW->HH in e+e-: BSM





The EWA even better approach for BSM!

The effective W approximation for VBS in pp : SM and BSM

- Effective W Approximation (EWA): Ws & Zs considered as partons inside the proton [S. Dawson, Nucl. Phys. B 249 (1985) 42]

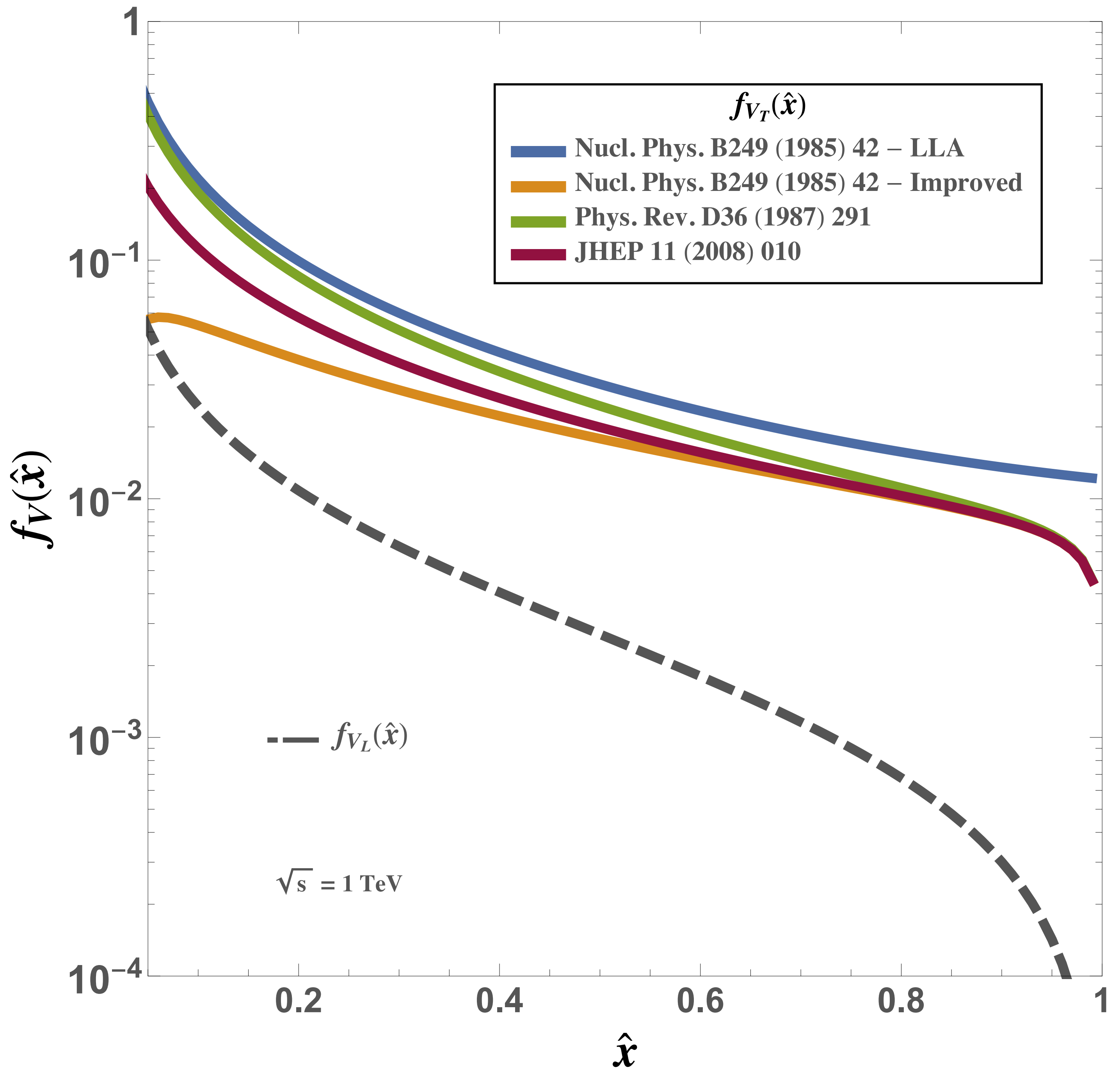
- They are emitted collinearly from the fermions (quarks) with prob. functions $f_V(\hat{x})$ & then scatter on-shell

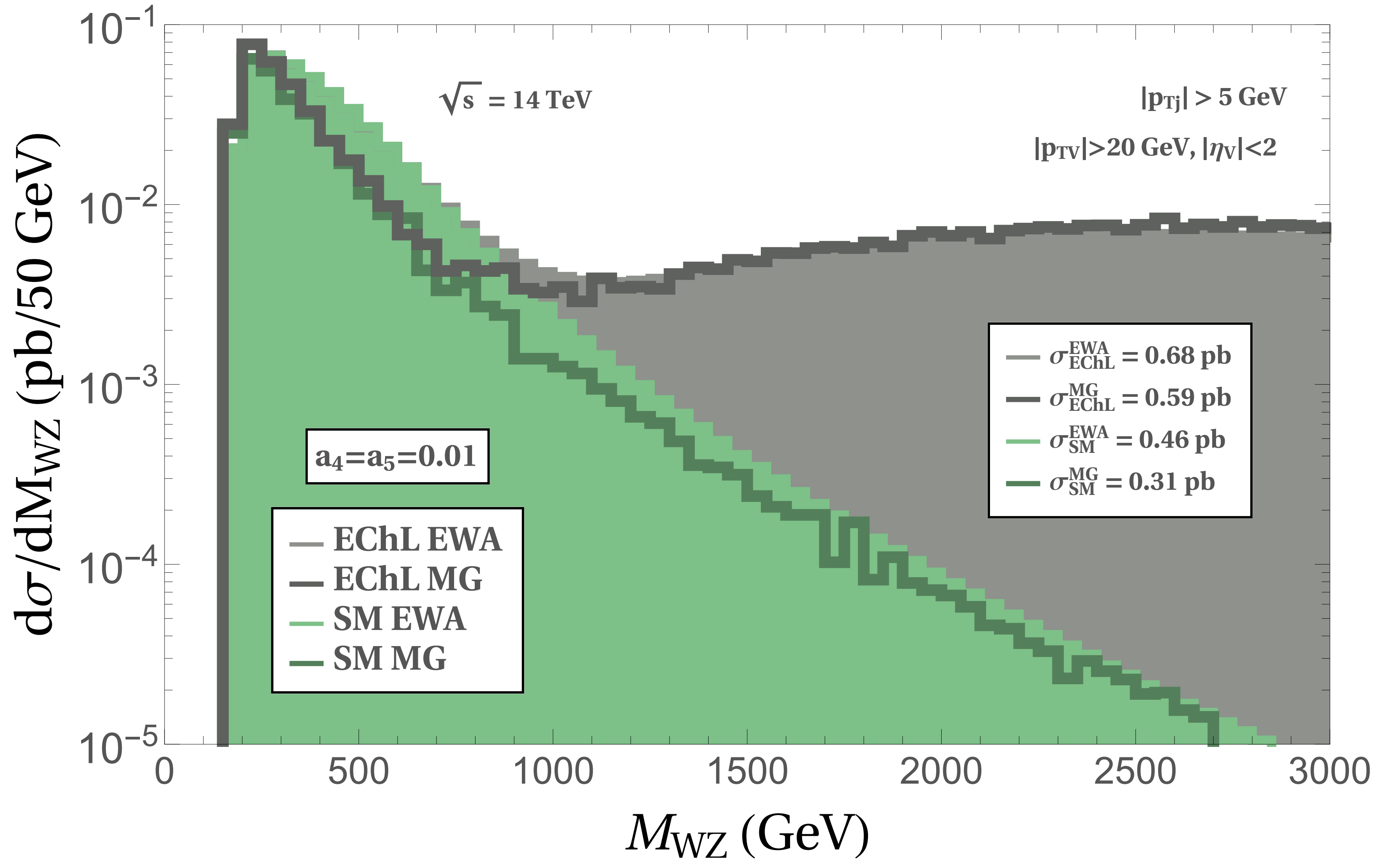
- Very intuitive interpretation: factorization using a sort of "PDFs"

$$\sigma(pp \to (V_1V_2 \to V_3V_4) + X) =$$

$$\sum_{i,j} \int\!\!\int dx_1\, dx_2\, f_i(x_1) f_j(x_2) \int\!\!\int d\hat{x}_1\, d\hat{x}_2\, f_{V_1}(\hat{x}_1) f_{V_2}(\hat{x}_2)\, \hat{\sigma}(V_1V_2 \to V_3V_4)$$

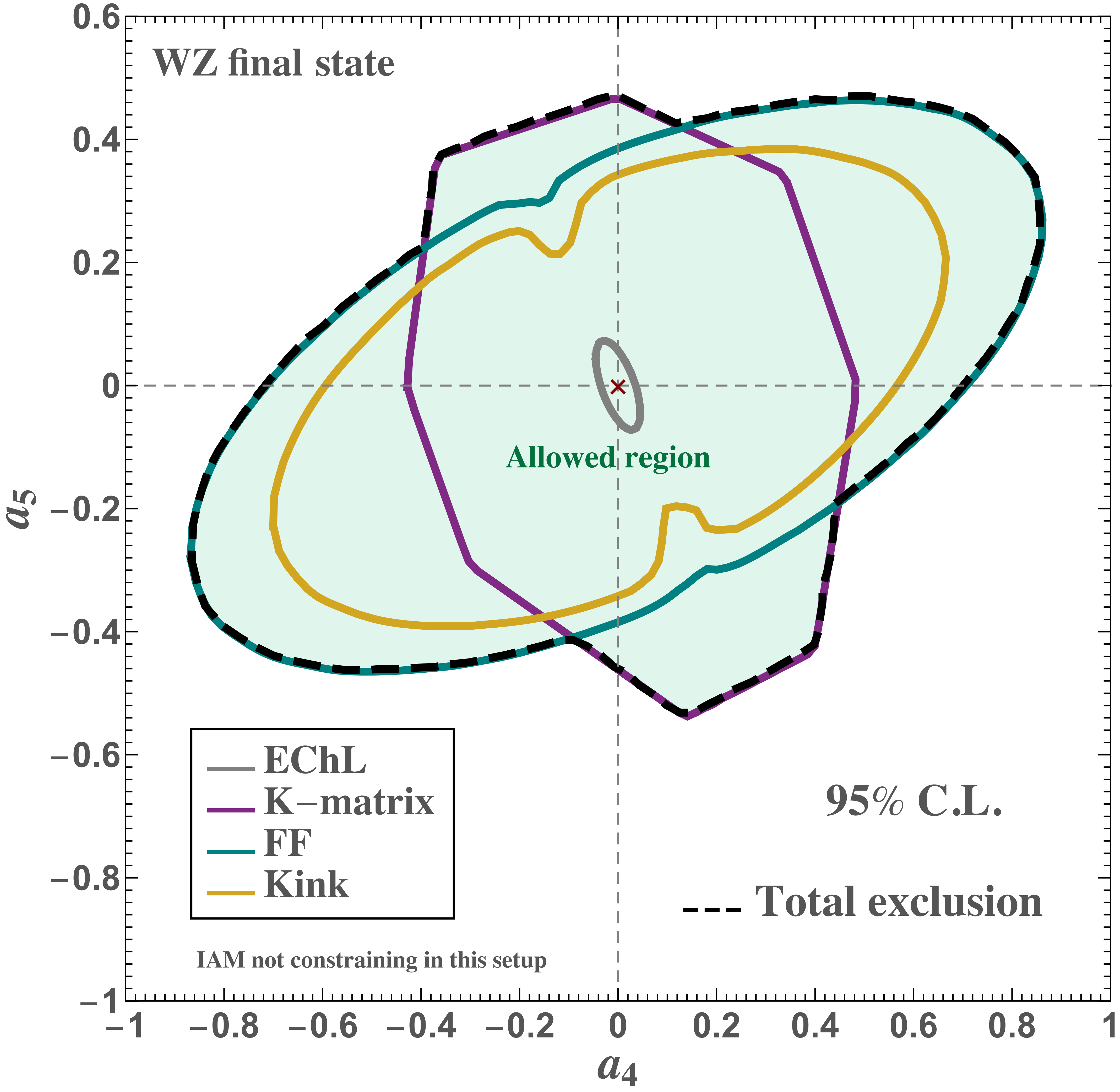
- We have tested with MG5 the accuracy of various probability functions (SM & EChL cases): Dawson's improved formulas work best



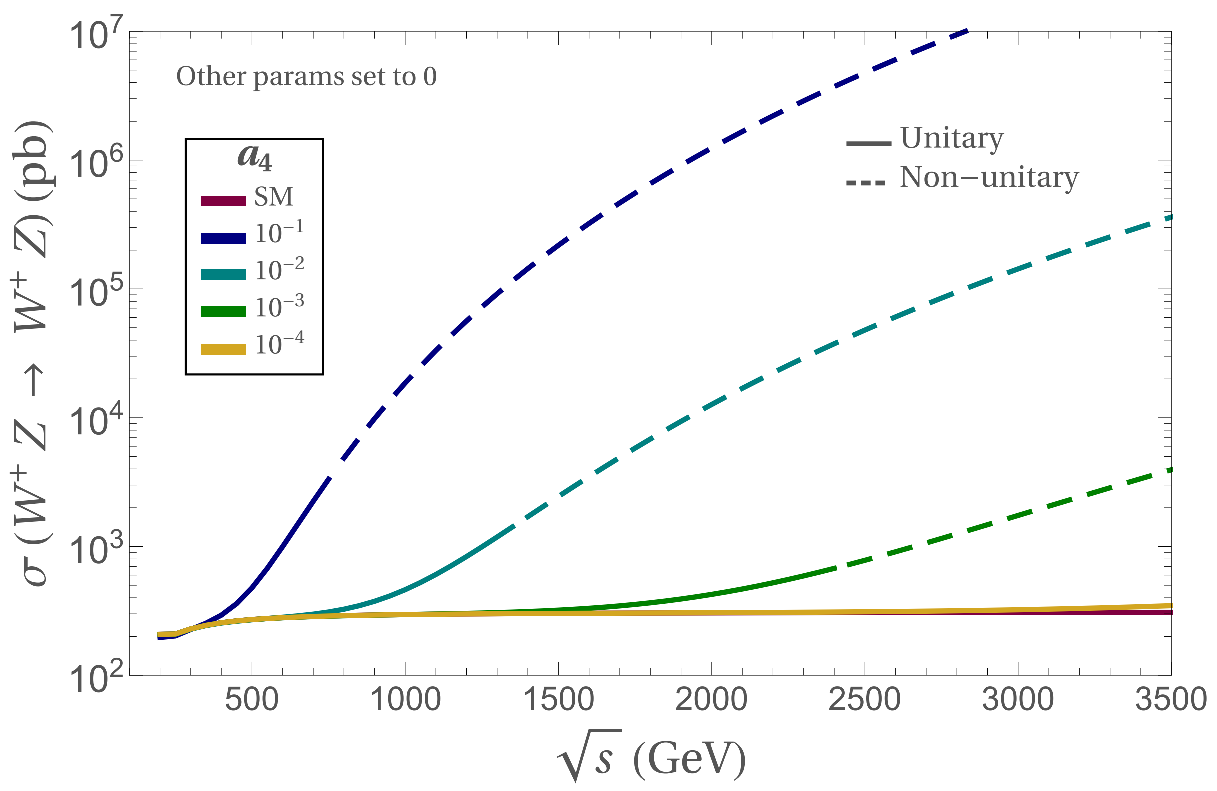


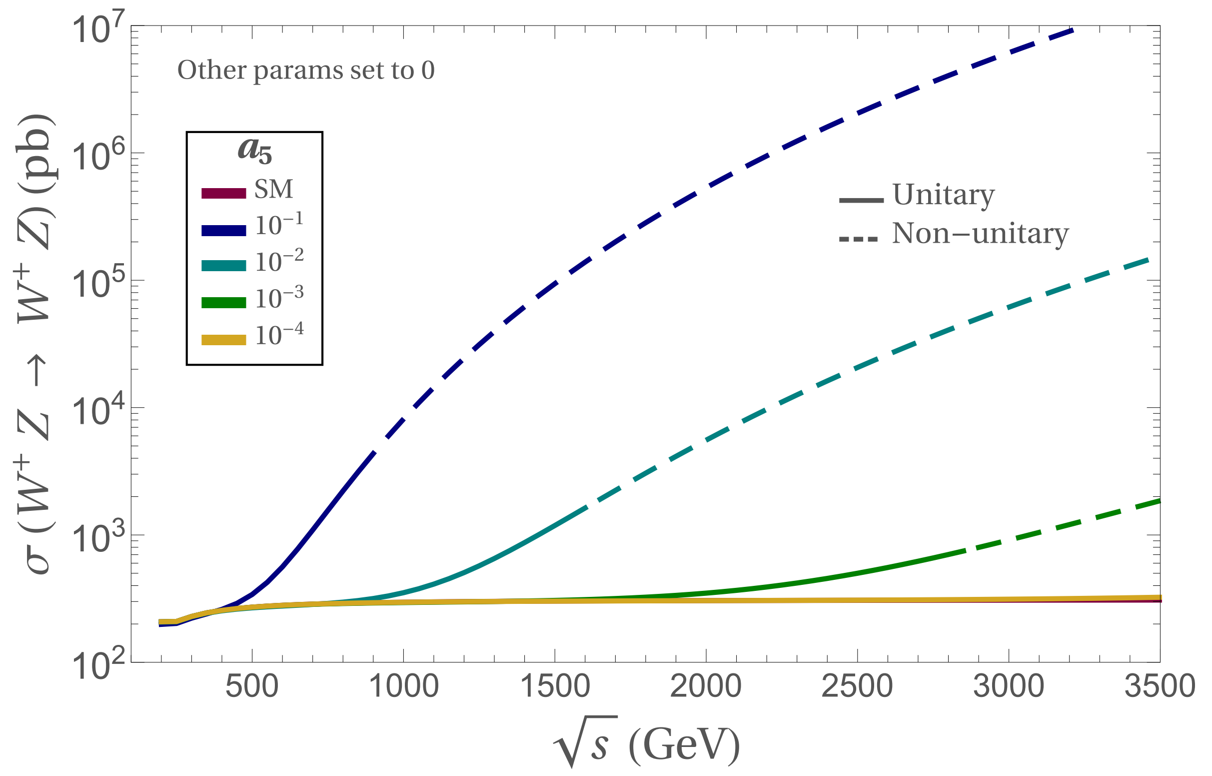
Unitarization effects in EFT predictions (example: WZ at LHC)

1907.06668, PRD 100 (2019)9, 096003, García-García, Herrero, Morales



Warning: the constraints on the anomalous couplings in EFTs depend strongly on the procedure to repair the unitarity violation, unavoidable at TeV energies





$$a_{4(5)} = \frac{v^4}{16}\frac{f_{S,0(1)}}{\Lambda^4}$$