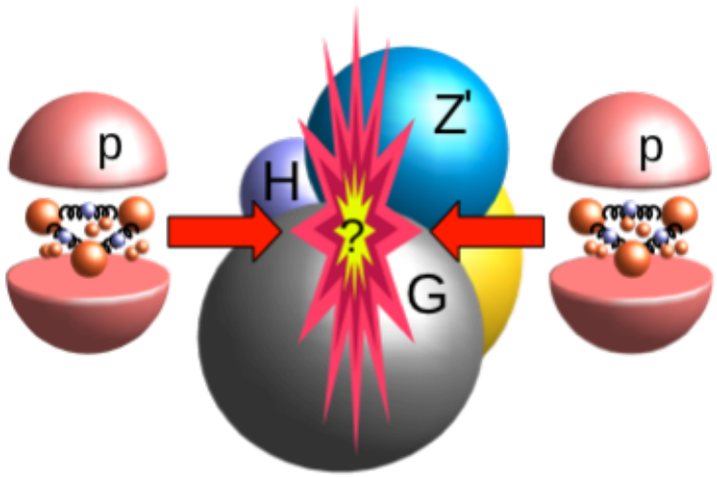
Interference and finite width effects in di-boson resonance searches with the **JHUGen** framework



Andrei Gritsan

Johns Hopkins University

for **JHUGen** / **MELA** framework developers

November 5, 2021

Extended Higgs Sector subgroup meeting

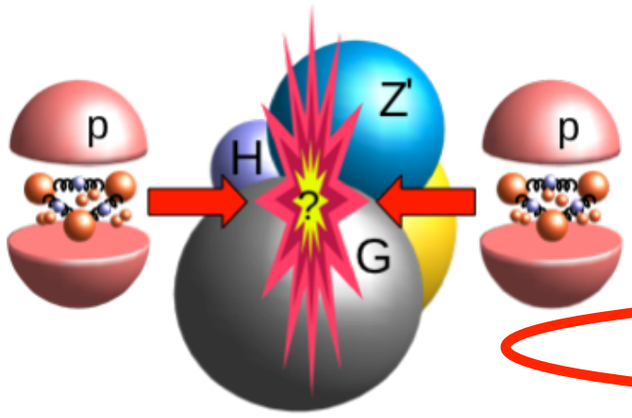
LHC Higgs Working Group WG3 (BSM)

JHUGen framework (for BSM and EFT)

JHUGen — generator

MELA — Matrix Element library

JHUGenLexicon — basis translation …



https://spin.pha.jhu.edu

Theory + Experiment collaboration

MC Generator based on the papers:

"Spin Determination of Single-Produced Resonances at Hadron Colliders"
Yanyan Gao, Andrei V. Gritsan, Zijin Guo, Kirill Melnikov, Markus Schulze, and Nhan V.Tran
http://arxiv.org/abs/1001.3396

"On the Spin and Parity of a Single-Produced Resonance at the LHC"
Sara Bolognesi, Yanyan Gao, Andrei V. Gritsan, Kirill Melnikov, Markus Schulze, Nhan V. Tran, and Andrew Whitbeck
http://arxiv.org/abs/1208.4018

"Constraining anomalous HVV interactions at proton and lepton colliders"
Ian Anderson, Sara Bolognesi, Fabrizio Caola, Yanyan Gao, Andrei V. Gritsan, Christopher B. Martin, Kirill Melnikov, Markus Schulze, Nhan V. Tran, Andrew Whitbeck, and Yaofu Zhou
http://arxiv.org/abs/1309.4819

"Constraining anomalous Higgs boson couplings to the heavy flavor fermions using matrix element techniques"
Andrei V. Gritsan, Raoul Rontsch, Markus Schulze, and Meng Xiao
http://arxiv.org/abs/1606.03107

"New features in the JHU generator framework: constraining Higgs boson properties from on-shell and off-shell production"
Andrei V. Gritsan, Jeffrey Roskes, Ulascan Sarica, Markus Schulze, Meng Xiao, and Yaofu Zhou
http://arxiv.org/abs/2002.09888

"Probing the CP structure of the top quark Yukawa coupling: Loop sensitivity vs. on-shell sensitivity"
Till Martini, Ren-Qi Pan, Markus Schulze, and Meng Xiao
https://arxiv.org/abs/2104.04277

"Constraining anomalous Higgs boson couplings to virtual photons"
Jeffrey Davis, Andrei V. Gritsan, Lucas S. Mandacaru Guerra, Savvas Kyriacou, Jeffrey Roskes, and Markus Schulze
https://arxiv.org/abs/2109.13363

contacts: Jeffrey Davis ,Jeffrey (Heshy) Roskes,Ulascan Sarica,Markus Schulze

New features in the JHU generator framework: Constraining Higgs boson properties from on-shell and off-shell production

Andrei V. Gritsan,[1,*] Jeffrey Roskes,[1,†] Ulascan Sarica,[1,2,‡] Markus Schulze,[3,§] Meng Xiao,[1,4,‖] and Yaofu Zhou[1,5,¶]

[1]*Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21218, USA*
[2]*Department of Physics, University of California, Santa Barbara, California 93106, USA*
[3]*Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany*
[4]*Zhejiang Institute of Modern Physics, Department of Physics, Zhejiang University, Hangzhou 310027, People's Republic of China*
[5]*Department of Physics, Missouri University of Science and Technology, Rolla, Missouri 65409, USA*

(Received 21 February 2020; accepted 22 July 2020; published 28 September 2020)

arXiv:2002.09888

Interference and finite width effects

- Conveners set the goal for this meeting:

  - Interference and finite width effects in BSM searches
  - Recasts of LHC searches on extra scalars
  - Overlooked signatures

- Focus on the tools for the first topic:

  — BSM $X(m_X)$

  — any (unknown) mass m_X , width Γ_X , or rate (cross-section)

  — spin-zero X, but any couplings of dim-4 (SM-like) or higher

  — singly-produced in gluon fusion or EW

  — focus on di-boson final state $X \to VV \to 4f$

  — interference with both “resonant” (H*) and “non-resonant” SM

  — production and decay correlated in interference

Interference and finite width effects

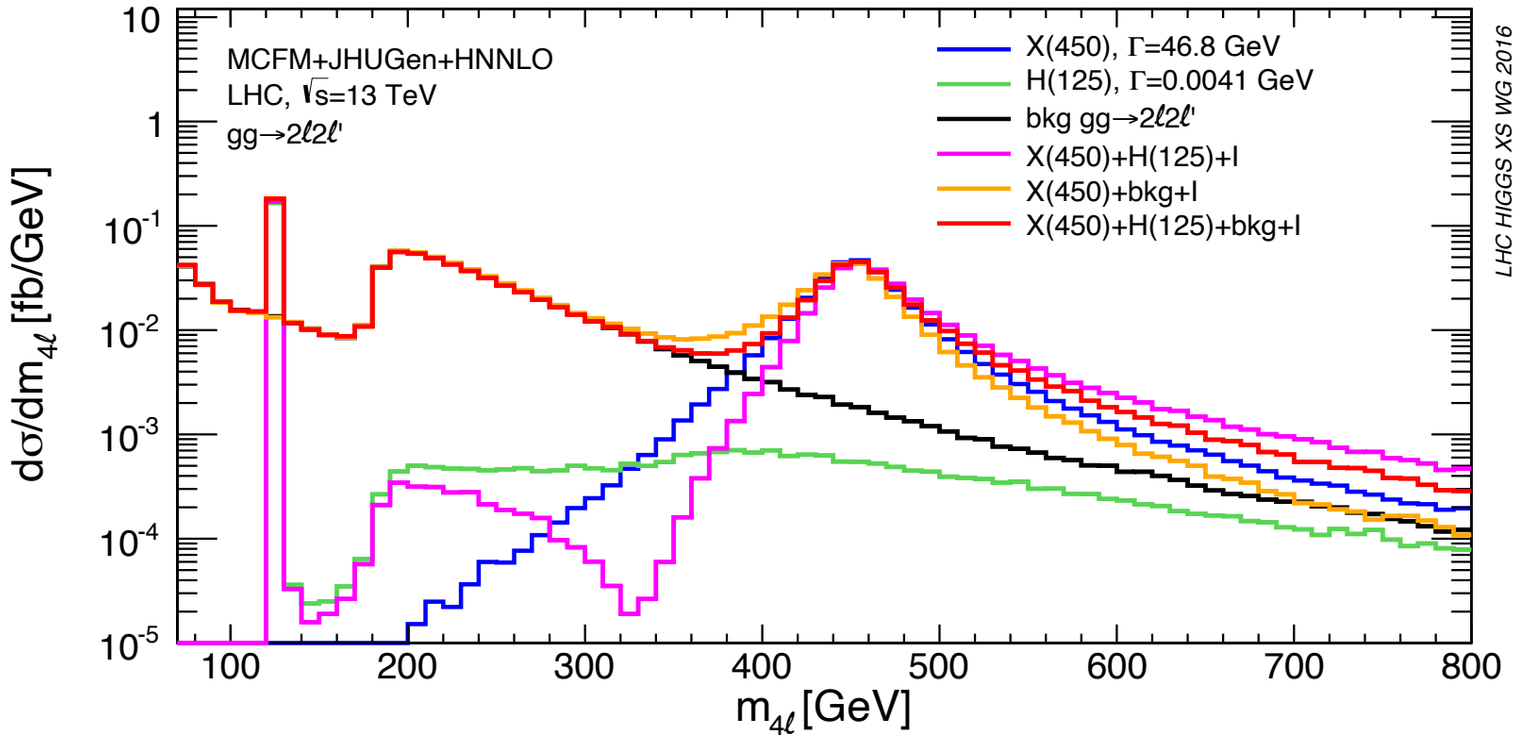
Plot from YR4 (2016)

with **JHUGen**+**MCFM**

example $X(450)$:

LO in QCD

+ k factor (m_{VV})



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JHUGen + MCFM

- Coherent framework to treat four effects in di-boson "continuum"
- Tools **JHUGen**+**MCFM** and **MELA**

H* + X + continuum + interference

include re-weighting and discriminants

cover both gg and EW (VBF, VH)

integrated with **POWHEG**, **MiNLO**…

(1) new resonance(s) X

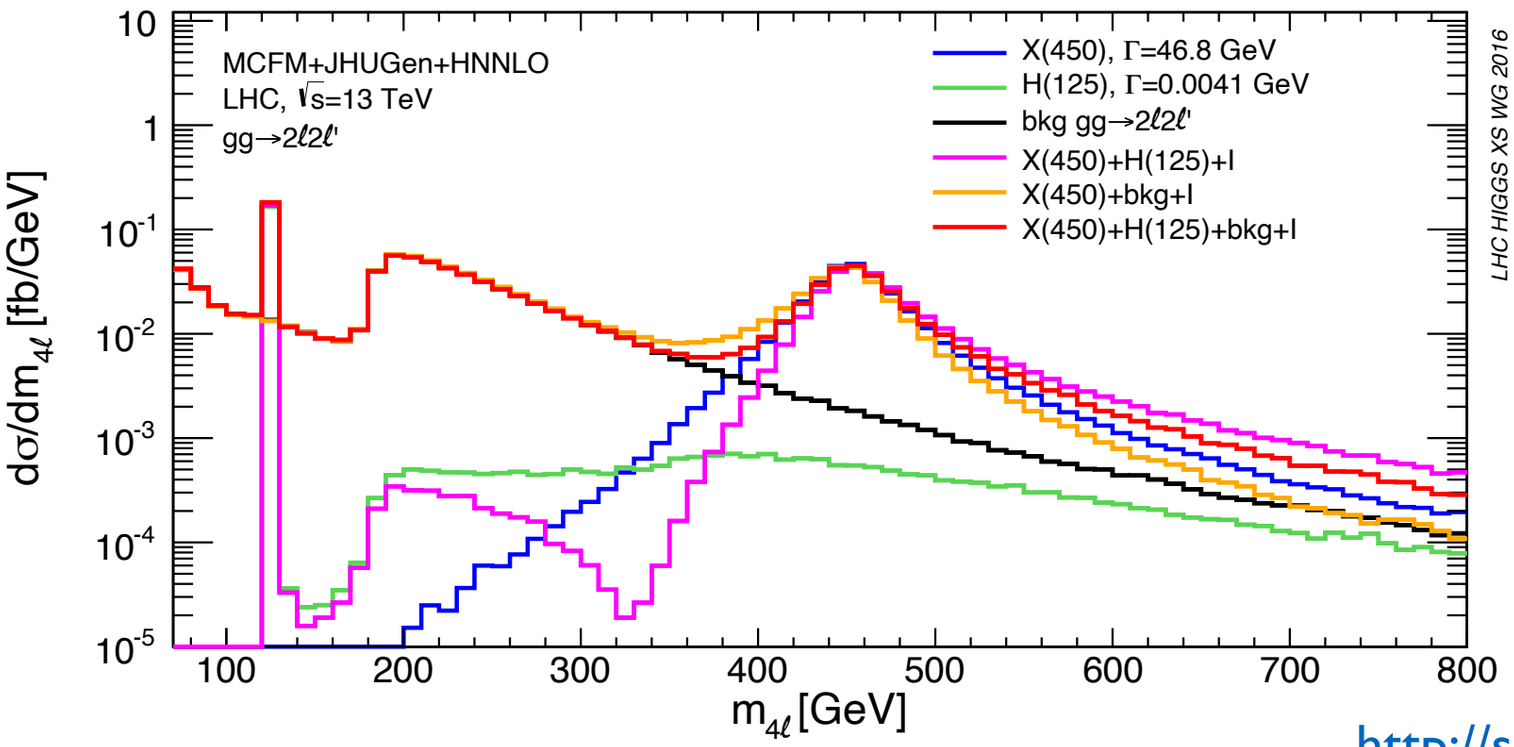
(2) width Γ_H modification

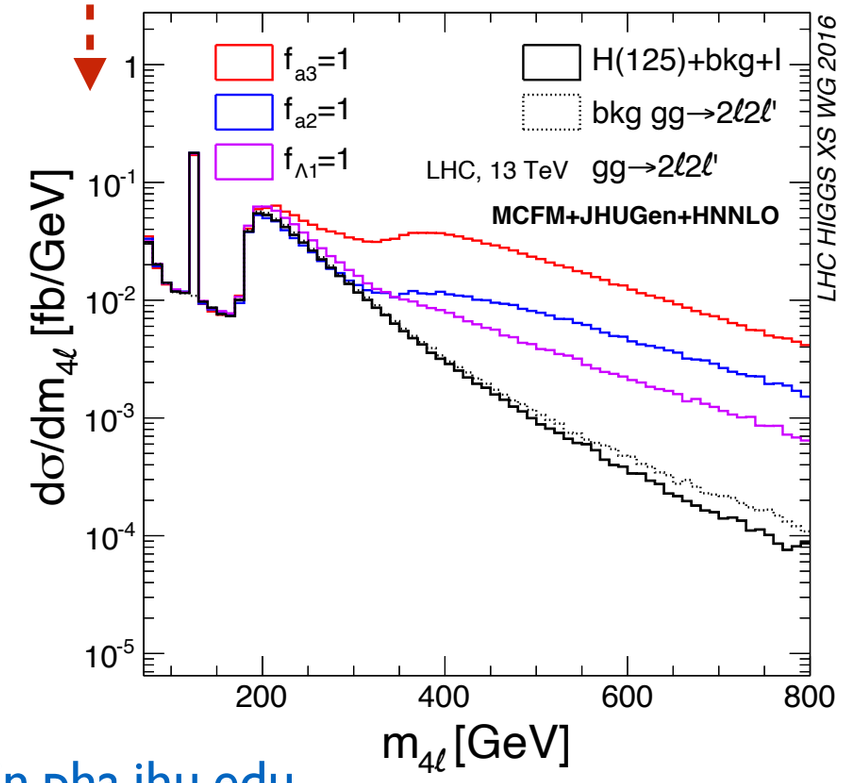
(3) anomalous couplings

X/HVV, X/Hgg, X/Htt

(4) anomalous VBS/gg

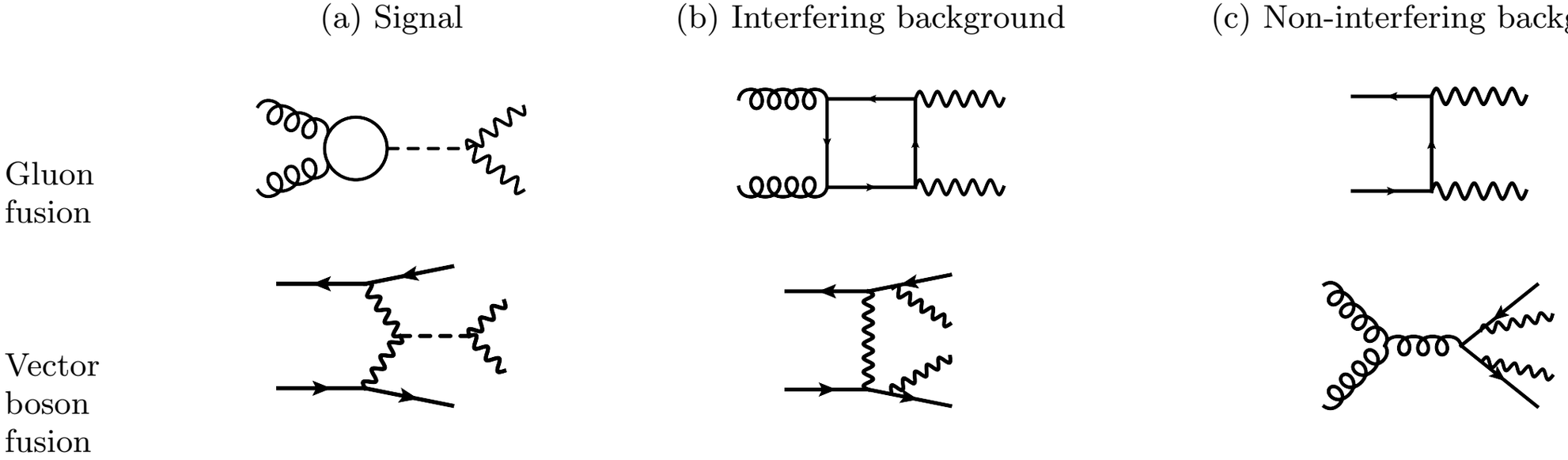
- Plots from YR4 (2016):



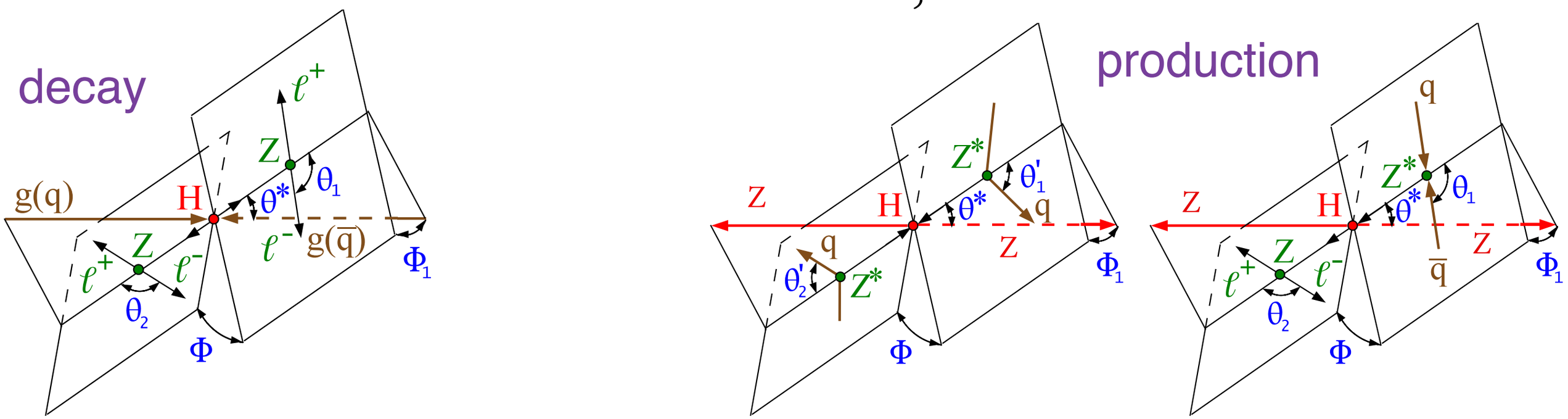


http://spin.pha.jhu.edu

Consider X/HVV and X/Hgg couplings for J=0



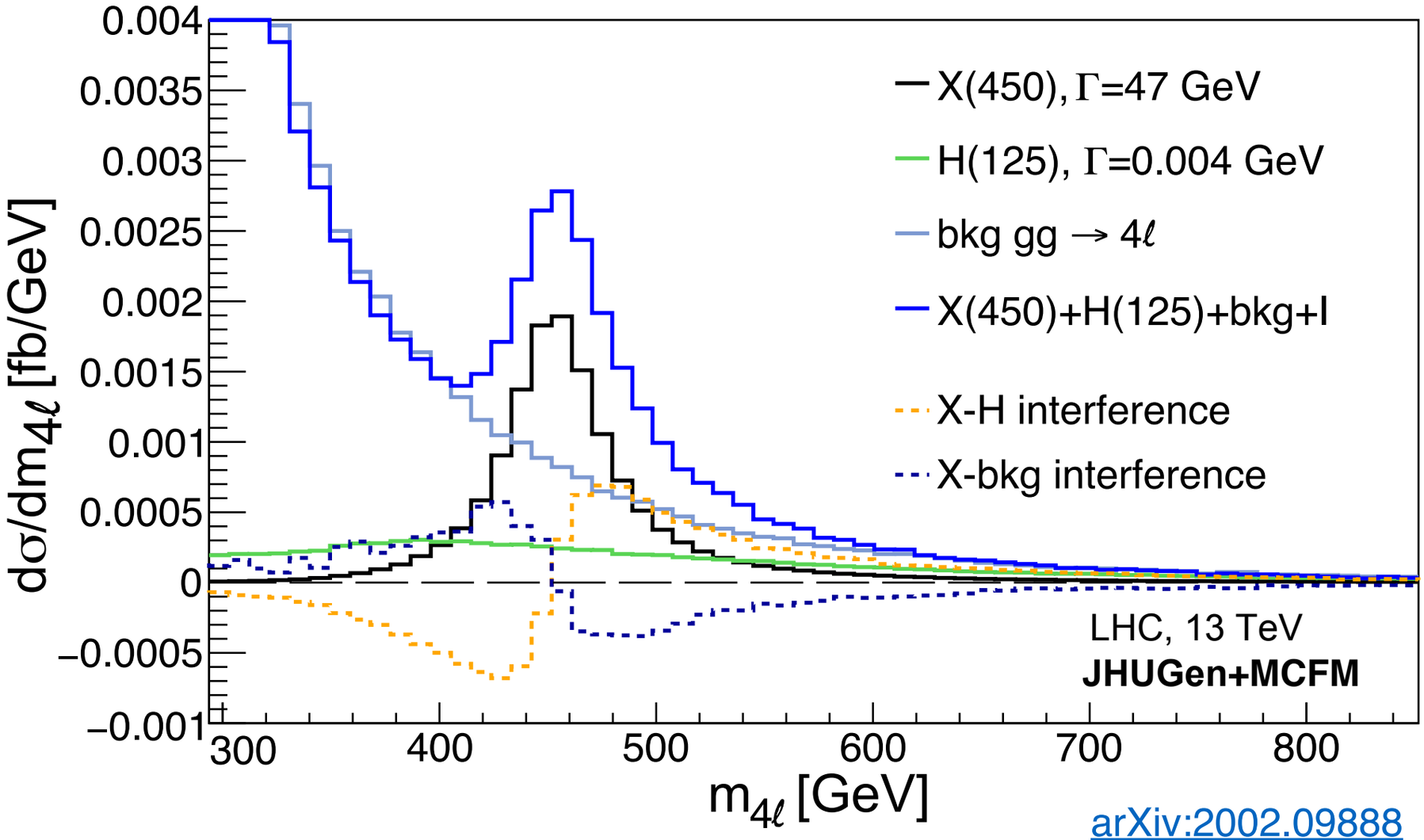
$$A(HV_1V_2)=\frac{1}{v}\left\{ M_{V_1}^2\left(g_1^{VV}+\frac{\kappa_1^{VV}q_1^2+\kappa_2^{VV}q_2^2}{\left(\Lambda_1^{VV}\right)^2}+\frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}+\frac{2q_1\cdot q_2}{M_{V_1}^2}g_2^{VV}\right)(\varepsilon_1\cdot\varepsilon_2)\right.$$
$$\left.-2g_2^{VV}\,(\varepsilon_1\cdot q_2)(\varepsilon_2\cdot q_1)-2g_4^{VV}\,\varepsilon_{\varepsilon_1\,\varepsilon_2\,q_1\,q_2}\right\},$$



Examples

- $gg \to (X/H^*) \to ZZ \to 4\ell$

  SM-like scalar couplings (tree-level)



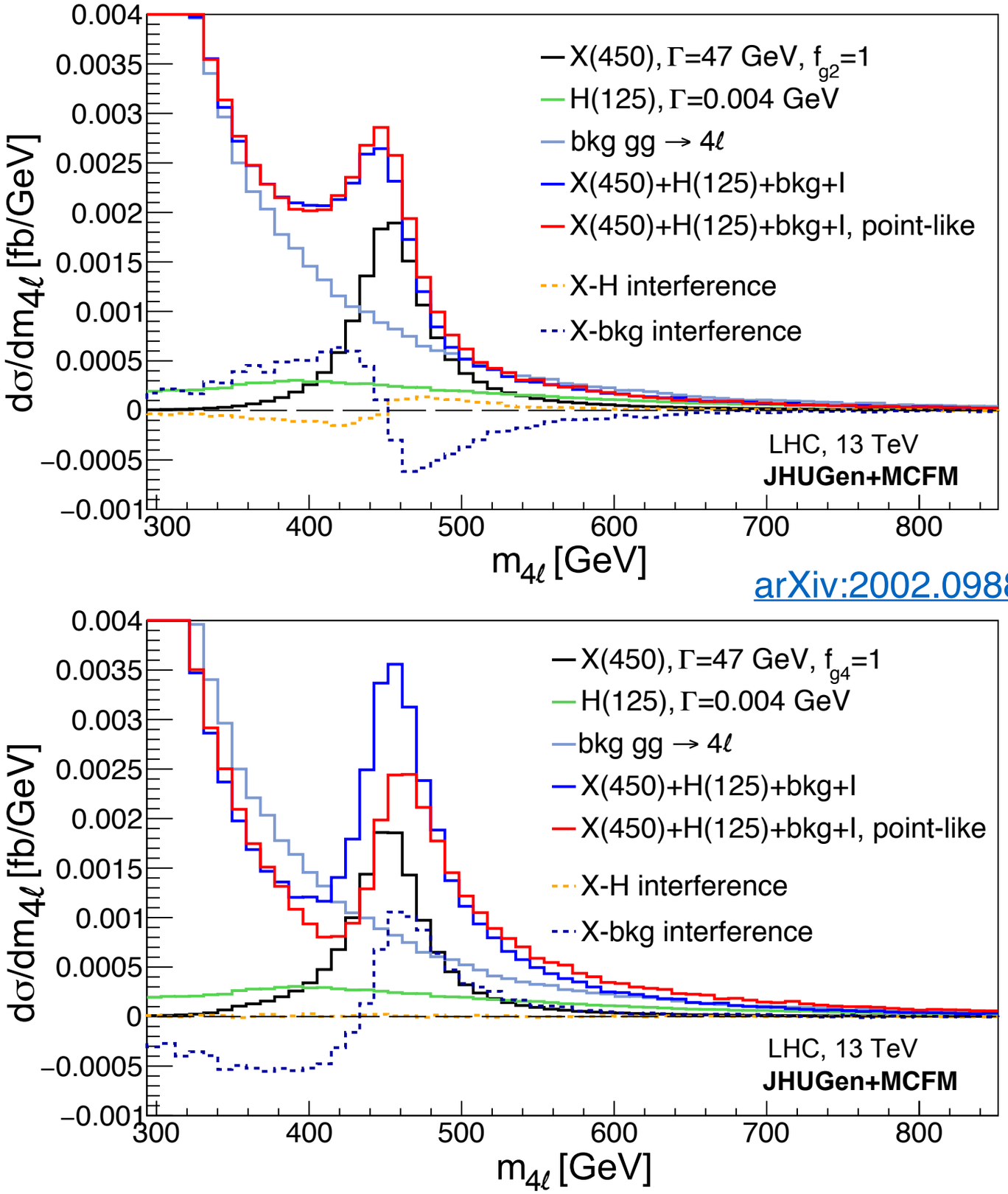
arXiv:2002.09888

Examples: $gg \to (X/H^*) \to ZZ/Z\gamma^*/\gamma^*\gamma^* \to 4\ell$

dim-6 scalar couplings

(a) top loop

(b) point-like coupling



arXiv:2002.09888

dim-6 pseudo-scalar

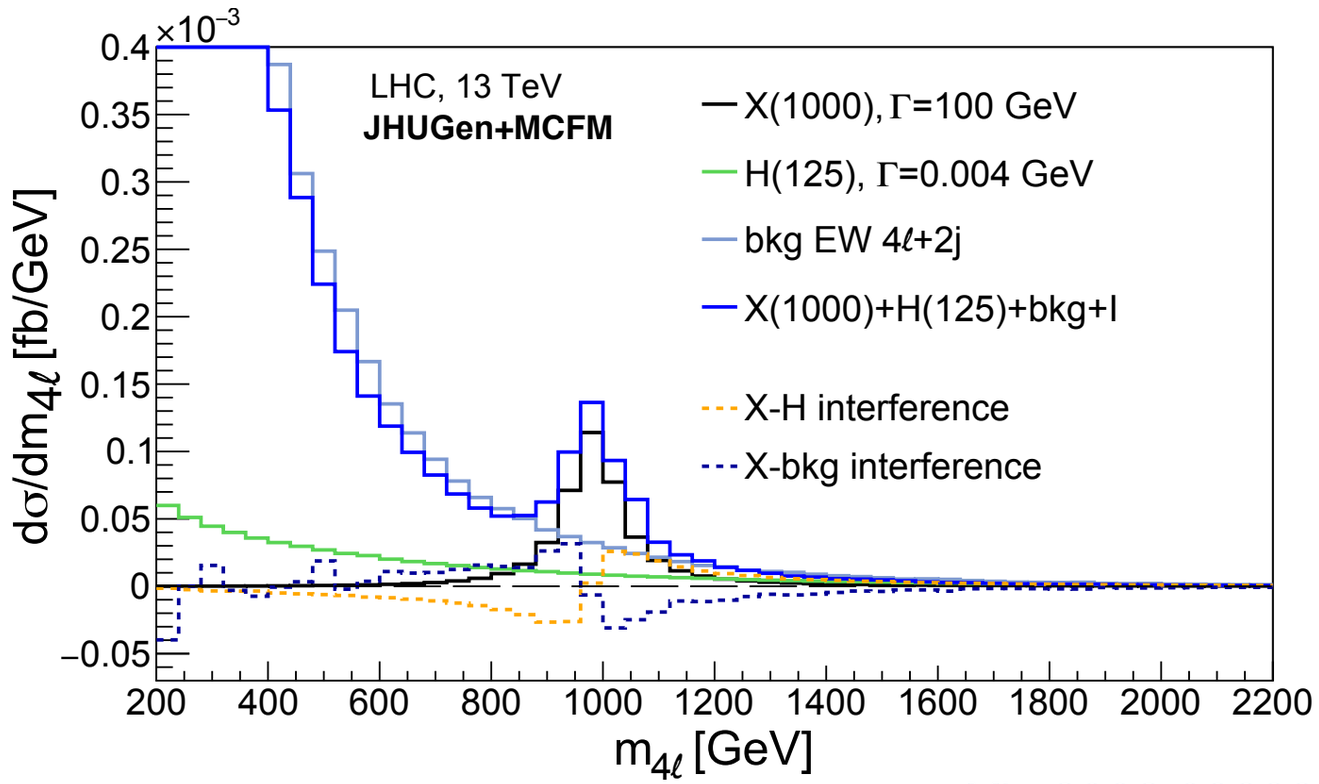
(a) top loop

(b) point-like coupling

Examples: EW $qq \to qq\ (ZZ/Z\gamma^*/\gamma^*\gamma^* \to 4\ell)$

dim-4 scalar couplings

SM-like

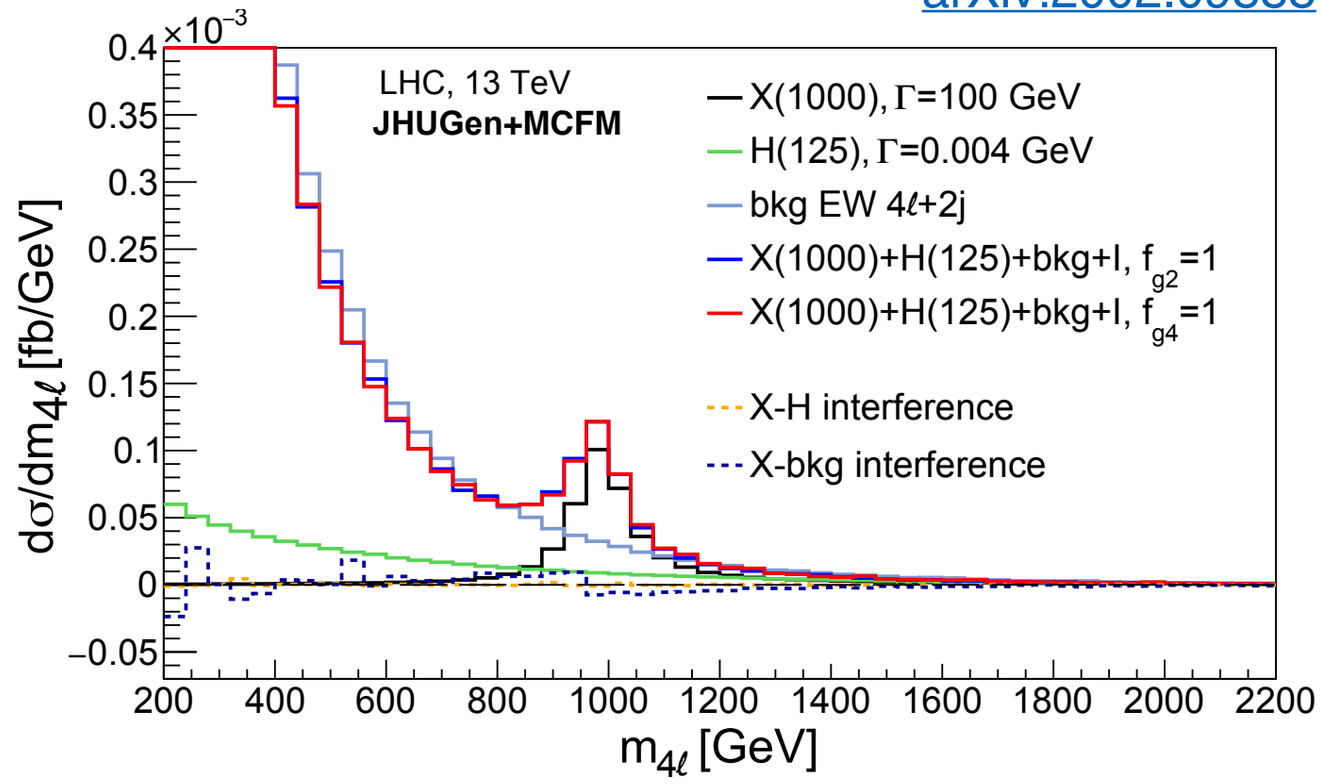


arXiv:2002.09888

dim-6 couplings
(in production and decay)

(a) scalar

(b) pseudo-scalar



Incorporating NLO in QCD effects

- Signal + Background + Interf. at LO in QCD: **JHUGen**+**MCFM**

  (only very recently NLO tools developed, but not for BSM yet…)

- For SM signal only: use **POWHEG** at NLO in QCD

  — additional corrections needed:

  only “stable” resonance is produced (in LHE)

  (1) line shape needs special care

  (2) need kinematics & phase space of $X/H \to ZZ/WW \to 4f$

  — **POWHEG** (production) + **JHUGen** (decay) fixes this

  — weights in LHE or off-line re-weighting with **MELA**

  — standard for BSM simulation $X/H \to ZZ/WW \to 4f$ on CMS

POWHEG + JHUGen

- Simplified picture for illustration:

$$\mathscr{P}(gg \to X \to V_1 V_2 \to 4f) =$$

done by **POWHEG** in LHE

$$\text{PDF} \times |A_{\text{prod}} \times X \text{ propagator}|^2$$

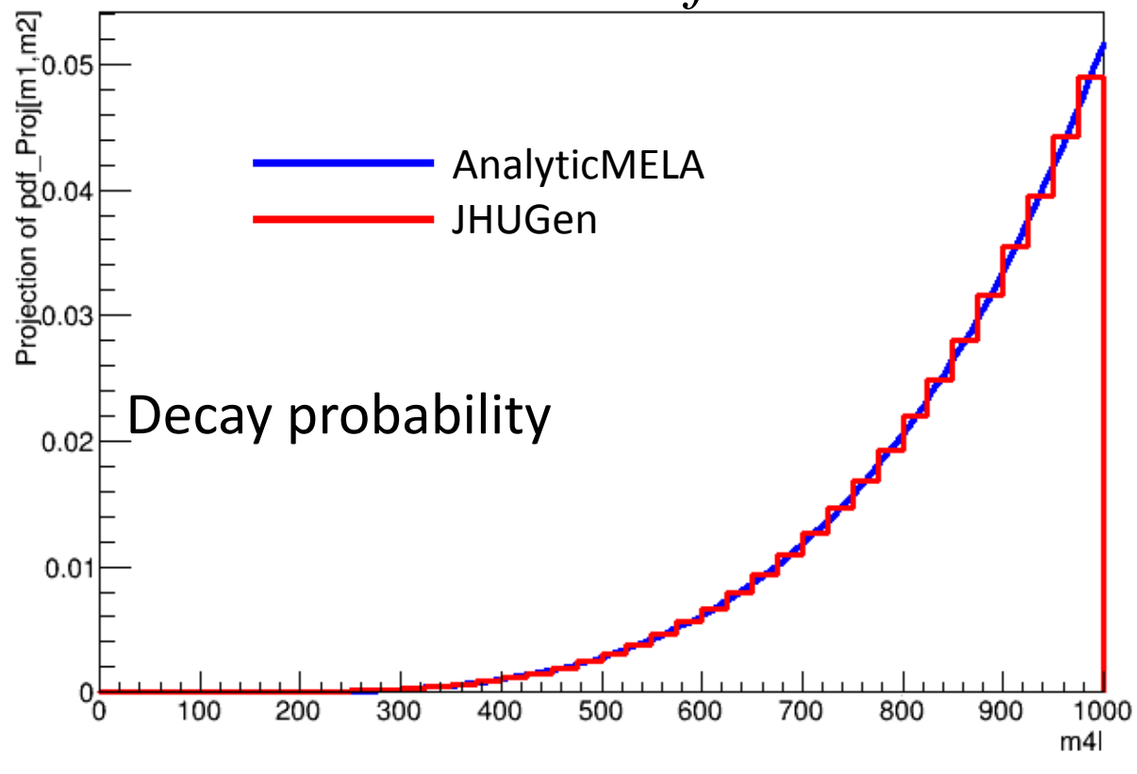
$$\times |A_{X\to V_1V_2\to 4f} \times V_1 \text{ propagator} \times V_1 \text{ propagator}|^2 \times (X \to 4f \text{ phasespace})$$

done by **JHUGen** in LHE → LHE

$P_{\text{dec}}(m_{4f})$ by **JHUGen**

checked with **Analytic MELA**

$P_{\text{dec}}(m_{4f})$



POWHEG + JHUGen

- CPS mode of **POWHEG** (Complex Pole Scheme)

  — approximate $P_{\rm dec}(m_{4f})$ as $m_{4f}\Gamma_{\rm CPS}$

  — change Γ_X from loop corrections assuming SM H boson

e.g. for $m_X = 600$ GeV

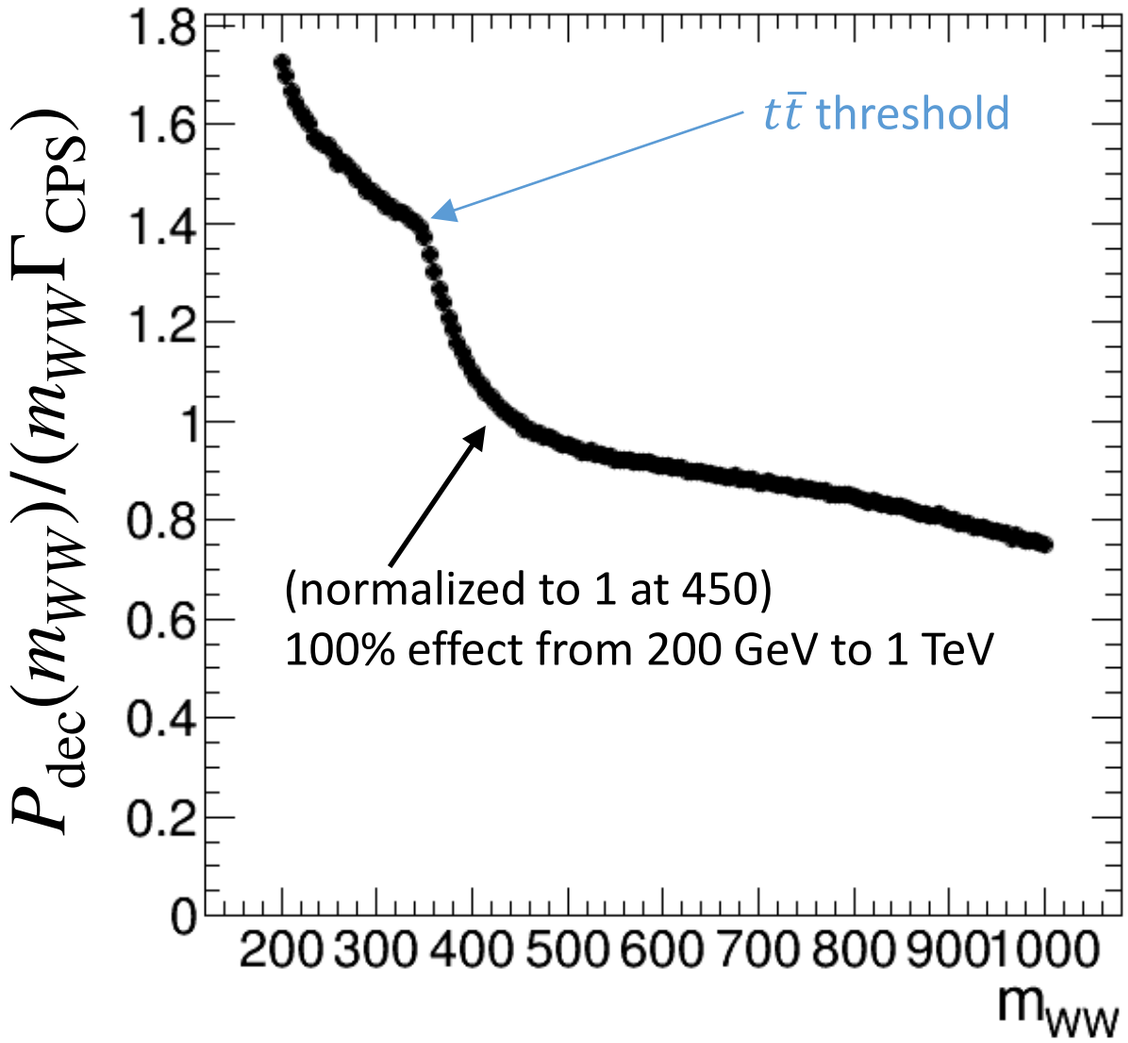
$\Gamma_X = 123$ GeV $\rightarrow \Gamma_{\rm CPS} = 104$ GeV

- Corrections in **JHUGen**

(1) drop CPS correction

(2) put exact $P_{\rm dec}(m_{4f})$ ----------→

get a BW with the desired Γ_X



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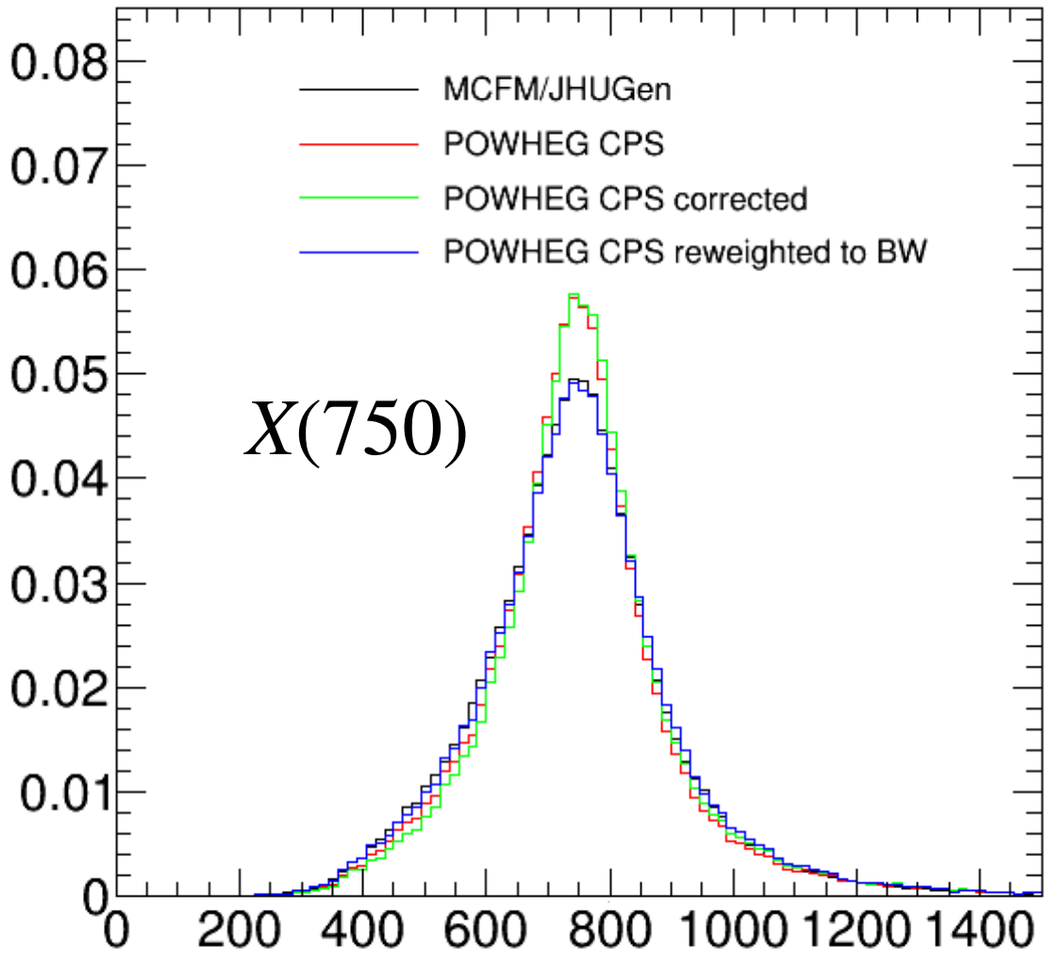
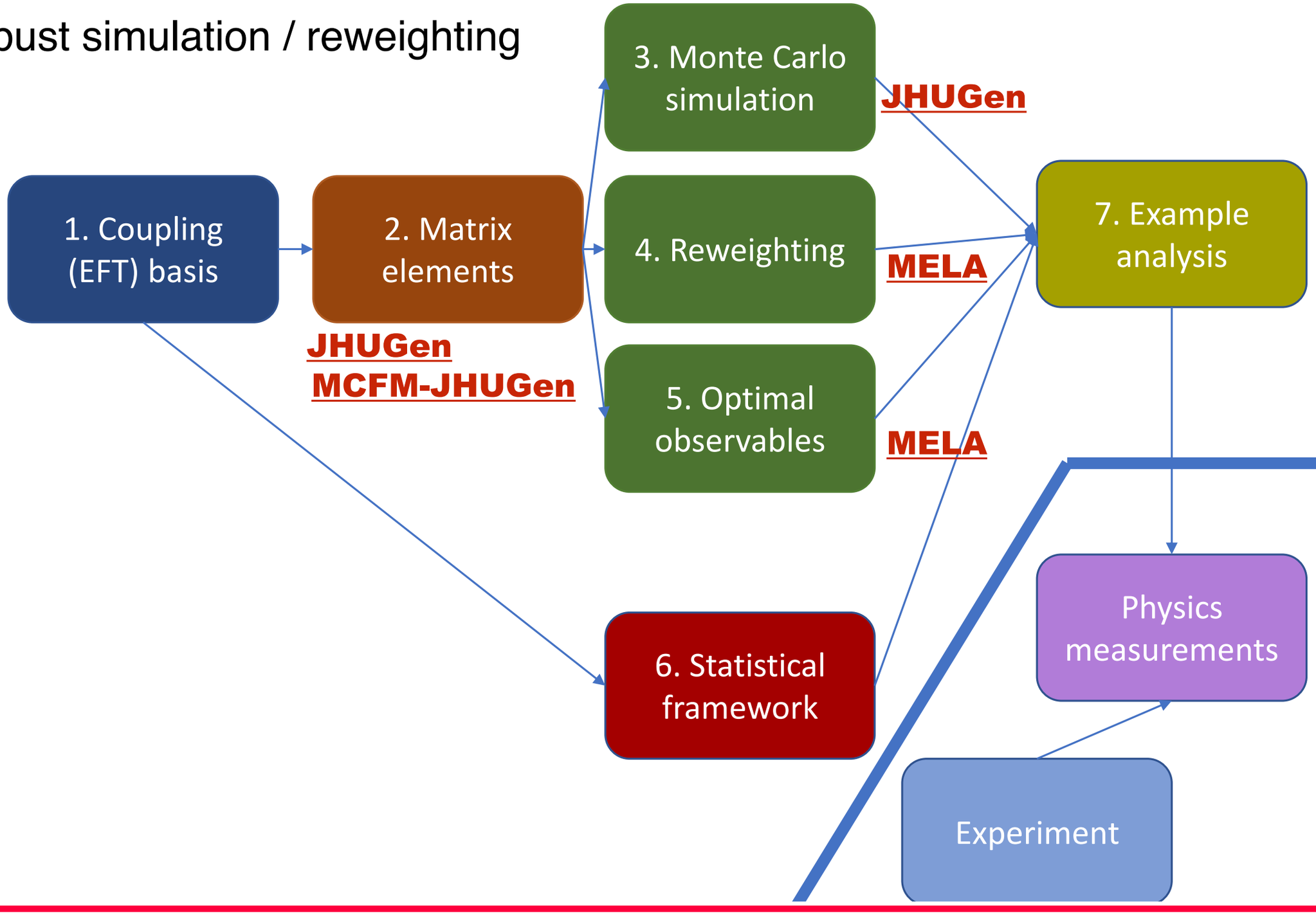


JHUGen framework (for BSM / EFT)

- Support: detector-level studies
  optimal observables
  robust simulation / reweighting

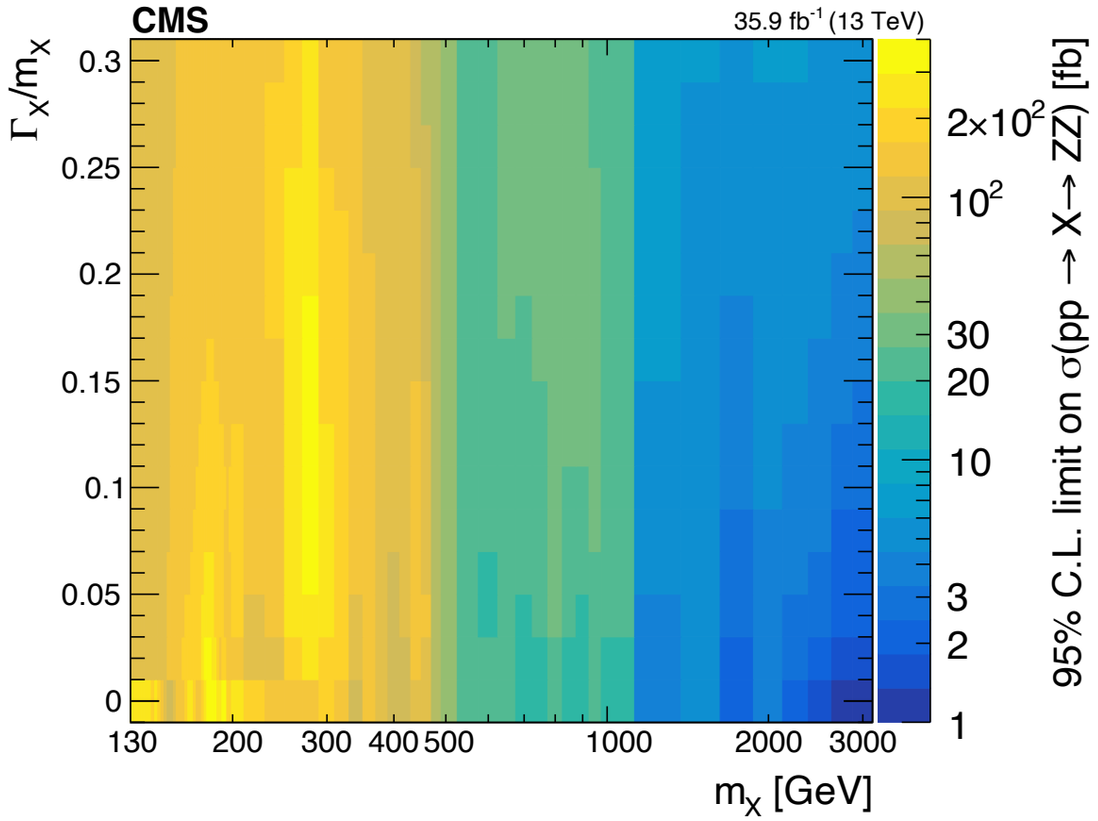
see talks: [Meng Xiao at ICHEP-2020]
[Heshy (J.) Roskes at Pheno-2020]

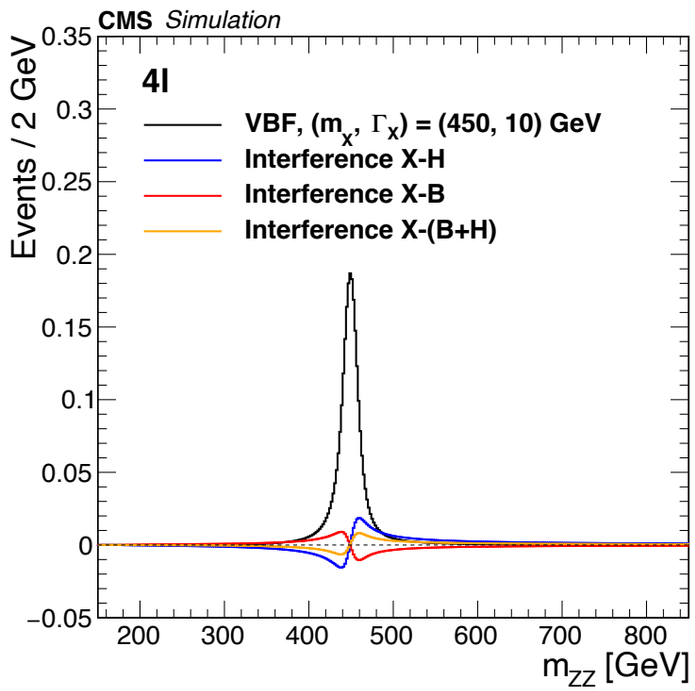


Application to LHC data: $X \to ZZ$

- $X \to ZZ \to 4\ell$ / $2\ell 2q$ / $2\ell 2\nu$

CMS: arXiv:1804.01939





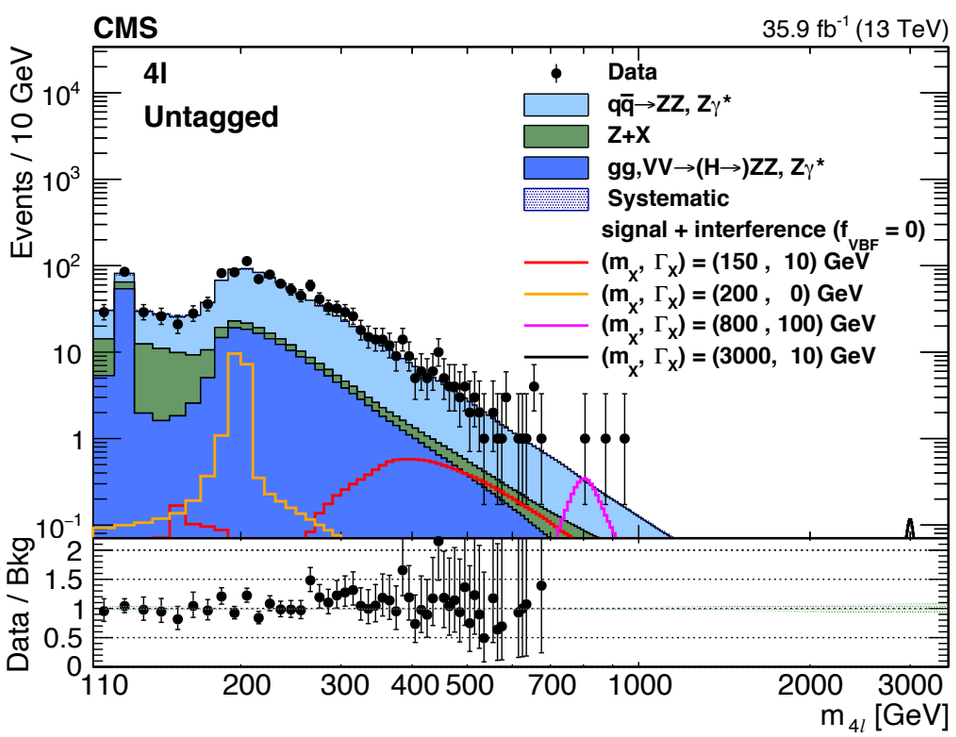
any mass
any width
any production (ggH or EW)
full interference
SM-like coupling (but can vary)

simulation (prod+dec):

POWHEG+**JHUGen**

MELA weights

analytic parameterization



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any mass
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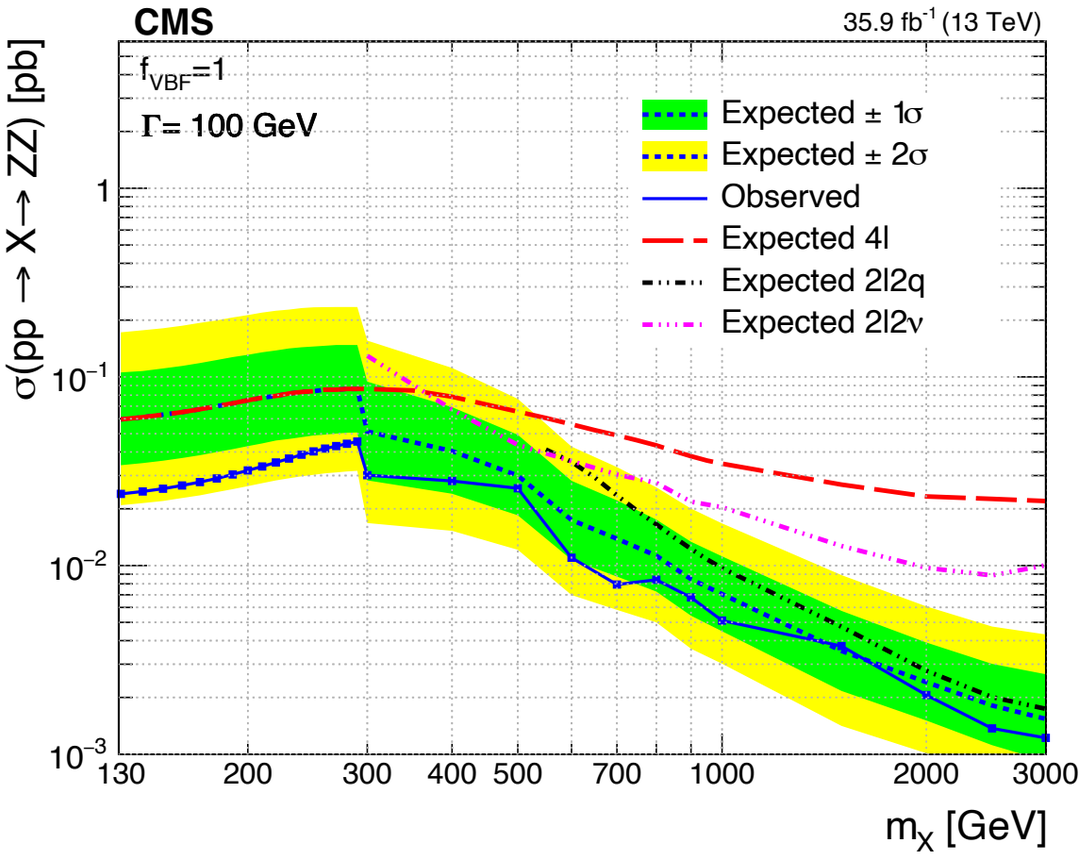
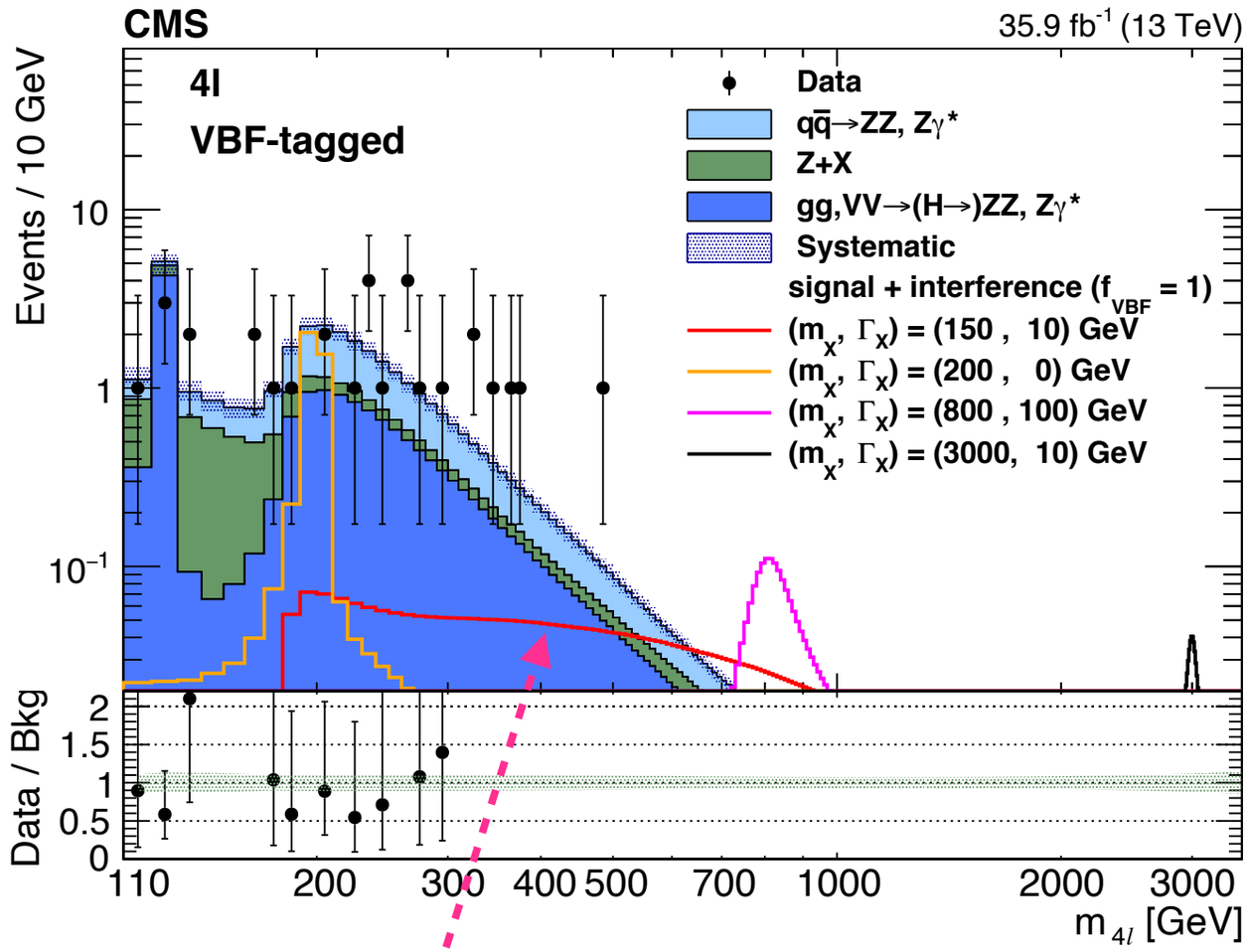
CMS limits:



with focus on VBF:



interesting off-shell $X(150)$ effect

Application to LHC data: $X \to WW$

- $X \to WW \to \ell\nu 2q$ / $2\ell 2\nu$

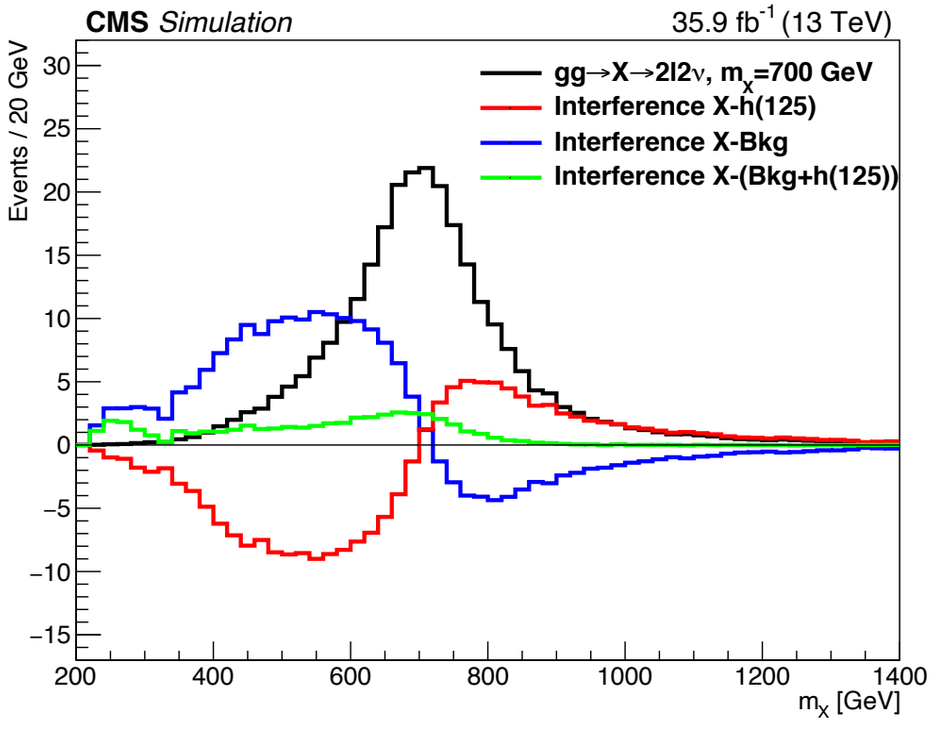
  CMS: arXiv:1912.01594

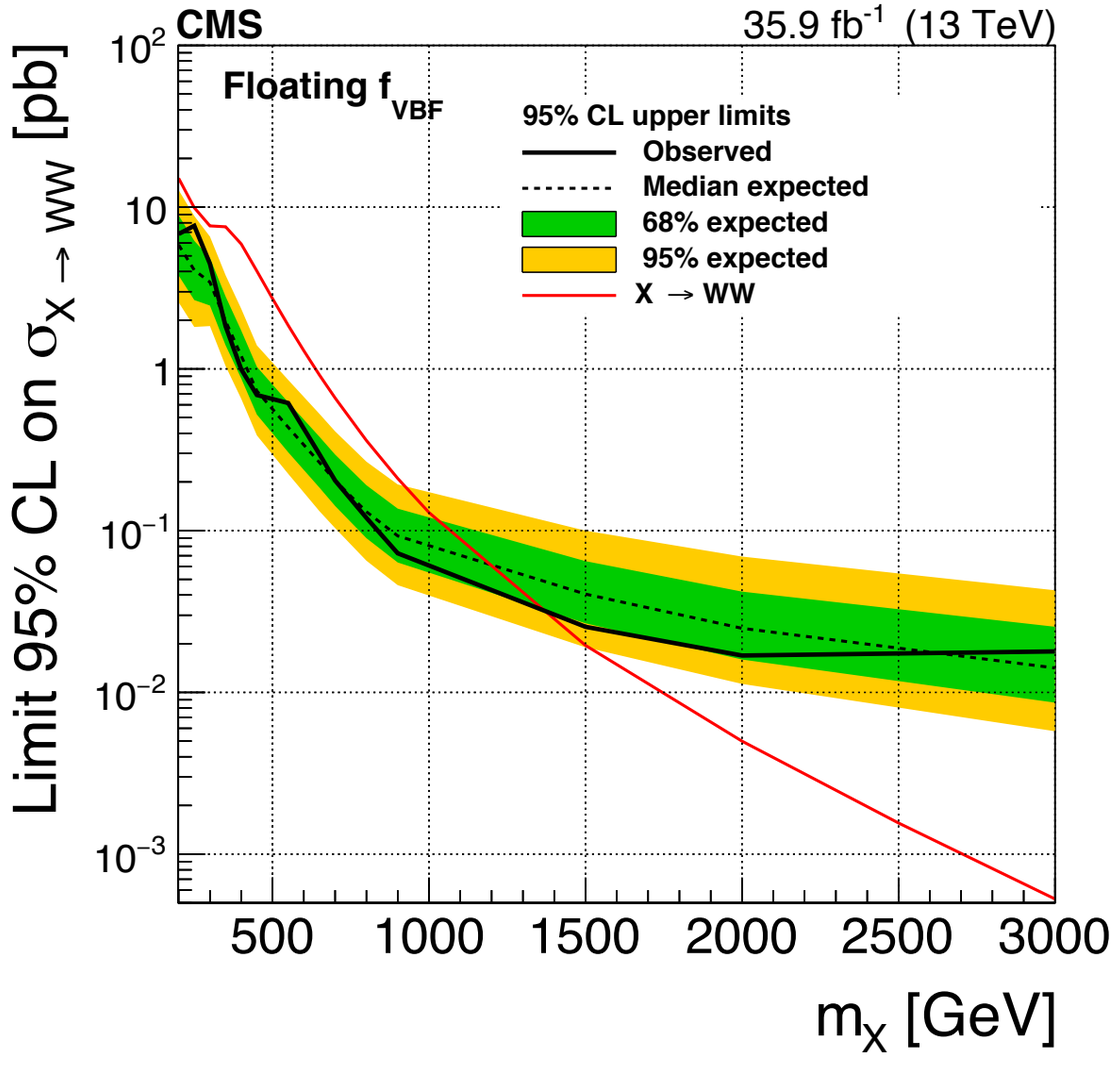
  simulation (prod+dec):

  POWHEG+**JHUGen**

  MELA weights

any mass
"SM width" as an approximation of the 2HDM
($\Gamma_X = m_X/2$ above 1 TeV)
any production (ggH or EW, float f_{VBF})
full interference
SM-like coupling





Summary

- Interference and finite width effects
  - — important to model properly when width is large
- Illustrated with $X \to ZZ/WW \to 4f$
- Technical implementations and examples:
  - — interference with **JHUGen** + **MCFM** (signal+background)
  - — large width with **POWHEG** + **JHUGen** (prod+decay)
  - — matrix elements with **MELA** for weights and observables
- Application to LHC data with $X \to ZZ/WW \to 4f$

BACKUP

JHUGen Physics (BSM and EFT)

- Framework for studies of BSM resonances / EFT of the Higgs
  - name attached by our ATLAS colleagues in 2012, so we learned to live with it…
- Available processes:

https://spin.pha.jhu.edu