Theory Outro

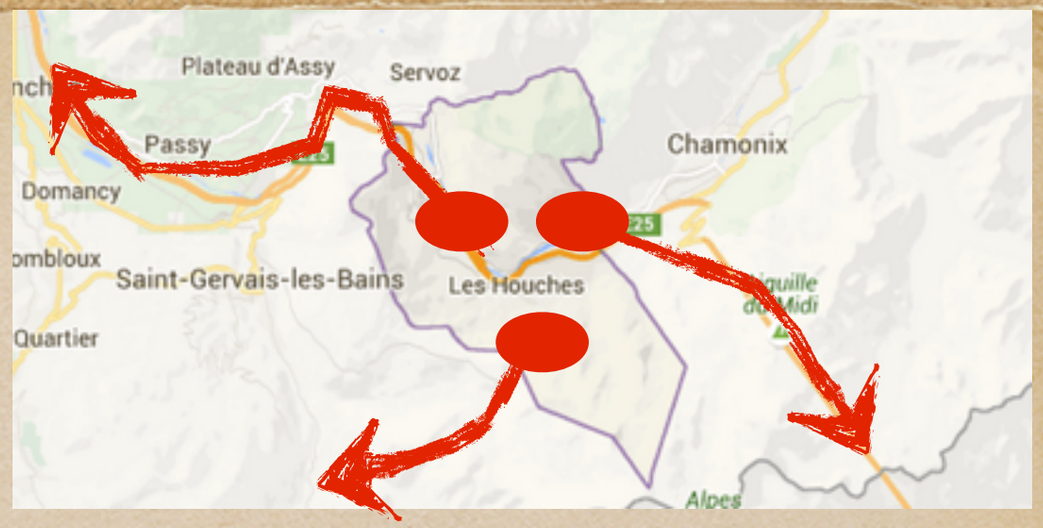
Les Houches

Physics in TeV colliders

Session 2 BSM Higgs

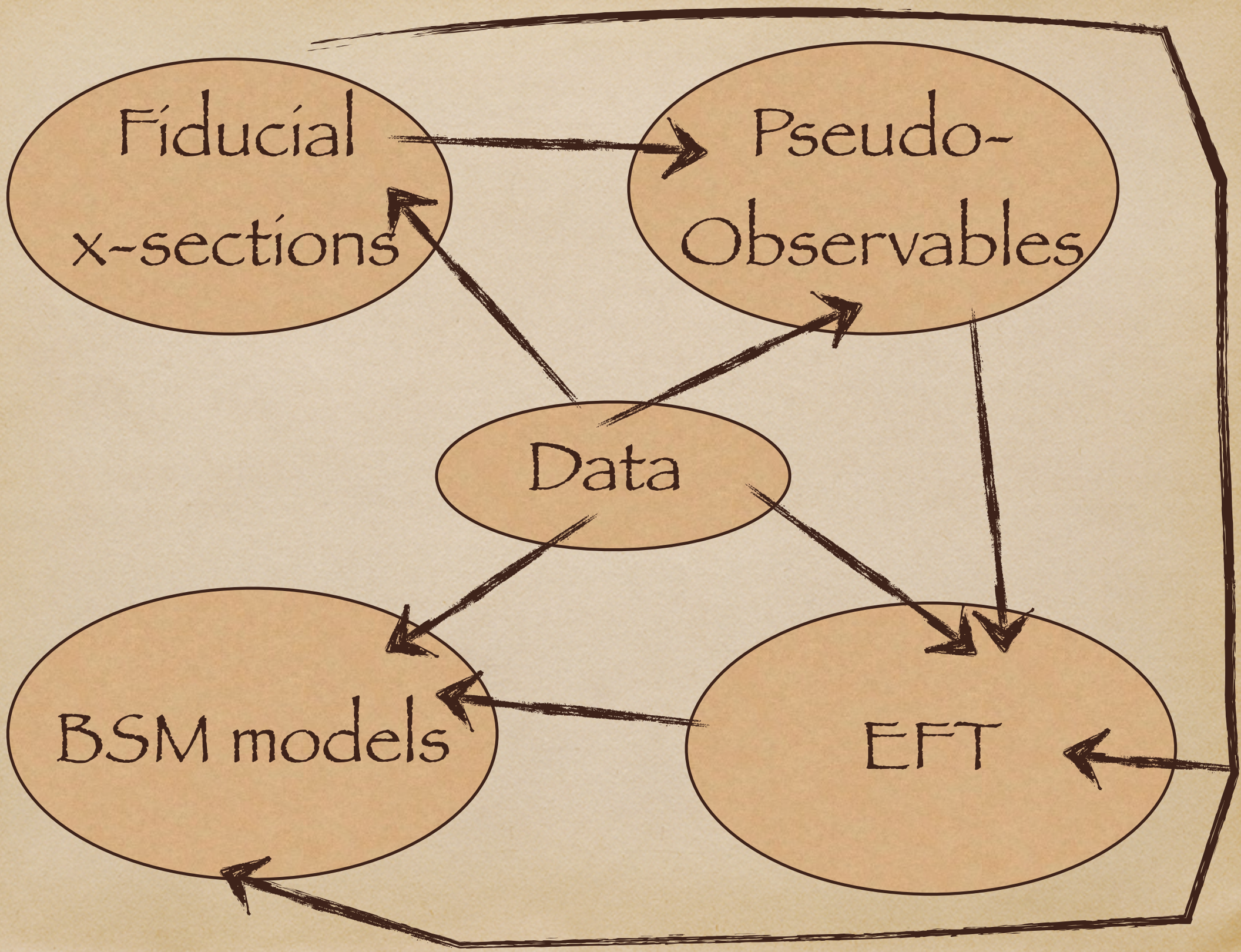
Summary of Higgs Working Group travails

Lines of attack



- Higgs Presentation
- Higgs EFT
- Extra Higgses
- Exotic Higgs Production
- Higgs & DM

Presentation



1307.5865

fiducial cross sections

- In situations in which the kinematic distribution of the signal depends on model parameters, simple scaling of production cross sections and decay branching ratios (relative to the SM) is not sufficient → one must account for the change in the signal selection efficiency.

- In order to address this broader class of theories, we advocate the measurement of fiducial cross sections, i.e. cross sections (total or differential) for specific final states within the phase space defined by the experimental selection and acceptance cuts.

- Fiducial cross sections can be interpreted in the context of whatever model, if a) the model and b) the selection criteria defining defining the "fiducial volume" can be implemented in a MC generator.

$$\sigma_i^{\rm fid} = \sum_j A_{ij}^{\rm th} \times \sigma_j^{\rm tot}$$

↑ fiducial volume acceptance

- Also has advantage of largely separating experimental and theoretical errors.

— fiducial cross sections were heavily discussed at Les Houches 2013
— effort is required also from the theory community to develop the necessary tools

- NB this is meant in addition to, not instead of, signal strength modifiers μ.
  Complementary to each other, both provide very valuable information in their own right.

Presentation

Toward pseudo-observables

- Experimentally accessible, well-defined from QFT point of view, and sensitive to BSM
- Background, as well as soft QED and QCD effects unfolded
- Advantage: independent of theory (higher-loops affect predictions but not measurements) or BSM models
- Task: agree on a set of PO for Higgs at LHC

Presentation

Sabine Kraml, Fawzi Boudjema, Veronica Sanz,
Adam Falkowski, Adam Martin, Ken Mimasu,
Aiofe Bharucha, Alexandra Oliveira, Nicolas Chanon

Example:

Session 2 discussion

jet selection anti-kT R=0.4, pt>25-30 GeV, |eta|<4.5

ggF

(|eta|<2.5)

0j : sigma times BR

1j : pT 100,200,(300,400)_mt,overflow

2j : bin in 2j exclusive and 3j inclusive, distributions mjj, Delta eta_jj, Delta Phi_jj

VBF

2j : mjj, Delta eta_jj, Delta Phi_jj

VH

fully leptonic: mVH 300…500, overflow

1l, 0l: mT>200 GeV

ttH

m_T(ttH) …,500,…

Coordinated effort of Les Houches and LHCHXSWG

Tue&Wed: LHCHXS kick-off meeting on fiducial cross sections
https://indico.cern.ch/event/399923/

Higgs EFT

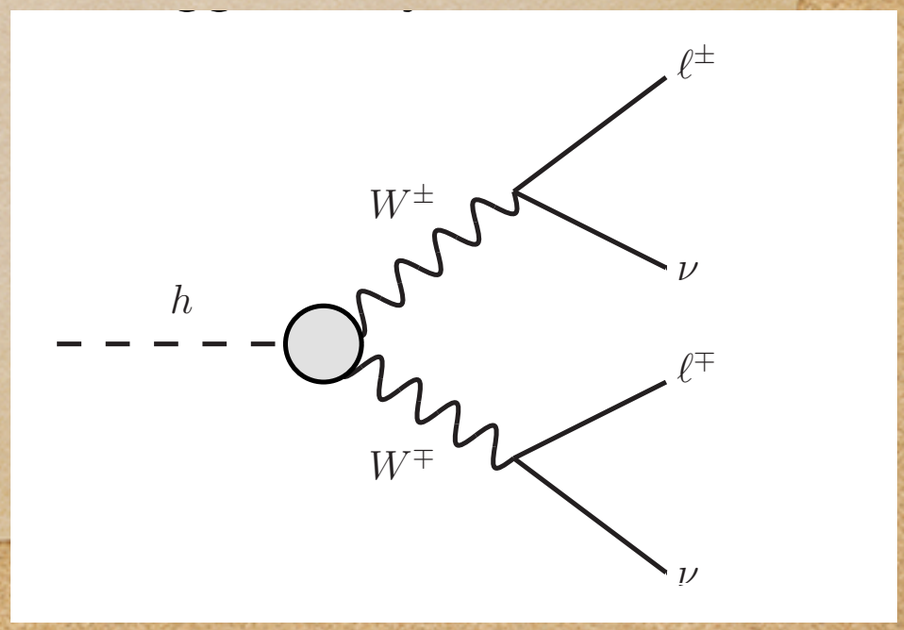
- Higgs to WW in general EFT
- Implementation of experimental constraints on parameters in Rosetta
- Validity of EFT in VH and HH
- QCD&NLO in EFT
- Identification where NLO EFT effects may be important

Higgs to WW in EFT

- There are hWW 4 couplings corresponding to different possible 0-derivative and 2-derivative tensor structures
- One combination affects h->WW partial width
- Measuring differential distributions will lift degeneracies
- This project: identify differential distributions sensitive to these parameters, and how they can be simultaneously constrained

$$\begin{aligned}\mathcal{L}_{\rm hvv} =& \frac{h}{v}[2(1+\delta c_w)m_W^2 W_\mu^+ W_\mu^- + (1+\delta c_z)m_Z^2 Z_\mu Z_\mu \\ &+ c_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box}g_L^2\left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) \\ &+ c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{eg_L}{2c_\theta}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}Z_{\mu\nu} \\ &+ c_{z\Box}g_L^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box}g_L g_Y Z_\mu \partial_\nu A_{\mu\nu} \\ &+ \tilde{c}_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{eg_L}{2c_\theta}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}\tilde{Z}_{\mu\nu}]\end{aligned}$$

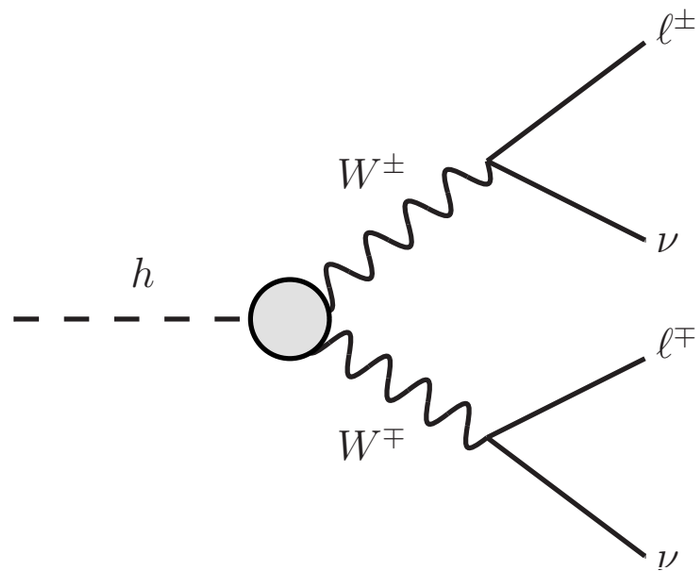
$$\begin{aligned}\delta c_w =& \delta c_z + 4\delta m, \\ c_{ww} =& c_{zz} + 2s_\theta^2 c_{z\gamma} + s_\theta^4 c_{\gamma\gamma}, \\ \tilde{c}_{ww} =& \tilde{c}_{zz} + 2s_\theta^2 \tilde{c}_{z\gamma} + s_\theta^4 \tilde{c}_{\gamma\gamma}, \\ c_{w\Box} =& \frac{1}{g_L^2 - g_Y^2}\left[g_L^2 c_{z\Box} + g_Y^2 c_{zz} - e^2 s_\theta^2 c_{\gamma\gamma} - (g_L^2 - g_Y^2)s_\theta^2 c_{z\gamma}\right], \\ c_{\gamma\Box} =& \frac{1}{g_L^2 - g_Y^2}\left[2g_L^2 c_{z\Box} + (g_L^2 + g_Y^2)c_{zz} - e^2 c_{\gamma\gamma} - (g_L^2 - g_Y^2)c_{z\gamma}\right]\end{aligned}$$



Roberto Vega-Morales, Ken Mimasu, Veronica Sanz, Adam Falkowski, Alexandra Oliveira, Benjamin Fuks, Florian Goertz, Nicolas Chanon, Adam Martin, Alberto Tonero

MEM Analysis of $h \to WW \to 2\ell 2\nu$ Decays

- We are interested in the Higgs decay $h \to W^+W^- \to 2\ell 2\nu$ at LHC



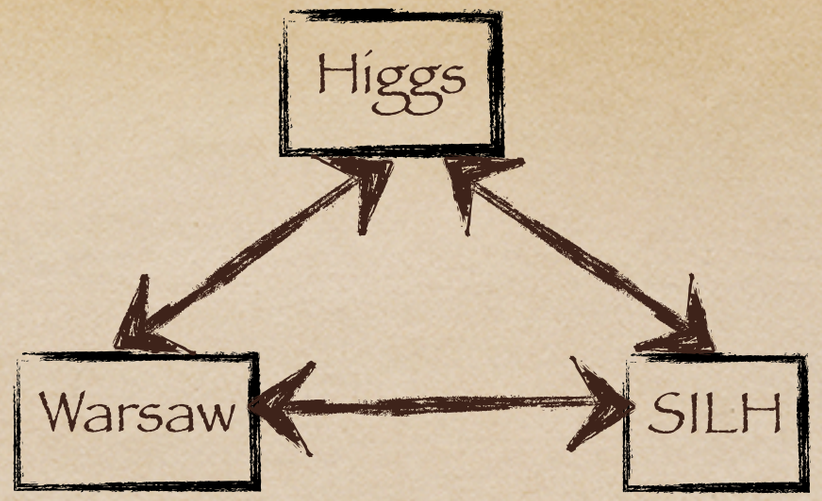
- We would like to use a Matrix Element Method (MEM) analysis, utilizing all observables available, to study this process
- Using the differential distributions, we'll construct an ('analytic') analysis to extract EFT couplings of the Higgs to WW pairs

$$\mathcal{L}_{hWW} = \frac{h}{v}\left[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + c_{ww}\frac{g_L^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g_L^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g_L^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right)\right]$$

- This should also give us the ability to directly study CP properties

Developed by B.Fuks, F.Maltoni, K.Mawatari, K.Mimasu, V. Sanz, F. Riva

Rosetta



- Interface of effective couplings Lagrangian defined in LHCHXSWG note to aMC@NLO (tree-level only so far)
- Modular architecture, easy to add user-defined extensions
- Accepts input in any popular basis (currently Higgs, SILH, or Warsaw basis) and provides translation between any pair

Ken Mimasu, Jeremy Mardon, Florian Goertz, Adam Martin,
Adam Falkowski, Alexandra Oliveira, Benjamin Fuks

Experimental constraints in Rosetta

- Planning to add functionalities to determine compatibility of input parameters with previous measurements (LEP-1, LEP-2, LHC)
- Planning interface to other existing Higgs tools: eHDECAY, HiggsBounds, Lilith, ...

Matching and Validity of EFT in VH/HH

Chair: Veronica Sanz (VH), Christoph Englert (HH)

Members: Fawzi Boudjema, Adam Falkowski, Benjamin Fuks, Florian Goertz, Jose Santiago, Jose Miguel No, Felix Yu, Adam Martin, Ciaran Williams, Ken Mimasu, Alexandra Oliveira, Alberto Tonero. **Please add your name if it is missing.**

Topics for discussion VH:

- Analyses
  1. ATLAS: VH(→ bb) in http://arxiv.org/pdf/1409.6212.pdf
  2. ATLAS: VH(→WW) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-005/
  3. CMS:VH(→bb) https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13012PubTWiki and legacy paper https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig14009PaperTwiki

- SM contributions to VH at one loop: Fawzi to dig old works on this. recast some one-loop V^3 into h V^2
- tree-level:
  1. Dilaton, radion exchange: Matching in http://arxiv.org/pdf/1502.07352.pdf. Ken for form factora.
  2. Composite Higgs type spin-one exchange: 2 Adams, Cedric, Andrey. Adam F, Florian, UV with S→0.
- one-loop:
  1. 2HDM: Matching in http://arxiv.org/pdf/1502.07352.pdf. Ken
  2. Colored scalars: region of cancellations in gg→ h can be seen in Eq.18 of http://arxiv.org/pdf/1207.7355.pdf, see also http://arxiv.org/pdf/1312.3317.pdf. Matching colored scalars with EFT in http://arxiv.org/pdf/1412.1837v1.pdf and http://arxiv.org/pdf/1504.02409.pdf for non-degenerate stops. Adam M and Felix Andrey
  3. Spin-one: From Composite-Higgs type. Alexandra O.
     a. Not possible from MC point of view, I understood that is maybe non relevant in kinematics point of view, it would act like more terms to the renormalization of three level coupling
- Pseudo-Observables: VS, FB
- Presentation of results together with the HXSWG, feducial cross sections: VS, CPE

lots of discussion!

no low-hanging fruit!

lots of work!

Matching and Validity of EFT in VH/HH

Chair: Veronica Sanz (VH), Christoph Englert (HH)

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- Pseudo-Observables: VS, FB
- Presentation of results together with the HXSW

Topics for discussion HH:

1. How big can pp>HH be in concrete UV scenarios
   - colored scalars (recast MSSM?) : region of cancellations in gg→ h can be seen in Eq.18 of http://arxiv.org/pdf/1207.7355.pdf, see also http://arxiv.org/pdf/1312.3317.pdf. Matching colored scalars with EFT in http://arxiv.org/pdf/1412.1837v1.pdf and http://arxiv.org/pdf/1504.02409.pdf for non-degenerate stops. VS, FY + BSM
   - 2HDM : Matching of the c_6 to 2HDM is in http://arxiv.org/pdf/1502.07352.pdf, Eq 3.41, and Eq. 3.28 in the alignment limit. CPE, BF
   - Scalar fourplet of SU(2)_L only induces c_6 at the tree level (see e.g. http://arxiv.org/abs/1412.8480): FG
   - Setup without relevant operator (mu^2=0) → large enhancement of pp>HH (factor 2-3), http://arxiv.org/pdf/1504.00355v2.pdf: FG
2. What is the EFT parameter range expected from such scenarios (→ *deliverable*: c_6 vs Lambda contour plot) CD (composite Higgs), JN (2HDM), CPE, FG
3. How much can we learn from binned distribution at a small expected signal yield (→ *deliverable*: compare differential distributions for H>hh (with m_H large) and EFT, binned log-likelihood hypothesis test to quantify consistency)
   - 5 parameters EFT scan translated to 2D kinematics to set experimental benchmarks https://twiki.cern.ch/twiki/bin/view/Sandbox/NonResonantHHAtLHC
   - Allow combination of different channels by coordinating bins/benchmarks
4. Backgrounds in HH
   - mass resolution of Higgs tagging (CP and CPE)
     - Can we control Z>bbar (→ *deliverable*: estimate, simulate or dig out expected resolution)
     - can we disentangle dim 6 effects from qq>HZ leakage

lots of discussion!

no low-hanging fruit!

lots of work!

Matching and Validity of EFT in VH/HH

- VH/HH as a guinea pig for realistic estimate of EFT coefficients

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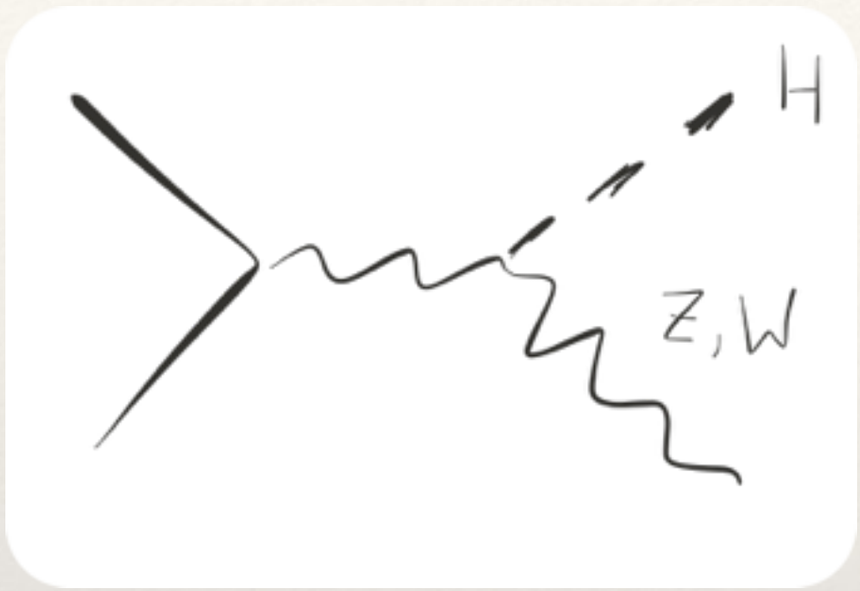

- dilaton/radion
- strongly interacting V’

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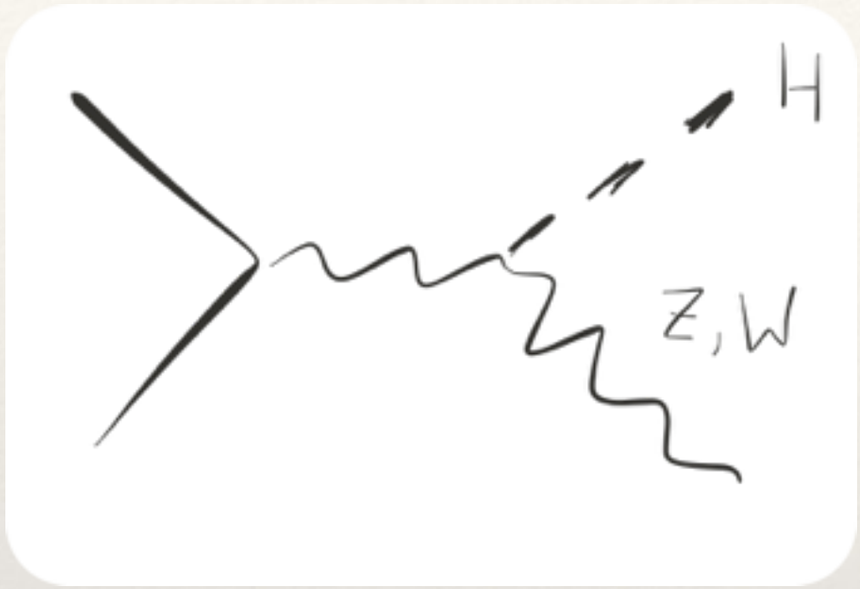

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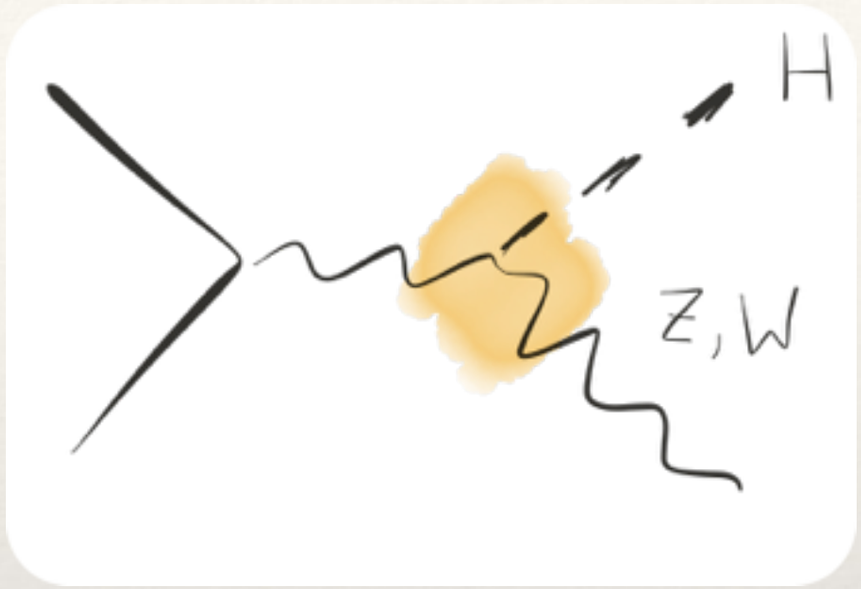

- 2HDM
- strongly interacting V’
- (• colored scalars (ggF))

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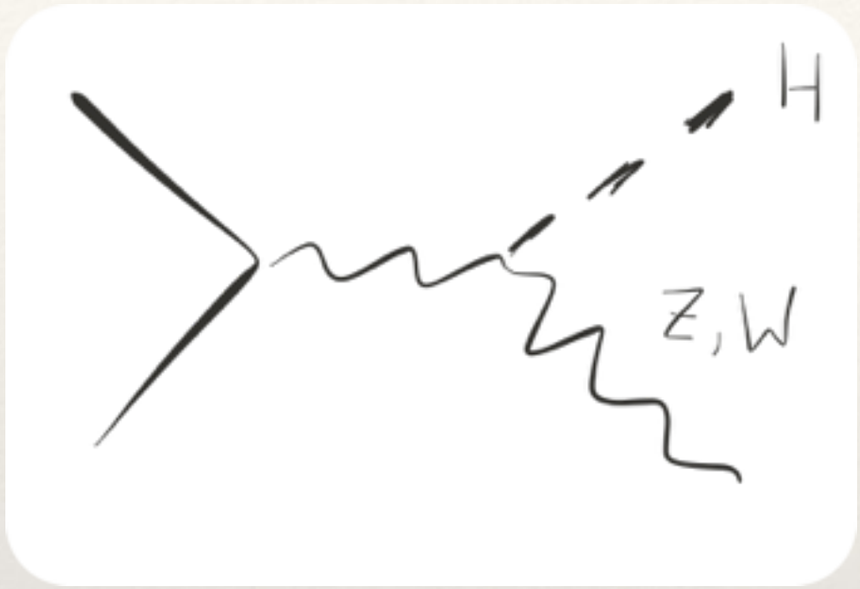

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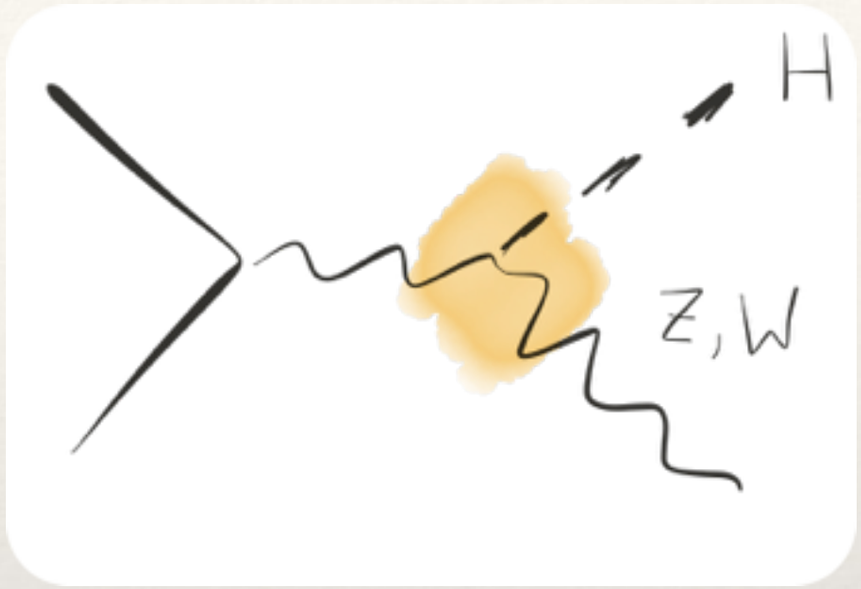

- 2HDM
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- power counting, unitarity,...

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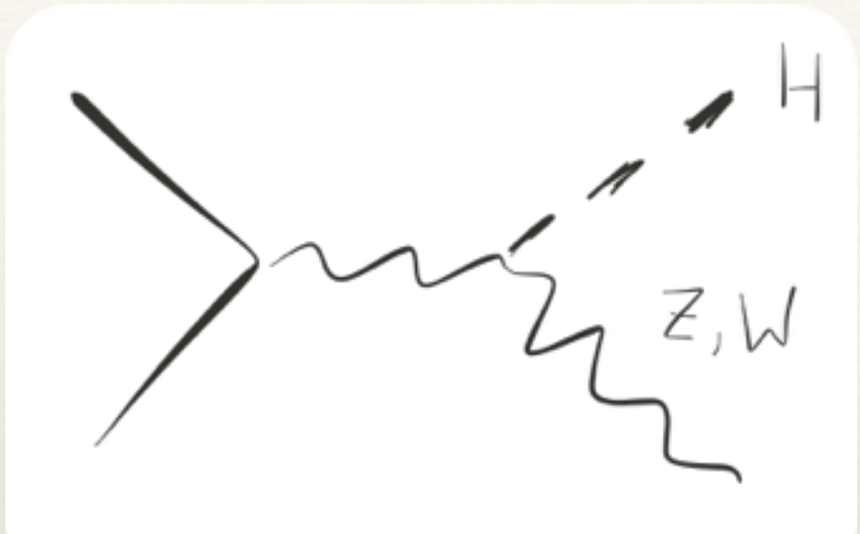

- dilaton/radion
- strongly interacting V'

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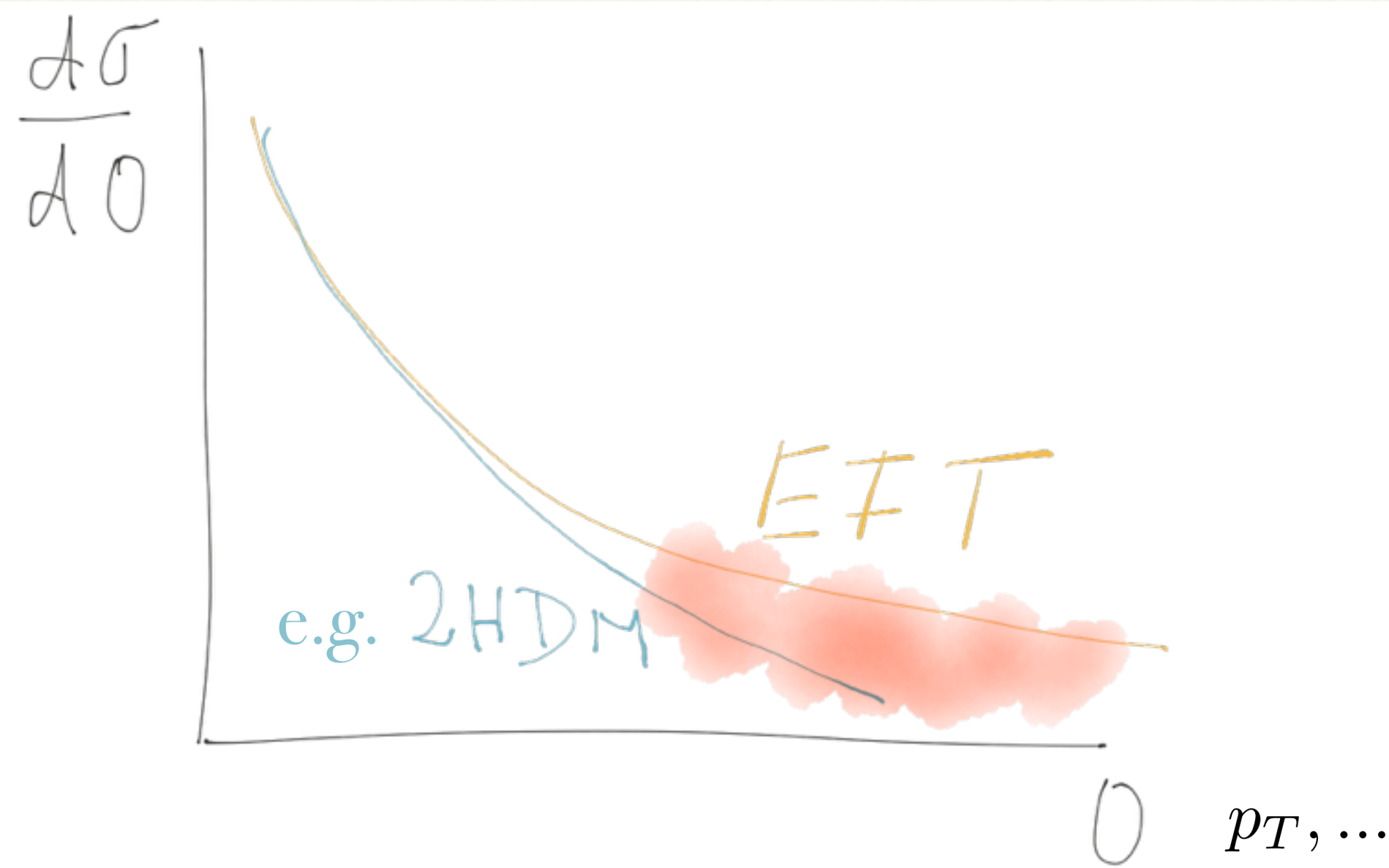
- (• colored scalars (ggF))

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

- power counting, unitarity,...

Matching and Validity of EFT in VH/HH

- VH/HH as a guinea pig for realistic estimate of EFT coefficients



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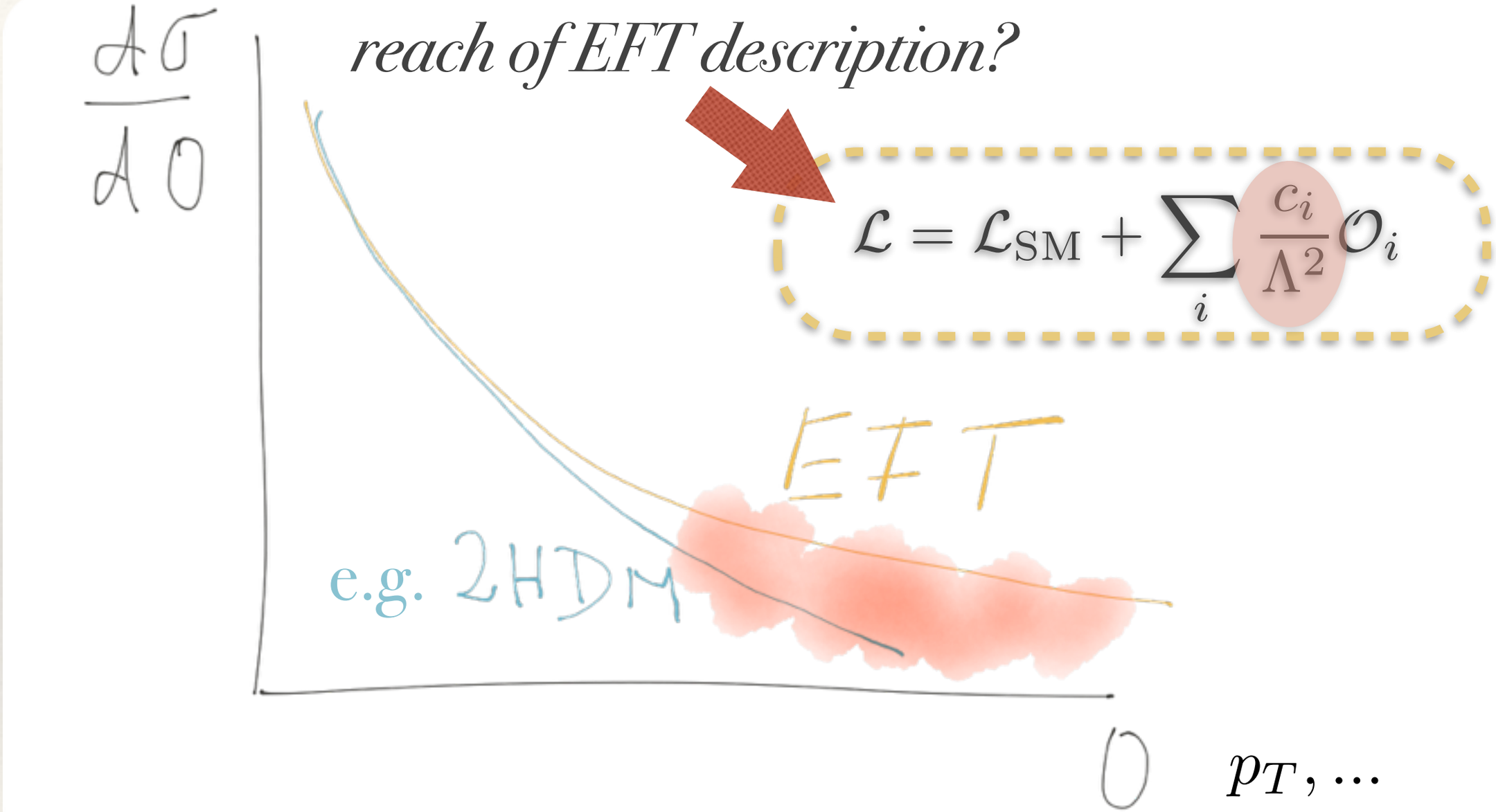

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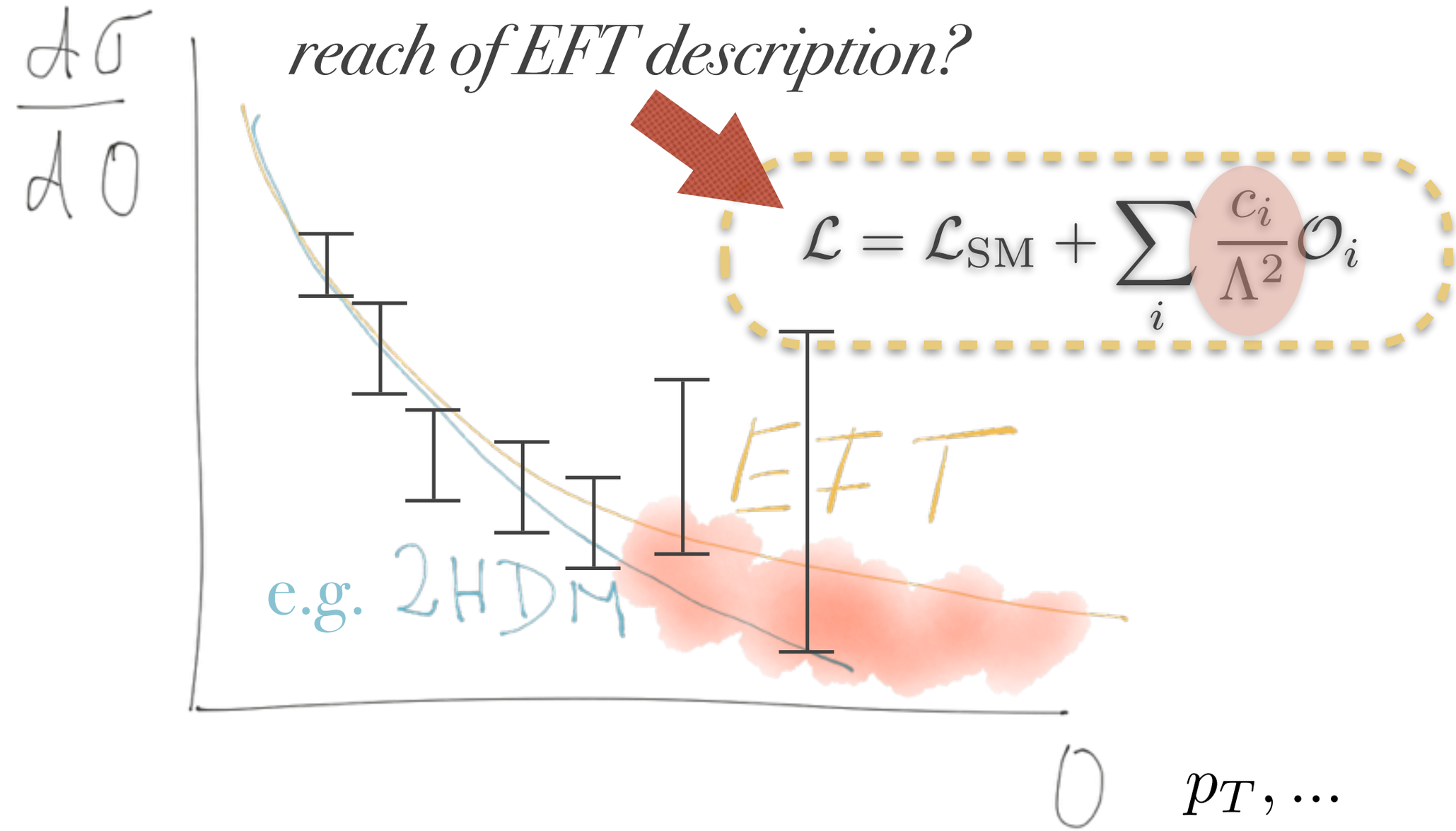

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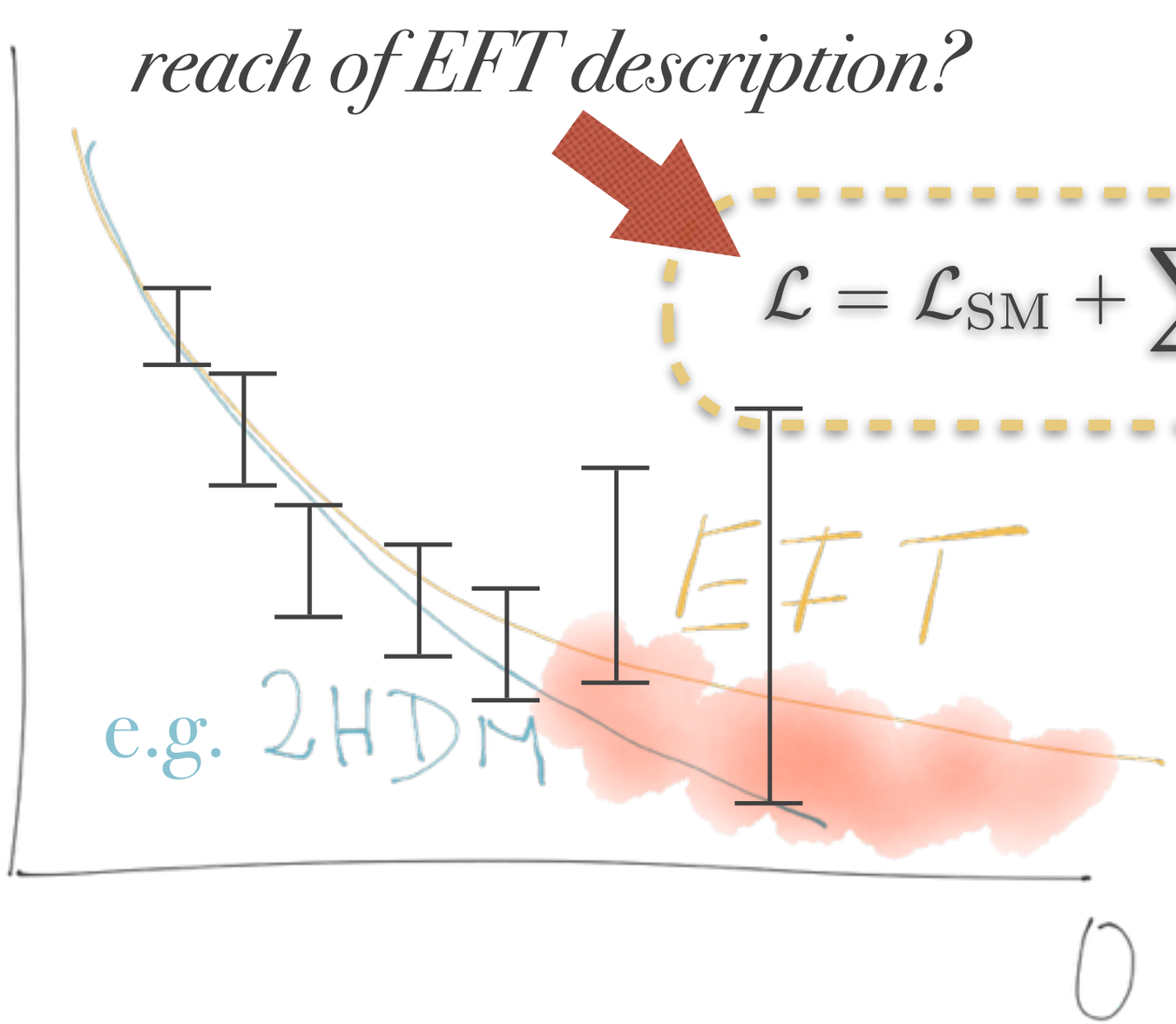

- binning
- combining channels
- "EFT bias"?

Fawzi Boudjema, Cedric Delaunay, Christoph Englert, Adam Falkowski, Florian Goertz, Andrey Katz, Ken Mimasu, Adam Martin, Alexandra Oliveira, Veronica Sanz, Alberto Tonero, Felix Yu

Matching and Validity of EFT in VH/HH

- settle Higgs pair production

Matching and Validity of EFT in VH/HH

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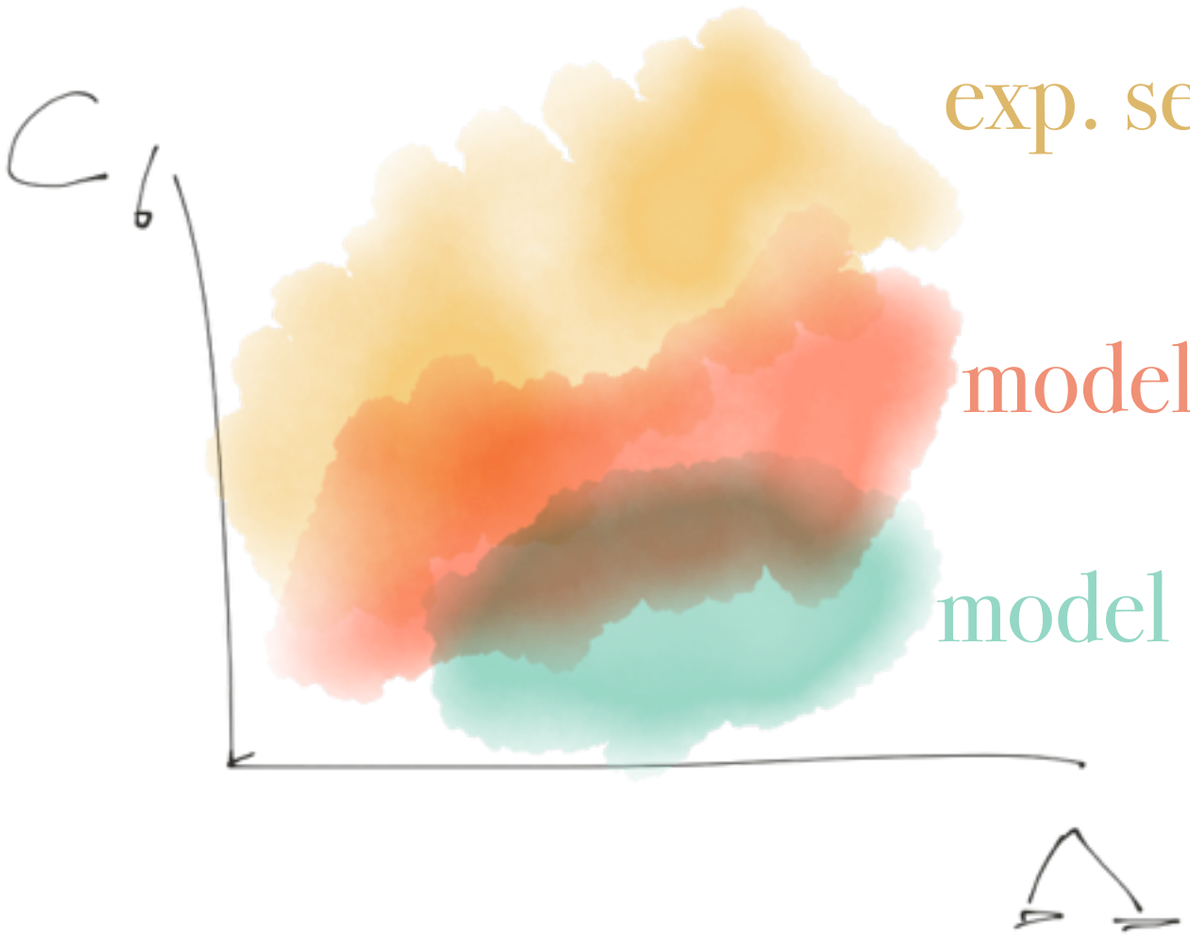
Matching and Validity of EFT in VH/HH

- settle Higgs pair production
- HH genuine sensitivity to c_6 i.e. the Higgs self interaction

how big?



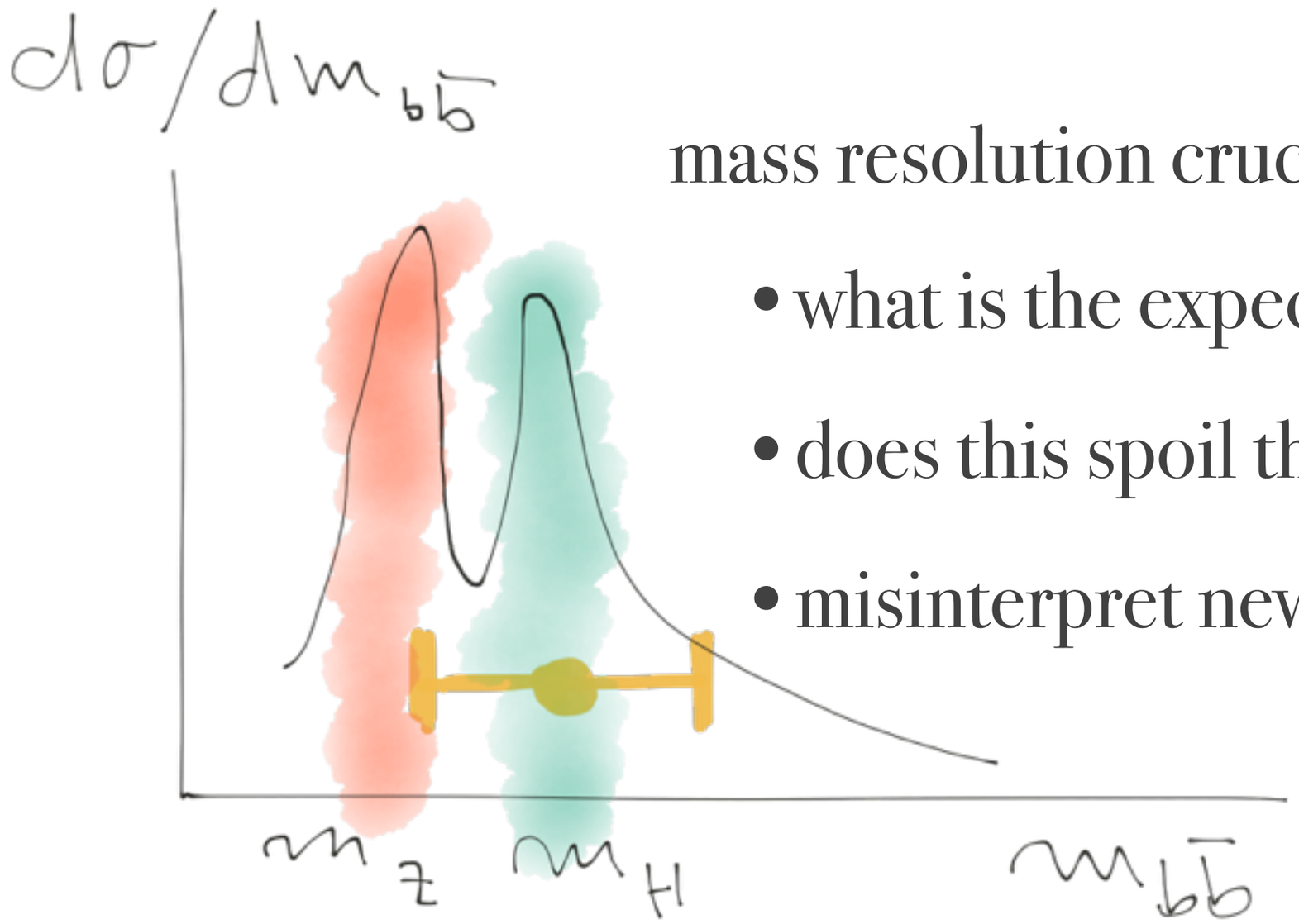
exp. sensitivity/maximum from theory

- *colored scalars*
- *2HDM (1-loop MG on wiki!)*
  Benjamin Fuks
- *scalar 4 under SU(2)*
- *mu-less SM*

Cedric Delaunay, Christoph Englert, Benjamin Fuks, Florian Goertz, José No, Alexandra Oliveira, Veronica Sanz

Matching and Validity of EFT in VH/HH

- HH: more synergy between theory and experiment needed

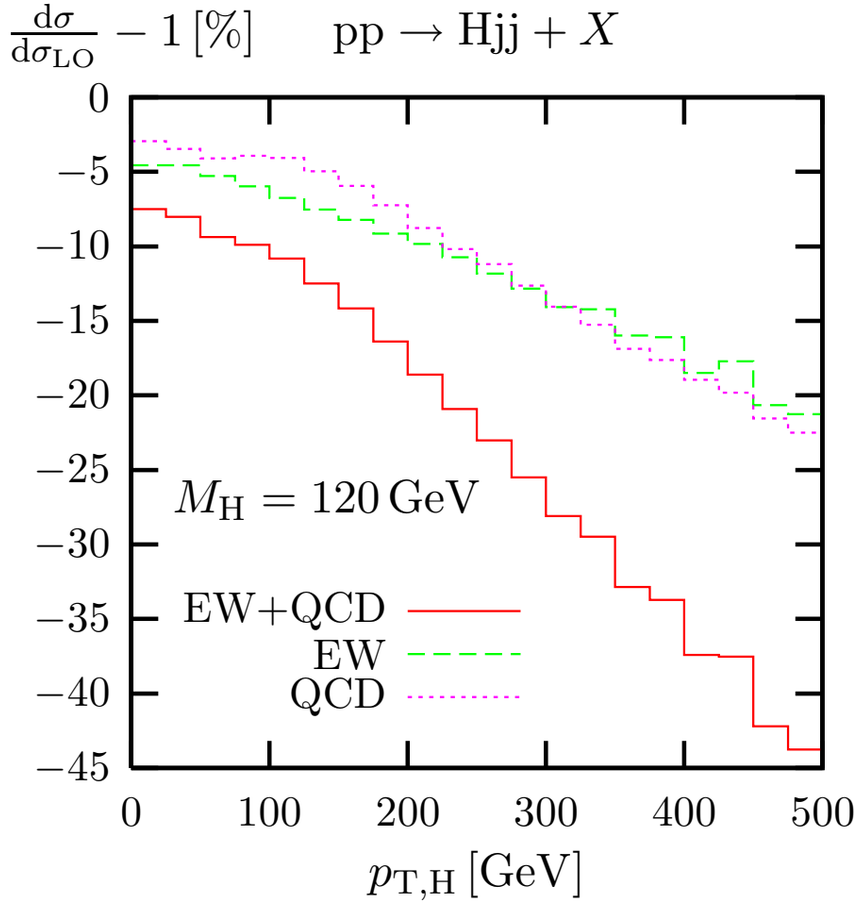


mass resolution crucial in Higgs tagging:

- what is the expected resolution
- does this spoil the party (bkg)
- misinterpret new physics (BSM)

Christoph Englert, Chris Pollard, anyone else?

Where is NLO EFT important + EFT & QCD



[Cicccolini, Denner, Dittmaier `07]

- Higgs production mechanisms
- importance of Sudakov logs
  (non-)universal?
- important when we push experimental and theoretical sensitivity below the 10% level

Aiofe Bharucha, Benjamin Fuks, Ken Mimasu, Alexandra Oliveira, Veronica Sanz, Michael Spira, Ciaran Williams

Dear Sally, Magda, Christoph, Maxime and Roberto,

with this email I would like to inform you that a new version 2.00 of HPAIR is public on my webpage which includes dim6 operators up to NLO now and has been linked to LHAPDF in order to allow for a more flexible use of different PDFs. Moreover, I changed the initialization of alpha_s by moving to the input value alpha_s(MZ) instead of Lambda_5. The new version of HPAIR includes the results of our recent paper

R.~Grober, M.~Muhlleitner, M.~Spira and J.~Streicher,
%``NLO QCD Corrections to Higgs Pair Production including Dimension-6

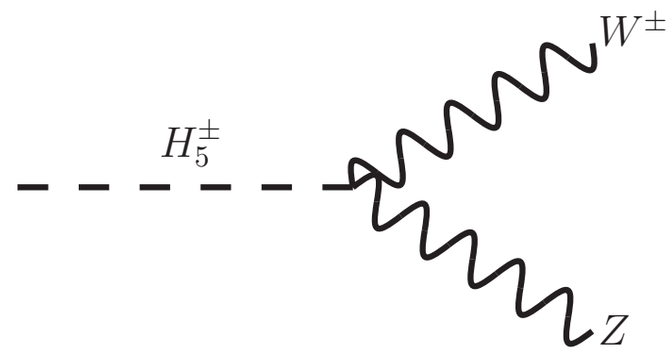
Michael Spira

Extra Higgses

- Search for "forbidden" decay H+ > WZ
- Pair production of heavy Higgs partners
- Heavy Higgs decaying to ttbar
- Heavy Higgs decays for large splitting between Higgs partners
- Low mass pseudoscalar produced in association with bbbar and decaying to mumu/tautau
- Heavy Higgs decays to charginos/neutralinos
- Low mass diphoton resonances - limits and theory interpretation

Charged Higgs Decay to WZ Pairs

- We are interested in the charged Higgs decay $H_5^\pm \to W^\pm Z$ at LHC

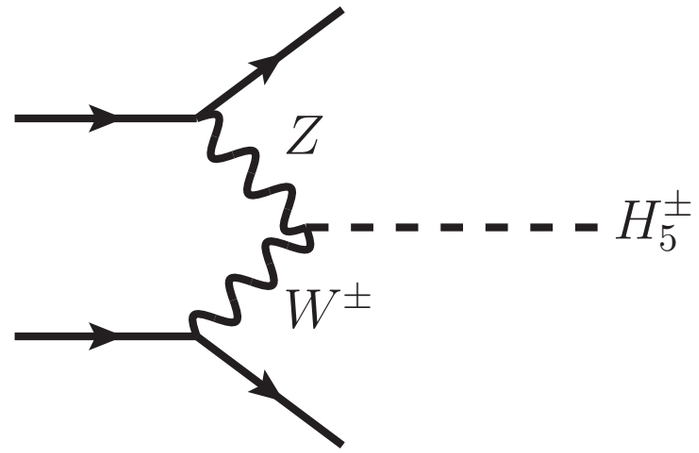


- This decay requires a non-zero VEV for $SU(2)_L$ triplet Higgs (or something else in representation larger than doublet)
- The constraint $\rho \simeq 1$ requires $H_5^\pm$ to be part of a custodial 5-plet
- This implies other neutral and doubly charged Higgs' must be present with (nearly) degenerate masses which decay to WW and ZZ pairs
- Such a 5-plet arises is in the well known Georgi-Machacek (GM) model (Georgi, Machacek: Nucl.Phys. B262 (1985) 463)
- Also arise in the Supersymmetric Custodial Triplets Model (SCTM)

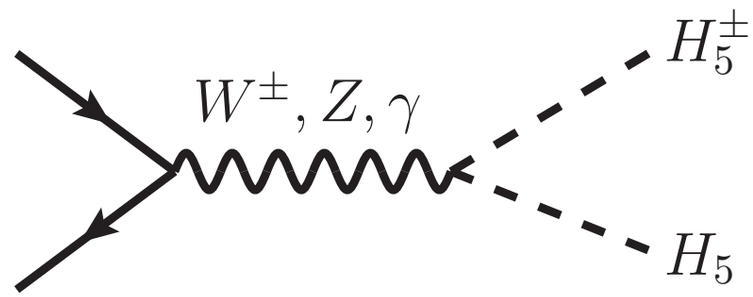
(Cort, Garcia-Pepin, Gori, Quiros, Vega, Vega-Morales, Yu: 1308.4025,1409.5737)

Single and Pair Production of $H_5^{\pm}$

- The dominant single production mode is VBF via a W and Z



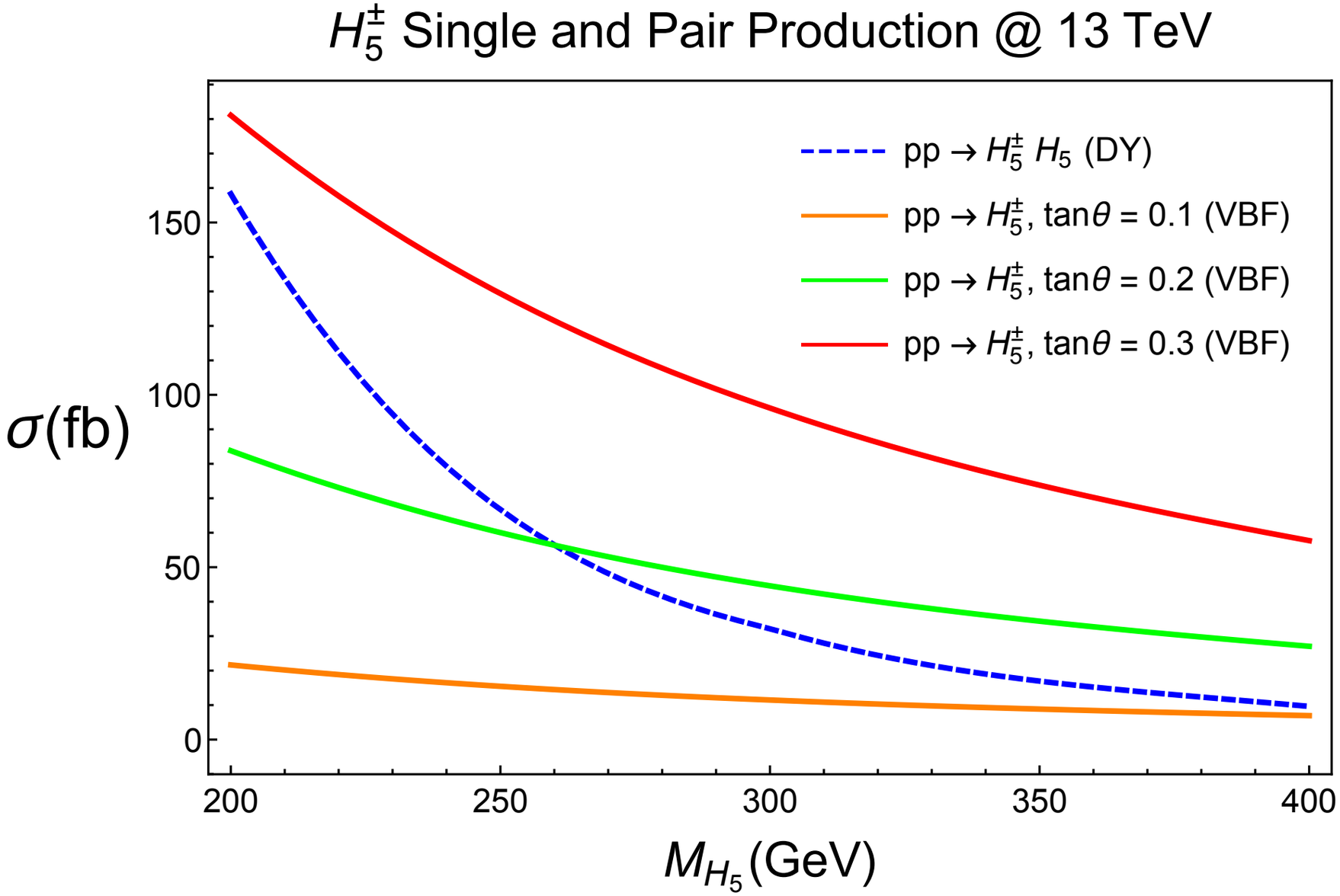
- The dominant pair production mode occurs through Drell-Yan



- This channel also will produce the neutral and doubly charged components of the H_5 custodial 5-plet
- The H_5 decays will lead to striking signatures which we are studying

Cross Sections for Production of $H_5^{\pm}$

- The $H_5^{\pm}$ production modes depend on M_{H_5} and in case of VBF single production the doublet-triplet VEV mixing angle $\tan\theta$



Exotic production of h(125): Main themes

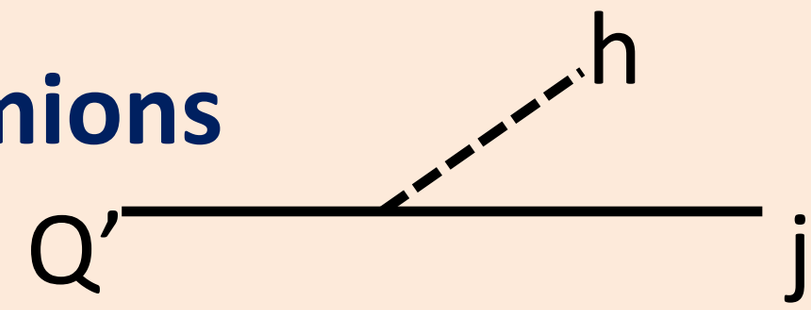
Giacomo Cacciapaglia, Aldo Deandrea, Thomas Flacke, Benjamin Fuks, Aurelio Juste, Andrey Katz, Devdatta Majumder, Jose Miguel No, Alexandra Oliveira, Alberto Parolini, Felix Yu

- ***Beyond*** Higgs EFT
  - Add **new production mechanisms** for h(125)
  - **Pollutes** SM Higgs fiducial cross sections
    - O(15%) uncertainty in ggF leaves room for **O(pb) NP xsec** @ LHC14
- **Differential distributions** are key
  - Higgs p_T, η, MET, counts and kinematics of associated leptons, jets will show deviations from SM
- Classification of production mechanisms*
  - **Resonant** (*e.g.* 2HDM A → Zh)
  - **Non-resonant asymmetric** (*e.g.* MSSM $\chi_1^{+/-}\chi_2^0 \rightarrow W^{+/-}h\,\chi_1^0\chi_1^0$)*
  - **Non-resonant symmetric:** Q'Q̄', L' L̄' (see next)
    - HH+X production is an important cross-channel

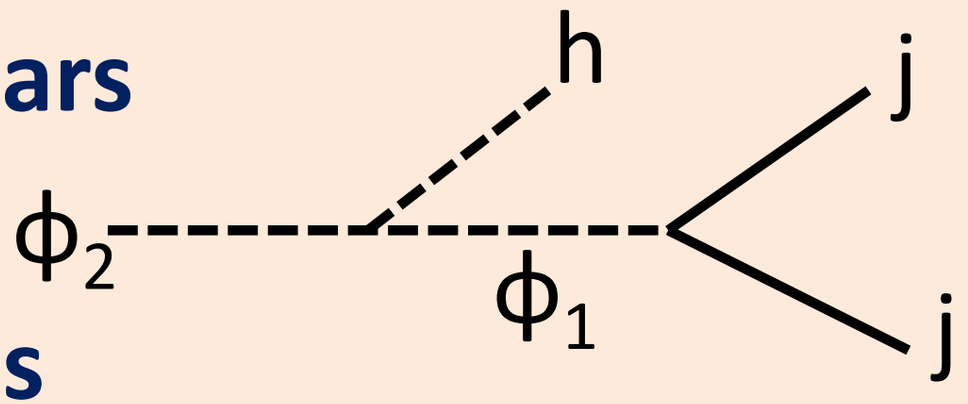
*Yu, PRD 90, [1404.2924]

Toy Models

- Pair-produced **colored fermions**
  - Example: decay to hj



- Pair-produced **colored scalars**
  - Example: decay to hjj



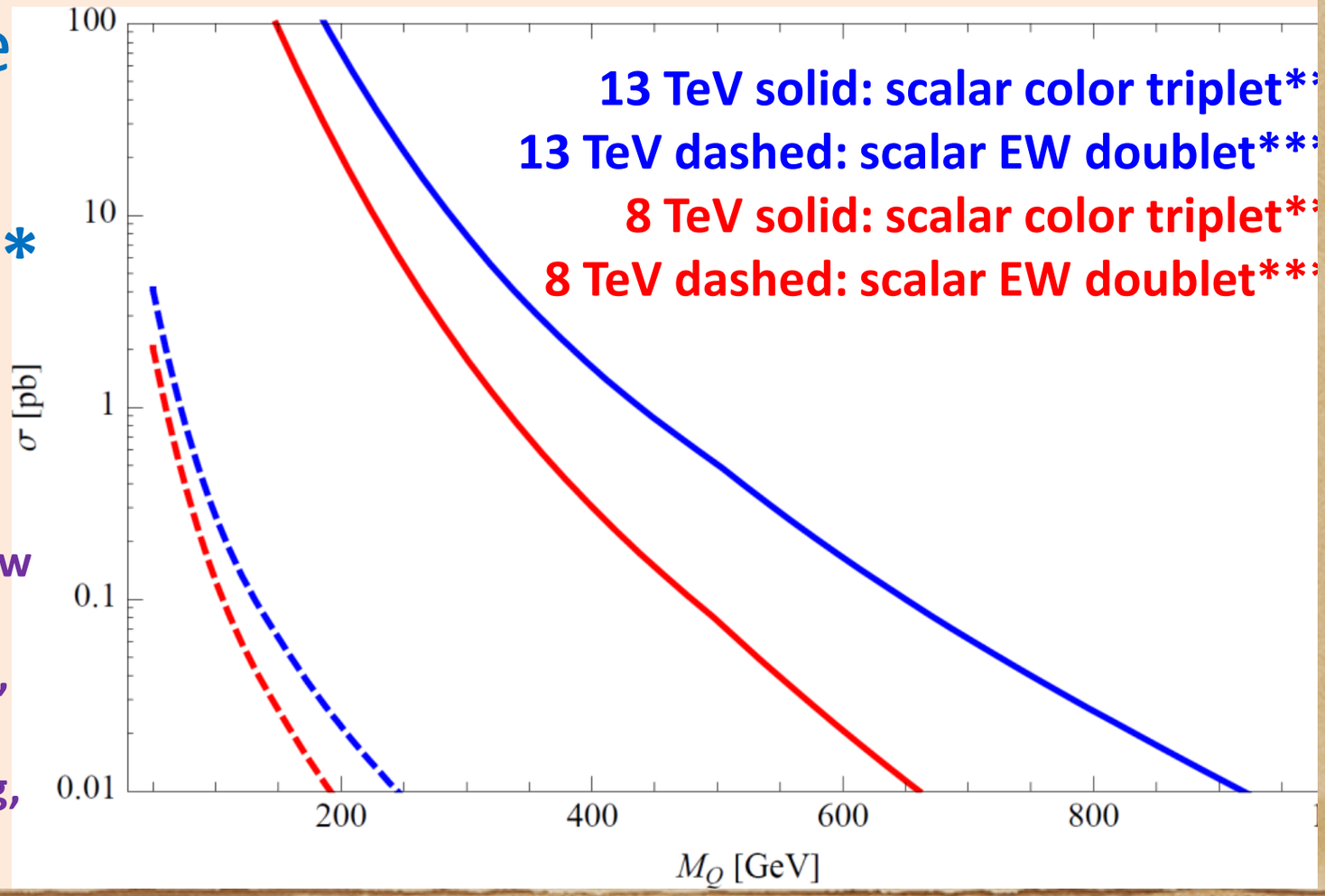
- Pair-produced **EW fermions**
- Pair-produced **EW scalars**
- **Drell-Yan EW** multiplet
- Overall: **important interplay** with 4th gen. t’, b’, τ’, SUSY neutralinos, and double Higgs production

Pair-production cross sections

- Large rates imply **strong current bounds** and great **prospective reach**
- Also can have **significant contamination** in single and **enhancement** of double Higgs production for large regions in parameter space

Figure of merit:
SM σ(gg→hh), NNLO*
9.96 fb @ 8 TeV
40.7 fb @ 14 TeV

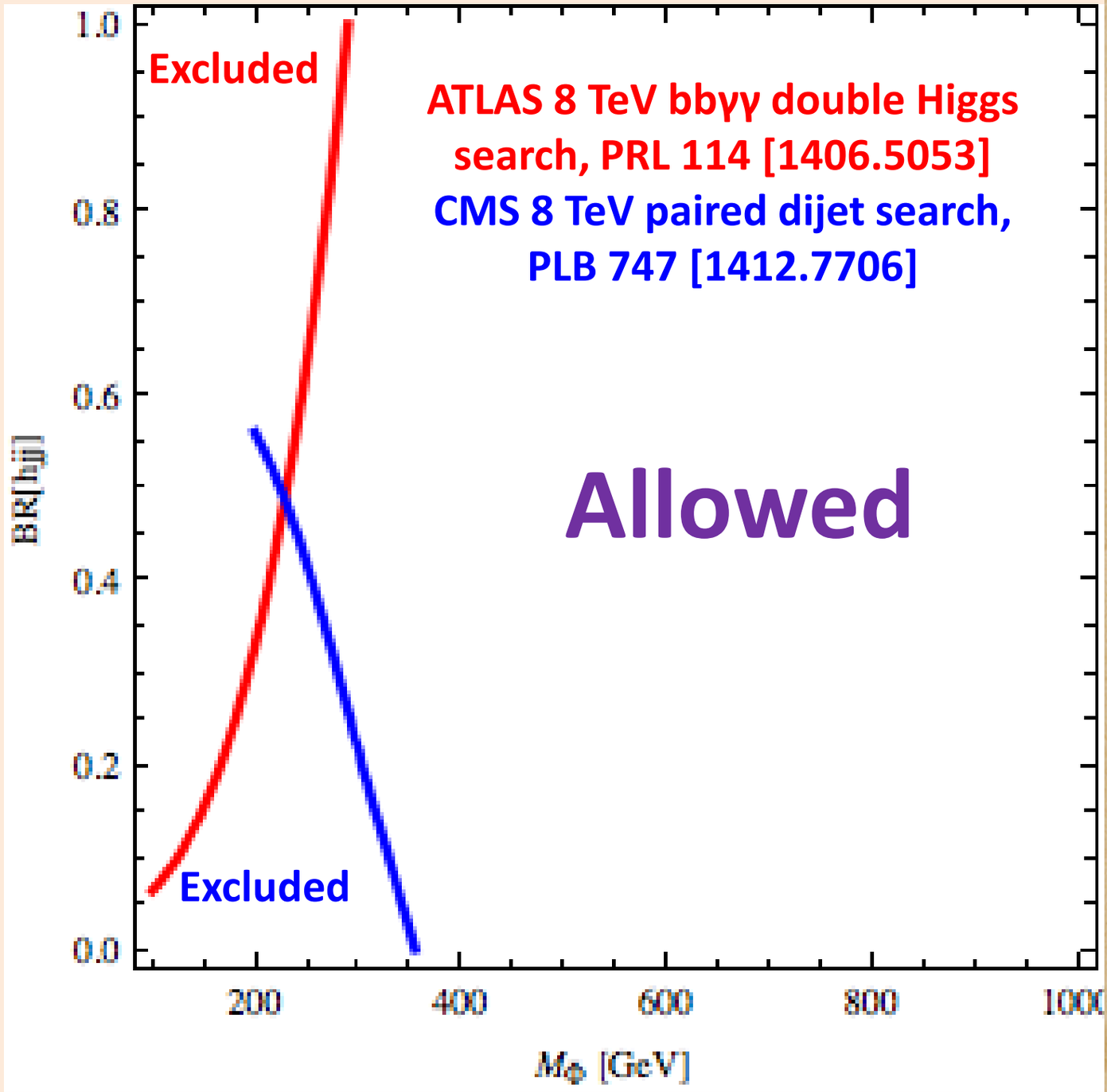
*https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGHH
**Degrande, Fuks, Hirschi, Proudom, Shao, PRD 91, [1412.5589]
***Fuks, Klasen, Lamprea, Rothering, JHEP 1401, [1310.2621]



Phenomenology and collider bounds

- Plan to adopt **benchmark simplified models**, check constraints
- Generate **efficiency tables** for contamination of single Higgs searches
- Identify key **differential Higgs distributions** for model discrimination

Simplified scalar color triplet



Higgs and DM

- Dark matter searches via monoHiggs production
- Complementarity of EFT and model approach to DM searches at the LHC

Dark matter @ the LHC WG

Basic observation:

In DM searches through monojets @ the LHC,
all simplified models look more or less the same

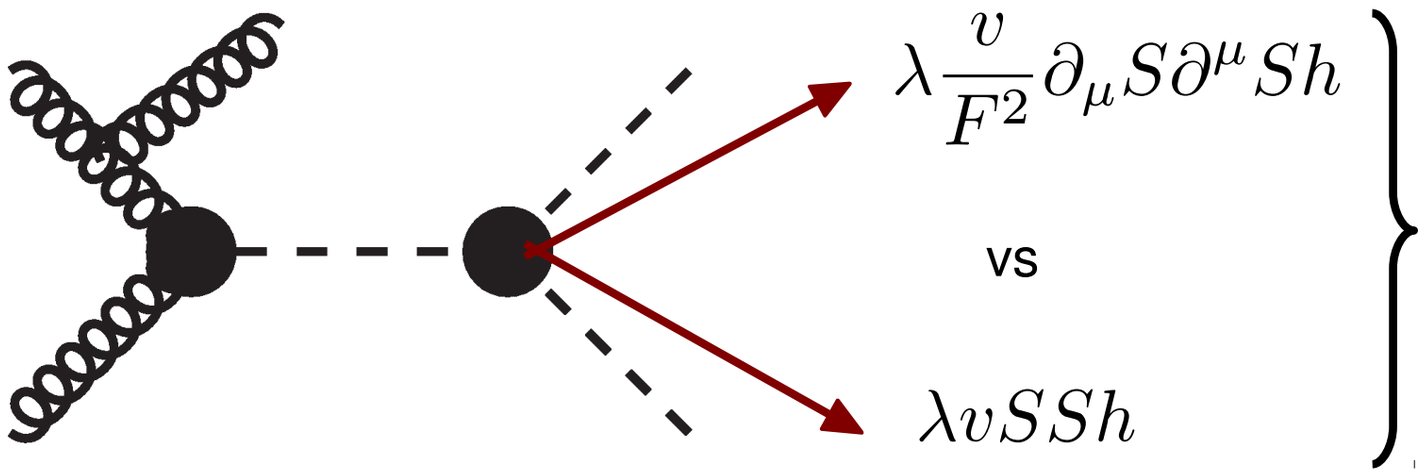
Our question:

How could one change the jet pT distribution?

Our idea:

Consider e.g. dark matter coupling to
the Higgs with derivatives

(e.g. from compositeness models)



Can the LHC
tell the difference?

Andreas Goudelis,Benjamin Fuks, Nishita Desai, Giacomo Polesello, Sanjoy Biswas,
Suchita Kulkarni, Dipan Sengupta, Björn Herrmann, Daniel Schmeier, Daniele Barducci

..and finally