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Pseudo Observables in Higgs Physics

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- Introduction [*Why PO?*]
- PO in Higgs decays
- PO in Higgs EW production
- PO vs. EFT, parameter counting & symmetry limits
- Conclusions

▶ *Introduction* [*Why PO?*]

The aim of the Higgs PO is to

characterize the properties of h(125) in generic BSM (with heavy NP) encoding the exp. results in terms of a limited set of simplified/idealized observables of easy theoretical interpretation (→ minimum th. bias)

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So far, this "characterization" has been achieved via the so called "κ-formalism"

$$\sigma(in \rightarrow \mathrm{h}+\mathrm{X}) \times \mathrm{BR}(\mathrm{h} \rightarrow fin\ ) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_{\mathrm{h}}} = \frac{\kappa_{in}{}^2\, \kappa_{fin}{}^2}{\kappa_{\mathrm{h}}{}^2}\, \sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}$$

Main virtues of the κ's (*defined as above*):

- Well-defined both on TH and EXP sides
- Clean SM limit [best up-to-date TH predictions recovered for $\kappa_i \rightarrow 1$]

Main problem:

- Loss of information on possible NP effects modifying the kinematical distributions

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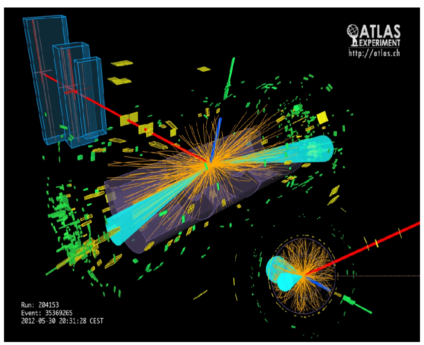
These "well-defined" κ's [*please never "break loops"!*] are nothing but a subset of the Higgs PO

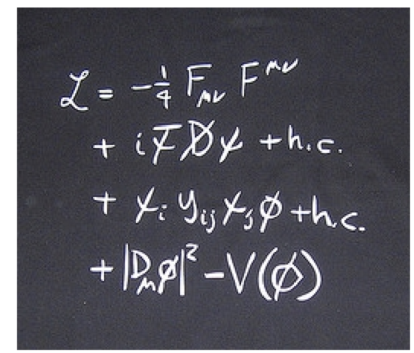
Aiming at high precision, in processes with non-trivial kinematics, we need a larger set of Higgs PO

<u>Introduction</u> [*Why PO?*]

- PO = *encoding of the exp. results in terms of a limited number of simplified/idealized observables of easy theoretical interpretation*
  Old idea - heavily used and developed at LEP [Bardin, Grunewald, Passarino, '99]

- The experimental determination of an appropriate set of PO will "help" and not "replace" any explicit NP approach to Higgs physics (*including the EFT*)





Experimental data — Pseudo Observables — Lagrangian parameters

The PO can be <u>computed</u> in terms of Lagrangian parameters in any specific th. framework (SM, SM-EFT, SUSY, ...)

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↓

- The PO should be defined from kinematical properties of <u>on-shell processes</u> (*no problems of renormalization, scale dependence, gauge dependence,…*)

- The theory corrections applied to extract them should be universally accepted as "NP-free" (*soft QCD and QED radiation*)

Introduction [*Why PO?*]

Some people ask the following question:
Why do we need to measure PO, given we can go to a “more fundamental level” and directly extract the Wilson coefficients of the EFT from data?

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Answer (I):

What is "more fundamental"?

A) The combination: $c_W(\mu)+c_{HW}(\mu)+\tan(\theta_W)[c_B(\mu)+c_{HW}(\mu)]$,

- *defined assuming a linear realization of the EWSB & employing the SILH basis for the EFT Lagrangian*
- *extracted computing amplitudes at LO in the EFT expansion, setting the renormalization scale μ=1 TeV (and assuming that at that scale NLO-EW effects are negligible)*

B) The partial width $\Gamma(h \to W_L W_L)$

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Answer (II):

There is no reason to consider Wilson coefficients and, more generally, Lagrangian parameters "more fundamental" than on-shell physical amplitudes (*or the elements of the S matrix*). Actually it is the opposite.

Lagrangians are noting but tools...

Extracting their parameters requires a series of additional assumptions, that we may change in the future with more data and/or better understanding of the underlying (BSM) physics theory.

...the "physics" is in the scattering amplitudes, hence in the PO.

Introduction

There are two main categories of PO:

A) "Ideal observables"

M_W, $\Gamma(Z \to ff)$, …

M_h, $\Gamma(h \to \gamma\gamma)$, $\Gamma(h \to Z\mu\mu)$, …
but also $d\sigma(pp \to hZ)/dm_{hZ}$ ...

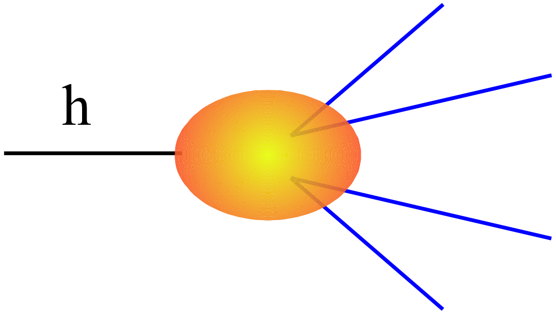
B) "Effective on-shell couplings"

$$g_Z^f,\ g_W^f, \ldots \leftrightarrow\ \Gamma(Z \to ff) = C\,[\,|g_Z^{f_L}|^2 + |g_Z^{f_R}|^2],\ \ldots$$

- Both categories are useful
(*there is redundancy having both, but that's not an issue...*).

- For B) one can write an effective Feynman rule, not to be used beyond tree-level (its just a practical way to re-write, *and code in existing tools,* an on-shell amplitude).

PO in Higgs decays



PO in Higgs decays

Multi-body modes

e.g. $h \to 4\ell$, $\ell\ell\gamma$, ...

↓

There is more to extract from data other than the κ_i

Two-body (on-shell) decays

[*no polarization properties of the final state accessible*]

e.g. $h \to \gamma\gamma$, $\mu\mu$, $\tau\tau$, bb

↓

The κ_i $(\leftrightarrow \Gamma_i)$ *is all what one can extract from data*

[+ *one more parameter if the polarization is accessible*]

▶ *PO in Higgs decays*

Multi-body modes
e.g. $h \to 4\ell,\ \ell\ell\gamma,\ \ldots$

↓

Form factors $\to f_i(s)$ [E.g.: $s = m^2_{\ell\ell}$]

↓

Momentum expansion of the *f.f.* around leading poles

E.g.: $$f_i^{\mathrm{SM+NP}} = \frac{\kappa_i}{s - m_Z^2 + i m_Z \Gamma_Z} + \frac{\epsilon_i}{m_Z^2} + O(s/m_Z^4)$$

Two-body (on-shell) decays

[*no polarization properties of the final state accessible*]

e.g. $h \to \gamma\gamma,\ \mu\mu,\ \tau\tau,\ bb$

General decomposition of the on-shell amplitudes based on Lorentz symmetry, Crossing symmetry, and Unitarity

Gonzales-Alonso *et al.* 1412.6038

PO in Higgs decays

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$\downarrow$

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- No need to specify any detail about the underlying theory but for the absence of light new states [*momentum expansion fully justified by Higgs kinematic*]
- The $\{\kappa_i, \epsilon_i\}$ thus defined are well-defined PO [*pole decomposition $\to$ gauge-invariant terms*] $\to$ systematic inclusion of higher-order QED and QCD (soft) corrections possible (and necessary...)

PO in Higgs decays [e.g.: $h \to 4l$]

The "physical meaning" of the parameters appearing in the $\{\kappa_i, \epsilon_i\}$ decomposition is not obvious at first sight...

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times\left[F_L^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_T^{e\mu}(q_1^2,q_2^2)\ T^{\alpha\beta} + F_{\rm CP}^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

longitudinal *transverse* *CP-odd*

↑

$$\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)} + \Delta^{\rm SM}_{\text{non-loc}}(q_1^2,q_2^2)\right)$$

double-pole *single-pole* *non-resonant (negligible)*

$$P_Z(q^2) = q^2 - m_Z^2 + im_Z\Gamma_Z$$

$$T^{\alpha\beta} = \frac{q_1\cdot q_2\ g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2}$$

$$\epsilon_{\gamma\gamma}^{\text{SM-1L}} \simeq 3.8\times 10^{-3}$$
$$\epsilon_{Z\gamma}^{\text{SM-1L}} \simeq 6.7\times 10^{-3}$$

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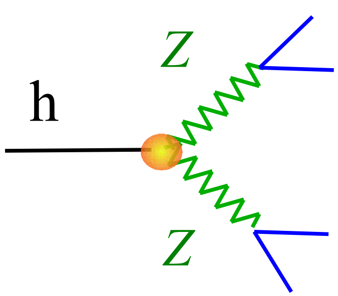
$$
\begin{aligned}
\mathcal{A} =\, & i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times \\
& \left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right)g^{\alpha\beta} + \Delta^{\rm SM}_{\text{non-loc}}(q_1^2, q_2^2)^{\alpha\beta}\right. \\
& + \left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\rm SM\text{-}1L}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\rm SM\text{-}1L}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)T^{\alpha\beta} + \\
& \left. + \left(\epsilon_{ZZ}^{\rm CP}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\rm CP}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\rm CP}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]
\end{aligned}
$$

"double Z-pole"



$$\boxed{\Gamma(h \to Z_L Z_L)} \equiv \frac{\Gamma(h \to 2e2\mu)[\kappa_{ZZ}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z \to 2\mu)} = 0.209\ |\kappa_{ZZ}|^2\ \text{MeV}$$

$$\boxed{\Gamma(h \to Z_T Z_T)} \equiv \frac{\Gamma(h \to 2e2\mu)[\epsilon_{ZZ}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z \to 2\mu)} = 0.0189\ |\epsilon_{ZZ}|^2\ \text{MeV}$$

$$\boxed{\Gamma^{\rm CPV}(h \to Z_T Z_T)} \equiv \frac{\Gamma(h \to 2e2\mu)[\epsilon_{ZZ}^{\rm CP}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z \to 2\mu)} = 0.00799\ |\epsilon_{ZZ}^{\rm CP}|^2\ \text{MeV}$$

PO in Higgs decays [e.g.: $h \to 4l$]

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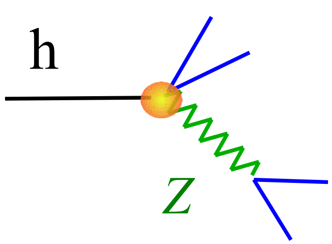
& + \left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\rm SM\text{-}1L}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\rm SM\text{-}1L}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) T^{\alpha\beta} + \\
& \left. + \left(\epsilon_{ZZ}^{\rm CP}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\rm CP}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma}^{\rm CP}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]
\end{aligned}
$$

“single Z-pole”

$$\boxed{\Gamma(h \to Z\ell^+\ell^-)} = 0.0366\, |\epsilon_{Ze}|^2 \text{ MeV}$$



N.B.: these contact terms are the only possible sources of flavor non-universality.

PO in Higgs decays

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PO	Physical PO	Relation to the eff. coupl.
$\kappa_f,\ \lambda_f^{\rm CP}$	$\Gamma(h \to f\bar{f})$	$= \Gamma(h \to f\bar{f})^{(\rm SM)}[(\kappa_f)^2 + (\lambda_f^{\rm CP})^2]$
$\kappa_{\gamma\gamma},\ \lambda_{\gamma\gamma}^{\rm CP}$	$\Gamma(h \to \gamma\gamma)$	$= \Gamma(h \to \gamma\gamma)^{(\rm SM)}[(\kappa_{\gamma\gamma})^2 + (\lambda_{\gamma\gamma}^{\rm CP})^2]$
$\kappa_{Z\gamma},\ \lambda_{Z\gamma}^{\rm CP}$	$\Gamma(h \to Z\gamma)$	$= \Gamma(h \to Z\gamma)^{(\rm SM)}[(\kappa_{Z\gamma})^2 + (\lambda_{Z\gamma}^{\rm CP})^2]$
κ_{ZZ}	$\Gamma(h \to Z_L Z_L)$	$= (0.209\ \rm MeV) \times \lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h \to Z_T Z_T)$	$= (1.9 \times 10^{-2}\ \rm MeV) \times \lvert\epsilon_{ZZ}\rvert^2$
$\epsilon_{ZZ}^{\rm CP}$	$\Gamma^{\rm CPV}(h \to Z_T Z_T)$	$= (8.0 \times 10^{-3}\ \rm MeV) \times \lvert\epsilon_{ZZ}^{\rm CP}\rvert^2$
ϵ_{Zf}	$\Gamma(h \to Zf\bar{f})$	$= (3.7 \times 10^{-2}\ \rm MeV) \times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h \to W_L W_L)$	$= (0.84\ \rm MeV) \times \lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h \to W_T W_T)$	$= (0.16\ \rm MeV) \times \lvert\epsilon_{WW}\rvert^2$
$\epsilon_{WW}^{\rm CP}$	$\Gamma^{\rm CPV}(h \to W_T W_T)$	$= (6.8 \times 10^{-2}\ \rm MeV) \times \lvert\epsilon_{WW}^{\rm CP}\rvert^2$
ϵ_{Wf}	$\Gamma(h \to Wf\bar{f}')$	$= (0.14\ \rm MeV) \times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$

→ PO section in YR4

PO in Higgs decays [e.g.: $h \to 4l$]

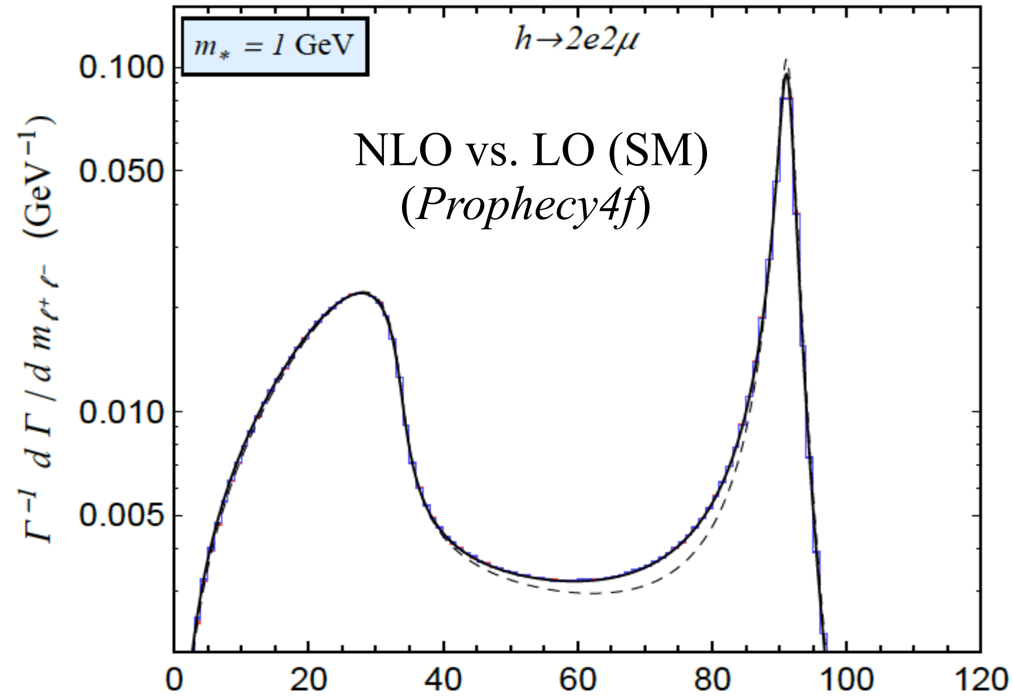
"Dressing" with QED radiation

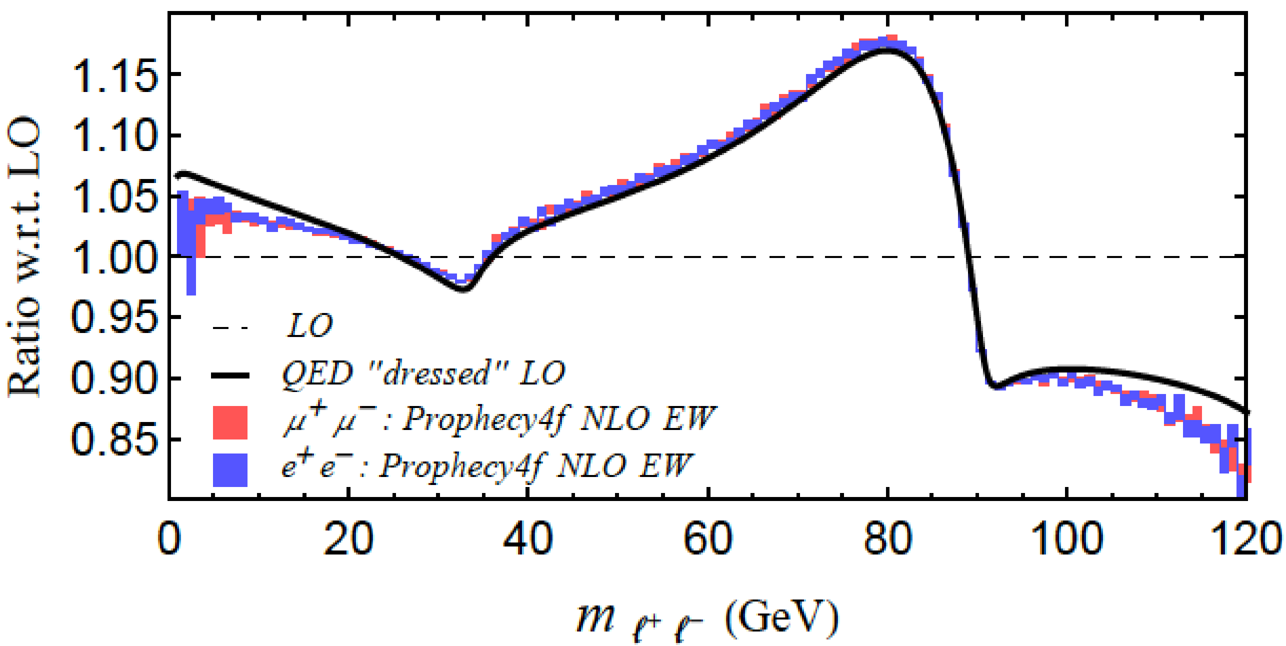
↓

excellent description of NLO SM
(*when setting PO to SM values*)

↓

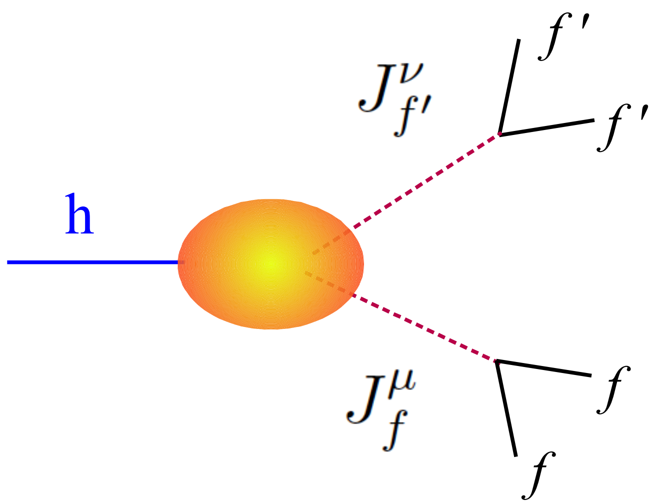
tool able to describe
(*general*) NP beyond LO



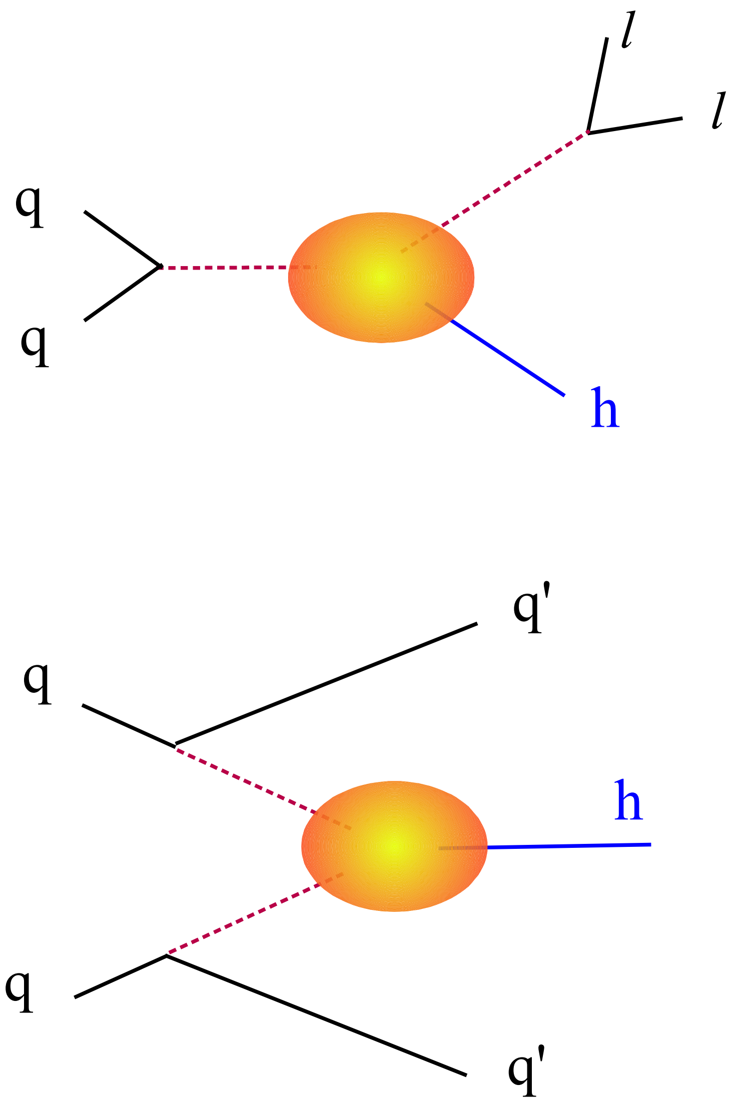


Bordone *et al.* 1507.02555

PO in Higgs EW production



vs.



PO in Higgs EW production

The same Green Function controlling $h \to 4f$ decays is accessible also in $pp \to hV$ and $pp \to h$ via VBF, i.e. the two leading EW-type Higgs production processes (*N.B.: this follows from crossing symmetry no need to invoke any EFT...*)

$$\langle 0|\mathcal{T}\left\{J_f^\mu(x), J_{f'}^\nu(y), h(0)\right\}|0\rangle$$

Same approach as in $h \to 4f$ (and, to some extent, same PO) but for three important differences:

Greljo et al. 1512.06135

- different flavor composition ($q \leftrightarrow \ell$) $\to$ new param. associated to the physical PO $\Gamma(h \to Zqq)$ & $\Gamma(h \to Wud)$

trivial

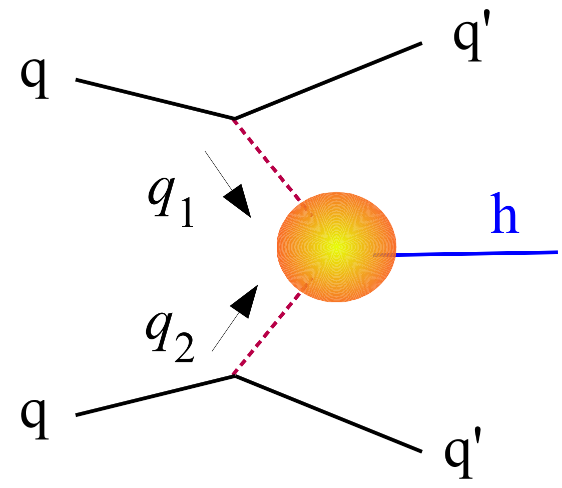
- large impact of (facotrizable) QCD corrections

conceptually easy

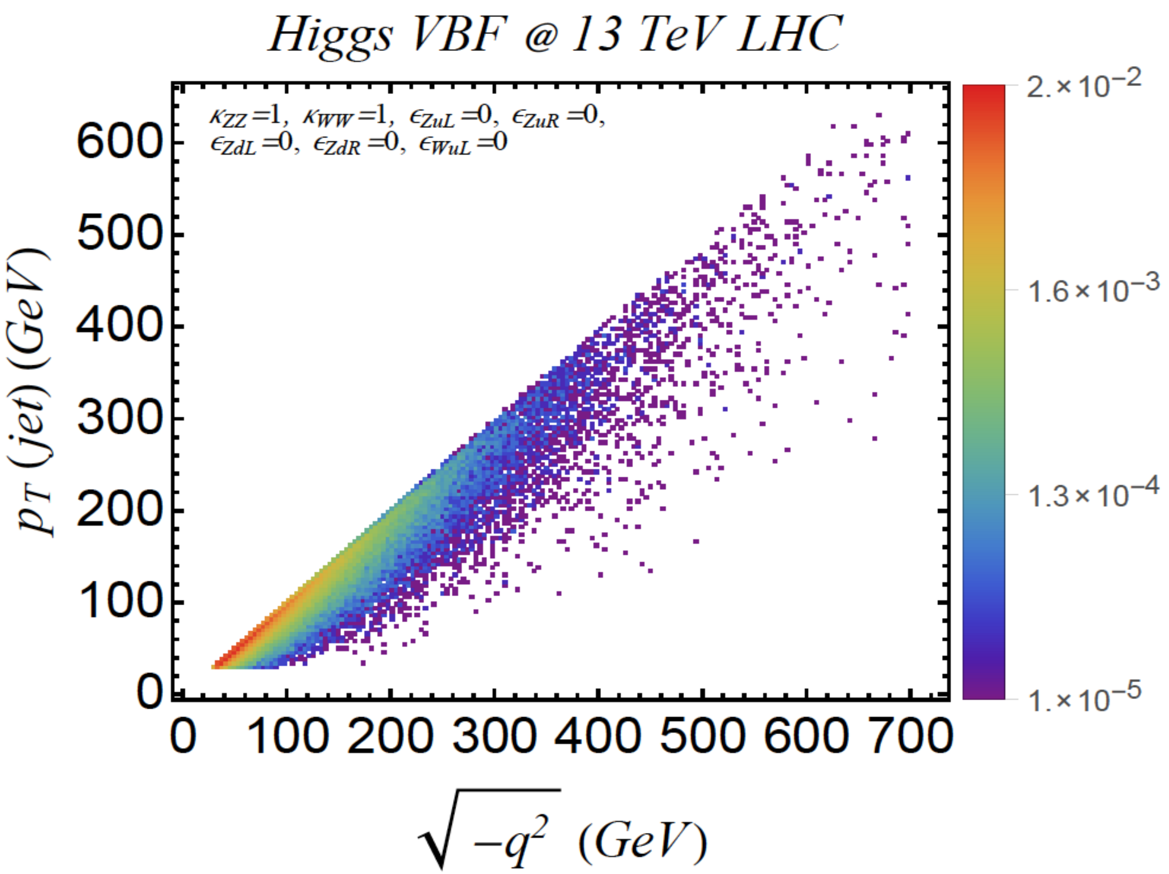
- different kinematical regime: momentum exp. not always justified (*large momentum transfer*)

delicate point

PO in Higgs EW production [the VBF case]



A practical problem is also posed by the difficulty to directly access the key variables for the f.f. decomposition → need to construct a proxy

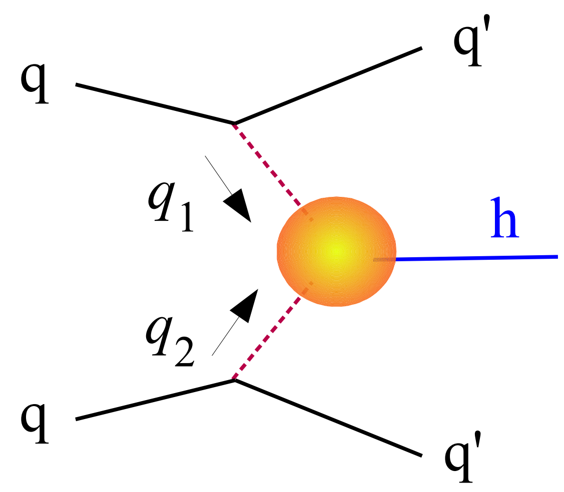


strong correlation

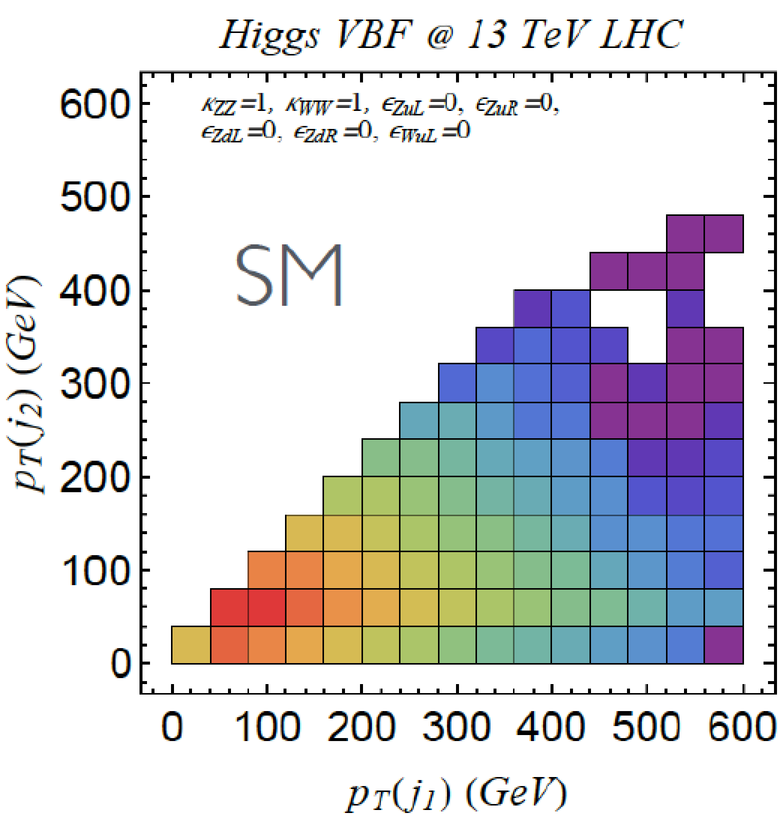
$$q_i^{\,2} \leftrightarrow -\,p_{T_i}^{\;2}$$

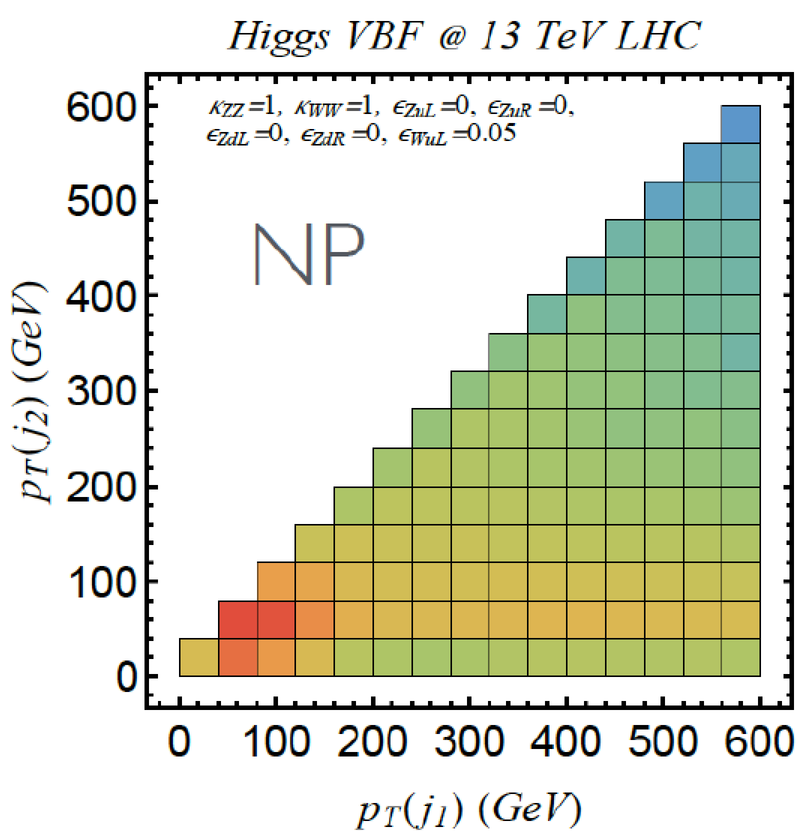
$$F(q_1^{\,2},q_2^{\,2}) \leftrightarrow \frac{d^2\sigma}{dp_{T_1}dp_{T_2}}$$

▶ PO in Higgs EW production [the VBF case]

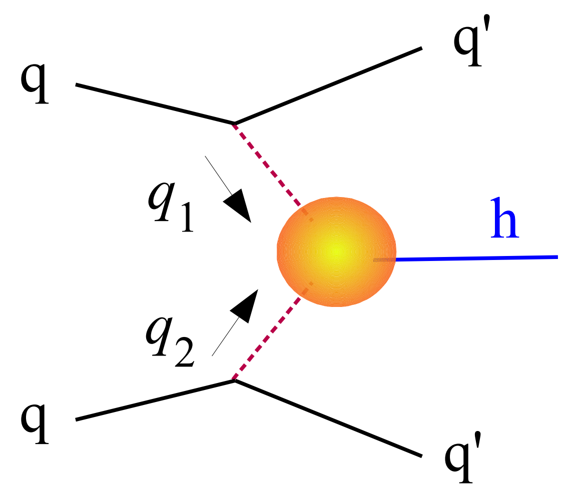


Key experimental distribution: $$\frac{d^2\sigma}{dp_{T_1}dp_{T_2}}$$





▶ *PO in Higgs EW production* [the VBF case]



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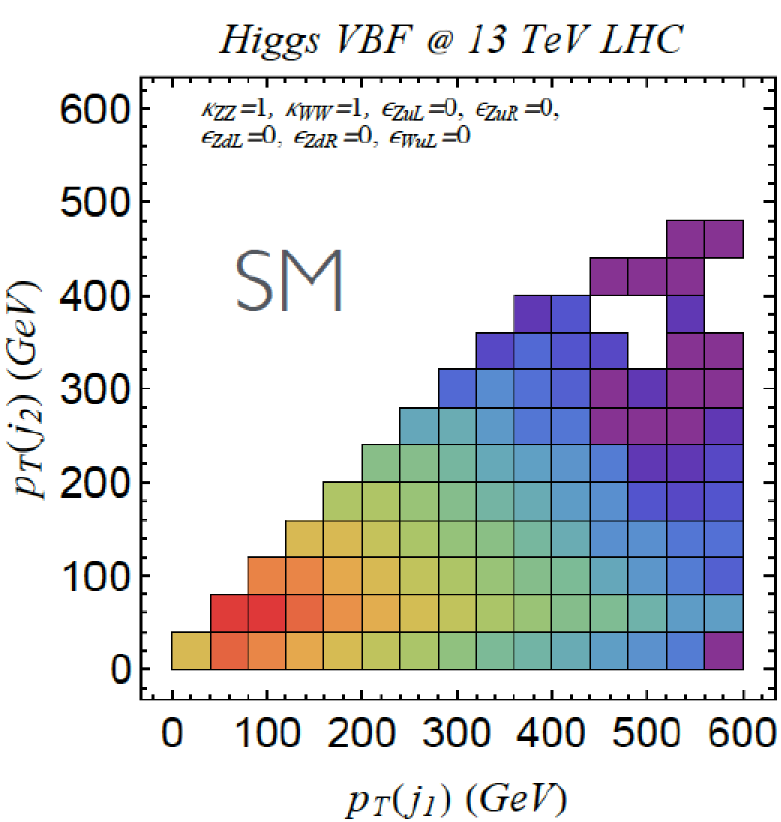
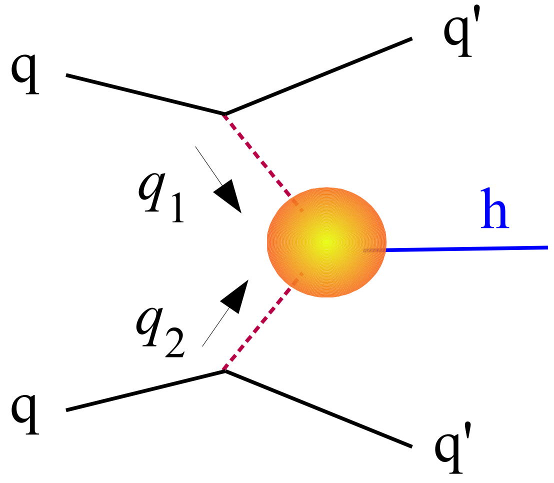


General procedure:

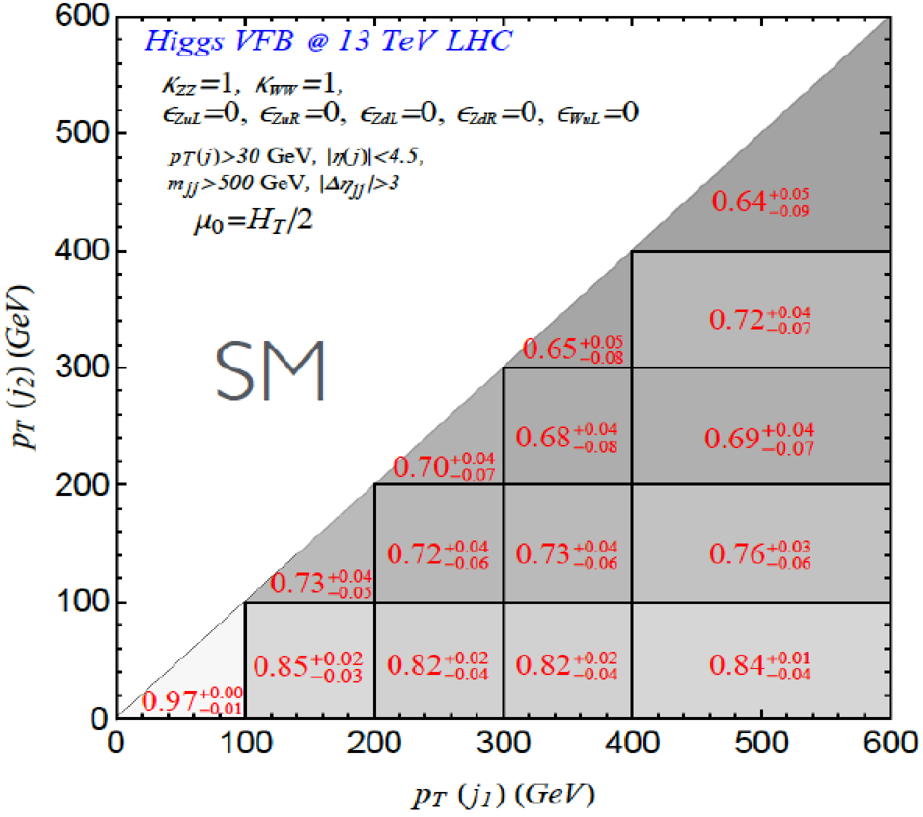
- Measure the PO close to the threshold region, setting a cut on the “dangerous” kinematical variables [→ a-posteriori data-driven check of the validity of the momentum expansion ↔ definition of threshold region]
- Report the cross-section as a function of the kinematical variables in the high-momentum region [→ natural link/merging with template cross-section]

▶ PO in Higgs EW production [the VBF case]



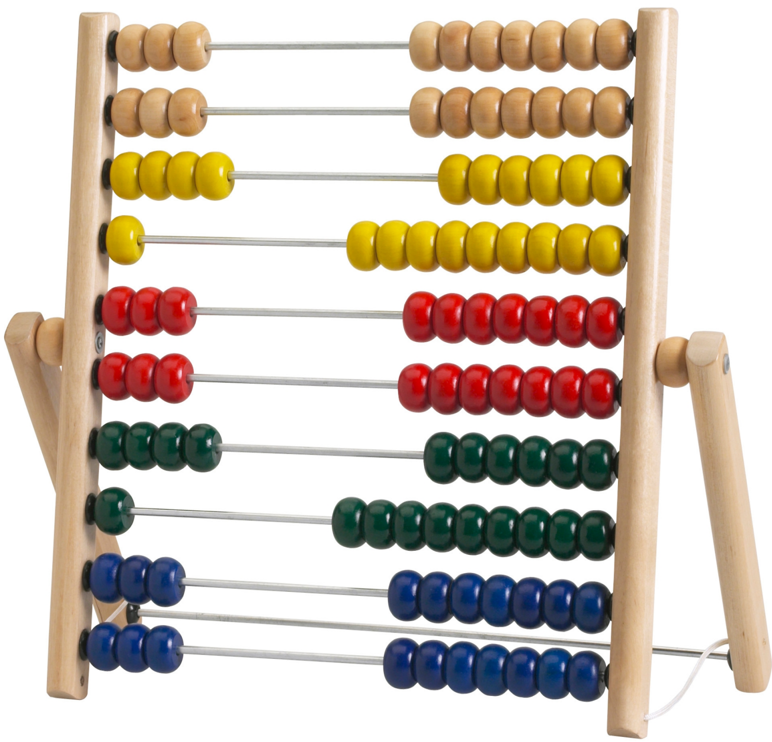
Key experimental distribution: $$\frac{d^2\sigma}{dp_{T_1}dp_{T_2}}$$

$d\sigma^{NLO}/d\sigma^{LO}$



Straightforward inclusion of (factorizable) NLO QCD corrections, which have a sizable impact on the distribution

PO vs. EFT, parameter counting & symmetry limits



PO vs. EFT

PO and couplings in EFT Lagrangians are *intimately related but are not the same thing* (on-shell amplitudes vs. Lagrangians parameters) → full complementarity

- The PO are calculable in any EFT approach (*linear, non-linear, LO, NLO...*)
  - In the limit where we work at the tree-level in the EFT there is a simple linear relation between PO and EFT couplings: each PO represent a unique linear combination of couplings of the most general Higgs EFT.
  - This does not hold beyond the tree-level (the PO do not change, but their relation to EFT couplings is more involved....)

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  - In the limit where we work at the tree-level in the EFT there is a simple linear relation between PO and EFT couplings: each PO represent a unique linear combination of couplings of the most general Higgs EFT.
  - This does not hold beyond the tree-level (the PO do not change, but their relation to EFT couplings is more involved....)

⬇

PO essential ingredient for EFT beyond LO

Ghezzi *et al.* 1505.03706
Passarino & Trott, YR4

More generally (*linear, non-linear, LO, NLO...*):

- PO → inputs for EFT coupling fits
- EFT → predictions of relations between different PO sets (that can be tested)

▶ PO vs. EFT

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  - This does not hold beyond the tree-level (the PO do not change, but their relation to EFT couplings is more involved....)
- For Higgs production also the PO involve an expansion in momenta; however, this is different than the operator expansion employed within the EFT
  - To define the PO we expand only on a measurable kinematical variables, this is why the validity of the *expansion can be checked directly by data* (on the same process used to determine the PO)
- In each process the PO are the maximum number of independent observables that can be extracted by that process only → naturally optimized for data analyses

Parameter counting & symmetry limits

Number of independent PO for EW Higgs decays

PO set with maximal symmetry [CP + Lepton Univ + cust.] ⟶ no symmetry

$h \to 4\mu$, $4e$, $2e2\mu$, $2\mu2\nu$, $2e2\nu$, $e\mu2\nu$, $\gamma\gamma$, $ee\gamma$, $\mu\mu\gamma$

Minimal set:

$\kappa_{ZZ}, \kappa_{Z\gamma}, \epsilon_{ZZ}$

$\kappa_{\gamma\gamma}, \epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{We_L}$

Without custodial symm.:

$\kappa_{WW}, \epsilon_{WW}$

$\epsilon_{Z\nu_\mu}$

7 ⟶ 10 (no CS) ⟶ 20 (no symm.)

Parameter counting & symmetry limits

Number of independent PO for EW production

PO set with maximal symmetry [CP + Lepton Univ + cust.] ⟶ no symmetry

	Minimal set:	*Without custodial symm.:*
VBF, Zh, Wh	$\kappa_{ZZ}, \kappa_{Z\gamma}, \epsilon_{ZZ}$	$\kappa_{WW}, \epsilon_{WW}$
	$\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$	ϵ_{Wu_L}

7 ⟶ 10 (no CS) ⟶ 20 (no symm.)

Parameter counting & symmetry limits

Number of independent PO for EW Higgs decays + EW production + Yukawa modes ($h \to ff$):

PO set with maximal symmetry [CP + Lepton Univ + cust.] → no symmetry

	Minimal set:	*Without custodial symm.:*
Prod. & decays	$\kappa_{ZZ}, \kappa_{Z\gamma}, \epsilon_{ZZ}$	$\kappa_{WW}, \epsilon_{WW}$
EW decays only	$\kappa_{\gamma\gamma}, \epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{We_L}$	$\epsilon_{Z\nu_\mu}$
EW prod. only	$\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$	ϵ_{Wu_L}
	11 → 15 (no CS) → 32 (no symm.)	
Yukawa modes	$\kappa_b, \kappa_\tau, \kappa_c, \kappa_\mu$	4 → 8 (no symm.)
	(as in the original κ-formalism)	
gg→h & ttH	κ_g, κ_t	2 → 4 (no symm.)

Conclusions

- The PO represent a general tool for the exploration of Higgs properties (in view of high-statistics data), with minimum loss of information and minimum theoretical bias → *full complementary to EFT* (and explicit BSM)

- The formalism is now fully developed for Higgs decays and Higgs EW productions [→ *see PO section in YR4*]. NLO tools are ready for all relevant Higgs decay channels and (almost) ready for EW production (VBF+VH) [http://www.physik.uzh.ch/data/HiggsPO]

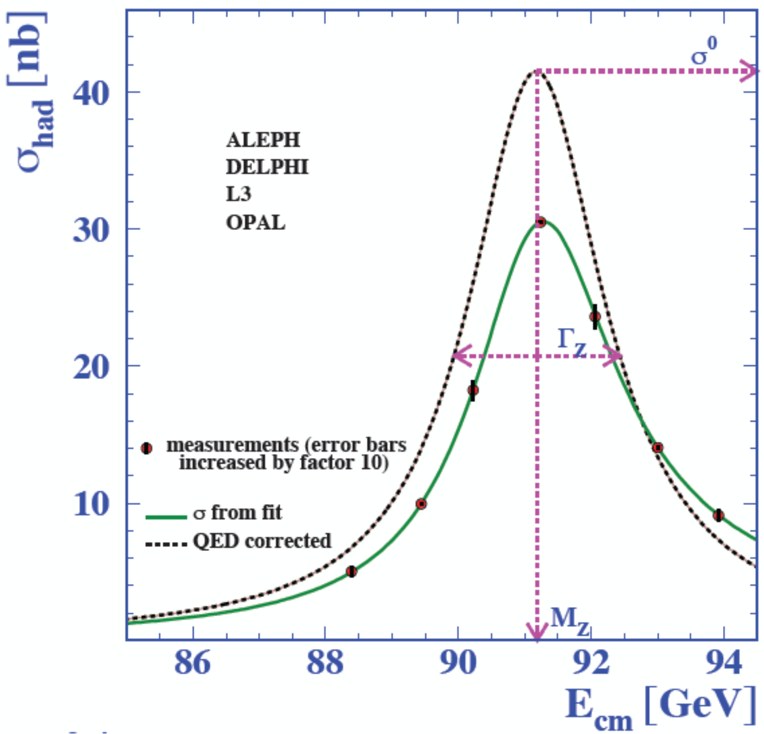
It's time to start doing the right thing...

- *kappa's from "broken loops"*
- *Incomplete lists of EFT ops.*
- *Undefined off-shell h → ZZ* f. factors*
- ...


Backup

▶ *PO @ LEP* [Bardin, Grunewald, Passarino, '99]

The goal was to parametrise on-shell Z decays as much model-independently as possible.



1) Unfold QED (and/or QCD) soft radiation effect

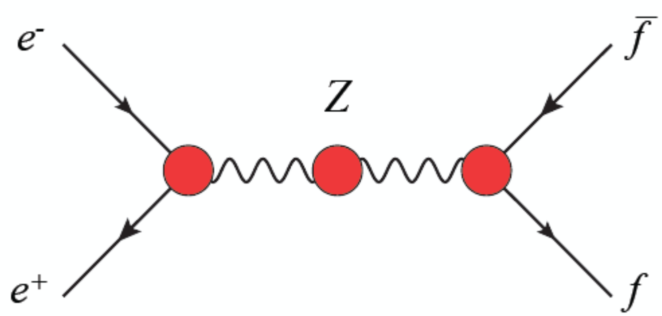
$$\sigma(s) = \int_{4m_f^2/s}^{1} dz\, H_{\rm QED}^{\rm tot}(z,s)\sigma_{\rm ew}(zs).$$

2) Parametrize the shape with some PO defined at amplitude level:

$$m_Z, \Gamma_Z$$

Lineshape

$$\chi(s) = \frac{G_F m_Z^2}{8\pi\sqrt{2}} \frac{s}{s - m_Z^2 + is\Gamma_Z/m_Z}$$



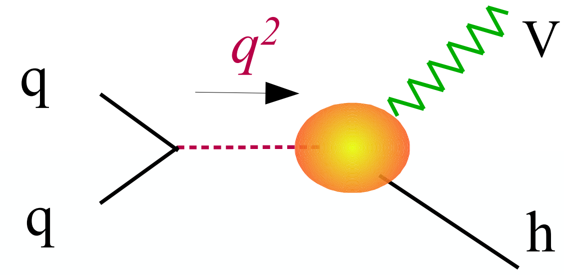
Parametrise the on-shell $Z\bar{f}f$ vertex as $\gamma_\mu\left(\mathcal{G}_V^f + \mathcal{G}_A^f\gamma_5\right)$

The PO are defined as

$$\boxed{g_V^f = {\rm Re}\,\mathcal{G}_V^f, \qquad g_A^f = {\rm Re}\,\mathcal{G}_A^f}$$

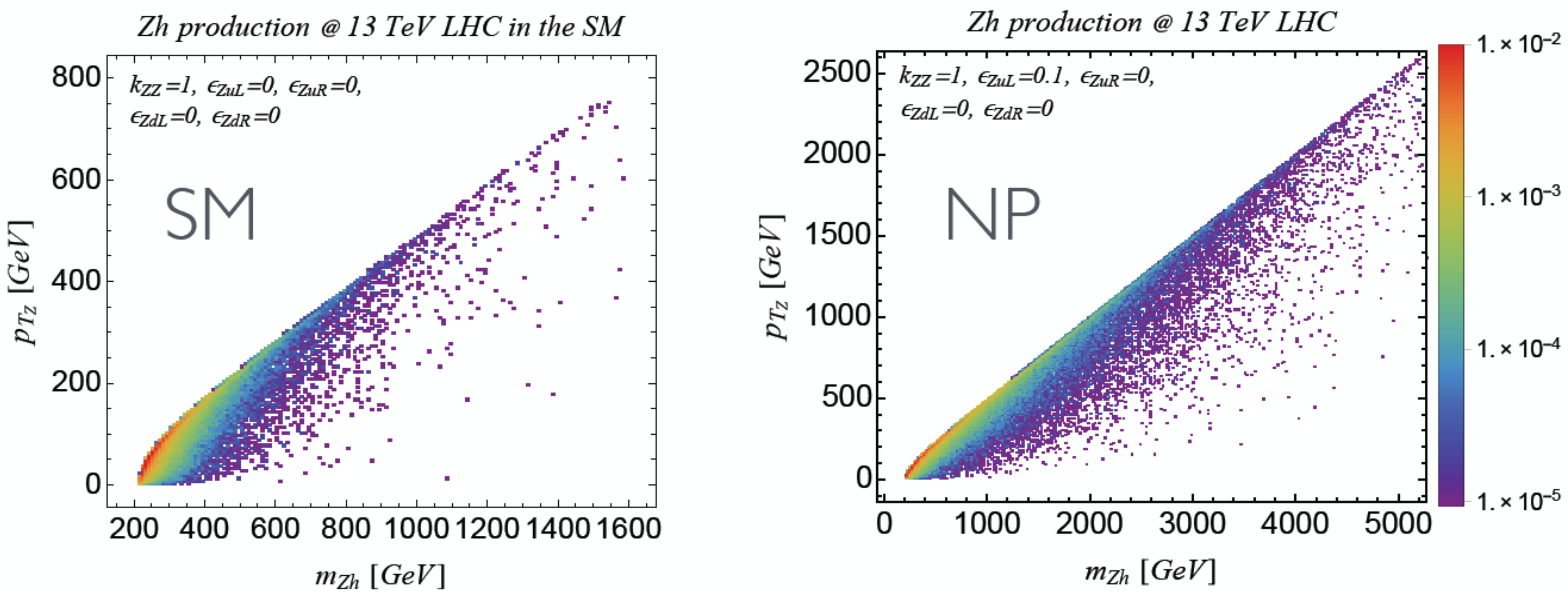
3) Fit the PO from data

PO in Higgs EW production [VH]



Practical problem:

- process governed by $q^2 = m^2_{Vh}$
- not measurable in all decay modes (V=W or H→WW)

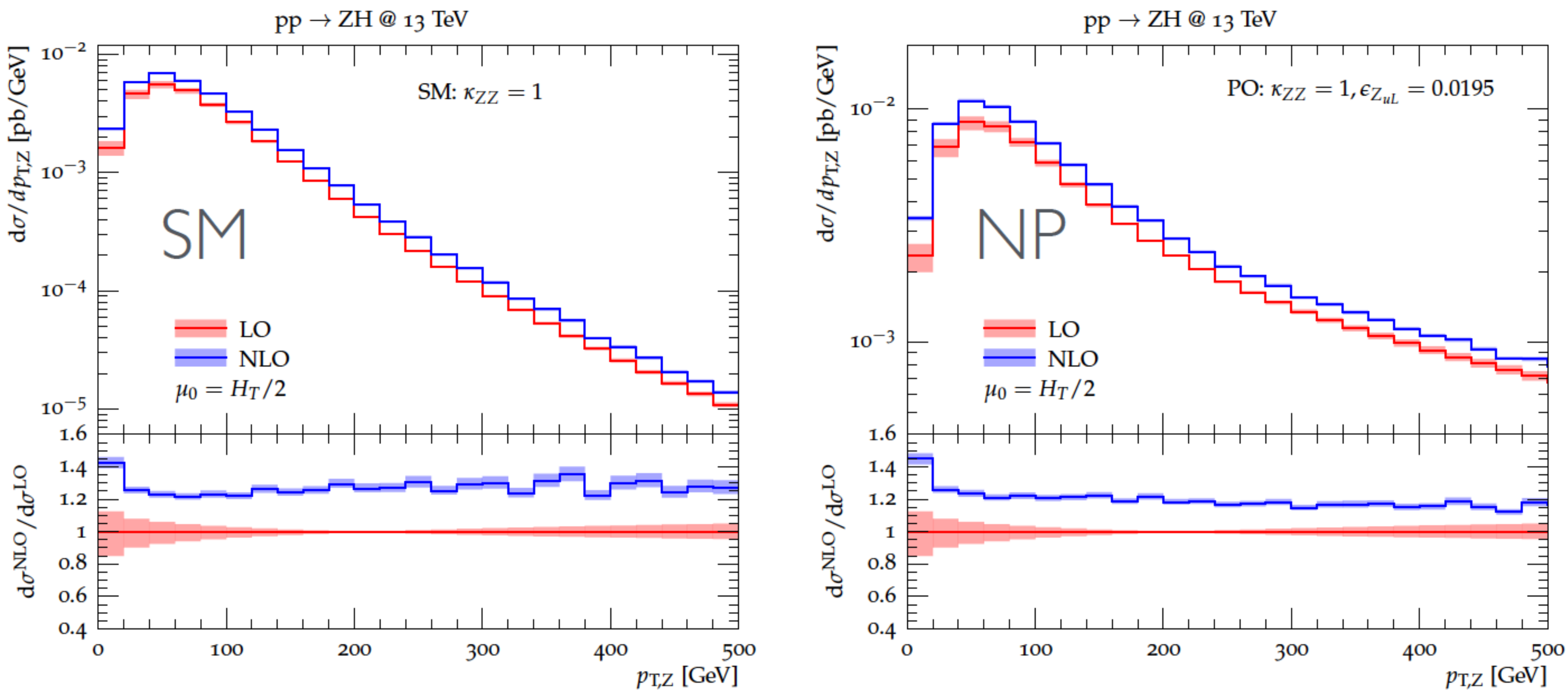


$$m^2_{Vh} \to 4p^2_{\mathrm{T}} \qquad \text{for} \qquad |p_{\mathrm{T}}| \to \infty$$

PO in Higgs EW production [VH]

NLO QCD corrections in PO

- process independent implementation of **Higgs PO @ NLO QCD** in Sherpa+OpenLoops
- via Sherpa's UFO functionality (1412.6478)



- NP shapes largely unaffected by QCD corrections
- detailed study @ NLO+PS in preparation

Dynamical constraints

Computing the PO in specific EFT (e.g.: *the linear EFT*) we get additional dynamical constraints dictated by the specific extra dynamical assumption of the EFT employed (e.g.: *h belongs to the $SU(2)_L$ doublet breaking the EW symmetry*)

The most powerful of such constraints is the link between the contact terms and EW precision measurements performed at LEP:

EPWO + Linear EFT $\longrightarrow$ small (tiny) & flavor-universal ε_{Zl}

Contino *et al.*, 1303.3876
Pomarol & Riva, 1308.2803

$\downarrow$

Excellent opportunity to test from data (via $h \to 4l$)
if h belongs to a pure $SU(2)_L$ doublet

G.I., Manohar, Trott, 1305.0663
G.I., Trott, 1307.4051

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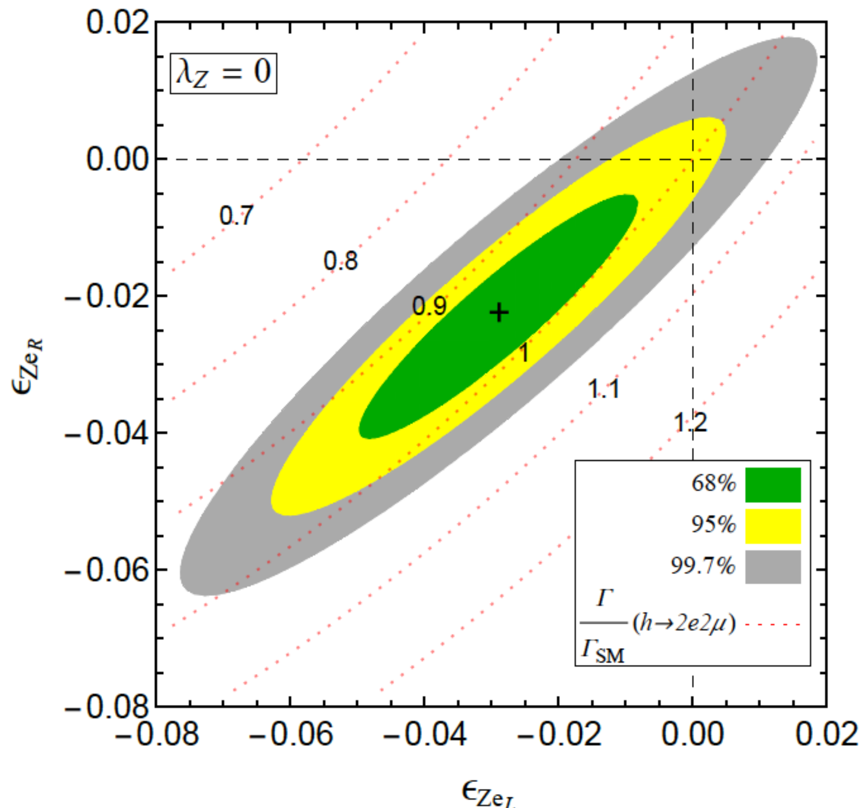

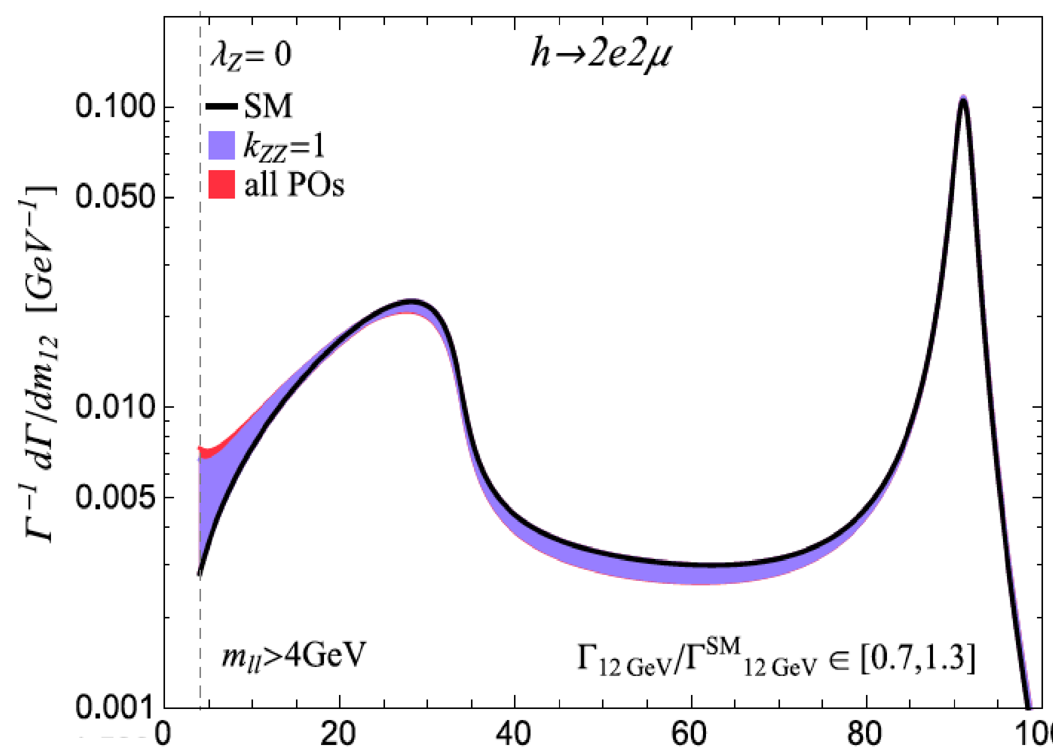

Gonzales-Alonso, Greljo, G.I., Marzocca, arXiv:1504.04018

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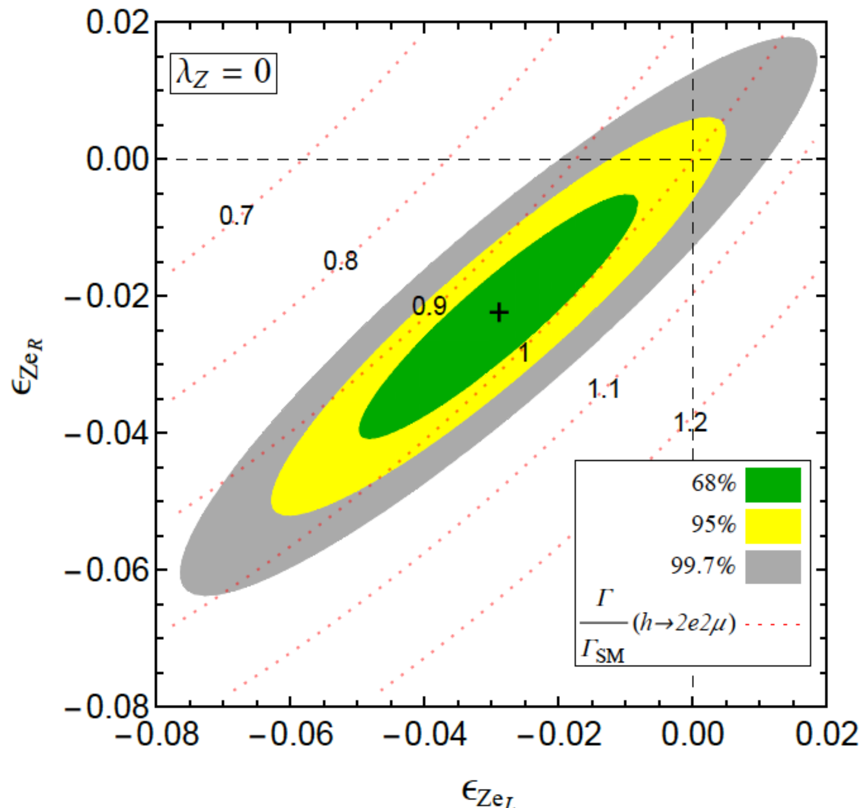

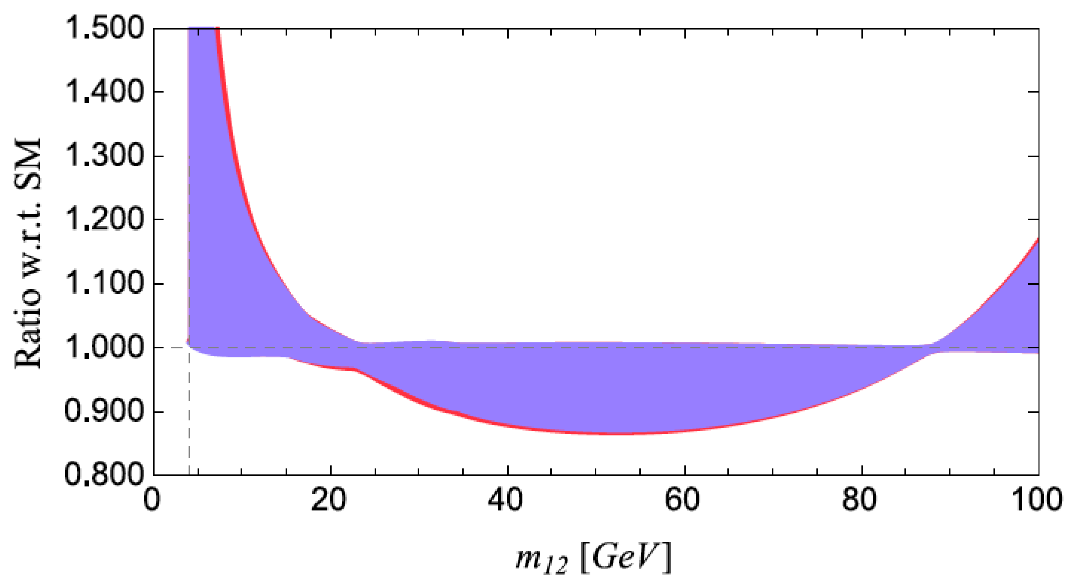

Gonzales-Alonso, Greljo, G.I., Marzocca, arXiv:1504.04018